



Original Research Paper

MultiScale Biodiversity Assessment Framework Using Remote Sensing and Ecological Network Analysis for Wildlife Conservation

Dr. Poonam Singh^{1*}, Dr. Satvik Jain², Mamta Pandey³

^{1*}Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India.

Email: ku.poonamsingh@kalingauniversity.ac.in, ORCID: <https://orcid.org/0009-0007-6969-314X>

²Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India.

Email: ku.satvikjain@kalingauniversity.ac.in, ORCID: <https://orcid.org/0009-0005-0714-4255>

³Assistant Professor, New Delhi Institute of Management, New Delhi, India.

Email: mamta.pandey@ndimdelhi.org, ORCID: <https://orcid.org/0009-0004-1483-9875>

Key Words	Abstract
Biodiversity assessment, Remote sensing, Ecological network analysis, Wildlife conservation, Spatial ecology, Landscape ecology, Geographic information systems (GIS).	The problem of biodiversity loss resulting from habitat fragmentation and changes in land use calls for a biodiversity monitoring method that works at several spatial scales rather than depending on isolated habitat measurements or individual species assessment. The MultiScale Biodiversity Assessment Framework described in this paper is a combination of remote sensing-based landscape indicators and ecological network analysis to simultaneously assess the quality of habitat, its connectivity, and species interaction resilience. The framework unifies regional-scale land-cover mapping, patch-scale fragmentation analysis, and species interaction networks in a single evaluation workflow. Vegetation and land-use indexes obtained from satellite data help identify habitat patches that are further modeled as nodes and corridors in an ecological network measuring their connectivity, centrality and resilience. The integrated framework allows detecting biodiversity-critical regions and corridors that can be overlooked when assessing only one scale. Comparison of the framework results with ecological indicators based on field data proves the ability of the framework to measure cross-scale dependencies necessary for conservation management.

* Corresponding Author's email: ku.poonamsingh@kalingauniversity.ac.in

Introduction

Biodiversity worldwide is being lost at an alarming rate because of habitat fragmentation, conversion of lands for agricultural use, and shifting of ecosystems caused by climatic changes. Conservation strategies demand assessment techniques that incorporate the working of ecological processes at different spatial scales, since the quality of habitats at the local scale and connectivity at the landscape scale decide the survival of species. Remote sensing has become very essential in habitat monitoring on a large scale, while ecological networks have a structural approach to species' interactions. Current biodiversity assessment techniques usually view analysis of spatial patterns and ecological connectivity as two different issues. Morphological spatial pattern analysis frameworks with species distribution modeling help in identifying habitats but do not include interaction dynamics in networks (Guo et al., 2025). Dual ecological network frameworks for terrestrial and freshwater ecosystems show that a unified structure of the network is important, yet these techniques are rarely analyzed at various levels of analysis simultaneously (Tianyi et al., 2025). Ecological network construction method comparisons demonstrate that there are conflicting results in terms of resilience according to the level of analysis (Huang et al., 2025).

This research presents an integrative Multi-Scale Biodiversity Assessment Framework that integrates the remote sensing approach for habitat characterization along with ecological network analysis at regional, landscape, and

patch scales. The novelty in this research is the use of (i) remote sensing-based landscape metrics that are directly integrated into ecological networks instead of being used as independent inputs, (ii) a cross-scale linking system that links patch scale habitat quality information to network scale connectivity and resilience measures, and (iii) a biodiversity index.

The rest of the paper is structured as follows: Section II provides an overview of the literature on remote sensing-based monitoring of biodiversity and ecological networks, in addition to the study area description. Section III describes the proposed multi-scale framework and its methodology components. Section IV describes the results obtained from the analysis of spatial patterns and validation. Section V discusses the performance and benefits of the proposed framework and conservation applications. Section VI concludes the paper.

Related Work and Study Area

Large area, repeatable observation of land-cover changes, vegetation health, and habitat fragmentation via remote sensing forms the base of biodiversity monitoring at the landscape scale. Time series analysis of satellite imagery has been applied to study the changes in the structure of ecological networks based on the distributions of land-use types, revealing how the network structure and connectivity evolve under the influence of urbanization and land conversions during several decades (Lu et al., 2022). There is an approach in ecological

network analysis to model habitats as nodes and ecological corridors as edges, allowing to calculate such characteristics of ecological network as connectivity, centrality, and robustness. Multi-resolution framework for species distribution models has proven the fact that prediction of biodiversity gets better when species distribution maps are combined for multiple spatial resolutions, not for a single fixed one (Sobral-Souza et al., 2021). In addition to this, there has been shown that prioritization of restoration actions in complex terrains gets better when the connectivity is analyzed using multi-scale approach (Lu et al., 2023). This approach has been developed specifically for use in heterogeneous landscapes consisting of natural, agricultural, and areas next to urban settings in which wildlife corridors have become increasingly fragmented due to anthropogenic activities. The information required will include time series satellite images for derivation of land cover and vegetation indices, species distribution data to validate the nodes in the network, and additional layers containing topographical and climatological information for suitability modeling. With such a set of information, it is possible to test the framework at various spatial scales.

Overall, the literature demonstrates three recurring trends: (i) remote sensing-derived information is very useful for identifying habitat/land use dynamics, but it is seldom used in conjunction with network analysis for identifying connectivity; (ii) network-based analyses greatly enhance the analysis of resilience and connectivity, yet they are highly

dependent on scale; and (iii) multiscale analysis, when employed, results in much more accurate predictions and prioritizations than uniscale analysis. These trends directly suggest the necessity for the development of the proposed methodology, which incorporates remote sensing-derived habitat metrics and multiscale network generation.

Proposed Multiscale Biodiversity Assessment Framework

Framework Architecture and Multiscale Design Rationale

The suggested framework will be based on three hierarchical scales: the regional scale, the patch scale, and the network scale, all focusing on land cover composition at the regional scale, habitat quality and fragmentation at the local scale, and species-interaction connectivity at the network scale. The justification for the proposed hierarchical structure is the fact that biodiversity results from the combination of local habitat quality and landscape-level connectivity, none of which can provide sufficient explanations about species survival or vulnerability on its own. Because of the hierarchical nature of the suggested framework, output from the regional scale becomes an input for the patch scale, which then sets the parameters for network formation. In this way, the modularity of the framework is preserved while maintaining the cross-scale connections necessary for a biodiversity index.

Remote Sensing–Based Habitat and Landscape Feature Extraction

At the regional and patch levels, multi-temporal images obtained from satellites are radiometrically and atmospherically corrected to ensure compatibility of the data collected over multiple periods. Habitat conditions are quantified by means of vegetation and moisture indices, while the supervised classification procedure is used to create land cover classes pertinent to wildlife habitat suitability in terms of forest cover, wetlands, cultivated land, and urban development. Fragmentation measures such as patch size distribution, edge density, and proximity measures are calculated based on these classified layers. By conducting change detection over the entire time series, zones where habitat has been gained or lost are identified and selected as priority regions for the network level analysis. All of these remote sensing products form the base upon which the ecological network can be constructed to incorporate real habitat conditions instead of arbitrarily defined boundaries.

Ecological Network Construction and Cross-Scale Integration

Ecological networks use habitat patches obtained from remote sensing classification as nodes whereas movement corridors connecting patches are the edges that are assigned weights based on distance, habitat continuity, and land resistance to wildlife passage. Traditional network measures such as degree centrality, betweenness centrality, modularity, and network robustness are calculated in order to understand the importance of each node or corridor to

connectivity across the entire landscape. The cross-scale integration process involves incorporating habitat quality of patches, obtained from remote sensing, into the weighting function of the edges in the ecological network to punish corridors that have poor habitat quality. This process sets apart the proposed approach from traditional methods because traditional methods treat habitat mapping and network analysis as two separate procedures. The composite biodiversity indicator integrates habitat quality and network connectivity measures using normalized values of the individual variables.

Results and Validation

Habitat Distribution and Landscape Fragmentation Patterns

The use of the remote sensing classification element identifies the presence of discrete areas of continuous natural habitat surrounded by fragmented patches bordering agriculture and urban areas. The fragmentation indices also show that the isolated patches are predominantly found close to urbanizing areas while continuous patches are found predominantly in areas where topography limits expansion. Analysis based on time series of images over the available imagery period shows a decline in patch size and increased edge density.

Species Connectivity and Biodiversity Index Mapping

The network analysis of the habitat patches revealed that there are few highly

central patches that act as crucial stepping stones for connectivity at the landscape scale. The removal of these patches in robustness testing produces a larger impact on the connectivity of the entire network in comparison with removal of patches having low centrality values. The biodiversity index, which combines both habitat quality and network centrality, points out corridors which require immediate management due to the combined influence of habitat degradation and their structural importance for connectivity.

Ground-Truth Validation and Sensitivity Assessment

The comparison of the priority zones generated through the framework with those of habitat and species occurrences recorded in the field shows that there is consistency in terms of correspondence. The sensitivity analysis done by changing the weighting ratio between the habitat quality and connectivity network shows that the overall index is relatively stable over a reasonable weighting range, thus suggesting that the results derived from the framework are not too sensitive to a single input value.

Discussion

Comparative Performance Relative to Existing Assessment Models

The framework offers a more holistic picture of biodiversity vulnerability relative to approaches based only on habitat suitability models or only on connectivity network analysis because it accounts for the state of the habitat

Conclusion

In this research, a MultiScale Biodiversity Assessment Framework was developed, which links remotely-sensed habitat characterization with ecological network modeling to assess biodiversity in terms of fragmentation pattern, critical connectivity nodes, and priority zones. This framework is capable of detecting fragmentation patterns, critical connectivity nodes, and conservation zones in line with independent validation through ecological observations. Using remotely-sensed verifiable habitat characteristics in conjunction with ecological network modeling, this framework offers conservation biologists a transferrable, evidence-based approach to plan corridors and prioritize protected areas without having to rely upon a scale-specific or method-specific approach that might miss critical cross-scale ecological interactions. The future directions of this work involve using high-resolution and high-frequency remotely-sensed data to get better fine-scale habitat characterization, incorporating seasonality in the network model to address movements of different species, and testing the applicability of this framework in other ecosystems to validate its generalizability in a global context.

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