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A 150-year avian bio-inventory on a global biodiversity hotspot island

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ABSTRACT

Knowledge of species inventory is crucial for identifying when and where species occur historically and geographically; yet few studies have gathered heterogeneous data from different sources to understand long-term spatio-temporal species dynamics in response to ongoing global environmental change. Hainan Island, China is a global biodiversity hotspot and an important transit station on the longest bird migratory flyway in the world. Here, we compiled a comprehensive database including 452 bird species recorded on Hainan Island. The records covered 150 years (1868–2017) and were sourced from published reports, museum specimens, field surveys, and citizen bird watching data. We showed that, since the first scientific report by Swinhoe (1869), the bird records on Hainan Island have increased with more intensive sampling efforts, wider survey areas, and more diverse investigation objectives. Overall, the birds recorded on Hainan Island were of the Oriental type, and the majority were tropical residents. Natural forests and coastal wetlands hosted the highest species richness, but some species were only recorded before 1910, indicating a high probability of species extinction owing to the loss of natural forest and wetland habitats. The spatial distribution of the birds showed a clear altitudinal pattern with more species below altitudes of 500 m. These species are not under effective protection because most of the protected areas are located between 500 and 1000 m. Our study provides a fundamental baseline dataset of the historical bird records on Hainan Island. We suggest that future conservation efforts on Hainan's birds should target the tropical endemic species and those sensitive to climate change to maximise the preservation of avian biodiversity in China.

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1. Introduction

Global biodiversity is declining rapidly at an unprecedented rate in the current era of the Anthropocene (Ceballos et al., 2015). The effective assessment of species conservation status is first dependent on reliable historical records, which are fundamental for developing targeted conservation strategies (Mace, 2013). Annotated records across taxa are abundant. However, they vary greatly in data quality, as most are usually short-term, fragmented, and incomplete because they are based

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on surveys by different research teams with varying aims. Understanding how to integrate these fragmented recordings into a unified inventory has been a bottleneck in evaluating the temporal changes in species distributions and the impacts of environmental changes on biodiversity (Mace, 2013).

Birds are among the taxa with the most rapid population declines worldwide (Monastersky, 2014). They are particularly sensitive to environmental disturbances such as habitat modifications, climate warming, and alien species invasions (Patten et al., 2010; Godet et al., 2011; Davey et al., 2012; Gils et al., 2016; Blackburn et al., 2019). This is particularly the case for insular birds, which are more vulnerable than the mainland species (Bellard et al., 2016). However, as a charismatic group, there is a relatively long investigation history and abundant observations by both individual bird watchers and institutions (Morrison, 1986; Koskimies, 1989), providing a unique opportunity to compile a bio-inventory across long temporal scales.

Hainan Island, China, is a global biodiversity hotspot (Myers et al., 2000) and one of the 200 key protection bioregions of the world, according to WWF (Olson and Dinerstein, 1998). Hainan Island is located in the south of China and the north of the Indo-Malay tropical area. It has a large proportion of forests and wetlands, providing birds with various habitats for food and reproduction; thus, it harbours abundant bird species that have been scientifically investigated for at least 150 years (Swinhoe, 1869). Hainan Island is also an important transit station on the longest bird migratory flyway in the world (BirdLife International, 2018; He et al., 2017). However, birds on the island suffer from habitat loss through human activities (Lin et al., 2017). For instance, a recent study showed that both the species richness and population abundance of birds on Hainan Island have decreased dramatically during the past two decades owing to the loss of natural forests (Xu et al., 2017). Some endangered and endemic species, such as the Hainan partridge (*Arborophila ardens*), are now only rarely observed in some primary and secondary forests (Yang, 2007). Thus, it is particularly urgent to establish a long-term bird bio-inventory of the island to facilitate our understanding of bird dynamics under anthropogenic pressures.

Since the first bird record and discovery of the Fork-tailed Sunbird (*Aethopyga christinae*) in 1868 (Swinhoe, 1869), there have been more than 80 independent studies surveying birds from the coastal wetlands to the central mountainous areas (Table S1, Table S2). However, most surveys vary in area, approaches, and objectives, making it difficult to obtain a unified, comparable, and systematic bird inventory on the island. In addition, the scientific names of some historical records need to be updated based on modern world bird checklists to reflect the updated taxonomy of birds. Furthermore, newly described species and new provincial records from more comprehensive sampling efforts are also needed to be incorporated. Here, we systematically collected and standardised the taxonomic and spatial distribution information of the bird species on Hainan Island for the past 150 years (1868–2017). This inventory can be used as a baseline for future assessments of the bird population dynamics and development of conservation planning on the island, which is under increasing anthropogenic pressures.

2. Materials and methods

2.1. Study area

Hainan Island is located in southern China (Fig. 1) and is the largest Chinese tropical island with an area of 34,400 km^2. The island topography represents a layered vertical, circular horizontal pattern from the mountains and hills in the centre of the island to platforms and plains in the coastal areas (Jiang et al., 2015). The diverse terrain and monsoon climate results in high bird species richness (Zheng, 2017).

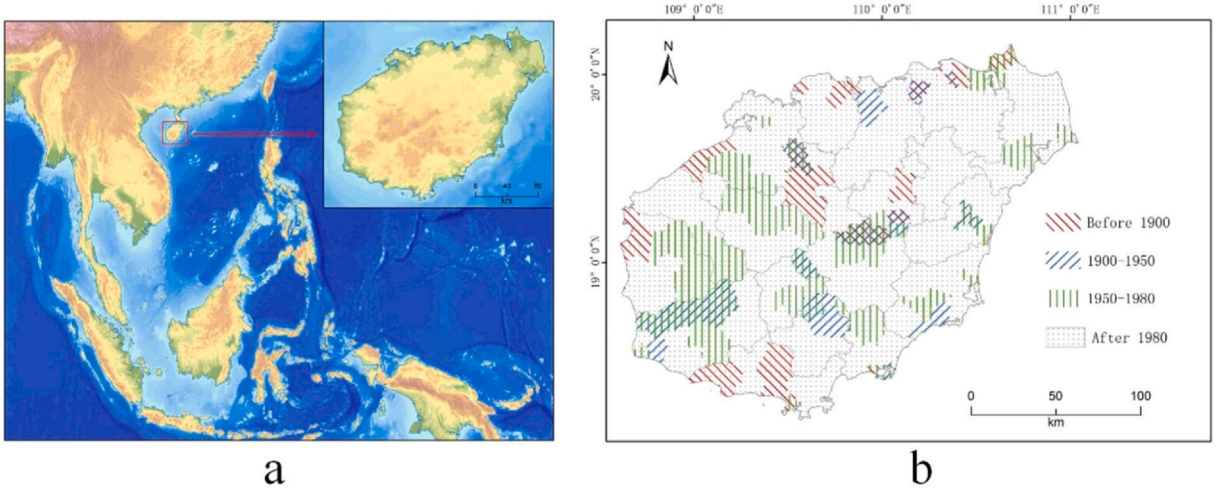


Fig. 1. Map of the study area, showing the location of Hainan Island (a) and spatial-temporal variations in main sampling areas during the past 150 years (b).

2.2. Data collection

2.2.1. Literature review

To collect the recorded information on Hainan Island's birds, we applied a general PRISMA approach (Moher et al., 2009) based on 25 different combinations of key words, such as (Hainan) * {(bird + avian + fauna + animal + species) * (1 + survey + report + checklist + catalogue)} using a total of nine databases (Table S1). We also re-conducted the searches using the citations within the initial literature. All these searches yielded a total of 86 scientific articles from 1868 to 2017 (Table S2).

2.2.2. Museum specimens

Scientists often collect bird specimens during field surveys. As field-survey reports provide bird specimen information, we consulted six online platforms of institutions, including the American Museum of Natural History, National Zoological Museum of China, Yamashina Institute for Ornithology Specimen Database, Museum of Guangdong Institute of Entomology, and the sub-platform of China National Specimen Sharing Platform Animal Specimen where the specimens had been deposited. We obtained a total of 3961 records of bird specimens from these databases, and we verified the species name, and collection time and location.

2.2.3. Field surveys

In addition to the published literature and museum records, over the past 20 years we have organised and conducted several field surveys across the whole island, which have accumulated a large dataset of local birds. There were two main types of field surveys: ones covered most of the island, including two standard and extensive transect surveys between 1997 and 1998 and 2012–2013 (Xu et al., 2017), the second wetland bird survey in 2012, the first national winter water bird census survey in 2016, and the Hainan animal census survey in 2016. The other type focused on ten independent surveys in representative national protected areas on the island. These field surveys were mainly conducted during the breeding season (March–October), and all investigators were bird experts who were familiar with the avian species in South China. All participants were trained to guarantee consistency in the survey methods, species identification, distance estimates, and recording approaches (Buckland et al., 2005). Overall, data from14 field surveys were used in the present study, which covered almost all accessible areas on Hainan Island (Fig. S1).

2.2.4. Citizen science data

During the past 20 years, citizen science has developed rapidly as an important supplement to traditional species monitoring, especially for birds (La Sorte and Somveille, 2019). Here, we obtained a total of 106 bird records from two complete bird watching reports provided by the Hainan Bird Watching Association and the Global Environment Fund (GEF) China Wetland Protection Project. These reports consist of personal communications and were treated as unpublished data in the present study.

2.3. Data standardisation

2.3.1. Species taxonomic validation

We updated the nomenclature of each species using the bird classification in the 'Catalogue of the distribution and classification of birds in China' (Zheng, 2017), which is a widely accepted and used taxonomy book for Chinese birds. We also compared the species taxonomic information collected from this book with the internationally acknowledged taxonomy (https://www.worldbirdnames.org/new/) and found a highly coincidence between these two sources. During the past 150 years, there have been variations in scientific names for some species. Fortunately, later literature generally cited the original species record in earlier literature using the alternative scientific names. For example, the Black-naped Monarch (*Hypothymis azurea*) was first recorded by Swinhoe (1870) and named *Myiagra azurea*. When Hartlaub (1892) reported this bird, he cited Swinhoe's corresponding record, despite the scientific name being changed to *Hypothymis azurea*. Through carful validation, we confirmed that *Myiagra azurea* referred to *Hypothymis azurea*. We checked the scientific names of all bird species following the same method and obtained a single species list after removing duplicate records from the literature.

2.3.2. Screening process

To improve the accuracy of the bird inventory, we determined the final list of bird species recorded on Hainan Island based on the following three standards:

(i) Excluded species: there were no registered observations or catalogued specimens, or records were identified as doubtful on the island by more than two reports;
(ii) Suspicious species: Some publications questioned the species presence in Hainan; or the information in the literature was so vague that it was difficult to confirm their distribution in Hainan; or the bird record was based on only one field survey, and no other documents confirmed the presence of the species in the island;
(iii) Identified species: all remaining species (after removing the excluded and suspicious species). These species were observed, cited in the literature, in unpublished data, in citizen scientific data, or identified as museum specimens. Finally, a total of 452 species were identified based on the recorded species (Table S3).

2.3.3. Spatio-temporal information

The recording time for each bird species was based on the survey time provided in the literature. In addition to the year information, we also extracted detailed time information from those reports with exact survey dates or months. The geographical information for each specimen and observations was based on the degree of recording accuracy at five levels: 1, exact longitude and latitude; 2, village; 3,town; 4, county or city; and 5, Hainan Province. We noted that some location names in the early literature differed from the current ones. We, therefore, referred to old maps of Hainan such as Zhang (1897) and cross-referenced each of the old locations to their current locations (Table S4). When we identified old places that were further than 5 km from the jurisdiction of Hainan Island, these records (mostly from islets) were removed. For instance, in Swinhoe's literature, there were some records on Naocow (Naozhou Island), which is more than 90 km from Hainan Island; these records were not included in our dataset. In addition, records from the Seven Islands and Paracel Islands that were more than 20 km and 100 km, respectively, away from Hainan Island were also excluded. We did include the records from the small islands within 5 km of the Hainan coastline in our dataset. Considering that many birds are recorded multiple times at different locations across the years, we provided the recording time information for each independent observation to facilitate our understanding of their range shifts across temporal scales (Table S5).

2.3.4. Residence and zoogeographical composition

We categorised all recorded birds into residents, migrants, and vagrants based on their residence types (Zheng, 2017). For resident and migrant birds, we determined their zoogeographical information based on the China animal geography (Zhang, 2011).

2.3.5. Phylogenetic composition

To explore the phylogenetic relationship of the island birds recorded in our present study with all other bird species in China (Zheng, 2017), we obtained a phylogeny of global birds online (Jetz et al., 2012; http://vertlife.org/phylosubsets) as the posterior distribution of trees (n = 1000) and used the R package '*phangorn*' (Schliep, 2011) to construct a maximum clade credibility phylogeny. We created a phylogenetic subset that comprised all birds of China using the '*math.phylo.comm*' function in the R package '*picante*' (Kembel et al., 2010). Finally, we used the Wilcoxon rank test to explore whether the branch length of the phylogenetic tree of birds on Hainan Island differed from that of Chinese birds not recorded on Hainan Island. In addition, to test if the presence of species on Hainan Island was randomly dispersed across the phylogeny of Chinese birds (D = 1), or if it was clumped because it had evolved under a Brownian motion model of evolution (D = 0), we calculated the phylogenetic statistic D (Fritz and Purvis, 2010) using the *phylo.d* function in the R package '*caper*' (Orme et al., 2018).

3. Results

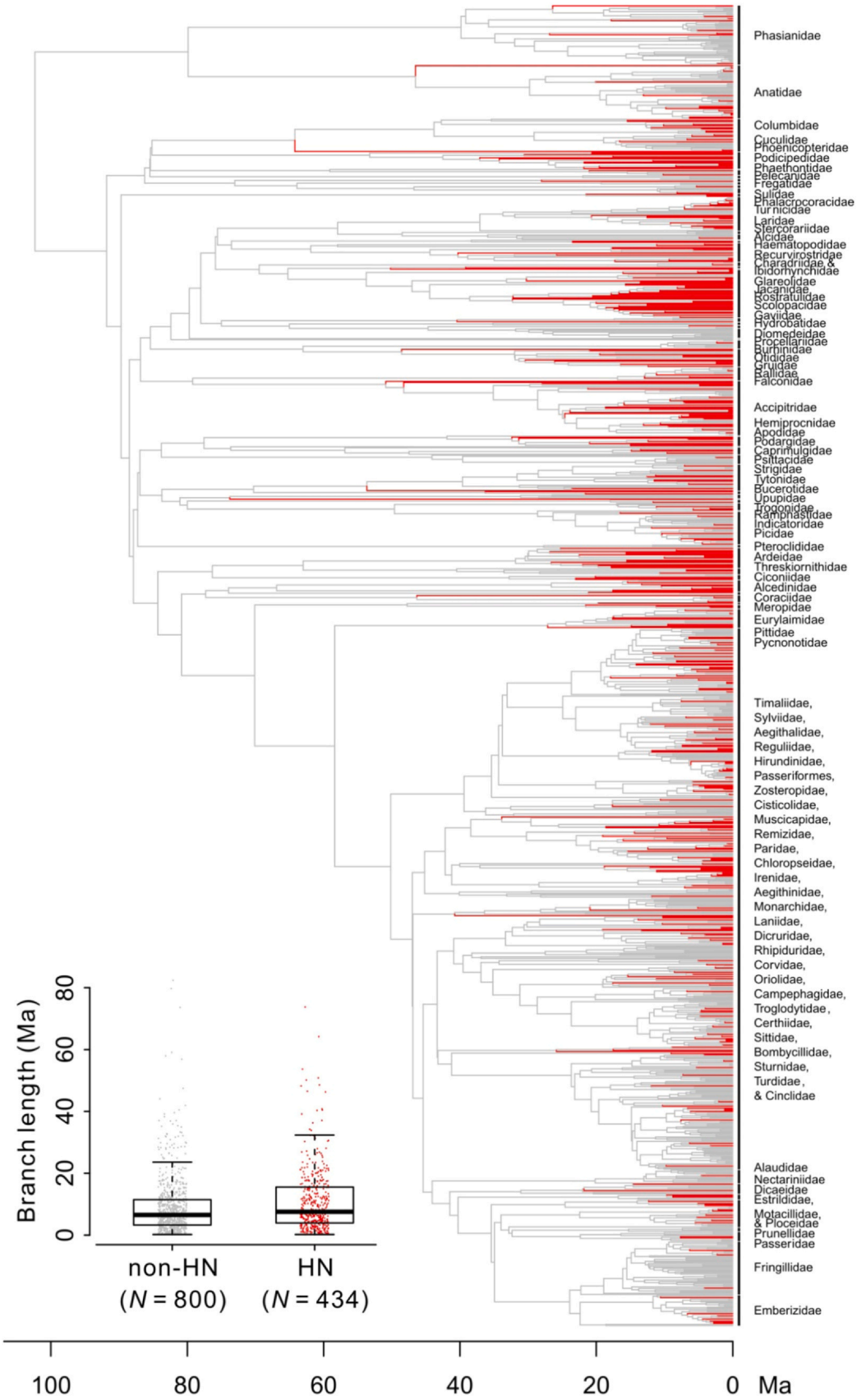
3.1. Overall description

In total, we identified 452 bird species recorded on Hainan Island (Table S3), representing a high taxonomic diversity of birds belonging to 22 orders, 80 families, and 254 genera. Four species were endemic to the island: the Hainan partridge (*Arborophila ardens*), Hainan Peacock Pheasant (*Polyplectron katsumatae*), Hainan Leaf Warbler (*Phylloscopus hainanus*), and Hainan Hwamei (*Garrulax Owstoni*). The Passerine and Charadriiformes birds accounted for 73% and 67% of the total families of these two orders recorded in China, and their conservation on the island is crucial for the biodiversity conservation of these two groups in China (Table S6).

Phylogenetic analyses revealed that the branch length of Hainan's birds (median = 7.56) was significantly longer than that of the Chinese birds not recorded on Hainan (median = 6.54; Wilcoxon rank sum test, $P < 0.05$). The island birds were evenly distributed across the phylogenetic tree of all Chinese birds (Fig. 2), as the D values were significantly greater than Brownian motion expectations ($D = 0.71$; $P < 0.001$). This result shows that the avian fauna on Hainan Island is highly representative of China and, therefore, the conservation of birds on Hainan Island is crucial for maintaining the evolutionary completeness of birds in China.

There were five orders with only one species, including Gaviiformes, Procellariiformes, Trogoniformes, Bucerotiformes, and Psittaciformes (Table S6). This means that the diversity of families, orders, and other high-level taxonomic groups on Hainan Island will be greatly affected if these orders with unique species disappear, demonstrating the high vulnerability and significant conservation implications of these bird orders on Hainan Island. Furthermore, we found that Hainan's birds comprised a high proportion of endangered species, which accounted for 30.7% (121/394) of all species on the national key protected list and 67.9% (55/81) of migratory birds in the Sino-Australian Migration Agreement. There were also 53 (11.8%) species listed as CITES I and II, and 20 (4.4%) species were among the IUCN red list (CR, EN and VU; Table S7).

The 452 identified birds included 297 species with specimens, 140 species with observations, and six unpublished species with deposited specimens (*Porzana paykullii*, *Psilopogon franklinii*, *Macropygia ruficeps*, *Treron pompadora*, *Garrulax ruficollis*, and *Garrulax sannio*; see Table S8 for detailed specimen information). There were seven species (*Mareca falcata*, *Corvus corone*, *Numenius minutus*, *Accipiter gentilis*, *Phylloscopus affinis*, *Garrulax perspicillatus*, and *Lonchura atricapilla*) only recorded in our field surveys, and two species (*Limnodromus scolopaceus* and *Seicercus soror*) only recorded in the citizen science data (Gu, 2015; Huang, 2015).



(caption on next page)

Fig. 2. Phylogenetic location of birds recorded on Hainan Island (red) among all birds in China (Units: Ma). The inset boxplots showing the distributions of branch length with the median indicated by a horizontal line, and 25th and 75th percentiles represented by whiskers. Number of species per group are n = 434 for Hainan Island species, and n = 800 for the non-Hainan Island species. Wilcoxon Rank Sum test revealed that the branch length of Hainan Island species was significantly longer than that of the Chinese birds not recorded in Hainan ($P < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Spatio-temporal characteristics

Based on literature records, the spatial extent of the surveys on Hainan Island expanded from the surrounding coastal areas in the early stages to the central-south mountainous areas and, thus, the current bird records cover nearly the whole island (Fig. 1). According to the species cumulative curve of recorded birds on Hainan Island, four survey periods can be identified: I, before 1900; II, 1900–1950; III, 1950–1980; and IV, after 1980 (Fig. 3). Before the 1950s, most bird surveys were based on individual specimen collections for faunal investigations. From the 1950s to the 1980s, the surveys gradually changed from individual collections to team collections. Bird investigations based on standard point or line transect method started in the 1980s (Figs. 1, 3).

There was great variation in sampling efforts, especially after the 1980s (Fig. 3). Despite the earliest records of birds on the island starting in 1868 (Swinhoe, 1869), there were no bird investigation reports in the following 20 years. Although there were several surveys at different stages, the surveys varied greatly in the number of surveyed sites among the stages. Initially, few sites were surveyed; however, this number increased after the 1980s. The increase was particularly rapid in local-scale investigations, such as surveys in protected areas (Fig. 3). Several regions, such as Wanling Town of Qiongzhong and Nada town of Danzhou, were surveyed across all four stages and, thus, can be further used to explore bird temporal dynamics (Fig. 1).

The species cumulative record curve showed that the total number of birds recorded on the island represented step-by-step growth with similar patterns for both residents and migrants (Fig. 4). From 1868 to 1910, the cumulative number of birds increased linearly with time, but it remained stable from the 1910s to the 1950s. After that, the number of birds recorded on the island showed another gradual increase then reached a second stable stage until 1980, when bird records increased again, especially for the migrants.

3.3. Avian composition

The majority of birds recorded on Hainan Island belong to the Oriental realm (229 species, 50.6%), followed by the Palaearctic realm (173 species, 38.3%), and other biogeographical types (50 species, 11.1%; Table S9). This is especially true for the 224 resident birds, 83.5% (187 species) of which belonged to the Oriental realm. Of the 217 migratory birds, 151 were from the Palaearctic realm, accounting for 69.6% of the migratory birds.

Most residents on the island are tropical-subtropical birds (69.6%), showing a typical mixture of tropical and subtropical regions. Based on the global range maps (BirdLife International & NatureServe geodatabase), of 46 tropical resident birds recorded on Hainan Island, we verified that Hainan Island was the northern margin of 21 species including *Dicrurus paradiseus*, *Dicrurus aeneus*, and *Temnurus temnurus* (Table S10). Considering that there are very few tropical regions in China, these northern margin tropical birds may have important implications for bird biodiversity conservation in China.

There was also a clear variation in elevation where the birds were observed, and the highest richness was below 500 m (Fig. 5). However, the currently protected areas in Hainan are mainly located between 500 and 1000 m, suggesting that there are conservation gaps between the bird diversity and the current conservation planning of protected areas at low-elevations on Hainan Island.

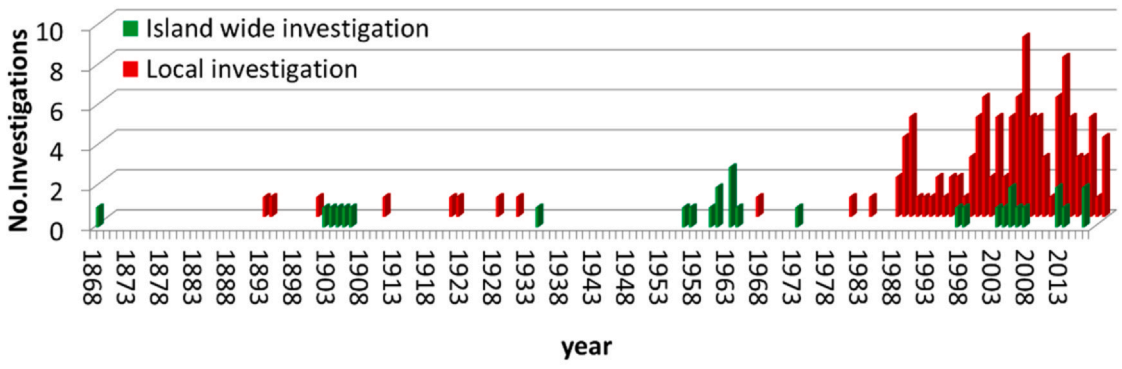


Fig. 3. Temporal distributions of bird field surveys on Hainan Island.

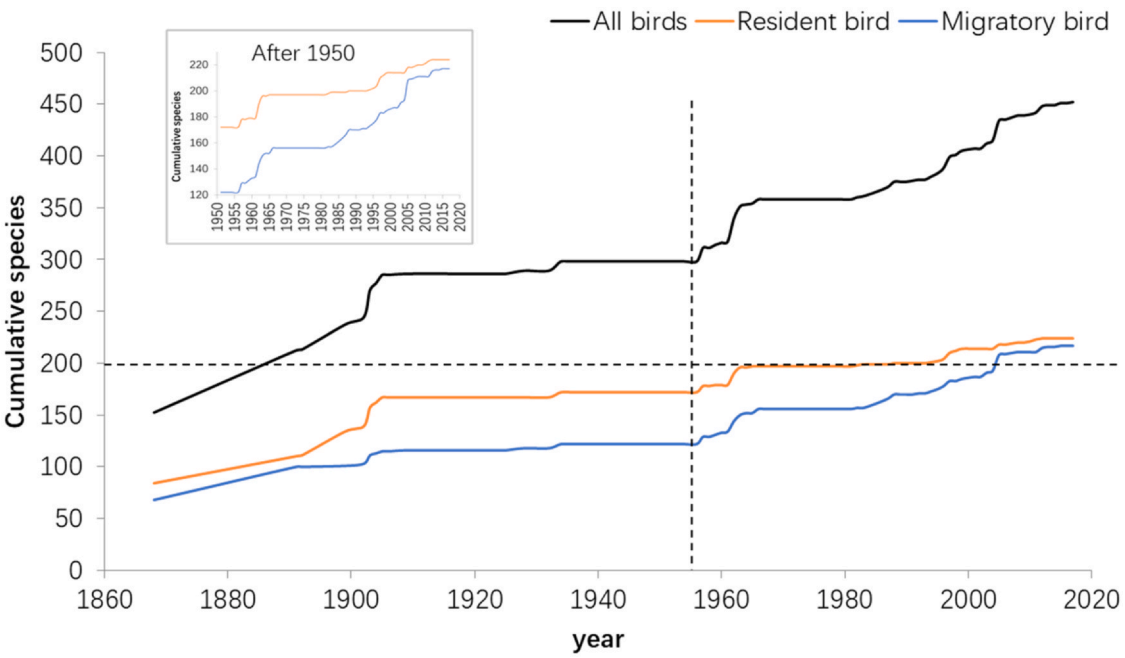


Fig. 4. Species cumulative curve of recorded birds on Hainan Island since the 1860s.

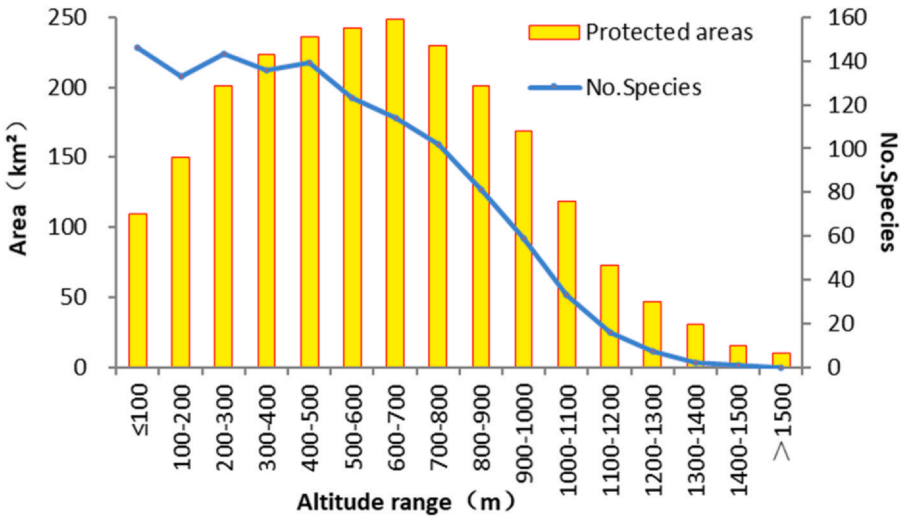


Fig. 5. The protected areas (km^2) and species richness of birds along elevational gradients on Hainan Island. The number of birds in each elevational interval is based on the field surveys conducted by the authors' research group from 1997 to 2017. The field survey method is detailed in Section 2.2.

4. Discussion

The present study outlines a 150-year record of bird species on Hainan Island, China. We showed that there was a high avian diversity on the island that is characterised as many endangered and biogeographically typical species with high conservation values. Bird records on the island have increased since the first report in 1868 and there is a growth point across all periods, indicating that the bird records of Hainan Island have not been completed. To our knowledge, we have provided the most complete list of birds on the island by integrating different published sources and field surveys. Nevertheless, we acknowledge that many bird species may have not been recorded yet, warranting future investigations using more diverse approaches, covering more habitats, and increasing the survey efforts.

4.1. Spatio-temporal characteristics

We found that migratory birds were the main source of new bird records, indicating that one explanation for the increase in recorded bird over the years is that some migratory birds are changing their routes to select the island as their candidate habitats to track climate warming (Hitch and Leberg, 2010; Sparks et al., 2010; Visser et al., 2010; Wauchope et al., 2017). For instance, birds in north-western Europe, such as the UK and the Netherlands, have shifted their distributional ranges northward in response to warming climates (Thomas and Lennon, 1999; La Sorte and Jetz, 2010), and some migratory birds will move to areas that are relatively short distances from their breeding places for wintering (Visser et al., 2010). Hainan Island, as the northern edge of the tropics, is located in an important midway point on the East Asia Australia West migration route (BirdLife International, 2018). It is an ideal wintering site or transfer station for migratory birds, owing to its rich intertidal wetlands along the island coastline (Bamford et al., 2008; Murray and Fuller, 2015). Consequently, Hainan Island is likely to become an important refugium from climate change for many migratory birds. Thus, it is crucial to further investigate and monitor migratory birds on the island in the future.

Our study revealed that there was a sustained increase in new records of birds in the past 150 years (Fig. 4). However, these records did not reflect the bird population trends because of great variations in sampling effort, survey areas, and methods used among historical stages. In fact, a recent quantitative study demonstrated that the bird species on the island had suffered a significant decline in abundance and species richness (Xu et al., 2017). For instance, 16 species were recorded in early years (e.g., *Leptoptilos javanicus*, *Mycteria leucocephala*, and *Graminicola striatus*) but they have never been observed since (Table S11), despite the increase in investigation intensity and survey area. Interestingly, most of these species typically inhabit wetlands and natural forest. This phenomenon might result from the degradation of natural wetland and forest habitats, which is also the top driver of global biodiversity loss (IPBES, 2019). For example, nearly 61% of the waterfowl populations in Asia have declined rapidly (BirdLife International, 2017). Monitoring of Hainan's wintering waterbirds from2008 to 2020 also detected continuous declines of waterbirds (Li et al., 2020). In addition, climate change may be a potential factor contributing to the decline, as species distribution modelling suggested that the suitable habitats for some water species, such as the Black-faced Spoonbill (*Platalea minor*), on Hainan Island will disappear under climate change (Hu et al., 2010). Finally, islands are the epicentre of alien species invasion resulting in a large number of species extinctions across the globe (Bellard et al., 2016). The Azure-winged Magpie (*Cyanopica cyanus*) and the Red-billed Leiothrix (*Leiothrix lutea*) are two alien species that have established feral population is many regions of the world (Dyer et al., 2017). The Red-billed Leiothrix has invaded and caused a population decline in several local bird species in Spain, Hawaii, and Japan (Riper et al., 1986; Eguchi and Amano, 2004; Herrando et al., 2010). These two species have both been recorded as exotic birds on Hainan Island in the literature (Wang and Liang, 2013); however, it is unclear what the introduction pathway was or whether the two aliens have established reproducing populations in the wild, which would warrant an urgent action to monitor and prevent future alien incursions onto the island.

4.2. Avian composition and conservation implications

Our study revealed that most of the resident birds on the island were tropical-subtropical distribution types. This not only supports the traditional view that Hainan Island is a subregion of South China Region (Zhang, 2011), but also coincides with a recently updated zoogeographical regionalisation of China (He et al., 2017). We found that although Hainan Island's birds were distributed evenly across the phylogenetic tree of all Chinese birds, the evolutionary history of Hainan's birds was older than that of the rest of China's birds (Fig. 2). These results highlight that the avian fauna of Hainan is an important subset of Chinese species in terms of the species richness and phylogenetic biodiversity. More importantly, as Hainan is the largest tropical island of China, many tropical birds recorded on this island cannot be found elsewhere in China. Thus, conservation on this island is crucial for sustaining China's biodiversity.

It should be noted that the aim of this study was not to compare the temporal changes in abundance or species diversity because the uncertainty mentioned before is difficult to account for. However, we provide the first avian dataset as a baseline of bird resources on the island through an intensive collection of multiple sources from field surveys, references, museum specimens, and citizen science data. The incorporation of these heterogeneous sources into one unified dataset is a common issue in long-term temporal comparison analyses (Mace, 2013). We suggest that future studies develop analysis techniques to account for these uncertainties in data quality which will facilitate comparisons in biodiversity dynamics over long-term spatio-temporal scales.

5. Conclusion

Our intensive bird history surveys and records provide important insights into the current research and conservation gaps on Hainan Island. First, Hainan Island remains the very few tropical rainforests in China, and there are many unique topographical environments on the island (Lin et al., 2017) that provide important habitats for many bird species with narrow distributional ranges (Li et al., 2020). However, there are still insufficient sampling efforts for these specialised birds. Furthermore, we observed higher bird diversity below 500-m altitude on the island; but, unfortunately, the current protected areas tend to cover the land between 500 and 1000 m. Thus, the protection of low-altitude birds must be strengthened. Additionally, except for winter migratory birds, we found that there was still a lack of continuous monitoring for most birds. We need more monitoring projects, such as the special investigation of water birds, to cover more species and make a more accurate

assessment of the long-term bird trends on the island. Finally, in addition to routine monitoring work, there are increasing numbers of birdwatchers participating in professional bird database construction; the aid of the citizen science, which is an area in development, provides an important avenue for future standardised long-term bird monitoring (Dickinson et al., 2010; Langendoen, 2017).

CRediT authorship contribution statement

H. J. designed the research. C. H., L. H., Y. J., Y. X., J. H., S. L., and H. J collected the data. C. H. and X. L. performed analyses. C. H., X. L., and H. J. wrote the manuscript. All authors contributed to the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2021.e01578.

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