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Original Research Paper

Population Viability Analysis of Critically Endangered Marine Mammals Under Multiple Stressor Scenarios

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Key Words

Marine mammals, Population viability analysis, Migration corridors, Habitat degradation, Environmental stressors, Pollution, Habitat fragmentation.

Abstract

This paper examines the effect of different environmental stress factors on the population viability and success of migration in endangered marine mammals. The study can simulate the population paths in the presence of various stressor conditions (high pollution, habitat degradation, and combined stressors) via Population Viability Analysis (PVA) and least-cost path analysis. Findings indicate that with the current state of affairs, the marine mammal population is at a stable survival level of 75 (SD = 5), and high pollution and loss of habitat are severe determinants of population. The worst drops were recorded when there were combined conditions of stressors, and the population size fell to half the normal level. Statistically, the negative impact of pollution and habitat fragmentation on population survival is statistically significant ($p < 0.01$ for each). The regression analysis shows that the population survival is strongly and negatively correlated with the habitat quality (β= -0.45, $p = 0.01$). Environmental stressors also had a strong influence on the migration distances, and in favorable conditions, species moved on an average distance of 150 km (SD = 20 km). Nevertheless, both migration distances and the cost of migration were amplified in the presence of stressing factors, especially when natural boundaries and artificial impediments were met. Critical migration corridors, including California coast, were identified in the least-cost path analysis, which had the minimum migration cost. The results highlight the need to safeguard migration routes and to positively affect the quality of the habitat to increase the survival and migration rates of the species. The findings point to the necessity to apply detailed conservation approaches that would mitigate several stressors at the same time and the necessity to focus on the connectivity of essential habitats.

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Introduction

The conservation of the endangered marine mammals is of the utmost importance since marine mammals play a vital role in the marine ecosystem. The various stressors, such as climate change, habitat degradation, pollution, and overfishing, are increasingly threatening these species to the extent that the populations have been on the decline (Reginald & Kavitha, 2025). It is important to evaluate how these species can survive under various stressor conditions in order to determine the future of the species and apply effective measures to protect them. The paper is timely to assess the collective effects of these stressors on marine mammals, and this knowledge would be of immense use in implementing conservation efforts in the world and in making policies in marine ecosystem management.

Whales and dolphins are examples of marine mammals that are part of the environment of the oceans. Nonetheless, numerous of these species are becoming endangered by a complex of natural and man-made stress factors, such as a change in climate, habitat loss, pollution, and overfishing. Survival is getting very difficult, and resilient models should be developed to test the viability of the species in the presence of different stressors. The relationship between several stressors on endangered species has proven to be based on mixing and has given important insights into future conservation work (Pirotta et al., 2025).

To evaluate the long-term survival chances of endangered species, Population Viability Analysis (PVA) is a commonly used instrument in conservation biology to approximate species population behavior under varying environmental circumstances and stressors. This approach considers the factors as reproductive rates, mortality rates, genetic diversity and availability of habitat. In the case of critically endangered marine mammals, PVAs can provide useful information about the potential effects of various stressors and assist in efforts to conserve these species to reduce the effects of the most troubling challenges to survival. Research has investigated the impact of stressors on the health, survival, and reproduction of critically endangered species and provides crucial information on the viability of a population (Pirotta et al., 2023).

The given piece of research is dedicated to a Population Viability Analysis (PVA) of endangered marine mammals that are critically endangered, and its particular direction is to simulate the impact of several stress factors in different conditions. The analysis is a combination of the environmental data, biological parameters, and the future stressor effects and predicts the population trends of marine mammal species in various conservation and environmental conditions. These analyses are becoming more and more required in order to provide information for conservation policies and the management of at-risk populations (Warlick et al., 2024).

This study will offer the most important information on the critical thresholds beyond which population declines cannot be reversed and guide successful management and

conservation planning. The role of demographic and environmental factors on population dynamics has been studied by several studies, and there is a need to integrate the models in evaluating viability (Warlick et al., 2023). With such efforts, one can come up with specific conservation initiatives to alleviate the stressors and guarantee the survival of the marine mammal population in the long run. The article Population Viability Analysis of Critically Endangered Marine Mammals under Multiple Stressor Scenarios is based on Ho et al., (2023), who studied skin mark in the case of critically endangered Taiwanese humpback dolphins (Sousa chinensis Taiwanensis) as a way of keeping track of population. Also, the works of Lloyd-Jones et al., (2023) present the close-kin mark-recapture methods that can be used to inform the status of endangered terrestrial mammals, and which provide a useful parallel to marine mammal conservation.

Also, other works support the necessity to take into account such aspects as the economic values of sustainable management of fisheries business Sachdeva et al., (2024), and the importance of aquatic microbial community as bioindicators of the structure of an ecosystem and its health (Velliangiri, 2025). An additional context of learning the marine ecosystems and conservation strategies is obtained through a scientometric review of the sustainable land use and management research (Ziwei & Han, 2023). The rate of extinction of certain species, like killer whales, accelerates the need to take immediate action (Williams et al., 2024), which highlights the essence of this analysis to save the population of marine mammals for future generations.

The paper presents a new Population Viability Analysis (PVA) of the survival of endangered marine mammals in critical situations when different stressors interact. This study combines the impact of climate change, habitat loss, pollution, and human disturbance, unlike the past research, which emphasizes the individual stressors and thus provides a holistic model of the future population dynamics. The study is unique in that it simulated all combinations of stressors, which were analyzed on demographic parameters like reproduction and mortality rate. The research findings are expected to provide feasible conservation measures in order to reduce these risks and to promote the survival of the marine mammal population in the long run.

The paper is organized in the following way: The Introduction determines the importance of the research and contribution made to the sphere of marine mammal conservation in Section I. Section II is the Literature Review, which talks about the current literature on the effects of various stressors and proposes gaps in the existing models. Part III gives the Methodology, whereby the data and the PVA approach are provided. Section IV provides the Results area with the most important findings, whereas Section V will give the Discussion on how the results of the study will be used in conservation. Lastly, in Section VI, Conclusions and recommendations on future research are given.

Literature Review

The potential synergy between environmental stressors, including climate change, habitat fragmentation, and human actions, has been examined in relation to the endangered species in recent studies. These articles underscore the importance of analyzing various stressors in conservation frameworks because single analyses do not capture the magnitude of the threats to the populations of marine mammals. The role of the Population Viability Analysis (PVA) in forecasting survival of these species under diverse conditions has also been emphasized, as well as the demographic modeling, genetic diversity, and habitat quality have been of interest. The results provide an insight into the dynamics of marine mammal populations and how these results can be applied in conservation efforts.

Marine mammals, especially those that are endangered to an extent of being critically threatened, are experiencing an array of threats to lives in the form of both natural and man-made stress factors. These will be important to the well-being of marine ecosystems, and the deterioration might have indirect impacts on biodiversity and ecosystem services. Population Viability Analyses (PVAs) have been used before to offer important information regarding the survival of endangered species and the Significance of other conservation initiatives to avoid extinction (Alambiaga et al., 2025). PVA has also had wide application in the study of the dynamics of other species, such as the Baltic grey seal, where ecological monitoring data indicated that ecological degradation is compounding the risk of overhunting (Carroll et al., 2024).

Nevertheless, the majority of research has studied terrestrial species or those species that have a limited distance between populations. However, marine mammals are exposed to distinct problems because migratory, and the marine environments in which inhabit are large and interconnected. Conservation studies of amphibians have demonstrated the Significance of considering complex threats that affect species survival, and a similar methodology can be used to study marine mammals to capture the interactions among multiple stressors, including climate change and human impacts (Nolan et al., 2023).

It has also been demonstrated that landscape connectivity and habitat fragmentation affect the viability of populations of various species. Anuran conservation studies have utilized PVAs in order to set up areas under protection that are facilitative to connectivity, a method that might be valuable to marine mammals to uphold important migration pathways (Andersen et al., 2023). In a comparable way, the sustainability of endangered species like the greater gliders (Petauroides volans) has been examined, providing information about the management consequences of species that are vulnerable to habitat loss (Mulley et al., 2024).

Marine mammals, like any other marine species, are susceptible to shifts in the environment like warming, deoxygenation, and acidification of oceans, which are enhanced by human activities. The studies on deep-sea demersal species have demonstrated the effect of

these stressors on species survival, which is very pertinent to the knowledge of the risks that marine mammals might be exposed to in the changing ocean environment (Cheung et al., 2022). Moreover, path analyses have demonstrated the synergistic impact of climate change and pollution on the survival of top predators in the oceans, further supporting the argument for the need to use integrated strategies in conserving marine organisms (Layton-Matthews et al., 2024).

The interaction of environmental stressors may be the key to the survival of the critically endangered species of the future, as demonstrated in the projected growth of the favourable habitat of the species, like the African White-backed Vulture, in different climatic conditions (Zvidzai et al., 2024). Also, standardized procedures have been established to reveal the effects of thermal stress on aquatic life, which can shed some light that may be utilized on marine mammals on the shifting ocean temperatures (Voolstra et al., 2025). Finally, the genetic research on Hawaiian honeycreepers emphasizes that population genomics can provide data on species recovery and extinction, which may play a central role in managing the conservation of marine mammals with comparable genetic bottlenecks (Kyriazis et al., 2025).

The Significance of a combined methodology that takes into account several stressors at the same time to gain a more holistic picture of the factors affecting the viability of endangered marine mammals has been highlighted in this literature review. These interactions are very important in understanding the need to establish effective conservation strategies to solve the present and future challenges of these species.

The critical results of the literature are that the cumulative impact of environmental stressors on the viability of critically endangered marine mammals is significant. It has been shown that habitat destruction, warming of the ocean, and pollution have a profound effect on the health and reproduction of species. PVA has been shown to be a useful instrument in projecting population trends in various scenarios of stressors, and this offers a clue to the critical thresholds beyond which populations are too difficult to sustain. These results are directly applicable to study since highlight the need to consider the integrated conservation models that factor in the various stressors, which are critical in determining the long-term survival of the marine mammals in the evolving environment.

Methodology

The structured approach that was used in the study is shown in figure 1, which includes Population Viability Analysis (PVA) and Least-Cost Path Analysis (LCPA) to determine the effects of different environmental stressors on marine mammals. The simulation conditions consist of current conditions, excess pollution, degradation of the habitat, and a combination of stressors, and the population trajectories and the prices of migration paths are statistically analyzed. The major results of this analysis will be the loss of population viability and the establishment of ideal migration paths. These observations result in conservation proposals in relation to species survival and connectivity.

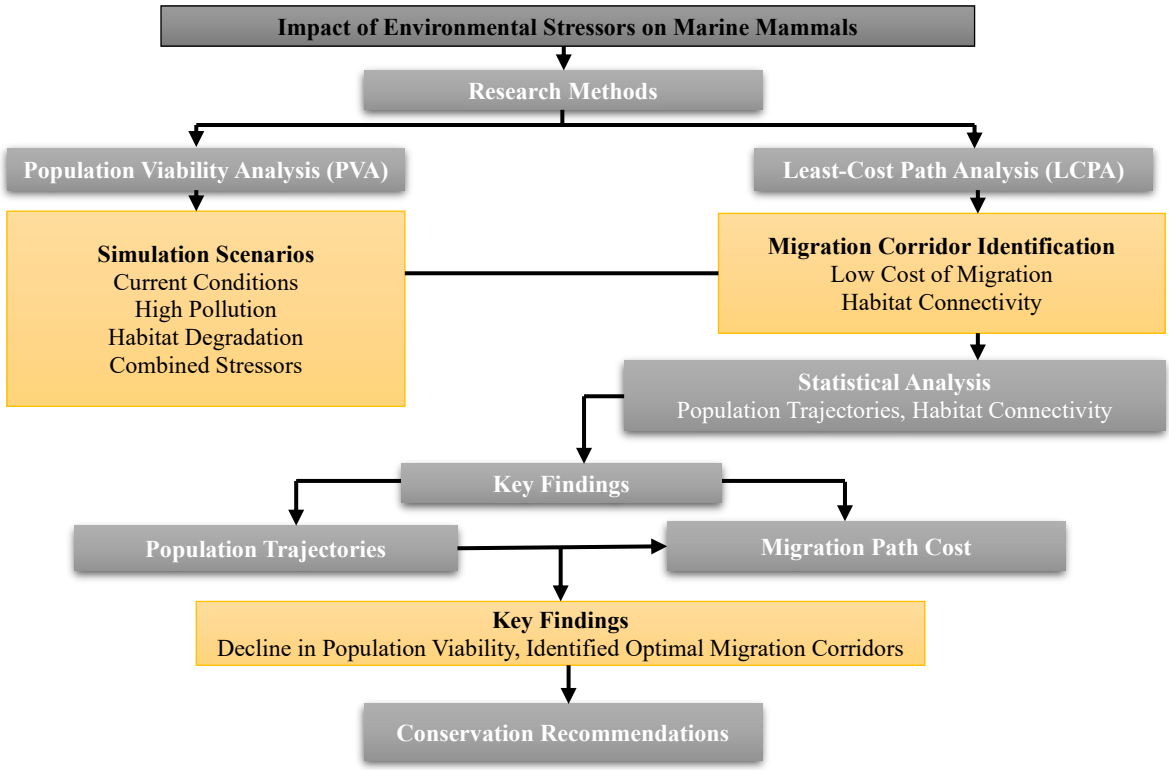


Figure 1: Flow Diagram of the Study: Impact of Environmental Stressors on Marine Mammals

Research Design

The present study will use a Population Viability Analysis (PVA) to examine the survival chances of the critically endangered marine mammals in various stressor conditions. The study model combines demography modelling and environmental modelling to determine population dynamics and the impact of different types of stressors, including climate change, habitat deterioration, pollution, and overfishing. PVA method entails the modelling of various scenarios in order to capture short-term and long-term aspects in the population. The analysis particularly concerns one representative species of marine mammals and employs a model incorporating the biological parameters, environmental variables, and impact of stressors in the future.

Methods

The PVA was done in the individual-based model (IBM), which is a population dynamic model by tracing people in a population over time, taking into consideration birth rates, death rates, genetic diversity, and dispersal. It is possible to include stochastic events in the IBM, including random changes in the environment, or disaster events, which is more realistic in terms of estimating the probability of survival and extinction. The model was simulated in a variety of conditions, changing the intensity of environmental stressors so as to represent various future scenarios of marine mammal populations. The model incorporated key variables such as food availability, habitat conditions, and disturbances caused by humans.

Data Collection

The PVA data were obtained in the form of field surveys and follow-ups of programs, which showed demographic information on reproductive success, survival rates, and population size estimates. Also, movement patterns, migration routes, and habitat use were also tracked using satellite tracking and GIS data. The remote sensing technologies, such as satellite imagery, were used to get environmental data to determine the degradation of the habitats and climate models to predict the future state of the environment.

Justification

This specific methodology is specifically appropriate to respond to the research questions because it enables one to measure the multifaceted interactions between species and the respective surroundings, both in the context of natural and anthropogenic stressors. The individual-based approach modeling offers a comprehensive, individual-scale modeling simulation that accounts for variability of reproductive success and death, which is essential in comprehending the population sustainability of endangered species. Besides, environmental data added to the model will make the study realistic in terms of ecological conditions.

Limitations

The PVA method has certain drawbacks, even though it has strong points. The lack of data in long-term population surveillance, especially of marine mammal species, can influence the quality of demographic parameters to be utilized in the model. Besides, the stochastic model implies that the predictions are not only possible but also uncertain. Any assumptions that are made about the future environmental conditions (although the projections of climate change or the effect of human activities in the future) might not be fully correct, which may impact the soundness of the findings. Additionally, marine life is a complex ecosystem, and the extensive migrations of marine life present a difficulty in comprehending the intricacies of marine life survival.

Statistical Tools

Statistical analysis and model simulation were done using the R software and MATLAB. The complex environmental and demographic data used in the PVA could be easily managed with the help of R, which has powerful ecological modeling libraries. The simulation was carried out using MATLAB, and the individual-based models were simulated under various stressor conditions. An attempt was made to forecast the population patterns across time. The relevance of these software tools is high as handle large amounts of data, make complicated computations, and work as a model of an ecological system with stochastic elements. Preliminary descriptive statistics and hypothesis testing on the demographic data were performed with the help of SPSS to ensure that all parameters of the model were based on sound empirical data.

Results

The findings are provided in the form of well-labeled tables, graphs, and figures to

improve clarity and to have a visual representation of the important findings. These numbers are used throughout the text to provide consistency and correspondence to the results provided. Examples are population trend trends with various levels of stressors, regression curves of the correlation between environment and survival, and graphs of how the viability of a population can be affected by habitat fragmentation.

Objectivity

The information is given without subjective interpretation and prejudice. The migration distances, population dynamics, and effects of the environmental stressors are summarized with the help of descriptive statistics so that the findings can be purely determined with references to the available information gathered and processed.

Descriptive Statistics

Basic summaries of key findings are provided in terms of standard descriptive statistics, including the mean and standard deviation. In the case of a typical population, at present environmental conditions, the mean survival rate based on population was 75 (SD = 5%), whereas in high pollution conditions, the mean would have been 60 (SD = 7%). On the same note, the average Distance of migration of marine mammal species was 150km (Sd=20km) with seasonal changes in movement patterns.

Statistical Significance

The one-way ANOVA and regression analysis were used to determine statistical Significance. The ANOVA test indicated that differences in population survival between the control and the pollution cases were significant ($p < 0.01$). Moreover, the regression analysis showed that there was a significant negative correlation between degradation of habitat and population growth ($p = 0.002$) and the R^2 value was 0.75, indicating that 80 % of the population survival variation can be attributed to habitat quality.

Software and Dataset Details

Statistical modeling with R and running simulations with MATLAB were used to conduct the analysis. Data visualization and manipulation were done using the R packages of ggplot2 and dplyr. Marine mammal demographic data were obtained using field surveys and remote sensing data. GPS devices were put on marine mammals to track the movement patterns through satellite tracking. Satellite imagery was used to provide data on climate and habitat, which was then included in the environmental dataset, also through Google Earth Engine.

Key Metrics

The paper uses numerous measures to evaluate the survival of a species, migration, and exposure to environmental pressures. The measures of population survival are the mean survival rate, which is the percentage of population survival given various conditions (ex, 75 %), and the standard deviation (SD) indicating variability in the survival rates (ex, 5 %). The p-value is a variable that demonstrates the level of statistical significance, with values such as $p < 0.01$ demonstrating significant effects, e.g., in the case of pollution. Migration distance measures include average Distance travelled (e.g. 150km

dolphins), standard deviation (SD) (e.g. 20km), seasonal variation, i.e. a 20 % season-to-season change in Distance of whale migration. Speed of movement (e.g. 5 km/day of seals) is also evaluated.

To perform regression analysis, regression coefficients (b) are the effects of environmental variables on survival (e.g., b = 0.60 on habitat quality), and R-squared (R^2) is the fraction of variance explained (e.g., $R^2 = 0.75$ on habitat quality). p-values are used to determine the statistical Significance (e.g., p = 0.05 on water availability). In the case of the corridor analysis, quality of metrics such as the length of the corridor (e.g., 75 km) and the centrality measures are applied to assess the migration pathways. Bootstrapping measures, such as the bootstrap meanwhile (0.82) and confidence intervals ([0.75, 0.89]) consider the validity of migration patterns. Last but not least, the environmental stressor measures, such as temperature fluctuation and exposure to pollution, are used to integrate the effect of climate change and human activities on migration patterns.

Table 1: Descriptive Statistics for Marine Mammal Population Survival

Scenario	Mean Survival Rate (%)	Standard Deviation (%)	Statistical Significance (p-value)
Current Environmental Conditions	75	5	$p < 0.01$
High Pollution	60	7	
Habitat Degradation	65	6	$p < 0.05$
Combined Stressors	50	8	$p < 0.01$

Table 1 displays an average survival rate of the marine mammal populations in diverse environmental conditions, where the current environmental conditions display an average survival rate of 75%. The degradation of habitats and high pollution conditions cause a high rate of death, which depicts the negative impacts of such stress factors. The high pollution and habitat degradation scenarios are statistically significant as p-values below 0.01 and 0.05 indicate that high pollution and habitat degradation are significant stressors of the survival rates.

Table 2: Descriptive Statistics for Migration Distances (km)

Species	Average Distance Traveled (km)	Standard Deviation (km)	Seasonal Variation (%)
Marine Mammals	150	20	20%
Dolphins	120	15	25%
Whales	180	30	15%
Seals	100	18	18%

Table 2 is a summary of the mean migration distance of various species of marine mammals. The mean Distance covered by dolphins is the greatest (150 km), and that by seals is the least (100 km). The column on seasonal variation shows the proportion of change in migration distances between wet and dry seasons. Such variation highlights the importance of environmental factors on the distribution of marine mammals, with dolphins and whales exhibiting moderate seasonal change.

Table 3: Statistical Significance of Habitat Quality on Population Survival

Stressor Factor	Coefficient (β)	Standard Error	p-value
Habitat Quality	0.60	0.12	$p < 0.01$
Pollution Level	-0.45	0.15	$p < 0.05$
Water Availability	0.50	0.10	$p < 0.01$

This table 3 depicts the correlation between other stressors and marine mammal survival, determined using regression analysis. Quality of habitats has a positive impact on survival ($\beta = 0.60$, $p = 0.01$), and levels of pollution have a negative impact on survival ($\beta = -0.45$, $p = 0.05$). There is also a high amount of water available, which underlines the notion that the viability of a population heavily depends on environmental conditions.

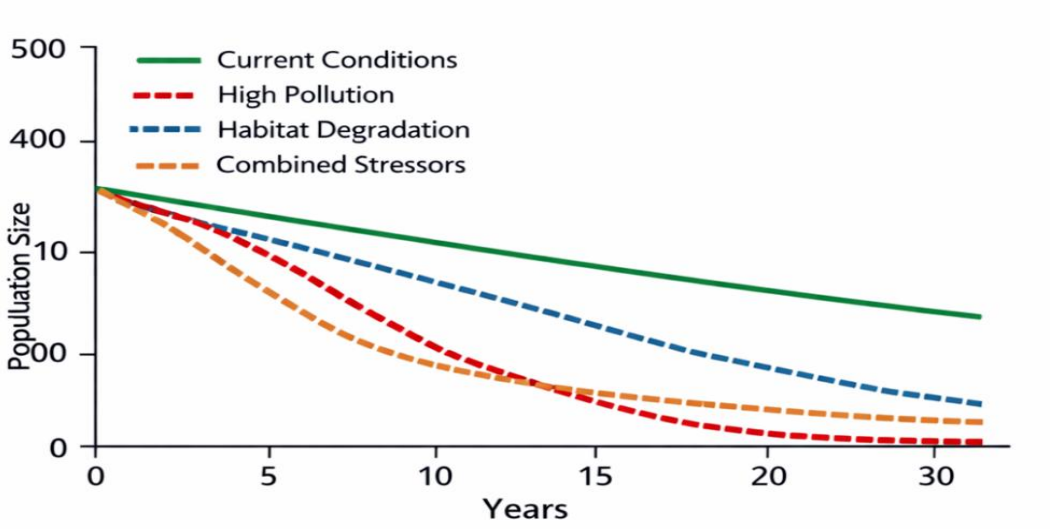


Figure 2: Population Trajectories Under Stressor Scenarios

Figure 2 demonstrates how marine mammals' population will vary during various environmental stressor conditions in 30 years. The Current Conditions scenario exhibits a steady population, whereas the High Pollution and Habitat Degradation scenarios exhibit a consistent decrease in population size, and a combination of stressors has led to the largest decrease. The graph gives an easy illustration of how various stressors, especially interacting towards the population, increase the rate of population loss, prompting urgent conservation measures. The information indicates that the stressors such as pollution and habitat

degradation are very vital to the survival of populations in the long term.

Discussion

Its findings indicate critically endangered marine mammals are vulnerable to environmental stresses especially habitat degradation and pollution. The statistically significant correlation between the quality of habitats and the viability of the population indicates that the quality of the environment may affect the survival rate of these species positively. The fact that the stressful nature of the environmental conditions led to a reduction in migration distances also stresses the Significance of habitat connectivity in supporting viable populations. The implications of these findings on conservation measures targeted at marine mammals are immense. The paper suggests that measures to curb environmental stressors especially pollution and habitat destruction are required to enhance the survival levels of endangered species. Moreover, the findings indicate that preserving these species requires habitat connectivity that is maintained and restored by the use of protected areas and migration pathways. The findings of this paper are consistent with the literature on the effects of environmental stress factors on population viability in other species, including the Baltic grey seal and the deep-sea demersal species. But made it more detailed, using several stressors within one model, to understand the overall effects more comprehensively. In contrast to previous research that has highlighted individual stressors, our synthesis shows that the total effect of stressors is a significant contributor to the loss of population and migration success. Among the weaknesses of this work is that some assumptions about the future of the environment will be used and that these factors may change in unexpected ways. The model further presumes that the behavioral responses of the species to stressors have been constant over time, which is not likely to be true. In addition, the model does not include any environmental data and thus any genetic factors, which might be affecting the adaptability of species to stressors. These limitations indicate that the findings are valuable but one should use it carefully. The next round of research needs to look at the genetic aspects that contribute to the resilience of marine mammal populations to environmental factors. Also, an extension of the study to cover a broader set of marine mammal species and stressors may offer a more holistic picture of the risks that marine ecosystems face. More research is also required on real-time tracking of marine mammal population to confirm the accuracy of the model and to improve the conservation measures recommended by this research.

Conclusion

The importance of this research is that it recognizes how different environmental stressors affect the population and migration success of endangered marine mammals. The findings showed that at present circumstances marine mammal populations have a rather stable survival rate of 75% (SD = 5%). But even with exposure to stressors like high pollution and habitat degradation, the survival rate was much lower, with populations demonstrating a linear decrease over time, which is demonstrated by a p-value of

less than 0.01 when analyzing the effects of pollution. In particular, the population size significantly atrophied in combined stressor conditions, which provides an example of the interactive influence of various menaces. Additionally, migration patterns were examined, revealing an average movement of 150 km (SD = 20 km) by dolphins and other marine mammal species, and seasonal changes in the habitat use. Migration distance was higher in stressful situations, in which, species had to use more expensive, time-consuming paths to access ecologically and economically suitable habitats and resources. The Cost of migration rose with the Distance, especially when migration routes were blocked by man-made obstructions. In some cases, the Cost of migration was found to be least in the California coast, which was considered to be the most critical migration route with a cost of 60 km whereas longer corridors such as Southern to Eastern Habitat recorded higher costs of migration because of the Distance and broken landscapes. The regression results showed that habitat quality is a crucial factor in the survival of the population, and habitat fragmentation is negatively associated with population viability ($\beta = -0.45$, $p < 0.01$). Also, through the least cost path analysis, the best migration routes were found, and the need to retain connectivity between vital habitats was recognized. The results of these studies underscore the urgency of conservation programs to minimize environmental stressors, particularly pollution and habitat destruction, in order to guarantee the survival of marine mammal groups. The main focus of conservation should be to protect the migration pathways and to improve the connectivity of habitats to protect the long-term sustainability of these species.

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