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COMMENTARY

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Aquatic ecosystem health assessment in China based on metacommunity theory: From theory to practice

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Aquatic ecosystems, as intricate and dynamic entities shaped by the complex interplay of natural and anthropogenic factors, necessitate comprehensive health assessments to inform effective watershed management, conservation, and sustainable utilization. In China, the assessment of aquatic ecosystem health has undergone a transformative journey, evolving from single- to multi-component integrated assessment approaches (Jin et al. 2023). Beginning in the mid-twentieth century, the focus was on monitoring and assessing water quality-related physicochemical parameters and pollutants, and later the scope expanded to integrated water resource management, emphasizing water supply and water level regulation (late twentieth century). The introduction of the index of biotic integrity (IBI) concept in the 1980s catalyzed a paradigm shift, propelling the extension of evaluation elements to include aquatic organisms and ecosystems and incorporating biotic community integrity, functional trait diversity, and ecosystem services (Chase et al. 2020). These changes marked a profound deepening of cognition in the assessment system, transitioning from a focus on "water environment" to "water resources" and ultimately to "aquatic ecology".

Despite these impressive advancements, current methods for assessing aquatic ecosystem health still possess several key limitations: 1) An overemphasis on taxonomic diversity indicators, such as species composition, abundance and diversity measures (Cazalis 2022) with insufficient attention to species' functional roles within food webs; 2) inadequate consideration of the nonlinear responses and stochastic processes of biological communities to multiple stressors, with excessive emphasis on the impact of a single factor (Birk et al. 2020); 3) a focus on ecological characterization at the expense of underlying ecological processes and mechanisms, such as environmental filtering, dispersal limitation, mass effect, and other factors (Leboucher et al. 2020), as well as the differences in biotic interactions, such as competition and predation, within communities at different spatial scales (Larsen and Ormerod 2014); 4) overreliance on empirical models

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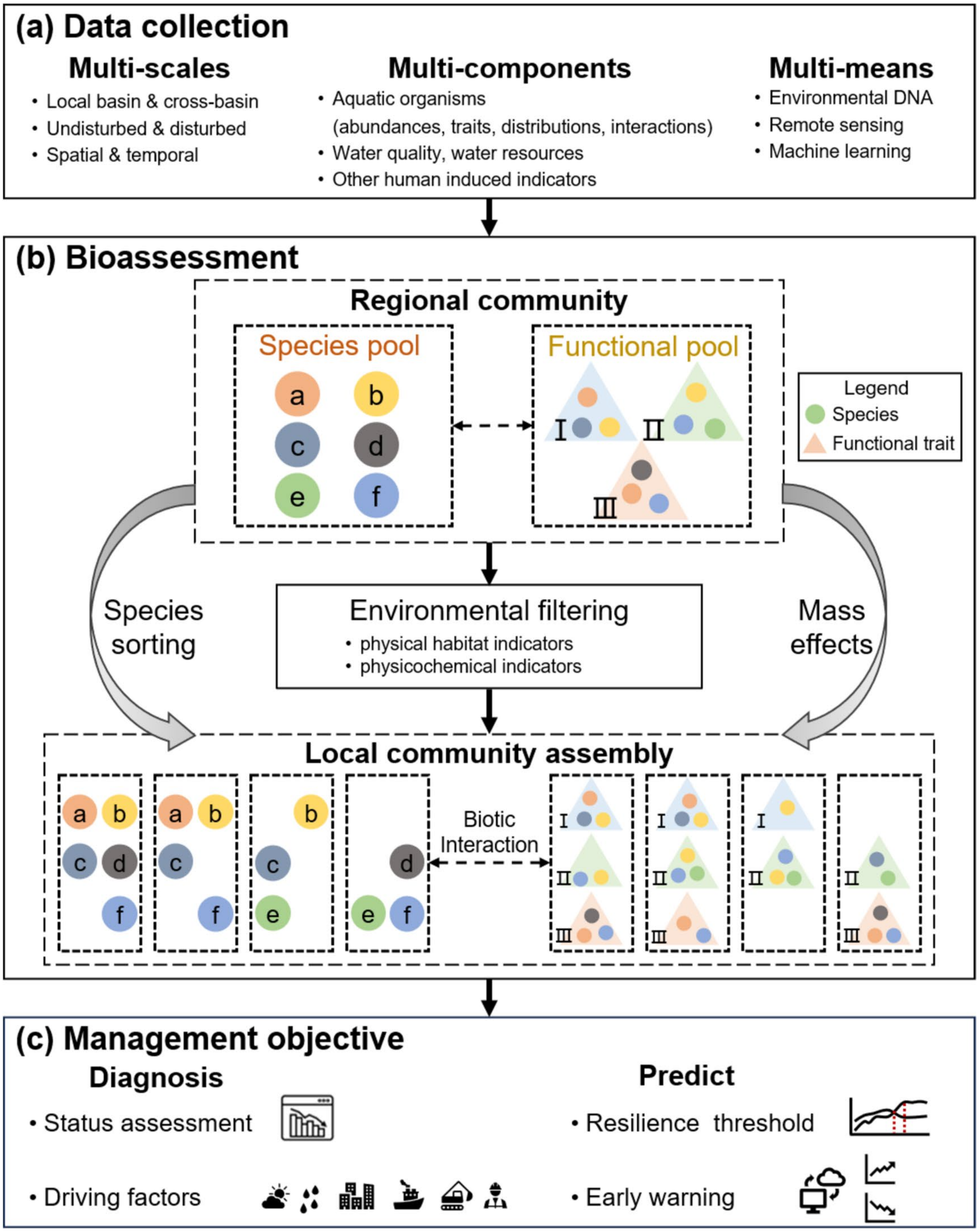

Fig. 1 Aquatic ecological assessment framework based on metacommunity theory. Different colored circles denote distinct species, while colored triangles represent distinct functional traits. The presence of differently colored circles within a single triangle demonstrates the cross-species distribution of that trait; correspondingly, the occurrence of identical-colored circles across multiple triangles indicates the multi-functional traits of individual species. Note: A metacommunity comprises local communities connected by the dispersal of interacting species. Species sorting (emphasizing environmental adaptation) and mass effects (focusing on species dispersal) are two paradigms commonly observed in watershed ecosystems within metacommunity theory. Environmental filtering selectively favors certain species based on their traits, influencing community composition and species distributions. Biotic interactions (e.g., competition, predation, mutualism, commensalism, and parasitism) describe the relationships among organisms within an ecosystem

detached from fundamental ecological theories limits understanding of internal mechanisms and ecological networks dynamics (Leboucher et al. 2020).

The development of metacommunity theory provides a solid foundation for developing a comprehensive aquatic ecological assessment system (Leibold et al. 2004). This theory emphasizes the critical role of interspecific interactions among organisms and their relationships with environmental factors, particularly highlighting how species dispersal and regional ecological processes (such as selective pressures and competition) jointly shape local community structure. It also fully considers the dynamic changes in community composition and functioning at regional scales (Heino 2013), thereby providing a novel perspective for analyzing the spatiotemporal heterogeneity and dynamic network relationships of biological communities. Previous studies have revealed significant differences in how environmental filtering affects the biological communities of the Yangtze and Yellow Rivers (Zhao et al. 2024; Li et al. 2024). Building upon this foundation, future aquatic ecological evaluation systems should prioritize the following aspects (Fig. 1): 1) Assessment indicators should incorporate both biotic and external environmental factors. Biotic indicators should encompass species composition, functional traits, and food web structure, focusing on taxa that are sensitive to anthropogenic disturbances and serve as indicators of key ecological processes. External environmental indicators should include those that characterize the integrity of the physical habitat, hydrological regime, and water quality; 2) research regions should target cross-watershed scales with both differences and similarities to reveal the dynamic networks of communities under different habitats and their scale-dependency (Thompson and Gonzalez 2017); 3) monitoring and assessment techniques should fully utilize high-throughput sequencing, environmental DNA, remote sensing, artificial intelligence technology and other means to obtain high-resolution spatiotemporal data at multiple scales, and employ machine learning and big data modeling to reveal and simulate community-level ecological processes and predict future development trends (Hartig et al. 2024).

To address the current issues in aquatic ecological evaluation systems, such as limited cross-scale monitoring capabilities, homogeneous evaluation methods, and unclear community interaction dynamics, the proposed metacommunity-based framework aims to clarify the external relationships and internal mechanisms among "water environment", "water resources" and "aquatic ecology". This system integrates processes across different geographical levels to understand the causes and consequences of aquatic ecosystem degradation and formulate precise restoration strategies. Additionally, through cross-scale assessment and dynamic monitoring, this system overcomes the problem of data homogeneity and comprehensively considers the interactions within and outside the aquatic ecology, enabling the prediction of nonlinear changes and the risk of abrupt shifts in ecosystems, thus providing decision support for watershed management. Therefore, the framework system incorporating multi-spatiotemporal framework both enables the transition of China's watershed ecological assessment from static, scattered quantitative analysis to dynamic, holistic spatiotemporal network analysis and ensures the comprehensiveness and accuracy of aquatic ecosystem health assessments, ultimately providing targeted restoration measures and theoretical guidance for watershed ecological protection.

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Authors' contributions
Xiaowei Jin and Huiyu Xie wrote the manuscript, Xianfu Zhao, Dekui He, Aibin Zhan, Yongjiu Cai, Naicheng Wu, Xiaowei Zhang, Jun Yang, Yeyao Wang and Andrew C. Johnson modified the manuscript, and Fengchang Wu modified the manuscript and provided constructive guidance.

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Availability of data and materials
Not applicable.

Declarations

Competing interests
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