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BioTrack: Adaptive Population Dynamics Model for Long-Term Monitoring of Threatened Wildlife Species

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Key Words

Population dynamics, Adaptive modeling, Wildlife monitoring, Threatened species, Biologging, Conservation management, Predictive ecology.

Abstract

Long-term monitoring of endangered animal populations faces increasing difficulties due to disjointed data streams, non-stationary environmental factors, and poor adaptability of classical demographic models to changing monitoring conditions. This paper proposes BioTrack, an adaptive population dynamics model capable of accommodating heterogeneous biologging, telemetry, and survey data into a unified framework for estimation of endangered species' populations. Contrary to static demographic models, BioTrack continuously updates its parameter set as more observations become available and thus allows estimating population trajectories, survival probabilities, and dynamic demographic signals triggered by individual movements. The proposed framework was tested on historic monitoring data of endangered terrestrial and avian species' populations, with the evaluation performed via the prediction accuracy of population trajectories obtained with respect to the periods of observation withheld for test purposes. The results show that adaptability of the BioTrack framework allows for improving tracking of short-term fluctuations in population trajectories and individual behavior over static approaches while maintaining interpretability for conservationists. The implications of the proposed approach for long-term monitoring of conservation, its comparison with other population modeling approaches, and its applicability for wildlife management agencies are considered.

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Introduction

Conservation efforts aimed at endangered fauna are only effective if there is the capability to detect any changes in population before management interventions are carried out. Population monitoring used to focus largely on census counting as well as demographic models based on parameters that were assumed to stay constant within the monitoring duration because of their presumed stability concerning how the individuals interact with the environment (Conklin et al., 2021). Nonetheless, recent findings from tracking and biologging research indicate that individuals can adapt their behavior in reaction to changing environmental conditions, and this behavior has an impact on the demographic fate of populations (Conklin et al., 2021). Long distance migratory animals have demonstrated a capacity to shift their life history stages in response to environmental change through behavioral adjustments of the individual and not genetic changes of generations (Conklin et al., 2021). Furthermore, movements of pelagic animals in response to changes in the climate have been found to occur due to the behavior of individuals as opposed to changes in the distribution of the entire population (Lewin et al., 2024). Consequently, the growing ability to obtain such data on individuals and biologging has provided the possibility to develop models that could take this kind of information into account in a continuous way, not as a once-and-for-all calibration of population models (Ellis-Soto et al., 2025). While there have been advances in the development of the biologging and remote tracking infrastructure, many population models applied in monitoring of threatened species tend to stay rather static after the calibration process and are not designed for updating in terms of reweighting with respect to incoming data. Such mismatch between the variety of individual level monitoring data and the flexibility of population models that can be used for analysis of those data, especially in cases when demographic dynamics of the studied species are not adequately described by one fixed set of parameters, raises an important issue. The goal of this article is to provide a solution to this problem by proposing BioTrack – a population dynamic model capable of adapting its internal parameters according to accumulating monitoring data. This work offers three main contributions. First, it proposes an adaptive population modeling approach that combines multi-source data from monitoring systems, such as biologging and telemetry data, in one continuous and adaptive estimation structure. Secondly, it shows, through comparison to monitoring data collected historically, that such adaptive population modeling structure enhances the responsiveness of population trajectory estimates in comparison with fixed parameter modeling techniques especially when dealing with short-term population dynamics. Thirdly, this work offers a practical modeling framework for application by wildlife managers, not a theoretical or simulation-only contribution. The rest of this paper is structured as follows. Section II provides an overview of literature relating to automated monitoring systems, reintroduction and metapopulation dynamics, and social and genetic influences on demographic evaluation in endangered species, followed by an inference on

the relevance of this literature to this study. Section III gives a brief description of the BioTrack system in terms of its data inputs and adaptive modeling structure. Section IV details the process of calibration and validation, covering the study species, locations, and methodologies involved. Section V reports the population trends and predictive power found through evaluation of the model. Section VI offers a discussion of the results, including comparisons to current models and a summary of advantages and disadvantages.

Literature Review

Recent studies have also focused on how habitat monitoring infrastructures and demographic assessment techniques can be more accurately aligned with the complexities of managing threatened populations under shifting environmental conditions. Monitoring systems for habitats in association with adaptive management practices have been presented as a new paradigm of species conservation, where the design of monitoring infrastructure is expected to inform iterative management actions, rather than operating as an external and retrospective monitoring practice (Shirk et al., 2023). In the case of reintroduction programs, survival and movement behaviors have been recorded among reintroduced metapopulations, showing asymmetrical movement behaviors and different survival probabilities among sites that cannot be detected using only one set of demographic parameters for the entire population (Rousteau et al., 2022). Behaviorally, genetic relatedness has also been demonstrated to influence social interactions within endangered populations, indicating how population assessments should consider the effects of social structure among members of the population rather than considering individuals independently (Müller et al., 2025). In aggregate, this body of literature represents the move from the conception of population monitoring as a static process to models that recognize the connection between continuous monitoring and adaptive management response. The focus on automation and management linked monitoring systems provides the practical argument for continuous model updating (Shirk et al., 2023). Research into asymmetrical movement and site-specific survival among reintroduced populations shows that assumptions about uniform demographic parameters across space and time may overlook important differences that are relevant for conservation efforts (Rousteau et al., 2022). Finally, evidence about the role of social and genetic structuring in populations suggests that even more than individual movement and survival records, individual relationship data carry demographic information not captured by standard models (Müller et al., 2025). It is clear from the literature review that threatened species monitoring can be improved through the use of models that can utilize the detailed data obtained from individuals in order to update itself according to this, as opposed to static parameters obtained once and then used throughout the process based only on population-wide estimations. This conclusion has a direct impact on the design goal of the current research: the BioTrack application is designed to utilize the individual-based variability discovered in

previous studies in order to build up a constantly updating model.

The BioTrack Framework

Data Sources and Inputs

BioTrack has been designed in such a way that it can accommodate many types of data streams that become available in the course of the ongoing wildlife monitoring program. Some examples of data types that have been incorporated in BioTrack are periodic census counts, telemetry and biologging records for individuals for movements and habitat use, mark-recapture or resighting history, and, wherever applicable, social or relatedness structure of the studied population. Each one of these data streams is run through the standardized ingestion layer where the observations are aligned with respect to time and space, and then they are fed to the core model estimation layer. Irregular data observations and gaps are dealt with through weighting in order to downweight the sparse observations without ignoring them altogether.

Model Architecture and Adaptive Algorithm

By definition, BioTrack combines a state space population model with adaptive updating of model parameters. In this context, a state space refers to the population being represented by latent states that describe the population in terms of abundance, survival and recruitment and are derived from the data streams. Unlike conventional models that rely on pre-defined functions for relating the latent states, BioTrack uses an adaptive calibration approach where the model is updated at every monitoring interval of data. With every update of data, the model is able to become increasingly sensitive to recent conditions, while keeping the information on historical data as a prior to stabilize the estimation process. The adaptive approach also utilizes movement and behavior at the individual level as covariates in the model to explain the changes in the trajectory of the population.

Model Calibration and Validation

Study Species and Sites

Model calibration and validation was done using data collected from long-term historical monitoring of threatened terrestrial and bird species populations that have been subjected to consistent monitoring efforts. The selection of sites was based on their having long-term historical monitoring data for the species populations, including survey counts and individual monitoring of species, in order to put the adaptive aspects of the model to work. Populations of varying levels of management intensity, including both intensively and passively monitored populations, were used to test the generalizability of the modeling approach across different monitoring scenarios.

Statistical Approach and Performance Metrics

Calibration was performed using a rolling-window strategy wherein the model was trained on the early portions of each time series, and tested on held-out observation windows subsequently, with parameter values updated in each successive window. This approach mimics how the model would be applied in practice, in

terms of making forecasts in advance of new data, instead of fitting the model to a full time series in retrospect. The accuracy of predictive ability was gauged through the comparison of estimated trajectories of populations against held-out observations for each window period, in terms of measures of trajectory accuracy and estimation variance. The performance of the adaptive model was compared against that of a non-adaptive version of the same underlying state-space model framework.

Population Trends and Predictive Performance

Predicted vs. Observed Population Trajectories

In the analysis of the monitoring data, the adaptive version of BioTrack performed better in matching the trajectory estimates in periods of demographic transition than the fixed parameter version, especially in the periods after disturbance events. In the stable periods of monitoring, the two versions of BioTrack performed equally well in trajectory estimation, suggesting that the adaptive algorithm does not cause instabilities when the underlying conditions do not change. The differences between the two versions were greatest in the transitional periods, when the adaptive algorithm changed its estimates of the trajectory within one or two intervals of observation after the start of the transition.

Model Accuracy and Case Study Findings

Predictive accuracy, measured in relation to withheld observation intervals, was always greater for the adaptive version compared to the fixed parameters version among the tested populations. The greater level of predictive accuracy is more pronounced in populations whose monitoring history is characterized by nonstationarity, where individual covariates have significant demographic signal. In populations that have relatively stable monitoring history, the difference in predictive accuracy between the adaptive and the fixed parameter versions is less but is still better. The results indicate that the benefits of adaptive estimation increase with demographic nonstationarity of the monitored population.

Implications for Conservation Monitoring

Compared to the standard fixed-parameter demographic models traditionally applied for monitoring threatened species, the primary difference of BioTrack is the ability of the model to process additional data from the monitoring program as a continual input, rather than as an occasional recalibration procedure. The model can thus be seen as an extension, not a replacement, to traditional demographic modeling techniques, because the idea behind the state-space structure is consistent with population modeling methodology, while the updating process brings extra flexibility to it. Where there is an abundance of multi-source data produced by monitoring programs, this flexible structure provides a possibility to convert that amount of information into faster population inference. The primary strength of the BioTrack modeling framework lies in its capability to synthesize heterogeneous sources of monitoring information into a unified dynamic estimation of

population status, especially useful when applied to endangered populations that have irregular and changing monitoring effort. The interpretable nature of the framework, due to its being state-space based, makes it practical for application in conservation biology since users need more interpretable outputs than predictions alone. However, there are limitations to the framework. First, it relies on having reasonably continuous monitoring data as its performance can suffer from having populations that have sparsely observed histories where the adaptive approach may not perform better than the fixed parameter approach. Furthermore, since it uses individual covariates like other models, the representativeness of the tracked individuals becomes important.

Applications and Future Directions

For wildlife management authorities, BioTrack should serve as a decision-support system which is able to be refined in conjunction with monitoring activities to produce up-to-date population trajectories, rather than necessitate an entire model re-calibration process at the end of each monitoring cycle. This would prove especially useful for species whose populations are managed actively through intervention procedures, such as reintroduction or habitat rehabilitation, when it is important to detect population's reaction to the management within one monitoring period rather than after it. In future, further development of the framework would concentrate on widening the applicability of BioTrack to different species and monitoring situations, as well as making it more capable of handling sparsity and irregularity of data, and developing an even more precise adaptive updating mechanism based on it. The question of incorporating a social and relatedness structure into the adaptive updating system of the framework, which might be quite relevant in light of social demographic importance revealed in the previous studies, will also be investigated. More tests on different threatened species will have to be made in order to verify the general reliability of this adaptive model.

References

[1] Conklin, Jesse R., Simeon Lisovski, and Phil F. Battley. "Advancement in long-distance bird migration through individual plasticity in departure." *Nature Communications* 12, no. 1 (2021): 4780. https://doi.org/10.1038/s41467-021-25022-7

[2] Ellis-Soto, Diego, Andrea Flack, Ariana Strandburg-Peshkin, Timm A. Wild, Hannah J. Williams, and M. Teague O'Mara. "From biologging to conservation: Tracking individual performance in changing environments." *Proceedings of the National Academy of Sciences* 122, no. 31 (2025): e2410947122. https://doi.org/10.1073/pnas.2410947122

[3] Lewin, Patrick J., Joe Wynn, José Manuel Arcos, Rhiannon E. Austin, Josephine Blagrove, Sarah Bond, Gemma Carrasco et al. "Climate change drives migratory range shift via individual plasticity in shearwaters." *Proceedings of the National Academy of Sciences* 121, no. 6 (2024):

e2312438121. https://doi.org/10.1073/pnas.2312438121

[4] Müller, Mara F., Cameron J. Baker, Sam C. Banks, Mariana A. Campbell, Tara L. Crewe, Mirjam Kaestli, Sydney J. Collett, Ian J. Radford, and Hamish A. Campbell. "Genetic relatedness shapes social dynamics in a threatened finch: implications for population assessment." *Animal Behaviour* 219 (2025): 123035. https://doi.org/10.1016/j.anbehav.2024.11.013

[5] Rousteau, Typhaine, Olivier Duriez, Roger Pradel, François Sarrazin, Thierry David, Sylvain Henriquet, Christian Tessier, and Jean-Baptiste Mihoub. "High long-term survival and asymmetric movements in a reintroduced metapopulation of Cinereous vultures." *Ecosphere* 13, no. 2 (2022): e03862. https://doi.org/10.1002/ecs2.3862

[6] Shirk, Andrew J., Gavin M. Jones, Zhiqiang Yang, Raymond J. Davis, Joseph L. Ganey, Rocky J. Gutiérrez, Sean P. Healey et al. "Automated habitat monitoring systems linked to adaptive management: a new paradigm for species conservation in an era of rapid environmental change." *Landscape Ecology* 38, no. 1 (2023): 7-22. https://doi.org/10.1007/s10980-022-01457-1