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An assessment of the Ecological Conservation Redline: unlocking priority areas for conservation

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Protected areas (PAs) are established to conserve wildlife habitats and biodiversity. To this end, the Chinese central government has initiated a pioneering environmental planning and management policy known as the Ecological Conservation Redline (ECR). While the ecological benefits of ECR policy have been extensively evaluated, spatially explicit assessment of the ECR remains understudied. Here, we propose an element-function-structure framework for assessing the concurrence of ECR areas and ecological conservation hotspots to further outline priority areas for conservation. Results show that 67% of existing PAs are protected by ECR areas, while that of ecological corridors is only 11%. Regional variation in the ECR representativeness can be leveraged by deliberately protecting tailored ecological conservation hotspots in specific locations and stepping stones in ecological corridors. This study highlights the substantial space for ecological management to achieve the goals of ECR policy, and discourses on the co-production of knowledge from researchers and policy makers.

Keywords: protected areas; biodiversity conservation; natural resource management; ecological security; assessment framework

1. Introduction

Originally, terrestrial Protected Areas (PAs) were established worldwide to constrain destructive human activities and safeguard endangered species in perpetuity (Folharini, Melo, and Cameron 2022; Kroner *et al*. 2019; Ribeiro *et al*. 2021). Yet, evidence suggests that PAs are confronted with increasing alterations from human activities that characterize the Anthropocene (Ellis and Ramankutty 2008; Geldmann, Joppa, and Burgess 2014), despite the rapid expansion of PA coverage over past decades (Buchadas *et al*. 2022). At a global scale, only 42% of PAs are free of any detectable human disturbance, whereas approximately 33% are extensively modified (Jones *et al*. 2018). For example, in the United States, national parks, wilderness areas, community conserved areas, and nature reserves are declining in their ability to conserve biodiversity due to human disturbance (Radeloff *et al*. 2010). Furthermore, established species-oriented indicators have played a key role in assessing the outcome of PAs (Gray *et al*. 2016), but they may fall short in the context of the increasingly divergent goals

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of conservation. For instance, Maxwell *et al.* (2020) state that PAs must effectively contribute to meeting global goals, ranging from preventing species extinctions to retaining the most intact ecosystems.

Consistent with the inclusive goals of conservation efforts, the central government of China has initiated a pioneering environmental planning and management policy known as the Ecological Conservation Redline (ECR, see Gao (2019) and Schmidt-Traub *et al.* (2021)). The ECR policy, which aims to protect more than one-quarter of China's territory, is currently one of the nation's highest priorities for policy implementation (Zhang *et al.* 2022). Basically, ECR boundaries outline regions with privileged ecological functions by assimilating the principles of ecosystem service, ecological sensitivity, and biodiversity priorities into management practices (Bai, Fang, and Hughes 2021; Gao, Wang, *et al.* 2020). Ideally, the establishment of ECR can benefit habitat quality and maintain habitat connectivity (Luo *et al.* 2020). Therefore, the ECR vision resembles the concept of ecological networks in terms of integrity and connectivity, but it is more conducive to safeguarding ecological security in terms of willingness for political action (Ma, Xue, and Ji 2022; Montoya, Pimm, and Solé 2006).

The joint legislation regarding the ECR policy by multiple central government departments[1] is going to play a critical role in ecological conservation, and assessments of management practices have been extensively conducted in such contexts (Gao, Wang, *et al.* 2020). These assessments help to better reconcile conservation goals with local economic development under the premise that ECR areas have been optimally identified (Busch and Amarjargal 2022). To the best of our knowledge, however, few studies have assessed the rationality of the issued ECR coverage. Given that no clear planning framework has been set to maximize the representativeness and effectiveness of conservation goals, government and local authorities are facing the dilemma of ECR conflicts with regional socio-economic development, despite the fact that they inherently prefer socio-economic development in most cases. This issue has largely led to spatial mismatch, isolation, and severe human interference inside or around the ECR areas. For example, Liang *et al.* (2022) find that, in the Jiangsu province of China, a large proportion of built-up land is located in ECR areas; in addition, ECR boundaries do not always match local landforms, which are prone to absurd patterns of regional development due to land-use conflict (de Jong *et al.* 2021).

As such, the objective of this study is to facilitate a framework for a comprehensive science-based assessment of ECR, and to potentially unlock priority areas for future optimization of ECR delineation. To achieve this, ecological conservation hotspots are first identified based on ecosystem element, function, and structure. These ecological conservation hotspots are further used to delineate the ecological representativeness of ECR coverage at both provincial and county scales. Finally, priority areas for conservation are identified by synthesizing ecological function zones and ecological stepping stones. We implement this approach for the case of Zhejiang province, which plays a critical role in China's ecological protection, as it is the place where the ECR policy originated.

2. Materials and methods

In this study, we propose a stepwise method to assess the effectiveness of ECR coverage (Figure 1). First, ecological conservation hotspots are identified accounting for

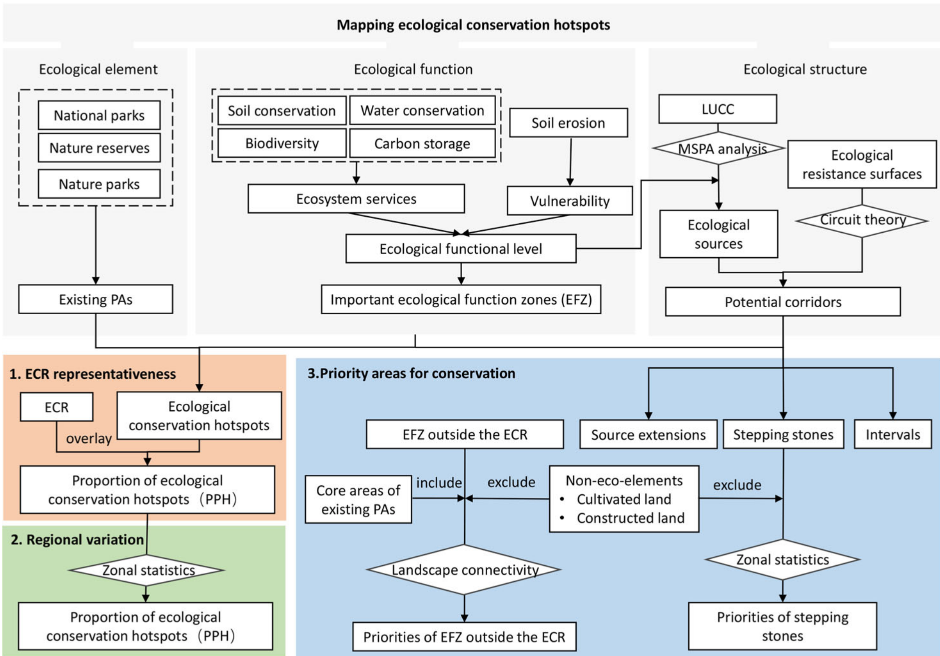

Figure 1. Workflow for the assessment of ECR coverage. The three columns in gray represent the element-function-structure that together depict ecological conservation hotspots.

ecological element, function, and structure. Specifically, ecological element is depicted by integrating the wide range of existing PAs. Ecological Functional Zones (EFZs) maximize the dominant ecological functions and serve the functional objective of ECR patches, which are connected by ecological corridors that serve the holistic ECR system objective. Second, the entire retention of these three ecological conservation hotspots in ECR areas is investigated (i.e. ecological representativeness) for each of the three components. Third, we compare the variation in ECR representativeness among Major Function-oriented Zones, the blueprint for the future development and protection pattern for China's territory (Fan 2015), in order to better reflect practical issues across different counties. In addition, management characteristics of ECR are discussed from the perspective of regional competition for land. Finally, we identify priority areas for conservation, to illustrate the gap between management practice and policy goals, and to inform sound policy-making for regional optimization of ECR coverage.

2.1. Study area

Zhejiang province is located on the southeast coast of China (Figure 2). This province covers an estimate of 105,000 km^2, of which forest land and cultivated land account for 62% and 23%, respectively (Supplementary material, Table S1). Owing to its abundant vegetation and valuable biological resources, Zhejiang province performs essential ecological functions at both regional and national scales. Notably, in 2000, a local flagship program analogous to the current ECR policy was first launched in the Anji County of Zhejiang province (Gao 2019, also see Figure 2).

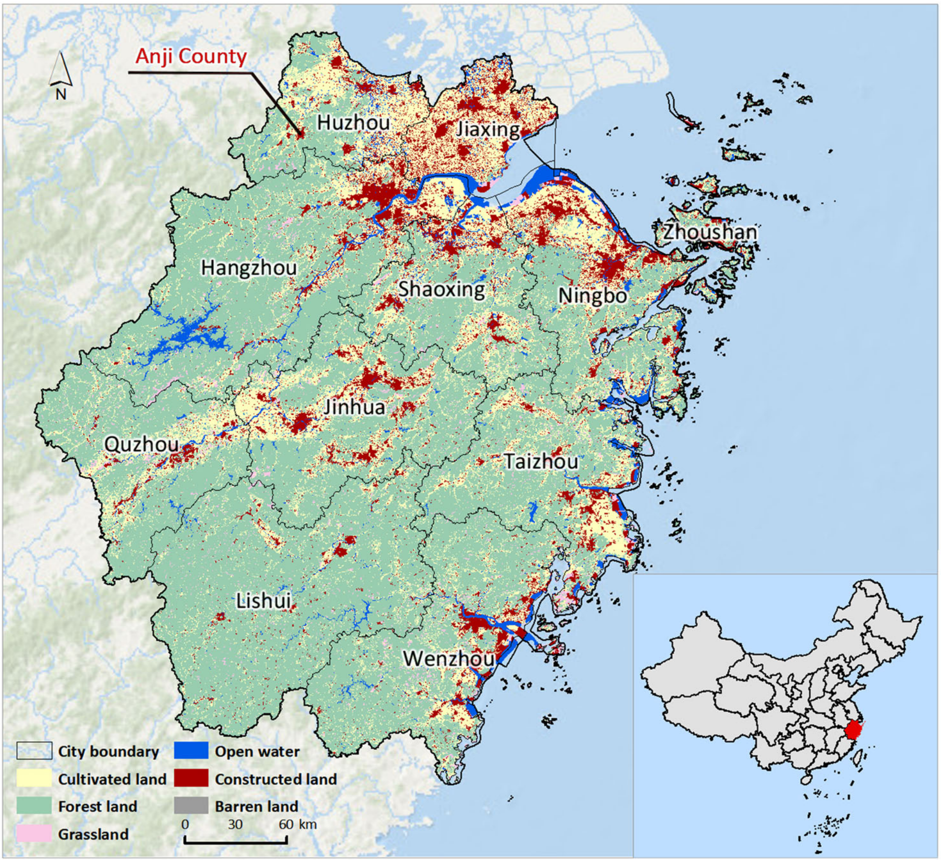

Figure 2. Location and land use patterns of Zhejiang province. Land use data are derived from the National Land Cover Datasets (NLCDs, see Liu *et al.* (2014)) for the year 2018. The topographic basemap is publicly available at ESRI ArcGIS ®.

In addition, Zhejiang is a densely populated province in the south wing of the Yangtze River Delta and it is now experiencing rapid urbanization (Wang *et al*. 2017). It governs 11 cities and 89 counties, with a total GDP and per capita GDP ranking among the top five in China. Currently, the terrestrial ECR areas in Zhejiang province cover an area of 24,852 km^2; more than 23% of the land (Supplementary material, Table S2).

2.2. Dataset

Various datasets are used in this study (Supplementary material, Table S3). These datasets can be categorized into four classes: 1) Land use. Land use data with a spatial resolution of 30 m were obtained from the Resource and Environmental Science and Data Center (https://www.resdc.cn/), and were reclassified into six categories: cultivated land, forest land, grassland, open water, constructed land, and barren land. 2) Terrain. Digital elevation models (DEM) with a spatial resolution of 30 m were downloaded from the Geospatial Data Cloud (http://www.gscloud.cn/); 3) Biophysical elements. Normalized Difference Vegetation Index (NDVI) and Net Primary Productivity (NPP) were derived from Landsat-8 satellite imaginaries; soil properties were provided by the World Soil Database, which includes soil depth, organic matter content, soil composition and others; temperature and precipitation were derived from the observation data of 42 meteorological stations covering Zhejiang Province, and precipitation and potential evapotranspiration in 1995–2018 were interpolated using the Kriging method. 4) Socioeconomic factors. Road network was obtained from the OpenStreetMap (OSM, https://www.openstreetmap.org/); ECR boundaries, major function-oriented zones, and existing PAs were acquired from the local government (https://www.zj.gov.cn/).

Pre-processing operations such as geo-referencing and merging are implemented on ArcGIS 10.5 platform. All data layers are uniformly projected to the spatial reference of WGS_1984_UTM_Zone_50N, and the grid size is resampled to $100\,m \times 100\,\mathrm{m}$.

2.3. Determination of ecological conservation hotspots

In this section, we elaborate the methods used to extract existing PAs, EFZs, as well as ecological corridors, which are the three most relevant components for ECR delineation (i.e. element, function, and structure, respectively).

2.3.1. Protected areas (PAs)

The existing spectrum of PAs in China consists of national parks, nature reserves and parks (Miller-Rushing *et al*. 2017), with a decreasing sequence of ecological importance and management intensity accordingly. We compile the scheme of PAs, and manually merge PAs regardless of their relative importance in the ArcGIS platform (https://www.esri.com/).

2.3.2. Important ecological functional zones (EFZs)

Ecological functions can be portrayed as the ecosystem services (ESs) and ecological vulnerability (Peng *et al*. 2019). According to Zhejiang's ecological conditions and expert knowledge, we select and assess four types of ESs and one indicator for ecological vulnerability with the InVEST model, NPP index, and the Revised Universal Soil Loss Equation (RUSLE). For more technical details, please see the Supplementary material. These four ESs are subsequently normalized using Min-Max value method, and summed with equal weights. Finally, we extract 20% of areas with the largest values as EFZs (Bai *et al*. 2018).

2.3.3. Potential ecological corridors

Regions protected by ECR areas are not isolated space for many large species that are largely dependent on habitat outside the ECR, and corridors linking them together are therefore crucial elements for animal movement (Dai, Liu, and Luo 2021; Ghoddousi, Loos, and Kuemmerle 2022). Literally, an ecological corridor that connects multiple sources is a narrow strip of vegetation that is distinct from other nearby ecological elements. The graph-based approach and circuit theory have been widely used to identify potential corridors (Huang, Hu, and Zheng 2020; Peng *et al*. 2018). Following the circuit theory, landscape can be regarded as a conductive surface and the probability in the biological migration conforms to Ohm's law:

$$I = U/R \tag{1}$$

where R characterizes the resistance of the conductive surface, U represents the voltage across a given node, and I is the current through the node. In this study, the regional ecological network is regarded as a circuit, and the flow is considered as the current between ecological sources.

As for the application of circuit theory, the key is to determine ecological sources and resistance surfaces. Ecological sources are the origin of species dispersal and provide important ecosystem services as well as taking great structural importance (Dai, Liu, and Luo 2021). In light of this, ecological sources are identified as those core areas with high ecological functions. Specifically, the research objects of the Morphological Spatial Pattern Analysis (MSPA) are divided into two categories: foreground (forest land, grassland, open water) and background (cultivated land, constructed land, barren land) to distinguish the core area (Lin *et al*. 2021). Consequently, the value of ecological functions is categorized into one out of the five levels following the natural break method, with the top 20% bin considered as ecological function zones (Peng *et al*. 2018).

Meanwhile, the resistance value indicates the difficulty for species to disperse, which is determined by natural conditions and human activities. According to the characteristics of the study area and existing research (Wang, Jiang, *et al*. 2021), the resistance value can be represented by land use/cover, elevation, slope, distance from road, and distance from constructed land (Supplementary material, Table S4).

2.4. *Ecological representativeness of ECR coverage*

We analyze the overall pattern of these different types of ecological hotspots (i.e. ecological element, function, and structure), the proportion of ecological conservation hotspots (PPH) within its area and the percentage of overlap with hotspots (PEH), to measure ecological representativeness (Bai, Fang, and Hughes 2021). PPH is obtained by calculating the percentage area of all hotspots that are protected in Zhejiang province, to assay the extent of the protection of ecological hotspots. PEH is obtained by calculating the percentage of ECR areas that concur with ecological conservation hotspots in each of the 89 counties, interpreting the representativeness of the current ECR. Thus, PPH reveals the overall protection of all ecological conservation hotspots, and PEH represents the percentage of ECR areas covering hotspots relative to non-hotspot areas (Bai, Fang, and Hughes 2021). To further examine the regional variation of ECR representativeness in Zhejiang province, we distinguish four clusters according to the major function-oriented zones, determined by natural conditions and human activities therein (Fan *et al*. 2012).

2.5. *Determination of conservation priorities*

Implementing official adjustments of the issued ECR coverage may be unrealistic in the short term. Hence, we determine the ecological optimization target through the overall analysis with regard to EFZ and ecological stepping stones.

2.5.1. Importance zoning of EFZ

After dissolving the core areas of the established PAs in ECR areas, the conservation priority of non-overlapping EFZ is graded into one of the four levels according to the summed level of ecological functions and the landscape connectivity of their ecological sources.

Moreover, we use graph-based connectivity indicators to characterize the overall connectivity in a landscape and the importance of each patch for connectivity (Saura and Pascual-Hortal 2007). Specifically, Integral Index of Connectivity (*IIC*) and Probability of Connectivity (*PC*) are chosen to calculate the relative importance (*dI*) of landscape connectivity by using Conefor 2.6 software. The main calculation formula is as follows:

$$IIC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \frac{a_i * a_j}{1+nl_{ij}}}{A_L^2} \tag{2}$$

$$PC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} P_{ij}^{*} a_i * a_j}{A_L^2} \tag{3}$$

$$dI = 0.5 * \ \mathrm{dIIC} + 0.5 * \ \mathrm{dPC} \tag{4}$$

where n is the total number of patches; a_i and b_j are areas of patches i and j, respectively; nl_{ij} is the number of connections between patches i and j; A_L is the area of the entire landscape; and P_{ij}^{*} represents the maximum probability that patch i and j are connected.

2.5.2. Ecological stepping stones

Ecological corridors play a crucial role in biological dispersal and species persistence (Rocha *et al*. 2021), while linear construction projects such as roads and railways threaten the protection of ecological corridors (Marcantonio *et al*. 2013). In that case, however, stepping stones in corridors can still provide essential ecological linkage (Rocha *et al*. 2021; Saura *et al*. 2014). In this study, we use the Pinchpoint Mapper to identify ecological stepping stones following the circuit theory. According to the maximum migration distance of terrestrial animals and plants (Rouget *et al*. 2006), the width of potential ecological corridors is determined to be 1.2 km, and the cost-weighted density (CWD) of corridors is graded into five classes using the natural break method. We assign the areas that fall into the highest density bin as the essential locations for ecological flow. Considering the exclusivity of ecological elements and integrity (Saura *et al*. 2014), we eventually define ecological patches with an area > 10 km^2 as stepping stones, of which the total current value can further reflect their relative importance.

3. Results

3.1. Ecological representativeness of ECR coverage

Overall, ecological conservation hotspots cover approximately 31% of the total terrestrial area of Zhejiang Province (Figure 3), and this proportion is moderately higher than the national target of ECR policy (25%). Specifically, PAs, which cover a terrestrial area of 10,110 km^2, are mostly distributed in Hangzhou City and Wenzhou City

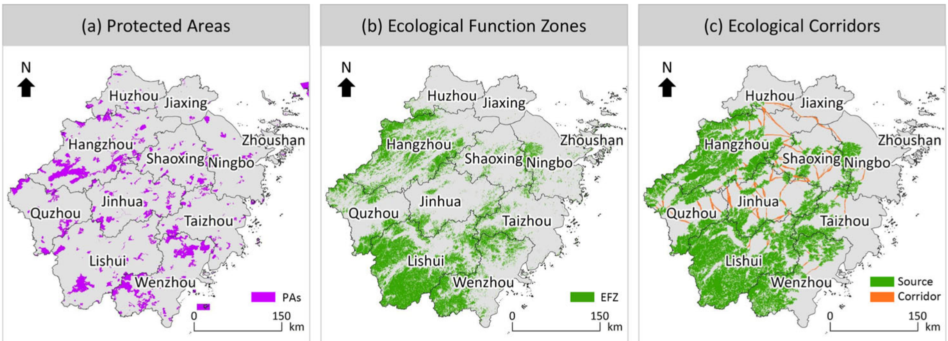

Figure 3. Ecological conservation hotspots. (a) Protected Areas; (b) Ecological Function Zones; and (c) Ecological Corridors. To further explore the enhanced visualization of these results, please check the interactive map viewer at https://landbigdata.github.io/ECR/.

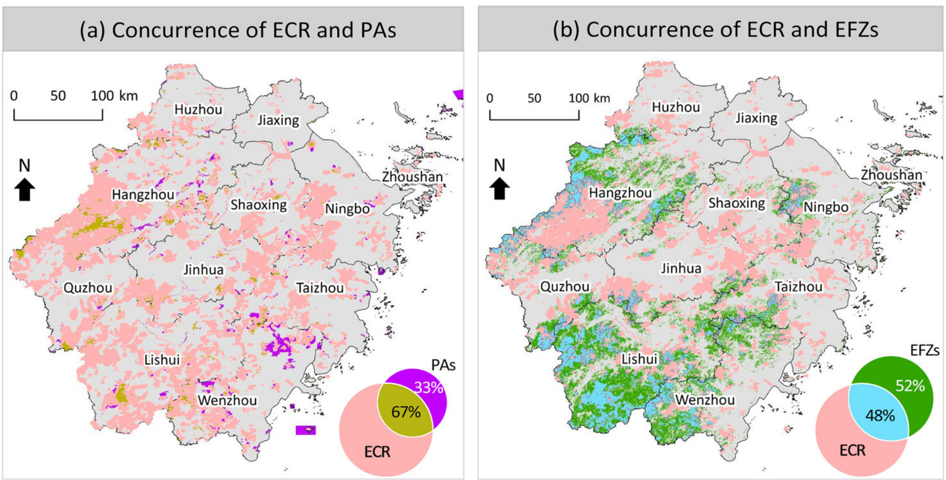

Figure 4. Concurrence of ECR and ecological conservation hotspots. (a) ECR and PAs, and (b) ECR and EFZ. For enhanced visualization of these results, please also explore the interactive map at https://landbigdata.github.io/ECR/.

(Figure 3a and Supplementary material, Table S5). Moreover, 84% of these PAs are established to restrict human activity in forestry areas (Supplementary material, Table S5). In contrast, the total area of EFZ hotspots reaches nearly 25,000 km^2 (Figure 3b and Supplementary material, Table S6), which is also dominated by forestry (Supplementary material, Table S6). Ecological corridors, however, only cover a small area of 8,297 km^2 (Figure 3c), with an average length of 56 km. The vast majority of land in ecological corridors is currently used for forestry and agricultural production, accounting for 47% and 36%, respectively (Supplementary material, Table S7).

The PPH, or the proportion of ecological conservation hotspots protected by ECR areas, for all of Zhejiang is only 48%, suggesting an enormous space for spatial optimization. Yet, there is a large variation in terms of PPH among the three dimensions (i.e. ecological element, function, and structure). In the dimension of ecological elements (i.e. PAs), PPH is roughly 67%. Local governments reserve space for tourism and construction development, and thus ECR protection is prone to leave gaps in PAs

(Figure 4a), especially in nature parks (e.g. in the northeast of Wenzhou city,). In terms of the dimension of ecological functions, 48% of the entire EFZ is protected by ECR areas (Figure 4b). However, ECR areas in the south and northwest of Zhejiang province cannot sufficiently protect EFZ, and those in central Zhejiang province protect a large proportion of land outside the EFZ. In terms of ecological structure (i.e. ecological corridors), however, PPH is only 11%, highlighting the remarkable insufficiency of ecological corridors protected by ECR areas.

3.2. Regional variation in ECR delineation

As the spatial congruity between ECR areas and ecological conservation hotspots differs across space, we compare the representativeness (PEH) among different counties, particularly with regard to four types of major function-oriented zones (i.e. urban development areas, priority development areas, main agricultural areas, and key eco-function areas). Results show that the proportion of non-ecological land in ECR areas increases substantially with the increasing priority for socio-economic activities in the 89 counties, manifested as the low ecological representativeness of ECR coverage (Figure 5a,b).

Among the four types of major function-oriented zones, the urban development areas exhibit the highest representativeness in terms of PAs (Figure 5c). As the main area of economic activities, local authorities tend to strictly protect the existing PAs in the process of socioeconomic development to meet local ecological needs. However, given the frequent disturbance of human activities, ecological corridors are largely preoccupied for residence and food production. In particular, many counties such as Lucheng county are in such a dilemma with 5% of construction land located in ECR areas (Supplementary material, Tables S8 and S9). Priority development areas are dominated by counties in the northeast of Zhejiang, where people are more multifarious and concentrated, and thus ecological functions are generally under the median (Figure 5c), which can be attributed to the scarcity of ecological land. Notably, the ratio of non-ecological land roughly increases with an increase in ECR coverage. For example, in Cixi County and Haining county, nearly 60% of the ECR areas are in non-ecological regions (Supplementary material, Tables S8 and S9).

Overall, ECR areas in the main agricultural production zones are less representative in terms of ecological function and structure (i.e. EFZ and ecological corridors, respectively). Quite a lot of non-ecological land is protected by ECR areas (Supplementary material, Table S9). For example, 63% of the total land in Pinghu County is used for cultivation, whereas 57% of its total cultivated land is found in ECR areas (Supplementary material, Tables S8 and S9). By contrast, almost all counties in the key eco-function areas effectively represent ecological functions. The proportion of ecological land in these counties is over 80% (Supplementary material, Tables S8 and S9), and thus land-use competition is less intensive in ECR areas.

3.3. Priority areas for conservation

To increase the ecological representativeness of ECR coverage at the provincial level, counties in the southwest of Zhejiang province can act as the leverage point for balancing ecological functions and landscape connectivity (Figure 6a). Thus, these counties are responsible for the most protection, but are still plagued by inadequate EFZ

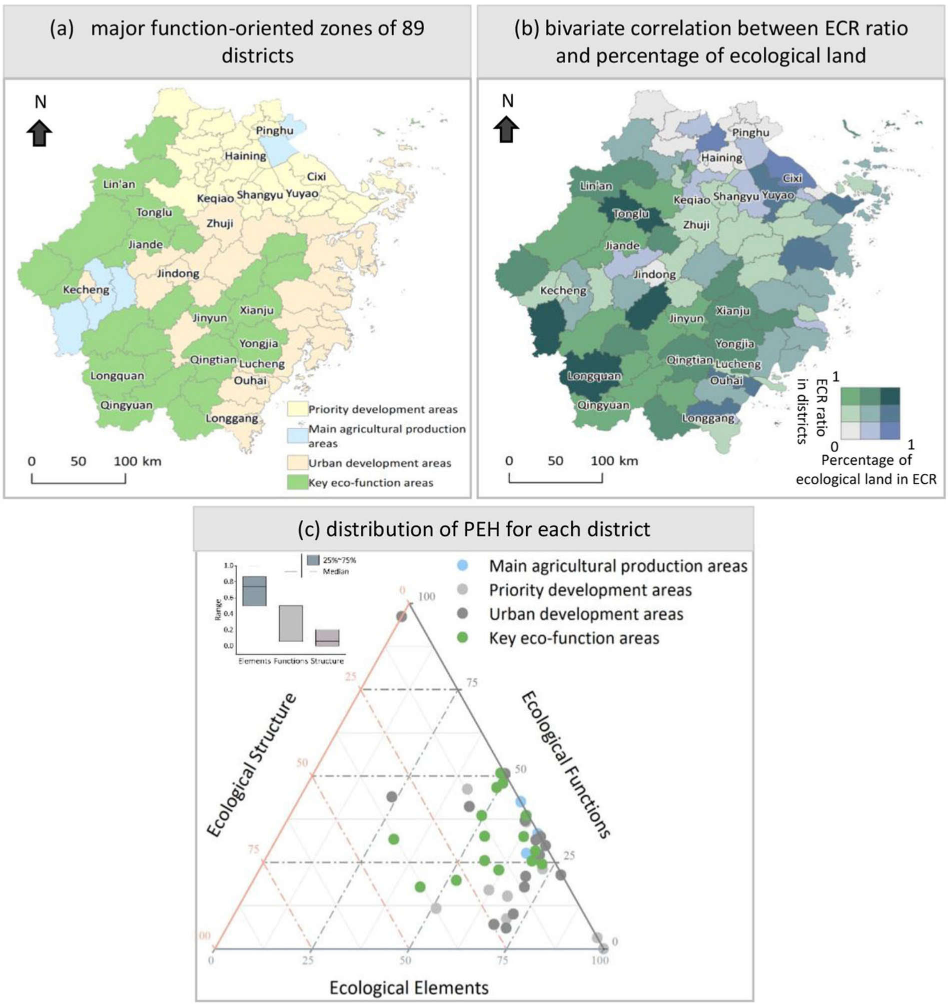

Figure 5. Regional variations in the ecological representativeness of ECR coverage. (a) division of major function-oriented zones; (b) bivariate correlation between ECR ratio and percentage of ecological land; (c) distribution of the ecological representativeness of three hotspots (PEH) for each county, with color indicating the categories.

protection despite the highest ECR ratios. Counties in the western mountains and coastal hills have high ecological functional importance and good landscape connectivity (*dI*-level = 3), which are potential areas for ECR protection. Notably, counties in the west of Zhejiang province already have large proportions of ecological conservation hotspots protected by the ECR areas, such as Lin'an County, Tonglu County, and Kecheng County. However, counties in coastal hills show relatively low representativeness of ecological hotspots, such as Xianju County, Qingtian County, and Jinyun County. Moreover, the coverage of ECR areas in the urban development areas, such as Yuyao County and Yongjia County, have only marginal contributions to the overall ecological security (*dI*-level = 1/2).

Several counties assume the important responsibility of maintaining landscape connectivity, although they may provide minimal ecosystem functions (Figure 6b). Based

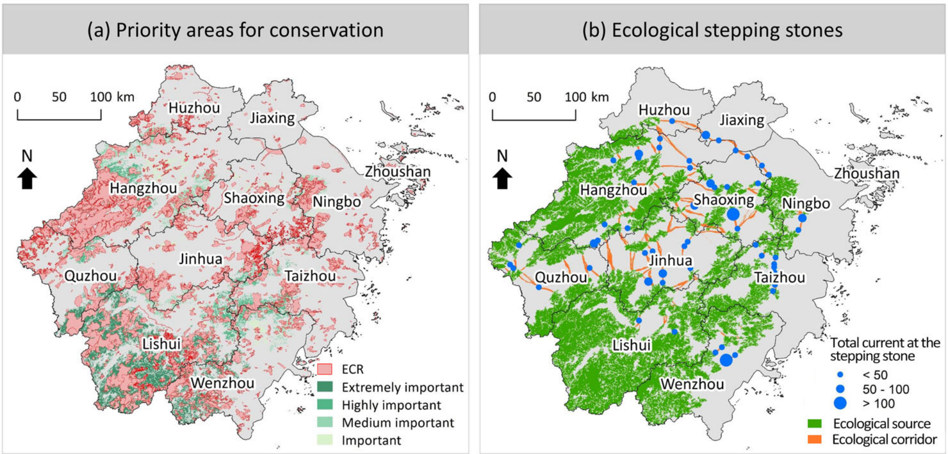

Figure 6. Priority areas for conservation (a) and ecological stepping stones at ecological corridors (b). To facilitate sound policy-making for local government and decision-makers, both maps can be explored interactively in the map viewer at https://landbigdata.github.io/ECR/.

on the circuit theory, we identify 59 stepping stones with an average size of 2.5 km^2 and a total area of 149 km^2, which accounts for 38% in size of potential ecological corridors. The hills and basins in the geographical center of Zhejiang province, such as Keqiao County, Zhuji County, and Jiande County are hotspots for ecological stepping stones (Figure 6b and Supplementary material, Table S10). Similarly, a large proportion of land in Ouhai County, Haining County, and Shangyu County is along river banks that act as ecological stepping stones (see the interactive map). However, many stepping stones in these counties have been occupied by non-ecological land (Supplementary material, Table S10), especially in Jiaxing City, where the vast majority of these stepping stones are used for agricultural production (Supplementary material, Table S11).

4. Discussion

4.1. Conservation policies in China

To resolve the sustainability crisis, the central government of China has enacted a wide range of nature conservation policies in the past few decades, including Three-north Shelter Forest Program, Natural Forest Conservation Program, and Grain for Green Program, among others (Bryan *et al.* 2018). In particular, these programs have largely contributed to forest restoration and biodiversity conservation in China (Chen *et al.* 2019; Deng, Liu, and Shangguan 2014; Viña *et al.* 2016). For example, China plays a leading role during the greening process on Earth (25%) with forests contributing to 42% of greening in China (Chen *et al.* 2019).

Moreover, the Chinese government have also launched a number of programs to address biodiversity issues; in particular the Wildlife Conservation and Nature Protection Program, through which PAs have been established all over the country (Bryan *et al.* 2018). In order to foster the effectiveness of PAs, which now cover ∼18% of the country's land, the Chinese government recently established a new scheme of PAs comprising national parks, nature reserves and parks (Miller-Rushing *et al*. 2017; Wei *et al*. 2021). In addition, a series of efforts have been carried out to warrant the maintenance of PAs, including establishment of conservation monitoring networks, synthesis of species catalogues, and legislation of conservation priority areas (Ma *et al*. 2017; Wei *et al*. 2021). These efforts have substantially contributed to the nationwide strategy for ecological civilization (Wei *et al*. 2021).

4.2. Significance of this study and implications for ECR policy

ECR policy is supposed to be distinguished from other conservation policies in China with regard to the integrity of ecological protection, strict requirements for spatial accuracy, and overall process management (Gao, Wang, *et al*. 2020). To the best of our knowledge, this study is a unique exploration in the assessment of ECR coverage and can, therefore, benefit the conservation community from the following aspects.

While other studies have explored approaches to the assessment of ECR coverage (Hu *et al*. 2020; Zuo and Gao 2021), this study broadens the scope for ecological assessments by incorporating multiple goals for conservation. Ecological benefits, among social outcome and nature-human interactions, have always been a key indicator for examining the management effectiveness of PAs (Ghoddousi, Loos, and Kuemmerle 2022). Prior studies, on the one hand, overwhelmingly investigate ecological vulnerability and habitat quality in PAs to illustrate protection effectiveness (Ke *et al*. 2017; Ribeiro *et al*. 2021; Xu *et al*. 2017), and on the other hand, analyze social and conservation outcomes of PAs (Oldekop *et al*. 2016; Porter-Bolland *et al*. 2012). These assessments are frequently carried out within a given area. However, ECR is the bottom line (threshold) of ecological security, which is irreplaceable space for ecosystem conservation. We prioritize potential ecological areas by assessing the ecological importance of the entire area.

Although ECR areas have been formally delineated across China (Gao, Zou, *et al*. 2020), local governments and authorities may fail to achieve their overall targets for conservation without an effective operationalization at an appropriate scale. The lack of definite standards still causes great uncertainty about how to define and implement ECR. However, we downscaled targets and analysis to counties, which are the operators of ECR delineation. In addition, the characteristics of counties with different functions are clustered; thus enabling local authorities to make informed decisions and optimization. Moreover, unlike the common research on a macro-scale (Barber *et al*. 2014; Edgar *et al*. 2014) or micro-scale (Jones, Graziano, and Dimitrakopoulos 2020; Liu *et al*. 2001). This study supplements the discussion from an intermediate perspective.

A preferable pathway to ECR implementation is site-specific management at the county scale, as it is the scale at which environmental planning and management policies are primarily targeted; in the meantime, this can account for the spatial heterogeneity therein. Specifically, we find that the proportion of ecological conservation hotspots protected by ECR is nearly 70% in many counties in the southwest of Zhejiang province. Yet, this proportion for many counties in the northeast of Zhejiang province is less than 5%. With equity as one consideration, we suggest that ECR coverage in the southwest counties should be extended to the highest priority regions identified in Figure 6a, while ECR coverage in counties elsewhere could be extended to less prioritized regions. Moreover, we suggest paying close attention to landscape connectivity in northeast counties by protecting ecological corridors, and particularly stepping-stones, as results show that only 11% of ecological corridors are protected by ECR areas. Finally, the core and non-core areas of ecological conservation need to be distinguished, and hierarchical regulation must be applied. Given the complexity of ecological security, establishing buffer zones outside ECR areas and coordinating all ecological land through hierarchical supervision are necessary to maintain ecosystem integrity.

4.3. Embracing the multifaceted goals of conservation

Globally, there is a growing recognition that government and local authorities should enact policies that are capable of mitigating trade-offs between biodiversity protection and other aspects of human well-being including cultural values, social relationships, as well as public health (de Omena and Hanazaki 2022; McKinnon *et al*. 2016). Similarly, the original goals of the ECR policy in China include protecting species from extinction, maintaining and restoring wildlife habitats, enhancing ecosystem services, and protecting biological diversity (Gao, Wang, *et al*. 2020; Wei *et al*. 2021). However, government and local authorities increasingly acknowledge that Indigenous communities and cultural landscapes need to be considered in the practice of ECR delineation. According to the latest protocol on the implementation of ECR policy, Indigenous people are authorized to build houses, raise livestock, and cultivate land in ECR areas; that is, ECR areas are not exclusively for biodiversity conservation. Our assessment demonstrates that a large proportion of ECR areas are in non-hotspot regions (in or nearby urbanized areas). We speculate that this is because the goal of ECR delineation to conserve natural habitat and biodiversity is compromised by people's demand for aesthetic enjoyment and perception (O'Connor *et al*. 2021).

It is challenging to establish clear conservation targets, as multiple conservation goals are often closely intertwined (Díaz *et al*. 2020). In particular, there are often trade-offs and synergies in terms of conservation outcomes for nature or for people (Carranza *et al*. 2020; O'Connor *et al*. 2021). For instance, studies investigating multiple outcomes of conservation policy suggest synergies between habitat quality and species richness (Zhou *et al*. 2021), but may also demonstrate potential trade-offs between habitat quality and economic prosperity (Jones, Malesios, *et al*. 2020). As such, the evaluation of conservation effectiveness should be critical, and preferably outcome-oriented (Ghoddousi, Loos, and Kuemmerle 2022; Maxwell *et al*. 2020; Rodrigues and Cazalis 2020). To better implement ECR, government and local authorities need to improve transparency and promote public participation in ECR delineation to bring multiple targets of conservation to the table, ensuring that ECR policy can spontaneously contribute to the conservation outcomes for nature and for people. Moreover, an open-access monitoring network is required to safeguard the implementation of ECR policy in a real-time mode (Mi *et al*. 2021; Wang, Li, and Huang 2021), as this allows for prompt feedback from governments, local communities and stakeholders, among many others.

4.4. Limitations

We acknowledge that our assessment has uncertainties and limitations. Conceptually, our assessment focuses on the ecological importance of ECR coverage without social dimensions. As a policy tool, researchers, government, residents, and other stakeholders are supposed to work together on the delimitation of ECR (Bai *et al*. 2018). However, their negotiation may affect the marginal distribution of local patches, causing ambiguous effects on the identification of regional ecological conservation hotspots. Therefore, the proposed framework is more helpful in intuitively judging the ecological representativeness of ECR coverage. Methodologically, although the InVEST model and circuit theory are widely adopted in the construction of ecological networks (Cai *et al*. 2020; Luo and Wu 2021), theoretical consensus on the determination of key parameters and thresholds, such as the width of ecological corridors, has still not been reached. However, exploratory analysis suggests that variation in thresholds has only marginal effects on the representativeness of ECR coverage. Finally, our assessment does not include dynamic factors. The ecosystem is in a dynamic state under the interaction of biology and environment, and the ecological data for a single year may be accidental. Thus, carrying out more meaningful prioritization and clearer policy guidance becomes challenging. In the following research, long-term data will be synthesized to increase the reliability and robustness of the assessment.

5. Conclusions

In this study, we propose a comprehensive framework of "element-function-structure" to assess the coverage of ECR areas in Zhejiang province, China. First, the InVEST model, MSPA analysis, and circuit theory are employed to identify three types of ecological conservation hotspots, and these hotspots are further used to assess the ecological representativeness of ECR coverage. Moreover, regional variation of ECR coverage among different counties is analyzed with regard to major function-oriented zones, the official zoning scheme to coordinate future development and protection pattern. Finally, priority areas for conservation are outlined to leverage ecological benefit. This framework provides a new perspective and feasible approach to ensure that key components for ecological security are prioritized, contributing to the optimization of ECR coverage. The conclusions are as follows:

- ECR areas and ecological conservation hotspots often do not coincide. The retention rate of existing PAs in ECR areas is nearly 67%, followed by ecological function areas, which is approximately 48%. However, the existing ECR coverage is remarkably insufficient to protect potential ecological structure – namely, ecological corridors.
- The ecological representativeness of ERC areas corresponds to key function zones. In key eco-function areas, for example, ECR areas account for a relatively large proportion of ecological lands.
- The priority areas for conservation suggest that regions in the southwest of Zhejiang province could be the leverage point to increase ecological benefits by maintaining ecological functions. Counties elsewhere with less ecological function can also contribute to ecological conservation, particularly by maintaining landscape connectivity via stepping stones.
- We argue that assessment of ECR coverage needs to account for multiple demands from conservation, ranging from biodiversity conservation to human well-being.

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Supplemental data

Supplemental data for this article can be accessed here.

Note

1. http://gi.mnr.gov.cn/202208/t20220819_2756940.html

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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Data availability statement

Datasets that support findings of this article are available at https://landbigdata.github.io/ECR/.

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