



Original Research Paper

Landscape Resilience Model for Evaluating Ecosystem Recovery Capacity After Habitat Disturbances

Arvind Kumar Yadav^{1*}, Indraves², Kunal Jha³

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

Email: ku.arvindkumayadav@kalingauniversity.ac.in, ORCID: <https://orcid.org/0009-0000-6102-5808>

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

Email: ku.indraves@kalingauniversity.ac.in, ORCID: <https://orcid.org/0009-0002-1710-2399>

³Assistant Professor, New Delhi Institute of Management, New Delhi, India. Email: kunal.jha@ndimdelhi.org, ORCID: <https://orcid.org/0009-0006-0902-0018>

Key Words	Abstract
Ecosystem resilience, Habitat disturbance, Wildlife recovery, Landscape connectivity, Habitat restoration, Species recolonization, Ecological recovery capacity.	Wildfire, drought, land conversion, and extreme climatic events are increasing in occurrence and scale to disturb habitat processes that support populations of wild animals, and are often creating landscapes that are fragmented such that species recolonization or population recovery is patchy in both space and time. Current methods of measuring post-disturbance recovery have been primarily single-indicator-based, measuring vegetation greenness or patch size, and provide little information on the restoration of wildlife populations, trophic interactions, and dispersal pathways. This paper proposes a Landscape Resilience Model that would assess the capacity of the ecosystem to recover after an animal-induced habitat disturbance, incorporating the recovery of the habitat structure, the recolonization pattern of species, the population demographic rebound, and the restoration of functional connectivity between habitat patches into one single comparable Resilience Value. The model focuses on recovery as a multi-stage, cyclical process not just a return to a previous baseline, based on concepts of adaptive cycle thinking and landscape connectivity science. The model has not yet been tested empirically across a variety of biomes, but the indicators used provide a coherent framework for comparing recovery processes among disturbed sites, prioritizing conservation activities, and identifying landscapes where recovery is threatened. Validation by field, across taxa and disturbance types, is recommended as a direction for future research.

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

Introduction

Habitat and food availability, and movement corridors among parts of a landscape, are critical elements of landscape continuity that support wild animal populations. Disturbances of any kind (fire, drought, agricultural conversion, storms) cause disruption of these continuities, and the rate at which recover will either support the survival of resident and migratory species, reduce the abundance, or eliminate them from the disturbed area altogether. Creating forest landscapes that are resilient to disturbance and to ongoing global change is a key priority of conservation planning, as landscapes that are planned for only a specific historical condition are poorly prepared to support wildlife in the context of changing climatic and disturbance regimes (Mina et al., 2022). The simulation of ecological resilience assessments that incorporate habitat suitability, landscape connectivity, and landscape diversity has demonstrated that recovery capacity is not even across the landscape of disturbance and is highly dependent on how well the remaining habitat patches remain connected for animal movement (Liu et al., 2025). Likewise, research based on the adaptive cycle approach to landscape ecological resilience demonstrates that the recovery of landscapes goes through identifiable phases of reorganization, growth, and conservation, and the speed at which these cycles occur is dependent on the intensity and nature of the disturbance (Peng et al., 2025). Assessments of pathways to social and ecological landscape resilience also highlight that recovery outcomes depend not

only on ecological processes, but also on the ecological management and governance context around a disturbed landscape, where a model that focuses solely on habitat metrics would fail to capture what has been found to be an important determinant of whether animal populations are to recover or not (Abelson et al., 2022).

In response to these observations, the Landscape Resilience Model is proposed in this paper. The model is designed to measure ecosystem recovery on a variety of indicators of animal presence, movement, and demographic performance on a recovering landscape, rather than a single structural or vegetative indicator. The model is designed specifically to measure ecosystem recovery using a variety of animal presence, movement, and demographic performance indicators, while placing these into the broader habitat and connectivity context established in previous ecosystem resilience studies.

This paper has three important contributions. First, it suggests a recovery assessment method that focuses on wildlife population and community indicators, and does not use vegetation structure as an indicator of faunal recovery. Second, it offers a staged scoring system for evaluating habitat structural recovery, species recolonization, and population demographic recovery, which can then be compared across disturbance type and site. Third, it places post-disturbance evaluation of recovery in an explicitly cyclical context, acknowledging that landscapes do not recover along a single trajectory back to a previous state; rather, enter

reorganization and renewal phases that vary in length and in outcome.

This paper is organized as follows: Section II summarizes the limitations of previous efforts to assess ecosystem recovery potential following disturbance, and uses the recent study of urban and post-fire ecosystem recovery to illustrate these limitations. In Section III, the proposed Landscape Resilience Model is presented, which is based on the indicator structure and staged scoring approach. Section IV covers anticipated scores for resilience as well as a comparison to traditional recovery monitoring practices. In Section V, the paper finishes with directions for empirical validation.

Shortcomings of Prior Ecosystem Recovery Studies

There are several recent studies that have begun to investigate the ability of ecosystems to recover from disturbance, and these help to clarify where current assessment systems are lacking for recovery assessment for wildlife.

A self-organization and resilience-based model that can be used to quantify recovery capacity has been developed to assess urban green space recovery capacity and can be used to guide ecological restoration strategy, but the work focused mainly on vegetation and green space structure, not animals, which rely on green space structure (Hong et al., 2024). Studies on post-fire recovery dynamics and the capacity of ecosystem services in Mediterranean-type ecosystems have revealed that the recovery of the capacity of ecosystem services after a fire varies considerably between different types of

ecosystem services, and often the recovery of an ecosystem service is significantly slower than the recovery of the vegetation cover, which means that any assessment of recovery based on the recovery of the vegetation cover will overestimate how far the ecosystem and animals living in it have recovered (Roche et al., 2024). The ecological vulnerability of wildfires has also been mapped and assessed throughout Europe and it is evident that the vulnerability, and hence the recovery difficulty, differs significantly between landscape types depending on the habitat configuration and fire history – one should not expect a uniform recovery benchmark for all the disturbed landscapes without considering the context in which habitats are found (Arrogante-Funes et al., 2024).

These are recent sources that all indicate in the same direction. Current recovery capacity assessments can reasonably measure structural and vegetative recovery, but less suited to measure if the landscape is being recolonized by animal populations, if successful reproduction is occurring, and if movement between habitat patches is reestablished. The research literature indicates that faunal-relevant ecosystem services may not regenerate for many decades, and vulnerability mapping indicates that recovery difficulty varies considerably in a local context, depending on the locality. There are systematic approaches to valuing the capacity to recover, such as those found in urban self-organization models, but do not go so far as the population level wildlife indicators that are valued in that work. These pieces of evidence suggest that a recovery assessment framework should be

established that considers habitat structural recovery as a necessary but not sufficient component of ecosystem recovery, and that consider species recolonization and population demographic rebound as the focus for assessment of recovery capacity.

Model Formulation for Post-Disturbance Assessment

3.1 Indicator Categories and Observation Approach

The proposed model for recovery assessment involves the regular re-observation of a disturbed landscape over a period of time that matches the life history of the animal groups of concern, which in most cases should be tied to the breeding season, migratory periods, and/or dispersal periods and not a set calendar time. Four classes of indicator are noted at each observation interval of the disturbed landscape and, if available, in similar undisturbed reference areas. Vegetation cover, canopy (ground) complexity and the presence of denning, nesting and shelter structures are habitat structural indicators. Species recolonization indicators include the presence of indicator species on the disturbed area and the first detection of indicator species on the disturbed area, and the number of species that are added to site records at each observation period. Population indicators used include breeding activity, juvenile recruitment and the relative abundance of resident and returning species to pre-disturbance or reference site baselines. Indicators of connectivity include repeated detections of the individual at multiple patches within the same or neighboring patches

or repeated detection of a species group at multiple patches, as evidence of movement between the disturbed patch and other habitat areas in the landscape, indicating if the disturbed area is becoming reintegrated with the rest of the landscape being utilized by wildlife.

3.2 Staged Assessment Structure

The indicator categories are connected to each other in three levels of assessment. There are two main steps: the condition scoring of the habitat, and the establishment of reference site conditions. In the condition scoring of habitat, a condition score is assigned to each disturbed area based on the raw structural data with respect to the reference site conditions. The second step is faunal recovery scoring, which is based on species recolonization and population demographic observations to give a recovery score depending on the number of species found, and on the performance of those species if present (e.g. a site with many species found but poor breeding success would be given a lower score than a site with species found and performing well). The third stage, connectivity integration, refines the recovery score of the combined patch based on evidence to show if functional patch-level recovery has been achieved that is linked to functional integration with other habitat types in the landscape. All three stages are meant to be used in a cyclic way, rather than in a one-off application, meaning that the position of a landscape within the reorganization, growth or conservation phase of the landscape's recovery can be identified as observations are repeated over time.

3.3 Recovery Outcome Classification

The model also indicates various stages of recovery: full recovery, partial recovery and arrested recovery. Habitat condition, faunal recovery, and connectivity scores should be within an ecologically reasonable timeframe for the species and disturbance type towards reference conditions for full recovery. Partial recovery is defined as habitat structural indicator restoration, but faunal recovery indicators or faunal connectivity indicators are either still low or never recovered, indicating that although the physical habitat recovered, the wildlife population has not, or may not, fully recover. When the model identifies that there is not much or any improvement over time for each indicator category in the series of observation intervals, it is assumed that the model is arrested and resuming improvement may be necessary, and the model recommends an intervention.

Resilience Scoring and Comparative Outcomes

4.1 Anticipated Performance of the Model

The Landscape Resilience Model has not yet been applied in the real world so the performance it is expected to achieve is based on insights from resilience research in related areas. In terms of application, the connectivity integration phase in the proposed model might be used to distinguish between a good and bad recovery, with the scenarios showing greater and faster recovery containing good levels of remaining habitat connectivity. In a similar way, landscape ecological resilience assessments have been adaptive, and results have shown recovery is a

process of different durations depending on the severity of the disturbance and that there is no such thing as a final recovery state but instead a cyclical scoring of recovery.

4.2 Comparison with Conventional Recovery Monitoring

The proposed model accounts for structural recovery as one of four categories of indicators (not as a proxy for overall ecosystem recovery) and it takes into account recovery across a disturbed landscape, which is not being measured by many other forms of recovery monitoring that focus on vegetation cover or remotely sensed measures of structural indicators. The use of the model should be complementary to structural monitoring and should also be used in conjunction with faunal recolonization, faunal and demographic observations, and recovery capacity which indicates that recovery can be very extensive (but does not mean structural monitoring should not be used). Ecosystem services and faunal-relevant processes can be delayed for many years after the disturbance until the vegetation recovers.

4.3 Implications for Conservation Management

The model has a number of practical conservation management implications. By differentiating partial recovery from full recovery, managers can start to recognize landscapes where there has been a physical recovery, but wildlife populations have not, and focus on enhancing connectivity and introducing specific species, instead of additional habitat structural projects. If arrested recovery occurs

prior to the second monitoring interval, if additional intervals without change occur before arrested recovery, then perhaps there is some window of opportunity to intervene before a landscape has become consistently degraded and is no longer able to respond to intervention.

4.4 Limitations

There are some drawbacks to the model, too. Baselines, observation periods and groupings of species suitable to each disturbance type and biome will likely have to be created empirically as species are different in the vulnerability to disturbance as well as in the difficulty of the recovery process. Another assumption of the model is that a similar reference site is available as a baseline to compare the landscape to, which may not occur in landscapes with high disturbance or where there is no reference undisturbed habitat nearby. The model is also more appropriate for medium and long-term assessment of recovery rather than the 'triage' approach to post-disturbance recovery as repeated observation over multiple breeding or dispersal cycles is also required to score the faunal recovery and faunal connectivity stages meaningfully.

Conclusion

The Landscape Resilience Model described here, an approach for the evaluation of post disturbance ecosystem recovery capacity focused on wildlife species recolonization, populations of recovered demographics, and landscape connectivity in addition to the recovery of structure itself, is a departure from previous perspectives that employ structural recovery of

habitat as a surrogate for ecosystem-wide recovery. The Landscape Resilience Model builds on the substantial recent literature of resilience in large landscapes to global changes, connectivity modeling and diversity estimation, adaptive-cycle trajectories of change at the landscape scale, and the social and ecological processes that determine resilience success or failure, while directly addressing the observed postfire and urban landscape restoration disconnects where the recovery of structure lags behind the restoration of faunal communities. The Landscape Resilience Model, structured by metrics scored in four closely related indicator classes and by defining the possibilities of full recovery, partial recovery, or arrested recovery, offers a framework to facilitate comparison across scales by conservation practitioners and supports targeting of restoration treatments where wildlife may lag structural recovery. Ongoing and necessary further work includes empirical validation and refinement of observation-site distance and selection criteria needed for broad application of the Model to different organisms, environments, and disturbances.

References

- [1] Abelson, Eric, Keith Reynolds, Angela White, Jonathan Long, Charles Maxwell, and Patricia Manley. "Evaluating pathways to social and ecological landscape resilience." *Ecology and Society*. 27 (4): 8 27, no. 4 (2022).
<https://doi.org/10.5751/ES-13243-270408>
- [2] Arrogante-Funes, Fátima, Florent Mouillot, Bruno Moreira, Inmaculada

- Aguado, and Emilio Chuvieco. "Mapping and assessment of ecological vulnerability to wildfires in Europe." *Fire Ecology* 20, no. 1 (2024): 98.
<https://doi.org/10.1186/s42408-024-00321-8>
- [3] Hong, Wuyang, Dong Han, Biao He, Yelin Li, Minde Liang, and Renzhong Guo. "Recovery capacity and ecological restoration strategy of urban green space based on the self-organization–resilience model." *Land Degradation & Development* 35, no. 1 (2024): 76-87.
<https://doi.org/10.1002/ldr.4898>
- [4] Liu, Fei, Hong Huang, Fangsen Lei, Ning Liang, and Longxi Cao. "Ecological resilience assessment and scenario simulation considering habitat suitability, landscape connectivity, and landscape diversity." *Sustainability* 17, no. 12 (2025): 5436.
<https://doi.org/10.3390/su17125436>
- [5] Mina, Marco, Christian Messier, Matthew J. Duveneck, Marie-Josée Fortin, and Núria Aquilué. "Managing for the unexpected: Building resilient forest landscapes to cope with global change." *Global Change Biology* 28, no. 14 (2022): 4323-4341.
<https://doi.org/10.3390/land14040709>
- [6] Peng, Huaizhen, Huachao Lou, Yifan Liu, Qingying He, Maomao Zhang, and Ying Yang. "Spatial and temporal evolution assessment of landscape ecological resilience based on adaptive cycling in Changsha–Zhuzhou–Xiangtan urban agglomeration, China." *Land* 14, no. 4 (2025): 709.
<https://doi.org/10.1007/s10021-024-00924-x>
- [7] Roche, Philip K., C. Sylvie Campagne, and Anne Ganteaume. "Post-fire recovery dynamics and resilience of ecosystem services capacity in Mediterranean-type ecosystems." *Ecosystems* 27, no. 6 (2024): 833-847. <https://doi.org/10.1007/s10021-024-00924-x>