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Editorial

Watershed Ecology: A New Perspective from 2D to 3D Ecology

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For more than a century, two-dimensional (2D) spatial representations have profoundly shaped ecological theory and methodology. The species–area relationship links area, the most basic spatial attribute, to species richness and remains one of the most stable and widespread macroecological empirical relationships [1]. Island biogeography further connected area and isolation with immigration and extinction processes [2], while landscape ecology established patches, distance, connectivity, and spatial pattern as its basic language, systematically advancing our understanding of the relationship between pattern and ecological processes [3]. Two-dimensional ecology was an effective scientific paradigm formed under particular conditions of observational capacity, theoretical needs, and management practices. It made complex natural systems amenable to measurement, comparison, and modeling, thereby laying a solid foundation for ecology.

Since the beginning of the 21st century, rapid progress in observational technologies has profoundly influenced research paradigms in ecology. Light detection and ranging (LiDAR) has turned three-dimensional (3D) ecological structures that were once difficult to quantify into measurable variables [4], and the integration of spaceborne LiDAR with satellite data can even reconstruct high-resolution patterns of canopy height at the global scale [5]. Overall, LiDAR, unmanned aerial vehicles, spaceborne laser altimetry, high-resolution remote sensing, and 3D animal tracking enable ecologists to describe canopy height, vertical vegetation structure, three-dimensional habitats, and organisms' use of space more continuously and precisely; these technological advances are pushing ecology into a three-dimensional era. Recent Global Ecosystem Dynamics Investigation (GEDI)-based studies have further mapped the near-global three-dimensional structural complexity of forest canopies, reinforcing the ecological importance of forest structure for ecosystem functioning [6].

From the earliest development of landscape ecology, interactions between pattern and process have already been a central ecological question [3]. The new opportunity brought by the 3D era is to place this classic question in real three-dimensional space and to investigate how processes across different media, interfaces, and scales jointly generate the ecosystem structures we observe.

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Watershed ecosystems are typical three-dimensional ecosystems. The classic Hubbard Brook study demonstrated that changes in vegetation can propagate to other parts of the system through hydrological processes and nutrient export [7]. The River Continuum Concept further revealed continuous changes in material loading, transport, utilization, and storage from headwaters downstream [8]. Ward explicitly proposed that river ecosystems simultaneously exhibit longitudinal upstream–downstream linkages [9], lateral channel–riparian–floodplain linkages, vertical surface–subsurface linkages, and continuous temporal change. In the era of 3D ecology, a watershed should be viewed not merely as a spatial unit whose boundary is determined by topography, but as a three-dimensional ecosystem continuously connected by multiple processes. Thus, as ecology moves toward three dimensions, watershed ecology will become an important driving force. Recent global evidence further shows that groundwater sustains a majority of river flow, underscoring that surface–subsurface exchanges are not peripheral but central components of watershed functioning [10].

Future watershed ecology can expand along the following perspectives.

First, the components that constitute a watershed—including abiotic, biotic, and human components—have different degrees of flowability. Water, solutes, sediment, soil, rocks, plants, animals, humans, and even infrastructure differ in their capacities for movement, exchange, and reorganization. Components with different flowabilities jointly form multiple flows within a watershed and continuously shape the watershed landscape: the movement of water and sediment helps shape river networks and channels; vegetation growth and renewal alter surface structure and hydrological processes; roads, reservoirs, and cities built by humans reorganize the movement of water, materials, and people; and changes in components with low flowability, such as bedrock, alter the state of the watershed. At the same time, the river networks, landforms, vegetation, and built infrastructure that have already formed determine where new flows occur, where they converge, and how rapidly they propagate. Differences in flowability are therefore a major mechanism driving internal watershed processes and a major source of habitat heterogeneity.

Second, a watershed is a self-evolving system. A watershed has the most fundamental bidirectional relationship: flow shapes structure, and structure regulates flow. As this feedback continues, a watershed is no longer merely a static structure but a system that continuously changes the conditions of its own future. Past flows therefore form today's structure; today's structure, in turn, alters the flows of the next stage; and new flows continue to modify structure. This continuous feedback process constitutes watershed self-evolution. Observing watershed self-evolution should include both understanding evolution within individual watersheds and understanding co-evolution among watersheds, with the potential to form a new paradigm for ecosystem research. Recent global analyses of deforestation likewise show that vegetation change can alter runoff through forest–climate feedbacks, illustrating how structural change can feed back to water flow at broad spatial scales [11].

Third, based on a systematic understanding of watershed self-evolution, watershed ecology should focus on sustainable development. Traditional wisdom accumulated by humans over nearly ten thousand years has developed a deep understanding of watershed self-evolution. Feng Shui, for example, has proposed many practical models of how watersheds shape human settlements. Modern societies typically assess and manage watersheds through state indicators such as water quality, runoff, vegetation cover, or resource supply, aiming to maintain a watershed in a short-term steady state. It should also be recognized, however, that any management action may simultaneously alter flow pathways and system structure. Therefore, watershed-based sustainable-development research should shift from maintaining selected desired states to understanding how human activities and environmental change alter feedbacks between flow and structure, enabling watershed management to achieve systemic regulation across both short- and long-term timescales.

The progression from 2D observation to 3D structure and then to 3D processes is an inevitable result of the continued expansion of ecological observational capacity and scientific questions. The opportunity

for watershed ecology lies in starting from differences in flowability among watershed components to understand how flows form structure, how structure reorganizes flows, and how their feedback drives the continuous evolution of watersheds. Along this path, a watershed can serve not only as a spatial boundary for studying ecological processes, but also as an important model system for understanding how ecosystems form, operate, and move into the future in three-dimensional space. In particular, the observational scale provided by the watershed level can also offer an effective tool for integrating human understanding from the microscopic to the macroscopic.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the author(s) used ChatGPT-6 (OpenAI) for English translation and language editing. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

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