Towards A Spatiotemporal Framework for Ecological Restoration Management based on Geo-ecological Zoning and Reference States

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Background

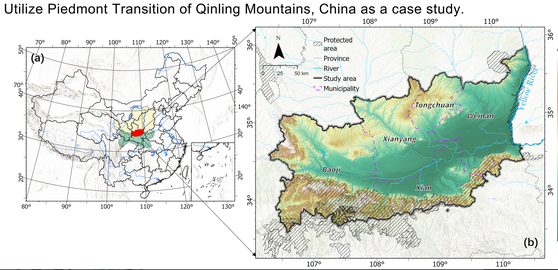
In the Anthropocene, terrestrial ecosystems are grappling with unprecedented anthropogenic disturbances and escalating environmental risks.

Reference states (RSs) serve as the establishment of recovery process, providing a multi-dimensional benchmark for characterizing ecosystem quality, resilience, and carrying capacity.

Over the past three decades, the research paradigm on RSs has evolved through a continuous process of scalar upscaling and spatiotemporal coupling.

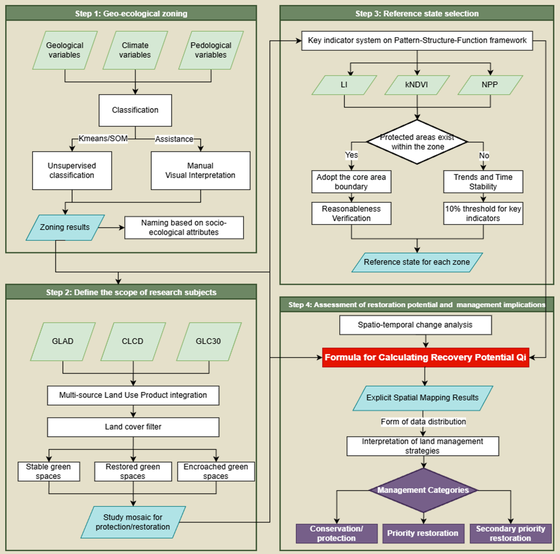
Crucially, restoration strategies must adhere to fundamental RS-oriented ecological principles while addressing the inherent challenges of landscape heterogeneity and diversity during upscaling processes.

Utilize Piedmont Transition of Qinling Mountains, China as a case study.



Methods

This framework integrates three core dimensions: Space, Time, and Reference Objectives



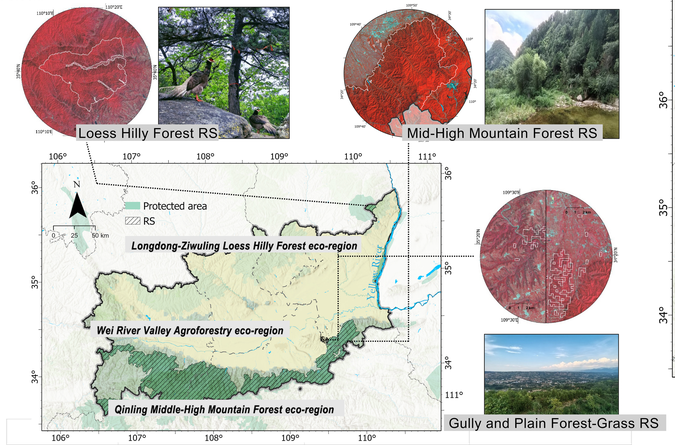
Analyses & Results

(1) Spatial Heterogeneity

In Earth's Critical Zone, it's the geodiversity and hydrothermal gradients set the real 'ecological ceiling'; Integrate these components into a cluster algorithm to delineate three distinct geo-ecological blocks;

(2) Reference State Delineation

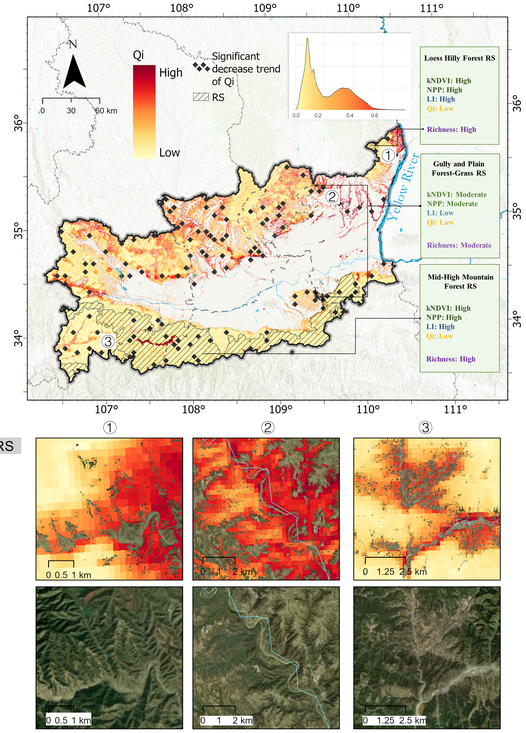
According to the protected area or with time stability and optimal threshold of key indicators, within each block.



Feature	Loess Hilly Forest RS	Mid-High Mountain Forest RS	Gully and Plain Forest-Grass RS
Representing Region	Longdong-Ziwuling Loess Hilly Forest eco-region	Wei River Valley Agroforestry eco-region	Qinling Middle-High Mountain Forest eco-region
Vegetation Type	Temperate deciduous broad-leaved forest and coniferous forest	Warm-temperate deciduous broad-leaved forest and sub-tropical	Deciduous broad-leaved forest, shrubland, and herb communities
Geomorphology & Soil	Southern foot of Huanglong Mountain; Soil-rock substrate with weathered debris and loessal deposits	Located within the Qinling Orogenic Belt. Soils consist of mountain cinnamon soil, brown soil, and dark brown soil.	Loess plateau and hilly-gully landforms; predominantly loessial soil.
Climate	Warm-temperate semi-humid to semi-arid climate.	Warm-temperate semi-humid monsoon climate.	Warm-temperate semi-humid to arid monsoon climate.
Key Protected Objects	*Crossoptilon mantchuricum*, *Pinus bungeana* communities, which serve as critical habitats and indicators of secondary succession.	Over 300 vascular plant species. National Class I: Ginkgo biloba, Abies chensiensis etc.; Class II: Cercidiphyllum japonicum, Fraxinus mandshurica. Fauna: Moschus	General ecological services such as soil-water conservation.
Reference Features	Historical representation	Historical representation	Novel ecosystem

(3) Q Index based on TOPSIS

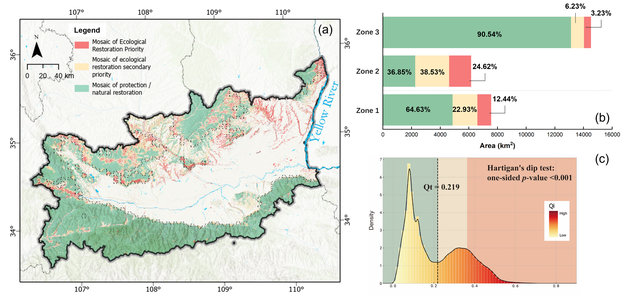
$$D_i^+ = \sqrt{\sum_{j=1}^{n} \omega_j \left(X_{ref} - X_{ij}\right)^2} \quad D_i^- = \sqrt{\sum_{j=1}^{n} \omega_j \left(X_0 - X_{ij}\right)^2} \quad Q_i = \frac{D_i^+}{D_i^- + D_i^+}$$



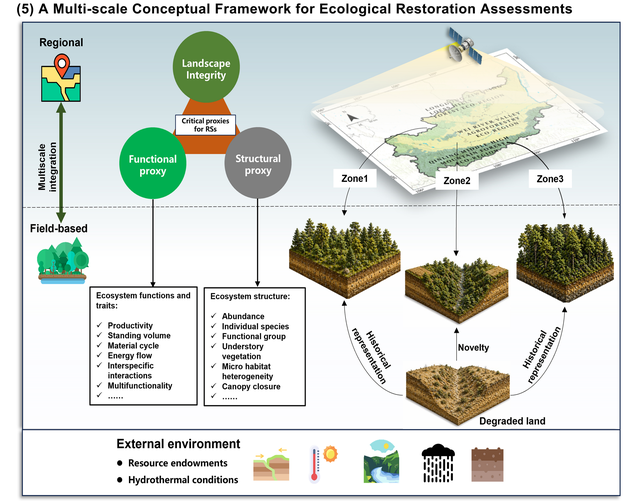
(4) Management Strategy Intrepretation

Draw on the bimodality test and identify the threshold to translate this map into the management strategy quantitively.

This allowed to objectively bifurcate the distribution into two categories.



(5) A Multi-scale Conceptual Framework for Ecological Restoration Assessments



Conclusions

As a foundational theoretical model in restoration ecology, the RS is increasingly pivotal under contemporary large-scale ecological mandates. This study developed an integrated management framework for ecological restoration by operationalizing multi-dimensional RSs, using the northern piedmont of the Qinling Mountains as a representative study area. We characterized landscape heterogeneity by delineating three distinct geo-ecological zones, primarily driven by hydrothermal gradients and geodiversity components within the Earth's Critical Zone. This zoning process defines the socio-ecological attributes and spatial scope for RS-guided interventions. Correspondingly, three site-specific RS types were defined, exhibiting significant structural and functional differentiation: the Gully and Plain RS represents a novel ecosystem adapting to intensive human-environmental shifts, while the Loess Hilly Forest and Mid-High Mountain Forest RSs serve as historical representations. A novel Q_i was developed based on a comprehensive 'pattern-structure-function' indicator system, accurately measuring the distance between current landscapes and relative native integrity. We then quantitatively interpreted spatially explicit management patterns, identifying mosaics that require either conservation/natural regeneration or active intervention. Ultimately, this study underscores the necessity of employing authentic RSs in large-scale restoration. Our top-down diagnostic framework facilitates equitable governance and multi-stakeholder collaboration, providing a scientific safeguard against over-restoration and misaligned resource allocation.