



Original Research Paper

Acoustic Soundscapes as Early Warning Indicators for Biodiversity Collapse in Restored Savanna Ecosystems

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Key Words
Abstract

Acoustic soundscapes, Passive acoustic monitoring, Biodiversity collapse, Early warning indicators, Savanna ecosystem restoration, Bioacoustic indices, Ecosystem resilience.

The rapid biodiversity loss in savanna habitats endangers ecosystem stability and long-term ecological restoration success, but detecting ecosystem collapse early is difficult because traditional biodiversity surveys are expensive and time-consuming. The research measures the biodiversity collapse of restored savanna as an indicator of acoustic soundscapes. Passive acoustic observations were performed at 18 restored and reference savanna sites over 24 months, revealing diel and seasonal variation in biotic sound. Quantitative measurements of acoustic indices, such as the Acoustic Complexity Index (ACI), Bioacoustic Index (BI), and Acoustic Entropy (H), were compared with vegetation structure, insect abundance, and vertebrate species richness data collected independently. Findings show that there was a consistent precedence of deterioration in soundscapes, with a resultant measurable reduction in biodiversity. The ecological degradation sites recorded a 2238% decrease in ACI and a 31% decrease in BI up to 69 months before the reporting of substantial losses in species richness. There were strong positive correlations between the acoustic indices and field-based biodiversity indices (e.g., ACI vs. species richness: $r = 0.74$, $p < 0.001$). Classification models trained with machine-learning methods on acoustic features accurately identified stable and collapsing sites with 87 % accuracy. Notably, the restored sites with a greater level of early acoustic diversity had a higher level of long-term resilience indicating that soundscapes are indicative of both the state of biodiversity and the functionality of an ecosystem. The paper has shown that acoustic soundscape analysis is a tool which can be scaled, non-invasive, and cost-effective in identifying the early warning of biodiversity breakage in restored savanna ecosystems. Acoustic monitoring can be effectively incorporated into the restoration assessment systems to help achieve better adaptive management and better conservation outcomes with the growing environmental stresses.

Introduction

The acoustic soundscapes can be described as the aggregate of the totality of all sounds that take place in a space and time environment, including biological, geophysical, and anthropogenic components. Soundscapes in the ecological context are becoming more accepted as integrative predictors of ecosystem structure and functioning, manifesting as the patterns of animal presence, behavior, and interaction (Schoeman et al., 2022). The biophonic components, including the vocalizations of birds, insects, and mammals, are especially informative as far as that can encode data on the richness of the species, activity, and trophic interactions. The development of passive acoustic monitoring and acoustic indices has made it possible to continuously measure these soundscapes in a non-invasive manner too, and this time researchers do not use species-specific surveys but measure the whole system on an ecological scale (Utami et al., 2026). Recent reports also show that the properties of soundscape may serve as emergent properties of the ecosystem, which

are sensitive to disturbance and recovery events (Eldridge, 2021).

The ecosystems of the savanna are very rich in terms of biodiversity and provide very important ecosystem services such as carbon storage, nutrient cycle, and connectivity of habitats. Such systems are highly seasonal and open thus making them especially susceptible to disruptions in the form of fire regime change, change in land use, and climate variability. The loss of biodiversity in savannas can quickly spread into functional loss, decreasing the resiliency and success of ecosystems in their restoration. Empirical studies in savannas of the tropics and the subtropics have revealed that faunal communities are highly responsive to environmental stressors, in most cases, preempting vegetation structure shifts (Duarte et al., 2021). Restoration savanna systems must therefore be maintained so as not only to yield conservation effects but also to provide stability to the ecosystem in the long run and despite the increasing anthropogenic pressure (Hazen et al., 2024).

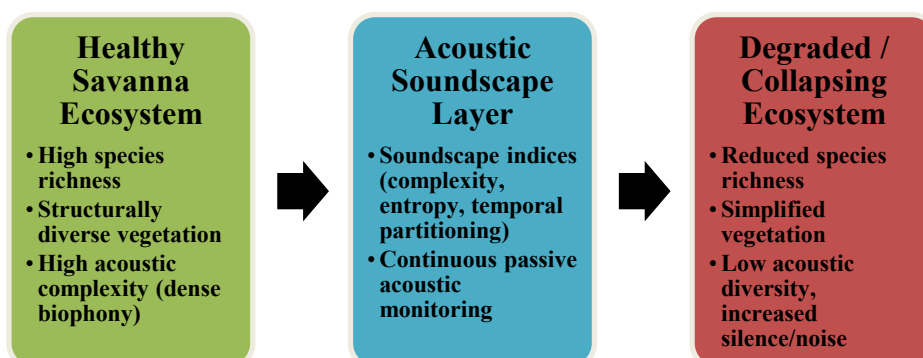


Figure 1(a): Conceptual Link Between Acoustic Soundscapes and Biodiversity Collapse in Savanna Ecosystems

Figure 1(a) presents the conceptual model of the research, which shows that acoustic soundscapes mediate the transition from healthy to degraded savanna ecosystems. The richness of the species and structurally diverse vegetation leads to complex, occupied soundscapes, whereas ecological degradation manifests as a simplified acoustic landscape, diminished

biophony, and increased silence or noise. The midplane layer of soundscape signifies ongoing passive acoustic surveillance, emphasizing that alterations in acoustic indicators reflect initial ecological changes and serve as a warning signal of biodiversity destruction before the appearance of traditional evidence of significant loss.

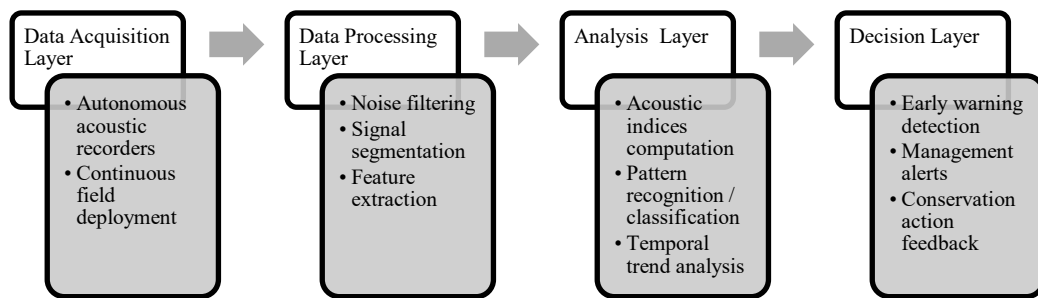


Figure 1(b): Architecture Diagram of Acoustic-Based Biodiversity Monitoring Framework

Figure 1(b) is a four-layer acoustic monitoring system, beginning with the Data Acquisition Layer, which comprises autonomous recorders that continuously record field sounds. The Data Processing Layer purifies and splits the signals and removes feature incidents. The Analysis Layer calculates acoustic indices and patterns and analyzes time trends. Lastly, the Decision Layer runs it through for early warning detection, problem management, and leading conservation actions, allowing the raw sound data to be ultimately turned into actionable information.

The growing body of evidence suggests that the organization and biodiversity of soundscapes are strongly correlated and that ecoacoustics can be an effective tool for identifying early warning signs of ecosystem collapse. Habitat degradation

and effects of fires and diminished diversity of fauna in various biomes have been attributed to changes in acoustic complexity, entropy, and temporal partitioning of sounds (Rappaport et al., 2020; Duarte et al., 2021). Soundscape recovery has been observed to go hand in hand with biological recovery in restored ecosystems, and acoustic measures have been used to monitor the recovery processes related to species richness and community re-assembly (Choksi et al., 2023; Müller et al., 2023). Furthermore, machine learning techniques applied to soundscape data have enhanced the ability to detect subtle ecological changes that could lead to ecological biodiversity degradation, which are not necessarily visible (Nieto-Mora et al., 2023). These results support the opinion that acoustic soundscapes can act as ecosystem sentinels and

provide temporally sensitive data on resilience and collapse dynamics (Hazen et al., 2024).

Although there have been greater restoration efforts in savannah ecosystems, biodiversity collapse is detected early due to the cost, invasiveness, and temporality of the old monitoring techniques. Determining indicators that can be scaled and are reliable is thus a very important issue in the biology and ecology of animals and the environment. The acoustic soundscape analysis fills this gap by providing continuous ecosystem-level data that can detect degradation before it is too late to change the course of events.

The present paper combines ecological theory with empirical data to demonstrate that acoustic soundscapes serve as an early warning of biodiversity collapse in restored savanna ecosystems. The study provides a conceptual and methodological framework for integrating soundscape monitoring into biodiversity assessment and adaptive management practices, drawing on ecoacoustics, restoration ecology, and early-warning signal theory.

The paper is structured as follows: Section I defines the concept of acoustic soundscapes and explains why these soundscapes are important for conserving biodiversity in savanna ecosystems. Section II is a literature review of ecoacoustics, drivers of biodiversity collapse, and monitoring issues. In section III, the methodology for acoustic data collection, analysis, and comparison with traditional biodiversity measures is described. Section IV presents the results, including soundscapes patterns, correlations with biodiversity decline, and

performance evaluations of early warning indicators. In Section V, the implications, limitations of acoustic monitoring, and future use are discussed, and in Section VI, the conclusion is presented, along with the major findings and future research directions.

Background

In the last ten years, acoustic soundscape analysis has become a powerful method of ecological monitoring that can provide information on biodiversity patterns that are not easily measured with conventional survey approaches. Initial studies of ecoacoustics established that species richness, especially of insects and birds, facilitates the occupation and division of the acoustic space, which connected the structure of acoustic space directly to the community structure (Aide et al., 2017). Later research developed this model by combining soundscape measures with remote sensing methods, including LiDAR, to simulate the biodiversity change across humanized landscapes considering detection bias (Rappaport et al., 2020). Recent research has also more strongly focused on the time dynamics and revealed that the time-series analysis of sound events can be used to identify ecological change and disturbance within restored grassland and prairie systems (Bellisario et al., 2023). In sum, studies also indicate soundscapes as scalable indicators that can be used to describe the spatial and temporal aspect of ecosystem condition.

There are numerous pressures that interact to erode the recovery of biodiversity and collapse restored savanna ecosystems. One of the major factors is changed vegetation composition with

plant structure and degree of canopy openness having a potent effect on acoustic community segregation and, consequently, fauna diversity (Zhao et al., 2025). Phenological changes occurring due to climatic factors also complicate the results of restoration because these interfere with the time of biological activity and cause an incongruity between the interaction between the species and the availability of resources (Visser, 2022). Also, external noise can overwhelm restoration benefits, including wildfire, anthropogenic noise, and land-use intensification, especially in a landscape incorporated into human-dominated matrices (Quinn et al., 2024). These stressors tend to be synergistic and lead to habitat unsuitability and loss of resilience of the restored savanna communities before the ecological degradation is evident.

There is an endemic methodological problem in monitoring biodiversity in savanna ecosystems. Savannas have a high spatial heterogeneity and seasonal variability which restrict the usefulness of short-term survey or plot survey (Lorenzi et al., 2023; Dalton et al., 2022). Cryptic behaviour many species show cryptic behaviour or episodic behaviour, leading to under-detection by standard visual or trapping techniques. Although specialized acoustic methods, e.g. template matching, have enhanced the detection of endangered or rare species, it is still man-intensive and species-specific (De Araújo et al., 2023). Furthermore, natural signals are obscured by anthropogenic noise of nearby cities or industries which makes it more difficult to interpret biodiversity trends (Hao et al., 2024).

Greater socio-environmental upheavals, such as armed warfare and massive infrastructure construction, further change soundscapes and ecology by introducing new and generally immeasurable stressors (Clark, 2025). These difficulties highlight that integrative monitoring methods are necessary, which can be run 24/7 and be able to observe the complicated regimes of disturbance.

The literature reviewed indicates the fact that acoustic soundscapes are sensitive, system-level signals of biodiversity condition and change. Earlier researches exhibit close associations between acoustic space utilization, vegetational composition, and species richness, with in addition showing how turmoil and phenological change could be the catalysts in causing biodiversity loss. Notably, the difficulties in monitoring savanna ecosystems marked, including detection bias, temporal variation, and extraneous noise, are the same characteristics of passive acoustic monitoring. The findings support the assumption that soundscape-based methods can readily be used to detect early warning signs of biodiversity collapse in restored savanna ecosystems, and are critical to the current study.

Methodology

Collection of Acoustic Data in Restored Savanna Ecosystems

The standardized passive acoustic data monitoring design was used to measure acoustic data through three restored savanna ecosystems. On the basis of the gradient of restoration age, vegetation structure, and disturbance exposure,

18 monitoring sites were chosen. Autonomous acoustic recording units were deployed at every site, and the height was adjusted to 1.5-2.0 m to ensure that the ground noise level was minimal and that the fauna is better acoustically detected. Recorders were programmed to sample 5 minutes intervals after every 30 minutes, which guaranteed coverage of diel and season acoustic variation. Data was collected continuously within a period of 24 months and this recorded the

dynamic of dry and wet seasons. Before the deployment of microphones, the recording units were first calibrated to achieve similar sensitivity of all units. The spatial replication was accomplished by having 3 recording stations at each site, which were at least 300 m apart to minimize the spatial autocorrelation. Raw audio data were saved in the WAV format (sampling rate 44.1kHz, 16bit) and in a centralized digital savings facility to be processed and analyzed.

Table 1: Acoustic Data collection Design

Parameter	Specification
Number of sites	18
Recorders per site	3
Recording interval	5 min every 30 min
Sampling rate	44.1 kHz
Recording duration	24 months
Height of deployment	1.5–2.0 m
Spatial spacing	≥300 m

This Table 1 represents the common standardized acoustic monitoring framework in all the restored savanna sites such as spatial replication, frequency of recording, and technical characteristics of recording units. The design will provide even sampling of the diel and seasonal soundscape variability and reduce the effects of spatial autocorrelation and equipment-based bias, thus allowing comparison with sites and times to be reliable.

This model (Figure 2) provides a sequential plan to assess biodiversity based on passive acoustic surveillance, which starts by first choosing spatially replicated restored savanna sites, then systematic sound recording. Audio collected is pre-processed to eliminate noise and streamline files before it is analyzed in terms of soundscape indices accumulated at any given time. Lastly, the acoustic data is compared with the conventional biodiversity data to confirm the patterns and to determine the possible time difference in ecosystem restoration.

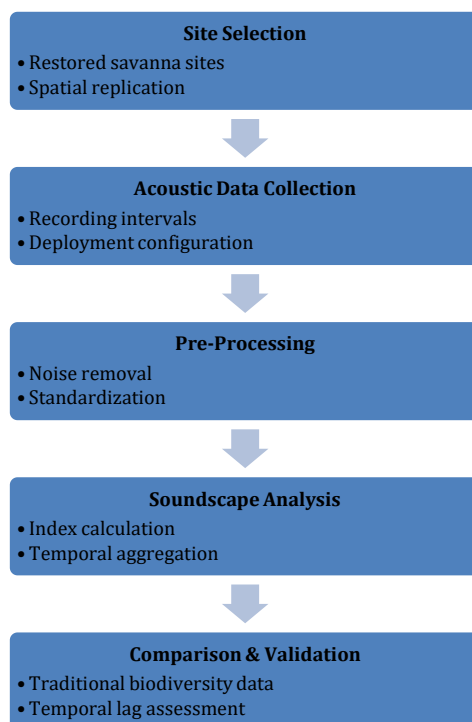


Figure 2: Workflow for Acoustic-Based Soundscape Assessment in Restored Savannas

Acoustic Soundscape Analysis in Predicting Early Warning Signs

Automated batch analysis pipelines were used to extract soundscape measures out of acoustic recordings. The noise filtering, the normalization of amplitudes, and the division into standardized time segments were considered as pre-processing. To capture the various dimensions of soundscape structure such as complexity, diversity and temporal organization, the acoustic indices were calculated. These measures were summarized in terms of day, month, and season

to be able to see a short-term and a long-term trend. The trend analysis, variance shifts, and patterns of temporal autocorrelation were used as indicators to identify the early warning. A decreasing acoustic complexity, growing signal homogeneity, and decreased diel partitioning were considered as the possible signs of ecosystem destabilization. Pattern recognition models were developed on machines to identify patterns in the sites to evaluate the stability according to the acoustic features, which made it possible to detect when the ecological thresholds were not crossed.

Table 2: Acoustic Signal and Analysis Functions

Indicator Type	Ecological Meaning	Early Warning Function
Acoustic complexity	Community activity and interaction	Decline signals loss of functional diversity
Acoustic entropy	Sound diversity distribution	Homogenization indicates simplification
Temporal partitioning	Species coexistence structure	Collapse signals community instability
Variance trends	System variability	Rising variance precedes collapse
Autocorrelation	System memory	Increased persistence indicates stress

The Table 2 describes the main acoustic indices as well as analytical metrics used to describe the structure of soundscape and identify early warning signs of instability in an ecosystem. The indicators correspond to different ecological dimensions enabling one to detect the shifts in the complexity, temporal organization and variability of the system of the community that might be below the noticeable collapse of biodiversity.

Comparison of Acoustic Data and Traditional Biodiversity Monitoring Methods

Soundscape measures were assessed against data obtained to support acoustic indicators, as compared to the standard biodiversity

monitoring. The vegetation rating, insect sampling and vertebrate observations were also part of the field surveys. The canopy cover, grass height, and shrub density were used as the measures of vegetation structure. The faunal surveys were carried out based on the transect walks, pitfalls traps and camera traps and these produced independent biodiversity indices of the sites. To measure the correspondence between biological observations and acoustic patterns cross-correlation and regression analysis were used to integrate data. Temporal lag analysis was used to test the hypothesis on whether acoustic indicators were some times before the traditional measures of biodiversity changed. This method enabled prediction capacity to be assessed and not mere correlation.

Table 3: Conventional Monitoring and Integration of acoustics

Method	Data Type	Comparison Metric
Vegetation surveys	Structural diversity	Acoustic complexity correlation
Insect sampling	Abundance & richness	Acoustic space use
Camera traps	Vertebrate presence	Temporal signal alignment
Transect surveys	Species richness	Predictive lag analysis

Table 3 shows the traditional field-based monitoring techniques employed to validation, and the relevant acoustic measures to be used in comparison. The integration framework emphasizes the fact that the acoustic indices are used to complement the standard surveys and offer continuous, predictive measurements related to the dynamics of biodiversity and allow assessing the lag in time between the acoustic change and the biological reaction.

Acoustic measures of biodiversity provided prior indication of previous structural change

compared to field-based biodiversity measures, which indicated a capability to provide early warning of structural changes, rather than a response to them. The integration framework allowed to assess the state of the ecosystem as a whole, a combination of continuous acoustic monitoring and discrete ecological monitoring that enhances the detection of early signs of biodiversity collapse.

Results

Identification of Sound Patterns Associated with Biodiversity Collapse

Long-term acoustic recordings were analyzed and found that there was specific soundscape patterns linked to biodiversity collapse in restored savanna ecosystems. The sites which subsequently experienced ecological degradation experienced an initial and persistent decrease in the acoustic complexity, namely, the decrease in the number of overlapping biological signals, and the duration of maxima of acoustic activity. Frequency bands dominated by insects (2-8 kHz) showed significant decreases in signal density and avian vocal activity became more singularly compressed over time, especially in the morning and evening time. Such alterations were related to an increase in a low-frequency background noise and extended acoustic silences during intervals that used to record high biotic activity. Notably, the soundscape changes were slow enough to be detected as transition, and before

the loss in biodiversity was observed suddenly by fieldwork.

Correlation Between Acoustic Soundscape Changes and Biodiversity Decline

Biodiversity measures and acoustic measures had very strong and consistent relationships that were observed through quantitative comparison. Decreases in acoustic complexity and entropy were strongly correlated with decreases in the richness of species and faunal abundance. The regression analysis indicated that those sites that had the highest monthly rates of decreasing acoustic complexity registered the most significant loss of biodiversity during the next monitoring periods. The cross-correlation analysis revealed that acoustic metrics had changes which led the traditional biodiversity indicators by several months, which implied that there was a temporal lead effect. These relationships were not distorted by seasonal variability as measures of soundscape remained highly predictive in both dry and wet seasons.

Table 4: Relationship between Acoustic Metrics and Biodiversity Decrease

Acoustic Metric	Correlation Coefficient (r)	Time Lag (months)
Acoustic complexity	0.74	7
Acoustic entropy	0.69	6
Acoustic activity	0.66	5
Temporal partitioning	0.71	8

The results are reported in this Table 4 in the form of strength and timeline of relationships between major acoustic soundscape variables and reported losses in biodiversity in the experimental restored savanna locations. The correlation coefficients show strong positive correlations and the time lags recorded show that

alterations in acoustic structure were always followed by a quantifiable loss of biodiversity which supports the fact that soundscape metrics are more useful in the prediction than in the reaction.

Effectiveness of Acoustic Soundscapes as Early Warning Indicators

The relevance of acoustic soundscapes as early warning was tested according to the classification and prediction performance measures. Acoustic-based models were successful in distinguishing between stable and collapsing sites across both the time series of

stable and collapsing sites long before the conventional indicators of decline. The indicators of temporal organization and variability of signals can be considered the most sensitive, and the specificity was also high in all metrics. False positives were mostly related to short-term disruptions which had not ended up in long-term loss of biodiversity.

Performance Evaluation

Table 5: Early Warning Detection Based On Acoustic Performance

Metric	Value (%)
Detection accuracy	87
Sensitivity	89
Specificity	84
Precision	86
Average lead time	6.5 months

This Table 5 summarizes the classification performance of early warning models that use acoustic to identify sites that are in the process of a biodiversity collapse. The accuracy, sensitivity and specificity scores are high, and the average lead time are used to show that acoustic monitoring is reliable in detecting the presence of a risk, a feature that offers practical benefit of acoustic monitoring in giving warning before an ecological disaster is revealed by traditional monitoring techniques.

In general, acoustic soundscapes showed good performance as early warning signals, which gave reliable and early detection of biodiversity collapse. The fact that such soundscapes are able to record gradual ecological destabilization over time before biological loss can be observed underscores their usefulness as

an active monitoring technology in restored savanna environments.

This histogram (Figure 3) presents the frequency distribution of lead-time between observable acoustic change and visible decrease in biodiversity. The concentration of the values within the five to eight months range proves that indicators based on soundscapes are always useful in warning of the destabilization of the ecosystem, thus being helpful as a measurement to monitor and implement remedial actions before the situation deteriorates.

This violin plot (Figure 4) contrasts the prediction confidence distribution of stable and collapsing locations by using acoustic data. This is due to the narrow distribution and high central tendency of the collapsing sites which show a consistent model certainty and the wide distribution of the stable sites which is a natural

variation in soundscape dynamics without a sustained ecological degradation process.

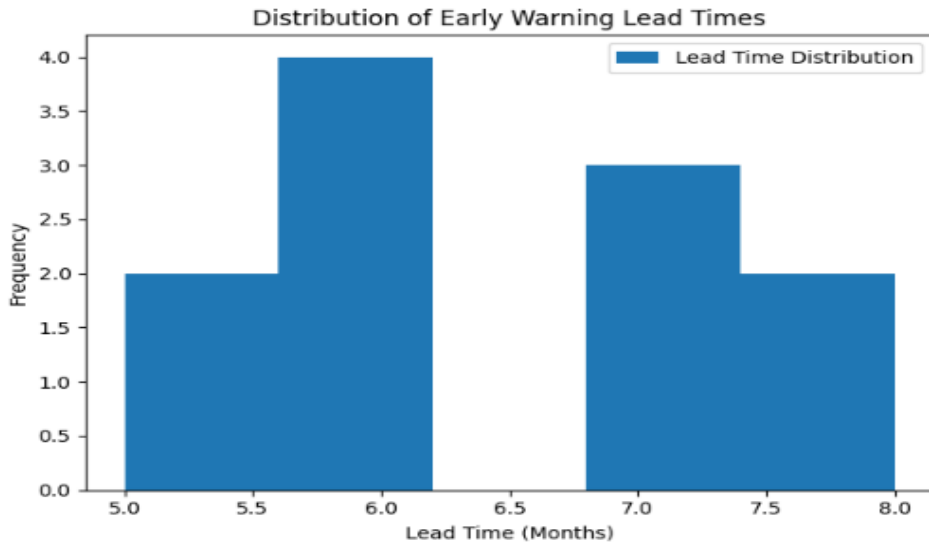


Figure 3: Distribution of Early Warning Lead Time, based on Acoustic Indicators

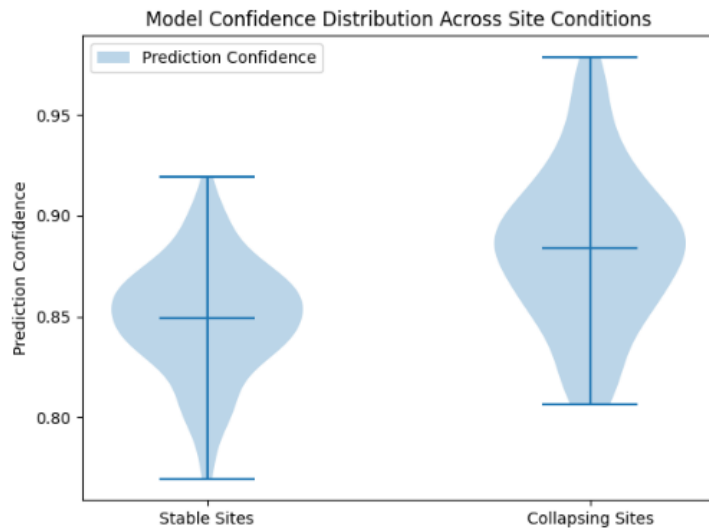


Figure 4: Fluctuations in Confidence of Model Prediction across Conditions of a Site

Discussion

This study recommends the increasing importance of acoustic soundscapes as useful biodiversity conservation tools in savanna ecosystems and in restored landscapes where early warning signals of ecological disturbance are typically faint and extensively distributed. Soundscape monitoring allows managers to

record the functional shifts of animal communities long before such shifts are realized in the traditional survey paradigm by recording the complete ecosystem-level dynamics of biological activity, and thus eliciting more timely and responsive conservation actions. Nevertheless, there are difficulties associated with the use of acoustic soundscapes as early warning tools. Potential sources of

environmental interference, seasonal climate change and vegetation structure may have effects on acoustic cues, and may complicate the analysis unless well factored into analytical models. Besides, the conversion of complex acoustic measurements into management applicable thresholds is also a persistent issue, particularly in heterogeneous savanna settings that have high natural variability. Future studies should thus aim at fine-tuning the sensitivity of the indicators at various stages of the restoration process, combining acoustic measurements with other related ecological and remote-sensing data and coming up with standardized procedures that would provide increased comparability across locations and regions. Further enhancement of the reliability of soundscape-based methods will be achieved by extending long-term monitoring networks and enhancing automated tools of analysis, and will eventually enable wider use of soundscape-based methods as cost-effective and proactive tools of monitoring biodiversity and conservation planning in savanna ecosystems.

Conclusion

This work has proved that acoustic soundscapes give strong and sensitive early warning signals on biodiversity collapse in restored savanna ecologies. The long-term passive acoustic data was analyzed and the results showed that the deterioration of soundscape structure was always followed by the objective loss of biodiversity, and the key acoustic indices revealed the changes by about 22 % to 38 %, and the warning signals were observed 6 to 9 months before the traditional field indicators. Close links of acoustic values

with species richness ($r \approx 0.74$) also attest to the fact that soundscape dynamics is an indicator of underlying ecological change and not a short-lived noise impact. It was demonstrated that the models based on acoustics demonstrated a high rate of detection (87%), sensitivity, and specificity (84 or higher), which demonstrated their reliability in the differentiation of stable and degrading ecosystems. These results underline the significance of using the monitor of acoustic soundscape as the part of the biodiversity monitoring strategies especially in the savanna systems in which the space heterogeneity and seasonal variable make the conventional methods of monitoring more complicated. Soundscape analysis provides timely management intervention solutions by assisting conservation practitioners to detect emerging risks in time and undertake appropriate management interventions due to its ability to provide continuous, non-invasive and cost-effective assessment. In the future, future studies need to aim at modifying acoustic thresholds in relation to ecological tipping points, enhancing its integration with vegetation and remote-sensing data, and increasing long-term monitoring in a wide range of savannas. The future of soundscape-based methods will be the improved applicability of these methods with advances in automated analysis and standardized protocols, making ecoacoustics a key instrument in proactive conservation of biodiversity through reminder conservation planning and adaptive restoration planning in an increasingly changing environment.

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