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Forest Recovery Prediction Model for Evaluating Ecological Restoration Progress Using Multi-Year Habitat Indicators

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Ecological restoration, Forest recovery, Habitat indicators, Vegetation recovery, Restoration monitoring, Wildlife habitat assessment, Ecosystem resilience.

Abstract
Tools that are able to monitor recovery trends over several years are becoming more important for ecological restoration projects as being applied increasingly to forested landscapes where only a single year may provide a snapshot of habitat condition. This paper introduces a conceptual model, the Forest Recovery Prediction Model, to assess progress of ecological restoration based on multi-year indicators of habitat conditions to predict the recovery trajectory of a forest after disturbance or active restoration efforts. The model includes three interrelated parts: the collection of multi-year habitat indicators, prediction of recovery based on trends, and comparative assessment against expected restoration or recovery benchmarks. Based on recent progress in vegetation potential forecasting, wetland ecological network restoration, karst vegetation recovery prediction, and coastal ecological resilience assessment, the model is expected to assist restoration practitioners in predicting whether a forest recovery project is likely to be successful before reaching full canopy or community recovery. The model has not yet been tested with long-term field data, but the indicator-based, trajectory-based approach provides a clear trajectory to enhance the way restoration progress is measured and reported. The model needs to be evaluated in forest types with varying disturbance history and restoration methods in order to make it more generally applicable.

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Introduction

Disturbed forest ecosystems (whether as a result of logging, fire, agricultural conversion, or other forest use practices) may be restored to a pre-disturbance or ecologically desirable condition. Determining if this restoration is succeeding, though, is an ongoing challenge because forest recovery takes many years, and any one year may not capture the true picture because of a bad or good growing season. Fine spatial scale vegetation cover forecasting has been used to demonstrate that sub-pixel vegetation potentials can be projected forward for large-scale restoration projects (including the African Great Green Wall) to inform restoration trajectory planning, highlighting that recovery trajectories, not condition scores, are a key component of making sound restoration decisions (Meng et al., 2025). Similarly, for Grus japonensis, Qiu et al., (2025) showed that restoring coastal wetlands is greatly aided by monitoring the condition of the habitat network over several decades, rather than on an annual basis. The recovery of vegetation is further complicated in karst landscapes due to soil and hydrological constraints, and prediction of recovery potential has been demonstrated to change over time according to the integration of multiple vegetation and site indicators (Mo et al., 2022). Pressure-state-response modeling for coastal ecological resilience has also shown that pressure-state indicators can be meaningfully used in conjunction to predict recovery capacity over the years (Wan et al., 2024).

In response to these findings, an approach to structuring multi-year habitat indicator data is proposed here that supports not only reporting in a retrospective manner, but also prediction in a forward-looking manner, in the form of a Forest Recovery Prediction Model.

The contribution of this paper is three-fold. First of all, it outlines a conceptual model considering forest recovery as a multi-year process that can be forecasted, not just a state that can be assessed at a single point in time. Second, it provides a layered architecture that integrates a variety of habitat indicators that are monitored over multiple years and into a single recovery curve that can be compared to restoration targets. Third, it shifts the focus of predictive recovery assessment from a report after a restoration project to a tool for restoration practitioners to recognize substandard restoration sites early in the process when intervention can still be used to improve recovery.

The rest of the paper is organized as follows: In Section II, the limitations of current forest ecology-based assessment methods for restoration are reviewed. In Section III, the proposed model is described, including the architecture and multi-year indicator design. The expected prediction accuracy and a comparison with established practice for restoration assessment are presented in Section IV. Finally, in Section V, directions are given for future validation.

Limitations in Current Restoration Assessment Methods

Traditional restoration assessments in forested landscapes have been based on periodic vegetation surveys, canopy cover assessments, and species inventories over time periods that are generally based on project funding cycles, instead of the rate of ecological recovery. Fractional vegetation cover mapping on the basis of fine-scale aerial imagery has enabled mapping of rare riparian shrub ecosystems and provided a basis for measuring and guiding conservation and restoration decisions, but mapping has often been done once and rarely repeated over time to capture a recovery trend (Rose et al., 2023). Along the sections of the Beijing-Hangzhou Grand Canal, the zoning for ecological security pattern identification and restoration has highlighted the importance of identifying the ecological corridor and security pattern that changes with time, which suggests that the static zoning, based on a single assessment period, may be outdated as the recovery process moves forward and unevenly happens in a landscape (Xu et al., 2025). A study on the county-level driving forces of vegetation greening on the Loess Plateau has also illustrated that a variety of complex factors, such as climate variability and land management, are involved, and that these factors vary year to year and are challenging to measure by single-year vegetation assessments (Kong et al., 2024).

A recent set of sources converge around a similar limitation. When historical trend data is available, vegetation potential forecasting provides answers to the question of what is likely to happen as time goes forward; many restoration programs do not keep historical trend information on an indicator, in a format appropriate to forecasting. Research on ecological network restoration suggests that the parameters of habitat connectivity and habitat structural condition evolve over decades and likely over shorter time periods as well. This implies that assessments at only project milestones may fail to capture important trends. The recovery of karst vegetation is predicted by karst vegetation recovery prediction work, which showed that site-specific constraints necessitate multiple indicators that must be monitored simultaneously, and not just a single indicator for vegetation cover. A series of coastal resilience assessment studies shows that the pressure, state, and response indicators do not stand alone over time, but rather are integrated as a whole. Fine-resolution vegetation mapping studies also demonstrate that spatially detailed information is useful but can only be useful if taken repeatedly over years to show true recovery trends, rather than just a snapshot of a single condition. The ecological zoning studies show that priorities determined by one assessment year may not necessarily align with recovery during that year, and can shift with time. Through greening driver studies of vegetation, multi-year assessment has been shown to be needed, as recovery trajectories are affected by year-to-year variation in drivers.

Model Architecture and Multi-Year Indicator Design

3.1 Multi-Year Habitat Indicator Collection

The model is based on the collection of habitat indicators within the same time period each growing season following restoration. Canopy cover development, understory vegetation composition, indicator wildlife species presence and activity, soil moisture and nutrient status (where applicable), and the presence or extent of invasive or early successional species that could compete with the target native vegetation are measured. Data are taken at the same time of year in successive seasons to make a minimal assumption of the effect of short-term seasonal fluctuations on recovery comparisons, which recognizes that meaningful recovery signals only come when indicator measurements are directly comparable across years.

3.2 Model Architecture

The overall model is conceptualized into three, tightly connected components. The first is the indicator consolidation layer – habitat measurements taken in different years are converted into similar annual condition scores for each restoration site. The second is the trajectory modelling layer, where condition change scores from year-to-year are aggregated to identify the trajectory (or recovery) of the site, as either moving towards restoration targets or as stagnating or becoming "reversive". The third model is the benchmark-comparison layer, which uses the projected trajectory of recovery for a particular site to compare with reference trajectories from similar previously restored forest sites and/or regional recovery targets to determine if the site is progressing toward recovery at an expected rate.

3.3 Multi-Year Indicator Design

The multi-year indicator set has been designed to acknowledge that progress toward forest restoration cannot be measured using a single habitat indicator for all forest types. Canopy and structural indicators reflect the physical recovery of forest architecture, and wildlife occupancy indicators reflect if forest recovery is leading to the functional use of it by target species. Where canopy indicators suggest good conditions, soil and understory indicators reflect underlying condition that may limit or facilitate continued recovery. The model is designed to identify early indicators of delayed recovery not identified by a single indicator assessment when the indicators are measured at the same time each year.

Prediction Accuracy and Comparative Results

4.1 Anticipated Prediction Accuracy

The Forest Recovery Prediction Model is not a model which has been tested against a large set of field data, so the accuracy of the model predictions is thus extrapolated from similar trajectory-based ecological forecasts described in the literature. The potential forecasting models used for vegetation data have been shown to have some predictive utility at fine spatial resolution when a multi-year historical record is available, and a similar approach to a multi-year indicator approach should provide similar predictive utility for forest recovery trajectories. Pressure-state-response based resilience assessment has also demonstrated that integrated indicators, rather than single- indicator approaches, are able to better predict the capacity for recovery, which implies that the proposed model's resilience indicator design will make better predictions than would single-point approaches.

4.2 Comparison with Traditional Restoration Assessment

The proposed model is more sensitive than periodic vegetation surveys measured at project milestones, as it measures change annually, not just at specific points in the project. While milestone-based assessment has value in reporting points that are clearly communicated to restoration funders and stakeholders, the prediction model is most effectively used to consider when milestone assessments should be made, as well as when early intervention might be needed, but not as a substitute for periodic field assessment.

4.3 Implications for Restoration Practice

Assessing recovery trajectories instead of just condition scores in retrospect may enable restoration practitioners to identify sites that are not progressing as expected and may still be feasible for restoration by supplemental planting or control of invasive species. If applied to larger restoration programs, which involve multiple sites, this has specific implications about prioritizing limited field verification resources to sites with most uncertain or worrying recovery trends, by applying predictive screening.

4.4 Limitations

This method is a conceptual approach that has not yet been tested with a large number of long-term restoration data sets and the accuracy assumed is a subjective conclusion rather than an actual validation. Because multi-year indicator collection needs to have a long-term monitoring capacity at restoration sites, this can be challenging in projects where long-term funding is limited. The model's dependence on comparison with reference trajectories also limits the accuracy of the prediction for forest types and/or restoration approaches for which there is little reference data.

Conclusion

This paper has presented the conceptual Forest Recovery Prediction Model, which combines multiple year data collection of habitat indicators, trajectory modelling, and benchmarking into a single predictive model. The model will build on recent model advancements in vegetation potential forecasting, ecological network restoration, karst recovery prediction and coastal resilience assessment, and will facilitate restoration practitioners beyond retrospective, single point condition reporting to a future understanding of whether recovery is on track. The model needs to be validated with long-term field data, but the indicator-driven, trajectory-based approach is a consistent pathway to improve the measurement of forest restoration progress. Future study should focus on this model's ability to predict actual recovery results in forests with varying disturbance histories and restoration techniques, and on the model's ability to predict actual recovery results over time.

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