Title: Closing conservation gaps for Chinese freshwater fish in protected areas

Authors:

Jinnan Chen [1,2], Jingrui Sun[3,4], Yuan Yuan[1,2], Xingchen Liu [5], Jianshuo Qian [1,2], Liuyong Ding [1*], Dekui He [1,2]

Addresses:

1. Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, China

2. University of Chinese Academy of Sciences, Beijing 100049, China

3. Yunnan Key Laboratory of International Rivers and Transboundary Eco-security, Institute of International Rivers and Eco-security, Yunnan University, Kunming 650091, China

4. Ministry of Education Key Laboratory for Transboundary Eco-Security of Southwest China, Yunnan University, Kunming 650091, China

5. Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK

* Corresponding author

Email addresses:

Jinnan Chen: chen_jinnan@126.com

Jingrui Sun: jingrui.sun@ynu.edu.cn

Yuan Yuan: yuanyuan@ihb.ac.cn

Xingchen Liu: x.liu81@lancaster.ac.uk

Jianshuo Qian: qianjianshuo@ihb.ac.cn

Liuyong Ding: lyding@ihb.ac.cn

Dekui He: hedekui@ihb.ac.cn

Keywords

freshwater biodiversity; spatial prioritization; endemic species; conservation shortfalls; environmental management

Abstract

Protected areas (PAs) are critical for halting biodiversity loss, yet their representativeness in conserving freshwater fish, one of the most threatened vertebrate groups, remains under-assessed. In this study, we evaluated the representativeness of China's PA network for freshwater fish using a novel conservation indicator, the final conservation score *in situ* (FCSin), which integrates species occurrence within PAs, the proportion of species' distribution under protection, and ecological zone coverage. Our results revealed pronounced spatial and taxonomic disparities in conservation representativeness. Nationally, freshwater fish were underrepresented in the current PA system, with most species (n = 910–1080) assigned medium conservation priority ($25 \leq$ FCSin < 50). Approximately one-quarter (294–425 species) demonstrated high conservation priority (FCSin < 25), predominantly located in southwestern China and the lower Zangbo River, regions known for high endemism and data deficiency. Species of the endemic genus *Sinocyclocheilus* were identified as facing the most urgent conservation needs. In contrast, well-protected species (FCSin ≥ 75) were primarily distributed in the upper Yangtze River and Pearl River basins, where recent national policies, including the decade-long fishing ban, have contributed to improved freshwater protection. These findings highlight critical gaps in freshwater fish protection within specific regions of China's PA system and propose a spatially explicit, indicator-based framework for improving conservation prioritization. Our approach supports targeted ecological management and provides transferable methodology for freshwater biodiversity conservation, particularly in underrepresented and biologically diverse regions worldwide.

Introduction

Establishing protected areas (PAs) has become a foundational strategy to mitigate biodiversity loss and respond to the ongoing sixth mass extinction (Chapin III et al., 2000; Hill et al., 2015; Rodríguez-Rodríguez and Martínez-Vega, 2022; Watson et al., 2014). Evaluating the conservation status within these areas is essential for guiding targeted biodiversity protection and implementing effective conservation actions (Bhola et al., 2021; He and Wei, 2023). According to *Protected Planet* (UNEP-WCMC and IUCN, 2024), terrestrial and inland water PAs, along with other effective area-based conservation measures (OECMs), currently cover 17.51% of the global land area, while marine PAs and OECMs encompass 8.46% of oceanic areas (UNEP-WCMC and IUCN, 2024). Although existing protected areas have demonstrated considerable effectiveness in safeguarding biodiversity (Huang et al., 2024; Xin et al., 2024; Yang et al., 2020), most assessments have focused primarily on geographical coverage, with issues of sampling adequacy and ecological representativeness often overlooked (Dong et al., 2024; Tao et al., 2023). Therefore, a comprehensive evaluation of both the representativeness and functional effectiveness of PAs is crucial to inform scientifically grounded conservation planning and management.

Conservation biologists have increasingly undertaken integrative efforts to address these gaps (Dong et al., 2024). Early studies indicated that China’s nature reserves did not sufficiently protect critical ecological functions such as water and soil conservation, sand stabilization, and carbon sequestration (Gao et al., 2020; Xu et al., 2017). More recent work by Dong et al. (2024) incorporated species occurrence data from five taxonomic groups (reptiles, amphibians, mammals, birds, and plants) to assess irreplaceability and vulnerability across China's protected areas. These studies underscore the need to move beyond quantitative conservation targets and to evaluate ecological representativeness within key reserve systems (Dong et al., 2024; Shrestha et al., 2021).

However, most assessments to date have focused predominantly on terrestrial biodiversity, while aquatic taxa remain underrepresented in conservation research, particularly freshwater fish (Cao et al., 2024; Dong et al., 2024). China harbors roughly one-tenth of the world's freshwater fish species, highlighting its global significance for freshwater biodiversity conservation (Cao et al., 2024; Chen et al., 2023; He et al., 2020; Tao et al., 2023). Yet these species are increasingly threatened by multiple stressors, including water pollution, dam construction, invasive species, and climate change (Chen et al., 2023; Dudgeon 2024; Guo et al., 2024). Recent studies indicated that nearly one-quarter of Chinese freshwater fish are at significant risk of extinction, underscoring the urgency for targeted conservation strategies (Cao et al., 2024; Chen et al., 2023; Sayer et al., 2025).

While China’s existing PA network contributes to freshwater fish conservation, its ecological representativeness remains limited, and the biodiversity benefits provided by these areas have not been comprehensively assessed (Xu et al., 2019; Tao et al., 2023). Given conservation goals under the Kunming-Montreal Global Biodiversity Framework (e.g., protecting at least 30% of land by 2030 and potentially 50% by 2050; Hughes and Grumbine, 2023; Nicholson et al., 2024), there is an urgent need to evaluate and enhance the conservation performance of China's PAs. In this study, we integrated freshwater fish distribution data with China's protected area network to systematically assess the conservation representativeness of these PAs, with a focus on sampling adequacy, spatial coverage, and ecological representation. Our objectives were twofold: 1) to evaluate the current conservation status of freshwater fish in China and establish a representativeness ranking, and 2) to identify spatial conservation priority. This work advances our understanding of freshwater fish conservation and offers actionable guidance for refining biodiversity policy and strategically improving the protected area network.

Materials and Methods

Species occurrences, protected areas, and ecological zones

We compiled distribution records of Chinese freshwater fish primarily from field surveys, published research (He et al., 2020; Tao et al., 2023), and supplemented these with reputable online databases including FishBase (https://www.fishbase.org), GBIF (https://www.gbif.org/), and the Taiwan Fish Database (https://fishdb.sinica.edu.tw). Furthermore, we cross-validated occurrence data across these sources to ensure completeness. Finally, species scientific names were verified and standardized using Eschmeyer's Catalog of Fishes (Fricke et al., 2024). To ensure data quality, we applied the *clean_coordinates* function from the R package *CoordinateCleaner* to remove duplicated or erroneous geographic records (Zizka et al., 2019). The final dataset contained 32,203 distribution records representing 1,657 species across 19 orders, 61 families, and 351 genera (Figure 1). Extinction risk assessments followed the China Red List of Biodiversity (CRL) and the International Union for Conservation of Nature Red List. When discrepancies occurred, CRL classifications were given priority (IUCN 2023; Zhang and Cao, 2021).

Protected area (PA) data were obtained from the Protected Area Platform of China (PAPC, http://www.papc.cn), GeoServer (https://geoserver.travelxj.cn), Key Biodiversity Areas (KBAs, http://www.keybiodiversityareas.org), and China's Aquatic Germplasm Reserves (CAGRs, http://www.moa.gov.cn). Spatial data gaps were addressed by buffering or digitizing PA boundaries in accordance with official national guidelines and processed using R software. After removing duplicates, we compiled a final PA dataset comprising 4,104 entries, which were converted into raster format using the ‘Polygon to Raster tool’ in ArcMap 10.8 (Figure 1; ESRI 2016). Freshwater ecoregions within China were extracted from the global freshwater ecoregion map provided by Abell et al. (2008), enabling ecological representativeness analysis at the ecoregional scale.

Species distribution modelling

To support the conservation gap analysis, we used ensemble species distribution models (SDMs) constructed through multiple algorithms to predict freshwater fish distributions (Tao et al., 2023). Model inputs included species occurrence data, geographic variables (slope, altitude, flow, water area, and river length; Lehner and Grill, 2013), and bioclimatic variables. Bioclimatic variables were selected following collinearity checks and principal component analyses on 19 WorldClim variables (https://www.worldclim.org), retaining the top three principal components. Distributions were modeled in raster format using two spatial delineation strategies: (1) SDMs with basin-clipping (“loose” method), and (2) SDMs with point-buffering (“strict” method), consistent with established approaches (Tao et al., 2023). All SDM outputs for 1,657 freshwater fish species (~4 GB, 1-km resolution) are openly available via Zenodo (Chen et al., 2025).

Gap analysis and spatial mapping of protection deficits

We first compiled and cleaned over 32,000 occurrence records, then used ensemble SDMs to translate these points into continuous distribution maps. With these spatial layers in hand, we conducted an in-situ conservation gap analysis using the R package *GapAnalysis* (Carver et al., 2021), which included three components: the sampling representativeness score *in situ* (SRSin), the geographical representativeness score *in situ* (GRSin), and the ecological representativeness score *in situ* (ERSin). Specifically, SRSin represents the percentage of species occurrences within PAs relative to total occurrences; GRSin denotes the proportion of species distribution areas located within PAs; and ERSin quantifies the proportion of freshwater ecoregions (Abell et al., 2008) represented within protected areas. It serves as a biogeographical proxy for ecological representativeness, capturing the inclusion of major aquatic biogeographic units rather than directly measuring ecological heterogeneity, ecosystem processes, or species-level community structures. The final conservation score in situ (FCSin) was calculated as the average of these three metrics:

$$SRSin = N_{in}/N_T \qquad \text{Equation 1}$$

$$GRSin = A_{in}/A \qquad \text{Equation 2}$$

$$ERSin = E_{in}/E \qquad \text{Equation 3}$$

$$FCSin = (SRSin + GRSin + ERSin)/3 \qquad \text{Equation 4}$$

Where N_{in}, A_{in}, and E_{in} represent occurrences within PAs, area (km^2) of SDMs within PAs, and the number of freshwater ecoregions within PAs, respectively. N_{T}, A, and E denote the corresponding total values for each metric. We used non-parametric Kruskal–Wallis tests (via 'kruskal.test' function in the R package *stats*) to assess differences in representativeness across taxonomic groups, threatened status, and three components of FCSin. Conservation priorities were classified based on FCSin values into four categories: high priority (HP; FCSin < 25), medium priority (MP; 25 ≤ FCSin < 50), low priority (LP; 50 ≤ FCSin < 75), and sufficiently conserved (SC; FCSin ≥ 75) (Carver et al., 2021). Spatial conservation priorities were visualized by overlaying species distribution outputs with the spatial framework of China's small watershed units (Chen et al., 2023). Spatial autocorrelation in conservation scores was assessed using Moran's I test via the *moran.test* function in the R package *spdep* (Bivand et al., 2017). All spatial and statistical analyses were performed in ArcMap 10.8 and R version 4.4.2 (ESRI 2016; R Core Team 2024).

Results

Conservation representativeness of Chinese freshwater fish

Our analysis revealed that the overall conservation status of Chinese freshwater fish, as measured by the Final Conservation Score *in situ* (FCSin), was moderate. The mean ± standard deviation values were 38.16 ± 16.6 and 35.22 ± 22.53 under the loose and strict methods, respectively (Figure 2a and b; Appendix Table S1). Most fish species were categorized as medium priority (MP) (loose method: 910 species; strict method: 1080 species), followed by high priority (HP) (425, 294), low priority (LP) (222, 235), and sufficiently conserved (SC) (100, 48). Notably, species composition varied significantly among conservation levels. The genus *Sinocyclocheilus* included the largest number of HP species, while the genus *Triplophysa* dominated both MP and LP categories. Species from *Schizopygopsis* and *Schizothorax* were most prevalent in the SC group (Appendix Table S1).

The three components of FCSin demonstrated differing degrees of conservation representativeness. Overall, freshwater fish in China showed particularly low levels of sampling and geographical representativeness, with average SRSin values of 21.75 ± 30.77 (loose) and 21.77 ± 30.77 (strict), and GRSin values of 9.07 ± 8.59 and 10.05 ± 11.94, respectively. In contrast, ecological representativeness (ERSin) was comparatively high (83.66 ± 28.39, 73.85 ± 40.45), suggesting relatively comprehensive ecological coverage (Figure 2a-b; Appendix Table S1).

Additionally, FCSin values declined progressively with increasing extinction risk, indicating a clear negative correlation ($p < 0.05$) between conservation representativeness and extinction vulnerability (Figure 2c-d; Appendix Table S1).

Taxonomic variations in conservation representativeness

We also observed significant variation ($p < 0.05$) in conservation representativeness among taxonomic groups (Figure 3; Appendix Figure S1). At the order level, FCSin scores ranged from 0 to 61.45 ± 11.71, and at the family level from 0 to 62.45 (Figure 3a-b; Appendix Figure S1a-b). Carangiformes (score: 61.45) and Tincidae (62.45) demonstrated the highest conservation representativeness at the order and family levels, respectively (Appendix Table S1). Conversely, Osteoglossiformes and three families (Nandidae, Notopteridae, Horabagridae) showed no evidence of effective conservation (FCSin = 0). Sampling representativeness (SRSin) ranged from 0 to 66.67 across both taxonomic levels (Figure 3c-d; Appendix Figure S1c-d). Carangiformes had the highest sampling representativeness (66.67 ± 47.14), while Cichliformes and Osteoglossiformes had none (SRSin = 0). At the family level, Cynoglossidae and Tincidae showed strong evidence of sampling representativeness (66.67), while 13 families, including Akysidae, Ambassidae, Badidae, and Belonidae, exhibited no representation (Appendix Table S1).

Geographical representativeness (GRSin) values ranged from 0 to 21.6 ± 6.5 (order) and from 0 to 21.65 ± 7.02 (family) (Figure 3e-f; Appendix Figure S1e-f). Acipenseriformes and Acipenseridae showed the highest levels of GRSin, while Osteoglossiformes and several families (Pangasiidae, Notopteridae, Nandidae, Horabagridae, etc.) scored zero. Ecological representativeness (ERSin) ranged from 0 to 100 at both levels (Figure 3g-h; Appendix Figure S1g-h). Gadiformes, Esociformes, Carangiformes demonstrated full ecological representativeness (ERSin = 100), while Osteoglossiformes again showed none. At the family level, approximately ten families, including Acipenseridae, Catostomidae, Cranoglanididae, and Cynoglossidae, achieved full ecological representativeness, whereas Horabagridae, Nandidae, and Notopteridae had no representation (ERSin = 0; Appendix Table S1).

Geographic disparities in protection among watersheds

Geographical distributions of Chinese freshwater fish varied markedly ($p < 0.05$) by conservation priority under both loose and strict assessment methods (Figure 4). High-priority species ranged from 0 to 66 (loose) and 0 to 67 (strict) per sub-basin, with concentrations in southwestern China and the lower Yarlung Zangbo River (Figure 4a-b). Medium-priority species ranged from 0 to 167 (loose) and 0 to 159 (strict), primarily distributed across southern China (Figure 4c-d). Low-priority (LP) species ranged from 0 to 25 (loose) and 0 to 22 (strict), concentrated in the Three-River Source region and the Liujiang River (Figure 4e-f). Sufficiently conserved (SC) species were fewer in number (0 to 11, loose; 0 to 13, strict) and mainly located in the upper Yangtze River and Pearl River basins (Figure 4g-h).

Discussion

This study presents a comprehensive evaluation of the *in situ* conservation status of freshwater fish in China, combining species distribution data, protected area coverage, and freshwater ecological zones. Our findings indicated that the overall conservation status, measured by the final conservation score *in situ*, was insufficient. Conservation representativeness varies significantly among taxonomic groups and geographic regions, highlighting specific gaps that require targeted interventions. While China's existing PA network supports freshwater fish conservation, it falls short of meeting the ecological needs of many species, particularly those with limited distributions or high extinction risks.

Rethinking protected area representativeness for Chinese freshwater fish

Our framework, which incorporates sampling, geographical, and ecological representativeness, reveals that only 2–6% of Chinese freshwater fish species are fully protected under the FCSin system, a notably lower figure than those reported in previous studies (Tao et al., 2023). For example, Li et al. (2022) identified 329 freshwater fish species under protection, including 284 high-risk species, while Tao et al. (2023) estimated that 16-23% of Chinese freshwater fish were effectively protected within China's PA network. These discrepancies are likely attributable to differences in the methodologies used to assess protection effectiveness (Dagosta et al., 2021; Miqueleiz et al., 2023; Raghavan et al., 2016; Tao et al., 2023). Unlike approaches that rely solely on the spatial overlap between species distributions and PAs, our FCSin-based method provides a more integrated and robust measure of protection by equally weighting three dimensions of representativeness (Carver et al., 2021; González-Orozco et al., 2021). Furthermore, our analysis identified approximately one-fifth of freshwater fish species (334) as not being covered by any existing PA, reaffirming similar conclusions in earlier assessments (Tao et al., 2023). Collectively, these results highlight the current network's limited capacity to safeguard freshwater biodiversity and emphasize the need for scientifically informed PA design and optimization (Li et al., 2024).

We also observed significant taxonomic variation in FCSin and its three components (Figure 2-3; Appendix Table S1). For example, species within Carangiformes and the family Tincidae exhibited the highest FCSin values, reflecting strong conservation representativeness. This is likely due to substantial spatial overlap between their distributions and existing PAs in China (Chen 1998; Tao et al., 2023; Xing et al., 2016; Zhu et al., 2023). Notably, the upper Yangtze River and Pearl River basins emerged as hotspots of high FCSin scores and dense protected area coverage, suggesting the positive impact of recent national conservation policies, such as China's decade-long fishing ban. These regions form a critical foundation for effective freshwater biodiversity protection (Chen 1998; Tao et al., 2023; Zhu et al., 2023). In contrast, taxa such as Osteoglossiformes and families including Nandidae, Notopteridae, and Horabagridae show the lowest FCSin scores (often zero) indicating critical conservation gaps (Appendix Table S1). These groups also had the lowest values in ERSin, GRSin, and SRSin values, suggesting a multidimensional conservation deficit. These species were mainly distributed in southern Tibet (Xizang) and southwestern China, areas known to be ecologically vulnerable and underrepresented in the national PA network (He et al., 2020; He et al., 2024; Ng 2010a; Ng 2010b; Ng 2020; Tao et al., 2023). The observed taxonomic heterogeneity in conservation representativeness has direct implications for conservation prioritization. Given the high proportion of species classified at medium or high priority (MP and HP), conservation strategies should be tailored to address the ecological and spatial needs of different taxonomic groups (Appendix Table S1).

While each of SRSin, GRSin, and ERSin captures distinct conservation attributes, their integration into the final conservation in situ score (FCSin) serves to represent the multidimensional nature of species' protection status within protected areas (Carver et al., 2021; Rouichi et al., 2025). The use of FCSin is methodologically aligned with the framework proposed by Carver et al. (2021), where averaging multiple normalized dimensions allows for comparative and comprehensive prioritization. Nevertheless, we recognize that a composite index like FCSin inevitably simplifies complex ecological realities (Carver et al., 2021; Rouichi et al., 2025). For this reason, we present the individual components separately in our results (Figures 2, 3) to allow for transparent examination of which dimensions are driving conservation gaps. Its utility lies in balancing interpretability with methodological rigor, particularly in data-limited yet high-diversity contexts such as freshwater ecosystems in China.

Identifying priority areas and implementation barriers

Our spatial analysis revealed strong heterogeneity in fish species distributions across conservation priority categories (Figure 4; Appendix Table S1). For example, species categorized at low-priority (LP) are predominantly found in the Three-River Source and Liujiang River regions, whereas high-priority (HP) species are largely concentrated in southwestern China and the lower Yarlung Zangbo River, areas that remain underrepresented in the current PA network (Figure 1, Figure 4; Appendix Table S1). One critical barrier to effective protection in these areas is political complexity, which poses substantial challenges to the establishment of national-level PAs in southern Xizang, complicating conservation efforts in this ecologically important but administratively sensitive region (Liang 2020; Lu 2012). Domestically, overlapping administrative jurisdictions further hinder conservation efforts (Schaaf and Rodrigues, 2017; Zheng and Cao, 2015). Inter-departmental competition, inconsistent policy implementation, and conflicting mandates can significantly impair PA governance, ultimately reducing their ecological effectiveness (Papageorgiou and Vogiatzakis, 2006; Xu et al., 2014; Xu et al., 2019; Zhang et al., 2017).

A second major challenge involves the tension between local economic development and PA expansion. In many regions, local governments perceive nature reserves as obstacles to economic growth, often favoring more flexible or symbolic forms of protection outside PA core zones (Wu et al., 2020; Xu et al., 2012). Nonetheless, China's national park system and aquatic germplasm conservation zones have played a vital role in safeguarding freshwater fish biodiversity (Figure 1 and 4; Tao et al., 2023; Xing et al., 2016). To date, over 500 national aquatic germplasm conservation areas have been established, covering 46.45% of inland waters and targeting the protection of approximately 320 fish species (Guo et al., 2019; Huang et al., 2021; Sheng et al., 2019).

Another important limitation lies in the spatial bias of the species occurrence data. Although the database comprises over 32,000 records across 1,657 freshwater fish species, the distribution is uneven, with disproportionately higher sampling intensity in southwestern China (Figure 1). As a result, species richness or conservation priority maps (Figure 4) may underestimate diversity and protection gaps in poorly sampled regions (Chen et al., 2023; Tao et al., 2023; Xing et al., 2016). While standardized modeling workflows and spatial smoothing strategies (e.g., basin-clipping and point-buffering) help mitigate some bias, they cannot fully compensate for the lack of data in underrepresented areas. We therefore recommend interpreting our results with caution in data-poor regions and emphasize the urgent need for targeted field sampling to support more equitable and robust conservation planning.

Finally, the spatial and temporal distribution patterns of fish biodiversity further explain the clustering of HP species in southwestern China, a region renowned for exceptionally high species richness (Cao et al., 2024; Chen et al., 2023; He et al., 2020; Knag et al., 2014; Tao et al., 2023; Xing et al., 2016). The pronounced regional variation in FCSin scores underscores the need to move beyond a one-size-fits-all approach and adopt region-specific, intensive conservation strategies.

Strategic solutions to address conservation gaps

To address the conservation gaps identified in this study (Figures 2-4), we propose the following strategies:

1. Improve connectivity across the protected areas network. Enhance the connectivity of existing protected areas to support species migration and genetic exchange, ensuring resilience under increasing anthropogenic pressures (Xu et al., 2024; Yang et al., 2024; Zeng et al., 2023). Addressing spatial mismatches between current protected areas and key biodiversity areas should be a high priority (Xu et al., 2024).

2. Mitigate human impacts in biodiversity hotspots. Implement targeted measures to alleviate pressure in regions with intensive human activity, particularly in data-deficient biodiversity hotspots, thereby improving the functionality and effectiveness of protected areas (Saunders et al., 2002; Su et al., 2021).

3. Leverage advanced technologies for adaptive management. Leverage technologies such as remote sensing and GIS to improve planning, monitoring, and adaptive management of protected areas (Duan et al., 2020; Rose et al., 2015; Wang et al., 2020). Remote sensing data can provide critical insights into landscape dynamics and guide the spatial configuration of protected areas to better align with species distributions and ecosystem processes (Wegmann et al., 2014).

Conclusion

This study underscores critical gaps in conservation representativeness for Chinese freshwater fish within the current protected area network. Our findings highlighted substantial variability in conservation representativeness across threat levels, taxonomic groups, and geographic regions. While most freshwater fish species in China were identified as medium priority, approximately one-quarter fell into the high-priority category, with species from the genus *Sinocyclocheilus* particularly prominent. Geographically, critical conservation gaps were predominantly concentrated in southwestern China, underscoring the importance of prioritizing this region in future research and protection efforts. Beyond clarifying the conservation status and spatial priorities for Chinese freshwater fish, this study provides robust, indicator-based evidence to inform the strategic planning and optimization of protected areas. Ultimately, our results offer valuable insights for strengthening biodiversity conservation policies and practices both in China and globally.

Data Availability Statement

The data and R code supporting this study are openly available on Zenodo at https://doi.org/10.5281/zenodo.15644992 and https://doi.org/10.5281/zenodo.15515032.

Ethics and permit approval statement

No ethical approval or research permits were required for this study.

Acknowledgements

We sincerely thank Professor Juan Tao for valuable comments and suggestions on an earlier version of this manuscript. This research was financially supported by the National Key Research and Development Program of China (Grant No. 2021YFC3200103), the Second Tibetan Plateau Scientific Expedition and Research Program (Grant No. 2024QZKK0200), the National Natural Science Foundation of China (Grant No. 42401074), and the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDB31010302_11).

Conflict of interest statement

The authors declare that they have no competing interests.

Authors' contribution

DH conceived and supervised the project. JC, LD, YY, and DH designed the research strategy and methodology. JC, XL, and LD conducted the data collection and analysis. JC and JS drafted the original manuscript. LD, JQ and JS critically revised the manuscript. All authors contributed to the interpretation of results and provided input on successive versions of the manuscript.

References

Abell, R., Thieme, M. L., Revenga, C., et al., 2008. "Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation." *BioScience*, 58: 403-414. https://doi.org/10.1641/B580507.

Bhola, N., Klimmek, H., Kingston, N., et al., 2021. "Perspectives on area-based conservation and its meaning for future biodiversity policy." *Conservation Biology*, 35:168-178. https://doi.org/10.1111/cobi.13509.

Bivand, R., Altman, M., Anselin, L., et al., 2017. "Package 'spdep'." *Spatial dependence: Weighting schemes, statistics, R package version*, 1-1.

Cao, L., Shao, W. H., Yi, W. J., et al., 2024. "A review of conservation status of freshwater fish diversity in China." *Journal of Fish Biology*, 104: 345-364. https://doi.org/10.1111/jfb.15606.

Carver, D., Sosa, C. C., Khoury, C. K., et al., 2021. "GapAnalysis: an R package to calculate conservation indicators using spatial information." *Ecography*, 44: 1000-1009. https://doi.org/10.1111/ecog.05430.

Chapin III, F. S., Zavaleta, E. S., Eviner, V. T., et al., 2000. "Consequences of changing biodiversity." *Nature*, 405: 234-242. https://doi.org/10.1038/35012241.

Chen J, Ding, C., He, D., et al. 2023. "Assessing the conservation status of Chinese freshwater fish using deep learning." *Reviews in Fish Biology and Fisheries* 33:1505-1521. https://doi.org/10.1007/s11160-023-09792-5.

Chen, J., Ding, L., & He, D. 2025. "1-km Resolution Species Distribution Models for 1,657 Chinese Freshwater Fish Species [Data set]." *Zenodo*. https://doi.org/10.5281/zenodo.15644992.

Chen, Y.Y. 1998. "Fauna Sinica, Osteichthyes, Cypriniformes II, Cyprinidae." Science Press, Beijing, 531 pp [in Chinese]

Dagosta, F. C., de Pinna, M., Peres, C. A., & Tagliacollo, V. A. 2021. "Existing protected areas provide a poor safety-net for threatened Amazonian fish species." *Aquatic Conservation: Marine and Freshwater Ecosystems*, 31: 1167-1189. https://doi.org/10.1002/aqc.3461.

Dong, X., Gong, J., Zhang, W., et al., 2024. "Importance of including Key Biodiversity Areas in China's conservation area-based network." *Biological Conservation*, 296: 110676. https://doi.org/10.1016/j.biocon.2024.110676.

Duan, P., Wang, Y., & Yin, P. 2020. "Remote sensing applications in monitoring of protected areas: A bibliometric analysis." *Remote sensing*, 12: 772. https://doi.org/10.3390/rs12050772.

Dudgeon, D. 2024. "Prospects for conserving freshwater fish biodiversity in the Anthropocene: A view from Southern China." *Integrative Conservation*. https://doi.org/10.1002/inc3.79.

ESRI. 2016. ArcGis Desktop: Release 10.4. Redlands: Environmental Systems Research Institute.

Fricke R, Eschmeyer WN, der Laan VR. 2024. Eschmeyer's Catalog of Fishes: Genera, Species, References. http://researcharchive.calacademy.org/research/ichthyology/catalog/fishcatmain.asp. (accessed April 02 2024).

Gao, J., Wang, Y., Zou, C., et al., 2020. "China's ecological conservation redline: A solution for future nature conservation." *Ambio*, 49: 1519-1529. https://doi.org/10.1007/s13280-019-01307-6.

González-Orozco, C. E., Sosa, C. C., Thornhill, A. H., & Laffan, S. W. 2021. "Phylogenetic diversity and conservation of crop wild relatives in Colombia." *Evolutionary Applications*, 14: 2603-2617. https://doi.org/10.1111/eva.13295.

Guo, X., Lin, Q., Zheng, X., et al., 2024. "Protect native fish in China’s Yellow River." *Science*, 383: 598-598. https://doi.org/10.1126/science.adn7432.

Guo, Z. L., Zhang, M. Y., Cui, L. J., et al., 2019. "Establishment and expansion of national aquatic germplasm reserves in China." *Journal of Hydroecology*, 40: 112-118. https://doi.org/10.15928/j.1674-3075.2019.05.017.

He D., Chen J., Ding L., et al., 2024. "The status and distribution pattern of fish diversity in the Yarlung Tsangpo River." *Biodiversity Science*, https://doi.org/10.17520/biods.2024143.

He D., Sui X., Sun H., et al., 2020. "Diversity, pattern and ecological drivers of freshwater fish in China and adjacent areas." *Reviews in Fish Biology and Fisheries*, 30:387–404. https://doi.org/10.1007/s11160-020-09600-4.

He, X., & Wei, H. 2023. "Biodiversity conservation and ecological value of protected areas: A review of current situation and future prospects." *Frontiers in Ecology and Evolution*, 11: 1261265. https://doi.org/10.3389/fevo.2023.1261265.

Hill, R., Miller, C., Newell, B., Dunlop, M., & Gordon, I. J. 2015. "Why biodiversity declines as protected areas increase: the effect of the power of governance regimes on sustainable landscapes." *Sustainability Science*, 10: 357-369. https://doi.org/10.1007/s11625-015-0288-6.

Huang, G., Ping, X., Xu, W., et al., 2021. "Wildlife conservation and management in China: achievements, challenges and perspectives." *National Science Review*, 8: nwab042. https://doi.org/10.1093/nsr/nwab042.

Huang, P., Xu, W., Zang, Z., et al., 2024. "Integration approaches for overlapping protected areas in the Qinghai-Xizang Plateau, China." Global Ecology and Conservation, 51, e02925. https://doi.org/10.1016/j.gecco.2024.e02925.

Hughes, A. C., & Grumbine, R. E. 2023. "The Kunming-Montreal Global Biodiversity Framework: what it does and does not do, and how to improve it." *Frontiers in Environmental Science*, 11: 1281536. https://doi.org/10.3389/fenvs.2023.1281536.

IUCN. 2023. IUCN, International Union for Conservation of Nature. https://www.iucn.org (accessed on December 11 2023).

Kang, B., Deng, J., Wu, Y., et al., 2014. "Mapping C hina's freshwater fishes: Diversity and biogeography." *Fish and Fisheries*, 15: 209-230. https://doi.org/10.1111/faf.12011.

Lehner B, Grill G. 2013. "Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems." *Hydrological Processes*. 27:2171–2186. https://doi.org/10.1002/hyp.9740.

Li, H., Tan, L., Li, X., & Cai, Q. 2024. "Aquatic protected area system in the Qinghai–Tibet Plateau: establishment, challenges and prospects." *Frontiers in Ecology and Evolution*, 12: 1204494. https://doi.org/10.3389/fevo.2024.1204494.

Li, H. R. 2022. "Research on the optimization of the aquatic protected area system in China." (Doctor). Institute of Hydrobiology, Chinese Academy of Sciences.

Liang, Q. 2020. "Sovereignty of Southern Tibet from the Perspective of International Law." (Master). Shandong University.

Lu, G. 2012. "Research on the International Law of the Belonging Issue in Southern Tibet and Exploration of Solutions." (Master). Shanghai International Studies University.

Miqueleiz, I., Ariño, A. H., & Miranda, R. 2023. "Spatial priorities for freshwater fish conservation in relation to protected areas." *Aquatic Conservation: Marine and Freshwater Ecosystems*, 33: 1028-1038. https://doi.org/10.1002/aqc.4000.

Ng, H.H. 2010a. Neotropius atherinoides. The IUCN Red List of Threatened Species 2010: e.T166637A6252491. https://dx.doi.org/10.2305/IUCN.UK.2010-4.RLTS.T166637A6252491.en. Accessed on 12 December 2024.

Ng, H.H. 2010b. Nandus nandus. The IUCN Red List of Threatened Species 2010: e.T166429A6207296. https://dx.doi.org/10.2305/IUCN.UK.2010-4.RLTS.T166429A6207296.en. Accessed on 12 December 2024.

Ng, H.H. 2020. Notopterus notopterus. The IUCN Red List of Threatened Species 2020: e.T166433A60584003. https://dx.doi.org/10.2305/IUCN.UK.2020-1.RLTS.T166433A60584003.en. Accessed on 12 December 2024.

Nicholson, E., Andrade, A., Brooks, T. M., et al., 2024. "Roles of the Red List of Ecosystems in the Kunming-Montreal Global Biodiversity Framework." *Nature Ecology & Evolution*, 8: 614-621. https://doi.org/10.1038/s41559-023-02320-5.

Papageorgiou, K., & Vogiatzakis, I. N. 2006. "Nature protection in Greece: an appraisal of the factors shaping integrative conservation and policy effectiveness." *Environmental science & policy*, 9: 476-486. https://doi.org/10.1016/j.envsci.2006.03.003.

Premate, E., Zagmajster, M., & Fišer, C. 2024. "Evaluating the overlap of surface protected areas with different facets of groundwater biodiversity: Glass half empty or half full?" *Biological Conservation*, 289: 110392. https://doi.org/10.1016/j.biocon.2023.110392.

R Core Team. 2024. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Raghavan, R., Das, S., Nameer, P. O., Bijukumar, A., & Dahanukar, N. 2016. "Protected areas and imperilled endemic freshwater biodiversity in the Western Ghats Hotspot." *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26: 78-90. https://doi.org/10.1002/aqc.2653.

Rodríguez-Rodríguez, D., & Martínez-Vega, J. 2022. "Effectiveness of Protected Areas in Conserving Biodiversity." A Worldwide Review. Cham, Switzerland: Springer.

Rose, R. A., Byler, D., Eastman, J. R., et al., 2015. "Ten ways remote sensing can contribute to conservation." *Conservation Biology*, 29: 350-359. https://doi.org/10.1111/cobi.12397.

Rouichi, S., Ghanem, M. E., & Amri, M. 2025. "In-situ and ex-situ conservation priorities and distribution of lentil wild relatives under climate change: A modelling approach." *Journal of Applied Ecology*, 62(2): 414-428. https://doi.org/10.1111/1365-2664.14842.

Saunders, D. L., Meeuwig, J. J., & Vincent, A. C. 2002. "Freshwater protected areas: strategies for conservation." *Conservation biology*, 16: 30-41. https://doi.org/10.1046/j.1523-1739.2002.99562.x.

Sayer, C. A., Fernando, E., Jimenez, R. R., et al., 2025. "One-quarter of freshwater fauna threatened with extinction." *Nature*, 1-8. https://doi.org/10.1038/s41586-024-08375-z.

Schaaf, T., & Rodrigues, D. C. 2017. "Managing MIDAs: Harmonising the Management of Multi-Internationally Designated Areas--Ramsar Sites, World Heritage Sites, Biosphere Reserves and UNESCO Global Geoparks." *Mountain Research and Development*, 37: 384-385.

Sheng, Q., Ru, H., Li, Y., & Ni, Z. 2019. "The distribution pattern of national aquatic germplasm reserves in China." *Journal of Fisheries of China*, 43: 62–80. https://doi.org/10.11964/jfc.20171211092.

Shrestha, N., Xu, X., Meng, J., & Wang, Z. 2021. "Vulnerabilities of protected lands in the face of climate and human footprint changes." *Nature Communications*, 12: 1632. https://doi.org/10.1038/s41467-021-21914-w.

Su, G., Logez, M., Xu, J., et al., 2021. "Human impacts on global freshwater fish biodiversity." *Science*, 371: 835-838. https://doi.org/10.1126/science.abd3369.

Tao J, Ding, C., Chen, J., et al., 2023. "Boosting freshwater fish conservation with high-resolution distribution mapping across a large territory." *Conservation Biology*, 37: e14036. https://doi.org/10.1111/cobi.14036.

UNEP-WCMC and IUCN. 2024. Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM) [Online], September 2024, Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net.

Watson, J. E., Dudley, N., Segan, D. B., & Hockings, M. 2014. "The performance and potential of protected areas." *Nature*, 515: 67-73. https://doi.org/10.1038/nature13947.

Wang, Y., Lu, Z., Sheng, Y., & Zhou, Y. 2020. "Remote sensing applications in monitoring of protected areas." *Remote Sensing*, 12: 1370. https://doi.org/10.3390/rs12091370.

Wegmann, M., Santini, L., Leutner, B., et al., 2014. "Role of African protected areas in maintaining connectivity for large mammals." *Philosophical Transactions of the Royal Society B: Biological Sciences*, 369: 20130193. https://doi.org/10.1098/rstb.2013.0193.

Wu, R., Hua, C., Yu, G., et al., 2020. "Assessing protected area overlaps and performance to attain China's new national park system." *Biological Conservation*, 241: 108382. https://doi.org/10.1016/j.biocon.2019.108382.

Xin, Y., Yang, Z., Du, Y., et al., 2024. "Vulnerability of protected areas to future climate change, land use modification, and biological invasions in China." *Ecological Applications*, 34: e2831. https://doi.org/10.1002/eap.2831.

Xing Y., Zhang C., Fan E., Zhao Y. 2016. "Freshwater fishes of China: species richness, endemism, threatened species and conservation." *Diversity and Distributions*, 22:358–370. https://doi.org/10.1111/ddi.12399.

Xu, D., Peng, J., Dong, J., et al., 2024. "Expanding China’s protected areas network to enhance resilience of climate connectivity." *Science Bulletin*. https://doi.org/10.1016/j.scib.2024.04.036.

Xu, J., Sun, G., & Liu, Y. 2014. "Diversity and complexity in the forms and functions of protected areas in China." *Journal of International Wildlife Law & Policy*, 17: 102-114. https://doi.org/10.1080/13880292.2014.953378.

Xu, W., Pimm, S. L., Du, A., et al., 2019. "Transforming protected area management in China." *Trends in Ecology & Evolution*, 34: 762-766. https://doi.org/ 10.1016/j.tree.2019.05.009.

Xu, W., Xiao, Y., Zhang, J., et al., 2017. "Strengthening protected areas for biodiversity and ecosystem services in China." *Proceedings of the National Academy of Sciences*, 114: 1601-1606. https://doi.org/10.1073/pnas.162050311.

Yang, X., Gu, T., & Wang, S. 2024. "Effectiveness of nature reserves in China: Human footprint and ecosystem services perspective." *Applied Geography*, 171: 103359. https://doi.org/10.1016/j.apgeog.2024.103359.

Yang, R., Cao, Y., Hou, S., et al., 2020. "Cost-effective priorities for the expansion of global terrestrial protected areas: Setting post-2020 global and national targets." *Science Advances*, 6: eabc3436. https://doi.org/10.1126/sciadv.abc34.

Zeng, W., Tang, H., Liang, X., et al., 2023. "Using ecological security pattern to identify priority protected areas: A case study in the Wuhan Metropolitan Area, China." Ecological Indicators, 148, 110121. https://doi.org/10.1016/j.ecolind.2023.110121.

Zhang E, Cao W. 2021. "China Biodiversity Red List." Science Press.

Zhang, L., Luo, Z., Mallon, D., Li, C., & Jiang, Z. 2017. "Biodiversity conservation status in China's growing protected areas." *Biological conservation*, 210: 89-100. https://doi.org/10.1016/j.biocon.2016.05.005.

Zheng, H., & Cao, S. 2015. "Threats to China’s biodiversity by contradictions policy." *Ambio*, 44: 23-33. https://doi.org/10.1007/s13280-014-0526-7.

Zhu, R., Sun, H. H., Ji, S. H., et al., 2023. "First wild record of tench, Tinca tinca (Linnaeus, 1758) in Tibet, China." *BioInvasions Records*, 12: 292-297. https://doi.org/10.3391/bir.2023.12.1.25.

Zizka, A., Silvestro, D., Andermann, T., et al., 2019. "CoordinateCleaner: Standardized cleaning of occurrence records from biological collection databases." *Methods in Ecology and Evolution*, 10: 744-751. https://doi.org/10.1111/2041-210X.13152.

Figure Legends

Fig. 1 Geographic distribution of freshwater fish occurrences and protected areas across China.

Fig. 2 Boxplots illustrating the components of the final *in situ* conservation score (FCSin) and species threat levels under two prioritization strategies: loose (orange) and strict (red). (a-b) Boxplots of FCSin components across strategies: sampling representativeness (SRSin), geographical representativeness (GRSin), and ecological representativeness (ERSin). (c-d) Boxplots of species classified by IUCN threat categories under different strategies: EX (Extinct), RE (Regionally Extinct), CR (Critically Endangered), EN (Endangered), VU (Vulnerable), NT (Near Threatened), and LC (Least Concern).

Fig. 3 Boxplots of FCSin components by taxonomic order under loose (orange) and strict (red) strategies. (a-b) FCSin across orders; (c-d) SRSin across orders; (e-f) GRSin across orders; (g-h) ERSin across orders. Abbreviations as in Figure 2.

Fig. 4 Spatial patterns of species richness across conservation priority categories under two prioritization strategies. (a-b) High-priority areas; (c-d) Medium-priority areas; (e-f) Low-priority areas; (g-h) Areas considered sufficiently conserved. Abbreviations as in Figure 2.

Figures

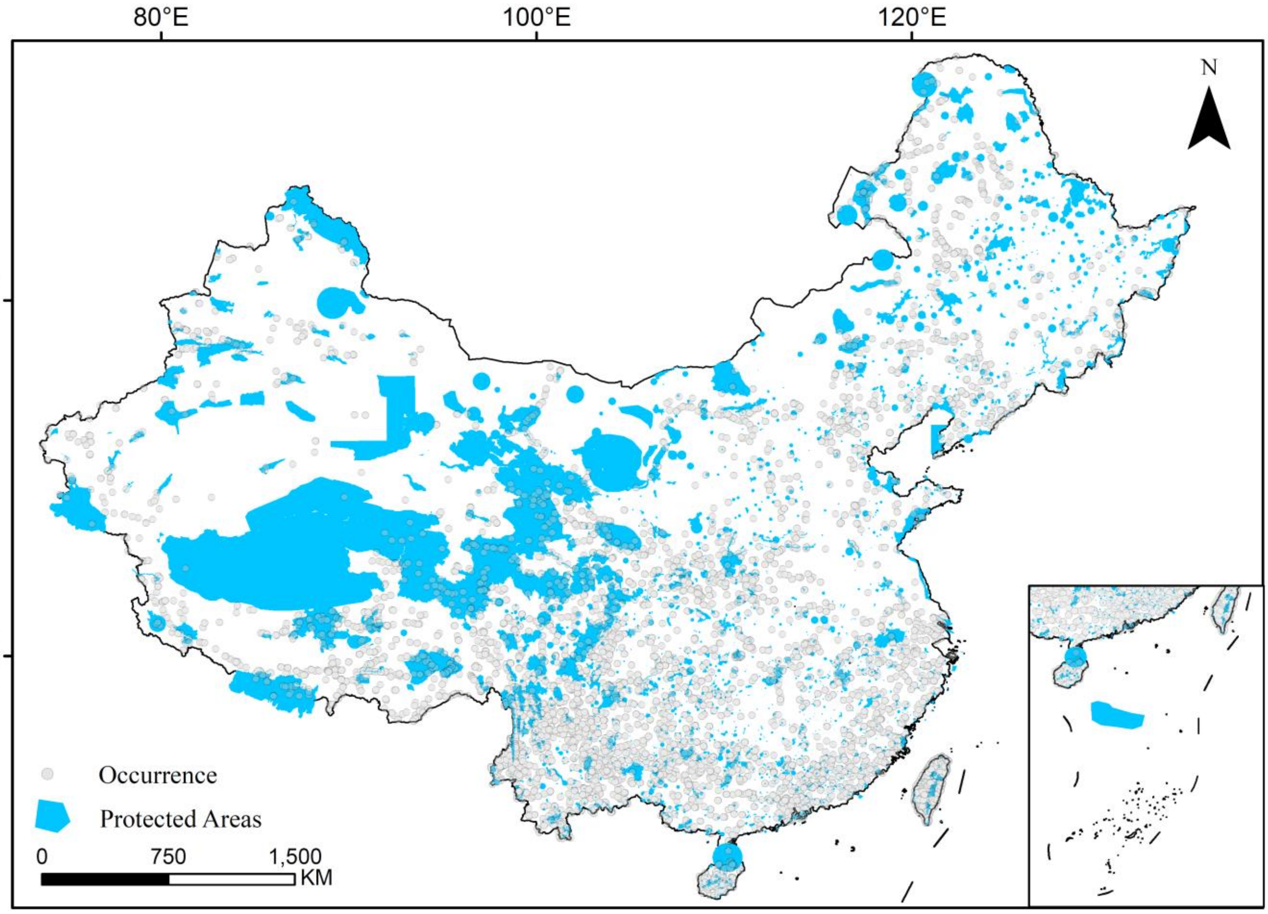

Fig. 1

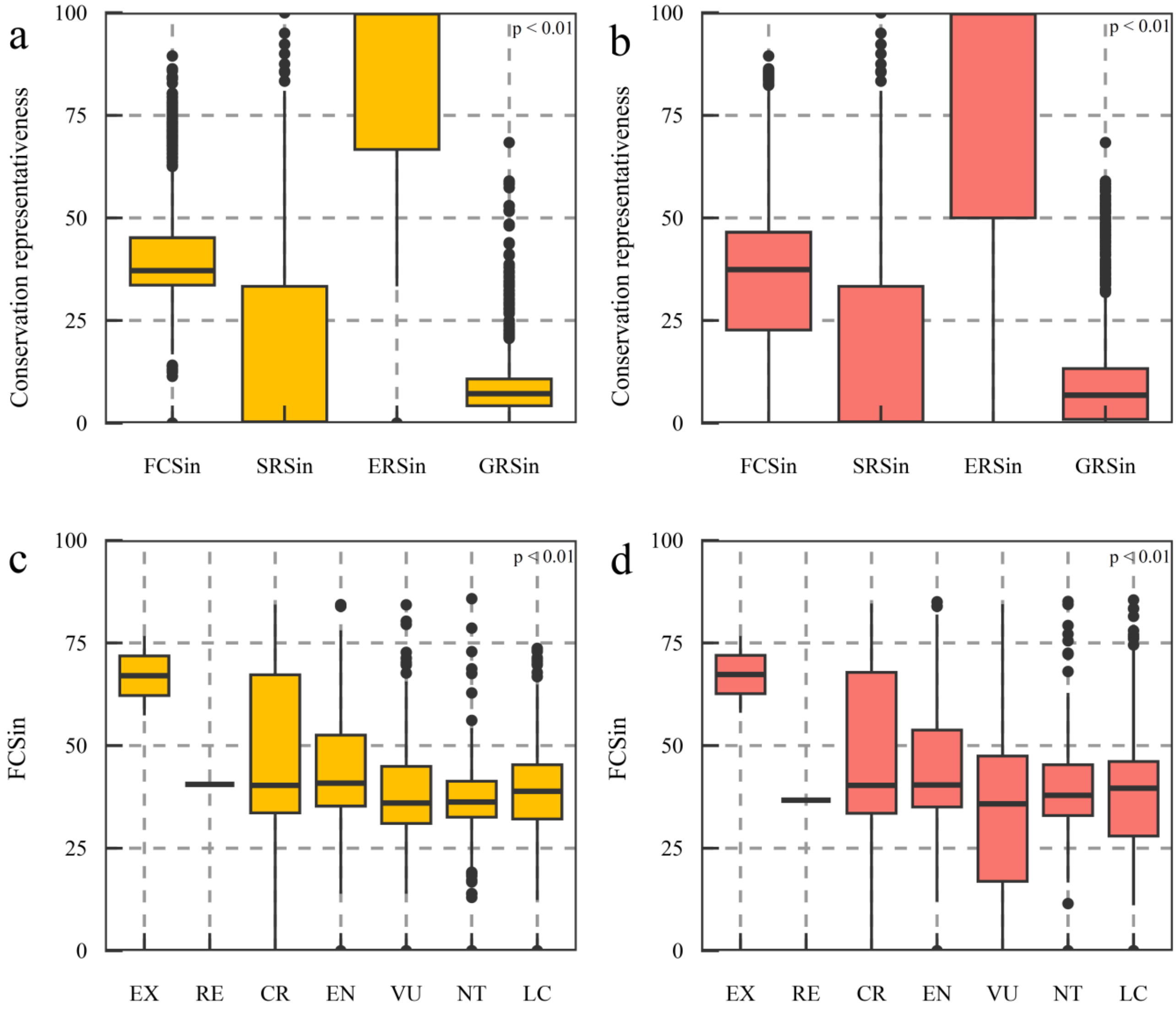
a
b
c
d
Conservation representativeness
FCSin
100
75
50
25
0
p < 0.01
FCSin
SRSin
ERSin
GRSin
EX
RE
CR
EN
VU
NT
LC

Fig. 2

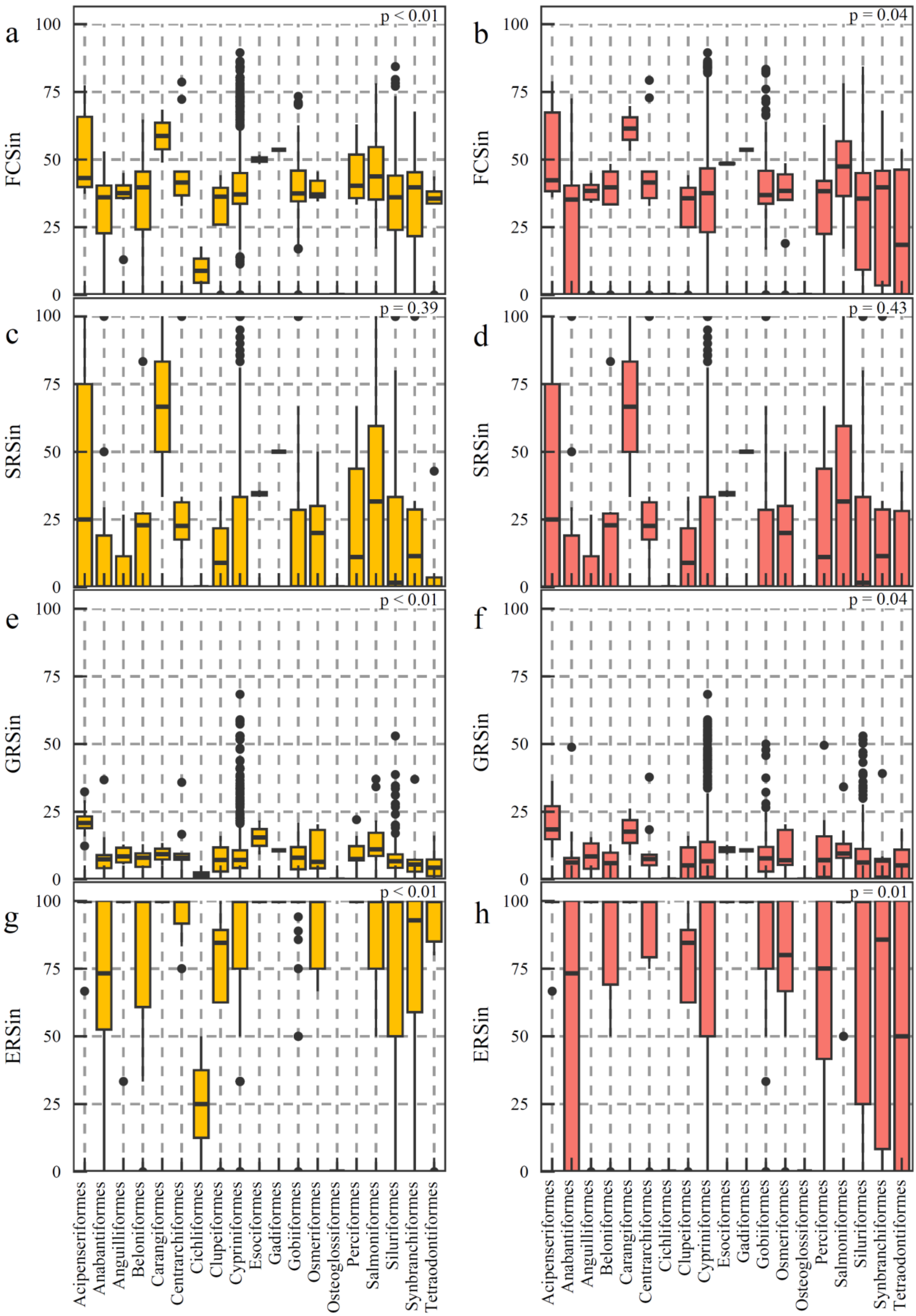
a
b
c
d
e
f
g
h
p < 0.01
p = 0.04
p = 0.39
p = 0.43
p < 0.01
p = 0.04
p < 0.01
p = 0.01
FCSin
SRSin
GRSin
ERSin
0
25
50
75
100
Acipenseriformes
Anabantiformes
Anguilliformes
Beloniformes
Carangiformes
Centrarchiformes
Cichliformes
Clupeiformes
Cypriniformes
Esociformes
Gadiformes
Gobiiformes
Osmeriformes
Osteoglossiformes
Perciformes
Salmoniformes
Siluriformes
Synbranchiformes
Tetraodontiformes

Fig. 3

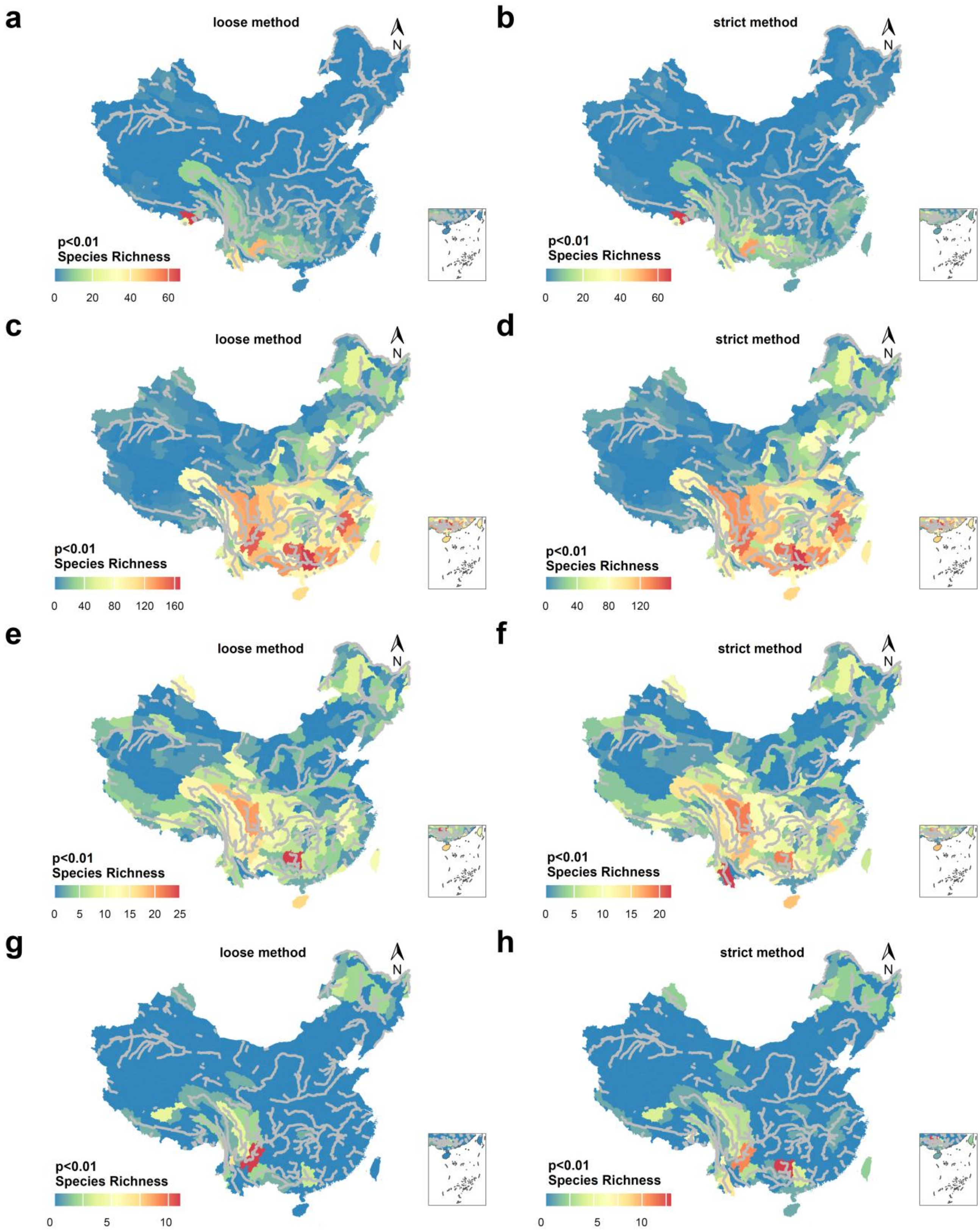
a
loose method
N
p<0.01
Species Richness
0 20 40 60
b
strict method
N
p<0.01
Species Richness
0 20 40 60
c
loose method
N
p<0.01
Species Richness
0 40 80 120 160
d
strict method
N
p<0.01
Species Richness
0 40 80 120
e
loose method
N
p<0.01
Species Richness
0 5 10 15 20 25
f
strict method
N
p<0.01
Species Richness
0 5 10 15 20
g
loose method
N
p<0.01
Species Richness
0 5 10
h
strict method
N
p<0.01
Species Richness
0 5 10

Fig. 4

573