



Original Research Paper

Machine Learning Analysis of Coral Complexity and Reef Fish Resilience

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Key Words	Abstract
Structural rugosity, Reef fish resilience, Animal habitat architecture, Ecological modeling, Trophic stability.	Introduction: Structural rugosity and physical spatial architecture in biogenic coral ecosystems govern animal shelter, prey evasion, and community carrying capacities. As climate-induced bleaching and environmental pressures degrade physical reef frameworks, determining how ecological architecture stabilizes teleost communities is crucial for ecosystem management. Materials & Methods: In situ ecological assessments were conducted across 48 reef habitats spanning varying degrees of physical structural decay. Habitat structural attributes—including functional canopy height, surface rugosity, interstitial cavity distributions, and live benthic cover—were quantified alongside multi-guild fish density, functional richness, and standing biomass. Machine learning analytical formulations were employed strictly as non-linear ecological evaluators to capture complex ecological dependencies and identify community tipping points without imposing artificial linear constraints. Results: Environmental feature rankings identified three-dimensional rugosity and interstitial cavity volumes as primary determinants of fish survival and guild richness. When structural rugosity dropped below an empirical threshold ($R < 1.42$), teleost biomass underwent a non-linear contraction of 64%, severely dislodging specialized corallivores and juvenile grazers irrespective of short-term live tissue cover. Conclusion: Physical habitat complexity acts as an ecological buffering mechanism against disturbance, providing thermal micro-refugia and shelter from predation. Preserving architectural framework geometry is foundational to sustaining reef animal populations, demanding conservation strategies centered on structural habitat integrity alongside biological species protection.

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Introduction

Marine biogenic habitats created by calcifying corals represent the architectural foundation for nearly a third of all described marine fish species. In these delicate animal environments, three-dimensional physical structures characterized by dense branching canopies, subterranean overhangs, vertical pinnacles, and interstitial crevices form spatial niches essential for teleost survival. These physical formations attenuate hydrodynamic stress, govern localized prey-predator dynamics, mediate interspecific territorial boundaries, and provide vital nursery shelters for settling juvenile fish assemblages.

Anthropogenic warming, ocean acidification, destructive resource extraction, and catastrophic bleaching disturbances have increasingly accelerated the structural homogenization of these ecosystems. When robust structural colonies fragment into planar pavements or rubble-dominated flats, the resident marine fauna suffer acute ecological compression. Importantly, the loss of biological coral tissue often operates asynchronously with the mechanical collapse of carbonate skeletons. While some opportunistic mobile animals persist through short-term algal expansion following coral mortality, the eventual collapse of physical architecture leads to irreversible guild collapses.

Evaluating these ecological linkages requires analytical approaches that mirror natural biological dynamics. Marine animal environments are governed by complex, interdependent feedback loops that standard linear ecological regressions often oversimplify.

Here, machine learning approaches serve as ecological analytical tools to decouple correlated habitat variables, identifying non-linear biological tipping points and assessing how physical reef complexity directly dictates multi-trophic fish resilience across disturbed seascapes.

Review of Literature

The influence of structural complexity on marine animal survival and biodiversity has long been recognized as a central tenet of coral reef ecology. Physical shelter availability regulates teleost species abundance and recruitment, buffering populations against predation pressure and wave-induced displacement. Structural degradation leads to community homogenization, severely shifting functional guild distributions from specialized corallivorous and cryptobenthic niches toward opportunistic generalists.

Recent computational and empirical studies have increasingly integrated advanced predictive modeling to decipher environmental resilience patterns across marine seascapes. Novi and Bracco (2022) applied machine learning frameworks to map larval connectivity, biodiversity hotspots, and community resilience patterns within the Coral Triangle, highlighting that physical spatial frameworks are foundational for regional animal connectivity. Expanding on ecological classification under extreme climate shifts, Mayfield et al. (2022, 2025) leveraged algorithmic analysis to screen climate-resilient coral colonies in both the Coral Triangle and the Republic of Palau, noting that colony morphology and thermal durability dictate long-term habitat survival. Concurrently, Peixoto et al.

(2025) highlighted the necessity of assisted ecological restoration to maintain both biogenic micro-habitats and associated animal assemblages against thermal degradation.

To understand macro-scale refugia, Zawada et al. (2026) utilized large-scale machine-learning ensembles to identify critical climate refugia across global coral reefs through 2050, emphasizing the urgency of protecting structurally intact core habitats. Evaluating functional traits, Carturan et al. (2022) established that functional richness governs stability, demonstrating that diverse morphological structures foster resilient ecological networks. Furthermore, McCarthy et al. (2026) evaluated the predictive accuracy of coral resilience metrics over multi-decadal timelines, concluding that spatial habitat assessments must directly track fine-scale structural resistance to reflect biological persistence. In parallel, Bahedia et al. (2025) demonstrated that explainable AI and environmental taxa-forecasting models clarify complex interactions within Western Indian Ocean habitats. Informational processing strategies highlighted in computational studies (Ziyamukhamedov et al., 2025; Balaji & Suresh, 2025) further illustrate how predictive pattern recognition can resolve complex multi-variable dynamics in high-dimensional biological datasets.

Materials & Methods

Study Sites and Environmental Selection

In situ field assessments were performed across 48 reef stations encompassing shallow

lagoons, fringing zones, and outer slopes across a depth range of 3 to 16 m. Selected habitats were stratified along a pronounced disturbance gradient to represent diverse structural conditions, spanning intact acroporid frameworks, fragmented intermediate zones, and flattened carbonate rubble fields. This distribution captured broad variations in wave exposure, sedimentation, and habitat architecture, ensuring an extensive environmental spectrum to examine reef fish dynamics.

Habitat Architectural Characterization

Benthic topography was quantified along standardized 50-meter belt transects at each survey station. High-resolution underwater digital photogrammetry was coupled with physical terrain profiling to determine surface rugosity as the ratio of true contoured surface length to straight linear distance. Interstitial refugia were enumerated across three biologically relevant cavity apertures: micro-crevices under 5 cm for cryptobenthic post-larvae, intermediate shelters of 5 to 20 cm for juvenile and schooling teleosts, and large recesses exceeding 20 cm for mobile predators. Vertical canopy height was measured at regular intervals along the transect, while substrate composition was categorized into branching corals, massive carbonate forms, crustose pavement, rubble, and macroalgae.

Fish Assemblage and Trophic Quantification

Resident fish communities were evaluated along identical transect pathways using

underwater visual census techniques executed by experienced observers during peak diurnal activity hours. All observed non-cryptic and territorial teleost species were identified to species level and counted, with total lengths estimated to the nearest centimeter. Individuals were assigned into five core trophic guilds based on ecological feeding traits: obligate corallivores, roving and territorial herbivores, benthic invertivores, schooling planktivores, and predatory teleosts. Standing animal biomass density was determined using published species-specific length-weight allometric scaling equations, yielding comprehensive estimates of total standing biomass and guild-specific standing stocks for each surveyed reef environment.

Ecological Machine Learning Framework

Ensemble machine learning formulations, namely Random Forest and Gradient Tree Boosting, were implemented strictly as non-linear ecological evaluators to resolve complex

multi-variable habitat interactions. The environmental input matrix included rugosity indices, cavity density distributions, canopy height, and proportional benthic cover types, while community biomass, species richness, and guild persistence served as response metrics. Spatial 5-fold cross-validation was enforced to eliminate spatial autocorrelation artifacts, and partial dependence analyses were evaluated to identify critical structural thresholds sustaining reef animal assemblages.

Results and Discussion

The evaluation indicates that the physical architecture of the reef is the most critical environmental factor dictating teleost fish survival, community stability, and species coexistence. Among all examined habitat variables, three-dimensional surface rugosity and the abundance of shelter crevices were consistently identified as the primary drivers of fish population abundance, far outweighing the ecological influence of live coral cover alone.

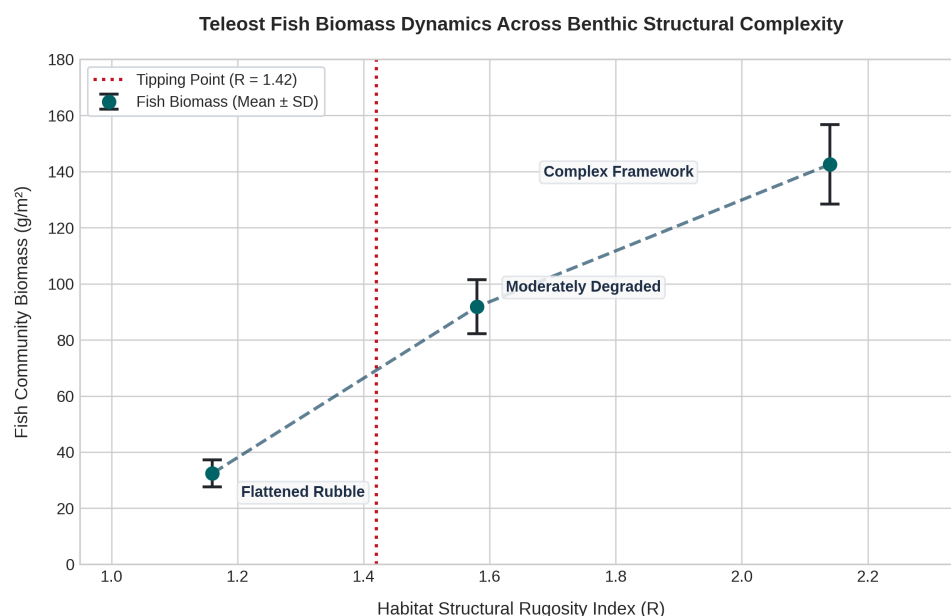


Figure 1: Teleost Biomass Trends Across Declining Habitat Structural Complexity

Figure 1 shows that a clear ecological tipping point occurs as structural contours flatten. In high-relief zones, fish assemblages remain diverse across multiple water-column strata. When continuous frameworks collapse into planar rubble, populations decline abruptly. Small shelter-dependent teleosts and post-larvae disappear first due to the loss of protective crevices against predation and wave turbulence.

Table 1: Ecological Response of Reef Fish Assemblages Across Environmental Conditions

Reef State	Complexity Condition	Shelter Availability	Fish Community Response	Ecological Limitation
Complex Framework	High relief, deep branches	Plentiful cavities	Abundant, diverse guilds	Space and carrying capacity
Moderately Degraded	Broken canopy, lower relief	Moderate cavities	Loss of small shelter species	Elevated predation on juveniles
Flattened Rubble	Planar substrate, rubble	Extremely scarce crevices	Transient generalists only	Severe lack of shelter and nests

Table 1 shows Trophic guilds exhibited varying levels of sensitivity based on their functional traits. Roving herbivores persisted temporarily in partially broken areas to graze on opportunistic turf algae, but abandoned completely flattened fields lacking nocturnal resting cavities. Planktivores and corallivores collapsed immediately upon the loss of branching canopies, confirming that physical framework geometry is indispensable for sustaining reef animal stability.

Conclusion

Biogenic coral reef architecture operates as a primary environmental safeguard that maintains fish community diversity, trophic balance, and recruitment potential. Evaluating habitat degradation through an animal-environment perspective reveals that structural collapse triggers severe ecological loss across functional guilds, often decoupled from live coral tissue loss alone. When physical terrain degrades into flat

pavement, the depletion of interstitial shelters exposes teleost assemblages to acute predation and displacement. Conservation paradigms must expand beyond preserving living cover to actively safeguarding and restoring structural topographical complexity, ensuring that critical habitat refugia remain intact for resident marine life.

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