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Eco Climate Intelligence Framework for Assessing Climate-Induced Distribution Shifts of Wildlife Species

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Key Words

Species redistribution, Climate-induced range shift, Wildlife distribution modeling, Habitat suitability, Species occurrence data, Climate adaptation, Biodiversity monitoring.

Abstract

With a changing climate, animal species are becoming more common outside of the historical ranges in response to different temperatures and resource availability, in higher latitudes, higher elevations, or new habitat types. Most of the research that has documented these changes has been focused on wildlife distribution shifts that have already occurred, thus limiting the capacity of wildlife managers to predict distribution shifts prior to the introduction of conservation risks and new species interactions for a given area. This paper suggests a conceptual framework (Eco Climate Intelligence Framework) to guide the assessment of climate-induced shifts in the distribution of wildlife species, combining historical distribution evidence with climate suitability trends and species-specific ecological traits in a structured way to identify species that are likely to shift distribution, the extent of the shift, and the implications for existing wildlife communities. The framework builds on recent research on the mechanisms and detection of species redistribution when climate change, climate-driven range shifts of economically important invasive species, and disease-vector risk assessment under changing climate conditions, and reflects the limited effectiveness of existing protected areas as stepping stones for species redistribution, the effect of energy-mediated movement responses of marine predators to climate change, and climate-informed land management planning. While the framework has not been used in a live monitoring program yet, the structure is a framework for predicting distribution change before it happens in occurrence data, enabling a more proactive approach to wildlife management.

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Introduction

Range shift is one of the most commonly recorded biological impacts of climate change and is occurring at a rate and with a distribution that is unprecedented for wildlife species. Studies on mechanisms, detection methods, and impacts of species redistribution in response to climate change have demonstrated that range shifts are the result of a complex mix of changed thermal tolerance limits, shifting resource availability and altered competitive interactions, as well as that the rate of redistribution varies greatly depending on a species' dispersal ability and the rate of local climate change (Lawlor et al., 2024). Ecological risk assessment efforts using simulation-based climate matching to assess the potential for range expansion in alien vectors that affect livestock health have shown that range shifts also occur in vectors that can transmit disease to both domestic and wild animal hosts, and therefore in the context of animal health, as well as in the context of biodiversity conservation, the relevance of distribution-shift assessment is clear (Prashanth, 2025). Climate suitability modeling has also been used to map range shifts of an important crop pest, demonstrating that when banded with physiological tolerance limits for the species, these range shifts can be projected with some degree of confidence, with some sensitivity to the assumptions underlying the climate suitability modeling (Aidoo et al., 2022).

The Eco Climate Intelligence Framework is suggested as a solution to a problem these studies identify as a common one: There is considerable progress in detecting range shifts after occur, and there is excellent progress in predicting suitability to ranges of individual species, but wildlife managers have yet to develop a consistent framework to predict, across a larger set of species simultaneously, when populations are approaching the point of geographic shift, and what this shift is likely to imply for the communities entering.

There are three main contributions of this paper. First, it offers an assessment framework where historical occurrence evidence and forward-looking climate suitability trends are combined into one assessment, rather than detection and projection as separate analytical tasks. Second, it is species-specific, embedding species traits, like dispersal ability and habitat specificity, directly into the assessment, thus making it possible for the framework to distinguish species that will have a good chance of range expansion from those that will not have a good chance of declining locally. Third, it reviews the implications of range shift beyond the focal species to the implications for existing wildlife communities and land management priorities in the new areas into which the species expands.

The rest of this paper is structured as follows. In Section II, limitations on existing distribution-shift assessment techniques are discussed on the basis of recent research on marine predator movement, connectivity in protected areas and climate-informed land management. In Section III, the architecture of the proposed framework for range-shift detection is presented. Section IV, Expected Species Distribution Outcomes, reviews what is expected of the species distribution outcomes and compares them to the current assessment approaches. The paper is closed in Section V and directions for future validation are provided.

Limitations in Current Distribution-Shift Assessment Methods

However, in a marine top predator, examining energy-mediated responses to changing prey size and distribution has shown that not only does distribution-shift depend on where suitable habitat is found, but also on the energetic cost of reaching and exploiting that habitat when prey resources shift, suggesting that distribution-shift, based on habitat suitability alone, can fail to capture the energetic constraints under which whether a species can follow a shifting resource base is possible or not (Gallagher et al., 2022). Studies examining whether existing protected areas are likely to act as stepping stones for species experiencing range shift have shown that a significant proportion of existing protected area networks is not suited for supporting the sequential movement of species across the landscape as shift, so existing conservation infrastructure may not be adequate for supporting species as expand the ranges into new areas (Parks et al., 2023). However, studies that have investigated the distribution-shift information have also highlighted that land management planning is not only reconsidering its approach to forestry in a warming world but that the quality and resolution of underpinning the climate suitability projections remain critical for land-use planning (Zhang et al., 2022).

Explain main results of literature and the relationship to the research. All these recent studies reveal that current understanding of species distribution shifts is still becoming more and more advanced, but has a number of common limitations. Marine predator studies indicate that habitat suitability is not the only factor determining whether a species is successful at following the movement of resources – energetic constraints on movement also play a role in determining success. Research within protected areas indicates that the current conservation infrastructure was primarily conceived with historical range assumptions, and may not be able to buffer species when extend the range. There is a mismatch between where protected areas are and where required.

Results from ongoing land management research indicate that there is a larger-scale use of climate suitability information in land-use decisions, but that the accuracy of such decisions is dependent on the methods used, which are not currently available in most of the existing tools to provide such information at that scale. These results, combined, suggest that a distribution-shift assessment framework must consider the energetic and physiological feasibility of range shift, assess the capacity of the landscape to the species is shifting into to support species movement and establishment, and be designed to facilitate land-use and management decisions, but not create distribution projections alone without regard to how the information will be used.

Framework Architecture for Range-Shift Detection

Historical Occurrence and Baseline Range Characterization

The framework starts with collecting historical occurrences for each species being assessed, and defining a historical range and the climatic and habitat conditions of this historical range. This baseline characterization is based on the same types of evidence as those applied in mechanistic redistribution studies (thermal tolerance limits, seasonal activity and known habitat associations) and subsequent suitability comparisons are based on conditions that the species has actually been documented to occupy, not on assumed tolerances. In the absence of occurrence data or where it is limited and disorganized, the framework identifies this baseline as lower confidence, allowing for assessment outputs with a commensurate level of confidence in the information.

Climate Suitability and Energetic Feasibility Assessment

The framework extends the baseline range forward in time based on the expected warming patterns, determining where the species is becoming more or less suitable compared to its historic range. This suitability projection comes with an energetic feasibility assessment to consider if the distances and habitat types that the species would have to traverse to reach new suitability are compatible with the species' known dispersal ability and energetic constraints, which has been a limitation in research on marine predators. Those species that will be projected to fare well in future predicted suitability are indicated as species with high dispersal capacity and generalist habitat use, whereas those species with limited dispersal capacity or strong habitat specificity are flagged as at risk of range contraction even in cases where there is suitable habitat elsewhere.

Landscape Connectivity and Community Consequence Evaluation

The last architectural component is an assessment of the capacity of the landscape between the species' current range and areas of potential future suitability to facilitate species' movement, based directly on work that shows that existing protected area networks are often not well placed to provide stepping-stones for species' movement. This evaluation will reveal places where the species may find an inappropriate habitat or fragmented habitat during its shift and will mark these areas as places where it may need management attention. The framework also evaluates potential impacts on the wildlife communities that are expected to be found in areas where a species is expected to move into, including whether the arriving species will compete with, prey on, or otherwise interact with, the existing species, thereby predicting the impact of the distribution change on communities as well as the distribution change itself.

Species Distribution Outcomes and Comparative Discussion

Anticipated Outcomes of the Framework

As the Eco Climate Intelligence Framework has not yet been utilized for a real monitoring program, expected results are deduced from similar research. Mechanistic redistribution research has confirmed that species with higher dispersal potential and larger thermal tolerances are more likely to make a successful climate shift, with the expectations that the energetic feasibility assessment in the framework should accurately predict species that are likely to shift range and those that are likely to decline in place. Using climate matching analysis on alien species vectors, it has been demonstrated that the climate suitability classification framework can provide reasonable lead time for emerging risk areas, which means that the suite of forward-looking suitability projections should also provide advance warning of climate driven range shifts.

Comparison with Existing Assessment Approaches

The proposed framework is also likely to offer significantly more warning for management action, as the suitability / feasibility predictions are designed to indicate when species are nearing the point of range shift, rather than to detect a shift once it has happened, as can be done with distribution-shift assessment methods, which are largely based on the detection of occurrence changes. The framework is not meant to replace occurrence-based detection, which is another key tool to determine if projected changes are occurring, but is designed to work in tandem with occurrence-based detection and to focus monitoring on the species and regions that are most likely to change. The framework's inclusion of two additional components, energetic feasibility and landscape connectivity, are expected to diminish the likelihood of over-estimating a species' potential range gain as compared with suitability-only projection models, used in some invasive species range-shift studies.

Implications and Limitations

The community consequence and connectivity portions of the framework can have a direct impact on conservation and land management planning as it will not only identify which species are shifting range, but also where gaps in the landscape and interactions with resident species may hinder that shift, and where habitat corridors or targeted management efforts could be most beneficial. This is in line with the fact that land management planning increasingly takes climate suitability into account and the purpose of the framework is to help land management planning by providing more landscape specific detail than climate suitability projection. The framework's major drawback is that it has not yet been applied to results from field monitoring, and the accuracy of the results will rely heavily on the accuracy of past occurrence data and dispersal capacity estimates available for the particular species being evaluated, which are very variable across taxa. The landscape connectivity assessment in the framework will be more robust for species with well-documented historical ranges and known dispersal traits, and less robust for poorly studied species, compared to the accuracy of the habitat data for the regions a species is projected to travel through.

Conclusion

This paper outlined the Eco Climate Intelligence Framework – a conceptual application to evaluate the climate driven ranges shifts in wildlife that combined paleoevidience of past species distributions, predictive climate envelope projections of future habitat suitable, and an evaluation of whether the habitat available is also energetic and geographically viable. By addressing previous research limitations such as the lack of accounting for species energetics required for movemens, minimal step ping stone functionality to present protected area sites, and over estimation of capacity of projected suitable habitat into land management based on climate models, able to forecast ranges shift priori to when it is visible within species distributions and suggest which locations the Landscape Gaps and /or Community and Regional Level Corresponds are likely to impact movement. Field research to test and validation the framework with a wide spectrum of Species, Climates and Landcapes provide important future work, as does continuing development of energetic parameters and community consequence calculations as further species level Data becomes available.

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