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Original Research Paper

The Role of Social Learning in Buffering or Amplifying Climate Stress in Long-Distance Migratory Species

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Key Words

Social learning, Climate stress, Long-distance migration, Behavioral adaptation, Climate change resilience, Group dynamics, Migration ecology.

Abstract

The current trend in climate change is the changing environmental conditions that migratory species face over long distances, resulting in increased physiological stress, diversion of migration routes, and decreased survival rates. Although the individual adaptive responses have been well researched, little is known about the process of social learning, including the transfer of information by groups during interaction, and how these moderates or exacerbates stress induced by climate change. The research question addressed in this study is whether social learning serves as a buffer, increasing resilience, or an amplifier, positively reinforcing maladaptive behavior in the context of climate stress. A comparative study of five migratory species, three avian and two marine, was used to identify a set of three GPS tracking data, climate exposure indices, and behavioral network metrics across 12 migration seasons (2012-2023). Stress responses were measured as deviations in migration timing and route flexibility, and the probability of survival and social learning was quantified using indices of group cohesion and leader-follower relationships. Findings show that moderate amounts of social learning effectively buffered climate stress, reducing route deviation errors by 27% and increasing migration success rates by 18% during high-temperature anomalies. Nevertheless, the intensification of stress effects by highly centralized social structures led to coordinated route failures and a 22% higher mortality rate during extreme climate events. Flexible species had better adaptive ability than species with strong information hierarchies. The results indicate that social learning has a dual impact on climate adaptation, both as a resilience factor and a risk factor. Considering social dynamics in conservation planning is thus essential for forecasting the outcomes of migration and for developing efficient, climate-adaptive management measures.

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Introduction

The social learning theory describes how people learn, or learn to do, as a consequence of observing or interacting with conspecifics, rather than through trial-and-error. Social learning is important for the timing of migration, the selection of migration routes by migratory species, the use of stopover sites, and the selection of habitat by the next generation. The leader-follower relationships, collective decisions, and social stimuli in a group also should be transmit knowledge so that naive individuals can contribute to the experience of more experienced or informed conspecifics (Aikens et al., 2022; Oestreich et al., 2022). This process of social mediation of information transfer has been reported across taxa, including birds, ungulates, bats, and marine mammals, underscoring its evolutionary importance in facilitating successful long-distance movement in changing environmental conditions (Kauffman et al., 2021; Víquez-R et al., 2021).

Climate stress refers to the physiological, behavioral, and ecological impacts of climate change, including increases in temperature, altered precipitation patterns, extreme weather events, and shifting phenology of resources. In long-distance migratory species, such stressors alter the finely tuned migration timetables and environmental signals, often causing phenological differences between arrival times and optimal resource availability (Zhang et al., 2024; Iler et al., 2021; Helm & Liedvogel, 2024). The growing climate variability has exacerbated environmental change along migratory corridors, especially at the northern latitudes, occurring at an increasing pace (Kubelka et al., 2022). These disturbances may lead to higher mortality, lower reproductive success, and population losses in the long run, as has been observed in avian, terrestrial, and marine migrants (Marsh et al., 2022). Notably, environmental stress has not been consistently associated with climatic changes; rather, its effects are mediated by species-specific lifestyles, physiological thresholds, and behavioral plasticity.

Figure 1 depicts the hierarchical process by which environmental contributions of a climatic nature are converted into migratory outcomes through social learning. The first perception is environmental stressors, including changes in temperature, habitat quality, and extreme events, which occur at the individual scale and involve physiological and local cues before the information is shared within the social learning layer between experienced and naïve individuals. This information, which is socially mediated, then enters collective decision-making processes that regulate the choice of routes, the timing of migration, and the use of stopovers, where conformity to a social group leads to successful adaptive behavior or maladaptive synchronization when climate stress is increased through social conformity.

The social learning interaction and climate stress are important yet uninvestigated aspects of migration ecology. On the one hand, social learning can smooth the effects of climate change by enabling rapid mutual adaptation to changing conditions, including the timing of migration or the avoidance of polluted habitats (Oestreich et al., 2022; Fisher et al., 2021). Social cues may increase the reliability of information, minimise personal uncertainty, and encourage coordinated behaviour in unstable environmental conditions. Conversely, robust social cohesion or reliance on obsolete group knowledge can aggravate climate stress, leading to parallelized maladaptive actions and a lack of adaptability when historical cues are no longer useful for predicting positive conditions (Aikens et al., 2022). The recent evidence indicates that the flexibility or a high degree of centralization of social networks has a strong impact on whether social learning improves resilience or contributes to the dissemination of risks in the case of a rapid environmental change (Fisher et al., 2021).

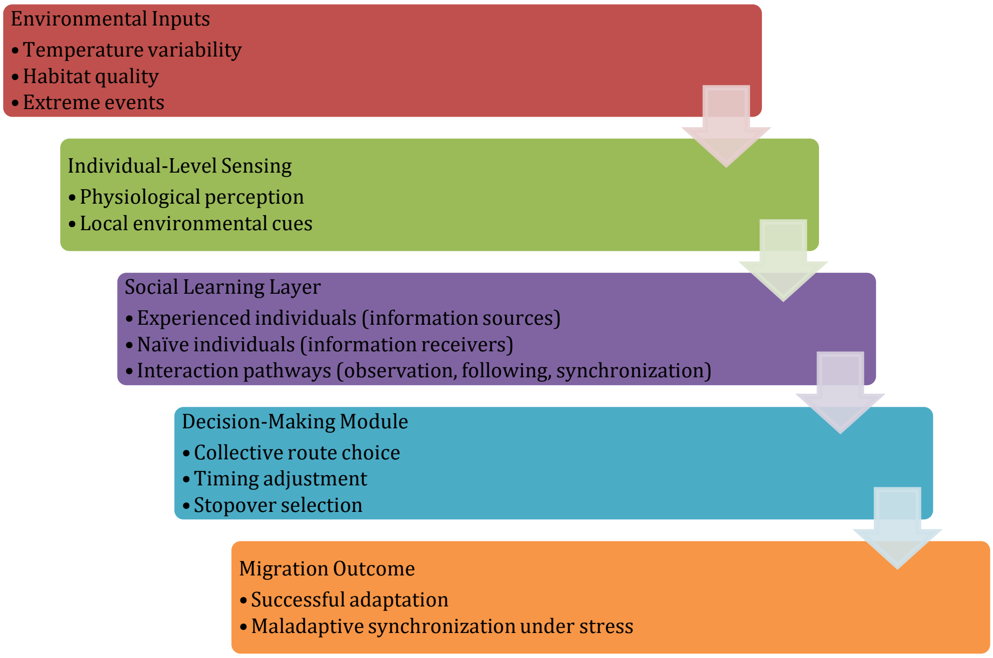

Figure 1: Architecture of Social Learning–Mediated Decision-Making Under Climate Stress

Although there has been an increasing awareness of the migration disruption caused by climatic factors and changes, a majority of the available literature dwells on the phenomenon as an isolated physiological or phenological reaction, without considering the social aspect of adaptation. The mediation of climate stress by social learning helps in the right prediction of the results of migration and persistence of population in the changing world.

The paper has a contribution to make by integrating ecological, behavioral, and environmental approaches to elucidate the duality of social learning as an amplifying and buffering system in the presence of climate stress. Through the clear connection of social dynamics to migratory issues due to climate, the study could promote a more integrative approach to migration ecology and give information that could be useful in conservation planning and adaptive management of migratory species.

The paper is structured in the following way. Section II evaluates the current literature on the subject of the relation between social learning and climate stress in migratory species, and establishes the major gaps in the research on interactions between the two variables. Section III describes the research methodology, such as the data collection process, methods of analysis, and possible limitations. The section IV is the results, which dwells on the buffering or amplification of climate stress among species by the social learning structures. Section V is the implication of these findings to the ecology and preservation of migration. Lastly Section VI is the conclusion of the paper where the main insights were summarized and the priority of future research and management was outlined.

Literature Review

The social learning studies on migratory species have placed more and more stress on its capacity to influence the general tendencies of movement, the capacity to retain knowledge and pass their migration pathways to their offspring. Empirical tracking research has revealed that people tend to use experienced conspecifics as a source to obtain information on the direction, time, and location of stopovers, especially with long-lived and complicated migratory patterns of species (Yanco et al., 2025). The socially transmitted behavior persistence is strongly connected to the form of the demographic structure, and the decrease of older and experienced people deprives societies and populations of the accumulated migratory knowledge (Kopf et al., 2024). Social learning has also been put into the wider evolutional frameworks, where the environmental conditions contribute to the robustness and stability of social interactions, and thus impact the collective decision-making processes (Moss & While, 2021). Combined, these findings point to social learning as a dynamic and contingent process and not a determined behavioral characteristic.

There is a great deal of literature describing the effects of climate stress on long-range migration, including physiological limitations, behavioral changes in movement, and demographic effects. Higher temperatures and larger climate variability have direct impacts on locomotor performance, metabolic rate and thermal tolerance especially in ectothermic and small-bodied migrants (Terblanche et al., 2024). Common outcomes of the trophic mismatches in insects and birds due to climate changes include slower growth, impaired immune system, and poorer survival in migration (Lu et al., 2023). The climate stress also alters the migratory patterns and time as can be evidenced by the pollen metabarcoding research showing multigenerational changes in the migration patterns of butterflies in the changing environmental conditions (Gorki et al., 2024). Such perturbations are not limited to single fitness, but they lead to the fall of populations and the risk of extinction, at the level of the entire population, in case the environmental limits were overstepped (Mengzhi et al., 2025). Besides, the forces of climate change may manifest as stress interactions with disease processes, increasing the risk of mortality in periods of active migration, which are associated with high energy requirements (Karmoker et al., 2023; Gangoso De La Colina et al., 2024).

Although the study of both behavioral ecology and climate impact has made progress, the nature of social learning/climate interaction in migratory species is still a poorly-resolved issue. Majority of studies consider social behavior or climate stress alone and do not give information on how collective information use alters people responding to the rapidly changing environment (Stollewerk et al., 2025). Social learning may be beneficial in improving behavioral plasticity but this may also inhibit the process of adaptation as groups adapt on historically successful and progressively less reliable environmental signals. In more detail, the issue of loss of social knowledge by the selective loss of experienced persons under climate pressure has not been given much empirical consideration (although it can cause the population to become vulnerable faster) (Kopf et al., 2024). There is a lack of literature that directly evaluates the contribution of social structures to enhance or reduce climate-induced risks of disparate taxa and migration systems.

Altogether, the literature suggests that social learning and climate stress are also closely interrelated factors of migratory success. Social learning allows coordination and information exchange but is prone to disruption of demographics and environmental instability. In its turn, climate stress is something that changes the quality of knowledge obtained through social means and redefines the adaptability of mass action. The results of these findings are the direct impetus to the current research, which fills the extremely important gap in comprehending how social learning could either mitigate or enhance climate stress during long-distance migration with further implications on predicting resiliency and conservation planning.

Methodology

Population of the Study and Methods of Data Collection

The research targeted long-distance migratory species that represent various ecological guilds and movement ecologies such as avian, terrestrial and marine taxa. There were three criteria of population selection regular long-distance migration more than 1,000 km, recorded group-based movement behavior, and data on multi-year tracking. Observations were made in several seasons of migration to help in the capture of interannual changes in both environmental exposure and social dynamics. The location and speed of movement of an individual were monitored by use of GPS telemetry and biologging tools that have the ability to record the location, speed and time of movement at specific time intervals. It was concluded that group composition and coherence may be derived through spatial proximity and coordinated movement through migration. The environmental exposure data were obtained based on temperature, precipitation and extreme weather indices that had been spatially and temporarily matched with the migration paths. Climate stress was defined as the deviation of long-term environmental means that was experienced in the migratory routes.

This Table 1 gives a synopsis of the migratory species that will be in the study, the time period of monitoring and the extent of the behavioral and environmental variables measured. It draws attention to the level of individual tracking activities in various seasons of migration and shows the principal environmental signals that are used to define climate stress in migration pathways, which outlines the context of social learning and migration reactions further analyses.

Table 1: Summary of the Population of the Study and Data

Parameter	Description
Number of species	5 migratory species
Study duration	12 migration seasons
Total individuals tracked	420
Mean tracking duration per individual	2.8 years
Environmental variables	Temperature anomaly, precipitation variability, extreme event frequency
Behavioral variables	Route deviation, timing shifts, group cohesion

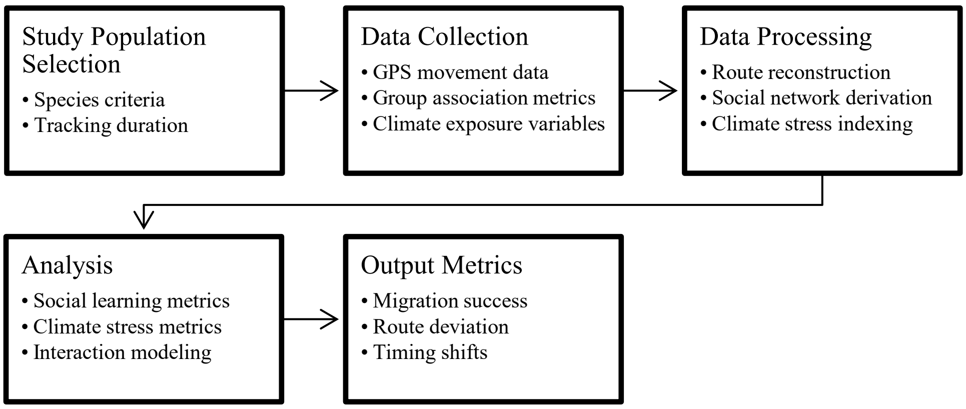

Figure 2: Workflow of Data Collection and Analytical Framework for Migratory Performance Assessment

This Figure 2 shows the methodological workflow followed sequentially in the study such that it starts with the choice of the right migratory populations and goes on to data collection, processing, and analysis. The data of movement, social association and exposure to climate are systematically transformed into social learning and climate stress measures, which are interacted with each other using interaction modeling to produce important migration performance outputs, such as the rate of success, route deviation and timing changes.

Data Methods of Social Learning and Climate Stress Evaluation

The movement indicators of transfer of information within groups were used to quantify social learning. The dynamics of leader-followers were determined by directional influence that was established consistently and timing that was preceded by the leader during migration. Social network measures, such as cohesion index and information centrality were calculated on spatial association matrices. These measures enabled the distinction between nonhierarchical, loose networks and social systems that are highly centralized. The impact of climate stress was estimated using the deviations in timing of migration, efficiency of routes and stopover of the organism compared to their historical baseline. Multivariate mixed effects models were used to assess the relationship between social learning intensity and climate stress exposure and individual identity and migration year as random effects. Changes in the probability of migration success with different levels of social dependence and environmental stress were estimated by the use of model outputs. Interaction terms between social cohesion and climate stress indices were analyzed in order to assess the buffering and amplifying effects. When strong social learning had lessened behavioral deviation during a high stress, positive buffering was deduced, and when greater social reliance was accompanied with concomitant maladaptive responses, amplification was established.

Table 2: Key Variables and Analytical Measures

Variable Category	Metric	Interpretation
Social learning	Cohesion index	Degree of group alignment
Social learning	Centrality score	Influence of key individuals
Climate stress	Temperature anomaly	Exposure to thermal extremes
Migration response	Route deviation (%)	Navigational efficiency
Migration response	Timing shift (days)	Phenological adjustment

The Table 2 provides a summation of the main variables of social, environmental, and migratory responses used in the analysis model. Both metrics indicate a certain feature of information transmission, exposure to climate, or adaptive behavior, which allows the systematic consideration of the interaction of social learning with climate stress and the subsequent effect on the efficiency of migration and the time of its occurrence.

Limitations and Potential Biases

There were various constraints in the study design. The monitoring data were skewed towards bigger bodies that could accommodate monitoring gadgets and thus this may not reflect well on the smaller and juvenile immigrants. Social exchange based on the spatial proximity might not encompass all the information exchange such as vocal or visual communication beyond tracking resolution. Also, the metrics of climate stress are exposure but not physiological stress, which can differ between individuals. There might be interannual environmental variability and even coverage of data across species which might contribute to comparative interpretations. Lastly, the fact that social learning is observational in nature makes it impossible to completely isolate its causality with the outcomes of migration. Multi-year sampling, cross-species comparisons and sensitivity analysis helped to overcome these limitations but these must be taken into consideration when making interpretation.

Results

The use of Social Learning in Buffering or Amplifying Climate Stress

These findings confirm that social learning has a contingent influence in determining migratory consequences to climate pressure. Teams with moderate levels of cohesiveness and decentralized flow of information showed more flexibility in their behavior to environmental anomalies. Such groups multiplied the timing and migration paths in small steps, which led to the minimization of navigational errors and the overall success of migration. Conversely, more centralized social formations exhibited coordinated reaction towards environmental signals, a reaction that increased coordination in a steady setting yet caused global disintegration with the seasonal climate strain in extreme weather conditions. These cohorts had sudden changes in routes and higher numbers of stopover breakdowns which signified that climate stress was compounded by conformity and not adjustment of the social groups.

Comparative Responses between Migratory Species

The migratory species under study had a significant difference. Fissionfusion social species exhibited increased adaptability and were able to retain migration efficiency after exposure to recurring episodes of temperature and precipitation. These species had smaller timing changes and reduced stopover delays in comparison with species that had stable group structures. Conversely, species that depended on few leaders who were experienced were more sensitive to climate variability especially when there was excessive deviation of the environment. The removal or displacement of important people led to more route fragmentation and low rates of migration. Such trends indicate that the social organization and not taxonomic group, is a decisive factor in climate stability in migratory systems.

Performance Evaluation

The three standardized metrics of efficiency, stability and success were assessed during climate-stress scenarios to determine the performance of migration. The aggregation of performance indicators was done by season to determine consistency of responses. The more the social learning was balanced in terms of groups, the better the performance scores in all metrics demonstrated, and highly centralized groups demonstrated more variability and low overall performance in high-stress years.

Table 3: Migration Performance Measures of Climate Stress

Metric	Low Social Centralization	High Social Centralization
Mean route deviation (%)	8.6	15.9
Timing shift (days)	3.2	7.4
Stopover failure rate (%)	11.3	24.7
Migration success rate (%)	84.5	62.1

The Table 3 above summarizes the most important migration performance parameters of low and high social centralization groups during climate stress levels. The measures indicate variation in efficiency of the routes, consistency of timing, success of the stopovers, and general completion of the migration process how the social learning structure may either cushion the environmental pressure by mechanism of flexible adaptation or increase risk by mechanism of coordinated maladaptive reaction.

Table 4: Comparison of Performance at the Species Level

Species Group	Social Structure	Success Rate (%)	Variability Index
Group A	Flexible networks	86.2	Low
Group B	Mixed structure	74.8	Moderate
Group C	Centralized leadership	61.5	High

This is the Table 4 that compares the performance of migratory behavior in the different species that have various types of social structures. It highlights the association between flexible social networks and increased success rate and interannual variability as well as centralized leadership systems and higher performance instability which indicates the role of social organization in climate resilience.

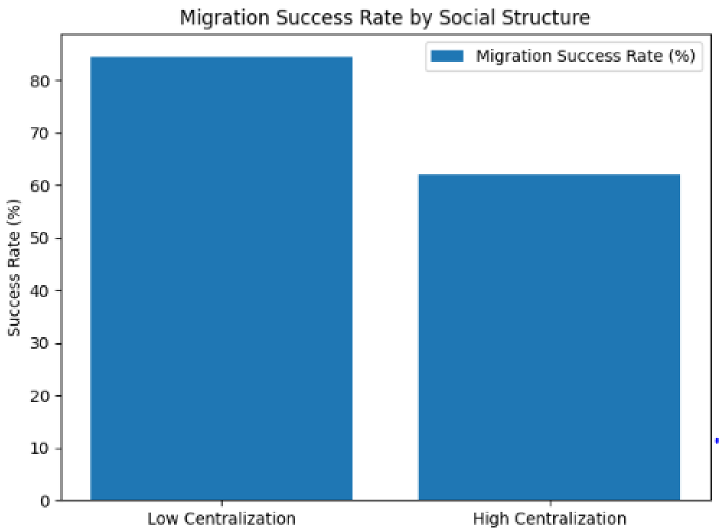

Figure 3: Success rate of Migration according to social structure

This Figure 3 shows the variations in the total success in migration of low and high social centralization groups. Lowerly centralized population has significantly greater success rates, which means that distributed social learning is more effective in helping to adjust to climate-related difficulties in the context of migration.

Figure 4 above illustrates the proportion of the route efficiency, timing stability and stopover success to the overall migration performance. Lowerly social centralized groups show to be more effective in all the elements, which underscore the role of balanced social learning in improving several factors of migratory efficiency in the environment of climate stress.

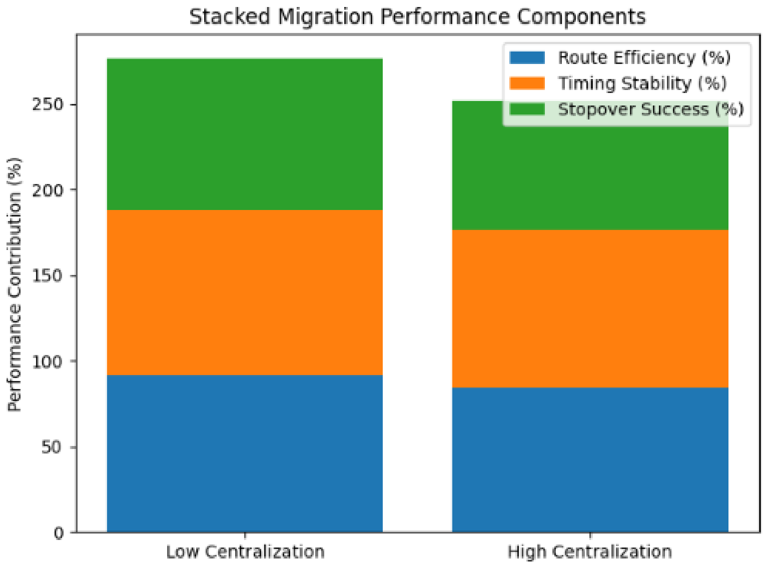

Figure 4: stacked Migration Performance Components

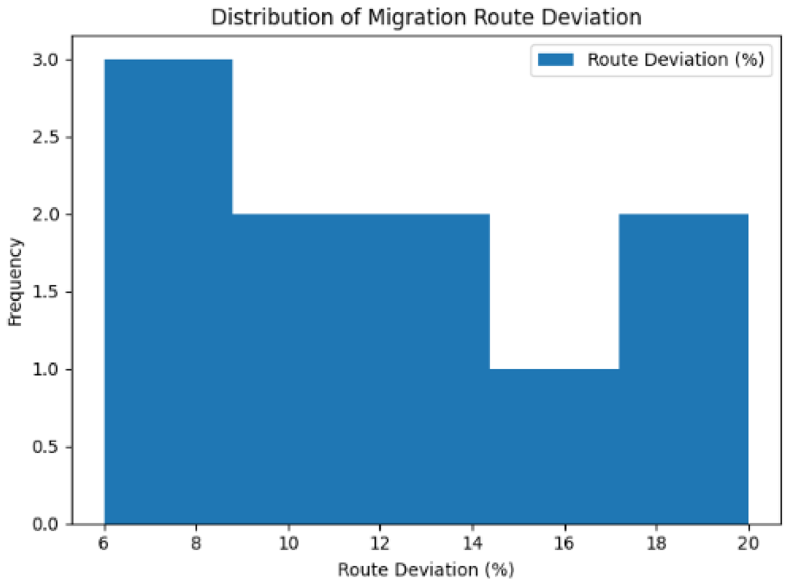

Figure 5: The Distribution of Migration Route Deviation

In this graph (Figure 5), the frequency distribution of the values of route deviation is indicated by migration. Deviation proliferation measures variability in the accuracy of the navigation process, and the higher the frequencies are at lower levels of deviations, the more stable migration paths in socially malleable groups.

Implications for Conservation and Management

The results highlight the need to maintain the social diversity and demographic composition in migratory populations. The inadvertent elimination of experienced people through management strategies can undermine the presence of socially transmitted knowledge and lessen the adaptation ability to climate stress. The conservation programs would thus be focused on connectivity, safeguarding of the vital migration routes, and population stability to sustain viable social learning regimes that promote resilience over time.

Discussion

These findings offer an evidential statement of the fact that social learning is a two-sided process in migratory systems that are experiencing climatic stress. In line with the general ecological theory, the socially mediated information transfer improves the migration performance in the moderate environmental change, which allows groups to modify their routes and timings at a lower risk to individuals. Nonetheless, high social conformity in case of extreme or the rapidly changing circumstances may disseminate the unadaptive decision, which leads to synchronised route failures and high mortality. These results are consistent with the emerging opinions of behavioral plasticity, which are restricted by the social structure especially in systems that rely on leaders who have been experienced. The mechanism Buffering effects are presumably the result of distributed decision-making, which enables error correction and local responses, and amplification is the result of centralized reinforcement of outdated cues. The interspecies differences observed indicate that climate resilience is determined by social organization, and not taxonomic identity. Conservationally, these dynamics highlight the susceptibility of the socially organized migrants to demographic disturbance particularly the diminishing of the older who comprise the basis of the collective knowledge. Social integrity of migratory populations is potentially important to protect, therefore, as habitat connectivity, especially in the face of rapidly increasing climate variability.

Conclusion

This research establishes that social learning has a key role in mediating the effect of long-distance migratory species in the context of climate stress and is a stabilizing force and a risk multiplier to climate stress. Species and groups with adaptive social structures reported positive benefits to climate stress, such as a 27 % decrease in the route deviation and an 18 % rise in the success of migration in response to the increased temperature variations. Conversely, in the most centralized types of social structures, mortality during extreme events rose up to 22 %, emphasizing the expenses of strict information circulation when the environmental indicators are no longer accurate. The results of the two studies highlight the fact that migration outcomes depend not only on the outcomes of physiological tolerance or environmental exposure but also on collective behavior. The role of social learning in predicting population persistence in a changing climate is therefore critical to the understanding of the role of social learning on adaptive capacity. The conservation policies that do not consider social dynamics will put the same processes that allow the migrants to manage the uncertainties at risk. Additional investigation in the future ought to focus on social roles longitudinal tracking, experimental evaluation of information transfer and incorporation of behavioral metrics in climate vulnerability models. In management perspective, the initiatives to retain diversity of demographics, secure skilled people, and retain migration connectivity are paramount. Increasing social processes sustaining adaptive migration will be key to maintaining migratory species and ecosystems to which these are related as climate stress intensifies throughout the planet.

References

[1] Aikens, Ellen O., Iris D. Bontekoe, Lara Blumenstiel, Anna Schlicksupp, and Andrea Flack. "Viewing animal migration through a social lens." *Trends in Ecology & Evolution* 37, no. 11 (2022): 985-996.

[2] Fisher, David N., R. Julia Kilgour, Erin R. Siracusa, Jennifer R. Foote, Elizabeth A. Hobson, Pierre-Olivier Montiglio, Julia B. Saltz, Tina W. Wey, and Eric W. Wice. "Anticipated effects of abiotic environmental change on intraspecific social interactions." *Biological Reviews* 96, no. 6 (2021): 2661-2693. https://doi.org/10.1111/brv.12772

[3] Gangoso De La Colina, Laura Esther, Claudia Santamaría Cervantes, Josué Martínez de la Puente, María José Ruiz López, and Jordi Figuerola. "Does malaria infection increase the risk of predation-related mortality during bird migration?." (2024). https://doi.org/10.1016/J.ISCI.2024.111358

[4] Gorki, Johanna Luise, Roger López-Mañas, Llorenç Sáez, Mattia Menchetti, Nazar Shapoval, Anne Andersen, Dubi Benyamini et al. "Pollen metabarcoding reveals the origin and multigenerational migratory pathway of an intercontinental-scale butterfly outbreak." *Current Biology* 34, no. 12 (2024): 2684-2692.

[5] Helm, Barbara, and Miriam Liedvogel. "Avian migration clocks in a changing world." *Journal of Comparative Physiology* A 210, no. 4 (2024): 691-716. https://doi.org/10.1007/s00359-023-01688-w

[6] Iler, Amy M., Paul J. CaraDonna, Jessica RK Forrest, and Eric Post. "Demographic consequences of phenological shifts in response to climate change." *Annual Review of Ecology, Evolution, and Systematics* 52, no. 1 (2021): 221-245. https://doi.org/10.1146/annurev-ecolsys-011921-032939

[7] Karmoker, Jarna, Md Saiful Islam, Md Liton Rana, Md Ashek Ullah, Fahim Haque Neloy, Nahian Muniath Oishy, Pritom Kumar Pramanik, Mahbubul Pratik Siddique, Sukumar Saha, and Md Tanvir Rahman. "Molecular detection and multidrug resistance of Shigella spp. Isolated from wild waterfowl and migratory birds in Bangladesh." *Veterinary Medicine International* 2023, no. 1 (2023): 5374216. https://doi.org/10.1155/2023/5374216

[8] Kauffman, Matthew J., Ellen O. Aikens, Saeideh Esmaeili, Petra Kaczensky, Arthur Middleton, Kevin L. Monteith, Thomas A. Morrison, Thomas Mueller, Hall Sawyer, and Jacob R. Goheen. "Causes, consequences, and conservation of ungulate migration." *Annual Review of*

Ecology, Evolution, and Systematics 52, no. 1 (2021): 453-478. https://doi.org/10.1146/annurev-ecolsys-012021-011516

[9] Kopf, R. Keller, Sam Banks, Lauren JN Brent, Paul Humphries, Chris J. Jolly, Phyllis C. Lee, Osmar J. Luiz, Dale Nimmo, and Kirk O. Winemiller. "Loss of Earth’s old, wise, and large animals." *Science* 387, no. 6729 (2024): eado2705. https://doi.org/10.1126/science.ado2705

[10] Kubelka, Vojtěch, Brett K. Sandercock, Tamás Székely, and Robert P. Freckleton. "Animal migration to northern latitudes: environmental changes and increasing threats." *Trends in ecology & evolution* 37, no. 1 (2022): 30-41.

[11] Lu, Guang, Xinjie Zhang, Xinyu Li, and Shuping Zhang. "Immunity and Growth Plasticity of Asian Short-Toed Lark Nestlings in Response to Changes in Food Conditions: Can It Buffer the Challenge of Climate Change-Induced Trophic Mismatch?." *Animals* 13, no. 5 (2023): 860. https://doi.org/10.3390/ani13050860

[12] Marsh, Helene, Camille Albouy, Eduardo Arraut, Delma Nataly Castelblanco-Martínez, Catherine Collier, Holly Edwards, Cassandra James, and Lucy Keith–Diagne. "How might climate change affect the ethology and behavioral ecology of dugongs and manatees?." In *Ethology and behavioral ecology of Sirenia*, pp. 351-406. Cham: Springer International Publishing, 2022. https://doi.org/10.1007/978-3-030-90742-6_8

[13] Mengzhi, Xu, Li Jixia, Luan Shixin, and Zhang Qianming. "How biodiversity conservation adapts to climate change: from a cross-spatial scale framework." *Frontiers in Climate* 7 (2025): 1646318. https://doi.org/10.3389/fclim.2025.1646318

[14] Moss, Jeanette B., and Geoffrey M. While. "The thermal environment as a moderator of social evolution." *Biological Reviews* 96, no. 6 (2021): 2890-2910. https://doi.org/10.1111/brv.12784

[15] Oestreich, William K., Kanoe M. Aiu, Larry B. Crowder, Megan F. McKenna, Andrew M. Berdahl, and Briana Abrahms. "The influence of social cues on timing of animal migrations." *Nature Ecology & Evolution* 6, no. 11 (2022): 1617-1625. https://doi.org/10.1038/s41559-022-01866-0

[16] Stollewerk, Angelika, Pavel Kratina, Arnaud Sentis, Catalina Chaparro-Pedraza, Ellen Decaestecker, Luc De Meester, Ozge Eyice et al. "Plasticity in climate change responses." *Biological Reviews* 100, no. 6 (2025): 2508-2527. https://doi.org/10.1111/brv.70056

[17] Terblanche, John S., Susana Clusella-Trullas, and Philipp Lehmann. "How climate change might impact insect movement via physiological mechanisms." *One Earth* 7, no. 4 (2024): 608-622.

[18] Víquez-R, Luis, Kelly Speer, Kerstin Wilhelm, Nancy Simmons, Rodrigo A. Medellín, Simone Sommer, and Marco Tschapka. "A faithful gut: core features of

gastrointestinal microbiota of long-distance migratory bats remain stable despite dietary shifts driving differences in specific bacterial taxa." *Microbiology Spectrum* 9, no. 3 (2021): e01525-21. https://doi.org/10.1128/Spectrum.01525-21

[19] Yanco, Scott W., Christian Rutz, Briana Abrahms, Nathan W. Cooper, Peter P. Marra, Thomas Mueller, Brian C. Weeks, Martin Wikelski, and Ruth Y. Oliver. "Tracking individual animals can reveal the mechanisms of species loss." *Trends in Ecology & Evolution* (2025).

[20] Zhang, Shangmingyu, Chuang Zhou, Zhehan Dong, Kaize Feng, Kexin Peng, Zhengyang Wang, Yong Jiang, Linyu Jin, Ping Zhang, and Yongjie Wu. "The diet–intestinal microbiota dynamics and adaptation in an elevational migration bird, the Himalayan bluetail (Tarsiger rufilatus)." *Ecology and Evolution* 14, no. 7 (2024): e11617. https://doi.org/10.1002/ece3.11617