Spatial priorities for biodiversity and ecosystem services considering theoretical decision-makers’ attitudes to risk

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Abstract
Choosing appropriate spatial priorities for protected areas (PAs) to conserve ecosystem services (ESs) and biodiversity is a challenge for decision makers under limited land resources, especially when facing uncertain protection consequences or conflicting protection objectives. Attitudes toward risk will influence actions, which will, in turn, impact consequences. To understand how theoretical decision-makers’ attitudes towards risk impact protection effectiveness for biodiversity and ESs (e.g., water retention, soil retention, flood mitigation, water purification and carbon sequestration) and how this information can be integrated into effective PAs management, we examined Hainan Island as a case study. We used the ordered weighted averaging (OWA) algorithm to assess the impact of attitude towards risk in PA management. Decision-makers’ attitude towards risk scenarios (from risk-averse and risk-taking) showed higher mean protection effectiveness (2.41–2.85) than existing PAs (2.37), indicating that there is still room for improvement in biodiversity and ESs conservation in existing PAs. In addition, among the seven examined risk scenarios, the higher risk aversion scenario showed the best outcome. In comparison to existing PAs, this scenario improved mean protection effectiveness (20.13%) as well as the protection effectiveness of water retention (24.84%), water purification (11.46%), flood mitigation (8.84%), soil retention (16.63%), carbon sequestration (5.31%), and biodiversity (12.84%). Thus, our research shows that the influence of theoretical decision-makers’ attitudes towards risk could be considered by OWA method which could provide a normative model of what the right choice given theoretical risk attitudes is while selecting priority area for biodiversity and ESs.

1. Introduction

Protected areas (PAs) are essential for curbing human threats to natural ecosystems, and not only improve environmental health but also human wellbeing (CBD 2010). Simultaneously protecting ecosystem services (ESs) supply and avoiding biodiversity loss are important objectives for PAs (Palomo et al 2014, Williams et al 2020). For example, China’s national parks policy aims to protect both biodiversity and ESs (He et al 2018a). However, ESs and biodiversity hotspots, i.e., areas with considerable distribution of one or multiple services, do not always overlap due to spatial heterogeneity (also known as spatial incongruence) (Cimon-Morin et al 2013; Fastré et al 2020, Schrötter et al 2016). Additionally, land resources for PA allocation are limited and often in conflict with land for agricultural and forestry activities (Palomo et al 2014). Identifying spatial priorities to sustain ESs supply for a growing population while avoiding biodiversity loss under limited land resources remains a great challenge for decision-makers (Cimon-Morin et al 2013).

Multi-Criteria decision-making is a commonly used approach to select spatial priorities for conservation of ESs and biodiversity, and could facilitate decision-making involving multiple and conflicting criteria.
Multi-Criteria decision-making could be analyzed mainly by two types of methods (spatial multi-objective decision-making and spatial multi-attribute decision-making) (Malczewski 1999). Spatial multi-objective decision-making is a kind of optimization method which chooses prior conservation area according to the protection objectives under specific constrains (e.g., cost, benefits or threats). For example, in the most commonly-used Marxan model, heuristic site prioritization method with simulated annealing algorithm was used to choose the most efficient protection sites (Watts et al. 2017; Zhang et al. 2018). In spatial multi-attribute decision-making, spatial priority areas were selected by the hierarchical prioritization method. For example, in the Zonation model, weighted linear combination or the maximum value method was used to choose priority areas by ranking the value of each cell in the whole study area (Moilanen et al. 2014; Xu et al. 2017a). The different aggregation operation (decision rule) used in spatial multi-attribute decision-making method will result in different priority areas, which is the source of uncertainty in the process of choosing priority areas for conservation of biodiversity and ESs (Beinat & Nijkamp 1998). Risk arise from the uncertainty under different decision rules reflecting decision-makers’ attitude to risk, including risk-averse, risk-neutral, or risk-taking attitude (Girardello et al. 2019).

Risk-taking decision makers usually are optimistic and confident. They usually only used the maximum value from different objectives to choose spatial priority area. For example, Xu et al. (2017a) used only the maximum value of one of the ESs or biodiversity objectives to choose priority PAs in China because they wanted to protect the most valuable areas. This may reduce the opportunity to protect other spatial-incongruence but relatively higher-value objectives (e.g., sandstorm prevention). Risk-averse decision-makers are pessimistic and cautious. They used the minimum value from different objectives to choose priority areas because they did not want to lose any objectives, such as fire management (Maguire et al. 2005) and protection of high extinction-risk species (Tulloch et al. 2015). Thus, different attitudes towards risk will influence the degree of importance that decision-makers give to different objectives, and in turn, the effectiveness of their final decisions. However, fewer research has considered the influence of differences in decision-makers’ attitudes towards risk (Runting et al. 2018; Tulloch et al. 2015) or assumes that decision-makers are risk-neutral in the process of choosing priority areas for biodiversity and ES protection (Xu et al. 2017a). Therefore, it is imperative to consider decision-makers’ attitudes towards risk in the selection of priority sites for the conservation of biodiversity and ESs.

Several methods have been used to identify the impacts of attitude to risk, such as, Holt-and-Laury Lottery (Holt and Laury 2002), Modern Portfolio Theory (Runting et al. 2018) and ordered weighted averaging method (OWA) (Yager 1988; Qin et al. 2019). Among these methods, OWA algorithm, a multi-criteria decision-making method, has been commonly applied for the selection of spatial priority areas and could consider different combination operations simultaneously (Makropoulos et al. 2006). OWA method expressed decision-makers’ attitude to risk by ordered weights (1, 0, 0). By varying order weights, OWA method allows for a broader range of aggregation operators (Yager 1988; Qin et al. 2019). For example, A, B and C represent three ecosystem services. If the criteria are ranked BAC (from lowest to highest) at one location, the ordered weights are (1, 0, 0) and the weighted aggregation will be 1B + 0A + 0C. This aggregation indicated that a location where all ecosystem services met the requirements could be chosen as priority area. Such a procedure is essentially risk-averse, and selects locations based on the most cautious strategy possible—a location succeeds in being chosen only if its worst quality (and therefore all qualities) passes the test (Beinat & Nijkamp 1998). On the opposite, if ordered weights are (0, 0, 1)—a location will be included in the decision set even if only a single ecosystem service passes the test. This approach has been used to select landscape ecological risk conservation areas (Cao et al. 2019), forest restoration areas aiming at water resource conservation (Vettorazzi and Valente 2016), urban infrastructure planning areas (Delgado Tellez et al. 2013) and setting conservation priorities based on ESs (Qin et al. 2019). To best of our knowledge, few studies clarify the impact of risk attitude on biodiversity and ESs protection effectiveness in PAs, which is very important in protected area planning.

Tropical regions harbor rich biodiversity and natural forests and provide habitat for many species (Xu et al. 2017a). Loss of natural forest is the principal cause of terrestrial biodiversity loss. Hainan Island in China, which represents a global biodiversity hotspot (Zhang et al. 2011), was used as a case study to explore how theoretical decision makers’ attitude to risk influence priority protection area and facilitate the choice of new PA sites. First, we illustrated the spatial distribution relationship of high-value area among selected ESs (water retention, soil retention, flood mitigation, water purification and carbon sequestration) and biodiversity. Second, compared with existing PAs, we analyzed the biodiversity and ES protection efficiencies under seven different scenarios related to risk attitude (from risk-averse to risk-taking) using ordered weighted averaging. Finally, we identified the new priority area with the highest biodiversity and ES protection efficiencies as the better attitude scenario to inform the selection of new PAs. In addition, it is also worth noting in advance that current decision-makers’ attitude to risk by OWA method is theoretical.
2. Methods

2.1. Study area
Hainan Island in southern China (108°37′–111°03′ E, 18°10′–20°10′ N) covers a terrestrial area of 3.54 × 10^4 km^2. Hainan Island harbors approximately 3 900 species of wild vascular plants, 650 species of wild higher-order animals, and 6 138 species of forest insects (Zhang et al 2011). There are 49 PAs (i.e., nature reserves) in Hainan (MEP 2017), which fall within the IUCN (strict nature reserve) protected area category of the International Union for Conservation of Nature (IUCN) (Dudley 2008). In this study, we choose 25 terrestrial PAs (table A1 available online at stacks.iop.org/ERC/3/115007/mmedia) which account for 8.6% of Hainan Island in area (figure 1) as existing PAs and exclude the other 24 marine and coastal PAs because of the lack of data availability for marine and coastal biodiversity and ESs. In addition, the central mountainous area is one of the nine important biodiversity conservation areas in China (Chen 1994) and here exist conflicts between rubber plantation expansion and nature conservation (Zheng et al 2019).

2.2. Assessing ecosystem services and biodiversity
China has established a network of ‘Ecological Function Conservation Areas (EFCAs)’ to conserve biodiversity and ESs, especially the regulating services. And the central mountainous area of Hainan Island belongs to national EFCAs, and plays a key role in protecting important biodiversity and regulation services (e.g., water retention, soil retention, water quality). Therefore, we chose biodiversity and water retention, soil retention, water quality, flood mitigation, and carbon sequestration services as protection objectives (Wang et al 2019; Zheng et al 2019; Li et al 2020). We used Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model (Sharp et al 2016) to assess ESs. InVEST consists of a suite of modules that are built upon land use and land cover (LULC) characteristics to estimate production functions and economic values of ESs and is widely used in the field of ecosystem services and also have been proved to perform good in this study area (Zheng et al 2019). In addition, InVEST model used local parameters from field work and publications in study area to make results valid (Wang et al 2019; Wen et al 2017; Zheng et al 2019). We used commonly used conceptual model to assess the importance of biodiversity and the model is based on the previous studies and the List of all sorts of species in both abiotic and biotic conditions (e.g., vegetation types, elevation, slope and administrative units) (Zhang et al 2018).

2.2.1. Data sources
Land use and land cover data for 2017 were interpreted from images provided by the China Remote Sensing Satellite Ground Station (30 m × 30 m pixel size). Using supervised classification, LULC was classified into...
natural forest, rubber plantation, grassland, farmland, garden, urban, wetland, and bare land. Classification accuracy was 93% according to 169 randomly distributed sample points collected in November 2017 on Hainan Island. Another 200 points were used for the training set. Information on spatial data is shown in Table 1, and all data analyses were run at 30-m pixel size. Furthermore, all biophysical parameters for the calculation of ESs are listed in the appendices (Tables A2 and A3) (Zheng et al. 2019).

2.2.2. Ecosystem services

(i) Water retention service

We used baseflow from the InVEST seasonal water-yield module to represent the water retention service (equation 1) (Zheng et al. 2019).

\[ WR = P - ET - Q \]  

where \( WR \) is the water retention service; \( P \) is the annual mean precipitation (mm); \( ET \) is the annual water evapotranspiration (mm); and \( Q \) is the annual quick runoff (mm).

(ii) Soil retention service

We used the InVEST sediment delivery ratio module to estimate the soil retention service (equations 2 and 3).

\[ SR_x = R_x \times K_x \times LS_x \times (1 - C_x \times P_x) + SEDRET_x \]  

\[ SEDRET_x = SEx \times \sum_{y=1}^{x-1} \left( R_y \times K_y \times LS_y \times C_y \times P_y \right) \times \sum_{z=y+1}^{x} \left( 1 - SE_z \right) \]  

where \( SR_x \) is the soil retention service (t/ha) of pixel \( x \); \( R_x \) is the rainfall erosivity calculated by mean monthly rainfall from 1981 to 2017 (MJ mm ha\(^{-1}\) h\(^{-1}\) a\(^{-1}\)) of pixel \( x \) (Zhou et al. 1995); \( K \) is soil erodibility based on the erosion-productivity impact calculator model (t ha ha\(^{-1}\) MJ\(^{-1}\) mm\(^{-1}\)) of pixel \( x \) (Wischmeier and Smith 1978); \( LS_x \) is the slope length-gradient factor of pixel \( x \) based on the digital elevation model; \( C_x \) and \( P_x \) are the crop management and practice factors of pixel \( x \), respectively (adopted from relevant publications in Hainan Island (Rao et al. 2013)); \( SE_x \) is the sediment retention efficiency of pixel \( x \); and \( y \) is the pixel uphill of pixel \( x \).

(iii) Water purification service

We used the inverse of \( N \) export as an index for the water purification service. The InVEST nutrient delivery ratio module, which is based on the export coefficient approach (Reckhow et al. 1980), generates two main outputs for nitrogen (N) and phosphorus (P); i.e., nutrient exported to the stream and nutrient retained by each pixel on the landscape. We assigned different values for N, retention efficiency, and length of each land use following Zheng et al. (2019).

(iv) Flood mitigation service

We used quickflow in the monsoon months (May–October in Hainan) to represent direct runoff entering streams after a rain event as an index for flood mitigation (Mandle et al. 2017). The InVEST seasonal water-yield model can estimate the relative contribution of each pixel to generate quickflow, local charge, and baseflow based on monthly climate values and curve number (CN) methods (equation 4). We assigned different values of CN and crop factors (Kc) for different LULC types (Allen et al. 1998; Zheng et al. 2019).

\[ FM = 1 - \frac{QF}{P} \]  

where \( FM \) is the index of flood mitigation (unitless), with higher \( FM \) values indicating higher flood mitigation capacity; \( QF \) is the sum of quickflow over the monsoon months (May–October) (mm); and \( P \) is the sum of precipitation over the monsoon months (mm).

(v) Carbon sequestration service

We calculated annual carbon sequestration on the assumption that carbon sequestration rates of different LULC types were at steady-state levels (equation 5) (Zheng et al. 2019).

\[ CS = A_i \times C_i \]  

where \( CS \) is the annual carbon sequestration (t); \( A \) is the area of each LULC (ha); \( C \) is the annual carbon sequestration ratio (t/ha); and \( i \) is the type of LULC.

2.2.3. Biodiversity importance index

We used the biodiversity importance index, i.e., the sum of each pixel among all taxon layers (Xu et al. 2017a; Zhang et al. 2011), to map important areas for biodiversity conservation. We first chose 150 indicator species, including 124 plants, seven mammals, seven birds, 10 reptiles, and two amphibians (Table A4) according to the ‘IUCN Red List of Threatened Species’, ‘List of Wildlife under Special State Protection’, ‘List of Wild Plants under Special State Protection’, ‘Red List of Chinese Species’. We then categorized the relative importance of these 150 species into three levels: Level I (weight = 3); national first-level endangered and critically endangered species; Level II (weight = 2): national second-level endangered and critically endangered species; and Level III (weight = 1): other endangered and critically endangered species and endemic species in Hainan Island.
| Definition                              | Model used                                    | Data requirement                                                                                     | Data source                                                                                   |
|----------------------------------------|-----------------------------------------------|------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| Water retention (WR)                   | Available water that can be used by people (e.g., domestic and industrial water) after evapotranspiration and storm runoff. | InVEST seasonal water yield module                                                                  | Monthly mean precipitation data, Monthly mean reference evapotranspiration calculated from 1981 to 2017 | China Meteorological Data Service Center (http://data.cma.cn) |
| Flood mitigation (FM)                  | Capacity of ecosystem to reduce storm runoff by intercepting rainfall and absorbing water through root systems and storage capacity (Brauman et al 2007). | Monthly Kc values                                                                                   | FAO online resource: http://www.fao.org/docrep/X0490E/x0490e0e.htm; Refer to appendices (table A2) for specific values |
| Soil retention (SR)                    | Difference between soil erosion without vegetation cover and soil erosion under current vegetation cover (Kong et al 2018). | InVEST Sediment delivery ratio module                                                              | Soil group                                                                                   | Hainan Academy of Environmental Sciences, China |
| Water purification (WP)                | Capacity of ecosystem to absorb and convert pollutants and purify polluted water. | InVEST Nutrient delivery ratio module                                                              | Nutrient retention efficiency (eff_n or eff_p); Distance of maximum capacity (crit_len_n); Proportion of dissolved nutrients (proportion_subsurface_n) | FAO online resource: http://www.fao.org/docrep/X0490E/x0490e0e.htm; Zheng et al 2019; Refer to appendices (table A2) for specific values |
| Carbon sequestration (CR)              | Function of plants to absorb atmospheric carbon dioxide via photosynthesis, convert it into carbohydrates such as glucose, fix it in plants or soil as organic carbon, and release oxygen. | Carbon sequestration ratio                                                                           | Zheng et al 2019; Refer to appendices (table A32) for specific values                          |
| Biodiversity                           | Variety of living organisms in ecosystems that play key roles in delivering ecosystem services (Mace et al 2012) | Species data (including plants, mammals, birds, reptiles, and amphibians) and their environmental data | Hainan Academy of Environmental Sciences, China. Report for Biodiversity Assessment in Hainan Province, and other species lists |
We then used the species habitat mechanism model to map the biodiversity importance index. We first collected the main distribution areas and habitat variables of the species (administrative units, distance to rivers, elevation, ecosystem, and slope) according to investigation data (table 1). We then overlaid the spatial data of habitat variables and treated those areas showing variable overlap as potential species habitats (equation 6).

\[
PH_{ij} = C_{ij} \times R_i \times E_i \times S_i \times W_i
\]

where \(PH_{ij}\) is the potential habitat of species \(i\) in \(j\) county; \(C_{ij}\) is whether species \(i\) exists in \(j\); \(R_i\) is whether species \(i\) is distributed within a suitable distance from a river; \(E_i\) is the type of ecosystem in which species \(i\) is distributed; \(S_i\) is whether species \(i\) is distributed on a suitable slope; and \(W_i\) is the protection level of species \(i\). For all above variables, there were only two states, i.e., 0 (not suitable) and 1 (suitable).

The overall biodiversity importance index map is the sum of the potential habitat of all species among the five taxa (Xu et al 2017a; Zhang et al 2011).

2.3. Quantification of decision-makers’ attitudes towards risk

Direct decision-makers refer to departments within the national or county-level governments (e.g., Department of Environmental Protection or Department of Forestry) who set goals and corresponding management rules for PAs under their jurisdiction (Xu et al 2019). These decision-makers also consider the attitudes of indirect decision-makers (e.g., other organizations, local farmers, developers, and investors).

The ordered weighted averaging algorithm is a multi-criteria combination operator. It sorts each criterion according to its attribute value in decreasing order without considering from which attribute map the value
comes, and multiply ordered weights to each of these maps, which are then aggregated into a final results map. It is calculated from four steps, as show in figure 2.

**Step 1.** normalize criterions maps (equation 7) (criterion maps refer to water retention, soil retention, flood mitigation, water purification, and carbon sequestration services and biodiversity importance index maps).

$$x_{ij} = \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}$$  \hspace{1cm} (7)

where $x_{ij}$ refers to ES or biodiversity (criterion) $i$ in pixel $j$ (30°×30m); and $x_{\text{max}}$ and $x_{\text{min}}$ are the maximum and minimum values of criterion $i$ in whole area, respectively.

**Step 2.** reorder normalized criterion maps ($S_0$). We ordered the value in the same position from different criterion maps in decreasing order.

**Step 3.** evaluate decision-makers’ attitude towards risk by giving a different ordered weight based on ordered location.

We set $w_i = [w_1, w_2, \ldots w_n]$ = [1, 0, … 0] to represent the most risk-taking attitude and $w_i = [0, 0, \ldots, 1]$ to represent the most risk-averse attitude. We set $w_i = [1/n, 1/n, \ldots, 1/n]$ ($n$ is number of criterion maps) according to the arithmetic mean, with ordered weights evenly distributed in all positions representing neutral attitude (Malczewski 1999).

We calculated and distributed ordered weights between ‘risk-averse’ and ‘risk-taking’ by solving the nonlinear mathematical programming problem (equations 8, 9, and 10) (Malczewski et al 2003; Malczewski and Rinner 2015).

$$R = (n - 1)^{-1}\sum_{i}^{n}(n - 1)w_i \ (0 \leq R \leq 1)$$  \hspace{1cm} (8)

$$\text{Maximize } T = 1 - \sqrt{\frac{n\sum_{i}^{n}(w_i - \frac{1}{n})^2}{n - 1}} \ (0 \leq T \leq 1)$$  \hspace{1cm} (9)

$$\sum_{i}^{n} w_i = 1$$  \hspace{1cm} (10)

where $R$ represents the degree of decision-makers’ attitude towards risk (the higher the value of $R$ is, the more optimistic the decision-makers are); $n$ is the number of criterion maps; $w_i$ is the ordered weights; and $T$ is the

**Figure 3.** Distribution of seven different scenarios related to decision-makers’ attitudes towards risk.
To study the effects of decision-maker attitude towards risk on biodiversity and ES protection effectiveness, we selected seven different risk-attitude scenarios. We set the degree of attitude between 0 and 1 at intervals of 0.2 (figure 3, black dots) to calculate ordered weights (table 2).

### Step 4. Aggregate ordered maps by multiplying steps 2 and 3 (final results) (equation (11)) (Yager et al 1988).

\[
\text{OWA}(x_{ij}) = \sum_{i} w_{i} s_{ij}, \quad (w_{i} \in [0, 1]) \quad \text{and} \quad \sum_{i} w_{i} = 1, \quad \text{for} \quad i = 1, 2, 3...n \quad \text{and} \quad j = 1, 2, 3...k
\]  

where OWA\(_{ij}\) refers to the final results map of the ordered weighted averaging method; \(w_{i}\) is the ordered weight of the reordered maps \(s_{ij}\); and \(n\) is the number of criterion maps.

### 2.4. Protection effectiveness calculation

To assess the protection effectiveness of the different risk-attitude scenarios, we chose 8.6% (because terrestrial PAs account for 8.6% of Hainan Island in our study) of Hainan Island as priority area according to the map from Step 4 (figure 2). Protection effectiveness was calculated as follows (equation 12) (Liu et al 2013; Qin et al 2019).

\[
E = \frac{E_P}{E_I}
\]  

where \(E\) is the protection effectiveness of a specific ES or biodiversity inside the 8.6% priority area (We defined priority area as the top 8.6% cumulated area according to the value from final result map in Step 4) under a specific risk-attitude scenario (unitless), with a higher \(E\) value indicating a more efficient scenario; \(\overline{E_P}\) is the average value of a specific ES or biodiversity inside the 8.6% priority areas under a specific risk-attitude scenario; and \(\overline{E_I}\) is the average value of a specific ES or biodiversity in whole Hainan Island.

After comparing the mean protection effectiveness of all protection objectives under all seven risk-attitude scenarios, we chose the scenario with the highest value as the optimal scenario.

In addition, we used Pearson correlation analysis to determine the spatial relationships between biodiversity and ESs, and also applied spatial overlap analysis of the 8.6% priority area of Hainan Island to show the spatial hotspot congruence degree of biodiversity and ESs (Wei et al 2020; Zhang et al 2011).

### 3. Results

#### 3.1. Spatial relationships among biodiversity, ESs, and existing PAs

Higher biodiversity importance index, soil retention, water quality, and carbon sequestration values were distributed in the central mountainous area of Hainan Island where existing PAs are located. The highest water retention and flood mitigation values were concentrated in the central eastern part of Hainan Island (figure 4).

**Note:** Nitrogen export was used as the proxy indicator of water purification service, with higher nitrogen export indicating lower water purification service.

Existing PAs with 8.6% of Hainan Island area could not simultaneously protect 8.6% area with the highest value of biodiversity and ESs in the whole island. Existing PAs protect 45.48% of the 8.6% highest-value carbon sequestration services in Hainan Island, but only 11.28% of the water retention service (figure 5). We found that existing PAs do not provide good protection for all high-value biodiversity and ES areas.

| Risk | Evenness | w1   | w2   | w3   | w4   | w5   | w6   |
|------|----------|------|------|------|------|------|------|
| 0    | 0.00     | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 |
| 0.1  | 0.41     | 0.00 | 0.00 | 0.00 | 0.08 | 0.33 | 0.58 |
| 0.3  | 0.74     | 0.02 | 0.08 | 0.14 | 0.20 | 0.25 | 0.31 |
| 0.5  | 1.00     | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 |
| 0.7  | 0.74     | 0.31 | 0.25 | 0.20 | 0.14 | 0.08 | 0.02 |
| 0.9  | 0.41     | 0.58 | 0.33 | 0.08 | 0.00 | 0.00 | 0.00 |
| 1    | 0.00     | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
3.2. Spatial correlation and overlap among biodiversity and ESs

Significant correlations were found between most ES and biodiversity pairs, except for water retention and water quality services \( (r = -0.01, p > 0.1) \). Biodiversity was significantly positively correlated with all ESs, with strongest positive correlation with carbon sequestration \( (r = 0.51, p < 0.001) \) and soil retention \( (r = 0.59, p < 0.001) \) and weakest correlation with water retention \( (r = 0.04, p < 0.001) \). Water retention was significantly negatively correlated with carbon sequestration \( (r = -0.05, p < 0.001) \), which may be because higher precipitation was concentrated in the central eastern part of Hainan Island, which had lower natural vegetation cover (table 3).

A high degree of spatial consistency was found between biodiversity and carbon sequestration (77.59%) and soil conservation (54.29%) in 8.6% priority areas. The overlap area between water retention and water quality

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**Figure 4.** Spatial distribution of biodiversity and ESs.

**Figure 5.** Proportion of top values of biodiversity and ESs in 8.6% of Hainan Island in existing PAs.
was the lowest (10.36%) (table 3). These results suggest that it is not possible to protect all ESs and biodiversity simultaneously.

### 3.3. Comparison of protection effectiveness between existing PAs and ordered weighted averaging scenarios

We compared the impact of different theoretical decision-makers’ attitudes to risk on the protection effectiveness of existing PAs. Results showed that the biodiversity and ES protection efficiencies under the different risk-attitude scenarios were higher than that in existing PAs (figure 6). Thus, considering decision-makers’ attitudes towards risk provides better protection for biodiversity and ecosystem services than existing PAs.

We compared protection efficiencies under the different risk-attitude scenarios. Results showed that the protection efficiencies varied for biodiversity (5.54 ± 0.95) and ESs (water retention: 1.25 ± 0.14; flood mitigation: 1.63 ± 0.08; soil retention: 3.26 ± 0.32; water purification: 2.34 ± 0.24; carbon sequestration: 1.90 ± 0.03). In addition, the spatial distribution of 8.6% priority areas differed under the various scenarios (figure 6). For example, the spatial 8.6% priority area under different decision-makers’ attitude towards risk outside existing PAs varied from 43.81% to 52.09% (figure 7). Thus, our results indicated that the different risk attitudes of decision-makers had a certain effect on the spatial planning of PAs and their protection effectiveness for biodiversity and ESs.
Based on the mean protection effectiveness, we chose the ‘risk = 0.1’ scenario as the optimal scenario as it showed the highest biodiversity protection and higher total protection effectiveness with only a small decrease in ESs compared with other scenarios. Compared with the existing PAs, the ‘risk = 0.1’ scenario improved the protection effectiveness for water retention (24.84%), water purification (11.46%), flood mitigation (8.84%), soil retention (16.63%), carbon sequestration (5.31%), biodiversity (33.45%), and mean protection effectiveness (20.13%), respectively (figure 6). Thus, our results indicate that both biodiversity and ESs can be protected with more risk-averse attitudes in Hainan Island.

4. Discussion

Simultaneously protecting both biodiversity and ESs is an important objective for PAs and sustainable development (Palomo et al 2014). The attitude of decision-makers towards risk can influence the protection effectiveness of PAs due to spatial incongruence in biodiversity and ESs (Cimon-Morin et al 2013). However, few studies have considered the impact of decision-makers’ attitudes towards risk on the protection effectiveness of biodiversity and ESs and inform selecting PAs. Clarifying this impact will help decision-makers choose more effective sites to protect biodiversity and ES under limited land resources (Liu et al 2013), thereby promoting PAs management.
Two possible reasons may explain the differences in spatial protection effectiveness under different attitudes towards risk: 1) Spatial incongruence exists in the high-value region of different conservation targets (such as water retention and carbon sequestration in Hainan). The spatial incongruence may be caused by innate biophysical factors (such as climate, parent material, topography or potential biota difference) (Chapin et al. 2011; Egoh et al. 2009; Zheng et al. 2014) or human activities (fertilizer and pesticide inputs) (Yan et al. 2003). Therefore, it is difficult to protect all biodiversity and ES objectives under limited land resources (Chan et al. 2006). 2) Decision-makers face difficult decisions under uncertainty, and decisions with multiple and conflicting objectives can be influenced by psychological reasons or personal will, which will determine the actions of decision-makers when choosing priority areas (Maguire et al. 2005, Malczewski et al. 2003). For example, the most risk-taking attitude (risk = 1 scenario) will just use the maximum value from one of the five ecosystems services (Xu et al. 2017a) or biodiversity maps to select spatial priority area. We found that a higher degree of risk aversion (risk = 0.1) provides improved protection effectiveness for both biodiversity and ESs in Hainan, consistent with previous studies using ordered weighted averaging to identify spatial priority areas (Liu et al. 2013; Zhang et al. 2015). This may be because a risk-averse attitude in PA management will include information from more objectives (ESs and biodiversity) that could inform the choice of spatial hotspots congruence area of more objectives. In turn, decision-makers will be more discriminating when selecting spatial priorities for PAs, which will improve total protection effectiveness for biodiversity and ESs (Malczewski et al. 2003).

We also found that existing PAs do not provide good protection for biodiversity and ES compared with scenarios that consider decision-makers’ attitudes towards risk, and therefore there is a room to improve protection effectiveness in existing PAs. This result is similar to previous studies that found existing PAs do not provide enough protection for biodiversity and ESs (Castro et al. 2015; Xu et al. 2017a). This may be because most existing PAs have been established for different protection objectives (e.g., protecting endangered species or unique ecosystems), and are usually distributed in remote areas that have little influence on economic development (Andam et al. 2008, Forleo et al. 2018). Furthermore, they were formed without considering decision-makers’ attitudes towards risk or under a risk-neutral assumption (Tulloch et al. 2015) during the process of choosing PAs locations. In addition, spatial incongruence among multiple ESs and biodiversity makes it difficult to meet all protection objectives simultaneously under limited land resources (Egoh et al. 2009, Wei et al. 2020). Spatial incongruence allows the risk attitudes of decision-makers to have a large influence on spatial protection effectiveness because risk-averse decision-makers tend to minimize the probability of very low values of protecting objectives, while risk-takers tend to maximize the probability of very high values (Makinson et al. 2012). Therefore, considering the different attitudes of decision-makers towards risk when choosing PAs for biodiversity and ESs is extremely important in order to improve protection effectiveness. This study provides a new perspective for improving the protection effectiveness of PAs under limited land resources, especially when the aim is to protect both biodiversity and ESs (He et al. 2018b). Our results indicate that spatial incongruence among high-value region of different conservation targets exists when we select a priority area with conflicting objectives (e.g., protecting habitat for species and certain ESs) (Chan et al. 2006). And our research could also provide method guidance for the selection of more efficient spatial priority areas for protected areas by considering decision-makers’ attitudes towards risks as follows: firstly, define decision-makers (whose preference will influence the selection of spatial priority areas) and their focused objectives. Secondly, design different risk-attitude scenarios (from risk-averse to risk-taking) and assess their impacts on protection effectiveness (Qin et al. 2019; Liu et al. 2013). Thirdly, compare protection efficiencies among different risk attitudes to select the most cost-effective scenario to improve management (Cao et al. 2019; Jiang and Eastman 2000). The application of decision makers’ attitude to risk by OWA method has strong implications for the choosing of priority area for ecosystem services. Because different aggregation approaches can yield strikingly different results, the decision rule is clearly a source of uncertainty in the decision making process, and has to be considered in the process of decision making. It’s usually difficult to consider all the decision makers’ attitude in the process of decision making. The OWA method considering theoretical risk attitudes could provide new perspectives for decision making in the field of choosing priority area for ecosystem services and biodiversity.

Although considering risk attitudes using ordered weighted averaging showed how such attitudes influence biodiversity and ESs protection effectiveness and PAs selection, we only examined seven risk-attitude scenarios, which could not provide a set of strategies that seek to achieve the maximum objective for decision makers (Billaurd et al. 2020). Over time, attitudes towards risk will change and can be influenced by social, cultural, opportunity cost and economic factors as well as decision-maker preferences (Trautmann and Vieider 2012). In addition, we just consider theoretical decision makers’ attitude towards risk which didn’t verify with actual attitude. Furthermore, biodiversity can be influenced by the connectivity and integrity of PAs, which were not considered in this study (Kukkala and Moilanen 2017). In the future, we had better integrate the multi-objective optimization model with ordered weighted averaging and include ecological information for different species to
provide optimal decision makers’ attitude towards risk (Tulloch et al 2015). This will, in turn, provide better information for selection of priority conservation areas for biodiversity and ESs in PAs.

5. Conclusions

Within the scope of limited land resources, simultaneously protecting biodiversity and ESs is a considerable challenge for decision-makers. Decision-makers’ attitude towards risk will influence the location selected for PAs. Considering different decision-makers’ attitude towards risk using the ordered weighted averaging method could improve the protection effectiveness of biodiversity and ES compared with existing PAs. For Hainan, a higher degree of risk aversion could provide better biodiversity and ESs protection effectiveness. Our research could provide a new perspective for improving the protection effectiveness of spatial priority for biodiversity and ESs under limited land resources and provides a potential reference for the construction of PAs in other regions. In the future, we had better consider actual decision makers’ attitude to risk instead of theoretical attitude.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Appendices
| Numerical order | Name of protected area | Area (ha) | Main protected objects | Protected type | Protection level in China | Setup time | Department in charge | IUCN protected areas categories |
|-----------------|------------------------|-----------|------------------------|----------------|--------------------------|------------|----------------------|---------------------------------|
| 1               | Liudao                 | 1 233.73  | Water conservation forests, tropical monsoon rain forests and wildlife | Forest ecosystem | City                     | 19960325   | Environmental Protection | Ia                              |
| 2               | Ganshiling             | 1 715.46  | Wuyipolei (Hopea reticulata Tardieu) and other rare plants | Wild plants     | Province                 | 19851101   | Forestry             | Ia                              |
| 3               | Kuaishan               | 4 462.4   | Tropical monsoon rainforest ecosystem | Forest ecosystem | Province                 | 19810925   | Forestry             | Ia                              |
| 4               | Fanjia                 | 3 100     | Tropical monsoon rainforest ecosystem | Forest ecosystem | Province                 | 19810925   | Forestry             | Ia                              |
| 5               | Qiejin                 | 7 588     | Tropical monsoon rainforest ecosystem | Forest ecosystem | Province                 | 19810925   | Forestry             | Ia                              |
| 6               | Liji qingpin           | 991.93    | Qingpi (Euonymus oxyphyllus Miq.) forest | Forest ecosystem | Province                 | 19800716   | Forestry             | Ia                              |
| 7               | Liulianling            | 2 745.47  | Tropical monsoon rainforest ecosystem | Forest ecosystem | Province                 | 19810925   | Forestry             | Ia                              |
| 8               | Nanlin                 | 5 775.26  | Tropical monsoon rainforest ecosystem | Forest ecosystem | Province                 | 19810925   | Forestry             | Ia                              |
| 9               | Jianling               | 10 898.73 | Tropical monsoon rainforest ecosystem | Forest ecosystem | Province                 | 19810925   | Forestry             | Ia                              |
| 10              | Shangxi                | 11 662.2  | Tropical monsoon rainforest ecosystem | Forest ecosystem | Province                 | 19810925   | Forestry             | Ia                              |
| 11              | Datian                 | 1 314     | Hainan Po Deer (Cervus eldi) and its habitat | Wild animal | National                 | 19761009   | Forestry             | Ia                              |
| 12              | Mihouling              | 12 215.33 | Tropical rain forest, karst cave | Forest ecosystem | Province                 | 19810925   | Forestry             | Ia                              |
| 13              | Yinggeling             | 50 464    | Tropical monsoon rainforest ecosystem | Forest ecosystem | Province                 | 19810925   | Forestry             | Ia                              |
| 14              | Bangzi Po Deer         | 361.8     | Hainan Po Deer (Cervus eldi) and its habitat | Forest ecosystem | Province                 | 19810925   | Forestry             | Ia                              |
| 15              | Bawangling             | 29 980    | Black-crested gibbon and its habitat | Wild animal | National                 | 19800129   | Forestry             | Ia                              |
| 16              | Baomending             | 3 844.3   | Tropical Rainforest | Forest ecosystem | Province                 | 20060518   | Forestry             | Ia                              |
| 17              | Jianfengling           | 20 170    | Rainforests and rare wildlife | Forest ecosystem | National                 | 19761009   | Forestry             | Ia                              |
| 18              | Baoguoshan             | 181.4     | Forest ecosystem | Forest ecosystem | County                   | 19920828   | Environmental Protection | Ia                              |
| 19              | Lizi                   | 8 326.67  | Tropical monsoon rainforest and rare wildlife | Forest ecosystem | Province                 | 19810925   | Forestry             | Ia                              |
| 20              | Diaoluoshan            | 18 389    | Tropical Rainforest | Forest ecosystem | National                 | 19840401   | Forestry             | Ia                              |
| 21              | Limushan               | 11 701    | Tropical monsoon rainforest ecosystem | Forest ecosystem | Province                 | 20040723   | Forestry             | Ia                              |
| 22              | Wuzhishan              | 13 435.9  | Tropical primary forest | Forest ecosystem | National                 | 19851101   | Forestry             | Ia                              |
| 23              | Baolong                | 36 316    | Forest ecosystem | Forest ecosystem | Province                 | 20061201   | Forestry             | Ia                              |
| 24              | Exianling              | 6 681.3   | Karst landforms, wildlife resources and tropical rainforest ecosystems | Forest ecosystem | Province                 | 20061201   | Forestry             | Ia                              |
| 25              | Nangaoling             | 4 529.4   | Forest ecosystem | Forest ecosystem | Province                 | 20061201   | Forestry             | Ia                              |
| LULC_type        | CN_A | CN_B | CN_C | CN_D | Kc_1 | Kc_2 | Kc_3 | Kc_4 | Kc_5 | Kc_6 | Kc_7 | Kc_8 | Kc_9 | Kc_10 | Kc_11 | Kc_12 |
|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|-------|-------|-------|
| Natural forest   | 0    | 55   | 0    | 79   | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1     | 1     | 1     |
| Garden           | 0    | 60   | 0    | 94   | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9   | 0.9   | 0.9   |
| Rubber plantation| 0    | 75   | 0    | 94   | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95  | 0.95  | 0.95  | 0.95  |
| Grassland        | 0    | 70   | 0    | 89   | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5   | 0.5   | 0.5   |
| Farmland         | 0    | 61   | 0    | 94   | 0.68 | 0.77 | 1.13 | 0.98 | 1.08 | 1.20 | 1.14 | 1.13 | 1.40  | 1.05  | 0.98  | 0.68  |
| Settlement       | 0    | 95   | 0    | 98   | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1   | 0.1   | 0.1   |
| Water body       | 0    | 1    | 0    | 1    | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05  | 1.05  | 1.05  | 1.05  |
| Bare land        | 0    | 80   | 0    | 86   | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3   | 0.3   | 0.3   | 0.3   |

Table A2. Biophysical table for InVEST model.
Table A3. Biophysical table for InVEST seasonal water-yield module.

| LU/LC_type            | USLE_C | USLE_P | LU/LC_veg | load_n | eff_n | crit_len_n | load_p | eff_p | crit_len_p | proportion_subsurface_n | Carbon sequestration ratio (t/ha) |
|-----------------------|--------|--------|-----------|--------|-------|------------|--------|-------|------------|-------------------------|----------------------------------|
| Natural forest        | 0.003  | 1      | 1         | 3      | 0.8   | 300        | 0.15   | 0.8   | 300        | 0.5                     | 7.1                              |
| Garden                | 0.06   | 1      | 1         | 10.21  | 0.45  | 30         | 3.1    | 0.45  | 30         | 0                       | 3.1                              |
| Rubber plantation     | 0.06   | 1      | 1         | 79.05  | 0.35  | 30         | 2.85   | 0.35  | 30         | 0                       | 4.53                             |
| Grassland             | 0.015  | 1      | 1         | 7      | 0.4   | 150        | 0.9    | 0.4   | 150        | 0                       | 0.74                             |
| Farmland              | 0.04   | 0.15   | 1         | 53.5   | 0.25  | 30         | 2.9    | 0.25  | 30         | 0                       | 0.5                              |
| Settlement            | 0.001  | 1      | 0         | 13.8   | 0.05  | 15         | 1.8    | 0.05  | 15         | 0                       | 0                                |
| Water body            | 0.001  | 1      | 0         | 15     | 0.05  | 15         | 0.36   | 0.05  | 15         | 0                       | 0                                |
| Bare land             | 0.2    | 1      | 0         | 0.88   | 0.05  | 10         | 0.01   | 0.05  | 10         | 0                       | 0                                |
Table A4. List of indicator species (150) and their conservation status.

| ID | Taxa                  | Binomial            | China’s red list | National key protection plants/wildlife list | Endemic species in Hainan | Importance level |
|----|-----------------------|---------------------|------------------|--------------------------------------------|----------------------------|------------------|
| 1  | Plants                | Chuniophoenix nana  | CR               | Not Listed                                 | No                         | III              |
| 2  | Plants                | Fortunella bawangica| CR               | Not Listed                                 | Yes                        | III              |
| 3  | Plants                | Pentastelma arsitrum| CR               | Not Listed                                 | Yes                        | III              |
| 4  | Plants                | Cyclobalanopsis albumcula| CR         | Not Listed                                 | Yes                        | III              |
| 5  | Plants                | Vanda brunnea       | EN               | Not Listed                                 | No                         | III              |
| 6  | Plants                | Dendropanax oligodonta| CR           | Not Listed                                 | Yes                        | III              |
| 7  | Plants                | Neolitsea howii     | CR               | Not Listed                                 | Yes                        | III              |
| 8  | Plants                | Liparis bautinogensis| EN             | Not Listed                                 | Yes                        | III              |
| 9  | Plants                | Adinandra howii     | EN               | Not Listed                                 | Yes                        | III              |
| 10 | Plants                | Carinella amplexifolia| EN              | Not Listed                                 | Yes                        | III              |
| 11 | Plants                | Decaspermum albociliatum| EN             | Not Listed                                 | No                         | III              |
| 12 | Plants                | Dendrobium changiae| EN               | Not Listed                                 | Yes                        | III              |
| 13 | Plants                | Vanda subconcolor   | EN               | Not Listed                                 | Yes                        | III              |
| 14 | Plants                | Aglaisia spectabilis| EN               | II                                         | No                         | II               |
| 15 | Plants                | Styrax macrocarpus  | EN               | Not Listed                                 | Yes                        | III              |
| 16 | Plants                | Dracontolmon macrocarpum| CR          | Not Listed                                 | Yes                        | III              |
| 17 | Plants                | Vanda ovata         | EN               | Not Listed                                 | No                         | III              |
| 18 | Plants                | Horsfieldia kingii  | EN               | Not Listed                                 | No                         | II               |
| 19 | Plants                | Symplcoba ovatiloba  | EN               | Not Listed                                 | Yes                        | III              |
| 20 | Plants                | Allophylus repandifolius| CR            | Not Listed                                 | Yes                        | III              |
| 21 | Plants                | Dendrobium terminale| CR               | Not Listed                                 | No                         | III              |
| 22 | Plants                | Cleyera obvata      | EN               | Not Listed                                 | No                         | III              |
| 23 | Plants                | Platea parvifolia   | EN               | Not Listed                                 | Yes                        | III              |
| 24 | Plants                | Cymbidium dayanum   | EN               | Not Listed                                 | No                         | III              |
| 25 | Plants                | Cymbidium eburneum  | EN               | Not Listed                                 | No                         | III              |
| 26 | Plants                | Elaeocarpus brachystachyus| CR        | Not Listed                                 | Yes                        | III              |
| 27 | Plants                | Neolitsea obtusifolia| EN             | Not Listed                                 | Yes                        | III              |
| 28 | Plants                | Pyrenocarpa sennanensis| EN           | Not Listed                                 | Yes                        | III              |
| 29 | Plants                | Apostasia ramifera  | CR               | Not Listed                                 | Yes                        | III              |
| 30 | Plants                | Schefflera heptaphyllu| CR             | Not Listed                                 | No                         | III              |
| 31 | Plants                | Dendrobium aduncum  | EN               | Not Listed                                 | No                         | III              |
| 32 | Plants                | Hokioglossum kimballianum| EN        | Not Listed                                 | No                         | III              |
| 33 | Plants                | Cephalotaxus hainanensis| EN           | Not Listed                                 | No                         | III              |
| 34 | Plants                | Polyspora hainanensis| EN               | Not Listed                                 | Yes                        | III              |
| 35 | Plants                | Sonnerati x hainanensis| CR            | Not Listed                                 | Yes                        | III              |
| ID | Taxa                  | Binomial              | China’s red list | National key protection plants/wildlife list | Endemic species in Hainan | Importance level |
|----|-----------------------|-----------------------|------------------|---------------------------------------------|----------------------------|-----------------|
| 36 | Plants                | Phaius hainanensis    | CR               | Not Listed                                  | Yes                        | III             |
| 37 | Plants                | Paranepheleum hainanensis | CR               | Not Listed                                  | Yes                        | III             |
| 38 | Plants                | Orchidantha insularis | CR               | Not Listed                                  | Yes                        | III             |
| 39 | Plants                | Litsea litseaefolia   | EN               | Not Listed                                  | Yes                        | III             |
| 40 | Plants                | Dendrobium hainanense | EN               | Not Listed                                  | No                         | III             |
| 41 | Plants                | Alphonsea hainanensis | EN               | Not Listed                                  | Yes                        | III             |
| 42 | Plants                | Baschnia hainanensis  | EN               | Not Listed                                  | Yes                        | III             |
| 43 | Plants                | Keteleeria hainanensis| CR               | II                                         | Yes                        | II              |
| 44 | Plants                | Malaxis hainanensis   | CR               | Not Listed                                  | Yes                        | III             |
| 45 | Plants                | Rynhuchostylis gigantea| EN               | Not Listed                                  | No                         | III             |
| 46 | Plants                | Sunneretia casularis  | EN               | Not Listed                                  | No                         | III             |
| 47 | Plants                | Acriopsis indica      | EN               | Not Listed                                  | No                         | III             |
| 48 | Plants                | Drypetes indica       | EN               | Not Listed                                  | No                         | III             |
| 49 | Plants                | Syzygium infrarubiginosum | CR               | Not Listed                                  | Yes                        | III             |
| 50 | Plants                | Phaius tankervilliae  | CR               | Not Listed                                  | No                         | III             |
| 51 | Plants                | Dendrobium williamsonii| EN               | Not Listed                                  | No                         | III             |
| 52 | Plants                | Scorpiothrys erythrotrichus | CR               | Not Listed                                  | Yes                        | III             |
| 53 | Plants                | Phalaenopsis aphrodite | CR               | Not Listed                                  | No                         | III             |
| 54 | Plants                | Castanopsis concinna  | EN               | II                                         | Yes                        | II              |
| 55 | Plants                | Dendrobium sinense    | EN               | Not Listed                                  | Yes                        | III             |
| 56 | Plants                | Sophora xanthantha    | CR               | Not Listed                                  | Yes                        | III             |
| 57 | Plants                | Bulleophyllum obtusangulatum | CR               | Not Listed                                  | Yes                        | III             |
| 58 | Plants                | Dendrobium dixanthum  | EN               | Not Listed                                  | Yes                        | III             |
| 59 | Plants                | Epipacthes elongata   | EN               | Not Listed                                  | No                         | III             |
| 60 | Plants                | Nothapodyte obtusifolia| CR               | Not Listed                                  | Yes                        | III             |
| 61 | Plants                | Syzgium buxifoliodeum| CR               | Not Listed                                  | Yes                        | III             |
| 62 | Plants                | Syzgium jinfunicum    | CR               | Not Listed                                  | Yes                        | III             |
| 63 | Plants                | Crotalaria jianfengensis| CR               | Not Listed                                  | Yes                        | III             |
| 64 | Plants                | Dendrobium acinaiforme| EN               | Not Listed                                  | Yes                        | III             |
| 65 | Plants                | Dalbergia odorifera   | CR               | II                                         | Yes                        | II              |
| 66 | Plants                | Impatiens ovateflora  | EN               | Not Listed                                  | Yes                        | III             |
| 67 | Plants                | Michelia foveolata    | EN               | Not Listed                                  | No                         | III             |
| 68 | Plants                | Paphiopedilium appletonianum | EN               | Not Listed                                  | No                         | III             |
| 69 | Plants                | Lirinanthalovenea     | EN               | Not Listed                                  | No                         | III             |
| 70 | Plants                | Gmelina hainanensis   | EN               | II                                         | No                         | II              |
| 71 | Plants                | Homalium kainantense  | EN               | Not Listed                                  | Yes                        | III             |
| ID | Taxa         | Binomial                    | China’s red list | National key protection plants/wildlife list | Endemic species in Hainan | Importance level |
|----|--------------|-----------------------------|------------------|---------------------------------------------|---------------------------|-----------------|
| 72 | Plants       | Syndiclis lotungensis       | CR               | Not Listed                                  | Yes                        | III             |
| 73 | Plants       | Liparis fusilabris          | EN               | Not Listed                                  | Yes                        | III             |
| 74 | Plants       | Dendrobium fimbriatum       | EN               | Not Listed                                  | No                         | III             |
| 75 | Plants       | Cyclobalanopsis subhainoiida| CR               | Not Listed                                  | Yes                        | III             |
| 76 | Plants       | Brassaiopsis glomerulata    | EN               | Not Listed                                  | No                         | III             |
| 77 | Plants       | Camellia kisii              | CR               | Not Listed                                  | No                         | III             |
| 78 | Plants       | Schismatoglossus hainanensis| CR               | Not Listed                                  | Yes                        | III             |
| 79 | Plants       | Lagerstroemia balansae      | EN               | Not Listed                                  | No                         | III             |
| 80 | Plants       | Allophylus trichophyllus    | EN               | Not Listed                                  | Yes                        | III             |
| 81 | Plants       | Buxus pubiramea             | CR               | Not Listed                                  | Yes                        | III             |
| 82 | Plants       | Cymbidium insignne          | EN               | Not Listed                                  | No                         | III             |
| 83 | Plants       | Dendrobium loddigesii       | EN               | Not Listed                                  | No                         | III             |
| 84 | Plants       | Dendrobium densiflorum      | EN               | Not Listed                                  | No                         | III             |
| 85 | Plants       | Blastus borneensis         | EN               | Not Listed                                  | No                         | III             |
| 86 | Plants       | Hopea hainanensis          | CR               | I                                          | No                         | I               |
| 87 | Plants       | Vanda conceolor             | EN               | Not Listed                                  | Yes                        | III             |
| 88 | Plants       | Vatica mangshapeloi         | EN               | II                                         | No                         | II              |
| 89 | Plants       | Lithocarpus chiungshungensis| EN               | Not Listed                                  | Yes                        | III             |
| 90 | Plants       | Chusniophoenix hainanensis  | EN               | Not Listed                                  | Yes                        | III             |
| 91 | Plants       | Bennettiodendron leptopiospes| EN             | Not Listed                                  | No                         | III             |
| 92 | Plants       | Chusia bucklandioides      | EN               | II                                         | Yes                        | II              |
| 93 | Plants       | Pothea chinensis           | CR               | Not Listed                                  | No                         | III             |
| 94 | Plants       | Michelia shihuenensis      | EN               | II                                         | Yes                        | II              |
| 95 | Plants       | Ilex shineica              | EN               | Not Listed                                  | Yes                        | III             |
| 96 | Plants       | Andrographis laxiflora     | CR               | Not Listed                                  | No                         | III             |
| 97 | Plants       | Scorpiothrysus olgaotrichus| CR               | Not Listed                                  | Yes                        | III             |
| 98 | Plants       | Homalium ceylanicum        | EN               | Not Listed                                  | No                         | III             |
| 99 | Plants       | Loropetalum subcardatum    | EN               | II                                         | Yes                        | II              |
| 100| Plants       | Ilex chiniana              | EN               | Not Listed                                  | Yes                        | III             |
| 101| Plants       | Lithocarpus elmerillii     | EN               | Not Listed                                  | Yes                        | III             |
| 102| Plants       | Syzygium howii              | CR               | Not Listed                                  | Yes                        | III             |
| 103| Plants       | Aglaia lawii               | CR               | Not Listed                                  | Yes                        | III             |
| 104| Plants       | Parashorea chinesis        | EN               | I                                          | No                         | I               |
| 105| Plants       | Lithocarpus caulinitimbres  | EN               | Not Listed                                  | Yes                        | III             |
| 106| Plants       | Adinandra eupunctata       | CR               | Not Listed                                  | Yes                        | III             |
| 107| Plants       | Diospyros corallina        | CR               | Not Listed                                  | Yes                        | III             |
| ID  | Taxa     | Binomial                     | China’s red list | National key protection plants/wildlife list | Endemic species in Hainan | Importance level |
|-----|----------|------------------------------|------------------|---------------------------------------------|---------------------------|-----------------|
| 108 | Plants   | *Stemona parviflora*        | EN               | Not Listed                                  | Yes                        | III             |
| 109 | Plants   | *Hopea chinensis*           | EN               | I                                           | No                         | I               |
| 110 | Plants   | *Carneliaia pseuopunctata*  | CR               | Not Listed                                  | Yes                        | III             |
| 111 | Plants   | *Lirianthe championiti*     | EN               | Not Listed                                  | No                         | III             |
| 112 | Plants   | *Michelia goni*             | EN               | Not Listed                                  | No                         | III             |
| 113 | Plants   | *Pinus massoniana var. hainanensis* | CR         | Not Listed                                  | Yes                        | III             |
| 114 | Plants   | *Peltophorum diyerhachis var. tokinensis* | EN         | Not Listed                                  | No                         | III             |
| 115 | Plants   | *Homalanthes fastuosus*     | CR               | Not Listed                                  | No                         | III             |
| 116 | Plants   | *Gmelina arborea*           | EN               | Not Listed                                  | No                         | III             |
| 117 | Plants   | *Lagerstroemia intermedia*  | EN               | Not Listed                                  | No                         | III             |
| 118 | Plants   | *Helicopsis terminalis*     | EN               | Not Listed                                  | No                         | III             |
| 119 | Plants   | *Ormosia inflata*           | CR               | Not Listed                                  | Yes                        | III             |
| 120 | Plants   | *Dendrobium hercoglossum*   | EN               | Not Listed                                  | No                         | III             |
| 121 | Plants   | *Syzygium rysuopodum*       | EN               | Not Listed                                  | Yes                        | III             |
| 122 | Plants   | *Alseaophne rugosa*         | EN               | Not Listed                                  | Yes                        | III             |
| 123 | Plants   | *Dendrobium salacense*      | EN               | Not Listed                                  | No                         | III             |
| 124 | Plants   | *Pupphiopidium puipuratum*  | EN               | Not Listed                                  | No                         | III             |
| 125 | Mammals  | *Neofelis nebulae nebulosa* | EN               | I                                           | No                         | I               |
| 126 | Mammals  | *Nomascus hainanus*         | CR               | I                                           | Yes                        | I               |
| 127 | Mammals  | *Viverra zibetha hainana*   | EN               | II                                          | No                         | II              |
| 128 | Mammals  | *Manis pentadactyla pusilla*| EN               | II                                          | No                         | II              |
| 129 | Mammals  | *Lutra lutra hainana*       | EN               | II                                          | No                         | II              |
| 130 | Mammals  | *Hylomys hainanensis*       | EN               | Not Listed                                  | Yes                        | III             |
| 131 | Mammals  | *Ruservus eldii*            | CR               | Not Listed                                  | Yes                        | III             |
| 132 | Birds    | *Arborophila ardens*        | EN               | I                                           | Yes                        | I               |
| 133 | Birds    | *Polyelectron katsumatae*   | EN               | I                                           | Yes                        | I               |
| 134 | Birds    | *Platalea minor*            | EN               | II                                          | No                         | II              |
| 135 | Birds    | *Tringa guttifer*           | EN               | II                                          | No                         | II              |
| 136 | Birds    | *Threskiornis melanoleucus* | EN               | II                                          | No                         | II              |
| 137 | Birds    | *Gracula religiosa intermedia* | EN          | Not Listed                                  | No                         | III             |
| 138 | Birds    | *Nettapus coromandelianus coromandelianus* | EN         | Not Listed                                  | No                         | III             |
| 139 | Reptiles | *Pelechelys cantorii*       | CR               | I                                           | No                         | I               |
| 140 | Reptiles | *Varanus salvator*          | CR               | I                                           | No                         | I               |
| 141 | Reptiles | *Python molurus bivittatus*  | CR               | I                                           | No                         | I               |
| 142 | Reptiles | *Geemyyla spengleri*        | EN               | II                                          | No                         | II              |
| 143 | Reptiles | *Palea steindachneri*       | EN               | II                                          | No                         | II              |
**Table A4. (Continued.)**

| ID | Taxa          | Binomial          | China’s red list | National key protection plants/wildlife list | Endemic species in Hainan | Importance level |
|----|---------------|-------------------|------------------|---------------------------------------------|---------------------------|-----------------|
| 144| Reptiles      | Cuora galbinifrons| EN               | Not Listed                                  | No                        | III             |
| 145| Reptiles      | Pyxidea mouhotii  | EN               | Not Listed                                  | No                        | III             |
| 146| Reptiles      | Ophiophagus hannah| EN               | Not Listed                                  | No                        | III             |
| 147| Reptiles      | Mauremys mutica  | EN               | Not Listed                                  | No                        | III             |
| 148| Reptiles      | Ocadia sinensis   | EN               | Not Listed                                  | No                        | III             |
| 149| Amphibians    | Tylototriton hainanensis | EN     | Not Listed                                  | Yes                       | III             |
| 150| Amphibians    | Parapedsphryne scalpta | EN     | Not Listed                                  | Yes                       | III             |

**Note:** National key protection plants/wildlife list is from ‘List of Wildlife under Special State Protection’, ‘List of Wild Plants under Special State Protection’; China’s red list categories: CR = critically endangered; EN = endangered. Importance level: Level I - national first-level endangered and critically endangered species; Level II - national second-level endangered and critically endangered species; and Level III - other endangered and critically endangered species and endemic species in Hainan Island.
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