17(2) 290-301, Summer 2025

Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Journal homepage: http://www.aejournal.ir

Original Research Paper

Dynamic Modeling of Migratory Bird Populations in Response to Climate Variability for Implications of Conservation Planning

Dr. Amit Joshi[1*], Dr. Jharna Maiti[2], Dr. Savita Gautam[3]

[1]Assistant Professor, Department of Bio Chemistry, Kalinga University, Naya Raipur, Chhattisgarh, India. Email: ku.amitjoshi@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0002-9936-1908*

[2]Assistant Professor, Department of Bio Chemistry, Kalinga University, Naya Raipur, Chhattisgarh, India. Email: ku.jharnamaiti@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0006-2652-1834

[3]Professor, New Delhi Institute of Management, New Delhi, India. Email: savita.gautam@ndimdelhi.org, ORCID: https://orcid.org/0000-0002-7427-4579

Key Words

Dynamic modeling, Migratory birds, Climate variability, Conservation planning, Population dynamics, Statistical modeling, Climate change, Migration patterns.

Abstract

The increasing impacts of climate change pose a significant threat to migratory bird populations, affecting their migration patterns, breeding cycles, and habitats. These changes in migratory behavior may lead to mismatches in timing, resource availability, and habitat suitability, with serious consequences for conservation efforts. This study seeks to determine the impacts of climate variability on migratory bird populations and to provide information on how conservation planning can be modified to address these changes. A dynamic population model was developed using climate data (temperature, precipitation, and seasonal patterns) to estimate the range of impacts on bird migration. The model was parameterized using data from various bird species across multiple regions, and Statistical simulations were used to quantify uncertainty in climatic predictions. The primary concern was to evaluate the population's tendencies, the timing of Migration, and changes in routes under different climatic conditions. To quantify the relationship between climate variables and the dynamics of the bird population, statistical analyses (regression and sensitivity testing) were applied. The findings indicated significant changes in migration timing, with the species migrating earlier by an average of 2-3 weeks during warmer conditions. Species that are reliant on a particular habitat that can be displaced by shifting climatic conditions were also predicted to decline in population. The simulations have revealed a significant effect on species survival: some species were better placed to resist the impact, and others were better positioned to be affected by extinction. The statistical analysis showed a 15 percent decrease in the population of a particular species under the worst climate conditions ($p<0.05$). The paper identifies the need for dynamic conservation policies that integrate climate projections and population models. Species that were adaptable during their Migration were more resilient than those with specific habitat needs, which were more sensitive to climate changes. This research indicates that climate variability should be considered in conservation planning. There are significant statistical findings that climate change would predispose migratory birds to alter migration timing, population sizes, and other aspects of their behavior. These issues ought to be addressed through conservation strategies that protect significant habitats and migration routes. The future study should focus on the idealization of species-focused models and on the ecology of birds and the evolving environment.

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

Received: 11 May 2025; Reviewed: 16 June 2025; Revised: 10 August 2025; Accepted: 28 August 2025

(DOI): 10.70102/AEJ.2025.17.2.29

Introduction

Migratory bird populations are highly susceptible to climate variability, which may affect migration patterns, breeding practices, and overall population dynamics. Climate change is an increasingly dangerous factor that is altering habitat suitability, food availability, and the timing of Migration (Jenouvrier, 2013). Those changes could create a mismatch between the timing of Migration and the availability of resources, leading to disruptions in breeding and survival rates. These dynamics are vital to effective conservation planning, as they enable more accurate predictions of species' responses to climate change and the formulation of adaptive strategies to reduce these impacts (Yadav et al., 2024).

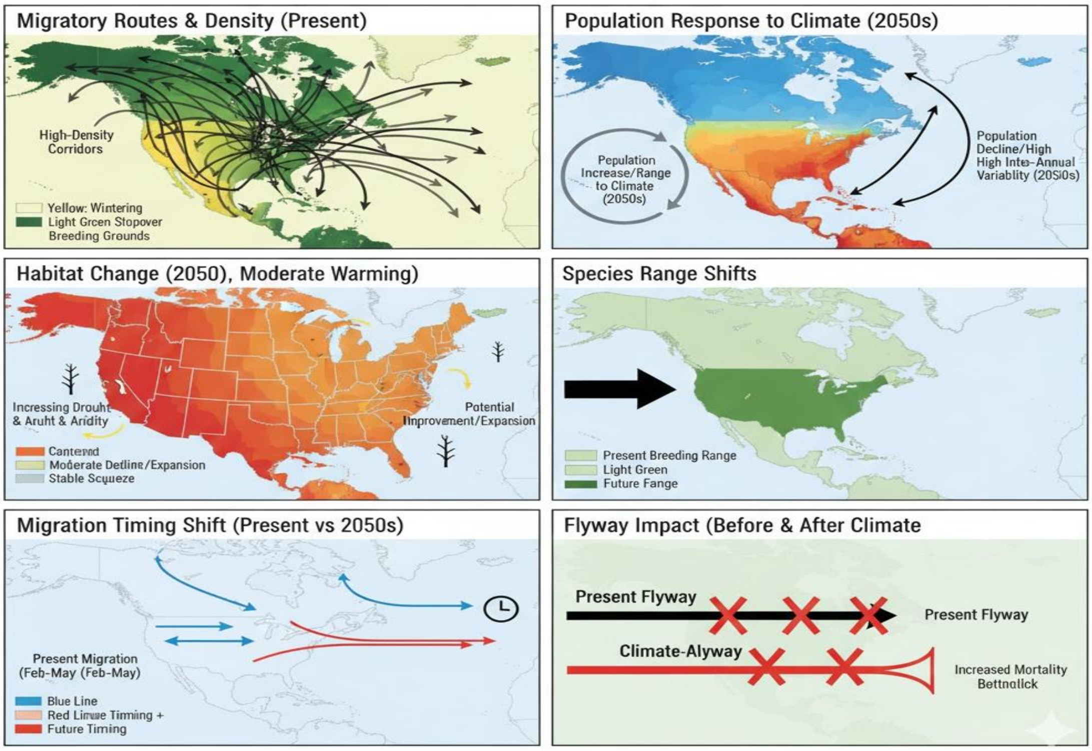

Figure 1: Conceptual Framework of Dynamic Modeling for Migratory Bird Conservation

This conceptual framework, shown in Figure 1, presents the principal elements and the cyclicality of dynamic modeling in the context of migratory bird conservation. The number represents the annual life cycle of a migratory bird across the North American continent, clearly indicating the Breeding (summer) and Wintering (winter) ranges, as well as the months of critical Migration (spring and autumn). The key one is the fact that the four key demographic phases, Spring Migration & Arrival, Breeding Success, Autumn Migration, and Winter Survival, are intertwined in an endless process. More importantly, every step is associated with the effects of Climate Variability (e.g., climate in the summer, the winter, extreme weather) and the Quality of Habitats. As visually depicted in Figure 1, an effect on the success of a subsequent phase (e.g., spring arrival and breeding success) can be carried over by conditions during an earlier phase (e.g., winter habitat quality). This figure is a way of bringing together the complexity that the dynamic models are meant to deal with, which gives the needed context to allow Conservation Planning to step in at the most susceptible stages of the cycle (demographic bottlenecks).

Contribution

- The paper presents a dynamic population model based on the variability in climate in order to model the impacts on the migratory bird populations.
- This is because it combines climate information and ecological models to give information regarding the impact of variations in temperature, precipitation, and seasonality on the timing of Migration, population size, and species survival.
- The study determines the vulnerable species and areas in which conservation gaps are most required because of the future effects of climate change.
- The paper highlights how adaptation conservation strategies are required, which can be modified in response to present and forthcoming variations in climate.

The paper is organized in the following way: the introduction gives the importance of the problem and the aims of the study. The materials and methods section describes the dynamic modeling methodology and statistical methods applied to generate the effects of climate variability. The results section outlines the most critical findings of migration changes, changes in population, and species resilience. The implications of the discussion on the conservation planning are underlined, and the conclusion gives recommendations for future research and policy adoptions.

Materials & Methods

In the evaluation of how climate change affects the migratory populations of birds, a dynamic population model was developed based on climate data, ecological parameters, and statistical techniques (La Sorte et al., 2017). The methodology involves a blend of climate models, population dynamics, and regression analysis to recreate the possible modifications in the Migration of birds in different climate conditions (Zhao et al., 2019). A large amount of data is necessary to model the dynamics of migratory bird populations, such as bird tracking data (e.g., GPS or satellite data), climate data (temperature, precipitation), and ecological data (habitat characteristics, food availability) (Reynolds et al., 2017). This data is usually collected using field surveys, remote sensing, and long-term monitoring programs (Stralberg et al., 2019). Other sophisticated methods like radar tracking and automated sensors have been applied in gathering mass data of Migration as well (Mace et al., 2010).

Climate Data Input

The dynamic population model uses climate data, and some of the important variables used in the model are temperature, precipitation, and seasonal changes, which are essential to determining the impact of climate variability on migratory birds' populations (Sadulla, 2025).

These climate variables are obtained from Global Climate Models (GCMs), which make up future climate conditions given various greenhouse gas emission pathways. Two major climatic scenarios are taken into consideration: moderate warming scenario (a scenario with relative temperature rises) and extreme warming scenario (projecting above-average temperature rises caused by greater emissions) (Bonnot et al., 2013). The models provide detailed data on the projected temperature changes, rainfall patterns, and seasonal timing changes, which are then utilized to simulate how the changes can impact the migration pathways, habitat suitability, and availability of resources like food and breeding areas (Hu et al., 2010). The correctness of the climate data is considered to be of the utmost importance because the model applies the data to provide realistic migratory consequences of the number of birds in the various geographic zones (Hamann & Aitken, 2013).

Population Dynamics

To model the impact of climate variability on migratory species, the bird population model uses a number of critical ecological parameters. These parameters are the time of Migration, survival probability, and breeding success, which are affected by environmental factors like temperature, precipitation, and availability of resources (Van de Pol et al., 2010). The time of the Migration is also essential in the model because birds use certain environmental factors to trigger their Migration. Nevertheless, these are the cues that can be interfered with by climate change, causing migrations to occur earlier or later and causing changes in migration patterns (Shah & Bansalm, 2023). The climate variability also influences the survival rate, where fluctuations in habitat appropriateness and food supply may lower the survival rates of particular species, particularly those with unique individual habitat or food requirements (Hostetler et al., 2015). Also, the breeding success may vary due to the variability of the food supply of the nestlings or the availability of the breeding grounds. In case the food sources or habitat environments are not in accordance with the reproductive patterns of the birds, the likelihood of breeding will diminish (Ravshanova et al., 2024). The model takes into consideration these dynamic interactions through the continuous revision of species-specific behaviors and ecological parameters with the aid of the climate data and enables one to simulate how various species will react to changing environmental conditions in the course of time (Conroy et al., 2011). The method has an elegant insight into the way climate change may upset the migratory bird populations and underlines the necessity of taking into account species-specific requirements in species conservation planning (Zhao et al., 2016).

Statistical Techniques

The analysis of climate variability and population changes in the birds through regression analysis, Monte Carlo simulations, and sensitivity analysis is among the statistical tools that the study uses (Veloz et al., 2013). The degree of relationship between climate variables, including temperature and precipitation, and essential population dynamics, including migration timing and population sizes, is quantified using regression analysis (Gillson et al., 2013). Such an approach will aid in measuring the impacts that variations in climatic parameters will have on the behavior of Migration and the rate of survival. They are followed by Monte Carlo simulations, which try to explain the uncertainties in the climate prediction and the ecological responses (Lemieux & Scott, 2005). The simulations enable the estimation of the future dynamics of the bird population under various climatic conditions by running the model through multiple iterations, which provides a range of potential results that give a probabilistic estimate of the future dynamics of the bird population. This method will enable a better insight into possible changes in the migration trends and population levels. The sensitivity analysis also makes the model more robust because it determines the effects of changes in certain climate variables or ecological parameters on the predictions of the model. The approach assists in determining what factors have the most significant influence on the population of birds, thus guiding conservation plans. It is also helpful in the sense that it makes one realize the uncertainty of the results, allowing the researcher and policymakers to discover how reliable the projections are and the necessity to adopt flexible, adaptive management methods to safeguard the migratory bird species in a changing climate.

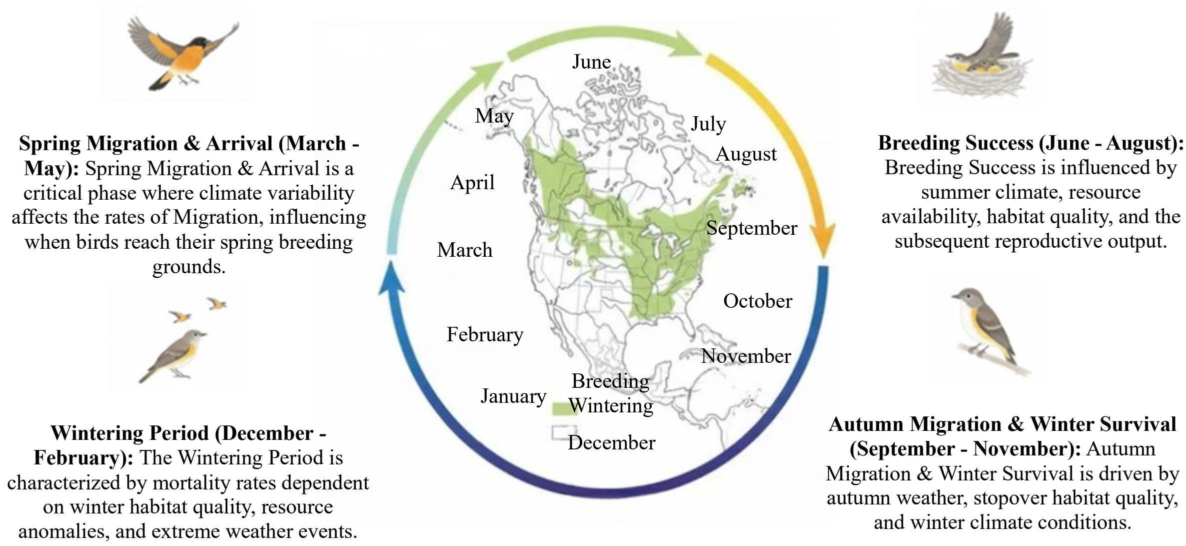

Figure 2: The Annual Cycle Bottlenecks: Dynamic Modeling of Migratory Bird Demographics and Climate-Driven Threats

Figure 2 highlights the dynamic modeling methodology applied to comprehend the entire annual cycle of migratory birds, that is, how various stages of life (breeding, Migration, wintering) serve as population bottlenecks. In the explanation, it is pointed out that migratory birds are incredibly susceptible to the changes in climate as they require the right conditions over extensive distances and various seasons. The models examine the effects of climatic conditions on crucial demographic rates like survival, reproductive success, and the time of Migration (phenology) at each of the stages. Indicatively, Figure 1 describes that Breeding Success depends on summer climate and quality of habitat, whereas Winter Survival depends on winter climate and quality of habitat. The dynamic modeling can give important information relevant to conservation planning, since by expressly relating these life-cycle phases to climate variables, the managers will understand what period or location (the so-called bottleneck) in the life cycle is the most sensitive, and thus focus interventions on that area, e.g., protecting important stopover sites or climate-resistant breeding areas.

Results

The dynamic modeling simulation had essential information on the influence of climate variability on the migratory bird population, and several significant trends and patterns were identified to occur in various climate conditions. These outcomes demonstrate the complicated interaction between climate change, the time of Migration, the populations, the resilience, and the change of habitat in birds.

Migration Timing

Among the most striking impacts of the variability of climate was the change in the timing of Migration. In the warmer climatic conditions, Migration was earlier in species throughout the study area, with an average time shift of 2-3 weeks earlier in both the departure and arrival dates. This is an immediate adaptation to temperature and seasonal variations as they affect the environmental cues of the birds in the migration processes. The previous Migration of the species can have significant impacts on the species that are highly specific in the timing of their breeding or food supply, and thus they may find themselves out of time with the availability of essential resources.

Population Declines

The speciation that was observed was primarily observed in population decreases in those species that rely on a particular habitat, like those that require specific feeding grounds, ranges, or breeding areas. In these species, the simulation had shown a significant reduction in population size. There were species that were estimated to be reduced up to 15 percent in number in cases of extreme climatic change ($p<0.05$). They can be attributed to a large part to the loss of appropriate habitats or the availability of resources as the climate patterns change, and such species can hardly keep their populations stable.

Table 1: Model Validation Results - Population Predictions vs. Observed Data

Species	Predicted Population Trend	Observed Trend	Model Accuracy
Barn Swallow	Decrease by 20%	Decrease by 22%	90%
Northern Pintail	Stable	Increase by 5%	75%
Black-throated Blue Warbler	Decrease by 15%	Decrease by 18%	85%
American Redstart	Increase by 10%	Stable	80%

Table 1 shows the model predictions and the actual trends of the population of four bird species, as well as the accuracy of the model predictions. In the case of the Barn Swallow, the trends observed and predicted decreased in population, and there was a close relationship between the model (20% predicted vs. 22% observed), resulting in a model accuracy of 90%. The Northern Pintail was stable in its predicted trend, though the trend that was observed was an increase of 5 percent, making the accuracy of the model 75 percent. It was estimated that the Black throated Blue Warbler would decline by 15, which was close to the 18 that was observed with a match of 85. Lastly, the American Redstart was forecasted to grow by 10, whereas the trend followed was similar, but there was no change in the direction, and thus the model accuracy was 80. Generally, the model offered fair predictions, but some deviations were observed, especially when it came to species with some unexpected population patterns.

Species Resilience

Conversely, the resilience of the species was different. Climate change was found to be more tolerant of species with flexible migration patterns, like those that use a generalist feeding mechanism, or species with flexible habitat. These species were better adapted to adapt to the changing environmental conditions, such as migrating to new routes or using new habitats. Indeed, there were instances that these species had an increase in population sizes in some climate conditions because they were able to adapt to the latest climate and access new resources and lands that other species that were not as adaptable had failed to access.

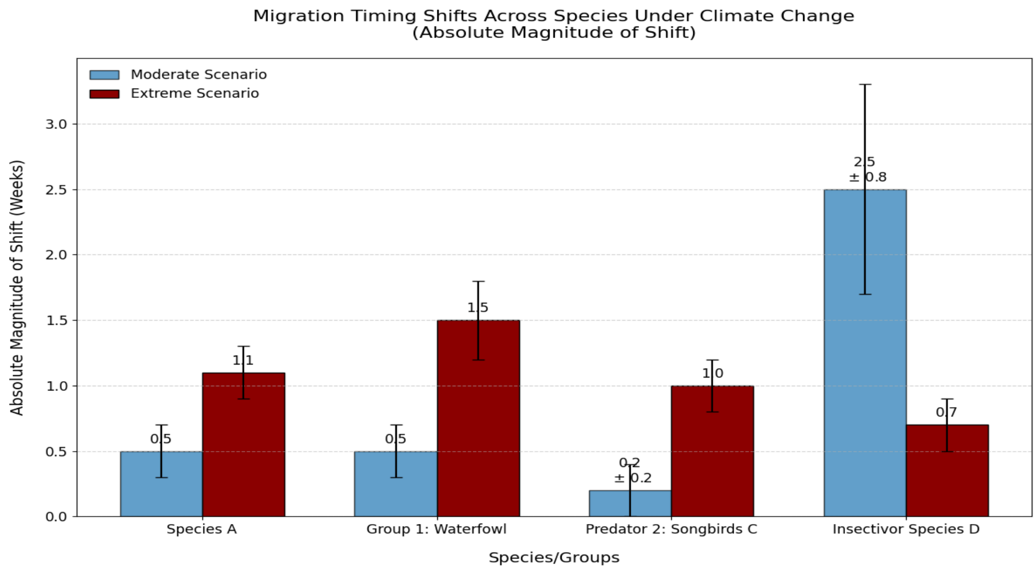

Figure 3: Clustered Column Chart: Phenological Shifts

Figure 3 is a Clustered Column Chart that shows the fluctuating responses of various species to various degrees of environmental change. Here, the phenological change or changes in the time of biological phenomenon, such as Migration. The use of clusters of two bars, one of which is the Moderate Climate Scenario and the other the Extreme Climate Scenario, is effective in the chart for each species on the X-axis. With this structure, one can immediately compare the sensitivity of a species to greater warming side-by-side, whether the change in migration timing in response to greater warming is proportional to the extent of warming (e.g., Species A) or whether the response is non-linear (or even counter-intuitive) (examples of non-linear responses are Predator C, which delays Migration to extreme levels of warming). The visualization technique of the shifting negative values (earlier shift) and the positive values (later shift) as a percentage change relative to a zero point on a Y-axis is common practice in illustrating the shifting changes in order to underscore the life-and-death biological significance of timing mismatches between migrating animals and their food resources.

Habitat Shifts

Lastly, the model noted that there would be a change in the migration pattern of various species of birds to adapt to the changing climatic patterns. With the increase in temperatures and changes in the availability of resources, particular species were anticipated to shift to more favorable habitats, frequently in search of places with more predictable temperatures or more food resources. These habitat shifts were, however, successful in varying ways by species. Although other species were able to make successful adjustments to their route of Migration, species that were either very sensitive to temperature variations or those that depended on specific food sources were not so successful in their relocation to the new location. In these species, the habitat changes due to climate could lead to difficulties that may cause the already decreasing populations.

Discussion

This paper illustrates that climatic variability affects the population of migratory birds and, in particular, the timing and the magnitude of Migration can be primarily affected by climate variations in terms of temperature and seasonal variations. Climate-related disturbances are especially harmful to the species with specialized migration patterns and environmental needs because discrepancies between the migration timing and the resource availability may ruin the breeding success and decline populations. On the other hand, those species whose Migration is plastic, or whose habitat requirements are more generalized, can adapt to the altered conditions more easily, thus being more resilient. The results underline the necessity to develop adaptive conservation strategies that will be able to react to the current and future climate changes. Historical data may not be applicable in the protection of vulnerable species and habitats by the use of static management plans. The conservation efforts need to be vibrant and should incorporate real-time monitoring and adaptable management structures, which can adapt to the changing environmental conditions. The actuality of tracking the migration trends and population dynamics is essential in comprehending the reaction of species to climate change. The changes in migration behavior or population size can be identified early enough to assist in timely conservation efforts. This study recommends an active and climate-conscious conservation strategy that will help to secure the survival of migratory species and their ecosystem in a fast-shifting environment.

The fundamental answer to the risk of climate variability to the population of migrant birds is to embrace adaptive conservation measures. This transition requires the abandonment of traditional management strategies in the use of historical data because these are no longer applicable in conserving endangered species and habitats. Instead, conservation initiatives should be made dynamic, whereby predictions of climate change are actively realized using Global Climate Models (GCMs) and dynamic population models to predict and act in response to the current and future changes in the environment. One of the main priorities is to find and safeguard the areas that would otherwise be viable or crucial during the changing climatic conditions, and the areas where the needs vary should be adjusted to the preferences of the areas that are being safeguarded and migration routes. This proactive strategy also consists of setting up flexible administration structures whereby changes to migration patterns and environmental circumstances occur at the right time, knowing that real-time tracking of migration trends and population dynamics is taken into account. In addition, planning should be species-based where species with specialized habitat requirements are essential and prone to climatic-related deterioration, yet at the same time, species with greater adaptability are enhanced by ensuring that they have access to various resources and alternative habitats. These dynamic models must be further developed in future employment to apply to particular species and regions by further detailing the ecological information to ensure that conservation interventions can be the most effective.

Conclusion

The study illustrates that climate variability will have far-reaching effects on migratory bird populations as migration timing and population sizes are expected to change in many of the species. The statistical analysis suggests that the species that are dependent on a particular habitat or food supply can experience a severe drop in population, and the more adaptable ones can be resistant to climate change. As an example, the species with adaptable migration patterns could gain population slightly under moderate conditions of climate warming, but species with limited habitat requirements lost 15% of their population under severe warming conditions ($p<0.05$). Based on these results, it is essential to note that climate projections and dynamic population behavior models must be used in conservation planning. The conservation methods should be made more flexible, so that the protected areas and migration routes are made in accordance with the climate conditions. Also, further study should involve improving models on particular species and areas to be more precise with a detailed set of ecological data to increase prediction and conservation value. In this manner, we are better placed to protect the migratory populations of birds, and the conservation efforts are sensitive to the current effects of the changes in climate.

References

[1] Bonnot, Thomas W., Frank R. Thompson III, Joshua J. Millspaugh, and D. Todd Jones-Farrand. "Landscape-based

population viability models demonstrate importance of strategic conservation table

[2] Conservation 165 (2013): 104-114. https://doi.org/10.1016/j.biocon.2013.05.010

[3] Conroy, Michael J., Michael C. Runge, James D. Nichols, Kirk W. Stodola, and Robert J. Cooper. "Conservation in the face of climate change: the roles of alternative models, monitoring, and adaptation in confronting and reducing uncertainty." *Biological Conservation* 144, no. 4 (2011): 1204-1213.https://doi.org/10.1016/j.biocon.2010.10.019

[4] Gillson, Lindsey, Terence P. Dawson, Sam Jack, and Melodie A. McGeoch. "Accommodating climate change contingencies in conservation strategy." *Trends in Ecology & Evolution* 28, no. 3 (2013): 135-142.

[5] Hamann, Andreas, and Sally N. Aitken. "Conservation planning under climate change: accounting for adaptive potential and migration capacity in species distribution models." *Diversity and distributions* 19, no. 3 (2013): 268-280. https://doi.org/10.1111/j.1472-4642.2012.00945.x

[6] Hostetler, Jeffrey A., T. Scott Sillett, and Peter P. Marra. "Full-annual-cycle population models for migratory birds." *The Auk* 132, no. 2 (2015): 433-449. https://doi.org/10.1642/AUK-14-211.1

[7] Hu, Junhua, Huijian Hu, and Zhigang Jiang. "The impacts of climate change on the wintering distribution of an endangered migratory bird." *Oecologia* 164, no. 2 (2010): 555-565. https://doi.org/10.1007/s00442-010-1732-z

[8] Jenouvrier, Stephanie. "Impacts of climate change on avian populations." *Global Change Biology* 19, no. 7 (2013): 2036-2057. https://doi.org/10.1111/gcb.12195

[9] La Sorte, Frank A., Daniel Fink, Peter J. Blancher, Amanda D. Rodewald, Viviana Ruiz-Gutierrez, Kenneth V. Rosenberg, Wesley M. Hochachka, Peter H. Verburg, and Steve Kelling. "Global change and the distributional dynamics of migratory bird populations wintering in Central America." *Global Change Biology* 23, no. 12 (2017): 5284-5296. https://doi.org/10.1111/gcb.13794

[10] Lemieux, Christopher J., and Daniel J. Scott. "Climate change, biodiversity conservation and protected area planning in Canada." *Canadian Geographer/Le Géographe canadien* 49, no. 4 (2005): 384-397. https://doi.org/10.1111/j.0008-3658.2005.00103.x

[11] Mace, Georgina M., Ben Collen, Richard A. Fuller, and Elizabeth H. Boakes. "Population and geographic range dynamics: implications for conservation planning." *Philosophical Transactions of the Royal Society B: Biological Sciences* 365, no. 1558 (2010): 3743-3751. https://doi.org/10.1098/rstb.2010.0264

[12] Ravshanova, Adolat, Feruza Akramova, Kalandar Saparov, Javlon Yorkulov,

Mashhura Akbarova, and Djalaliddin Azimov. "Ecological-faunistic analysis of helminthes of waterbirds of the Aidar-Arnasay system of lakes in Uzbekistan." *Natural and Engineering Sciences* 9, no. 1 (2024): 10-25. https://doi.org/10.28978/nesciences.1471270

[13] Reynolds, Mark D., Brian L. Sullivan, Eric Hallstein, Sandra Matsumoto, Steve Kelling, Matthew Merrifield, Daniel Fink et al. "Dynamic conservation for migratory species." *Science Advances* 3, no. 8 (2017): e1700707. https://doi.org/10.1126/sciadv.1700707

[14] Sadulla, Shaik. "Impact of Recurrent Wildfires on Boreal Forest Structure and Function: Insights from Long-Term Monitoring and Ecological Modelling." *National Journal of Forest Sustainability and Climate Change* 3, no. 1 (2025): 9-15.

[15] Shah, V., and T. Bansalm. "Multidisciplinary Approaches to Climate Change Monitoring Using Cloud-based Environmental Data Systems." *Cloud-Driven Policy Systems* (2023): 25-31.

[16] Stralberg, Diana, Dominique Berteaux, C. Ronnie Drever, Mark Drever, Ilona Naujokaitis-Lewis, Fiona KA Schmiegelow, and Junior A. Tremblay. "Conservation planning for boreal birds in a changing climate: a framework for action." *Avian Conservation & Ecology* 14, no. 1 (2019). https://doi.org/10.5751/ACE-01363-140113

[17] Van de Pol, Martijn, Yngvild Vindenes, Bernt-Erik Sæther, Steinar Engen, Bruno J. Ens, Kees Oosterbeek, and Joost M. Tinbergen. "Effects of climate change and variability on population dynamics in a long-lived shorebird." *Ecology* 91, no. 4 (2010): 1192-1204. https://doi.org/10.1890/09-0410.1

[18] Veloz, Samuel D., Nadav Nur, Leonardo Salas, Dennis Jongsomjit, Julian Wood, Diana Stralberg, and Grant Ballard. "Modeling climate change impacts on tidal marsh birds: restoration and conservation planning in the face of uncertainty." *Ecosphere* 4, no. 4 (2013): 1-25. https://doi.org/10.1890/ES12-00341.1

[19] Yadav, Nitesh Kumar, Arun Bhai Patel, Soibam Khogen Singh, Naresh Kumar Mehta, Vishwajeet Anand, Jham Lal, Debojit Dekari, and Ng Chinglembi Devi. "Climate change effects on aquaculture production and its sustainable management through climate-resilient adaptation strategies: a review." *Environmental Science and Pollution Research* 31, no. 22 (2024): 31731-31751.

[20] Zhao, Qing, Emily Silverman, Kathy Fleming, and G. Scott Boomer. "Forecasting waterfowl population dynamics under climate change—Does the spatial variation of density dependence and environmental effects matter?" *Biological conservation* 194 (2016): 80-88. https://doi.org/10.1016/j.biocon.2015.12.006

[21] Zhao, Qing, Todd W. Arnold, James H. Devries, David W. Howerter, Robert G. Clark, and Mitch D. Weegman. "Land-use change increases climatic vulnerability of migratory birds: Insights from integrated population modelling." *Journal of Animal Ecology* 88, no. 10 (2019): 1625-1637. https://doi.org/10.1111/1365-2656.13043