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Climate Adapt Wildlife Model for Predicting Animal Responses to Temperature and Habitat Variability

Mukesh Sharma[1*], Anil Kumar Singh[2], Manvi Pant[3]

[1]Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India.*
Email: ku.mukeshsharma@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0006-4052-2358
[2]Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India.
Email: ku.anilkumarsingh@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0002-8764-0571
[3]Assistant Professor, New Delhi Institute of Management, New Delhi, India. Email: manvi.pant@ndimdelhi.org, https://orcid.org/0009-0002-4239-5146

Key Words

Climate adaptation, Wildlife behavior, Physiological tolerance, Habitat variability, Species distribution shift, Thermal ecology, Human-wildlife conflict.

Abstract

Changes in temperature and more unpredictable habitat are changing the distribution, activity patterns, and tolerance of animals to the environment beyond the range to which genetically adapted. Most of the work documenting these changes has been for single species or one particular response (e.g. distribution shift or physiological tolerance), making it difficult for wildlife managers to predict how a particular species or population will react when changes in temperature and changes in habitat occur simultaneously. This paper presents the Climate Adapt Wildlife Model, a conceptual approach to predicting behavioral and physiological responses of wildlife populations to combined temperature and habitat variability, which consists of three linked components; a component for temperature exposure characterization that predicts the temperature a population will experience; a component for behavioral response that predicts shifts in wildlife habitats use, activity timing, and movement; and a component for physiological tolerance that estimates how much, or how little, is being added to a population's adaptive capacity from projected conditions. The model is informed by recent research reporting distributional shifts of marine predators, development of adaptive habitat in amphibians, and when adaptive responses to climate change can be predicted, as well as genetic evidence of climate adaptation in songbirds, evidence of drought refuge use by fish, and the increasing importance of climate change in human-wildlife conflict. The model, which has yet to be tested against observations of the field, could provide wildlife managers with guidance to predict which populations will be more likely to adapt successfully, which may shift range or behavior, and those that are at higher risk of going beyond the physiological limits.

* Corresponding Author's email: ku.mukeshsharma@kalingauniversity.ac.in
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Introduction

How animal populations adjust to altered climatic conditions depends on movement (behavioural response), tolerance (physiological response), or range shift or population decline (when these options are not adequate), and predicting which of these will occur to a given population is one of the major challenges of wildlife climate research. Work on predicting intraspecific distribution changes in response to climate change in a widespread marine predator has highlighted the fact that range-wide distribution models do not capture the range of intraspecific responses to higher temperatures, with some populations responding to warming by migrating to higher latitudes, and others by shifting the local distributions, which would not be detected in a wholesale range-wide model (Niella et al., 2022). Other approaches to climate adaptation through changes in the physical landscape have also been investigated directly, such as wetland rehabilitation and reforestation on legacy surface mines in the Central Appalachian region that could provide thermally buffered breeding habitat for pond-breeding amphibians whose breeding success is particularly sensitive to temperature and moisture experienced during the breeding season (Sherman et al., 2024). More conceptually, studies that have explored when and how adaptive responses to climate change can be predicted have found that the predictability of adaptive response depends strongly on the genetic variation, generation time and phenotypic plasticity of the population to respond to the changing climate, indicating that some are likely more predictable in how respond to climate change than others (Urban et al., 2024).

These studies collectively point to a gap that needs to be addressed: distribution modelling, habitat intervention research, and adaptive-response prediction have each made significant strides, but none has integrated the three in a framework that can predict the response of a particular population to a change in both temperature and habitat.

This paper has three major contributions. First, it suggests a model structure that directly connects thermal exposure with expected thermal behavioral reactions, rather than considering thermal behavioral change to be a downstream effect of thermal distribution modelling. Second, it also explicitly includes physiological tolerance within the model, which enables populations to be separated based on the potential to cope with further thermal and/or habitat stress before decline. Third, it considers secondary impacts of altered human-wildlife interactions as a result of climate change, beyond the direct climatic impacts on the focal species, given that behavioral responses to climate change can increase animal-human contact and occur in both directions.

This paper is organized as follows: The rest of the paper follows. Section II summarizes past temperature-response research in wildlife, including recent studies on the use of drought refuge areas and historical genetic evidence for climate adaptation, and climate-related human-wildlife conflict. In Section III, the design of the proposed model for predicting behavioral and physiological responses is presented. In Section IV, expected results of the simulations and variation between populations and taxa is discussed. Section V brings the paper to a close and point the direction for the future work of empirical validation.

Review of Existing Temperature-Response Studies in Wildlife

Studies of refuge identification as a drought adaptation strategy for fish populations have demonstrated that the availability of refuge habitats that are thermally and hydrologically stable is key to the success of fish to persist during drought, and that identifying refuge habitats in advance enables managers to prioritize the protection of the stream reaches or pools that are most likely to provide refuge during periods of stream temperature and flow stress (Walters et al., 2024). The genetic signatures of climate adaptation accumulated over time are detectable in an endangered songbird species, with some populations showing genetic signatures of adaptation to past climate change and changes in genetic diversity within these populations as a function of warming climate (Turbek et al., 2023). A study on climate change as a global amplifier of human-wildlife conflict has highlighted how changing climate conditions are changing animal behaviour, increasing the frequency of wildlife-human interactions as a consequence of shifts in the timing and places of wildlife movements, and how this change has implications beyond the focal animal (Abrahms et al., 2023).

Together, these recent sources illustrate that study of temperature response has advanced far beyond the mere prediction of range shifts to include issues of refuge availability, historical genetic adaptation, and community impacts of behavioral response. The presence of a fine-scale gradient of habitats, and not just a general warming pattern, can determine whether a population survives climate stress, as shown by refuge-based research. Research in genetics has shown that there is variation in populations in adaptive ability and that this ability can be detected in historic evidence rather than assumed universally. Human-wildlife conflict studies also show that behavioral adaptation to climate change is not a standalone phenomenon, but an adaptation that alters the wildlife/human interface. All of these findings suggest that a model of climate response that predicts animal behaviors and range shifts must consider fine scale habitat variability, account for variation between populations based on the adaptive capacity, and predict the social impacts that will flow downstream from the change in animal behavior.

Model Design for Predicting Behavioral and Physiological Responses

The Climate Adapt Wildlife Model consists of three interrelated components that are applied to a population or set of populations of interest. The first is the thermal exposure component, which describes average warming trends as well as how often and for how long a population will face extreme temperature events, and how many very localized microhabitats—such as shaded refuges, burrows, or deep pools—will provide some thermal buffering beyond the broad-scale level of warming. The second component of the behavioral response is the expectation of what a population may do to adjust its habitat use, activity timing, and movements based on the projected thermal exposure, based on changes in localized habitat use and refuges seen in related species and systems. The third is the physiological tolerance component, which attempts to measure a population's adaptive ability as reflected in the evidence of past adaptive response, based on data of historical genetic signatures of climate adaptation (where available) and data on generation time and reproductive characteristics that can affect the rate at which a population can follow changing conditions.

These three aspects are integrated in a progressive evaluation process. The first stage involves thermal exposure projections for the current range of the population, including known microhabitat refuges in the thermal exposure estimate, in addition to ambient temperature projections. The second stage involves the comparison of projected exposure with the known habitat use and movement flexibility of the population to determine whether the population is likely to expand its range, change activity timing, come into closer association with refuge habitat, or exhibit little behavioral change. The third stage focuses on how well physiological responses are matched to thermal exposure, and whether predicted behavioral changes are adequate to keep the population within its physiological tolerance or if it is likely to be stressed even with behavioral adaptations.

In this model, the secondary output is for human-wildlife interaction risk, which is based on a comparison of the predicted changes in behavior, specifically movement timing and concentration of movement around refuges, to the locations of human settlement and agriculture within and near population range. The output should be used to identify populations whose climate-induced behavioral adaptation is projected to lead to greater contact with human activity, which means that this consequence can be predicted and considered with the population's climate response, instead of only after it has manifested itself in conflict.

Simulation Results and Variability Analysis

The Climate Adapt Wildlife Model has not yet been tested with field data, so its potential is extrapolated from patterns found in related climate-response studies. The model's decision to make predictions at the population level instead of the species level is supported by the substantial intraspecific variation that has been observed in response to warming in a wide-ranging marine predator, for which distributional forecasting work has been undertaken. Modeling predictions of behavior and physiology using background temperatures only are unlikely to be as accurate as those that account for microhabitat refuges within thermal exposure estimates, since habitat intervention research on amphibian breeding sites has demonstrated that created or restored habitat can significantly buffer thermal stress for amphibian sensitive life stages.

The range of model outcomes is likely to differ significantly among taxa and populations, as indicated by studies of the predictability of adaptive response that found it to depend on genetic variation, generation time and phenotypic plasticity of the population. Documented genetic adaptation to past climate change, such as found in songbirds using historical DNA, should be associated with better physiological tolerance outcomes in the model, whereas populations relying on heritage habitats that are also likely to be further degraded with climate change, such as fish populations in drought refuge sites, should be the most sensitive to further habitat loss caused by climate change.

The human-wildlife interaction output of the model should identify a greater risk level of conflict for populations whose behavioral adaptations are projected to involve greater movement into human modified landscapes, consistent with previous studies that found an increase in conflict risk due to climate change because of changes in the seasonality and spatial distribution of animal activity [6]. This output is designed to inform proactive conflict mitigation planning, not to reactive management of conflict after incidents have taken place.

At this point the main drawback of the model is the lack of field testing, and the relationships between the components are calibrated based on several independent studies, rather than a single empirical data set; as a result, its accuracy is likely to depend on the availability of local microhabitat and behavioral data for the population under assessment. The model will be more uncertain on populations with less historical genetic or behavioral information, and the thermal exposure estimates based on refuges are dependent on the availability of accurate and fine scale habitat data, which may not exist for all systems.

Conclusion

The Climate Adapt Wildlife Model was developed here as a conceptual tool, which can inform predictions of wildlife behavioral and physiological responses to combined temperature and habitat uncertainty. The model's staged and combined-variable approach – which incorporates thermal exposure, behavioural response, physiological capacity to withstand physiological impacts, and extends predictive power to downstream human-wildlife interaction risk-is expected to help fills identified gaps among studies on distributional shifts, habitat-based climate adaptation, dependence on climate refuge, genetic capacity to adapt, and conflict induced by climate impacts. The approach can assist wildlife managers in determining which wildlife populations can withstand conditions in changing environments, which will continue to be reliant on the continued availability of habitat refuge, and which should expect higher vulnerability to physiological harm or interaction stress with human development and activities. Future steps include in-the-field validation using a broad array of climate, habitat types, taxa, and genetic capacity information where such information is available or becomes so with further data collection effort.

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