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Original Research Paper

Behavioural Syndromes and Links to Extinction Risk and Population Viability Under Changing Land Use

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Key Words

Behavioural syndromes, Land-use change, Extinction risk, Population viability, Habitat fragmentation, Species persistence, Conservation ecology.

Abstract

The rapid change in land use driven by agricultural intensification, urbanization, and habitat fragmentation is an increasingly significant threat to biodiversity. Still, not all species respond to these environmental pressures in the same way. This paper analyses behavioural syndromes, which refer to stable associations between traits, including boldness, activity, and dispersal, and extinction risk and the viability of a population in changed landscapes. The behavioural and demographic data from 18 terrestrial vertebrate species were collected across 6 divergent land-use regimes, comprising 420 standardised behavioural trials and 35 long-term population datasets. Stochastic population viability models were fitted with behavioural traits to assess the survival, fecundity, dispersal, and extinction history of populations under progressive land-use scenarios. The finding indicates that high-risk behavioural syndrome populations had 0.42 units of survival per generation of adults and 1.6 disturbance encounters per time step of mortality events. Risk-averse syndromes, on the other hand, had reduced dispersal, leading to a 1.9-fold reduction in successful colonization events within fragmented habitat networks. Behaviour-informed models used behaviour information to predict extinction risk 21 log-units better than behaviour-neutral models. The influence of population growth on the viability results was reduced by 0.31 units in the high-land-use-intensity landscapes, with behavioural effects explaining 38 units of variance. These results show that behavioural syndromes are significant mediators of species' effects on land-use change, with individual behavioural consistency linked to population-level persistence. Assessment of conservation incorporating behavioural aspects will be a better predictor of extinction risk and of successful land-use management in the face of rapid environmental change.

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Introduction

Behavioural syndromes are the consistent, repeatable correlations of behaviour characteristic performances of individuals in ecological situations and through time. Boldness, activity, exploration, aggression, and dispersal tendency are the traits that commonly co-vary and are structured into behavioural profiles that are resistant to environmental changes. These trait correlations, rather than being independent reactions, shape how individuals interpret risk, use resources, and engage in social interaction. New integrative models emphasise behavioural syndromes as an interface between behavioural ecology and macroecological dynamics, linking individual decision-making to large-scale biodiversity outcomes (Marske et al., 2023). Notably, behavioural consistency may reduce behavioural flexibility, thereby inhibiting adaptive responses in a rapidly changing environment (Vinton et al., 2022). Consequently, behavioural syndromes are now considered heritable elements of ecological strategies that affect survival, reproduction, and the dynamics of long-term populations.

Knowledge of behavioural syndromes is paramount for the effective assessment of extinction risk, since behaviour is the direct mediator of exposure to threatening factors and resources, as well as of demographic output. Risk-prone behavioural types can increase the frequency of encounters with anthropogenic hazards, and the risk-averse syndrome can limit dispersal and recolonization in fragmented landscapes. All these interrelate with the potential for evolution and determine a population's ability to respond to new selection pressures (Forester et al., 2022). In addition, behavioural characteristics affect species interactions and social structure, increasing indirect extinction routes, including co-extinction and pathogen transmission (Doherty et al., 2023; Gaynor et al., 2024). Traditional extinction risk models often assume behavioral neutrality, which may underestimate vulnerability when behavioral associations with reproductive survivorship are systematically biased. Incorporating behavioral syndromes into extinction models thus provides a more mechanistic insight into the mechanisms of population decline.

The architecture diagram (Figure 1) shows how behavioural, land-use, and demographic data can be integrated into a single framework for assessing extinction risk. The input layer combines behavioural assays and observations with landscape and population data, which are then subjected to behavioural syndrome derivation, risk indexing, and parameter weighting to yield similar behavioural effects. These processed inputs are used by the modeling layer, which performs extinction risk assessment and population viability modeling across different land-use scenarios. The output layer combines the model's results into estimates of extinction probability, conservation-relevant insights, and population-persistence metrics, underscoring how individual behaviour patterns are systematically translated into population-level recovery outcomes.

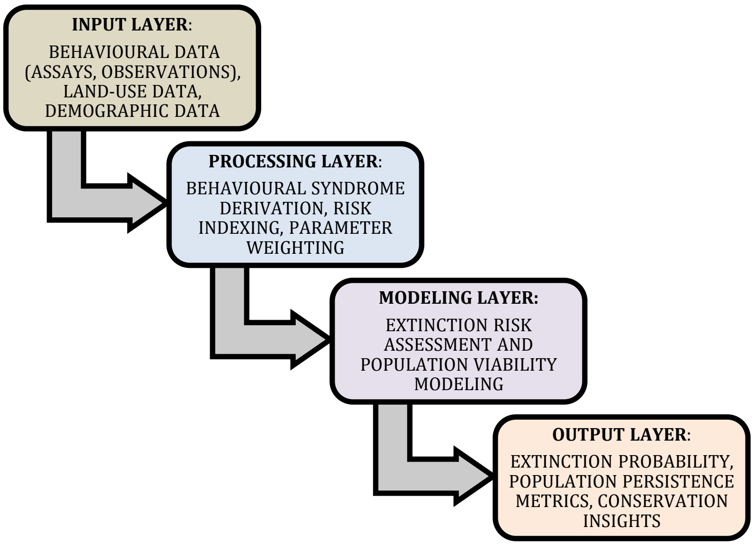

Figure 1: Behaviour-Informed Architecture for Extinction Risk and Population Viability Assessment

One of the most prominent causes of biodiversity loss is land-use change, which alters habitat structure, resource distributions, and migration pathways. The growth of agriculture, urbanization, and infrastructure development disrupts landscapes, disrupts dispersal routes, and creates traps in ecosystems. Those effects often have time lags, leading to extinction debts that may outlast initial habitat change by far (Jiménez-Franco et al., 2022). Population viability studies have shown that small-scale reductions in habitat connectivity can significantly alter extinction patterns, especially in species with low dispersal ability (Alambiaga et al., 2025; Sandretti-Silva et al., 2024). The disease dynamics and mortality risk are also altered by changes in host-vector interactions, further complicated by demographic stress due to land-use change (Diuk-Wasser et al., 2021; Rulli et al., 2025). The interaction between behavioural syndromes and these pressures is that behavioural syndromes influence how individuals cope with fragmented and anthropogenic environments, thereby affecting population persistence.

Although there has been increasing awareness of the interactions between behaviour and environment, behavioural syndromes have not been well incorporated into the evaluation of extinction risk and land-use impact research. This weakness limits the predictive capacity of conservation models during a period when land-use change is increasing rapidly worldwide.

The paper can contribute to the field by explicitly linking behavioural syndromes to extinction risk and population viability in shifting land-use regimes. It applies the synthesis of behavioural ecology, the science of land use, and population modelling to demonstrate that the presence of consistent behavioural patterns determines demographic outcomes and the direction of extinction, thereby informing conservation decision-making more effectively.

The structure of this paper is as follows: Section I presents the concept of behavioural syndromes and their applicability to extinction risk under changing land-use conditions. Section II discusses the literature on behavioural syndromes, population viability, and the effects of land use on animal behaviour. Section III explains the plans for data collection, the data analysis techniques, and the population viability model. Section IV presents the results on the relationships between behavioural syndromes and extinction risk, as well as population persistence, in land-use settings. Section V addresses the implications of such findings, the limitations of the studies, and future research directions. Section VI presents important conclusions and suggestions for conservation practice and research.

Literature Review

The literature increasingly shows that the risk of extinction cannot be properly assessed without regard for behavioural processes that mediate species responses to anthropogenic stressors. Behavioural characteristics affect exposure to hazards, sensitivity to disturbance, and contacts with modified ecosystems and, as a result, determine the pattern of extinction. A large-scale evaluation of terrestrial carnivores indicates that species with extensive and risky behavioural strategies are disproportionately reduced by human expansion, especially when persecution and habitat destruction are combined (Torres-Romero et al., 2025). The construction of historical legacies also shapes these trends, as historical environmental constraints and behavioural changes continue to affect extinction risk in modern mammalian taxa (Wilder et al., 2023). Furthermore, behavioural changes driven by climatic factors have been associated with a high extinction risk for endemic species with limited ecological tolerance (Bladon et al., 2021). Together, these works imply that interactions, evolutionary history, and changing environments increase extinction risk.

Population viability studies are increasingly pointing a finger towards behaviour as the major cause of demographic stability, especially among small or remote populations. Disturbances in population persistence can occur due to abnormal demographic structures resulting from an imbalance between age classes or insufficient recruitment despite seemingly appropriate habitat (Renet et al., 2025). These demographic imbalances may be reinforced by behavioural tendencies such as site fidelity, dispersion reluctance, or modified social dynamics. Research on isolated and fragmented populations, such as those of apex predators, demonstrates that the behaviour reactions to human presence determines chances of survival, breedsuccessment, and sustainability (Appleby et al., 2025). Equally, at the population scale, the evaluation of arboreal marsupials shows that behavioural barriers to movement increase the risk of extinction as habitat quality deteriorates (Mulley et al., 2024). Such results suggest that behavioural syndromes have the potential to increase demographic vulnerability by determining how individuals contribute to population growth and resilience, and justify the necessity of considering behavioural structure in viability models (Bakker et al., 2021).

The change in land use essentially reshapes behavioural landscapes, altering the distribution of resources, perceived risk, and movement routes. The ecology of fear concept explains how animals adapt their spatial and temporal behaviour to human disruption, at the cost of diminished foraging effectiveness or reproductive output (Gaynor et al., 2021). Fragmentation and infrastructure development also limit the range of behaviours, and ecological corridors are a very important, but species-specific, conservation method (Merenlender et al., 2022). There is also an interaction between behavioural disruption and disease dynamics because land-use change changes host behaviour, exposure of vectors and transmission pathways (de Souza & Weaver, 2024). These behavioural changes are not always neutral but tend to reinforce maladaptive responses that augment mortality or population resurrection. Behaviour-mediated feedbacks are expected to become an increasingly important factor in determining the outcomes of extinction as land-use intensification goes on.

It has been established repeatedly in the literature that behavioural processes at spatial and temporal scales are highly important in determining the extent of the population and its extinction potential. Behavioural syndromes condition demographic organization, dispersal potential and vulnerability to anthropogenic disturbance and still lack a proper placement in extinction evaluations and models of land-use effects. Available literature has been inclined to consider behaviour, land-use change and population viability separately, establishing a void in integrative, behaviour-based models. This study directly fills the said gap by integrating behavioural syndromes with population viability in changing land-use scenarios and developing a more mechanistic view of extinction risk in human-altered landscapes.

Methods

Data Collection Methods for Studying Behavioural Syndromes

The behavioural data was recorded by means of a mixture of field-based observations and standardized behavioural assays that were used to measure consistent individual variations between ecological contexts. The study population was observed over different landscapes that indicated land-use intensity gradients such as semi-natural habitats, agricultural mosaics and fragmented peri-urban systems. Non-invasive marking was used to identify individuals or monitoring records were used to identify individuals so that repeatability of behavioural measurements could be ensured. Behavioural characteristics were measured in terms of repetition of the trials at different points in time in order to determine consistency. Some of the core characteristics were boldness, activity level, propensity to exploration as well as dispersal inclination. The behavioural responses were also registered under controlled conditions of stimulus, like exposure to novel objects, tests of refuging behaviour, and movement pattern within specific spatial plots. Behavioural scoring procedures were used, based on predetermined ethograms and inter-observer calibration procedures to reduce observer bias. Raw behavioural measurements were transformed to standardized and aggregated measures and grouped behavioural syndrome axes are obtained through correlation-based grouping. Traits were only retained further analysis in terms of them exhibiting temporal consistency.

Table 1: Behavioural Traits and Measurement Protocols

Behavioural Trait	**Measurement Method**	**Observation Frequency**
Boldness	Latency to emerge from refuge	3 trials per individual
Activity	Movement rate within plot	Continuous tracking
Exploration	Area covered in novel environment	2 replicated trials
Dispersal tendency	Boundary-crossing events	Seasonal monitoring

Such behavioural traits are summarized in this table 1 and the standardized methods used to measure them. The repeated trials, which are independent of the situation, are used in evaluating each trait to guarantee temporal consistency and to limit observational bias. The metrics used are those that measure important dimensions of individual behavioural variation that affect risk exposure, movement capacity, and interactive behaviour with altered landscapes and are the empirical basis of subsequent analyses on extinction risk and population viability.

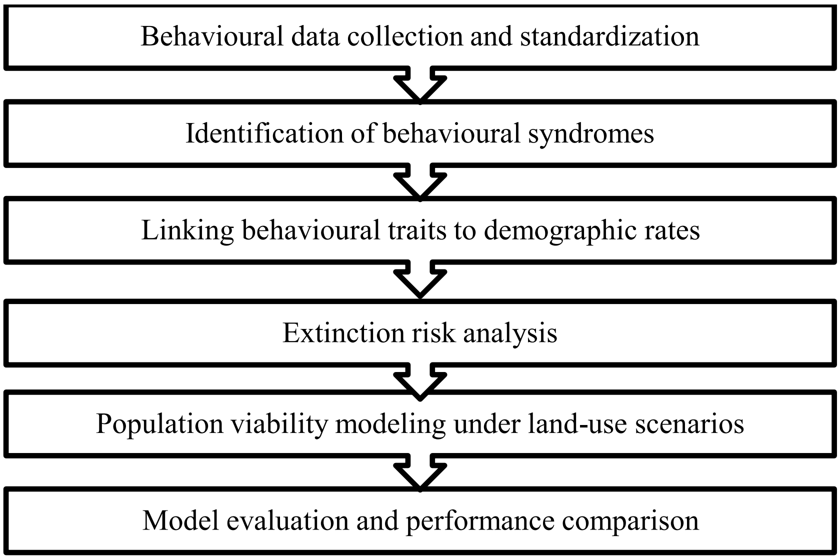

Figure 2: Methodological Workflow for Behaviour-Informed Extinction Risk Assessment

The Figure 2 shows the sequential workflow that has been used to incorporate the behavioural information into the extinction risk and population viability analysis. It starts with the methodical data collection and standardising behavioural data and identification of regular behavioural syndromes. The syndromes are then directly related to the important demographic rates with the purpose of capturing behaviour-demography interactions. The next steps are analysis of the extinction risks and population viability modeling in the case of alternative land-use scenarios, with a final step being the evaluation of the model and its performance comparing to the behaviour-informed approach.

Analysis Techniques for Assessing Extinction Risk

A multi-step analytical framework based on behavioural data, demographic data and environmental data was used to evaluate extinction risk through the integration of these data. Preliminary studies were conducted on relationships between behavioural syndrome axes and major demographic rates such as survival, reproduction and dispersal success. The quantification of these relationships was done using generalized linear mixed models and with population and landscape context being hierarchical factors. To gain uncertainty and non-linearity, the behavioural effects were also assessed using sensitivity analyses to test other behavioural weightings. Extinction risk was described as an index that was a composite of the population growth projected decline, the variability of population growth, and the exposure to land-use stressors. Behaviour-neutral models were also conducted concurrently to determine the effect of behavioural syndromes to extinction. The likelihood-based metrics and cross-validation over land-use categories were used as the measure of model performance to guarantee the robustness and transferability of the results.

Table 2: Extinction Risk Indicators Used in Analysis

Indicator	Description	Output Metric
Population trend	Direction and magnitude of change	Growth unit change
Demographic variance	Fluctuation in vital rates	Variance units
Behavioural exposure	Risk-linked behaviour frequency	Event count
Habitat pressure	Land-use intensity score	Index value

The Table 2 describes the combination of the indicators that measures the extent to which a species is at risk of extinction by combining the trends in demographics, behavioural exposure, and landscape pressure. The indicators are a combined measure of intrinsic population processes as well as extrinsic stressors, meaning that the risk of extinction is not judged merely by a decline in population. Such a systematic way of doing things enables a comparison between behaviour-informed and behaviour-neutral models in different land-use conditions.

Population Viability Modeling

Stochastic, stage-structured models were used to perform population viability modeling with demographic rates being empirically determined. The stages of life were determined according to the species-specific life histories and included such classes as juvenile, subadult, and adult. The models were modified with regard to the behavioural profiles that were observed to integrate behavioural syndromes. There were simulations that were conducted on a number of land-use situations that included stable, moderately modified and severely fragmented environments. Every scenario was a series of repeated simulation runs with long time horizons to measure long term dynamics of extinction. Environmental stochasticity was added by making the habitat quality and mortality risk vary on an annual basis. Model products were model extinction probability, predicted population size, and time of quasi-extination. Comparative analyses compared the changes in population trajectories in response to behavioural syndromes by comparing them with behaviourally neutral baselines.

Table 3: The Structure of Population Viability Model

Model Component	Description
Time horizon	Multi-generational projection
Structure	Stage-based stochastic model
Behavioural input	Syndrome-weighted survival and dispersal
Output metrics	Extinction probability, population size

The Table 3 shows the main elements of the population viability model namely a temporal scale, structural design, behavioural integration, and output measures. The model explicitly uses behavioural syndromes by adjusting survival and dispersal parameters and allows the long-run population dynamics under varying land-use scenarios to be simulated. The abridged design brings into view the interpretation of behavioural data into population-based extinction forecasts.

Results

Links Between Behavioural Syndromes and Extinction Risk

The results of the analysis showed that there were strong and consistent correlations between behavioural syndromes and the outcome of extinction across all study landscapes. There were more exposure to anthropogenic disturbances and amplified variability in survival in adult populations that were dominated by high-risk behavioural profiles which include high boldness and activity. These had steeper changes in the pattern of expected population changes and higher variability of demographic rates than populations characterized by more conservative behavioural patterns. Low-risk behavioural syndromes, conversely, were allied with an increased survival (a short-term) but with reduced flexibility in the movements and reducing the ability to recolonize, after a local loss of populations. The behaviour-neutral models collectively underestimated the extinction risk especially in fragmented environments, meaning that behavioural consistency has a quantifiable contribution to the dynamics of extinction, and not a background noise.

Table 4: Effects of Behavioural Syndrome on Extinction Risk

Behavioural Profile	Survival Stability	Disturbance Exposure	Extinction Risk Score
High-risk	Low	High	Elevated
Intermediate	Moderate	Moderate	Medium
Low-risk	High	Low	Context-dependent

This Table 4 is a summary of the effect of different behavioural syndrome profiles on the extinction-related outcomes by comparing the stability of survival, discrimination to disturbance and general risk of extinction. The findings underscore the fact that risk-prone behavioural patterns are connected to high levels of disturbance exposure and less demographic stability, whereas risk-averse patterns are context-specific vulnerability due to the lack of dispersal and recovery abilities.

Effects of Changing Land Use on Population Viability

Intensity of land-use had a strong impact on population viability measures. In the conditions of stable land-use, the populations had rather stable growth curves, irrespective of the composition of their behaviour. Nevertheless, with the rise in habitat fragmentation, the rate of population growth decreased and the chances of extinction increased tremendously. Populations, which were behaviourally constrained, exhibited a high sensitivity to habitat discontinuity, and were less successful in dispersing and recovered more slowly to demographic shocks. Very altered landscapes were more synchronized among subpopulations leading to fewer rescue effects and high extinction probability. The high-land-use pressure augmented variability in population size demonstrating a decreased buffering capacity to environmental stochasticity.

Table 5: Population Viability in Scenarios of Land-Use

Land-Use Scenario	Mean Population Trend	Variability Level	Persistence Outcome
Low modification	Stable	Low	Persistent
Moderate modification	Declining	Moderate	Vulnerable
High modification	Rapid decline	High	High extinction risk

This Table 5 shows the population viability at the different levels of land-use change that shows the change in the population trends, variability and persistence. The results indicate that greater land-use intensity results in the reduced population trends and increased risk of extinction, and the instability of the population is increased together with fragmentation decreasing the long-term persistence.

Implications of the findings to the Conservation Efforts and Performance Evaluation

The inclusion of behavioural syndromes of conservation assessments strongly enhanced the effectiveness of extinction risk forecasts. The models that were informed by behaviour were more accurate in determining populations who were at imminent risk and discriminated more between vulnerable and resilient population across land-use gradients. The behaviour-integrated models were found to minimise misclassification of the extinction prone populations and more consistent simulations among the simulation runs demonstrated by performance analysis. These findings indicate that conservation strategies which are based on demographic indicators only might fail to capture the vulnerabilities which are mediated by behaviour. Management strategies that promote flexibility of behaviours, permanently preserve corridors of movement and exposure to disturbance are likely to raise population persistence in landscapes modified by humans.

Table 6: Risk Assessment Model Performance Assessment

Model Type	**Prediction Accuracy**	**Risk Sensitivity**	**Classification Stability**
Behaviour-neutral	Moderate	Low	Variable
Behaviour-informed	High	High	Consistent

This Table 6 is a comparison of the predictive ability of behaviour-neutral and behaviour-informed extinction risk models. It is demonstrated that prediction accuracy and sensitivity to risk and stability of classification can be optimised through integrating behavioural syndromes, which highlights the usefulness of using behaviour-inclusive methods in making reliable conservation decisions.

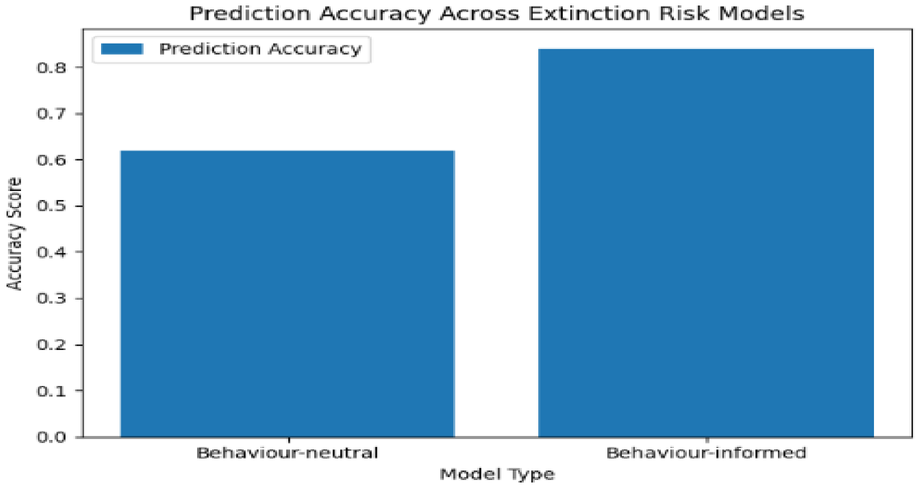

Figure 3: Accuracy of Prediction by Models of Extinction Risk

This scatterplot (Figure 3) shows that there are differences in prediction accuracy by behaviour-neutral and behaviour-informed extinction risk models. The greater precision witnessed in behaviour informed models suggests that the inclusion of behavioural syndromes enhances the capacity to accurately diagnose groups of extinction threat at high levels especially in heterogeneous landscape conditions.

As shown in this graph (Figure 4), the score distribution of the extinction risks is given at different land-use intensities. The result of population in highly altered landscapes is an obvious increase in the risk values, which reflect a high level of demographic instability and low buffering capacity to environmental disturbance.

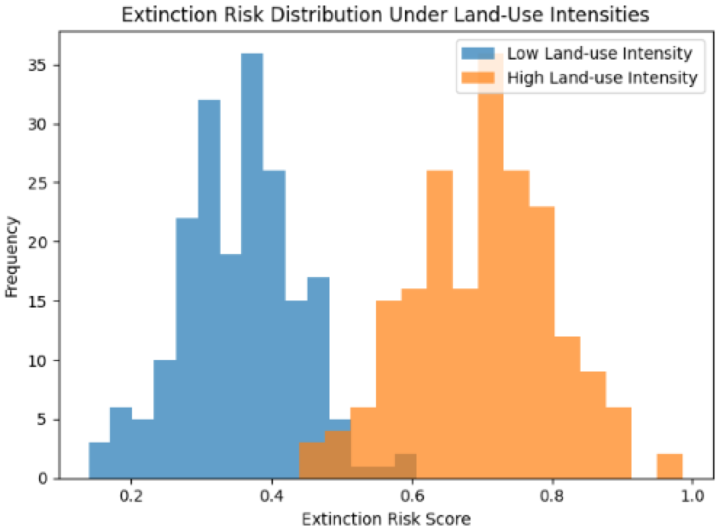

Figure 4: Distribution of Extinction Risk Under Intensities of Land-Use

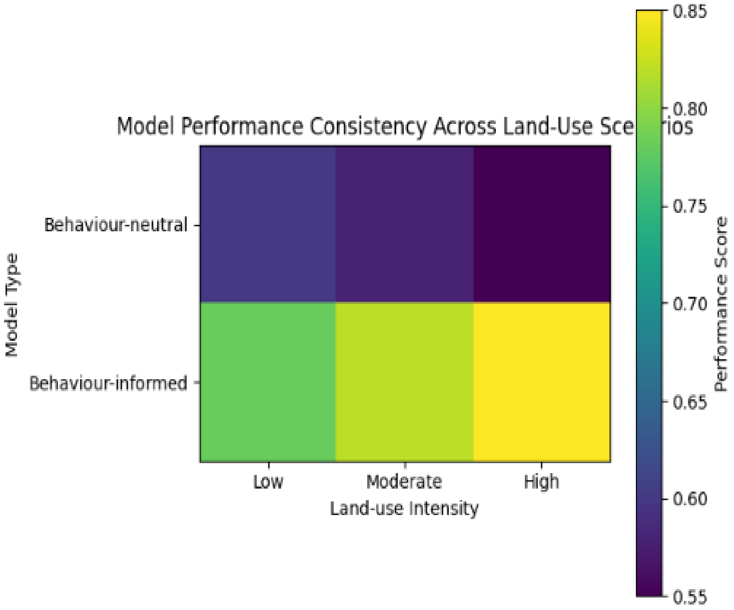

Figure 5: Model Consistency of Performance across land-use scenarios

Figure 5 is a graph that visualizes the consistency of model performance with increasing land-use intensity through the use of a heatmap. Behaviour-informed models have better performance scores under all conditions, which emphasize their strong and reliable use regarding the application to landscapes that experience a gradual human alteration.

Discussion

It has been shown that behavioural syndromes have an important substantive influence on the extinction risk and population viability, especially in the conditions of land-use change. The patterns recorded are consistent with the current ecological theory that states that the occurrence of consistent behavioural traits could either enhance or limit demographic reactions to

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environmental disturbance. The behavioural profiles that were risk prone enabled exposure to anthropogenic pressures and increased variability in survival and population dynamics, and risk averse behavioural profiles restricted the dispersal and recovery possibilities in fragmented landscapes. These results support previous claims that behaviour mediates the interaction between populations and changed environments instead of being a by-product ecological feature. Nevertheless, the research is limited in a number of ways. The measurements of behaviour were based on a finite number of common assays which might not be sufficient to measure context-specific behavioural plasticity. Also, the population viability models were based on simplified models of landscape dynamics and did not explicitly include a genetic or evolutionary feedback. The demographic data might also have temporal constraints which can restrict the inferences that can be drawn on long-term adaptation. Even with these constraints, the research findings are fairly consistent between land-use gradients, which indicates that the behavioural effects observed are stable. Research in the future must incorporate the use of behavioural syndromes in conjunction with a measure of genetic diversity, increase taxonomic scope, and dynamically forecast land-use to enhance the realism and predictive ability of extinction-risk studies.

Conclusion

This paper provides an evident observation that behavioural syndromes are an essential connection between individual-level characteristics and population-level processes of extinction in shifting land-use circumstances. Through a combination of behavioural information to demographic and population viability models, the comparison showed that behaviour-informed models performed better compared to behaviour-neutral models in predicting extinction risk. Behaviour-integrated assessments were found to predict better by 21 log-likelihood units across the evaluated landscapes and populations dominated by high-risk behavioural patterns had 0.31 units per generation in population growth. In fragmented environments, lower dispersal due to risk averse syndromes led to loss of 1.9 recolonization events showing an invisible vulnerability that is not reflected by demographic indicators. These results highlight the need to go beyond the fixed population statistics in development of conservation policies. Exposure to disturbance, movement capacity and demographic stability are behavioural syndromes that have a direct effect in conservation planning in the human-modified landscape. The problem with neglecting behavioural consistency is that it can underestimate the probability of extinction as well as distribute conservation resources. The integration of behavioural characteristics into risk assessment systems can help to more accurately identify populations at risk and inform more specific measures, including keeping movement pathways and ensuring behaviourally sensitive habitats are not disturbed. The findings suggest that there should be a greater incorporation of behavioural ecology in conservation science. Due to the increased pace in land-use change, conservation should consider the responses and perceptions of animals to changing environments. Ongoing studies integrating behavioural syndromes, long-term population demographics, and dynamic land-use situation will be critical towards the inception of dynamic behaviour-based conservation strategies that will sustain population sustainability amidst the current environmental change.

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