LAND USE-DRIVEN ECOSYSTEM SERVICE CASCADE ANALYSIS: CURRENT STATUS AND PERSPECTIVES

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Key-words: cascade model; ecosystem services; land use; machine learning; ecosystem management.

Abstract. Land use-driven ecosystem services cascade analysis has emerged as a focal point in social-ecological system research, providing an analytical framework for constructing conceptual models, identifying core issues, modular modelling, and consolidating research consensus. This study adopts a systematic review approach in line with the PRISMA guidelines, retrieving literature from databases such as Web of Science and CNKI for the 2013–2024 period. Core challenges, including uncertainty in service transmission and insufficient cross-scale integration, were identified, and future research should strengthen extreme climate scenario simulation and policy tool integration. This study reviews current applications of and trends in cascade analysis in integrated ES assessment, model validation, prediction of interactions, and integration of emerging technologies. Research demonstrates that land use-driven ES cascade analysis holds significant application value in revealing complex feedback relationships between land use patterns, ecosystem services, and human well-being, as well as informing territorial spatial planning and ecosystem management policies.

1. INTRODUCTION

Land use-driven ecosystem services (ESs) are a core scientific theme in social-ecological system research (Zhang *et al.*, 2022), with critical applications in territorial planning and ecological management (Wang *et al.*, 2019). For instance, afforestation and agricultural management enhance ecological functions (Xiao & Xiong, 2022), yet these efforts are simultaneously influenced by population growth, consumption preferences, trade dynamics, ES supply patterns, and policy interventions (Hou *et al.*, 2021), highlighting the need for interdisciplinary research frameworks. The cascade concept – a structural paradigm balancing methodological innovation and technological advancement – has gained rapid traction in ES classification (Finisdore *et al.*, 2020), agricultural landscape monitoring (Liu *et al.*, 2022), and mapping assessments (Wolff *et al.*, 2015). By distinguishing between differential characteristics of ecosystems, services, and benefits, it enables indicator screening, substitution, and optimization (Lai *et al.*, 2018). Cascade frameworks have been applied to multifunctional agriculture (Zhang *et al.*, 2023), ES supply potential (Grêt-Regamey *et al.*, 2020), urban land development (Wu *et al.*, 2022), and urban climate adaptation (Zhang *et al.*, 2022), demonstrating strengths in analysing complex relational networks, though usability and generalizability challenges persist (Verhagen *et al.*, 2018).

Scenario analysis serves as a key tool for cascade modelling, effectively revealing potential cascade dynamics (Muhammad *et al.*, 2023). Human well-being – a multidimensional metric encompassing economic wealth, health, social cohesion, and system sustainability – exhibits complex interactions with land use and ESs (Hasan *et al.*, 2020). For example, combined scenario matrices of Shared

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Socioeconomic Pathways (SSPs) (Gütschow *et al.*, 2021) clarify the cascade effects of climate-land policies on ES-well-being linkages (Gilman & Wu, 2023), while natural capital optimization through biodiversity-ES synergies is being explored (Beisner *et al.*, 2023). However, current research lacks clear regulatory frameworks for well-being modulation and stakeholder accountability (Huynh *et al.*, 2022). Natural capital investments enhance regional economic competitiveness, yet their mechanisms in multi-actor competition remain unclear (Trifonova *et al.*, 2022) – a gap addressed by the ES-well-being cascade analysis. The EU Horizon 2020 framework has pioneered cascade analysis of sustainability competitiveness and socio-ecological challenges to enhance well-being and land system resilience (Faivre *et al.*, 2018).

Cascade analysis models provide technical support but face validation challenges. Few studies employ independent datasets for multi-scale ES process calibration, while scale mismatches in socio-ecological processes introduce systemic biases and uncertainties (Cord *et al.*, 2017). Furthermore, ES simulation outcomes under varying confidence levels struggle to fully integrate with decision-making processes (Aryal *et al.*, 2022). While increased model complexity improves reliability, it demands big data and expertise, creating trade-offs between research investment and multi-scale management needs (Feng *et al.*, 2021). For instance, poverty alleviation efforts often lack information on ES potential versus actual utilization (Mandle *et al.*, 2021), failing to reflect beneficiaries' realities (Roy *et al.*, 2024). Advancing cascade methodology will thus prove crucial for unravelling complex land use-ES-well-being interdependencies. Based on the above background and objectives, this study aims to: (1) systematically review current applications and trends of the land use-driven ES cascade analysis; (2) critically identify core challenges, particularly regarding uncertainty in service transmission and cross-scale integration; and (3) propose future research priorities for enhancing scenario simulation, model parameterization, and policy integration. The following sections will elaborate on the research methods, results, and discussions.

2. CASCADE ANALYSIS PARADIGM

2.1. Framework Overview

The Cascade Analysis Paradigm explains the bridging role of ecosystem services in human-environment relationship research from a systemic perspective, identifying ecological functional characteristics that provide key products/services and their supported benefits. To visualize this conceptual pathway, Figure 1 presents a structural diagram of the land-use-driven ES cascade framework, illustrating the sequential transitions from land use to ecological functions, services, and human well-being benefits (Fig. 1).

By distinguishing services from benefits, the cascade framework incorporates the regulatory dynamics of social-ecological systems that drive service changes. This framework enables comparative analysis of research perspectives, conceptual frameworks, and organizational approaches across projects. Cascade analysis further assists users in decomposing complex system requirements into concise objectives, helps prioritize critical tasks, provides effective interdisciplinary thinking models for complex relationships, and facilitates the identification of common interests among multiple stakeholders. To achieve these objectives, model approaches are classified according to the degree of multi-party involvement, biophysical realities, and cascading responses. Different approaches differ in revealing the holistic expression of the environment based on ESs. Integrated modelling approaches can better support cascading expressions of ESs for attributes such as biophysical, socio-cultural and monetary values (Wu, 2013). However, model development faces technical challenges, including multiple sources of data input-output, concept-information-knowledge transfer learning, the optimisation of cross-validation and development environments, and open-source information sharing.

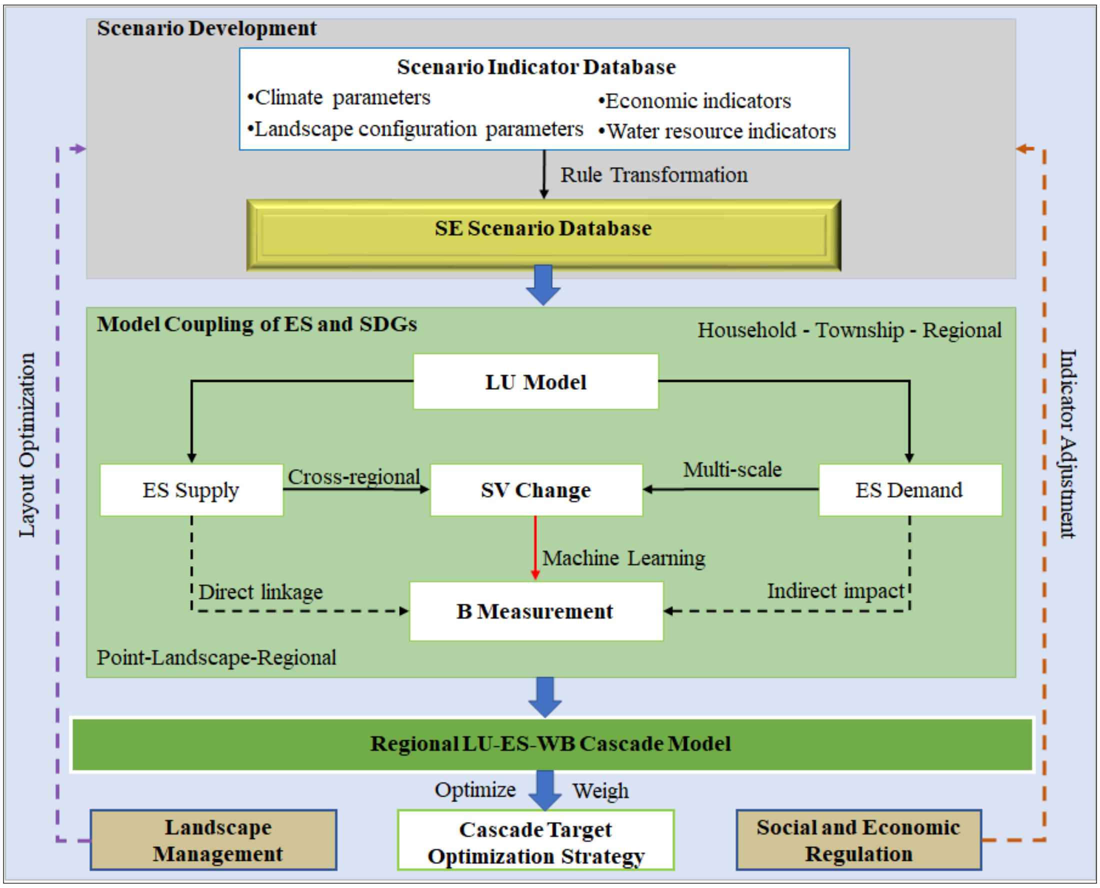

Fig. 1 – Structural diagram of the land-use-driven ecosystem services (ES) cascade framework. Key components are labelled as follows: Spatially Explicit (SE), Land Use (LU), Ecosystem Service (ES), Supply Value (SV), Benefit (B), and Human Well-being (WB). Arrows indicate the primary directional flow and feedback relationships within the cascade.

2.2. Modelling Approaches

Modelling approaches can be categorized into five main types: (1) **Spatially explicit models**: mechanistic models dominated by the integration of climatic-ecological-hydrological processes, which reveal the service pattern-processes and cascading mechanisms in changing environments, but with insufficient emphasis on stakeholders. For example, land use conversion models driven by a combination of socio-ecological factors reveal ecosystem change trajectories for understanding ecological function changes and trade-offs/synergistic processes (Morris *et al.*, 2024). (2) **Economic valuation**: includes willingness-to-pay, cost-benefit, costing, and potential value assessment based on value conversion coefficients from the perspective of stated/behavioural preferences, which take into account the interests of stakeholders and have the methodological advantage of the cascading value/benefit assessment (Kleemann *et al.*, 2020). (3) **Land use matrix scoring**: using expert scoring to establish land use matrix and the correlation evaluation information of supply and demand of ESs (Fan *et al.*, 2024), which can quickly capture potential changes in service functions, but is difficult to validate. (4) **Socio-cultural spatial analysis**: combining the participative GIS technology and socio-cultural value survey to obtain the spatial socio-cultural attributes of participants and the corresponding assessment value. For example, the spatial and temporal differences in group preferences for types of ESs can be obtained through open discussions, landscape photographs, social media, questionnaires, etc., and multi-party information sharing scenarios can be established (Liu *et al.*, 2020a). (5) **Multi-source big data integration assessment**: e.g., the Bayesian Belief Networks use conditional probabilities to describe social-ecological system data information as a graphical network of nodes associated with ecosystem service changes (Peng *et al.*, 2022); and using multi-objective decision analysis to screen and optimise the weight assignment of ESs regulation schemes (Su and Liu, 2023).

To achieve effective cascade analysis, it is necessary to obtain the needs of multiple parties for cascading information, quickly clarify the core problem and communication mechanism, and determine the optimal solution through the combination of multiple methods. The application of models should weigh the relationship between time, cost, data-technical constraints and model complexity, and strengthen the cost-benefit assessment; the sample survey and organization should take into account localization and generality, and enhance the reproducibility of the results; reduce the uncertainty of the assessment through the integration of multivariate methods and the standard classification system of the ESs; promote the re-development of cross-disciplinary methodological tools and the exchange of personnel, and develop correlation with the cutting-edge understanding of the information geography in terms of the scale, scope, and spatial-temporal resolution.

2.3. Model Validation

Integrated assessment models are used to reveal the relevance of ecological resources to complex process models by providing diverse validation datasets that have been tested for fidelity. However, model validation assessments should consider at least the following criteria: (1) **fidelity**: consistency between the reference value and the model mean, affected by model systematic error; (2) **precision**: consistency of repeated model runs, affected by the distribution of model random variables or key features; (3) **accuracy**: a description of precision and veracity that reflects the consistency between reference and model-calculated values; (4) **Development of complexity metrics** oriented towards model complexity, spatial extent, and cascade beneficiary evaluations for accurately describing process feedbacks in the socio-ecological system cascade. The model validation environment requires trade-offs between model complexity, objectives and management regulation purposes.

2.4. Scenario Prediction

Scenarios reflect typical human socio-economic challenges to mitigate and adapt to environmental change. When coupled with the cascade framework, they are used to describe pathway changes in the impacts of land use on ESs driven by complex factors such as policy, climate change, etc. (Giupponi *et al.*, 2022). For example, models such as GCAM explicitly include land use units (Wise *et al.*, 2014), and their projections can be directly used for SSP scenario development. However, the socio-ecological process representations and parameterization schemes of different models vary widely, leading to large impacts of land supply services on cascading processes and increasing scenario prediction uncertainty (Rahman *et al.*, 2024).

In the SSP land use scenarios (Table 1), for example, the greatest global loss of ecological land occurs in SSP3; global demand and prices for agricultural commodities are lowest in SSP1, with the lowest area of cultivated land, and the opposite is true for both in SSP3; cumulative CO_2 emissions are lowest in SSP1 and highest in SSP3 in terms of food consumption, agricultural productivity growth, and global trade. Agricultural demand is generally lower in SSP4 than in SSP2, while SSP5 and SSP2 had the smallest overall difference (Popp *et al.*, 2017). Scenarios are influenced by model structure and rationale, endogenous uncertainties, and scenario parameters, and high-resolution scenario products are critical for cascade assessments (Fastré *et al.*, 2020).

Table 1

Description of Land Use and Socioeconomic Dimensions for Typical Shared Socioeconomic Pathway (SSP) Scenarios. SSPs represent alternative global development trajectories: SSP1 (Sustainability), SSP2 (Middle of the Road), SSP3 (Regional Rivalry), SSP4 (Inequality), and SSP5 (Fossil-fuelled Development)

Scenario	SSP1	SSP2	SSP3	SSP4	SSP5
Land	Ecological regulation and mitigation trade-offs	Slow decline in deforestation rate	Limited regulation and continued deforestation	Strict control in high- and middle-income countries; high deforestation elsewhere	Slow decline in deforestation rate
Production	Increased production and promotion of best practices	Rapid technological change	Low technological progress	Large-scale mechanized production, reduced smallholder farming	Highly managed, resource-intensive; rapid productivity growth
Consumption	Low food consumption, low meat diet	Material-intensive consumption, moderate meat consumption	Resource-intensive consumption	High-income groups consume heavily; others have low consumption	Material-intensive, rich in meat consumption
Trade	Moderate	Moderate	Highly constrained	Moderate	Specialization in production
Globalization	Connected markets, regional production	Moderate globalization	Deglobalizatio, regional security concerns	Global elites participate in globalization	Highly globalized
Land Mitigation Policies	Enhanced international cooperation on climate change, full participation of the land sector	Moderate climate change cooperation, partial participation of the land sector	Poor climate change cooperation, limited land sector participation	Strengthened climate cooperation, partial land sector participation	Reduced climate cooperation, full participation of land sector

Development focus directions include: multiple impacts and trajectory consistency of land use on ecological processes (Li *et al.*, 2021); mutual feedback processes of climate change impacts, adaptation and vulnerability with ESs (Weiskopf *et al.*, 2020); multi-scale sustainable development policy pathways (Gao *et al.*, 2025); multi-scale land use-climate-ecological-sustainability complex relationship-based SSP extension (Fu *et al.*, 2020). Therefore, advancing scenario-based cascade analysis requires developing integrated, high-resolution frameworks to reduce uncertainties and enhance its practical value in supporting land-use and climate policy decisions.

2.5. Ecosystem Service Interactions

Building on the scenario-based analysis of land-use impacts, understanding the spatial dynamics of ecosystem service interactions becomes essential for effective policy implementation. The differential statistical characteristics of trade-offs/synergies in cross-scale cascade analyses provide new ideas for the scientific understanding of supply-demand interactions among ESs. For example, water-holding-food production synergies in semi-arid zones show strong correlations with increasing scales, while trade-offs exhibit non-linear processes (Li *et al.*, 2024), and global regression analyses were used to identify ecological value maximization scenarios and interaction drivers for regional management (Xia *et al.*, 2023; Palliwoda *et al.*, 2021).

Geographically weighted regression models have advantages in analysing eco-spatial non-stationary responses, providing methodological support for developing spatially heterogeneous interventions for ESs (Liang *et al.*, 2023). For example, vegetation restoration in semi-arid areas increases NPP but decreases water retention and food production (Shi *et al.*, 2021), and reduces the synergistic relationship between soil conservation and other services as the vegetation cover increases (Raji *et al.*, 2021). There is also heterogeneity in the response to the climate in terms of changes in ESs interactions (Lavorel *et al.*, 2020).

Optimal urban vegetation design can regulate surface temperature (Estoque *et al.*, 2020), and more trees can create shaded spaces and reduce evapotranspiration. Policy makers mitigate urban ecosystem stress by reducing trade-offs and increasing synergies. Therefore, it is important to identify spatially non-stationary correlations between ESs and influencing factors to improve multiple ecosystem services and regional sustainability from the perspective of ESs interactions in a site-specific manner.

3. CASCADE MODELLING TECHNOLOGY PROGRESS AND CHALLENGES

3.1. Emerging Technologies in Cascade Analysis

The advancement of cascade modelling is supported by several key technologies:

(1) **Air-Space-Earth observations**: they provide continuous information for the cascade monitoring and assessment of ESs, revealing the scale, volume, and accuracy of data (Li and Wang *et al.*, 2023). This approach is suitable for large-scale assessment, with advantages in resolving data deficiencies in remote regions and efficiency in integrating spatial data from multiple sources, but an insufficient assessment of service benefits. The technique needs further development in multi-scale observation calibration (Willcock *et al.*, 2019), spectral data monitoring authenticity, missing mobile data and autocorrelation (Agudelo *et al.*, 2020), and technical training. (2) **Open-source data analysis**: multi-dimensional-multi-modal data analysis techniques are provided for the cascade through open-source tools and data models (Huang *et al.*, 2006). However, there's a general lack of model training data leading to low simulation accuracy (Bergez *et al.*, 2022), while the transparency and implementability of the data model needs improvement. (3) **System simulation**: has advantages in integrating information from multiple sources and increasing causal understanding. Challenges include modelling knowledge, techniques for model development and parameterisation, model complexity and structural accuracy validation (Martinez *et al.*, 2021). (4) **Immersive-visualisation**: the use of interactive tools, web pages, etc. to accomplish cascade knowledge learning sharing (Bereznoy *et al.*, 2021), scenario setting, visual-auditory presentations, etc., effectively reduces the experimental cost of assessing ESs, taking into account the multiple objectives-data-scenarios needed for cascade trade-offs (Meraj *et al.*, 2022) but requires high-tech equipment and software support.

3.2. Deep Learning Applications and Limitations

Deep learning has advantages in complex nonlinear socio-ecological processes, complex spatial-temporal feature extraction and remote coupling prediction. By being combined with big data technology, it can extract feasible pattern features and adaptive methods from cascading relational spatial data streams with multiple sources, scales and dimensions. This technology effectively improves the physical pattern and adaptive methods in vegetation feature classification, climate detection, multivariate regression and ecological patterns and processes prediction. However, problems of interpretability, overfitting, and lack of large-scale labelled data lead to insufficient model bias and generalisation (Stupariu *et al.*, 2022). Complex statistical properties and multiple noise sources lead to high computational costs and hardware requirements, and uncertainty of results and ethical issues also need to be addressed.

3.3. Methodological Integration and Future Directions

While emerging technologies facilitate an integrated understanding of the structure-function-value of cascades, there is a need to strengthen social science assessment methods such as policy mechanisms and community regulations associated with them. In addition, testing different cascade assessment methods is critical in terms of the complex linkages between human well-being, sustainable management, governance and competitiveness. It is recommended that the cascade framework be used to expand research topics and identify methodological integration pathways, reconstructing core societal challenges and highlighting linkages with general societal concerns.

4. CASCADE ANALYSIS APPLICATION VALUE

4.1. Conceptual Clarification and Policy Impact Assessment

Cascade analysis uses sound baseline analyses and structural descriptions to reveal core issues, support the screening of supply and demand for key services and methodological development, and clarify the paradigm of cascade thinking through visual modelling. Firstly, cascade modelling facilitates the understanding of confusing concepts such as 'ecological functions', 'ecosystem services' and the service-benefit distinction among different groups, and identifies the multiple impacts of ecosystem services management policies on human well-being, sustainable governance and competitiveness. The core feedback relationships underpinning these impacts are synthesized in Figure 2, which maps the key interlinkages within the social-ecological system, highlighting the critical connections between ecosystem services, human well-being, and policy interventions (Fig. 2). Secondly, the Cascade Framework provides new perspectives for addressing the paradox of ecological degradation and increased human well-being: emphasising the importance of accounting indicators such as security and mental health, weighing the combined contribution of increased provisioning ecosystem services, such as food production, and declining other services for human well-being, and increasing the efficiency of the use of ESs through technological innovation and management, among others.

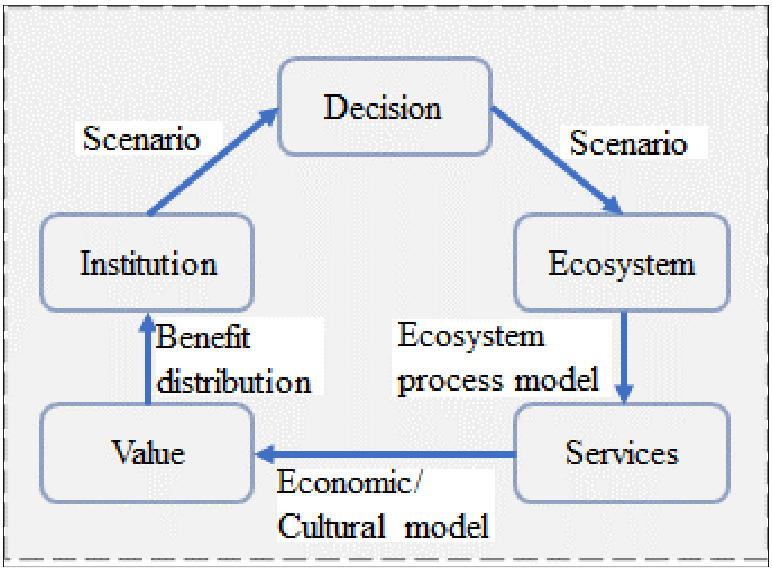

Fig. 2 – Key feedback loops in the social-ecological system as revealed by the cascade model, highlighting the interconnections between policy interventions, ecosystem services, and human well-being components.

4.2. Applications in Ecological Sustainable Management

In terms of an ecologically sustainable management, the cascade framework supports several important applications: implementing the integrated protection of land-ecological restoration, and strengthening the integrated research on ecosystem health, land management diversity, ecological integrity, and ecological-social equity; constructing a food security cascade framework, and promoting analyses of arable land protection measures, the development of modern agriculture and the construction of high-standard farmland, and the increase of food subsidies and compensation mechanisms in the face of regional, structural, and technological challenges.

4.3. Applications in Ecological Restoration Policy Assessment

In terms of ecological restoration policy assessment, the cascade framework emphasises the integrated provision of biodiversity and ecosystem services. The 'watershed-function-landform' cascade framework is used for ecological protection and restoration, to enhance the ecological functions of water conservation, biological habitats and soil and water conservation, and to provide scientific support for the zonal management of the protection and restoration of 'mountains, waters, forests, lakes, grasses and sands'. This approach provides comprehensive support for regional ecological management and policy formulation.

5. CONCLUSIONS AND RESEARCH CHALLENGES

The Land Use-Ecosystem Services-Wellbeing (LU-ES-WB) Cascade Framework serves as an effective and powerful structured approach for diagnosing and communicating complex social-ecological interdependencies. It enables diverse stakeholders to better understand problems, recognize cascade relationships, and develop shared solutions. However, a critical assessment reveals that the framework's full potential is currently constrained by several methodological limitations. Key among these are the oversimplified, often linear parameterization of ES transmission processes which fails to capture non-linear dynamics under extreme conditions; persistent challenges in cross-scale integration that lead to systemic biases; and inadequate model validation frameworks that lack independent, multi-scale data for robust testing. These limitations collectively undermine the precision and practical reliability of cascade analyses.

Therefore, the primary challenge for future advancement lies in enhancing the framework's practical decision-support value by directly addressing these shortcomings. Policymakers should prioritize the integration of more nuanced cascade insights into spatial zoning and ecological compensation schemes, but must do so with an awareness of current model uncertainties. Therefore, policymakers should prioritize the integration of validated cascade model outputs into spatial planning instruments (e.g., ecological redline delineation) and environmental accounting schemes, using them to identify policy entry points that leverage synergistic ecosystem service interactions and mitigate key trade-offs. For model developers, the focus must shift from purely increasing complexity to improving model accessibility, transparency, and the integration of socio-economic feedbacks for end-users. Simultaneously, model developers should focus on enhancing model usability for decision-support by adopting open-source coding practices, developing modular model components for specific ES transmission processes, and improving the representation of non-linear dynamics and socio-ecological feedbacks within cascade models. Moving forward, interdisciplinary research should prioritize: (1) applying novel technologies, such as deep learning, to illuminate key non-linear causal pathways; (2) strengthening the empirical foundation for model validation through advanced monitoring and data fusion; and (3) rigorously evaluating the impact of policy interventions through coupled human-natural system models. By confronting its current methodological limitations, the LU-ES-WB Cascade Framework can evolve from a conceptual tool into a robust platform for achieving tangible management and sustainability outcomes.

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