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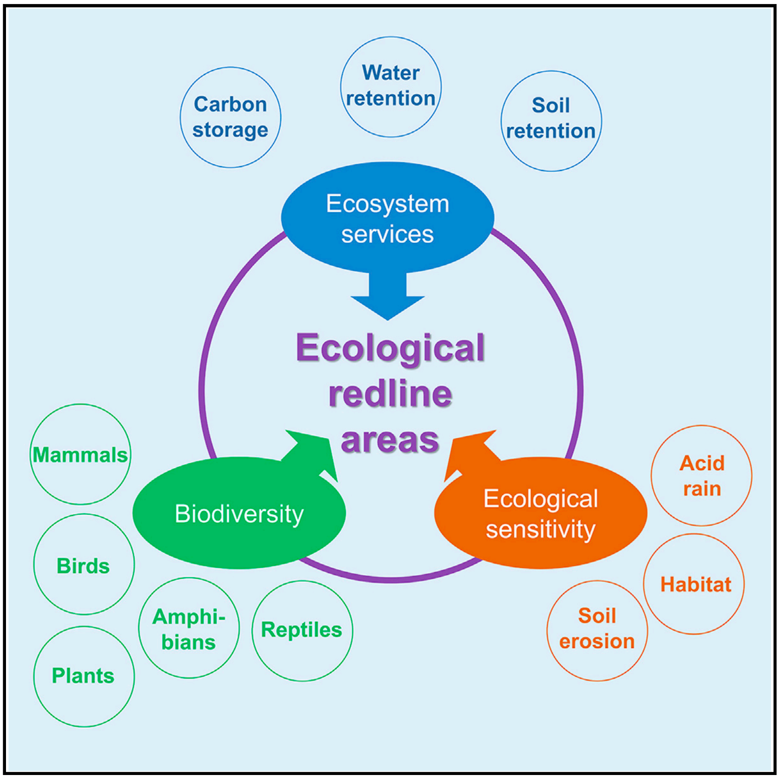
Article

Ecological redlines provide a mechanism to maximize conservation gains in Mainland Southeast Asia

Graphical abstract



Highlights

- ECRs integrate biodiversity and ecosystem service priorities
- ECRs synergistically consider biodiversity, ecosystem services, and ecological sensitivity
- ECRs maximize benefits of targets for the post-2020 global biodiversity framework
- ECRs could enable transnational cooperation and green infrastructural development

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In brief

Practical conservation targets need to balance ecological and human needs. China's ecological conservation redlines (ECRs) reconcile this challenge by synergistically considering biodiversity, ecosystem services, and ecological sensitivity, as a target for new protected areas. This study suggests that Southeast Asia use ECR to fulfill national CBD commitments, and which could be implemented as a pilot project under China's Belt and Road initiative, to provide a clear framework for greening infrastructural development.

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Ecological redlines provide a mechanism to maximize conservation gains in Mainland Southeast Asia

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SCIENCE FOR SOCIETY With the upcoming launch of the post-2020 global biodiversity framework, identification of conservation targets is essential. Ecological conservation redlines reconcile the challenge of different types of priority by considering biodiversity, ecosystem services, and ecological sensitivity. We evaluate the representativeness of protected areas in Mainland Southeast Asia (M-SEA) and provide a three-tier implementation plan to meet global and regional targets for area-based conservation and maximizing benefit provision. Our results show that the workload faced by M-SEA countries varies, and that some countries have very few priorities protected. Our proposed goals of 16% for priorities for all three facets, 33% for dual benefits, and 51% to protect all priorities, could thus provide targets for the 2030 mission and 2050 vision. M-SEA could implement ECR under China's Belt and Road initiative, to enable transnational co-construction of ecological protection and green infrastructural development.

SUMMARY

Developing effective targets for conservation remains a topic of global debate. Ambitious targets for 50% or more of the Earth's land surface have been proposed, yet balancing human needs with area-based conservation measures remains challenging. Current global conservation targets focus on biodiversity conservation, ignoring ecosystem services and vulnerabilities. Using China's ecological conservation redline as a basis, here we put forward a framework that combines ecosystem services, ecological sensitivity, and biodiversity indicators (including 10,311 species) to determine ecological priorities across Mainland Southeast Asia (M-SEA). We find that, based on the redline 15.8% of the M-SEA's land would cover all overlaps between biodiversity, service provision, and sensitivity hotspots, and much is already protected. Following this, 32.9% would cover all areas with at least hotspots for two priority facets, and 51% for all priorities. These targets are in line with those proposed in the post-2020 global biodiversity framework to maximize effectiveness of proposed targets.

INTRODUCTION

The United Nation Sustainable Development Goals aim to help us navigate our way to a more sustainable life on Earth. Although the goals cover a huge breadth of human development, goals 14 and 15 emphasize the link between humans and other species. Yet, despite conventions and resolutions, such as the Convention on Biodiversity (CBD), we continue to see progressive loss of global diversity, which is widely stated as the sign of sixth mass extinction under a consequence of the unsustainable use of natural resources.[1] To address these challenges, the CBD developed a strategic plan for 2011–2020 (the Aichi targets) to provide a set of achievable goals to ensure that, by 2020, adequate measures were in place to protect global biodiversity. Target 11 focuses on coverage of protected areas,[2,3] which has now reached 15% of Earth's land and 7% of Earth's oceans[4] (still below the goal of protecting 17% of Earth's land and 10% Earth's oceans). Moreover, only one-third of current terrestrial protected areas (PAs) and one-tenth of current oceanic PAs assessed were deemed to be effectively managed.[4]

The expansion of PAs does not necessarily mean better protection of biodiversity,[5] and in fact the loss of native diversity is increasing.[6–9] However, although PA implementation attempts to effectively encompass biodiversity, the synergy among ecosystem services, ecological sensitivity, and biodiversity are difficult to coordinate.[10–12] Although species-centered conservation measures are crucial, there is often insufficient funds or data to target priority areas to effectively conserve biodiversity and the benefits brought by nature to human beings.[13] This issue is urgent as the 15th Meeting of the Conference of the Parties of the United Nations Convention on Biological Diversity (CBD COP15) will be held soon in Kunming, China, which will determine the global biodiversity protection strategy for 2030 and 2050 within the post-2020 biodiversity framework. It represents a key opportunity to reframe how we develop targets for global conservation,[1] which requires agreement on how to expand the existing PA plan to reflect different ecological facets and protect biodiversity and ecosystem service provision, which could be implemented in parallel with China's Belt and Road initiative (BRI).

Ecological redline policy is a comprehensive approach implemented by China to safeguard biodiversity and natural resources based on a number of different provisions, with the ecological conservation redline (ECR) forming a major component. ECR integrates ecosystem service provision, ecological sensitivity, and biodiversity priorities into a conservation and management framework, thereby enabling an effective and dynamic approach for developing targets within the landscape context[14] to achieve the goal of "ecological civilization" and enable human needs to be met while maintaining healthy natural systems. The inclusion of these other elements of ecosystem service provision and fragility takes these redlines beyond simply maintaining biodiversity and carbon, to a more holistic approach that maintains intact functional ecosystems and the services they provide. Areas within the "redline" are defined as ecological redline areas (ERAs), which identifies the key ecological areas and sets the limit of human land development and economic activities. The scientific boundary of a PA should be defined based on ERAs, combined with the management needs of different regions according to applicable international standards (e.g., IUCN PA management categories). At present, 18% of China's territory has been included in ERAs,[15] although some species are not protected fast enough once they are noted to be threatened, due to the policy delay effect, and of course many species are unlikely to be considered individually (lack of funding, perceived charisma, etc.).[16] This underscores the need for an overarching approach to proactively identify key regions for biodiversity to target protection. When compared with the existing PA system (without ERA basis), ECR also focuses on the integrity of ecological function and service, and aims to overcome the shortfalls of existing PA policy[14] as demonstrated by:

(1) ECR considers ecosystem services, ecological sensitivity, and biodiversity in a unified way, and relies on remote sensing and spatial analysis of ecological modeling, ground-truthed and calibrated with locally collected data, which is conducive to making quantitative assessments and positioning countermeasures quickly and accurately.[17]
(2) ECR can access financial support, from a ministry level within China and likely through sustainable development mechanisms implemented in parallel with BRI. The trade-off between ecological protection and economic development is often portrayed as an antagonistic relationship,[18] yet better planning can enable the two to act in synergy and for development to be sustainable and work to guarantee continued provision of services.
(3) ECR is compatible with other land policies in China. In 2020, ECR was integrated into China Overall Framework of National Land Planning System. In this framework, ecological integrity and value is considered as a basic constraint, while planning regional land-use design (including residence, agriculture, industry, etc.) for the next 15 years.[19] This means the system has the potential to be translated to other regions, especially with local government support, and has already been extensively tested within China.

China has already provided a useful test-case that integrated conservation prioritization systems, such as ECR, can be effectively implemented across scales. This suggests that such a system could also be developed and integrated in concert with BRI, which as the largest infrastructural project of all time is in urgent need of mechanisms to develop sustainably, while it simultaneously could provide a fundable mechanism for complementary conservation measures.[20]

The Belt and Road project provides a logical extension of China's ECR, and the non-maritime parts of the Belt and Road include six major economic corridors. The China-Indochina Peninsula Economic Corridor starts from Kunming in China, and finally arrives in Singapore through Vietnam, Laos, Cambodia, Thailand, Myanmar, and Peninsula Malaysia (Mainland Southeast Asia [M-SEA]). M-SEA represents the ideal test case for such an approach, as a global biodiversity hotspot frequently stated to be one of the most threatened in terms of biodiversity loss,[21] and it is also adjacent to the Chinese mainland with strong ecological connectivity. At present, China is also committed to endowing BRI partners with more regional cooperation plans for sustainable development, e.g., The Belt and Road Ecological and Environmental Cooperation Plan in 2017 (BRI-EECP), and the Belt and Road Science plan. If ECR is implemented as a component of BRI, it could lead to the development of an eco-connected China-M-SEA ERAs Belt, and such a concept would complement existing policy and strategy, as well as contributing toward the likely goals of the post-2020 framework.

Learning from China's ECR, we outline a scientific framework that builds on core elements of other recognized frameworks (the Millennium Ecosystem Assessment, United Nations Millennium Development Goals, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, etc.), but emphasizes and details the methodological standard for public policy, and the implications for spatial conservation and management (Figure 1), to maximize synergistic priorities for conservation and ecosystem service provision. In recent years the combination of conceptual frameworks and spatial approaches[22,23] have enhanced the ability to develop priorities for biodiversity protection and ecosystem service provision

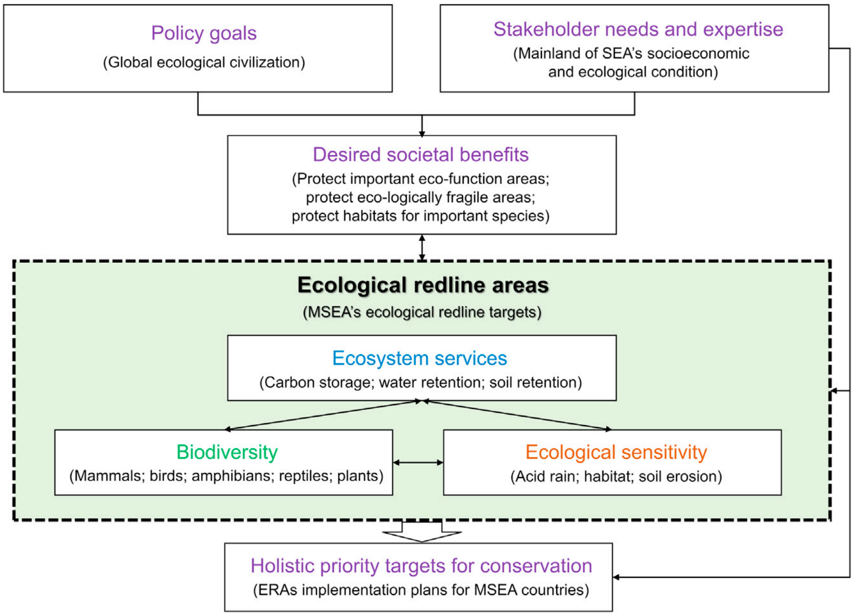


Figure 1. ECR policy-making process
ERAs are determined by the interaction among regional ecosystem services, biological diversity, and ecological sensitivity. The needs of regional stakeholders affect the current land-use pattern, and in turn both biodiversity and ecological sensitivity. The needs of stakeholders determine societal benefits, and these must be integrated with global ecological goals to enable meaningful targets to meet human needs and maintain diversity; thus both must be considered in concert for successful delineation of ERAs.

regionally and globally, yet most of these have only incorporated biodiversity and carbon dimensions.[24] There is a fundamental lack of integration of scientific frameworks to support the developments of policies to meet the needs of humans and biodiversity. By synthesizing different types of data to map ecosystem service provision and biodiversity while developing methodological standards to enable scientifically meaningful and consistent recommendations for policy development, we can move past theory to policy and management practice. Using synergies not only enables more efficient use of resources, but also means that, given the relevance to more UN conventions, additional sources of funding may be available to support implementation and provide maximum benefits.

Here, we show that a scientific framework based on ECR to develop spatially targeted priorities for biodiversity and protection of key ecosystems, in view of the challenges faced in achieving a meaningful and implementable regional framework, the development of effective delineation methods for the region's priorities can provide a template based on ECR. Such a framework could provide a tangible way to realize ecological civilization and a shared future for all life on Earth (as adopted by the CBD-COP15 for the launch of the post-2020 global biodiversity framework). We evaluate the representativeness and gaps of the existing protecting networks and ERAs targeted at M-SEA for transnational cooperation on multi-objective ecological protection for the shared future. The results describe the trade-offs and synergies between priorities, which could be balanced accordingly in each country, and such approaches can usefully inform global frameworks.

RESULTS

Mapping conservation hotspots

The spatial distribution of multiple indicators were calculated using InVEST to assay appropriate indicators for ecosystem services and ecological sensitivity (Figures 2A–2F). We selected 11 indicators based on the M-SEA's role as a global biodiversity hotspot[25] and the needs of regional stakeholders (such as practitioners of major economic sectors and government through the continued provision of key ecosystem services). These fall into three major categories; ecosystem service provision (carbon, soil, and water related), ecological sensitivity (degradation sensitivity), and biodiversity. We extracted the top 10% highest value areas for each parameter as the "hotspots" for that parameter, which is based on species-area curves' most efficient percentage choice for identifying and maintaining key areas.[26] While multiple methods can be used to delineate priorities, we used the highest values because they provide the greatest efficiency in maintaining key areas for each indicator,[17] while given the large numbers of indicators used neither risk an unpractically large area, nor the selection of sub-optimal areas by using a lower threshold. The total water retention, carbon storage, and soil retention for the whole M-SEA in 2015 was 793.75 billion m^3, 3.11 billion t, and 17.6 million t, respectively. The hotspots of water retention and acid rain sensitivity correspond, and are mainly in the northeast, south, and northwest parts of M-SEA (Figure 2). Carbon storage and habitat sensitivity hotspots are mainly in the southeast and northwest of M-SEA; and soil retention and soil erosion sensitivity hotspots are mainly in the north of M-SEA.

Southeast Asia is a global biodiversity hotspot.[27] In this study, five taxa (mammals, birds, amphibians, reptiles, and plants) modeled with Maxent (through running individual species models for 10,311 species and then stacking them to map richness for each taxa [see Hughes[28]] frequently used in prioritization studies[29] were used to characterize biodiversity patterns (Figures 2G–2K). The hotspots of mammals, amphibians, and reptile richness largely correspond, showing hotspots in the east and west of M-SEA; the hotspots of birds and plants richness are mainly in the central and south part of M-SEA. We used species richness alone rather than additional metrics of rarity, endangerment, turnover, or range size because obtaining representative data for more than a subset of easy to record species can be challenging. Other metrics are more vulnerable to bias as more data exist for large-bodied and common species, meaning that rarer species are more likely to have too little data to model, or be limited to a subset of better studied areas and not representative for the region overall.[28] As most of these

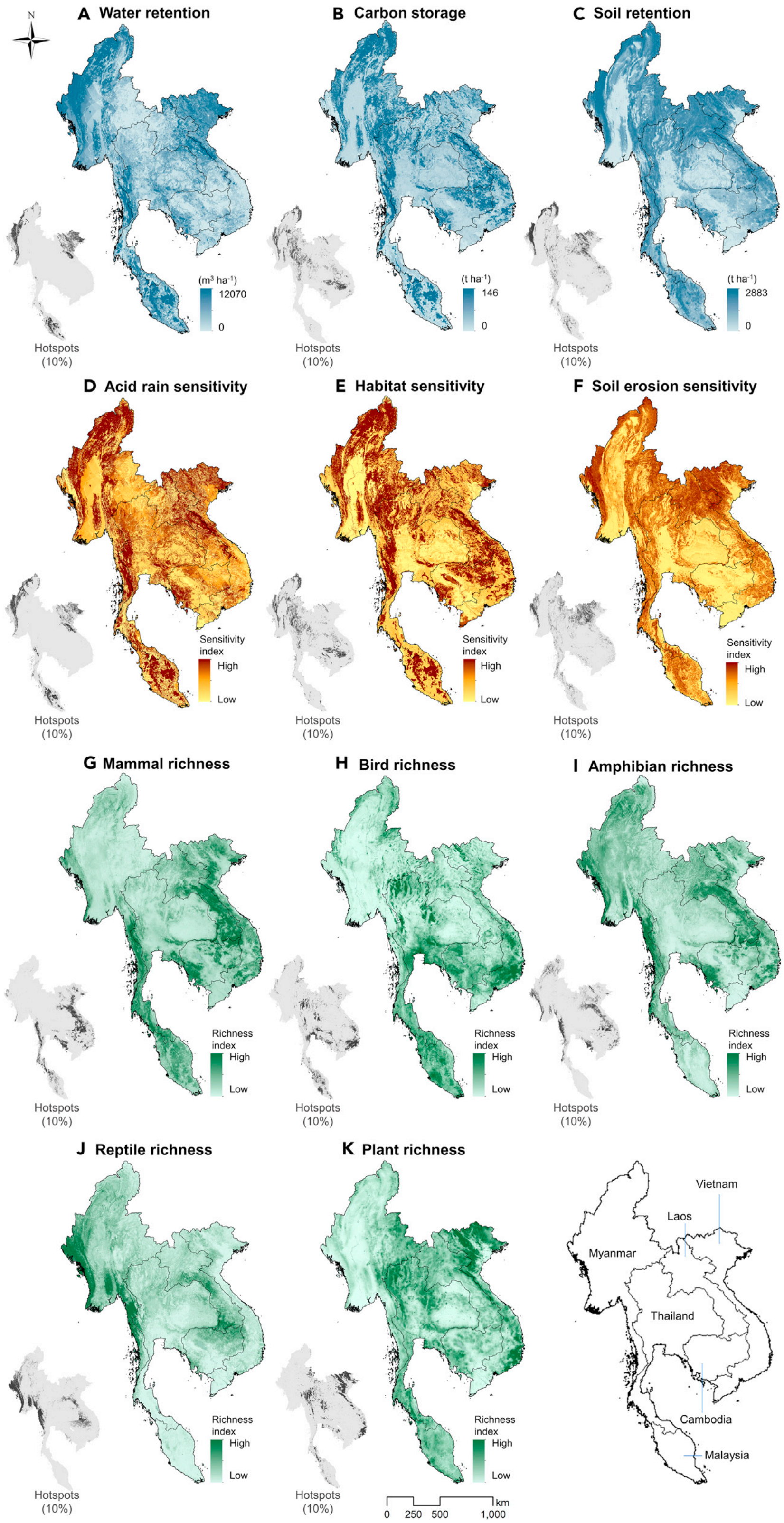


Figure 2. Richness patterns for each metric and the hotspots for each service and biodiversity metric were calculated

(A–C) represent ecosystem service; (D–F) represent ecological sensitivity; (G–K) represent biodiversity. The darker the color, the greater the importance of the area.

traits (except endemism) generally correlate with diversity, this is likely to be the most representative metric for priority setting across taxa. Furthermore, as endangerment will relate to habitat loss, prioritizing key areas for maximum numbers of species is likely to reduce the loss or population declines in the greatest numbers of species.

Representativeness of the existing protection networks

The world database of protected areas (WDPA) provides the latest global boundary vector data for PAs.[30] Using the ArcGIS spatial overlay tool, the protection coverage for priorities for all 11 indicators was calculated (Figure 3), and the overall coverage of these different indicators provides a measure of representativeness. To quantitatively assess the proportion of protected hotspots (PPH) and percentage of overlap of PAs with priorities (PPP) were calculated. PPH was obtained by calculating the percentage of the area of all hotspots that is protected, to assay the extent of the protection of hotspots. PPP was obtained by calculating the percentage of PAs that overlapped with hotspots, which represents the representativeness of current PAs. Thus, PPH assays the protection (and under-protection) of all regional hotspots and PPP assays what percentage of PAs cover priority relative to non-priority areas.

The representativeness of ecological protection varied among countries. Thailand and Cambodia have relatively good protection coverage, with PPH of all indicators in Thailand at >44%, and those of Cambodia at >26%. The areas of PAs in two countries were also relatively large, which helps to protect various ecological hotspots in their territories, although this may lead to lower PPP in these two countries. Contrary to this, Myanmar and Vietnam have relatively poor protected area coverage. At least five types of ecological hotspots lack protection in the west of Myanmar and northern Vietnam. The PPH and PPP of most indexes for the whole M-SEA are around 20% (Figures 3A–3K). However, the protection coverage of key areas for water retention, soil erosion, and reptile diversity were inadequate (PPH is only 12%–13%), and the representativeness of existing reserves is also insufficient (PPP is only 10%–11%). In essence, it is also due to the fact that a large number of hotspots in the three indicators are located in the unprotected western Myanmar and northern Vietnam, and neither have high protected area coverage.

Conservation priorities and gaps

The proportion of PAs in M-SEA has increased from 1.24% in 1973 to 12.19% in 2020, but this is still significantly below Aichi target 11 (17%) (Figure 4A).[30] We quantified the gaps of the current PAs from the perspective of ECR. By integrating the above indicators, we determined that the percentage of protected hotspots for ecosystem services was 23.1% (Figures 4B), 33% for biodiversity (Figure 4C), and 27.8% ecological sensitivity (Figure 4D). M-SEA's current PA network is insufficient to wholly protect any of the ecological indices. We integrated all hotspots to map the total distribution of ecological hotspots (Figure 4E).

The final comprehensive combined ecological priorities cover about 51% of land (Figure 4E), providing ideal targets for the concept of "Half-Earth."[1,31] To cover current ecological hotspots, existing PAs must be expanded by around four times their present extent, a difficult task for M-SEA. Therefore, we suggest ERAs should be implemented in three tiers based on the level of co-benefits among all the 11 indicators provided by any given area (Figure 4F). In tier 1, areas with ≥ 3 types of overlapping hotspots are protected, which accounts for 15.8% of M-SEA's land, many of which are already covered by existing PAs. In tier 2, areas with ≥ 2 types of overlapping hotspots (32.9%) are protected. Tier 3 protects all remaining non-overlapping hotspots (51%). With the continuous implementation of different tiers, the connectivity of ERAs will increase from 73.1% to 77% (Figure 4F).

The protection coverage of ERAs for each indicator will rise from 20% to 40% with each tier (Figure 5A) in line with CBD targets. While many targets in CBD and similar initiatives propose that targets for protection should be achieved at a national level, the burden of responsibility based on the area of priority in different countries is uneven across the region. Overall, the area included in ERAs varies among countries, with both area of priority for each category of priorities and level of protection varying dramatically. Myanmar is responsible for the most protection with 241,000 km^2 (Figure 5B). This is followed by Vietnam (114,000 km^2), Thailand (106,000 km^2), and Laos (89,000 km^2). The need in Cambodia (60,000 km^2) and Peninsula Malaysia (46,000 km^2) is lower. Thailand and Cambodia already had large proportions of hotspots included in the current PAs system in each tier of ECR (Figure 5B), while Myanmar and Vietnam are the opposite, with Myanmar showing the poorest representation of protected priorities. Notably, Malaysia also does poorly, showing the smallest total area protected within any priority tier. Lowland forest, lower montane forest, regrowth/planting, and lowland deciduous forest are the most common land uses in ERAs (Figure S1). The distribution of all tiers decreased with the increase in altitude (Figure 5C), which means that low altitude areas where human activities are more common should be more protected. Tier 1 has a local (not global) peak value at about 1,500 m, which is due to the relatively small impact of human activities on the ecological conditions and the higher provision ability of ecological services.

Synergies between hotspots

The correlation of ecological indicators highlights the difficulty of the implementation of the ERAs, and there are six correlation sections among the three types of ecological indicators (Figure 6, sections I–VI). When indicator correlations show synergy (positive correlations), the distribution of hotspots overlaps (Figure S2), and each PA can simultaneously better protect different indicators. On the contrary, trade-offs (negative correlations) between indicators makes the distribution of different types of hotspot more dispersed (Figure S2).

Section I–III are the correlations between the same types of indicators. Ecosystem service indicators in all countries show synergy (Figure 6, section I), while the ecological sensitivity indicators show trade-offs (Figure 6, section II), particularly between soil erosion sensitivity and other factors. Thus, countries can maximize benefits by prioritizing protection of overlaps between ecosystem service hotspots, and paying additional attention to the protection of soil erosion hotspots, given their frequent overlap. However, the correlations among biodiversity indicators vary among countries (Figure 6, section III). For example, Malaysia and Vietnam show high degrees of synergy, while other countries have some trade-offs in plants or reptiles, so it is necessary to protect these taxa individually, and endemism

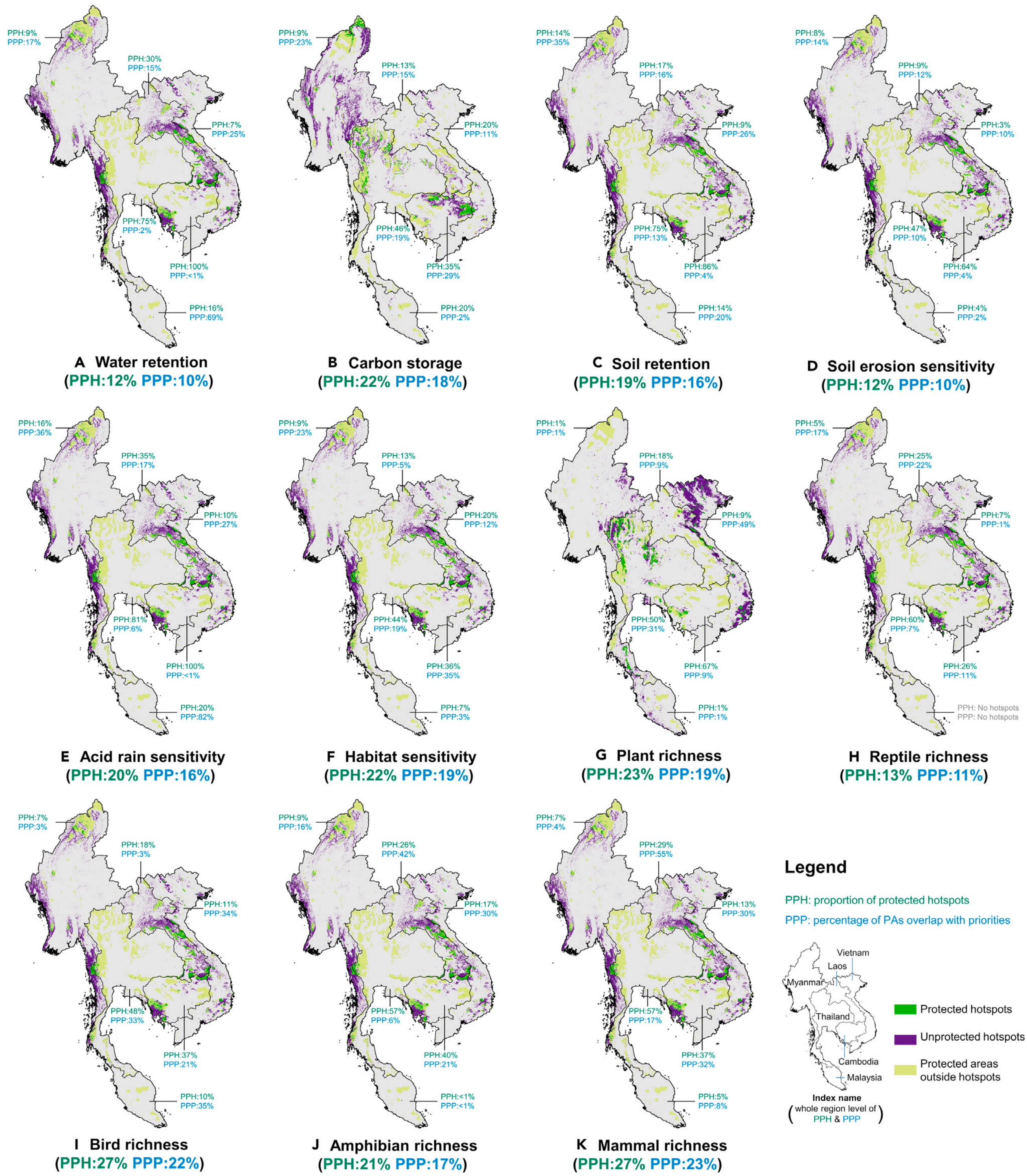


Figure 3. The representativeness and gaps of the existing protecting networks in M-SEA

patterns may heighten this disparity. Sections I–III are the relationships between the different types of indicators. The greatest trade-off relationship is with soil erosion (Figure 6, section IV), and once again highlights the need of its special protection. For synergies between biodiversity and the other two indicators (Figure 6, sections V–VI), some countries have trade-offs of specific taxa, which need special attention, such as Malaysia's amphibians and Laos's reptiles. However, most of the relationships

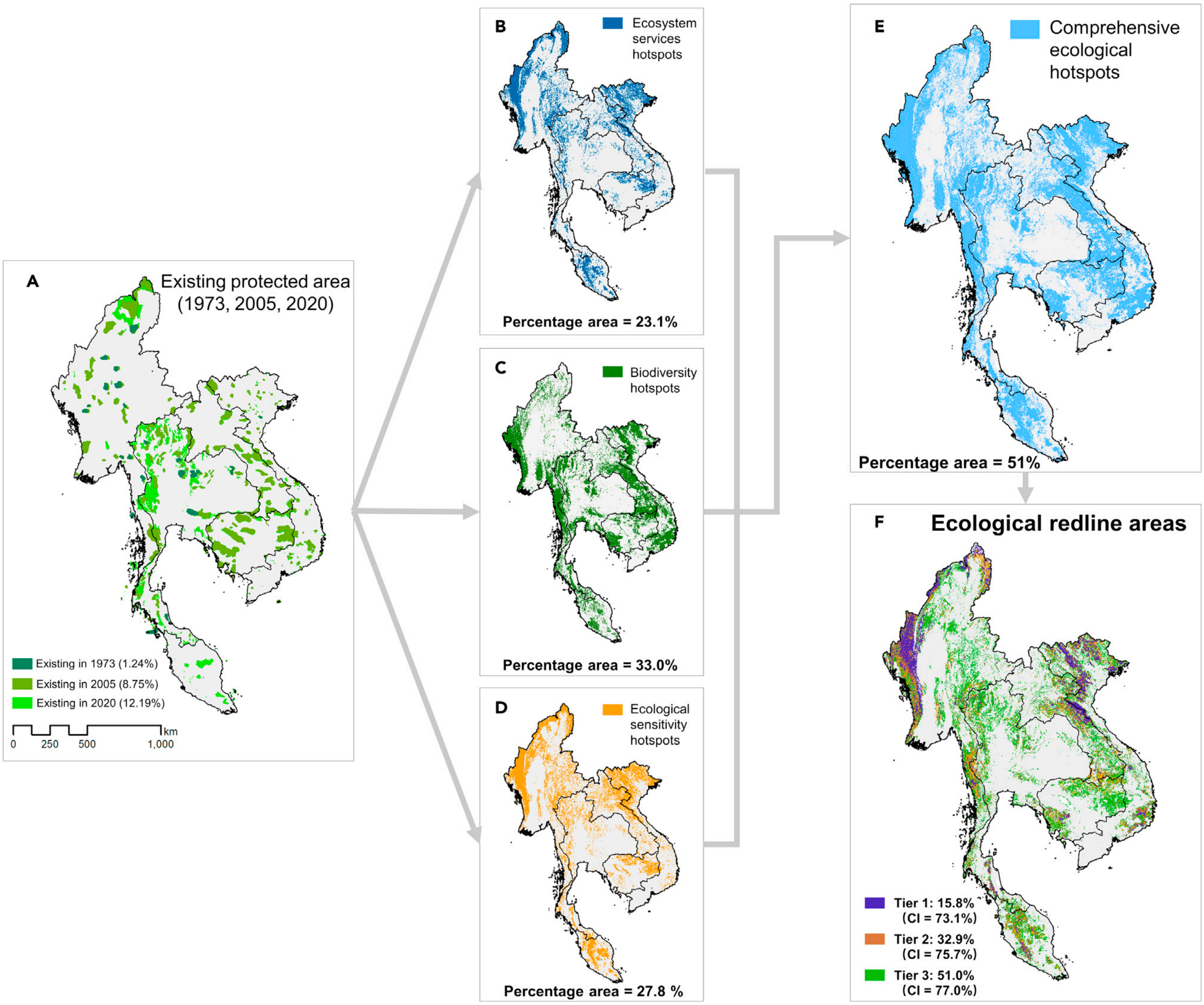


Figure 4. Each step of ERAs designation process

(A) Distribution of PAs in M-SEA 1973, 2005, and 2020.

(B–D) (B) Ecosystem service hotspots; (C) ecological diversity hotspots; (D) ecological sensitivity hotspots. The next best ERAs were proposed to the stakeholders to meet the economic and social ecological development.

(E) Comprehensive ecological hotspots with the duplicated part deducted.

(F) ERAs gradually can be implemented in three tiers: tier 1 contains ≥3 overlapping hotspots (15.8%), tier 2 contains ≥2 overlapping hotspots (32.9%), tier 3 contains all hotspots (51%). CI represents the Connectance index calculated by Fragstats 4.2.

are in weak synergies, which requires improving habitat quality through PA planning in areas with the potential for biodiversity but where degradation of former intact habitats has reduced current diversity, and restoring these areas would enhance the synergy between biodiversity and other ecological indicators, especially ecosystem services.

Correlation differences between each priority require each country to set its own priorities when implementing ECR. We integrate the synergies and trade-offs between indicators of each country, the ERAs of whole M-SEA, and the representativeness of the existing PAs in each country, and develop the ecological protection priority sequence for each country (Table S1). Generally, in tier 1, countries focus on improving their existing PAs to achieve the Aichi 11 target[4] on a national basis. In tier 2, countries focus on balancing trade-off indicators to further expand the scope of protection and maximize co-benefits. In tier 3, Half-Earth marks the final vision[1] to match the post-2020 framework, countries focus on further improving the protecting and reconnecting of fragmented ecological hotspots.

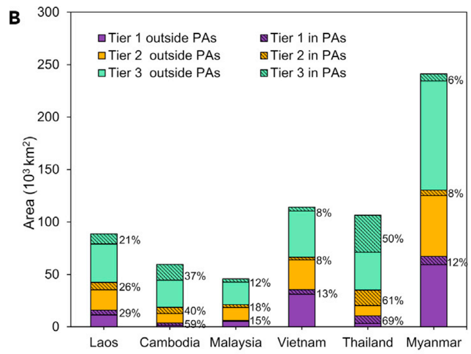
DISCUSSION

The need for integrated targets

After a decade of biodiversity, we have failed to meet the Aichi targets. In the CBD's global biodiversity framework we must take steps to better enable the translation of science to policy

A

	Tier 1	Tier 2	Tier 3
Water retention	17.53%	27.76%	39.19%
Carbon storage	20.54%	31.00%	40.49%
Soil retention	21.97%	41.16%	63.80%
Acid rain sensitivity	18.64%	29.27%	42.96%
Habitat sensitivity	23.99%	36.09%	47.53%
Soil erosion sensitivity	23.32%	42.67%	56.15%
Mammal richness	21.46%	35.11%	45.05%
Bird richness	19.24%	29.77%	38.97%
Amphibian richness	21.31%	35.32%	47.52%
Reptile richness	21.23%	36.17%	48.46%
Plant richness	21.14%	33.18%	43.89%
Timeline	2025	2030	2050



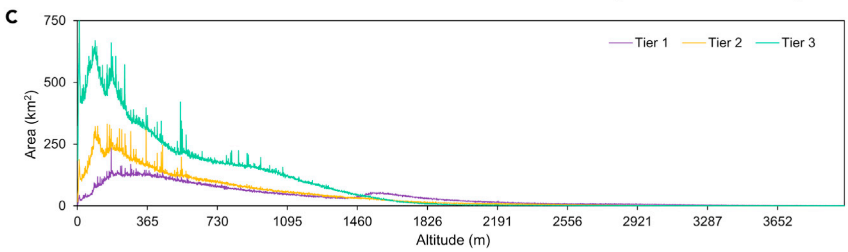


Figure 5. ERAs designation in M-SEA

(A) Protection representativeness of the three tiers in ERAs (ecosystem service indicators accounted for the protected proportion of material quality; other indicators accounted for the protected proportion of dimensionless index).

(B) Areas of the three tiers in ERAs inside and outside the current PAs system for each country. The percentage represents the proportion of hotspots where already included in the current PAs in each country per tier.

(C) Area distribution of the three tiers in ERAs at different altitudes.

and practice, and ensure that the 2030 and 2050 mission and vision are not only actionable, but work to maximize co-benefits and generating effective and meaningful priorities. We aim to provide a better global scientific framework for decision-making and planning of PAs. By integrating biodiversity, ecosystem sensitivity, and ecosystem service provision, we propose a scientific framework and standard method to efficiently prioritize positive conservation gains, and illustrate it for Southeast Asia as such a framework could be implemented in line with the BRI. This advances from other frameworks in several major ways. Firstly, while other frameworks have explored co-benefits between biodiversity conservation and carbon sequestration for climate goals, and to an extent water retention,[24] we have broadened this to include other key indicators of service provision. Secondly, while many approaches are coarse, especially at the global scale, we have downscaled targets and analysis to a more ecologically meaningful scale (250 m) that better reflects priorities, especially in heterogeneous regions.

The framework provides an action plan for M-SEA in addition to a framework that could be adapted for different regions to provide effective priorities to safeguard biodiversity and ecosystem services. To develop more holistic recommendations for PAs, we integrated ecosystem services and ecological sensitivity as existing standards for PAs mainly focus on biodiversity.[10,32] An ecological hotspot identification process based on remote sensing information and a spatial mapping ecological assessment model[22,23,33] (e.g., InVEST) were integrated to provide the standard for the spatial planning of the reserves. The assessment results under this comprehensive index expand the scope of existing PA planning and help to increase the connectivity of the ecosystem by reducing redundancy, and ensuring effective regional prioritization for not only biodiversity but also environmental services.[34] Such an approach has already been initiated in China through integrating the former green (forest) and blue (water) lines to provide an integrated approach to conservation as a basis for ECR,[14] and more than one-fourth of China's territory has been included in ERAs.[15] ECR is no longer simply a macro-strategic approach, but a specific, measurable, aspirational, realistic, and time-bound systematic approach that can be incorporated effectively into ecological protection and land planning within and beyond China.[10] The framework is developmental and should adjust its indicator system and study the importance of indicators according to the ecological needs and the demands of stakeholders of different regions. For example, an expert evaluation system of the importance of indicators can be introduced in the implementation process, and the contribution of each indicator in delimiting hotspots can be regulated by indicator empowerment to achieve more regional adaptation of a new vision of the security framework. Furthermore, implementation within each country of cost-effectiveness analysis could be integrated through engagement with appropriate government departments, but this was not included in this analysis due to the complexity of adequately incorporating accurate financial metrics without local engagement.

Yet, while ECR has been implemented across China, the Southeast Asian biodiversity hotspot, as a region under threat from development, is in urgent need of such an approach, especially if it is to meet the targets set within the post-2020 framework.[35,36] This is important not only as a basis for meeting new targets but can also help to form a transnational ecological corridor with policy consensus throughout China and the M-SEA, which is especially important in the light of the BRI.[37,38] M-SEA has the best ecological cooperation conditions in BRI cooperation with China, as all four specific regional eco-cooperation projects in BRI-EECP are located in M-SEA. In the last 5 years, China has cooperated in Cambodia and the Lancang-Mekong River Basin. Furthermore, the development of such a framework also provides a translatable approach that can be applied to other regions aiming to develop integrated regional targets and thus optimize the maintenance of biodiversity while simultaneously maintaining provision of ecosystem services.

Selecting indicators is notably challenging, as a framework needs to balance representative indicators that are also accessible. For example, while for biodiversity we used only richness rather than other metrics, hotspots of endemism, such as Lao Cai, Ha Giang, and BiDoup in Vietnam, and Kanchanaburi in Thailand, were reported by Hughes in 2017.[21] Yet, these endemism centers have still been captured as tier 1 priorities. Other indicators were also selected on the basis of representativeness of the given facets, while still being accessible. Thus the

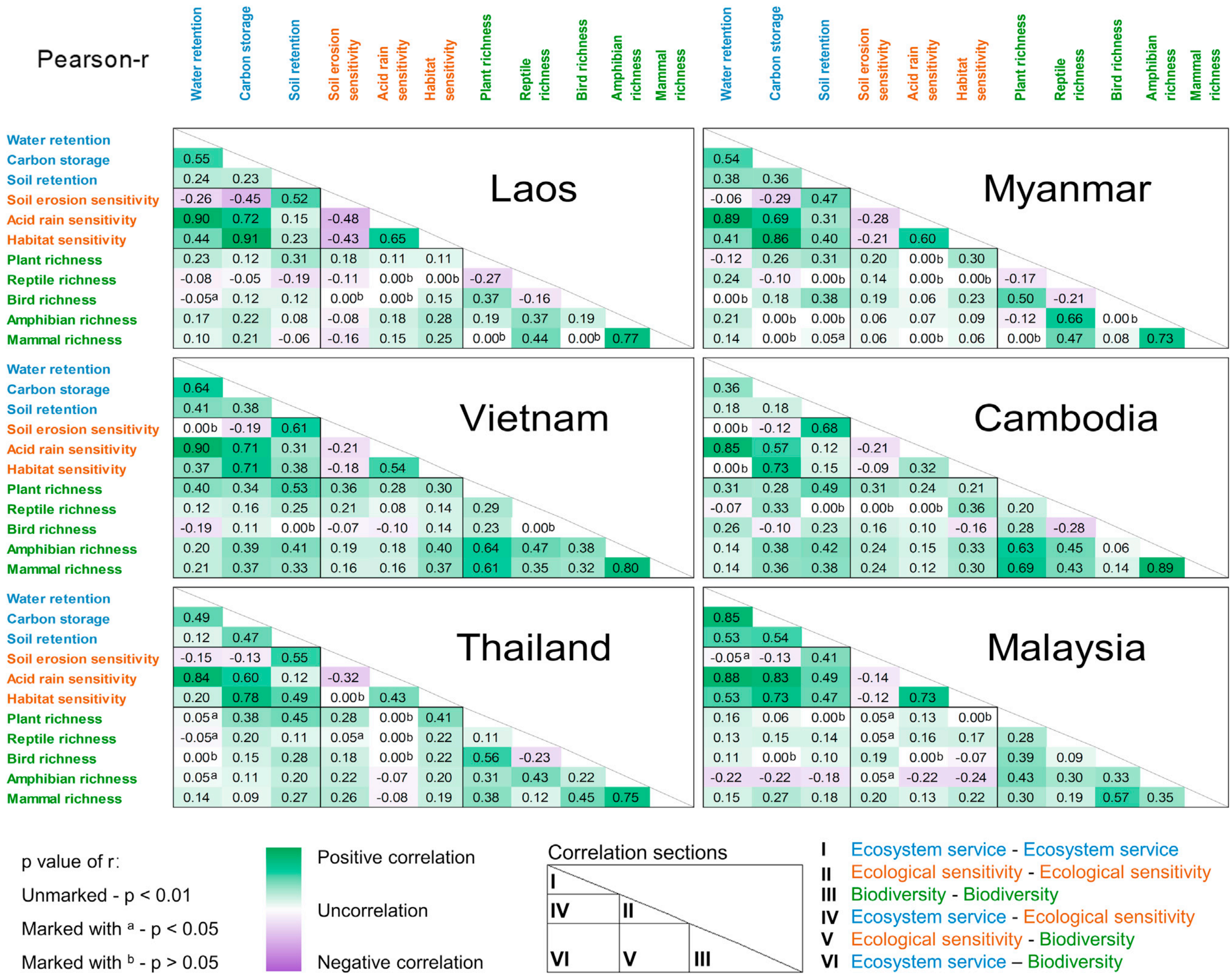


Figure 6. Synergy and trade-off analysis

Pearson correlation results for each country's ecological indicators (n = 18,000).

framework can be modified to meet regional needs, and provides sensible priorities that balance these different facets. In total, 33% of the region represents biodiversity hotspots (Figure 4C), thus the "17% land conservation" stipulated in the Aichi 11 target if implemented[4] would cover less than half of the regional priorities for biodiversity, and protection of multifunctional areas would require an even greater area (Figures 3A–3K). To achieve the best protection results of M-SEA, 51% of land area would fall within a redline, similar to the aspirational goals of Half-Earth.[1,31] Yet, expanding the PAs from the current 12.19% to 51% may prove to be impossible; thus, further work is needed to develop core priorities before exploring additional mechanisms to safeguard diversity and services elsewhere. Synergies and trade-offs should be analyzed to distinguish key priorities in different areas (Figure 6),[39,40] and national-level priorities should reflect synergies between these different environmental facets representatively across taxa. By optimizing design and factoring in co-benefits, additional mechanisms (i.e., payment for ecosystem services) can be used to further bolster the system, to provide local support and enable more diverse systems to both finance protecting these systems and to prevent a lack of social support undermining successful protection.[41]

ECR design within and beyond M-SEA

The level of existing protection varies between countries (Figure 3). Many of the ecological hotspots are concentrated in mountainous areas (Figure 4), where poor agricultural suitability has slowed the rate of loss of natural ecosystems, although lowland habitats are still reflected in our priorities. The identification of these regions highlights the need for high resolutions in analysis, as such areas may be missed at coarser resolutions. Yet, even this has started to change, with increasing growth of tree crops in these regions leading to high rates of deforestation across large parts of Cambodia and Laos in recent years.[21] As these countries develop, and GDP increases, further loss of natural habitats can be expected, thus technology transfer to enable higher productivity for existing agricultural regions in return for meeting protected area targets may enable more sustainable development in these regions.[42]

Thailand has the second highest annual GDP among the six countries in M-SEA[43]; thus, while potentially economically valuable regions have already been converted to agriculture, PAs effectively cover the majority of remaining biodiversity priorities.[44] Conversely, Malaysia has the highest GDP in the region, and has some of the lowest protection of key regions.[43] This likely stems from a combination of proactive work to identify key regions in Thailand and protect them; thus, while other areas were lost, these key regions remained protected,[45] and ambitions to grow the protected area system have provided a good coverage throughout the country. Counter to this, Malaysia has until recently maintained a greater proportion of natural forest without active conservation planning, and deforestation rates have accelerated more recently, thus developing appropriate protections against the tsunami of palm oil production has been a much slower process and the development of PAs has consequently lagged.[20] This highlights the importance of national-level priorities in developing effective means of safeguarding biodiversity, ecosystems, and related services.

The BRI provides an important opportunity for M-SEA to achieve win-win economic development and facilitate sustainable development[42] by using an approach now used across China in concert with the implementation of the BRI. Developing such an approach could enable the BRI to facilitate the implementation of an integrated green corridor with both ecological sustainability and economic development, e.g., an eco-connected China-M-SEA ERAs belt. Thus, while much of the West is alarmed by initiatives, such as the BRI, the technologies utilized in its development, including those outlined in the Science plan, have the potential to actively improve sustainability.[37] The standards being enacted within China as part of ECR provide a mechanism for a more integrated and effective means of target setting for holistic environmental protection goals and monitoring.

As implementing a Half-Earth target may be impossible in the short term, we provide stepwise suggestions for strategic setting of priorities at a regional and national level (Table S1) to complement the effective implementation of the 2030 and 2050 visions. By aiming to implement tier 1 by 2025, we can achieve the Aichi 11 target across the region. Myanmar and Vietnam are the countries that particularly need to protect more areas in tier 1 to cover the most important parts of the region, and these are the areas that are under-protected at present (Figures 3A–3K). Myanmar and Vietnam could be used for ERA construction pilots of M-SEA, as these are regions where the greatest gap in necessary protection exists. To meet with the 2030 vision, tier 2 would provide an effective target, further enhancing targets with co-benefits. Tier 3 provides a good fit for the 2050 vision "2050 vision for biodiversity: living in harmony with nature."

The overall analysis of hotspots provides the ecological optimization target (in global or regional), and by balancing ecological trade-offs this provides a strategic approach to achieving the CBD targets. Each country can start by protecting important indicators with the greatest level of synergy to rapidly improve protection and maximize benefits. Laos and Myanmar are countries with some of the greatest trade-offs between priorities, providing a particular challenge to holistic goal development, as most areas mark a trade-off between optimizing different targets. Furthermore, our ECRs would act to enhance connectivity with the implementation of tiers rather than merely expanding the area (Figure 4), which may be critical to the long-term survival of various species (especially those with a minimum viable population size), aid gene flow across the landscape and enable adaptive shifts in species in response to a changing climate.

However, for meaningful regional priorities and targets to be effectively conserved, long-term intergovernmental cooperation and communication are needed for transboundary construction of ecological corridors.[14] Diverse lowland forests are still a major land cover in many regions, and are particularly vulnerable to the impacts of human activities. Thus, as these forests are responsible for both maintaining biodiversity and ecosystem services, urgent steps are needed to halt the increasing rates of deforestation and degradation.[20] Within tiers 2 and 3 of ERAs, areas that score highly on metrics other than biodiversity may be the focus of restoration (fitting with the UN decade of restoration) as much of the region has already lost diversity, but have the capacity to host greater diversity if adequately restored. Countries should focus on the protection of biodiversity of areas and other indicators, and the restoration of areas that show synergies between sensitivity and service provision when implementing ERAs, as they have the greatest potential for co-benefits, but require slightly different approaches.

Strengths and limitations of implementation of ERAs

Any form of prioritization analysis has advantages and limitations. Various other approaches have been used for the identification of priorities for conservation and management. For example, a recent analysis on global ecological hotspots[24] indicates that the first 10% ecological priority covers 46.1% of all species hotspots, 27.1% of the total carbon, and 24.1% of the potential clean water globally, and it also explores trade-offs and synergies between three type of indicators (ecosystem services; ecosystem sensitivity and biological richness) to develop protection targets. Yet, some ecosystems and hotspots may be missed at coarse-grain resolutions, and consequently we used 250 m data resolution to reflect the ecological characteristics of the M-SEA, including more heterogeneous areas, such as mountains, karst, or patchily developed areas. The data and ecological index calculation methods in this study also require a temporal dimension, and for some taxa insufficient data exist for meaningful prioritization to be conducted (e.g., endemism analysis is challenging, and phylogenetic endemism or diversity have not been integrated). However, any analysis must compromise between how many dimensions can be incorporated, and the representativeness and comprehensiveness of available data, and find an appropriate compromise to maximize benefit while maintaining confidence in the analysis. Economic factors and cumulative impacts (such as climate change)[46] have not been included in the ECR framework, which requires further data acquisition and research in the future. It should also be mentioned that the simulating models, such as InVEST, may have deviation risks, even after the calibration of limited comparable research data (e.g., Nguyen et al.[47]). For example, the carbon storage hotspots in Malaysia only account for 6.95% of the total in its region, which does not reflect the global carbon sink in Malaysia. However, due to the high synergy of carbon storage in ecosystem services and ecological sensitivity (Figure 6), 46.63% of the carbon storage in Malaysia in the M-SEA region is included in final ERAs, especially in tier 3 (23.38%). This explains why this framework emphasizes the value of synergies in delimitation of ERAs to correct the challenges in measurement calibration caused by hotspot extraction. Despite these limitations, this scientific decision-making framework of ecological reserves can improve the efficiency in the current reserve formulation process and provide a stepwise plan for meeting future conservation targets based on ECRs.

Synthesis

The BRI provides the potential to better integrate infrastructure planning and conservation between M-SEA and China, and provides a good basis for economic cooperation. Through BRI-EECP, China proposes to deepen environmental cooperation in policy communication, facility linkage, and financial integration, which can be an important solution to rebalance the economic burden disparity between different regions. China can share its experience in ecological governance with other BRI developing countries and can also form an integrated planning of land use covering ecological goals by promoting eco-friendly engineering projects, which is both politically appealing (as a complement to existing efforts) and feasible based on regional, national, and UN standards. In our approach, we adapt China's ECRs to provide a flexible framework to best protect regional biodiversity and ecological services by targeting areas with the greatest chance of providing co-benefits. Such targeting means that other income streams may be available to support implementation both through financial institutes and through climate-funding initiatives. Furthermore, given that these services relate to agricultural productivity and other key services, there is a clear national interest in maintaining these systems and services. The promotion of ECR in the M-SEA area shares the goal and vision of the CBD. Yet, given the manifold pressures on land, using integrated targets and relying on approaches of effective area-based conservation measures to promote the realization of global ecological goals may be more efficient than traditional indicators. Thus, our recommendations, in addition to providing a pathway forward for one of the world's most threatened biodiversity hotspots, also provides a framework to enable spatial priorities to be developed elsewhere, both to enable sustainable development and to meet the challenges set forth in the post-2020 global biodiversity framework.

Our study extends the existing standards for the development of ecological PAs to ERAs, and provides an operational scientific framework for ecological hotspot analysis and reserve delineation. Over the past decade, we have continued to see rapid rates of biodiversity loss across M-SEA,[20] and with major infrastructural initiatives, such as the BRI, this is set to increase unless using the ECR approach pioneered by China. We showcase that such an approach can be scaled across regions and enable the protection of key benefits.[15,37] Identifying key areas that protect both biodiversity and maintain key services that humans rely upon provides a fundable approach to ensure that key regions for biodiversity are prioritized, and given that resources are finite we present an approach that scales prioritization to maximize benefits across 11 diverse indicators of diversity, sensitivity, and service provision. Furthermore, priorities identified here provide a stepwise framework that matches the goals of the CBD's early drafts of the post-2020 global biodiversity framework to maximize benefits achieved through the 2030 agenda and the 2050 vision.

The post-2020 biodiversity framework provides the opportunity to better utilize data-driven approaches to develop practical targets for conservation. Here, we demonstrate that it is possible to identify areas that provide the greatest co-benefits, and by using these priorities in a stepwise manner to meet each stage of the present, 2030, and 2050 visions, we can achieve the greatest gains for conservation and service provision, which could then also be eligible to other sources of funds, such as climate change funding to implement both more effectively. Countries, such as Myanmar, have a particularly long way to go to protect key areas highlighted here, yet by maintaining these services through the implementation of ECRs such economies can develop sustainably and prevent the loss of key services derived through natural resources. While most remaining forests are key targets, we also highlight that some countries have a much greater task ahead of them if they are to secure and protect key areas, and consequently in allocating funding and effort such countries may require more support to maintain these areas and the vital services they provide.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Yang Bai (baiyang@xtbg.ac.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

The raster results of this research models can be obtained directly from the following addresses. Water retention (https://doi.org/10.13140/RG.2.2.15992.78087); carbon storage (https://doi.org/10.13140/RG.2.2.14315.05926); soil retention (https://doi.org/10.13140/RG.2.2.21025.94562); soil erosion sensitivity (https://doi.org/10.13140/RG.2.2.17670.50244); acid rain sensitivity (https://doi.org/10.13140/RG.2.2.24381.38881); and habitat sensitivity (https://doi.org/10.13140/RG.2.2.27736.83208). Please obtain biodiversity data from the original research (https://doi.org/10.13140/RG.2.2.10117.47843).

Selection of indicators

The ecological indicator selection criteria for this study are referenced from: (1) Millennium Ecosystem Assessment[40] and Common International Classification of Ecosystem Services,[48] which have received wide acceptance. (2) Stakeholder concerns. We are particularly concerned about the needs of governments in M-SEA because they are the most important decision-makers and participants in the formulation of ecological protection policies.[49] As the world's most diverse forest area and a high grain yielding area,[27] regional governments pay special attention to the coverage, distribution, and productivity of important land use and land cover (LULC) types, such as forest and agriculture.[50] (3) Ecological indicators closely related to the accounting and social development of human well-being relate to water security, food security, and human health.[49,50] (4) Data availability. We arranged detailed indicator selection in Note S1.

The indicators of ecosystem services included water retention, carbon storage, and soil retention. These services are closely related to water resources, land resources, and food supply for human survival and development. The ecological sensitivity indicators included acid rain, habitat, and soil erosion. These indicators directly affect the quality of human existence. Five taxa (mammals, birds, amphibians, reptiles, and plants), consistent with the baseline biodiversity indicators reported by various countries, were used to characterize regional biodiversity patterns, but only richness was used to try to minimize bias in representation of rarer species in smaller, less readily collected, and identified taxa.[29]

Measurement and verification of models

The spatial distribution of multiple indicators estimated by InVEST (Figures 2A–2F), a GIS-based approach for estimating ecosystem services across the landscape based on LULC condition,[33] was used to make up for the lack of representation of existing indicators on ecosystem services and ecological sensitivity. Figure S3 shows a map of digital elevation model (DEM) and LULC in M-SEA. See data requirement for the InVEST model in Table S2, and introduction and validation of models in Note S2.

We calculated carbon storage using the InVEST carbon storage and sequestration model to estimate aboveground biomass, underground biomass, soil, and dead organic matter per LULC type (Table S3), and the sum is equal to carbon storage. Although no carbon storage data can be directly found for comparison, we use the net primary production (NPP) research results of Potter et al. in Southeast Asian countries for comparison.[51] There is a strong positive correlation between NPP and carbon storage of vegetation. We found the R^2 values of carbon storage with the evergreen broadleaf forests and open woodlands and savannas were 0.8268 and 0.7963, respectively. We also used carbon storage data of forests in Vietnam provided by Nguyen et al. for simple mean level validation with an interval of 130.93–135.55 t ha^{-1}, while our result was 134 t ha^{-1}.[47]

Soil retention was calculated using the InVEST sediment delivery ratio model as the average annual soil loss from each parcel of land. InVEST uses a universal soil loss equation to identify potential soil yield and capacity to retain sediment.[33] The input data is DEM, management practices, sediment retention values, vegetation cover, and management factors for each type of LULC (Table S3). We verified the results of sediment retention by using the statistical results in Vietnam. We used ArcGIS to sample 1,000 random points in the sediment retention spatial distribution of this study, and ensured that the sampling range was consistent with Nguyen et al.[47] Note S2 shows the frequency distribution histogram and mean level of 1,000 sampling points. The average sediment retention amount of this study was 747.56 t ha^{-1} $year^{-1}$, while the sediment retention amount in 2010 and the mean sediment retention level of three scenarios in 2020 were 760.42 and 760.45 t ha^{-1} $year^{-1}$, respectively (Note S2), reported by Nguyen et al.[47]

Water retention refers to the capacity of an ecosystem to intercept or store precipitation water resources calculated by deducting evaporation and runoff from precipitation. The InVEST model estimates the relative contributions of water from different parts of the landscape to evaluate how possible changes in LULC patterns could impact the annual surface water yield.[33] The model does not differentiate between surface, subsurface, and base flow, but assumes that water yield from a pixel reaches the point of interest via one of these pathways. We derived input values using local data on rainfall, runoff, and evapotranspiration coefficients (Table S3). The water retention was then calculated by water yield minus runoff. We verified the results of water yield by using the statistical results in Vietnam. The average water yield amount of this study was 9,586.01 m^3 ha^{-1} $year^{-1}$, while the water yield amount in 2010 and the mean water yield level of three scenarios in 2020 were 9,270.87 and 9044.48 m^3 ha^{-1} $year^{-1}$, respectively, reported by Nguyen et al.[47] Other parameters in the InVEST model are described in Table S4.

The ecological sensitivity was calculated by dimensionless index method. The sensitivity of acid rain is based on the index system established by Fan et al.,[52] which can reflect the characteristics of subtropical ecosystems. The main input data are LULC and water budget, which was obtained from the results of the InVEST water yield model.[33] Habitat sensitivity is assigned according to different LULC types (Table S1), based on the method adopted in the National Ecological Function Regionalization issued by the Ministry of Ecology and Environment of the People's Republic of China.[53] Soil loss sensitivity was directly determined sediment loss amount, an intermediate output result of the InVEST sediment delivery ratio model.[33] All ecological sensitivity indicators were normalized to a dimensionless index from 0 to 1.

Biodiversity richness methods

Species richness maps were created for 10,311 animal and plant species based on 458,011 records (6,173 plants [orchids, 117,947 records], 1,706 reptiles [25,891 records], 308 mammals [(12,928 records], 304 amphibians [14,642 records], 1,820 birds [286,603 records]). Orchids were the only modeled plant group because, as accuracy of identification is highly variable in plants, sampling biases can misrepresent true diversity patterns. Orchids represent a highly diverse group of angiosperms, with better sampling than most other groups, and because of their wide habits (epiphytic, terrestrial, etc.) are a useful indicator of diversity in other plant groups.

Models were created in Maxent[54] using the outputs of the analysis in Hughes and colleagues.[21,28,38] Models included 23 environmental data layers (including a range of climatic and physical variables) to encapsulate the range of conditions experienced by species across this region. The input environmental data layers and final results were displayed at 1 km resolution in Hughes,[21] and the resampling at 250 m resolution by ArcGIS in this study. These models aimed to assess species current distributions, and thus included a number of parameters based on habitat quality relating to tree density and distance to high-quality natural forest areas, to assess the distribution of forest-dependent species.[28] Three replicates were run for each species and the average probability of distribution output for each species was then reclassified using the average 10 percentile training presence threshold for each species to reclassify each map to show suitable and unsuitable habitat. Outputs were then summed for each taxa using the Mosaic new raster tool in ArcMap and then summing the overall diversity across taxa. The final hotspots were obtained by spatial extraction of the top 10% high value areas of each taxa in ArcGIS software.

ERAs delimitation

On the basis of all the spatial distribution of ecological hotspots (top 10% high value areas), the representativeness of existing PAs was reflected by two indexes. PPH was obtained by calculating the area PPH in all hotspots, which indicated the extent of the protection of hotspots in the study area. PPP was obtained by calculating the area proportion of PAs containing hotspots in all PAs, which represented the representativeness of current PAs. The latest global boundary vector data for PAs was provided by the WDPA.[30] We mapped protected hotspots (green), unprotected hotspots (red), and existing PAs outside the hotspots (yellow) for each selected indicator in M-SEA (Figure 3), to help governments to clarify their most important tasks in the goal of optimizing or expanding their current PAs.

The final ERAs were obtained by overlaying the hotspots of 11 indicators. The higher the number of hotspots overlap, the higher their ecological importance, and the more it is included in the scope of priority protection. We classified all hotspots by importance from high to low. We classified $\geq$3 hotspot overlap areas as tier 1, accounting for 15.6% of the total land area, which is almost equivalent to Aichi 11 target.[4] This time node is set to be 2025 of this stage and aims to optimize the representativeness of the PAs set out in the 2020 Aichi 11 target in the next 5 years. Tier 2 classified as $\geq$2 hotspot overlap areas, accounting for 32.9% of the total land area, which is comparable with the results of a large number of studies advocating the protection of 30% of the hotspots.[24] The time node for this stage is set to be 2030, which is consistent with the next 10-year plan of biodiversity conservation of "30 by 30." All the hotspots make up tier 3, accounting for 51% of the total land area, close to the Half-Earth conservation approach.[1] The Half-Earth target is set to be completed by 2050, and is synonymous with the "2050 vision for biodiversity: living in harmony with nature." The third-tier target is increasingly protecting all the indicators. To consider the connectivity of ERAs, we use the Connectance index in Fragstats 4.2 as an index to characterize the connectivity of ERAs with different tiers.

We analyzed the PAs that each country needs to implement to protect goals set in each tier, and used 250 m resolution LULC data[55] to analyze the land structure at different tiers in each country, and marked the main types to facilitate ECR implementation. The data was analyzed by MODIS data and Sentinel-1 data in 2015, which divided the entire Southeast Asian l LULC into 18 types with a data resolution of 250 m (Figure S2), and all sampling points reached more than 75% accuracy.

ECR implementation in each country

Synergies and trade-offs between ecological indicators are the basis of ECR implementation in each country. Using the ArcGIS spatial analysis tool, 18,000 sample points (3,000 in each country) were extracted for Pearson's r analysis, and the results were divided into six sections by pairwise comparison among the three kind of indicators. We mark the synergies as green and the trade-offs as red, and the darker the color represents the more relevant of them (Figure 6). We further analyzed the current situation of hotspots by the overlap proportion and area to help countries understand their current ecological situation, and used this as the basis for target development. To highlight these priorities and the mismatch between priority and protection in each country we use different colors to represent different countries, the circle size represents the size of the overlapping area, and the different heights represent the proportion of the overlapping area (Figure S2). A list of recommended tasks is given containing important locations, ecological indicators, and the main LULC types that each country needs to pay attention to in the three tiers of ECR (Table S1), considering the ERA delimitation in the whole region, the representativeness of the existing PAs, and the synergies and trade-offs between ecological indicators in each country.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.09.010.

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AUTHOR CONTRIBUTIONS

Conceptualization, Y.B. and A.C.H.; methodology, Y.B. and Z.F.; software, Y.B. and Z.F.; validation and formal analysis, Z.F.; writing – original draft, Y.B., Z.F., and A.C.H.; writing – review & editing, Y.B., Z.F., and A.C.H.; visualization, Z.F.; resources, Y.B. and A.C.H.; supervision, Y.B. and A.C.H.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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