Proceedings of the 7th International Conference on Statistics: Theory and Applications (ICSTA'25)
Paris, France - August, 2025
Paper No. 151
DOI: 10.11159/icsta25.151

Assessing Ecosystem Dynamics under Disturbance: A Hidden Markov Model Framework for Species Detection Data

Litty Mathew[1], Caroline Brophy[1], Ian Donohue[2], Samuel RP-J Ross[3] and Silvia D' Angelo[1]
[1] School of Computer Science and Statistics, Trinity College Dublin, Dublin 2, D02 PN40, Ireland
mathewli@tcd.ie; caroline.brophy@tcd.ie; dangelos@tcd.ie
[2] School of Natural Sciences, Trinity College Dublin, Dublin 2, D02 PN40, Ireland
DONOHUI@tcd.ie
[3] Integrative Community Ecology Unit, Okinawa Institute of Science and Technology Graduate University, Okinawa, 904-0495, Japan
S.Ross.Res@outlook.com

Extended Abstract

Pulse disturbances are sudden and short-term disruptions in ecological conditions that can play an important role in ecosystem dynamics. As the impacts of global environmental change worsen, understanding imbalances caused by disturbances such as typhoons, heatwaves or wildfires is necessary for early conservation interventions to mitigate long-term ecological change [1]. Advances in passive acoustic monitoring have enabled continuous monitoring of ecosystems and “soundscapes” by generating high-resolution, real-time acoustic data across space and time [2]. Vocalising animal species can be identified from audio files using automated tools that incorporate machine learning algorithms trained on large libraries of animal sounds [3]. Processed acoustic time series data can provide valuable insights into species distribution and behaviour changes in response to disturbances. Ecosystem dynamics can be represented by different underlying states, capturing varying levels of stress in an ecosystem. These underlying states cannot be observed directly but can be inferred from observed ecological data such as species detections [4].

Hidden Markov models (HMMs) are statistical tools for analysing time series data by combining observations at discrete time points with underlying discrete state processes. HMMs can account for autocorrelation in species detections, incorporate environmental covariates to address non-stationarity, and capture short-term ecological memory through the Markov property, making them suitable for studying ecosystem dynamics and abrupt change [4]. Here we present a HMM-based framework to identify periods of increased variability in species detections that may be associated with disturbances. Our framework applies a log difference transformation to the species detection data and measures the change in vocalisation between consecutive time points to directly assess temporal variability, a key component of ecosystem stability [5]. We fitted and compared a range of Gaussian HMMs that varied in their number of states, constraints on state-specific means, and covariates included. Our model selection process was based on a combination of in-sample and out-of-sample methods that balanced fit, forecasting ability, and biological relevance.

We applied our framework to bird detection time series from the Okinawa Environmental Observation Network (OKEON), which includes a multi-site passive acoustic sensor array across the main island of Okinawa, Japan [6], [7]. We considered log-transformed changes in vocal activity between consecutive days for three focal bird species across 66 days in 2018, during which two category-five typhoon pulse disturbances hit the area. We also explored the influence of wind speed and precipitation on the hidden state dynamics using non-homogeneous HMMs. Based on the model selection process, we identified a parsimonious three-state zero mean constraint HMM and a more flexible non-homogeneous alternative incorporating precipitation. These models identified normal, warning, and disturbed states, characterised by low, medium, and high variability, respectively. A warning state was detected before each transition to disturbed states, which aligned with the typhoon disturbances in the data. This indicated the potential of our approach to provide an early warning system for identifying time periods of increased variability that may be driven by disturbance. Our framework can be applied to derive ecological insights from acoustic monitoring data across diverse ecosystems.

References

[1] A. Jentsch and P. White, “A theory of pulse dynamics and disturbance in ecology,” *Ecology*, vol. 100, no. 7, p. e02734, Jul. 2019, doi: 10.1002/ecy.2734.

[2] R. Gibb, E. Browning, P. Glover-Kapfer, and K. E. Jones, “Emerging opportunities and challenges for passive acoustics in ecological assessment and monitoring,” Methods Ecol. Evol., vol. 10, no. 2, pp. 169–185, 2019.

[3] J. Cauzinille, B. Favre, R. Marxer, and A. Rey, “Applying machine learning to primate bioacoustics: Review and perspectives,” Am. J. Primatol., vol. 86, no. 10, p. e23666, 2024, doi: 10.1002/ajp.23666.

[4] B. T. McClintock, R. Langrock, O. Gimenez, E. Cam, D. L. Borchers, R. Glennie, and T. A. Patterson, “Uncovering ecological state dynamics with hidden Markov models,” Ecol. Lett., vol. 23, no. 12, pp. 1878–1903, Dec. 2020, doi: 10.1111/ele.13610.

[5] D. Tilman, “Biodiversity: Population Versus Ecosystem Stability,” Ecology, vol. 77, no. 2, pp. 350–363, 1996, doi: 10.2307/2265614.

[6] S. R. P.-J. Ross, N. R. Friedman, K. L. Dudley, M. Yoshimura, T. Yoshida, and E. P. Economo, “Listening to ecosystems: data-rich acoustic monitoring through landscape-scale sensor networks,” Ecol. Res., vol. 33, pp. 135–147, 2018.

[7] S. R. P.-J. Ross, N. R. Friedman, K. L. Dudley, T. Yoshida, M. Yoshimura, E. P. Economo, D. W. Armitage, and I. Donohue, “Divergent ecological responses to typhoon disturbance revealed via landscape-scale acoustic monitoring,” Glob. Change Biol., vol. 30, no. 1, p. e17067, 2024.