frontiers | Frontiers in Ecology and Evolution

TYPE Original Research
PUBLISHED 13 January 2025
DOI 10.3389/fevo.2024.1483133

OPEN ACCESS

EDITED BY
Sharif A. Mukul,
University of the Sunshine Coast, Australia

REVIEWED BY
Tarit Kumar Baul,
University of Eastern Finland, Finland
Mohammed Abu Sayed Arfin Khan,
Shahjalal University of Science and Technology, Bangladesh

*CORRESPONDENCE
Lijuan Wang
wanglijuan15@mails.ucas.ac.cn

RECEIVED 19 August 2024
ACCEPTED 16 December 2024
PUBLISHED 13 January 2025

CITATION
Wang L, (2025) A comparative analysis of protected area expansion strategies for biodiversity and ecosystem services: a case study of Hainan Island.
Front. Ecol. Evol. 12:1483133.
doi: 10.3389/fevo.2024.1483133

A comparative analysis of protected area expansion strategies for biodiversity and ecosystem services: a case study of Hainan Island

Lijuan Wang*

Research Institute for Eco-civilization, Chinese Academy of Social Sciences, Beijing, China

Introduction: The allocation of limited resources to simultaneously protect biodiversity and provide ecosystem services (ESs) is a critical global challenge in achieving the Kunming–Montreal Global Biodiversity Framework. One common strategy for this challenge is to expand existing protected areas (PAs), but the efficiency of different expansion methods for biodiversity and ESs remains unknown.

Methods: This study investigated two strategies, preserving existing PAs ("locking") versus reassessing their boundaries ("unlocking"), to evaluate their effectiveness in achieving biodiversity and ES targets. The study used Marxan, a spatial modeling tool, to assess the effectiveness of PAs expansion strategies on Hainan Island in China.

Results and discussion: The current PAs system, which encompasses 8.82% of the island, is inadequate for protecting the target levels of biodiversity and ES. We experimented with expanding the PAs to 15% using both strategies. The results revealed that, compared with the "unlocking" strategy, the "locking" strategy favored ES protection (66.49% vs 86.84%), but did so at the expense of biodiversity conservation. In contrast, the "unlocking" strategy required a larger area for expansion and led to increased habitat fragmentation compared wtih the "locking" approach. These findings underscore the need for a strategic approach to expanding PAs and balancing between biodiversity conservation and ES provision. This study offers valuable insights that could be used for broader applications in PAs management and biodiversity conservation planning.

KEYWORDS

biodiversity, ecosystem services, protected area expansion, Marxan model, Kunming-Montreal global biodiversity framework

1 Introduction

Biodiversity is the foundation of ecosystem service (ES) essential for human survival (Balvanera et al., 2016), and is facing an unprecedented decline due to the intensification of human activities, such as land use change and overexploitation (IPBES, 2019; Pereira et al., 2020). This alarming trend poses a severely threatens to ES provision and human well-being. Balancing the growing demand for ESs with biodiversity conservation is a critical challenge for sustainable development (Cimon-Morin et al., 2013; Williams et al., 2020).

Establishing protected areas (PAs), such as nature reserves and national parks, is widely recognized as the most effective strategy for safeguarding biodiversity and ES (Zeng et al., 2022). Since the establishment of Yellowstone National Park in the United States in 1872, a growing global PAs network has emerged, with nearly 16% of global land and 7.4% of oceans now under protection (UNEP, 2021). The Kunming–Montreal Global Biodiversity Framework has further elevated this commitment, setting a target of protecting 30% of land and sea by 2030 (CBD (Convention on Biological Diversity), 2022). Although some countries, such as Cambodia, Panama, and Tanzania, have already exceeded this target (Zabala et al., 2024), progress varies globally. Many countries in the global south (Farhadinia et al., 2022; Loos, 2021), especially densely populated countries, such as India, Bangladesh, Malaysia, Pakistan, and parts of Africa, face significant challenges and pressures in expanding their PAs to meet this ambitious international compliance (Li and Pimm, 2020; Waldron et al., 2020; Zang et al., 2022). Consequently, expanding existing PAs effectively under limited land resources poses a global challenge.

Various methods and tools have been used to identify priority areas for PAs expansion (Moilanen et al., 2014; Zhang and Li, 2022). The following two primary approaches have emerged: (1) “locking”, which focuses on expanding existing PAs, and (2) “unlocking”, which considers the entire landscape (Yang et al., 2019). Most of studies used the unlocking method and established new PAs based on focused objectives (Xu et al., 2017; Zhang et al., 2018), such as representative ecosystems or high biodiversity or ES values. Few studies have used the locking method, such as China’s newly established national park pilots (Li and Pimm, 2020; Xu et al., 2016). The preference for unlocking is often attributed to its perceived ability to enhance protection efficiency for conventional goals. Comparing the protection efficiency of these two strategies is crucial to inform real-world PA expansion decisions. Many PAs expansions have been established with specific goals, often focusing on individual species or unique ecosystems (Hermoso et al., 2019) rather than comprehensively addressing biodiversity and ES conservation. Moreover, as the global PAs network expands, its effectiveness in conserving biodiversity and ES in many areas is still under protected (Zeng et al., 2022, 2023). Consequently, there is a growing recognition of the need to expand PAs networks considering biodiversity and ES (Li and Pimm, 2020). Although some studies have compared the locking and unlocking PAs expansion approaches (Yang et al., 2019), they often lack a comprehensive focus on both biodiversity and ES, relying on limited data or simplified methodologies.

Hainan Island, China, boasts a unique and ecologically rich tropical rainforest in its central mountainous regions. This invaluable ecosystem provides essential ES for local, regional, and global communities while safeguarding critical biodiversity. However, the island faces the inherent trade-offs between provisioning services, regulating services, and biodiversity conservation. Despite establishing numerous PAs, expanding existing PAs to safeguard both ES and biodiversity effectively remains a significant challenge. Hainan Island offers a valuable case study to address the research gap by comparing the effectiveness of locking and unlocking approaches in achieving biodiversity and ES conservation goals. This study investigated the extent to which existing PAs safeguard these values and determined the most effective expansion strategy under a fixed protected area size. Our study aimed to provide valuable insights for PAs expansion strategies in Hainan Island and other regions worldwide, ultimately supporting the ambitious biodiversity protection targets of the Kunming–Montreal biodiversity framework.

2 Study area and methods

2.1 Study area

Hainan Island (108°37′–111°03′ E, 18°10′–20°10′ N) is located in the southern part of China and harbors the most concentrated and well-preserved continental island tropical rainforest in the country (Figure 1). This rainforest ecosystem, which is located in the central mountainous region of the island, is a harbor for diverse species and is designated biodiversity conservation area, recognized as one of the nine hot spots for biodiversity conservation in China (Wang et al., 2021). Furthermore, these central mountains serve as a vital source of ES for local communities, providing ES like forestry products, water provision, and flood mitigation (Zheng et al., 2019). A significant portion (8.82%) of Hainan Island has already been designated as natural reserves in recognition of its ecological treasures. Such nature reserves aim to protect the representative rainforest and its diverse inhabitants. However, this existing nature reserve network, called exsiting PAs in this paper, falls short of achieving comprehensive conservation goals for both biodiversity and the vital ES it provides (Wang et al., 2021). Therefore, Hainan Island presents a compelling case study area for comparing the locking and unlocking methods for PAs expansion. These contrasting approaches can help identify the most effective strategy for expanding PAs and provide valuable insights for other areas facing similar challenges.

2.2 Assessment of biodiversity and ecosystem services

We employed a biodiversity importance index, which is the sum of potential habitat suitability for all species across five taxonomic groups: plants, mammals, birds, reptiles, and amphibians, to quantify biodiversity (Wang et al., 2021; Xu et al., 2017). Habitat suitability models were developed by correlating species distributions with environmental factors, such as elevation, slope,

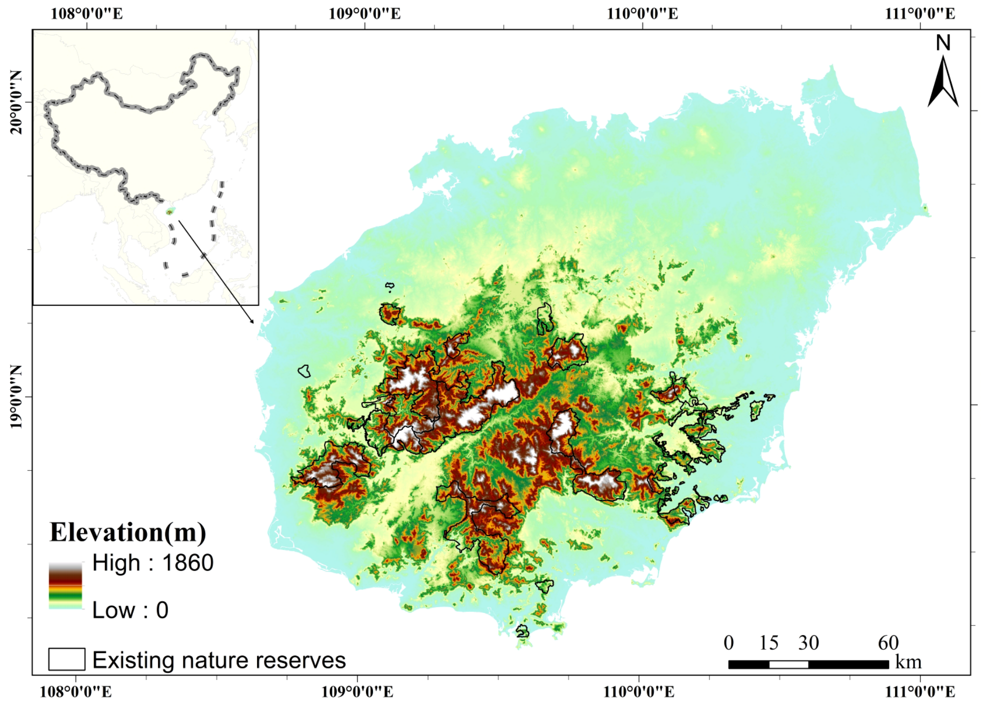

FIGURE 1
Map of Hainan Island.

and ecosystem types (Zhang et al., 2011). Refer to Wang et al. (2021) for more details.

We focused on five ES (e.g., water yield, soil retention, water quality, flood mitigation, and carbon sequestration) to evaluate the ES provided by PAs in this region. These ESs are crucial for the local community, downstream populations, and global efforts to address environmental challenges. We utilized the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model to generate spatial distribution maps for each ES (Sharp et al., 2019). A detailed methodology and data description can be found in Wang et al. (2021).

2.3 Protection priority area analysis

We used a marine reserve design, applying the spatial explicit annealing algorithm in Marxan tool to identify priority areas for expanded PAs. This tool is a widely used decision-support tool in systematic conservation planning (Watts et al., 2017; Zhang and Li, 2022). Marxan prioritizes PAs for biodiversity and ES by minimizing a composite score that balances three factors (Equation 1) (Watts et al., 2017). 1) Cost: represents the cost of protecting each planning unit. 2) Boundary length: penalizes long and complex boundaries (measured by the boundary length modifier, BLM) to create compact, manageable PAs. 3) Species penalty: penalizes solutions that inadequately protect target species and habitats (assessed by the Species Penalty Factor, SPF). A high SPF indicates a greater shortfall of that conservation feature in protection.

$$\text{Score} = \sum_{PUs} Cost + BLM \times Boundary\ \ Length + \sum_{Features} SPF\ \ for\ \ missing\ \ features \tag{1}$$

This study identified one biodiversity element and five ESs as protection targets to safeguard 40% of the biodiversity and each ES throughout Hainan Island. These targets were established based on the research specificity of Hainan Island. Watersheds across Hainan Island were used as planning units, with their area determining the cost of protection. Adjacent planning unit lengths were incorporated as boundary data to enhance calculation accuracy. All protection targets were assigned the same weights during the Marxan model execution to ensure equal consideration. An SPF of 1 was set to meet all protection goals. We employed an iterative approach to determine the BLM parameter. We determined an appropriate BLM value of 0.72 by gradually increasing the BLM value and evaluating the resulting spatial compaction of multiple scenarios (Zhang et al., 2014). We used Marxan to run two distinct scenarios and investigated various strategies for expanding PAs: (1) locking existing PAs during expansion. In this scenario, we prioritized extending PAs beyond the current network while keeping the boundaries of existing reserves intact. We designated the planning units as priority conservation areas, where over 5% of their total area overlapped with existing PAs (Yang et al., 2019). This procedure was made by "locking in" these units, thus ensuring their inclusion in conservation planning. (2) Unlocking existing PAs: this approach allowed Marxan to consider the entire landscape, without being limited by existing reserve boundaries, for potential expansion opportunities.

We ran Marxan simulations 1,000 times to calculate the irreplaceability index for each planning unit. This index reflects the number of times a unit is selected within the optimal solutions generated by Marxan, indicating its relative importance for achieving conservation goals. The higher the irreplaceability index, the greater the priority. We identified the 15% high-ranking areas of Hainan Island as priority expansion areas for protected zones, effectively doubling the size of the existing PAs. This selection aligns with the area designated by the national park pilot initiative, ensuring consistency with broader conservation efforts (Li et al., 2022).

2.4 Data analysis

Independent samples *t*-tests were conducted to assess the differential impacts of locking and unlocking existing PAs on biodiversity and ESs. The protection target achievement rate was calculated as the percentage of protection objectives met within PAs relative to the desired targets. For instance, if our goal for PAs on Hainan Island was to protect 40% of biodiversity, and under a locking strategy, the selected PAs could only protect 30%. The protection target achievement rate would be 30% divided by 40%, equaling 75%. PAs fragmentation was simply represented by the number of patches (Santiago-Ramos and Feria-Toribio, 2021).

3 Results

3.1 Ability of existing PAS to protect biodiversity and ES

Existing PAs in Hainan Island, covering only 8.82% of the total area of the island, are insufficient for comprehensive protection of biodiversity and ES. Although the existing PAs provide partial protection for some ES—including water quality (98.50%), and soil retention (81.17%)—significant gaps exist in safeguarding biodiversity (55.67%), carbon sequestration (55.78%), water yield (35.66%), and flood mitigation (47.42%) (Figure 2). This limited coverage necessitates strategic expansion of PAs to ensure the robust conservation of biodiversity and the vital ES they support.

3.2 The efficiency of locking and unlocking methods for protecting biodiversity and ES

According to the results of the independent-samples t-test (Figure 3), the locking and unlocking of existing PAs strategies significantly influenced the protection of biodiversity, soil retention, water quality, and flood mitigation services ($p<0.05$). However, no significant influence on water yield or carbon sequestration was observed ($p>0.05$).

Comparing the locking and unlocking methods for expanding the PAs of Hainan to 15% of the island revealed distinct outcomes for biodiversity and ES protection outcomes. The unlocking approach, which considered the entire island for potential expansion, was more effective in protecting species habitats than the locking method (86.84% vs. 66.49%, respectively). However, it showed slightly lower performance in safeguarding the overall ES. Interestingly, both methods achieved near-complete protection for soil retention (locking: 112.82%, unlocking: 103.81%) and water quality (locking: 120.01%, unlocking: 115.52%) (Figure 4). This result highlights the complex trade-off between biodiversity and ES goals when selecting a PAs expansion strategy with limited resources.

The locking method, focusing on expanding existing PAs, resulted in a more concentrated expansion (41.19% increase in adjacent land) and few protected patches (12). This approach may offer increased efficiency by building upon existing conservation efforts and potentially minimizing habitat fragmentation. Conversely, the unlocking method yielded a broader expansion

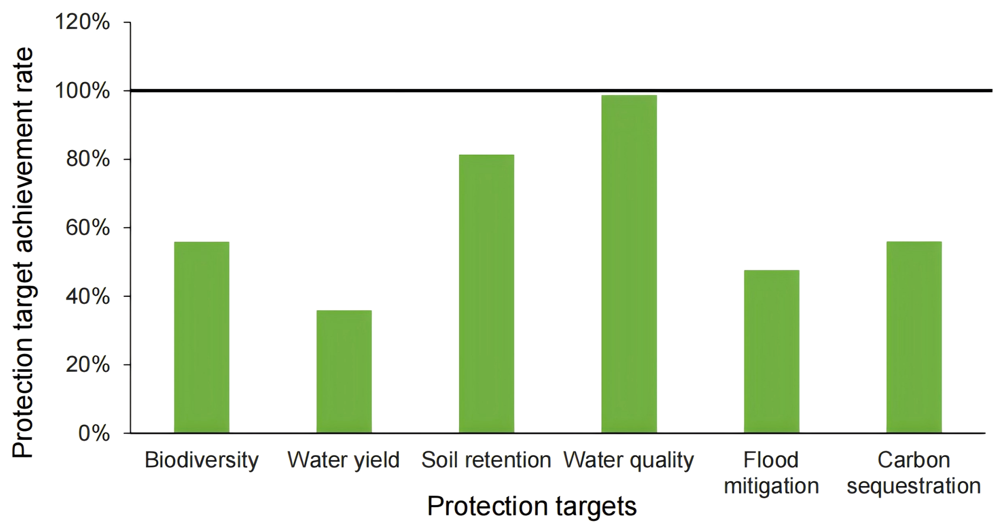

FIGURE 2
The target achievement rate of existing protected areas.

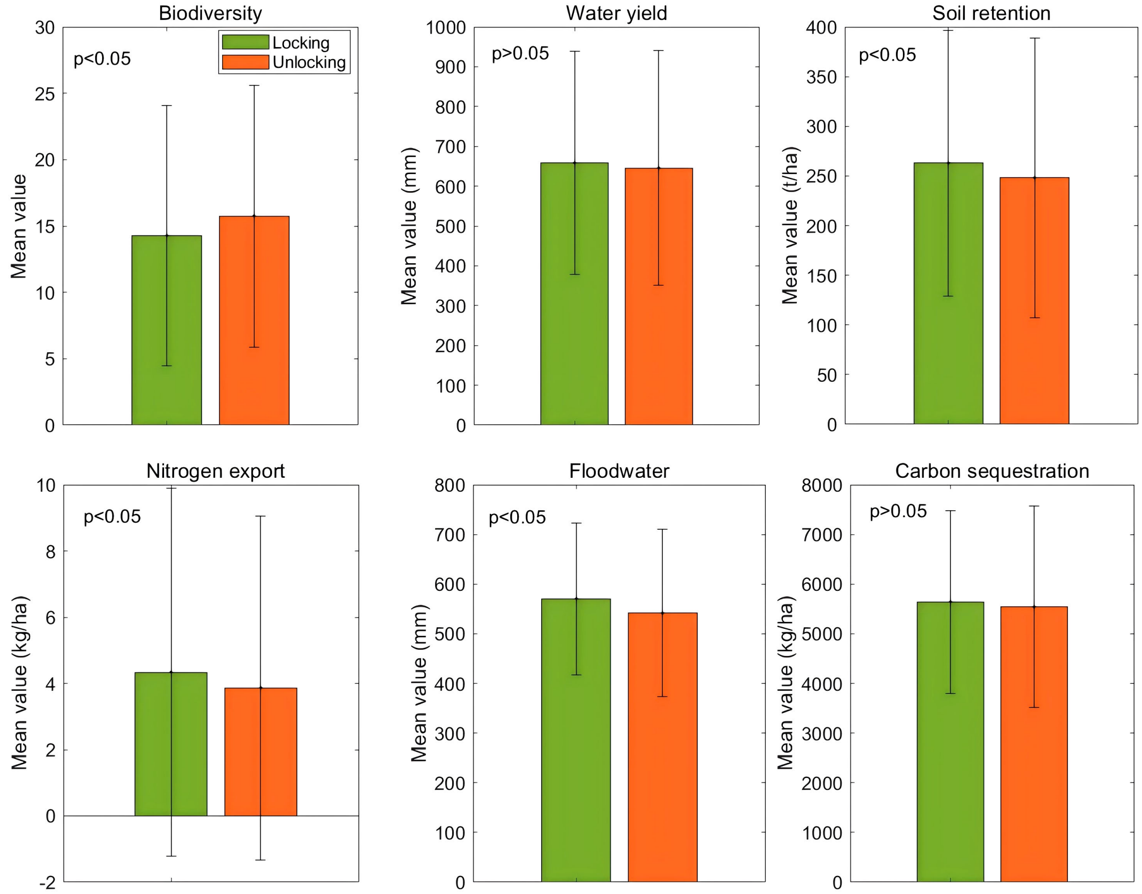

FIGURE 3
Mean values of biodiversity and ecosystem services under locking and unlocking existing protected areas scenarios. The inverse of nitrogen export and floodwater represents water quality and flood mitigation services.

(56.32% increase outside existing areas) but with a significantly high number of protected patches (102) (Figure 5), raising concerns about potential fragmentation within these new areas.

4 Discussion

4.1 Effectiveness of the two expansion strategies

Our study examined the effectiveness of different strategies for expanding PAs to enhance biodiversity and ES conservation. By comparing the "locking" and "unlocking" approaches on Hainan Island, we identified critical trade-offs and implications for PAs management. Our protection-efficiency analysis revealed that existing PAs on Hainan Island demonstrate a insufficient protection for both biodiversity and ES, a common trend in many other locations (Neugarten et al., 2020; Watson et al., 2020). This result may be attributed to two reasons. First, the initial aim of the existing nature reserve was to protect specific species (e.g., Hainan black crested gibbon) or rainforest ecosystems, which did not include ES (e.g., water yield) and some other species as protection objectives at that time. Second, there exists a spatial mismatch among different protection objectives, which is influenced by biophysical conditions (e.g., soil and climate), a common phenomenon in the spatial protection of ES and biodiversity (Wang et al., 2021; Zheng et al., 2016). These findings highlight the urgent need for strategic PAs expansion to address these gaps.

By comparing two PAs expansion strategies, we found that the locking approach, which focuses on expanding adjacent to existing nature reserves, demonstrated a preference for ES protection rather than biodiversity. In contrast, the unlocking approach, which considers the entire landscape, achieved broader biodiversity coverage but at the cost of increased fragmentation and potential management challenges. These differences may be attributed to several factors. The spatial inconsistency between ES and biodiversity on Hainan Island (Wang et al., 2021), coupled with the greater spatial flexibility afforded by the unlocking strategy, likely played a significant role. Additionally, small PAs, which are more common in the unlocking approach, may be more effective at protecting biodiversity than ES (Volenec and Dobson, 2020). Consequently, these findings emphasize the complexity of balancing biodiversity and ES conservation in PA expansion (Fastré et al., 2020).

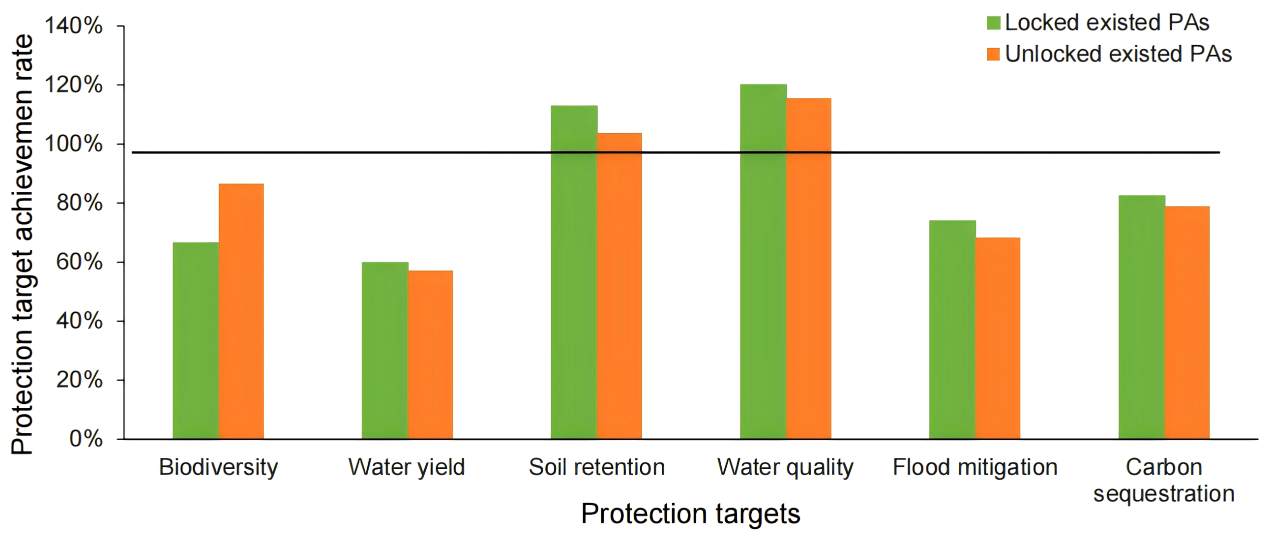

FIGURE 4
Target achievement rate under locking and unlocking existing protected areas (PAs) scenarios.

4.2 Management implications

Although the locking and unlocking methods employed in this study offer valuable insights into potential strategies for expanding existing PAs, it is important to acknowledge that they represent only one perspective. Real-world PA expansion is influenced by a complex interplay of factors beyond biodiversity and ES (Yang et al., 2020). Challenges such as conflicting economic development interests, cultural factors, and the associated costs and benefits must be carefully considered (Hoffmann, 2022; Waldron et al., 2022). Effective PA expansion strategies should be tailored to specific site conditions and involve active engagement with local communities. Moreover, successful PA expansion requires robust management practices, particularly legislation. Implementing clear and enforceable regulations is essential

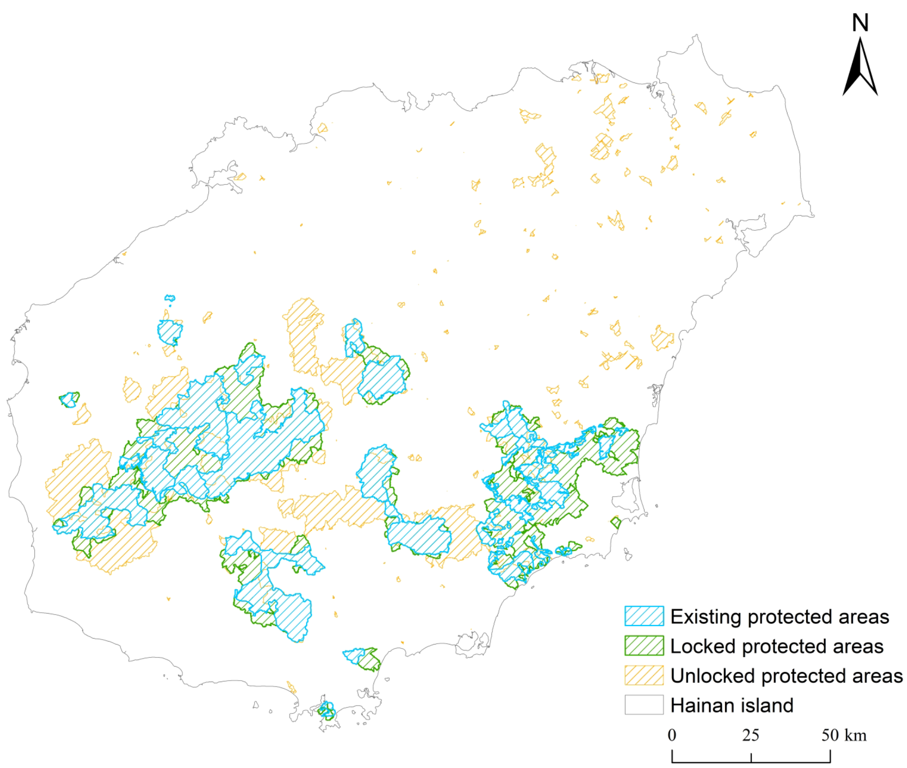

FIGURE 5
Distribution map of protected areas.

to ensure the long-term sustainability of expanded PAs and their contribution to biodiversity conservation (Zabala et al., 2024).

Decision-makers must carefully weigh the costs and benefits of different expansion strategies based on specific conservation goals and available resources. We recommend developing robust decision-support tools to quantify trade-offs and identify optimal expansion scenarios to address these challenges. Additionally, exploring innovative financing mechanisms to support PA expansion and management is crucial (Huang et al., 2024; Zafra-Calvo and Geldmann, 2020). This scenario includes diversifying revenue sources beyond government funding, such as payments for ES and private conservation investments. Moreover, integrating PAs expansion with broader landscape-scale conservation initiatives can enhance overall conservation effectiveness. Finally, collaborative governance approaches involving local communities, Indigenous peoples, and other stakeholders can facilitate the successful implementation of PAs expansion plans (Poppenborg and Koellner, 2013).

4.3 Limitations and future research priorities

Although this study provides valuable insights into the trade-offs between biodiversity and ES conservation in PAs expansion, it is essential to acknowledge its limitations. First, the expansion of PAs did not consider local livelihood and other human impacts or costs, which substantially influence PAs expansion (Geldmann, 2023). Second, the study primarily considered biodiversity and ES as static variables, neglecting potential changes in their distribution due to future climate change or other environmental factors and ES flow (Lu et al., 2022; Wang et al., 2022). Third, the lack of cost-benefits analysis of the two methods may weaken the robustness of the findings.

Future research should explore the dynamics of biodiversity and ES over time, incorporating climate change projections and other relevant drivers. Furthermore, conducting comparative studies across different regions with varying ecological characteristics and governance systems would enhance the understanding of the generalizability of our findings. Developing more sophisticated spatial modeling tools that can incorporate multiple, often conflicting, conservation objectives is crucial to refining the decision-making process. In conclusion, our study provides a possible expansion of PAs, which is important for realizing the ambition of Kunming–Montreal biodiversity initiative.

5 Conclusion

Effective PAs expansion is crucial for safeguarding biodiversity and ES. Our study compared two primary approaches: locking and unlocking. The results indicate that although locking prioritizes ES protection, it often compromises biodiversity conservation. Conversely, unlocking can capture a wider range of biodiversity but faces challenges related to fragmentation and management.

However, our study has certain limitations. We primarily focused on biodiversity and ES, neglecting other important factors such as local livelihoods and potential impacts on human well-being. Our analysis did not account for future biodiversity and ES distribution changes due to climate change or other environmental factors. Future research should focus on developing more sophisticated models, incorporating long-term perspectives, and exploring innovative financing mechanisms to support effective PAs management. Ultimately, this research contributes to the growing knowledge of PAs expansion and supports the ambitious goals outlined in the Kunming–Montreal Global Biodiversity Framework. By carefully considering the trade-offs and implementing effective strategies, we can create a more sustainable future for people and nature.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

LW: Conceptualization, Funding acquisition, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing- review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This research was funded by the National Natural Science Foundation of China (grant nos. 42201304) and the Funding Program for the "Peak-Climbing Strategy" in Discipline Development of the Chinese Academy of Social Sciences (DF2023XXJC05).

Acknowledgments

I want to thank YC from the university of Hong Kong and Xiaofei Hu from the Hainan Academy of Environmental Sciences, China, for their invaluable feedback on the draft of this paper. And I also want to thank the reviewers for their insightful comments. Finally, I also thank the Charlesworth Group (https://www.cwauthors.com.cn/frontiers/) for editing the language of this manuscript.

Conflict of interest

The author declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Balvanera, P., Quijas, S., Martín-López, B., Barrios, E., Dee, L., Isbell, F., et al. (2016). "The links between biodiversity and ecosystem services," in *Routledge Handbook of Ecosystem Services*. Ed. P. Marion, et al (Routledge, London and New York), 45–61.

CBD (Convention on Biological Diversity) (2022). The Kunming-Montreal global biodiversity framework. Available online at: https://www.cbd.int/doc/c/e6d3/cd1d/daf663719a03902a9b116c34/cop-15-l-25-en.pdf (Accessed 20th June, 2024).

Cimon-Morin, J., Darveau, M., and Poulin, M. J. B. C. (2013). Fostering synergies between ecosystem services and biodiversity in conservation planning: a review. *Biol. Conserv.* 166, 144–154. doi: 10.1016/j.biocon.2013.06.023

Farhadinia, M. S., Waldron, A., Kaszta, Ż., Eid, E., Hughes, A., Ambarlı, H., et al. (2022). Current trends suggest most Asian countries are unlikely to meet future biodiversity targets on protected areas. *Commun. Biol.* 5, 1221. doi: 10.1038/s42003-022-04061-w

Fastré, C., Possingham, H. P., Strubbe, D., and Matthysen, E. (2020). Identifying trade-offs between biodiversity conservation and ecosystem services delivery for land-use decisions. *Sci. Rep.* 10, 7971. doi: 10.1038/s41598-020-64668-z

Geldmann, J. (2023). Safeguarding biodiversity requires understanding how to manage protected areas cost effectively. *One Earth.* 6, 73–76. doi: 10.1016/j.oneear.2023.01.008

Hermoso, V., Morán-Ordóñez, A., Canessa, S., and Brotons, L. (2019). Realising the potential of natura 2000 to achieve EU conservation goals as 2020 approaches. *Sci. Rep.* 9, 16087. doi: 10.1038/s41598-019-52625-4

Hoffmann, S. (2022). Challenges and opportunities of area-based conservation in reaching biodiversity and sustainability goals. *Biodivers. Conserv.* 31, 325–352. doi: 10.1007/s10531-021-02340-2

Huang, P., Xu, W., Zang, Z., and Du, A. (2024). Integration approaches for overlapping protected areas in the Qinghai-Xizang Plateau, China. *Glob. Ecol. Conserv.* 51, e02925. doi: 10.1016/j.gecco.2024.e02925

IPBES (2019). *Global assessment report of the Intergovernmental Science-Policy Platform on biodiversity and Ecosystem Services*. Eds. E. S. Brondízio, J. Settele, S. Díaz and H. T. Ngo (Bonn, German: IPBES secretariat).

Li, B. V., and Pimm, S. L. (2020). How China expanded its protected areas to conserve biodiversity. *Curr. Biol.* 30, R1334–R1340. doi: 10.1016/j.cub.2020.09.025

Li, L., Tang, H., Lei, J., and Song, X. (2022). Spatial autocorrelation in land use type and ecosystem service value in Hainan Tropical Rain Forest National Park. *Ecol. Indic.* 137, 108727. doi: 10.1016/j.ecolind.2022.108727

Loos, J. (2021). Reconciling conservation and development in protected areas of the Global South. *Basic Appl. Ecol.* 54, 108–118. doi: 10.1016/j.baae.2021.04.005

Lu, Z., Wang, L., Meng, N., Dai, X., Zhu, J., Yang, Y., et al. (2022). Consideration of climate change impacts will improve the efficiency of protected areas on the Qinghai-Tibet Plateau. *Ecosyst. Health Sustain.* 8, 2117089. doi: 10.1080/20964129.2022.2117089

Moilanen, A., Pouzols, F., Meller, L., Veach, V., Arponen, A., Leppänen, J., et al. (2014). *User Manual. Zonation–Spatial conservation planning methods and software. Version 4* (Finland: C-BIG Conservation Biology Informatics Group, Department of Biosciences, University of Helsinki, Finland).

Neugarten, R. A., Moull, K., Martinez, N. A., Andriamaro, L., Bernard, C., Bonham, C., et al. (2020). Trends in protected area representation of biodiversity and ecosystem services in five tropical countries. *Ecosyst. Serv.* 42, 101078. doi: 10.1016/j.ecoser.2020.101078

Pereira, H. M., Rosa, I. M., Martins, I. S., Kim, H., Leadley, P., Popp, A., et al. (2020). Global trends in biodiversity and ecosystem services from 1900 to 2050. *Science*. 384 (6694), 458–465. doi: 0.1101/2020.04.14.031716

Poppenborg, P., and Koellner, T.J.L. (2013). Do attitudes toward ecosystem services determine agricultural land use practices? An analysis of farmers' decision-making in a South Korean watershed. *Land Use Policy.* 31, 422–429. doi: 10.1016/j.landusepol.2012.08.007

Santiago-Ramos, J., and Feria-Toribio, J. M. (2021). Assessing the effectiveness of protected areas against habitat fragmentation and loss: A long-term multi-scalar analysis in a Mediterranean region. *J. Nat. Conserv.* 64, 126072. doi: 10.1016/j.jnc.2021.126072

Sharp, R., Tallis, H., Ricketts, T., Guerry, A., Wood, S., Chaplin-Kramer, R., et al. (2019). *In VEST user's guide* (The Natural Capital Project, Stanford University, University of Minnesota. The Nature Conservancy, and World Wildlife Fund). Available at: https://naturalcapitalproject.stanford.edu/software/invest

UNEP (2021). Protected Planet Report (WCMC, U. I.U.C.N). Available online at: https://livereport.protectedplanet.net/ (Accessed 20th June, 2024).

Volenec, Z. M., and Dobson, A. P. (2020). Conservation value of small reserves. *Conserv. Biol.* 34, 66–79. doi: 10.1111/cobi.13308

Waldron, A., Adams, V., Allan, J., Arnell, A., Asner, G., Atkinson, S., et al. (2020). Protecting 30% of the planet for nature: costs, benefits and economic implications. *Campaign for Nature.* doi: 10.13140/RG.2.2.19950.64327

Waldron, A., Besancon, C., Watson, J., Adams, V., Sumaila, U., Garnett, S., et al. (2022). The costs of global protected-area expansion (Target 3 of the post-2020 Global biodiversity Framework) may fall more heavily on lower-income countries. *bioRxiv.* doi: 10.1101/2022.03.23.485429

Wang, L., Zheng, H., Chen, Y., Ouyang, Z., and Hu, X. (2022). Systematic review of ecosystem services flow measurement: main concepts, methods, applications and future directions. *Ecosyst. Serv.* 58, 101479. doi: 10.1016/j.ecoser.2022.101479

Wang, L., Zheng, H., Polasky, S., and Long, Y. (2021). Spatial priorities for biodiversity and ecosystem services considering theoretical decision-makers' attitudes to risk. *Environ. Res. Commun.* 3, 115007. doi: 10.1088/2515-7620/ac34c6

Watson, K. B., Galford, G. L., Sonter, L. J., and Ricketts, T. H. J. E. S. (2020). Conserving ecosystem services and biodiversity: measuring the trade-offs involved in splitting conservation budgets. *Ecosyst. Serv.* 42, 101063. doi: 10.1016/j.ecoser.2020.101063

Watts, M. E., Stewart, R. R., Martin, T. G., Klein, C. J., Carwardine, J., and Possingham, H. P. (2017). "Systematic conservation planning with Marxan," in *Learning Landscape Ecology: A Practical Guide to Concepts and Techniques*. Eds. S. E. Gergel and M. G. Turner (Springer, New York), 211–227.

Williams, B. A., Grantham, H. S., Watson, J. E. M., Alvarez, S. J., Simmonds, J. S., Rogéliz, C. A., et al. (2020). Minimising the loss of biodiversity and ecosystem services in an intact landscape under risk of rapid agricultural development. *Environ. Res. Lett.* 15, 014001. doi: 10.1088/1748-9326/ab5ff7

Xu, W., Li, X., Pimm, S. L., Hull, V., Zhang, J., Zhang, L., et al. (2016). The effectiveness of the zoning of China's protected areas. *Biol. Conserv.* 204, 231–236. doi: 10.1016/j.biocon.2016.10.028

Xu, W., Xiao, Y., Zhang, J., Yang, W., Zhang, L., Hull, V., et al. (2017). Strengthening protected areas for biodiversity and ecosystem services in China. *Proc. Natl. Acad. Sci. U. S. A.* 114, 1601–1606. doi: 10.1073/pnas.1620503114

Yang, F., Wu, R., Jin, T., Long, Y., Zhao, P., Yu, Q., et al. (2019). Efficiency of unlocking or locking existing protected areas for identifying complementary areas for biodiversity conservation. *Sci. Total Environ.* 694, 133771. doi: 10.1016/j.scitotenv.2019.133771

Yang, R., Cao, Y., Hou, S., Peng, Q., Wang, X., Wang, F., et al. (2020). Cost-effective priorities for the expansion of global terrestrial protected areas: setting post-2020 global and national targets. *Sci. Adv.* 6, eabc3436. doi: 10.1126/sciadv.abc3436

Zabala, A., Palomo, I., Múgica, M., and Montes, C. (2024). Challenges beyond reaching a 30% of area protection. *NPJ Biodivers.* 3, 9. doi: 10.1038/s44185-024-00041-x

Zafra-Calvo, N., and Geldmann, J. (2020). Protected areas to deliver biodiversity need management effectiveness and equity. *Glob. Ecol. Conserv.* 22, e01026. doi: 10.1016/j.gecco.2020.e01026

Zang, Z., Guo, Z., Fan, X., Han, M., Du, A., Xu, W., et al. (2022). Assessing the performance of the pilot national parks in China. *Ecol. Indic.* 145, 109699. doi: 10.1016/j.ecolind.2022.109699

Zeng, Y., Koh, L. P., and Wilcove, D. S. (2022). Gains in biodiversity conservation and ecosystem services from the expansion of the planet's protected areas. *Sci. Adv.* 8, eabl9885. doi: 10.1126/sciadv.abl9885

Zeng, Y., Senior, R. A., Crawford, C. L., and Wilcove, D. S. (2023). Gaps and weaknesses in the global protected area network for safeguarding at-risk species. *Sci. Adv.* 9, eadg0288. doi: 10.1126/sciadv.adg0288

Zhang, J., Xu, W., Kong, L., Hull, V., Xiao, Y., Xiao, Y., et al. (2018). Strengthening protected areas for giant panda habitat and ecosystem services. *Biol. Conserv.* 227, 1–8. doi: 10.1016/j.biocon.2018.08.016

Zhang, L., and Li, J. (2022). Identifying priority areas for biodiversity conservation based on Marxan and InVEST model. *Landsc. Ecol.* 37, 3043–3058. doi: 10.1007/s10980-022-01547-0

Zhang, L., Xu, W.-H., Ouyang, Z.-Y., and Zhu, C.-Q. (2014). Determination of priority nature conservation areas and human disturbances in the Yangtze River Basin, China. *J. Nat. Conserv.* 22, 326–336. doi: 10.1016/j.jnc.2014.02.007

Zhang, L., Zhiyun, O., Xiao, Y., Xu, W., Zheng, H., and Jiang, B. (2011). Priority areas for biodiversity conservation in Hainan Island: evaluation and systematic conservation planning. *J. Appl. Ecol.* 22, 2105–2112. Available at: https://www.cjae.net/CN/Y2011/V22/I08/2105

Zheng, H., Wang, L., Peng, W., Zhang, C., Li, C., Robinson, B. E., et al. (2019). Realizing the values of natural capital for inclusive, sustainable development: informing China's new ecological development strategy. *Proc. Natl. Acad. Sci. U. S. A.* 116, 8623–8628. doi: 10.1073/pnas.1819501116

Zheng, Z. M., Fu, B. J., and Feng, X. M. (2016). GIS-based analysis for hotspot identification of trade-off between ecosystem services: A case study in Yanhe Basin, China. *Chin. Geogr. Sci.* 26, 466–477. doi: 10.1007/s11769-016-0816-z