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Research Highlight

STERE: a framework for addressing ecosystem degradation using an integrated hydrology approach

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The recently published work by Liu et al. [1] introduced the Stepwise Ecological Restoration (STERE) framework, offering an innovative, systematic and modular methodology for ecological restoration. As ecosystem degradation continues to pose a significant global threat to biodiversity, ecosystem services, and human well-being, traditional restoration methods often fail to account for the complexities and levels of degradation encountered in different ecosystems. The STERE framework represents a groundbreaking solution by providing a systematic theory that adapts restoration efforts to the unique conditions and specific needs of an ecosystem.

At its core, the STERE framework is built upon three distinct modalities: environmental remediation, ecological rehabilitation, and ecological restoration. Each of these modalities serves a specific purpose in addressing varying levels of ecosystem degradation. Environmental remediation targets ecosystems that have been severely degraded and focuses on the removal of contaminants. It is critical for restoring essential ecological functions and creating a foundation for further recovery efforts. For instance, in urban areas where industrial activities have led to soil and water contamination, environmental remediation techniques can help restore ecological health and support subsequent management. Ecological rehabilitation is aimed at moderately degraded ecosystems and involves a combination of chemical and physical interventions, as well as the reintroduction of native species. By restoring key ecological functions and enhancing biodiversity, ecological rehabilitation plays a crucial role in promoting resilience and recovery within ecosystems. For example, restoring wetlands in agricultural landscapes can improve water quality, reduce nutrient runoff, and enhance habitats for different species. Ecological restoration targets ecosystems that retain remnants of their original characteristics but are still in a degraded state. The goal of ecological restoration is to rely on the resilience of the ecosystem, allowing natural recovery processes to self-regulate and reinstate ecological functionality. Successful ecological restoration requires a deep understanding of the historical context and ecological dynamics of the targeted ecosystem, as well as the engagement of local communities and stakeholders.

A central strength of the STERE framework is its emphasis on systematic thinking. As we navigate the intricacies of ecological restoration, we must recognize that ecosystems are not static entities; they are dynamic systems that evolve over time. Therefore, the STERE framework calls for continuous monitoring and evaluation at all stages of the restoration process. By incorporating a stepwise progression through carefully planned stages, STERE supports restoration practitioners in setting clear, measurable goals and tracking the effectiveness of their efforts. This allows for adaptive management at each stage of the restoration process, ensuring that interventions are responsive to new challenges. Systematic thinking also encourages due consideration of the connection between ecological components, human activities, and environmental conditions. This interconnection highlights the importance of understanding how different ecosystem components and human activities influence one another, ensuring that restoration efforts address these linkages in a coordinated manner.

Building on this foundation of systematic thinking, an important consideration in better applying the STERE framework is the role of hydrological processes in regulating ecosystem health. Integrating hydrological principles into restoration efforts enhances the STERE framework's capacity to address ecosystem degradation effectively. By understating the interactions between hydrology and ecosystem processes, practitioners can develop targeted interventions that address ecological challenges.

(i) Integrated ecosystem-based and landscape-based hydrology. The effectiveness of STERE can be significantly enhanced by integrating ecosystem-based and landscape-based hydrology into the restoration process. Hydrology should be regarded as the "bloodstream" of the biosphere, playing a crucial role in regulating ecosystem health and functionality by facilitating processes such as nutrient distribution, sediment transport, and soil moisture

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maintenance [2,3]. By incorporating hydrological principles into the STERE framework, we can improve our understanding of how water interacts with ecosystems and inform more effective restoration strategies.

An ecosystem-based hydrological approach emphasizes the importance of ecosystem functions in regulating water cycles. Understanding the relationships between ecosystems and hydrological processes allows restoration practitioners to tailor their interventions to enhance both ecological health and water quality. For example, vegetation restoration or woody encroachment can enhance the water retention capacity of the soil by expanding root systems, thereby contributing to the retention of water resources [4]. In doing so, ecosystem-based hydrology contributes to achieving restoration goals outlined in the STERE framework. Landscape-based hydrology considers the broader landscape context in which restoration efforts take place. Ecosystems do not exist in isolation; rather, they interact with topography, land use, climate, and human activities. By adopting a landscape-based approach, restoration practitioners can identify potential synergies between different land uses and ecological restoration. For instance, restoring riparian zones can improve water quality by filtering pollutants, stabilizing stream banks, and providing habitat for aquatic and terrestrial species [5]. Landscape-scale hydrological management not only improves the local ecosystem's hydrological conditions but also achieves broader ecological conditions through promoting soil and water conservation, enhancing carbon sequestration, and increasing biodiversity [6].

(ii) Supporting STERE implementation through ecosystem-based and landscape-based hydrology. The integration of ecosystem-based and landscape-based hydrology into the STERE framework offers practical benefits for the implementation of restoration projects. For environmental remediation, restoring water flow and quality is essential to removing contaminants from severely degraded environments. In heavily polluted areas, hydrology helps to remove pollutants and improve soil conditions, creating conditions that allow future ecological interventions. For ecological rehabilitation, hydrology helps to enhance biodiversity by restoring natural water cycles, improving root zone moisture retention, and regulating nutrient flows and biogeochemistry cycles. Reintroducing native biota adapted to specific hydrological conditions can prevent further degradation. For ecological restoration, maintaining natural hydrological flows connects water bodies and supports the natural habitat for both terrestrial and aquatic species, leading the natural recovery processes to self-regulate and reinstate ecosystem functionality. By understanding the hydrological dynamics of specific ecosystems, restoration practitioners can implement strategies that enhance these functions. Building upon the role of hydrology in enhancing ecological functions, ecosystems are encouraged to self-regulate and gradually restore their health through a stepwise approach, which aligns with natural processes of ecological evolution. By facilitating conditions that support these processes, such as improving water retention and hydrological connectivity, restoration practitioners can create a resilient foundation for long-term recovery.

The dynamic nature of ecosystems necessitates an adaptive management approach, particularly in the context of climate change. By incorporating hydrological data into restoration planning, practitioners can identify vulnerabilities and opportunities for enhancing ecosystem resilience. For example, continuous monitoring of hydrological change, such as fluctuations in groundwater levels or altered streamflow patterns due to extreme weather events, can inform timely adjustments to restoration strategies. These adjustments may include modifying water diversion plans to maintain critical wetland habitats or adjusting planting schedules to align with new hydrological conditions, ensuring that restoration strategies remain effective under changing environmental conditions [7]. This adaptive management framework aligns seamlessly with the iterative nature of the STERE approach, reinforcing the importance of flexibility and responsiveness in restoration efforts.

As an illustration of the stepwise approach, the Loess Plateau (China) stands out as a prominent example showcasing the importance of hydrological processes in ecological rehabilitation, especially the role that the root zone plays in ecological recovery. The Loess Plateau, once one of the most environmentally degraded regions in China, faced severe ecological challenges due to its fragile soil structure, arid climate, and high intensity rainfall. Over centuries, deforestation had reduced the infiltration capacity and the capacity of the root zone to store water storage, ultimately leading to soil erosion and subsequent sedimentation of rivers and reservoirs (Fig. 1). Moreover, overgrazing and unsustainable farming practices exacerbated soil erosion, leading to extensive land degradation, loss of biodiversity, and sedimentation [8]. To address these issues, the first phase of restoration efforts, initiated under China's "Grain for Green" program at around 2000, focused on reforestation, aiming to increase infiltration and root zone storage, reduce surface runoff, improve soil retention, and reduce sediment deposition in rivers and reservoirs. Compared to the reference period (from 1980 to 1999), the implementation of the "Grain for Green" program significantly improved vegetation cover and altered hydrological dynamics in the main watersheds of the Loess Plateau. The vegetation cover increased from approximately 25% in 1980 to 46% in 2010, with NDVI (Normalized Difference Vegetation Index) values rising from around 0.26 to 0.33 [9]. These improvements indicate the program's success in enhancing vegetation coverage. Hydrological modelling shows that the average root zone water storage capacity increased by approximately 20 mm over three decades, rising from around 80 mm to about 100 mm. Furthermore, surface runoff decreased by 26% and soil retention improved, with sediment load concentrations decreasing by 21%. Sediment loads dropped from 0.73 ± 0.28 Gt per year in 1980–1999 to 0.32 ± 0.24 Gt per year in 2000–2010 [10] (Fig. 1). Despite these ecological successes, some researchers remain skeptical about the long-term effects of afforestation on the region's hydrology because the regional water yield decreased during the same period, with runoff decreasing by an average of 10.3 mm/year across the plateau [11], raising concerns about potential water scarcity. Scientists argue that increasing artificial forests could lead to higher consumption of deep soil moisture, potentially exacerbating soil dryness and contributing to the formation of dry soil layers [12]. As a result, the second phase of the restoration strategy aims to ensure the sustainability of these gains while addressing new challenges. The focus now shifts towards maintaining the vegetative cover, enhancing water retention in the root zone, and promoting socio-economic development in the region [13]. This aligns with the concept of STERE, as seen in ecosystem- and landscape-based approaches, where each phase builds upon the previous one to ensure long-term environmental and human well-being. The ultimate goal is to achieve a resilient, self-sustaining ecosystem that balances ecological restoration with regional develop-

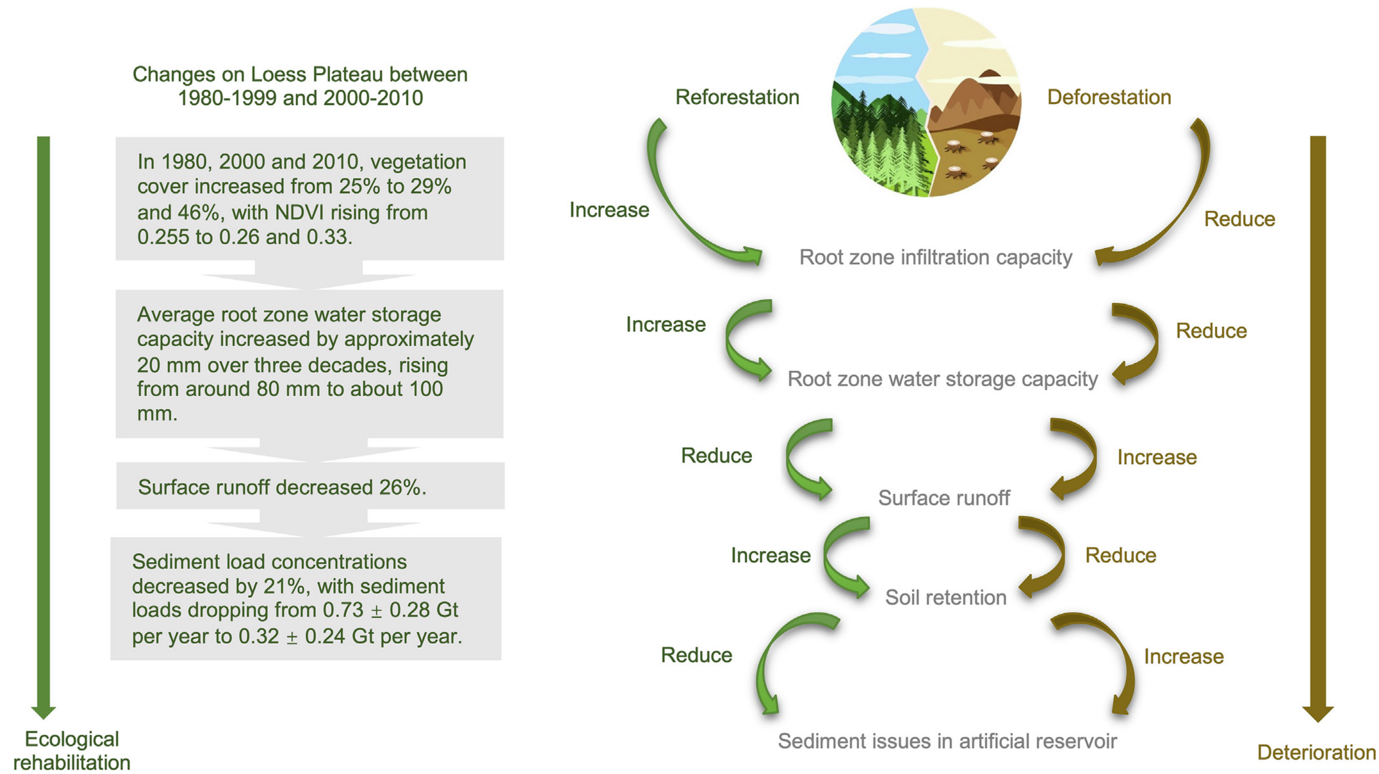

Fig. 1. Diagram showing how reforestation/deforestation changes the ecosystem and the changes on the Loess Plateau before and after "Grain for Green".

ment, enhancing both the quality of the environment and the livelihood of local communities.

The successful restoration of the Loess Plateau serves an as exemplary case of integrating hydrological management methods and STERE. It helps ecosystems to gradually regain their function, thereby improving their resilience. The STERE theory not only fills critical gaps in current restoration practices but also brings a new level of adaptability to ecosystem recovery efforts worldwide. The combined strength of the STERE framework and hydrology-driven restoration paves the way towards more accessible and resilient restoration outcomes globally. It demonstrates how strategic environmental planning can mitigate ecological degradation while promoting long-term environmental and socio-economic benefits.

Conflict of interest

The authors declare that they have no conflict of interest.

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