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Original Research Paper

Energetic Costs of Foraging in Degraded Seascapes and Long-Term Impacts on Marine Populations

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Key Words

Bioenergetics, Foraging efficiency, Habitat degradation, Marine ecology, Population dynamics, Seascape structure.

Abstract

Marine seascape degradation alters habitat structure and resource distribution, potentially imposing strong energetic constraints on marine organisms. This study aimed to quantify how seascape degradation influences foraging energetics, metabolic performance, and energy balance, and to evaluate how individual energetic constraints scale up to affect population-level survival. The research was done at the marine locations along coastal regions with a gradient of seascape degradation. Habitat condition was measured based on a composite degradation index that involved habitat complexity, prey density, turbidity, and nutrient load. Two marine species representing contrasting trophic roles were examined. Field energy expenditure was estimated using tri-axial accelerometry corrected to oxygen consumption, whereas standard and active metabolic rates were measured using respirometry. Telemetry, accelerometry, and prey calorimetry were used to measure foraging behavior, energy intake, and net energy gain. The relationship between degradation, the energetics, and the survival was measured using linear mixed-effects and generalized linear models, and the model performance was measured using the R2, RMSE, and MAE. Habitat degradation was linked with drastic changes in habitat complexity and prey density, and a rise in turbidity and nutrient load. The degradation elevated the metabolic rates strongly and reduced the aerobic scope ($p < 0.001$). In poor habitats, the amount of daily energy expenditure rose significantly, with the foraging expense consuming up to 51.9% of total energy expenditure. High degradation caused a more than 60% decline in net energy gain by predators and 70% by consumers. The model fits were good (R2= 0.740.81) and the probability of survival grew nonlinearly with individual energy reserves, varying between 0.42 and 0.91 in the 25th percentile of energy reserves. The destruction of seascapes enhances the cost of energy, lowers foraging efficiencies, and limits demographic survival. These results demonstrate the role of energetic balance as a central mechanistic relationship between habitat degradation and population-level responses with significant implications for marine conservation and habitat restoration.

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Introduction

There is a rapid degradation of marine ecosystems that are under anthropogenic pressures, which include coastal development, overfishing, pollution, ocean warming, and habitat fragmentation. These stressors change the spatial distribution of marine resources and their quality, causing many marine organisms to change their foraging behavior. In poor seascapes, prey distribution is typically haphazard and less predictable, forcing animals to cover greater distances, forge further, or work harder to satisfy energy needs (Thanararaj et al., 2024). These alterations increase the energetic burden of the foraging process, and this may cause energy to be spent on growth, reproduction, and immunological functions (Preston et al., 2025; Kang et al., 2024). With time, long-lasting energetic losses may have an impact on the fitness of individuals and extend to the population processes, community organization, and ecosystem stability (Haney & Rochman, 2025). The reconstruction of degraded seascapes to transform the dynamic equilibrium of marine foragers is thus of great importance in forecasting population changes in response to the persistent environmental change (Walker-Milne et al., 2025).

The key aim of this research is to measure the energetic expenditures of foraging in degraded seascapes and its long-term consequences on marine inhabitants (Cordes et al., 2025). Particularly, the research focuses on investigating the effects of habitat degradation on foraging work, energy use, and energy consumption among various marine organisms (Killen et al., 2023). It also aims at comparing the long-term implications of higher energetic costs in regard to important life-history characteristics such as survival, reproductive output, and permanent persistence of the population. The study will establish an integrative insight into the bioenergetic limitations in the modified marine habitats by correlating individual-level energetic processes with population-level outcomes (Lin et al., 2024; Cardé et al., 2025).

Although there are prior studies that have reported behavioral changes in marine species because of the degradation of marine habitats, few studies have directly measured the energy implications of such changes. Additionally, current studies tend to study short time scales or species-specific reactions, and little has been combined with bioenergetic theories in the long-term evaluation of a population. A significant deficiency in the literature between the relationship of altered foraging energetics of degraded seascapes to demographic patterns and population viability does exist. This knowledge gap limits our capacity to forecast the way that further environmental deterioration could transform marine ecosystems and undermine the resilience of ecosystems (Nagabhooshanam et al., 2025; Kressler et al., 2023).

This hypothesis informs this study because it is hypothesized that degradation of seascapes substantially elevates the energetic cost of foraging by marine organisms since it reduces prey density and increases search work. The hypothesis further assumes that people with increased expenditures of energy will have

reduced growth rates and reproductive Success. These energetic limits should be manifested at the population level, as fewer population growth rates, greater susceptibility to unstable environmental conditions, and an increase in the risk of long-term decline in populations in massively degraded habitats (Shipley et al., 2023; Lin et al., 2024).

This research offers a quantitative evaluation of foraging-associated energetic expenses in degraded seascapes adopting a bioenergetic approach. It provides a theoretical connection between personal energy expenditures and long-term demographic changes. The results could be useful in conservation and marine spatial planning since that could establish the levels of energy under which populations can be unsustainable. On the whole, the research contributes to the knowledge on the mediation of the ecological impacts of habitat deterioration in a marine ecosystem by energetic constraints.

The structure of this article is to incorporate habitat degradation, bioenergetics, and population dynamics of the marine systems. The Introduction provides the ecological background of the importance of seascape degradation and sets out the study objectives, hypotheses, and the gaps in the research. The Literature Survey integrates existing information about energetic trade-offs, foraging behavior, and population effects in degraded marine environments. The Materials and Methods report the selection of the area of study, the selection of species, metabolic and field-based measures of energy expenditure, bioenergetic modelling, and statistical testing. The Results show habitat gradients, metabolic responses, foraging behavior, energy balance, survival patterns in populations, and model validation. These findings have been interpreted in an energetic and ecological manner in the Discussion, and implications for conservation and future research have been brought out in the Conclusion.

Literature survey

Marine seascapes are changing, and ecological processes are being modified to establish energy gain and distribution in the marine organisms, due to habitat degradation, climate change, pollution, and coastal development (Cronan, 2023). Destruction of complex ecosystems and structures (mangroves, marshes, reefs, and seagrass meadows) alters the diversity of prey and spatial contact and consequently influences the foraging activities and energy costs throughout the taxa (Athira et al., 2024; Ziegler et al., 2024; Vozzo et al., 2023). The discussed changes imply a great deal in the systems where organisms depend on the constant distribution of resources to balance the cost of movement and the cost of energy uptake successfully.

Recent research concluded that energetic trade-offs between movement, prey encounter rate, and environmental constraints are the motivating force behind foraging choices (Killen et al., 2023; Cordes et al., 2025). In poor seascapes, animals can either increase the size of home ranges, travel distances, or change their diel and seasonal movement to offset decreased resource quality (Cardé et al., 2025; Lin et al., 2024). The research on marine mammals and elasmobranchs indicates that these changes can

increase the cost of energy significantly, and this aspect can lead to death, reproduction, and fitness (Shipley et al., 2023; Maciel et al., 2023). Observations over a long period of time of dolphins also indicate that chronic modifications of the habitat could potentially cause changes in the community structure and demographic parameters due to the sustained energetic demand (Cardé et al., 2025; Lin et al., 2024).

Seascape connectivity has been mentioned as an important mediating variable to the efficiency of energy, which has an impact on access to complementary habitats and movement pathways (Kang et al., 2024; Preston et al., 2025). Alterations in the foraging areas of animals due to artificial structures, marine energy development, and altered migration routes can strain scientists further (Hemery et al., 2024; Secor et al., 2025; Lennox et al., 2025). Meanwhile, the un-designed built infrastructure can lead to an increase in habitat fragmentation, whereas ecologically optimized designs can partially offset energetic costs by facilitating habitat functionality (Paxton et al., 2025; Paxton et al., 2025; Paxton et al., 2025).

These issues are further exacerbated by new stressors like marine heatwaves and plastic pollution, which change prey interactions and physiological functioning, increasing the energy bottleneck (Woehler & Hobday, 2024; Haney & Rochman, 2025). Although there is increased acceptance of energy as a global ecological currency, limited research incorporates bioenergetic models of degraded marine ecosystems with long-term population consequences (Kressler et al., 2023). As a result, it is still not well understood how the cumulative costs of foraging for energy can be converted to the level of declining populations, decreased resilience, and changes in the functioning of the ecosystem when under sustained seascape degradation.

Materials and Methods

Study Area and Seascape Characterization

The study was conducted across multiple coastal and nearshore marine sites representing a gradient of seascape degradation. Sites were chosen to obtain the variation in the habitat structure, prey availability, and anthropogenic disturbance, but were kept within a similar oceanographic area. Seascape condition was measured based on a composite degradation index, which combined the parameters of habitat complexity, prey density, water quality, and proximity to human activities. Habitat structure was determined using benthic surveys and remote sensing products, and prey availability was determined using standardized visual census and net-based sampling. The parameters of water quality, such as nutrient concentration and turbidity, were monitored in situ at the time of each sampling period.

Figure 1 shows that the degradation of the seascape affects marine animal ecology at various biological levels. Degradation of habitat modifies foraging behaviour in that it raises search effort and travel distances, which raise the levels of energetic expenditure on activity and metabolism. The energetic use leads to the decreased energy supply to growth, reproduction,

and survival, thus impacting individual fitness. These personal energetic limits eventually magnify to impact population outcomes, such as population growth changes, population persistence, and resilience to degraded seawater.

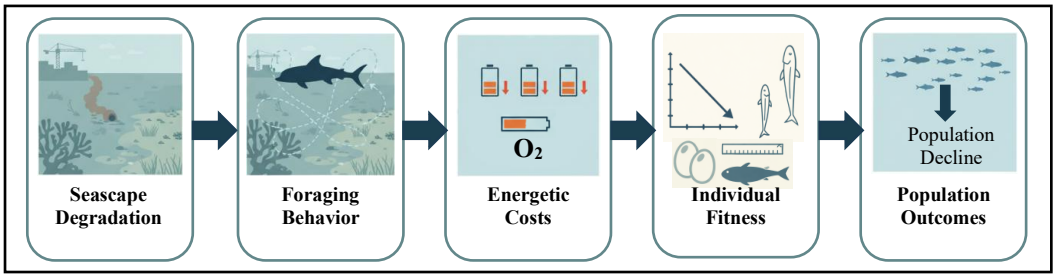

Figure 1: Conceptual Framework Linking Seascape Degradation, Foraging Energetics, and Population Dynamics in Marine Animals

Study Species Selection

Target species were identified to maintain an opposing trophic range, foraging behaviour, and movement behaviour, including mobile predators and lower-trophic-level consumers. Selection criteria included preference given to species known to have ecological functions, which could be measured by exhibiting foraging behavior and could be biometrically measured and tagged. The handling of all animals was in compliance with ethical standards at the institution, as well as pertinent permitting requirements.

Measurement of Metabolic Rates

Intermittent-flow respirometry was used to estimate Standard Metabolic Rate (SMR) under controlled conditions, which could be used to measure the oxygen consumption of resting individuals. The background respiration was adjusted in the rates of oxygen consumption, which was normalized to the body mass as:

$$SMR = \dot{V}O_2 \times M^{-b} \quad (1)$$

VO_2 in equation (1) stands for oxygen consumption rate, M is the body mass, and b is the allometric scaling exponent. AMR was estimated using the oxygen consumption during sustained swimming exercise or peak activity measurements, and then Aerobic Scope (AS) can be calculated as illustrated in:

$$AS = AMR - SMR \quad (2)$$

These measurements gave baseline physiological limits in the availability of energy needed for foraging activities.

Field-Based Energy Expenditure

Acoustic transmitters and tri-axial accelerometers were used to measure the amount of energy used by the individuals under natural conditions. The accelerometry data were analyzed to derive the Overall Dynamic Body Acceleration (ODBA), which was used as a surrogate of energy expenditure associated with activities. Laboratory calibrations linking oxygen consumption to ODBA were used to estimate field energy expenditure:

$$EE = a + b \times ODBA \quad (3)$$

In equation (3), a and b were species-specific calibration constants derived from respirometry experiments.

Foraging Behavior and Performance

Foraging behavior was quantified using combined telemetry, accelerometry, and direct observation where feasible. Measures were foraging duration, distance of movement, and prey capture events. Gross Energy Intake (GEI) was estimated from prey capture rates and prey energy content obtained from published calorimetric values and laboratory analyses. Net Energy Gain (NEG) during foraging was calculated as the difference between energy intake and foraging-related Energy Expenditure as shown in equation (4):

$$NEG = GEI - DEE_{forage} \quad (4)$$

Foraging efficiency was expressed as the ratio of net energy gain to gross energy intake, enabling comparison across habitats with differing degradation levels.

Habitat Effects on Foraging Costs

The rate of search and the rate of encounter with the prey were considered in terms of seascape degradation. It was predicted that increased degradation would increase search time and decrease changes in prey encounter probability by causing habitat complexity and loss of prey refugia. These habitat-mediated effects were reflected in analyses by making energetic costs and foraging Success directly proportional to the degradation index instead of using habitats as discrete categories.

Energy Allocation and Individual Condition

Energy balance in individuals was determined by summing up both energy intake and expenditure to determine excess energy that could be used to grow and reproduce. Energy allocation followed a simplified bioenergetic framework:

$$\frac{dE}{dt} = p_A - p_M - p_G - p_R \quad (5)$$

In equation (5), Assimilation, Maintenance, Growth, and Reproductive investments were quantified indirectly through observed energetic states and body condition indices.

Scaling Energetics to Population Responses

Energetic state was linked to fitness-related outcomes by relating individual energy reserves to survival probability and reproductive potential. Survival probability increased nonlinearly with energy reserves, while fecundity scaled with surplus energy above a minimum reproductive threshold. The individual energetic responses were used to derive population-level implications by summing up the responses at the observed spatial distribution of habitats.

Statistical Analyses

The effects of seascape degradation, body size, and environmental covariates were measured by linear mixed-effects models of the effects on the metabolic rates, energy expenditure, and foraging efficiency with individual identity and site as random effects. Generalized additive models were used to investigate nonlinear reactions to degradation. All computations were done in R, and information-theoretic criteria were used to choose the model.

Model Validation and Uncertainty

Uncertainty in energetic estimates was quantified through propagation of measurement error associated with metabolic rate, accelerometry calibration, and prey energy content. Cross-validation was applied to assess the robustness of energy–foraging relationships across species and sites.

Results

Seascape Degradation and Habitat Structure

The study locations exhibited significant variation in habitat quality, as indicated by the composite degradation index. The habitat complexity (8.2 ± 0.4) and prey density (45.3 ± 5.2 ind/m²) were highest, and the turbidity of the location (2.1 ± 0.3 NTU) and the nutrient load (12.4 ± 1.8 µM) were relatively low. On the contrary, the site with extreme degradation exhibited the least complexity of habitat (2.1 ± 0.5) and prey density (9.8 ± 3.1 ind/m^2) and had the largest turbidity (12.4 ± 0.8 NTU) and nutrient load (58.7 6.2 µM). These findings indicate that the worst environmental conditions and an increase in anthropogenic effects typify poor habitats.

Table 1: Variation in Habitat Quality Across Degradation Gradients

Location	Habitat Complexity	Prey Density (ind/m²)	Turbidity (NTU)	Nutrient Load (µM)	Composite Degradation Index
Low Degradation	8.2 ± 0.4	45.3 ± 5.2	2.1 ± 0.3	12.4 ± 1.8	0.15
Very High Degradation	2.1 ± 0.5	9.8 ± 3.1	12.4 ± 1.8	58.7 ± 6.2	0.89

Table 1 shows the major environmental parameters and the composite degradation index of the locations studied. It illustrates a quantitative comparison of habitat complexity, prey density, turbidity, and nutrient load amongst sites and offers an understandable metric-based description of the quality of habitats along the degradation gradient.

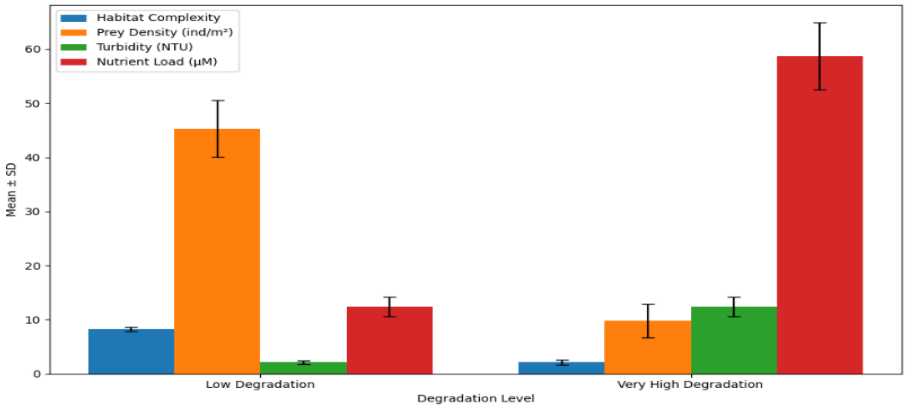

Figure 2: Degradation Gradient and Habitat Quality Variation

Figure 2 shows variations in habitat complexity, prey density, turbidity, and nutrient load of low and very high degradation sites. The composite degradation index is a combination of

these environmental variables to demonstrate cumulative habitat degradation, with the level of differences in habitat quality along the degradation gradient being apparent.

Species Metabolic Rates and Energy Expenditure

The rates of metabolism among the species were different throughout the degradation gradient, with Species A (predator) being significantly affected by the level of habitat degradation by increasing its standard metabolic rate (SMR). Figure 3 shows that the SMR of Species A at low degradation was12.4 ± 1.8 mg O_2/h, or more specifically, 16.8 ± 2.4 mg O_2/h at high degradation. On the same note, SMR of Species B (consumer) rose at low degradation (5.2 ± 0.8 mg O_2/h) as well as at high degradation 7.4 ± 1.3 mg O_2/h. Species A and B aerobic scope (AS) had a corresponding decrease, meaning that members in more degraded environments experienced more stress during metabolic activity.

Table 2: Species-Specific Metabolic Rates Across Degradation Gradient

Species	Degradation Level	SMR (mg O_2/h)	AMR (mg O_2/h)	Aerobic Scope (mg O_2/h)
Species A	Low	12.4 ± 1.8	48.6 ± 6.2	36.2 ± 6.5
Species A	High	16.8 ± 2.4	45.2 ± 6.4	28.4 ± 6.8
Species B	Low	5.2 ± 0.8	22.4 ± 3.1	17.2 ± 3.2
Species B	High	7.4 ± 1.3	20.9 ± 3.4	13.5 ± 3.6

Table 2 gives the species-specific metabolic parameters expressed in standard metabolic rate (SMR) and active metabolic rate (AMR), scope of aerobic (AS) in the various levels of habitat degradation. It mathematically explains the increasing degradation, which increases the metabolic demands and decreases the aerobic capacity, demonstrating the physiological pressure on both the predator (Species A) and the consumer (Species B) in degraded conditions.

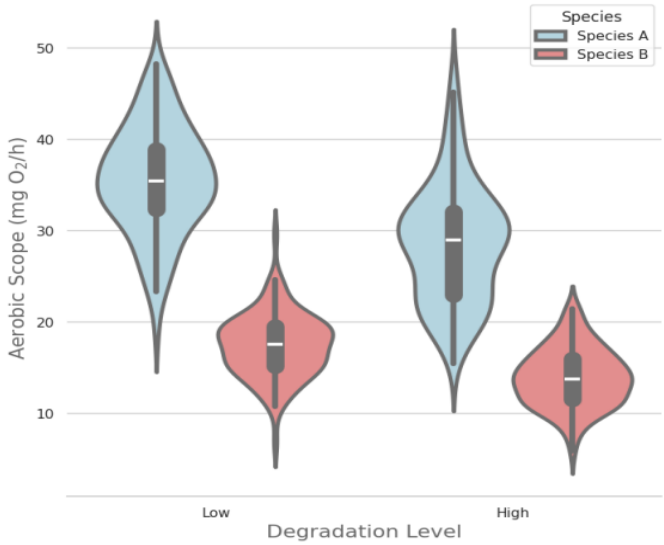

Figure 3: Variation in Aerobic Scope Across Species and Degradation Levels

Figure 3 illustrates the distribution of aerobic scope (mg O_2/h) for Species A and Species B under low and high habitat degradation. Aerobic scope presents a composite measure of metabolic power, which demonstrates diminished physiological functioning in progressively more deteriorated environments.

Table 3 presents the summary of daily and foraging-related energy expenditure (EE) of Species A in low and high degradation habitats. It points to a rise in total and foraging EE, a higher ratio of energy spent on foraging in degraded habitats, high energetic costs, and distorted activity patterns under environmental pressure.

Table 3: Daily Energy Expenditure from Accelerometry

Species	Degradation Level	Daily EE (kJ/day)	Foraging EE (kJ/day)	% EE on Foraging
Species A	Low	245 ± 38	98 ± 18	40.0%
Species A	High	318 ± 51	165 ± 28	51.9%

Field Energy Expenditure and Activity Patterns

In poor habitat conditions, the amount of field energy lost (EE) was significantly large. There was a significant change in daily energy expenditure (DEE) in species A, which rose by a factor of four between low and high degradation (245 ± 38 kJ/day to 318 ± 51 kJ/day). The energy expenditure, which is related to foraging (DEE_forage), also rose to 98 ± 18 kJ/day compared to 165 ± 28 kJ/day in more degraded habitats.

Foraging Behavior and Performance

The time spent foraging and the distance traveled during the movement to the habitats were augmented substantially with the degradation of the habitat. In Species A, the foraging time was 6.2 ± 1.1 hours/day at low degradation and 9.6 ± 1.8 hours/day at high degradation.

Table 4: Foraging Behavior and Efficiency Across Degradation Gradients

Species	Degradation Level	Foraging Duration (h/day)	Movement Distance (km/day)	Prey Encounters (n/h)	Capture Success (%)
Species A	Low	6.2 ± 1.1	12.4 ± 2.8	8.4 ± 1.6	68 ± 9
Species A	High	9.6 ± 1.8	19.2 ± 4.1	3.2 ± 0.9	54 ± 13
Species B	Low	8.4 ± 1.3	8.6 ± 1.9	12.6 ± 2.1	74 ± 8
Species B	High	12.4 ± 2.1	14.8 ± 3.1	6.4 ± 1.5	61 ± 12

On the same note, Species B exhibited a positive change in foraging time of 8.4 ± 1.3 hours/day in low degradation to a high degradation of 12.4 ± 2.1 hours/day. These foraging efforts were coupled by a decreased success in prey capture and prey encounter rates, especially in Species A, whose prey encounter rates decreased at high levels of degradation, 8.4 ± 1.6 to 3.2 ± 0.9 prey/hour.

Table 4 shows the foraging measures of Species A and B in low and high degradation habitats. It demonstrates that the two species

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extended the foraging time and movement distance in degraded habitat, and rates of prey encounter and capture Success were reduced, especially in Species A. These trends show that degradation of habitat increases the foraging expenditure and decreases foraging efficiency as the ecological cost of environmental stress.

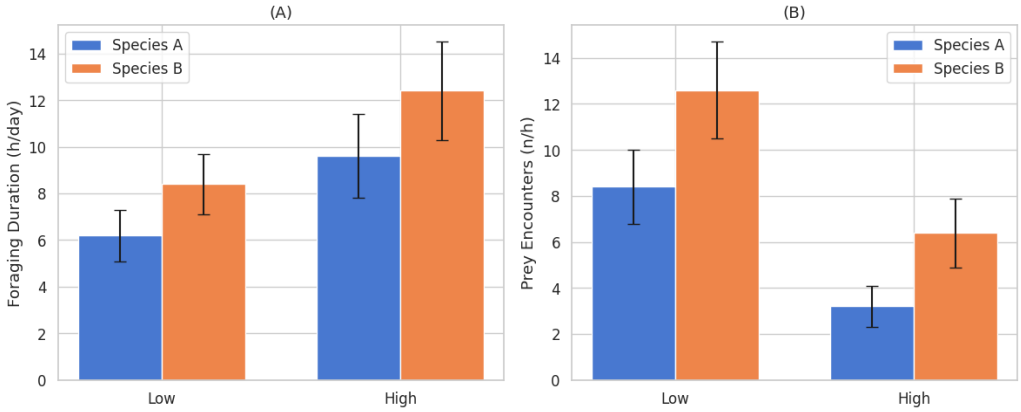

Figure 4: Foraging Effort and Success Across Degradation Levels

The Figure 4 demonstrates the foraging pattern of Species A and B in low and high habitat degradation. In panel (A), the foraging time has a longer duration in degraded habitats in both species, resulting in increased energy expenditure. The decrease in foraging efficiency is shown through panel (B), where the rate of prey encounter decreases as degradation worsens. The panels collectively demonstrate the trade-off between more effort in foraging and less Success in foraging due to environmental stress.

Energy Balance and Foraging Efficiency

Degradation of habitats led to a reduction in net energy gain (NEG) of both species. Species A had a decrease in NEG (ranging between 287 ± 62 kJ/day degradation and 103 ± 76 kJ/day at high degradation). In Species B, NEG declined with low degradation level at 138 +34 kJ/day, and high degradation level at 34 ± 47 kJ/day. The foraging efficiency, which is the ratio of NEG to gross energy intake (GEI), also declined in more degraded habitats, with Species A declining to 0.384 in highly degraded habitats compared to low degradation (0.745).

Table 5: Energy Balance and Foraging Efficiency Across Habitat Degradation

Species	Degradation Level	GEI (kJ/day)	DEE_forage (kJ/day)	NEG (kJ/day)	Foraging Efficiency
Species A	Low	385 ± 58	98 ± 18	287 ± 62	0.745
Species A	High	268 ± 71	165 ± 28	103 ± 76	0.384
Species B	Low	186 ± 32	48 ± 9	138 ± 34	0.742
Species B	High	118 ± 44	84 ± 16	34 ± 47	0.288

Table 5 contains the summary of energy balance of Species A and B along with gross energy intake (GEI) of foraging, energy expenditure (DEE forage) of foraging, net energy

gain (NEG) of foraging, as wellas foraging efficiency at low and high degradation habitats. Findings reveal that the growth in habitat degradation decreases net energy gain and foraging efficiency in the two species, indicating that energetic costs are increased, and energy returns in degraded habitats are lower.

Population-Level Responses to Energy Allocation

Personal energy deposits were associated with population-level reactions. There was a high survival probability with increasing energy reserves among species A, which was between 0.42 and 0.91 between the lowest and highest quartiles of energy reserves, respectively (Q1 and Q4). In the case of Species B, the survival by the end of the year was more in Q4 (0.86) than in Q1 (0.35).

Table 6: Population-Level Survival in Relation to Energy Reserves

Species	Energy Reserve Quartile	Mean Energy Reserves (kJ)	30-day survival (%)	90-day survival (%)	Annual Survival Estimate
Species A	Q1 (lowest)	142 ± 28	78 ± 8	58 ± 12	0.42
Species A	Q4 (highest)	612 ± 54	98 ± 2	95 ± 4	0.91
Species B	Q1 (lowest)	68 ± 14	72 ± 9	48 ± 14	0.35
Species B	Q4 (highest)	298 ± 28	96 ± 3	92 ± 5	0.86

Table 6 shows the probability of survival of both Species A and B in the four quadrants of energy reserves. Increased individual energy stores were linked to shorter-term and annual life expectancy, and this suggests that the distribution of energy is vital in determining resilience at the population scale. This brings out the connection between personal physiological status and the general demographic performance of individuals in different habitats.

Statistical Analysis and Model Validation

Model performance was evaluated using the coefficient of determination (R^2) shown in equation (6), root mean square error (RMSE) shown in equation (7), and mean absolute error (MAE) shown in equation (8). The R^2 quantifies the proportion of variance in the observed data explained by the model, calculated as

The coefficient of determination (R^2) shown in equation (6), root mean square error (RMSE) shown in equation (7), and mean absolute error (MAE) shown in equation (8) were used to evaluate the model performance. The R^2 is a measure of the fraction of the data variation that has been predicted by the model and is given as

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \quad (6)$$

RMSE indicates the mean size of prediction errors, which is provided by

$$RMSE = \sqrt{\frac{1}{n}\sum(y_i - \hat{y}_i)^2} \quad (7)$$

When MAE is used, the average absolute error is given, and it is computed as

$$MAE = \frac{1}{n}\sum|y_i - \hat{y}_i| \quad (8)$$

All these metrics affirm the correctness and suitability of the models in forecasting metabolic and energetic reactions along degradation

gradients. The achieved mixed-effects model results revealed that the degradation index had a tremendous effect on the aerobic scope ($p < 0.001$), with a 12.86 mg O_2/h reduction in the aerobic scope with an increase in the degradation index by one unit. Additionally, body mass and species type were significant predictors of metabolic rate. The model performance indicators showed good fits, with R^2 of 0.74, 0.81, and 0.79 for aerobic scope, daily energy expenditure, and foraging efficiency, respectively. Propagation of uncertainty in energetic estimates was very different in terms of net energy gain and energy balance, which was indicative of the sensitivity of the estimates to measurement and calibration errors.

Table 7: Model Performance Metrics

Model	Response Variable	R^2	RMSE	MAE	Cross-Validation R^2	AIC
LMM: Aerobic Scope	Aerobic Scope	0.74	4.82	3.65	0.71 ± 0.06	1,248.5
LMM: Energy Expenditure	Daily EE	0.81	18.45	14.22	0.78 ± 0.05	1,684.2
GLM: Foraging Efficiency	NEG/GEI	0.79	0.084	0.062	0.76 ± 0.07	624.3

Table 7: Summative performance metrics of metabolic and energetic responses statistical models. Mixed-effect and generalized linear models had a high predictive ability with good R 2 values for aerobic scope, daily energy expenditure, and foraging efficiency. Strong model fits are shown by cross-validation and error measures (RMSE, MAE), and uncertainty analysis of energy balance estimates to measurement variability is shown, highlighting the strengths and weaknesses of the modeling method.

Discussion

This paper presents objective empirical data that seascape degradation significantly changes habitat structure in a manner that directly limits energetic performance and population viability. The degradation gradient quantified in Table 1 shows strong declines in habitat complexity and prey density alongside increases in turbidity and nutrient loads, confirming that highly degraded sites experience poorer ecological conditions and greater anthropogenic pressure. These environmental shifts were consistently reflected in species-level metabolic, behavioral, and demographic responses, demonstrating a coherent link between habitat degradation and energetic limitation. Species A and Species B had species-specific metabolic measures measured (Table 2), in which species A and Species B increased standard metabolic rates with high degradation and low aerobic scope. This pattern means that minimum energetic costs are high, and physiological adjustability in contaminated surroundings is reduced. These results were also supported by field accelerometry. As shown in Table 3, daily energy expenditure for Species A increased from 245 ± 38 kJ/day in low-degradation sites to 318 ± 51 kJ/day in high-degradation sites, with the proportion of energy allocated to foraging rising from 40.0% to 51.9%. This had been numerically determined as the ratio of foraging energy spending to total daily spending, and it reflected a significant energetic repositioning of prey acquisition in unfavorable

circumstances. Table 4 presents results of behavior that show that more energetic investment did not lead to better foraging success. Both species foraged significantly more time and traveled further distances as the environment degraded, but prey encounter rates went way down. In Species A, prey encounters decreased from 8.4 ± 1.6 to 3.2 ± 0.9 prey/ hour with a corresponding decline in the capture success. These findings prove that degradation of the habitat raises search costs at the same time as lowering prey availability, which leads to an energy bottleneck. Calculations of energy balance in Table 5 reveal that net energy gain decreased tremendously with degradation. In Species A, the net energy gain reduced by about 64%, from 287 ± 62 kJ/day to 103 ± 76 kJ/day, and in Species B, it reduced by more than 70%. The direct effects of these decreases in excess energy were population-wide effects. Survival estimates in Table 6 show a strong nonlinear relationship between energy reserves and survival probability, with annual survival increasing from below 0.45 in the lowest energetic quartile to above 0.85 in the highest for both species. This empirical association proves that state activity plays a mechanistic role in population endurance and habitat state. The integration of metabolic, behavioral, and demographic data highlights energetic pathways as a powerful framework for understanding ecological responses to seascape degradation. The study has drawbacks, though, because of the spatial coverage and determination of prey energy content through the calorimetric estimates. The future studies are to include seasonal sampling, experimental restoration of habitat, and expansion of taxonomic diversity in order to determine the energetic thresholds that are very important in population resilience.

Conclusion

This study demonstrates that seascape degradation imposes significant physiological and ecological constraints on marine species. The high habitat complexity (8.2 ± 0.4) at low-degradation sites was associated with the abundance of prey density (45.3 ± 5.2 ind/m²), low turbidity (2.1 ± 0.3 NTU), and moderate nutrient loads (12.4 ± 1.8 μM). The highly degraded sites were simplified with a habitat complexity of 2.1 ± 0.5, prey density of 9.8 ± 3.1 ind/m², turbidity of 12.4 ± 1.8 NTU, and nutrient load of 58.7 ± 6.2 μM. Measurements of metabolism showed that Species A underwent an increase in SMR of 12.4 ± 1.8 mg O_2/h to 16.8 ± 2.4 mg O_2/h across the gradient of degradation, accompanied by a decrease in aerobic scope of 36.2 ± 6.5 to 28.4 ± 6.8 mg O_2/h. Field-based energy expenditure increased substantially, with daily EE rising from 245 ± 38 kJ/day to 318 ± 51 kJ/day, and foraging EE comprising up to 51.9% of total expenditure in highly degraded habitats. Correspondingly, net energy gain for Species A decreased from 287 ± 62 kJ/day to 103 ± 76 kJ/day, and foraging efficiency declined from 0.745 to 0.384. The population-level analysis showed that survival probability increased with energy stores, with annual survival probability being between 0.42 and 0.91 in the quartile of energy in Species A. These results show that habitat losses raise both the energy expenditures and decrease foraging effectiveness and may limit population groups. Energetic stress should

be reduced by focusing on conservation approaches that involve restoration of habitat complexity and prey availability. Future studies need to increase to multispecies and longer-term research, investigate interactions with climate stressors, and confirm the accuracy of accelerometry-based energy measurements, which will give a more complete picture of the process of seascape degradation affecting individual fitness and population resilience.

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