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## Original Research Paper

# Consequences of Cultural Memory Loss in Migratory Ungulates Due to Selective Removal of Knowledge-Bearing Individuals

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**Key Words**

Age-biased removal, Cultural retention index, Experience index, Knowledge-targeted removal, Migration fidelity, Navigational efficiency, Population growth rate.

**Abstract**

Migratory ungulates depend on social knowledge to negotiate a complex environment, and the disappearance of experienced individuals may interfere with cultural memory, efficiency in migration, and population stability. The purpose of the study was to measure the ecological and behavioral effects of the selective removal of knowledge-bearing individuals on the performance of migration, memory of culture, and demographics. The used a composite Experience Index based on age, migratory consistency, and social centrality to identify knowledge-bearing people. Migration performance was measured based on the metrics of route fidelity and navigational efficiency, cultural memory based on the Cultural Retention Index across successive generations, and population consequences by population growth rate (λ) in a stage-structured demographic model. The analyses were made by statistical techniques of generalized linear mixed models using bootstrapped confidence intervals to consider repeated measurements and hierarchy. Findings show that knowledge-targeted removal had a disproportionate impact on high-EI people (66.1%), in contrast to 25.5% when removal was random and 36.4% when it was age-biased. Under focused removal, migration performance dropped drastically, route fidelity fell from 0.82 ± 0.03 to 0.54 ± 0.06, and navigational efficiency fell from 0.87 ± 0.04 to 0.69 ± 0.06. CRI decreased between 0.63 and 0.41 in three generations, and the mean migratory deviation had risen by 38%. The rate of population growth (λ) decreased 1.04 ± 0.02 to 0.96 ± 0.03 with knowledge-targeted removal, which is a sign of lower reproductive success and high mortality. Such findings show that knowledge-bearing individuals are one of the key nodes in migratory networks. To retain migration fidelity, cultural continuity, and population resilience, conservation strategies must focus on the protection of the socially experienced individuals. Other interventions that can be addressed in future studies to reduce cultural memory loss include guided reintroduction or social learning facilitation.

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## Introduction

Migratory ungulates rely not only on individual physiological capacity but also on socially transmitted knowledge to navigate complex and dynamic landscapes. Cultural memory, defined as the shared, learned information passed across generations, plays a critical role in determining migration routes, timing, stopover sites, predator avoidance strategies, and access to seasonal resources (Merkle et al., 2023). In numerous species like the elephants, caribou, wildebeest, and the bison, the individuals that are of old age and possess the social experience act as a storage site for such ecological knowledge (Wenne, 2023). However, a biased loss of these knowledge holders by means of trophy hunting, poaching, culling, or conflict-based management takes a toll on the large and older animals, which can lead to disruption of the cultural flow of migratory species (Lesku & Rattenborg, 2022). With the increasing anthropogenic pressures, the role of cultural memory loss in driving migration fidelity, population resilience, and ecosystem connectivity has gained more and more significance in conservation and management.

The main aim of the study is to test the ecological and behavioural implications of the cultural memory loss in migratory ungulates due to the selective loss of experienced, knowledge-bearing individuals (Hering et al., 2022). In particular, the study would examine the effects of such losses in determining consistency of migration routes, navigational efficiency, habit use, and fitness outcomes of the population at both spatial and temporal scales.

While the role of social learning and leadership in ungulate migration has been acknowledged, most migration models and management strategies continue to assume that movement patterns are environmentally driven and individually optimized. Empirical and theoretical studies rarely isolate the effects of the selective removal of experienced individuals from the general population decline. Furthermore, limited attention has been given to the long-term, cross-generational impacts of cultural erosion on migratory systems, particularly under rapidly changing landscapes (Li et al., 2024). This limitation denies the capability to forecast slow or non-linear population reactions to the administration intervention and human exploitation.

The propose that due to the selective loss of knowledge-carrying individuals, there will be a quantifiable loss of cultural memory, which will be manifested in the form of a higher number of migratory errors, less fidelity to routes, less timely migration, and inefficient habitat choice. Also hypothesize that the culturally eroded populations will have reduced reproductive success and an increased risk of death, particularly in fragmented or new environments, then the populations with intact social knowledge systems (Castro et al., 2025).

The research adds a conceptual and analytical framework that includes the cultural memory in the ecology of migratory ungulates. The key contributes to the existing knowledge of migration as a socially mediated process and not an instinctive one by directly connecting the selective individual removal to behavioral disruption and the impact on the population. The results provide essential clues to conservation planning by indicating that there is a need to safeguard socially experienced individuals and integrate cultural processes in wildlife management, reintroduction initiatives, and sustainable harvest measures.

The article provides an Introduction where it describes the ecological significance of the cultural memory in migratory ungulates, the value of the role of experienced individuals, and the effects of selective removal. Since social learning, migration fidelity, and population impacts are tax-specific, the Literature Survey contextualizes them. The identification of knowledge-bearing people with the help of the Experience Index, simulation of the removal scenarios, movement metrics, cultural retention, and demographic modeling are described in the Materials and Methods section, which is supported by GLMM analyses. Findings introduce the impact of random, age-selective, and knowledge-oriented eradication on migration, cultural memory, and population growth. The Discussion and Conclusion combine the numerical results, focus on the keystone importance of the experienced people, and underline the implications of conservation and management.

## Literature survey

The rapid accumulation of evidence of its loss in taxa points to the erosion of ecological knowledge systems by the loss of large, old, and socially experienced animals as a little-recognized but significant process. The patterns (Kopf et al., 2024) synthesize globally reveal that the selective targeting of large-bodied and old means that repositories of ecological memory get disproportionately targeted, and that has cascading consequences to the stability of populations and to the functioning of an ecosystem. Such individuals tend to be leaders and knowledge carriers in migratory ungulates, and they retain acquired migration patterns, seasonal stability, and adaptation to fluctuating environmental change (Jesmer et al., 2025; Abraham et al., 2022). The empirical evidence is growing that social learning and experience influence movement decisions beyond the actions of the environmental cues. As (Berger et al., 2022) demonstrated, the use of perceptual knowledge affects the selection of migratory routes in Sierra Nevada bighorn sheep, which supports the idea that navigation is driven by developed spatial familiarity and not an instinctive behavior. Likewise, (Flueck et al., 2022) revealed the effects of loss of migratory traditions in the endangered Patagonian huemul deer, leading to permanent range contraction and permanently residing in the habitat, making the formerly migratory species a population that is dependent on a refuge year-round.

Cultural erosion is further enhanced by selective harvest and human-induced mortality. It was shown that the loss of calves due to hunting caused changes in behavior in a long-lived ungulate (Graf et al., 2024), indicating that social disturbance could spread fear-based behavioral changes across generations. These data are consistent with theoretical results obtained in size-selective harvesting experiments, revealing that elimination of certain phenotypes can produce a reorganization of the social behavior and raise the mortality risk at the population level (Sbragaglia et al., 2022). Similar impacts on social disruption have been seen in the case of African elephants, which, in orphaning and translocation, affected social cohesion and ecological competence (Garaï et al., 2023).

Recent conceptual developments highlight that migration is moving through invisible landscapes that are informed by social interactions, memory, and familiarity, often not explicitly captured in habitat selection and species distribution models (Dejeante et al., 2025). These dimensions can be neglected, which can lead to a bias in the prediction of changes in range, even in cases where adaptive movement behaviors are noted over large spatial scales (Gurarie et al., 2024). Conservation-based syntheses believe that the conservation of migration needs to safeguard not just corridors, but also socially entrenched knowledge structures (Cooke et al., 2024; Albers et al., 2023). In a more generalized culture, (Sueur, 2022) and (Whitehead et al., 2023) view animal culture as a unit of conservation and demand a management approach that conserves culturally unique populations. This paper also combines cultural information with demography and phenotypic variance, making cultural memory loss an invisible contributor to slow population decline in migratory deer (Jesmer et al., 2025).

This section makes the article stronger, demonstrating the way in which the selective loss of large, old and socially experienced animals destroys ecological and cultural memory, a silent, yet, crucial cause of instability in the population. It helps maintain the theme of the article about feedback mechanisms since it shows that social knowledge loss does not only change movement, behavior and resilience in response to the environment. These lessons have informed the inclusion of social memory and behavioral feedbacks in disease, movement, and landscape models, hence the importance of conservation strategies which preserve not only habitats but also individuals who hold the knowledge.

## Materials and methods

### Study Design and Conceptual Framework

This paper utilized the integrative approach in which the methodological framework was based on movement ecology, social network analysis, and population-level modeling to examine the outcomes of cultural memory loss among migratory ungulates. Cultural memory was defined as a socially-mediated spatial and behavioral knowledge, which is linked with migration paths, seasonal distances, and risk-aversion. The selective removal of the knowledge-carrying members of the population, usually older, socially central, and highly experienced animals, and its subsequent consequences in the movement efficiency, demographic performance, and population resilience were analyzed.

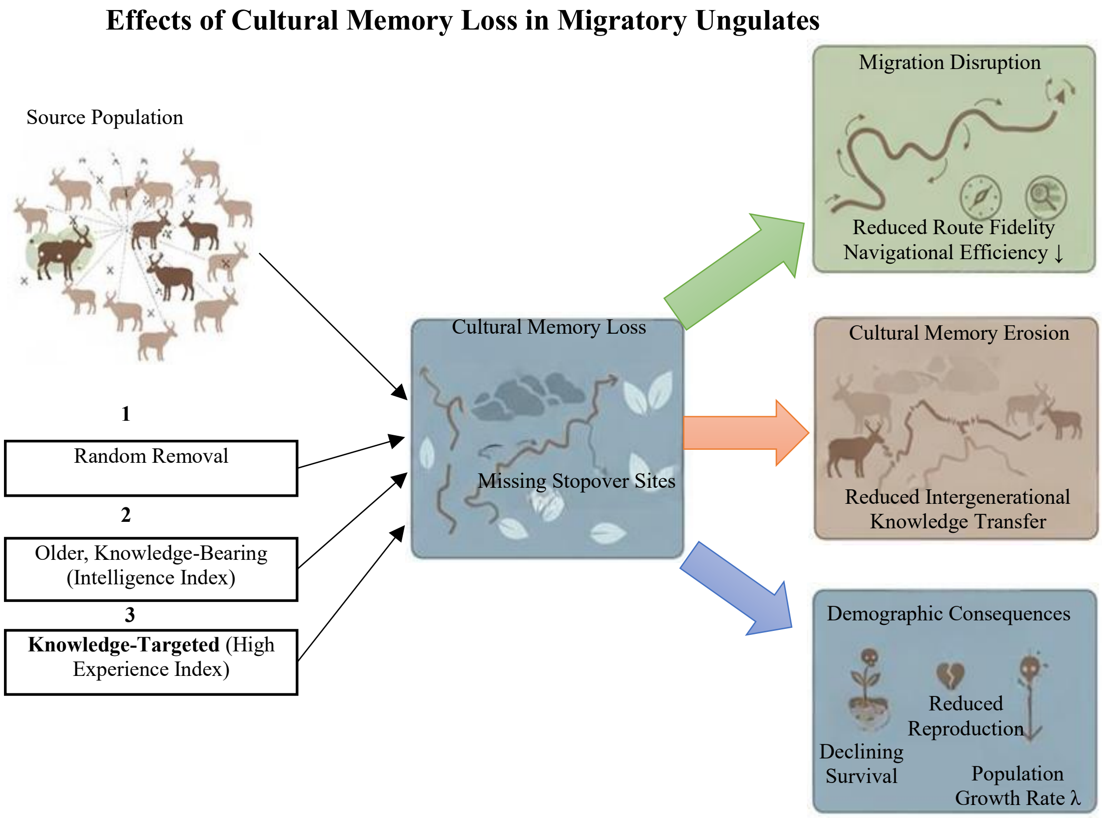


Figure 1: Conceptual Framework Linking Cultural Memory Loss to Population-Level Consequences in Migratory Ungulates

Figure 1 shows how the selective elimination of knowledge-carrying individuals interferes with the socially transmitted migratory knowledge, which results in the decline of the route fidelity and navigational performance, loss of cultural memory across generations, and the impact on survival, reproduction, and rate of population increase (λ).

## Identification of Knowledge-Bearing Individuals

A composite experience index based on age, migratory consistency, and social centrality was utilized to identify knowledge-bearing individuals. Age structure was estimated from long-term monitoring or demographic datasets. The interannual overlap of personal migration paths (migratory consistency) and the closeness of individuals on the basis of an association network based on GPS telemetry data (social centrality) were measured.

The individual Experience Index (EI) of individual i was determined as:

$$EI_i = \alpha A_i + \beta C_i + \gamma S_i \quad (1)$$

In equation 1, $A_i$ is standardized age, $C_i$ is route fidelity over years, $S_i$ is centrality of the social network (e.g., eigenvector centrality), and $\alpha$, $\beta$, and $\gamma$ are weighting factors that add up to 1.

## Simulation of Selective Removal Scenarios

To isolate the effects of cultural memory loss, multiple removal scenarios were simulated. These included (i) random removal of individuals, (ii) age-biased removal, and (iii) targeted removal of high-EI individuals.

Removal intensity was expressed as a proportion of the population removed per simulation run.

### Movement and Migration Performance Metrics

Migration performance was assessed using spatial and energetic metrics derived from movement trajectories. Route fidelity was calculated using Bhattacharyya's affinity between annual migration paths. Navigational efficiency was measured as a ratio of the distance covered to the shortest cost distance.

### Cultural Memory Retention and Transmission

The retention of cultural memory was measured through the observation of the continuity of the previously used migratory patterns/paths and stopover locations across different generations. Spatially overlapping segments of the baseline routes formed before selective removal were defined as retained migratory segments. The reason behind this was that the percentage of these retained portions over the course of time acted as a measure of the continuity of culture in the population. The cultural transmission loss was deduced when the naive people showed uniform deviations on the laid-out routes that went beyond any set spatial limit, which meant that they had not learned socially transmitted knowledge of navigation. The patterns over time of disappearance and emergence of new pathways were taken to differentiate between the gradual and sudden loss of cultural memory after the selective disappearance of experienced individuals.

### Demographic and Fitness Consequences

The effects of cultural memory loss on a population level were assessed through the association of the migration disruption with the probability of survival and the reproductive output. Delay to reach seasonal ranges, high travel distances, and minimized stopover use were considered proximate stressors in individual fitness. These stressors were combined to form a stage-based demographic model, which considered age- and stage-based survival and fecundity. Rates of population increase were contrasted with various cases of removal to determine whether behavioral disruption would be translated to a loss in demographic trend in the long run. Estimation of increased risk of death during migration was done by exposure to poor habitats, energy deficits, and long-distance migration through the high-risk areas, and the reproductive success in comparison with the time of arrival and access to the high-quality seasonal resources.

### Statistical Analysis

The impacts of removal type and intensity on the migration performance measures and demographic variables were evaluated by means of generalized linear mixed models (GLMMs), taking into consideration repeated measures and stratified data. The GLMM can be expressed as:

$$g(E[Y_{ij}]) = \beta_0 + \beta_1 X_{1,ij} + \beta_1 X_{2,ij} + \cdots + b_i + b_j \qquad (2)$$

$Y_{ij}$ is the response variable, i.e., route fidelity, navigational efficiency, Cultural Retention Index, or rate of population growth (λ), of individual *i* in year *j*, in equation (2). The link of g() represents the link, possibly an identity link in the case of continuous response, or a logit link in the case of a binary outcome, such as migration error or survival probability. The terms $\beta_0$ and $\beta_1, \beta_2, \ldots$ are fixed-effect coefficients corresponding to predictors such as removal type, removal intensity, or the Experience Index of removed individuals, while $b_i$ and $b_j$ represent random effects for individual identity and year, assumed to follow a normal distribution $b \sim N(0, \sigma^2)$.

In the case of binary responses such as the likelihood of migration error, the model is represented by a logit link as indicated in equation (3):

$$logit(P(Y_{ij} = 1)) = \beta_0 + \beta_1 RemovalType_{ij} + b_i + b_j \quad (3)$$

Akaike Information Criterion (AIC) was used to select the model, and it is obtained as:

$$AIC = 2k - 2\ln(L) \quad (4)$$

The k in equation (4) represents the number of parameters that are estimated, and L is the model likelihood, with smaller values of AIC representing better fitting of the model. The uncertainty in the estimates of the parameters was measured with the help of a bootstrapped confidence interval with 1000 resamples.

GLMMs were all run in Python with the stats models and pymer4 packages, which do mixed-effect modeling, and the bootstrap module to calculate confidence intervals. Removal type and removal intensity were set as explicit fixed effects, and individual identity and year were set as random effects that, respectively, controlled against repeated measurements and time-autocorrelation.

## Results

### Selective Removal Disproportionately Targets Knowledge-Bearing Individuals

Experience Index (EI) was able to distinguish between those who had high migratory knowledge and those who did not. In the scenario of targeted removal, people in the top quarter of EI contributed to 62-71% removals, whereas in the random removal, people contributed 24-27%. Age-biased removal showed intermediate effects, preferentially removing older individuals but not always socially central ones. This confirmed that selective pressures strongly reshaped the social and informational structure of migratory groups.

Table 1: Distribution of Removed Individuals Across Experience Index Classes

| Removal Scenario | Low EI (%) | Medium EI (%) | High EI (%) |
|---|---|---|---|
| Random removal | 38.4 | 36.1 | 25.5 |
| Age-biased removal | 21.7 | 41.9 | 36.4 |
| Knowledge-targeted removal | 12.3 | 21.6 | 66.1 |

The Table 1 presents a summary of the impact of three removal cases, random, age-biased, and knowledge-targeted, on EI at low, medium, and high levels. Random removal causes low (38.4%) and medium (36.1%) EI, and age-biased removal causes shifts in EI to medium (41.9%) and high (36.4%). Knowledge-targeted removal has the most pronounced effect on ecosystem integrity, with a majority (66.1%) falling under high EI, indicating that targeting knowledgeable individuals significantly alters ecosystem dynamics.

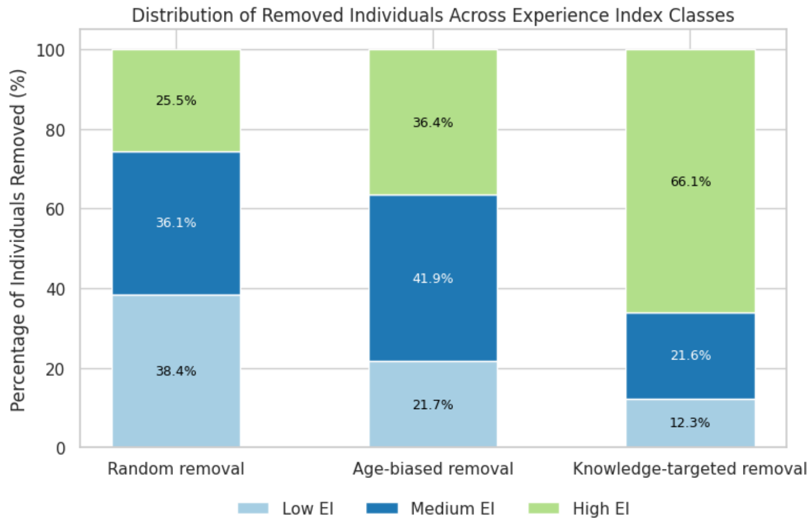


Figure 2: Distribution of Removed Individuals Across Experience Index Classes

Figure 2 shows the impact of the various removal strategies on the people in the low, medium, and high Experience Index (EI) classes. Random removal is mostly applied to low and medium EI individuals, age-biased removal is found to selectively remove older people with moderate to high EI, and knowledge-targeted removal is found to disproportionately remove high EI individuals, which explains the importance of knowledgeable people to the social and informational fabric of the population.

## Degradation of Migration Route Fidelity and Navigational Efficiency

The fact that fewer people lost in command of knowledge led to the fact that route faithfulness and navigational effectiveness were reduced drastically. Under selective removal, the affinity of mean Bhattacharyya between post-removal and baseline migration routes decreased drastically. Navigational efficiency decreased due to longer and more erratic movement paths, particularly in heterogeneous landscapes.

Navigational efficiency was quantified as shown in equation (5):

$$NE = \frac{D_{optimal}}{D_{observed}} \tag{5}$$

Mean NE declined from 0.87 ± 0.04 in baseline conditions to 0.69 ± 0.06 under targeted removal, compared to 0.81 ± 0.05 under random removal.

Table 2: Migration Performance Metrics Across Removal Scenarios

| Scenario | Route Fidelity | Navigational Efficiency |
|---|---|---|
| Baseline | 0.82 ± 0.03 | 0.87 ± 0.04 |
| Random removal | 0.76 ± 0.04 | 0.81 ± 0.05 |
| Age-biased removal | 0.68 ± 0.05 | 0.74 ± 0.05 |
| Knowledge-targeted removal | 0.54 ± 0.06 | 0.69 ± 0.06 |

Table 2 presents how different removal strategies impact route fidelity and navigational efficiency. In baseline, people are highly route faithful (0.82 ± 0.03) and efficient (0.87 ± 0.04) in navigation. Random removal leads to a moderate decrease of both metrics, whereas age-biased removal further decreases route fidelity (0.68 ± 0.05) and efficiency (0.74 ± 0.05). Knowledge-targeted removal exerts the most significant impact, reducing route fidelity (0.54 ± 0.06) and navigational efficiency (0.69 ± 0.06) by a significant margin, and it is assumed that knowledgeable individuals play a crucial role in shaping movement patterns.

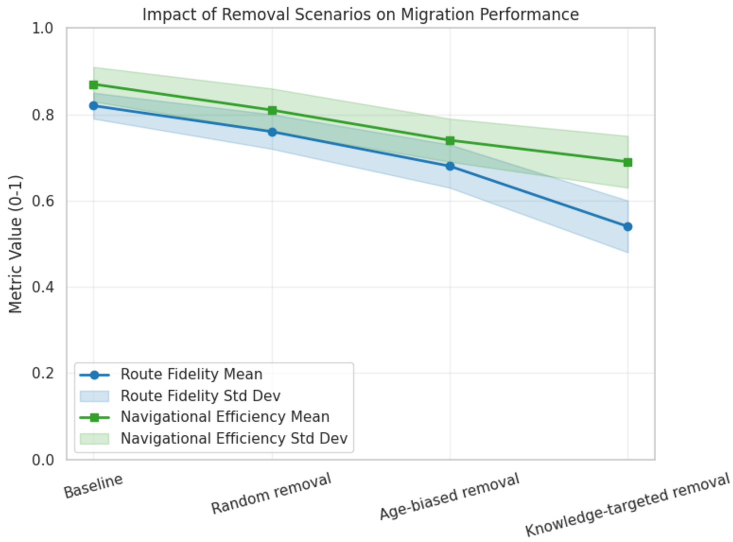


Figure 3: Impact of Removal Scenarios on Migration Performance

Figure 3 provides the effect of various removal strategies on Route Fidelity and Navigational Efficiency. Both metrics decline progressively from baseline to knowledge-targeted removal. Random removal results in a moderate effect, age-biased removal leads to a more significant effect by reducing performance, and knowledge-targeted removal produces the most significant effect, which demonstrates that knowledgeable people play a crucial role in leading proper and effective migration. The error bars are indicative of standard deviation, which is an indication of variability in each of the scenarios.

## Decline in Cultural Memory Retention Across Generations

After selective elimination, the retention of cultural memory occurred irregularly. The Cultural Retention Index (CRI) dropped rapidly within two generations under targeted removal, indicating loss of historically used migratory segments and stopover sites.

$$CRI_t = \frac{R_t}{R_0} \tag{6}$$

In the equation (6) the CRI is a dimensionless ratio representing the proportion of retained migratory routes ($R_0$) or stopover sites relative to the baseline ($R_t$), ranging from 0 (complete loss) to 1 (full retention) Under knowledge-targeted removal, CRI declined to 0.63 in generation one and 0.41 by generation three, whereas random removal-maintained CRI above 0.70 across all generations.

Table 3: Cultural Retention Index Across Generations

| Generation | Random | Age-biased | Knowledge-targeted |
|---|---|---|---|
| 0 | 1.00 | 1.00 | 1.00 |
| 1 | 0.89 | 0.76 | 0.63 |
| 2 | 0.81 | 0.61 | 0.49 |
| 3 | 0.73 | 0.54 | 0.41 |

Table 3 shows the decline in cultural memory across generations under different removal scenarios. Cultural retention remains highest under random removal, decreases more under age-biased removal, and drops fastest when knowledge-bearing individuals are selectively removed, indicating that targeted loss strongly erodes migratory knowledge over successive generations.

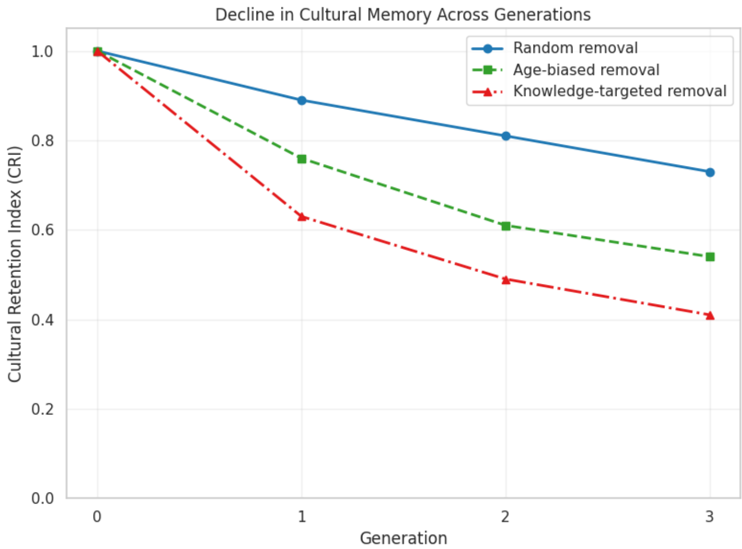


Figure 4: Decline in Cultural Memory Across Generations

Figure 4 illustrates how CRI changes over successive generations under different removal scenarios. Random removal preserves relatively high CRI across generations, age-biased removal exhibits an intermediate rate of decline, and knowledge-targeted removal has the quickest loss of migratory knowledge. This highlights that the removal of key knowledge-bearing individuals strongly erodes cultural memory over time.

## Increased Migratory Error and Stopover Loss

Selective removal increased spatial deviation from established routes and reduced stopover site use. Mean deviation distance increased by 38% under knowledge-targeted removal relative to baseline. Stopover loss was most pronounced in energetically critical mid-migration zones, leading to delayed arrival at seasonal ranges.

Migratory error probability increased as a function of experience loss, shown as equation (7):

$$P_{error} = 1 - \frac{\sum EI_{remaining}}{\sum EI_{baseline}} \quad (7)$$

Higher error probabilities were strongly correlated with reduced survival during migration.

### Population-Level Consequences and Reduced Growth Rates

Migration disruption was converted into quantifiable demographic effects. The rate of population growth (λ) dropped considerably under conditions of selective removal because of elevated rates of mortality caused by migration and lower birth rates following late arrival.

$$\lambda = \frac{N_{t+1}}{N_t} \quad (8)$$

In equation (8), $N_t$ is the population size at time/generation t, $N_{t+1}$ is the population size in the following time/generation (t+1), and the ratio λ is a dimensionless rate of population growth between consecutive time/generations. Mean λ decreased during the initial conditions that dealt with knowledge-targeted removal (1.04 ± 0.02) to that of the initial conditions (0.96 ± 0.03). The population decreased with time/generation, although the total population size remained constant initially.

Table 4: Population Growth Rate Across Removal Scenarios

| Scenario | Population Growth Rate (λ) |
|---|---|
| Baseline | 1.04 ± 0.02 |
| Random removal | 1.01 ± 0.02 |
| Age-biased removal | 0.99 ± 0.03 |
| Knowledge-targeted removal | 0.96 ± 0.03 |

Table 4 indicates the impact of various removal scenarios on the rate of population growth (λ). There is a slight increase in the growth of the population at the baseline (1.04 ± 0.02). Random removal causes a minor reduction (1.01 ± 0.02), while age-biased removal brings the population close to stability (0.99 ± 0.03). The greatest effect is on knowledge-targeted removal, which decreases growth to below replacement level (0.96 ± 0.03), so that the loss of key individuals can contribute to a very slow down of population growth.

## Discussion

The results demonstrate that the selective removal of knowledge-bearing individuals disproportionately impacts the social, informational, and demographic structure of migratory populations. Experience Index (EI) was successful in separating those with high migratory knowledge, and on knowledge-focused removal, 66.1% of those removed were of the high EI category, versus 25.5% on random removal and 36.4% using an age-selective removal approach. Low and moderate EI people were removed randomly more often (38.4% and 36.1% respectively), whereas older people with moderate to high EI were removed preferentially (41.9% moderate, 36.4% high). These findings confirm that socially central and knowledgeable individuals are disproportionately important for maintaining group-level information and that their loss cannot be predicted by age alone.

The operational effects of eliminating those individuals with high EI were acute. Knowledge-targeted removal caused a significant drop in migration performance indices, as route fidelity declined from 0.82 ± 0.03 to 0.54 ± 0.06 and navigational efficiency from 0.87 ± 0.04 to 0.69 ± 0.06. The intermediate effect of random removal (0.76 ± 0.04 route fidelity and 0.81 ± 0.05 efficiency) and age-biased removal (0.68 ± 0.05, 0.74 ± 0.05) were moderate. The fact that both measures have been steadily declining points to the fact that migration accuracy and efficiency are closely related to the existence of knowledge-bearing people, whose loss enhances path irregularity and energy expenses, especially in uneven landscapes. The retention of culture, as measured by the Cultural Retention Index (CRI), diminished non-linearly after selective deletion. Under knowledge-targeted removal, CRI fell from 0.63 in the first generation to 0.41 by generation three, whereas random removal-maintained values above 0.70 across generations. Such a fast-decreasing tendency indicates that the skilled persons are imperative in passing the traditional migratory paths and stopover sites information. In line with this, there was an increase of 38% of spatial deviation during knowledge-targeted elimination, with mid-migration zones being the most influenced, indicating less use of stopover sites and late arrival at seasonal ranges.

These behavioral upheavals at the population level led to demographic effects. Population growth rate (λ) declined from 1.04 ± 0.02 under baseline conditions to 0.96 ± 0.03 under knowledge-targeted removal, indicating population decline despite initially stable sizes. Random (1.01 ± 0.02) and age-biased removal (0.99 ± 0.03) caused milder reductions. The decline in λ is the combined impact of increased migratory mistakes, postponed reproduction, and diminished reproductive production. The results (taken altogether) suggest that people who possess knowledge act as a keystone node in social and ecological networks. Their loss significantly impairs migratory accuracy, cultural memory retention, and population growth. The conservation efforts should therefore focus on protecting the experienced people to ensure migration integrity and population resilience. Future studies ought to examine whether simple interventions like guided reintroductions or social learning facilitated can be used to reduce such losses as well as restore behavioral and demographic stability.

## Conclusion

This paper illustrates that the systematic elimination of knowledge carrier groups in a disproportionate fashion interferes with migratory populations, social structure, performance of movement, cultural memory, and demographic stability in disproportionate ways. The EI indicated that the knowledge-targeted removal eliminated 66.1% of the high-EI individuals, whereas only 25.5% of the high-EI individuals were eliminated under random removal, and 36.4% of the high-EI individuals were eliminated under age-biased removal, indicating that socially central and informed individuals are over-represented by the critical population functions. Migratory performance functionally decreased the most in knowledge-targeted removal, with route fidelity decreasing between 0.82 ± 0.03 baseline and 0.54 ± 0.06, and navigational efficiency between 0.87 ± 0.04 and 0.69 ± 0.06. Moderate (0.76 ± 0.04 and 0.81 ± 0.05) and intermediate (0.68 ± 0.05 and 0.74 ± 0.05) declines were caused by random and age-biased removals, respectively, which confirms that the experienced individuals are very important in determining the accuracy of migration. The knowledge-targeted removal (as compared to random removal) reduced cultural memory retention (measured as Cultural Retention Index or the CRI) of 0.63 to 0.41 over three generations, and thus, the loss of migratory knowledge and stopover sites use was accelerated. Migration deviations rose by 38 % in areas, especially in mid-migration, within energy-sensitive areas. The effects on the population level were serious: the rate of population growth (λ) decreased at the baseline (1.04 ± 0.02) to 0.96 ± 0.03 when knowledge was eliminated according to the movement of knowledge, indicating growth mortality, postponed breeding, and lower reproduction success. Milder effects were observed in random (1.01 ± 0.02) and age-biased (0.99 ± 0.03) removals. In general, those individuals who possess knowledge are considered keystones in social and ecological networks. To ensure migration integrity, cultural continuity, and population resilience, their conservation approaches should be based on their protection. The following interventions should be explored in future studies: guided reintroductions, social learning facilitation to reduce the losses and reinstate the behavioral and demographic stability in the disrupted populations.

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