Evaluating effects of bycatch and fisheries-induced evolution on oceanic trophic systems

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Abstract

Human activities, particularly fishing, have been recognized as a primary contributor to the decline in biodiversity in the open ocean. This article examines the diversity trends and ecological characteristics of bycatch populations in Fish Aggregating Devices (FADs) and Free School settings within the tropical tuna purse-seine fisheries in the eastern Atlantic Seaboard. Information was gathered from scientific observer programs conducted from 2000 to 2025 aboard Spanish and French ships. Based on the fishing method, the findings indicated varying structural and diversity trends in bycatch assemblies, revealing more species and variety in FAD sets compared to Free School settings. Bycatch populations showed preferences for particular oceanographic features of the Atlantic Seaboard, including the tropical and annual coastal rising structures, the Cape Lopez front structure, and the Guinea domes. The kind of habitat and surface water temperature significantly influence the diversity trends of these organisms. These findings validate the necessity of incorporating several methodologies to investigate the marine environment for the practical application of the Ecosystem Approaches to Fishery Management (EAFM).

Keywords: Bycatch, Fisheries, Oceanic trophic systems, Ocean

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Introduction

The excessive use of marine fishing resources degrades the productivity of species and aquatic ecosystems globally, with only a few healthy fisheries resulting from effective management methods (Carneiro and Martins, 2022). The exact degree of exploitation remains a contentious issue among experts. Current fisheries statistics unequivocally demonstrate that the thresholds for fish extraction from natural stocks were attained (Zamanpoore *et al.,* 2024). Fishing directly influences stock motion, and its effects can extend well beyond the species of interest through trophic cascades across the food web (Hočevar and Kuparinen, 2021). Characterizing ecosystem responses to fisheries extraction and other human stresses, such as pollution, rising temperatures, and introduced species, is essential for ensuring ethical fishing methods and a healthy marine environment (Agnes Pravina, Radhika and Ramesh Palappan, 2024). Sustaining current capture quantities and augmenting them will hinge on the capacity to rehabilitate reduced populations and restore compromised ecosystem conditions (Frietsch *et al.,* 2023).

Human exploitation of marine ecosystems, leading to elevated fishing or harvesting magnitude, significantly contributes to biodiversity loss. In 2012, the 12 most prolific species constituted around 28% of global marine capture fisheries production, while roughly 29.2% of fish stocks were classified as overfished. In tropical regions, 62% of worldwide tuna captures are achieved with purse-seine equipment. The tropical fish purse net fishing can be categorized according to the methodology employed for locating tuna.

A robust safety margin is essential in managing fisheries to accommodate inter- and intra-trophic interactions, including predator-prey dynamics, resource rivalry, and ecological load capacity fluctuations (Yu and Wang, 2021). The study revealed that the number and type of prey were significantly influenced by predator abuse, which is crucial for assessing its impact on the life history traits of predator organisms, including food intake, circumstance, rate of development, spawning cycles, and recruitment possibility. The fish stocks and their interactions with prey and predators are interconnected with the patterns of lower-trophic-level species, the primary producers, and zooplankton, influencing the entire food web (Mihalitsis *et al.,* 2021). Fisheries production can have cascade effects, indirectly influencing plankton patterns and the ecosystem's load. Unregulated fishing, along with other anthropogenic factors such as global warming and contamination, undermines the adaptability of aquatic ecosystems, degrades their health, and leads to irreversible alterations. Identifying the effects of human activities, such as aquaculture, on the entire food web yields insights for Ecosystem-Assisted Fisheries (EAF) regulation (Cooke *et al.,* 2023). Ecological models serve as valuable instruments for elucidating alterations in the framework and operation of aquatic environments.

Two tactics pertain to executing the set in the Gulf of Mexico. Initially, Free Schools sets often consist of mono- or paucispecific tuna groups identified through sonar signals, avian activity, surface disturbances, or splashes. The term "Fish Aggregating Devices" (FAD) refers to any floating item utilized to enhance the catchability of fish (Pons *et al.,* 2023). There are fundamentally two primary categories of Drifting FADs (DFADs): organic and artificial. Natural DFADs predominantly consist of logs and branches adrift from the coastline. Most DFADs comprise a FAD float made of purse-seine closures or bamboo frames supplemented with additional corks for buoyancy, together with underwater netting screens affixed to the float (Sredić, Knežević and Milunović, 2024). FADs can be outfitted with satellite-linked echo-sounder boats to facilitate the convenient identification and remote assessment of the existence and size of underlying aggregations (Tu *et al.,* 2019). Both categories of DFADs have been delineated and examined throughout several oceans.

Thus far, this research has yielded fresh insights into the variety of bycatch species collections throughout the eastern Atlantic Ocean; further information is required regarding the structural patterns of variety and the ecological components of these species' natural environments. The rise in FAD utilization since the 1990s augmented purse seine captures of tropical tuna by around 60%, with environmental problems related to bycatch overseen by the International Committee for the Preservation of Atlantic Tunas (ICPAT). Oceanic species have variable distribution in aquatic settings and are often associated with specific habitats (Assegid and Ketema, 2023). Pelagic ecosystems are, indeed, dynamic in both spatial and temporal dimensions. In areas characterized by significant seasonal variation, the species inhabiting the same marine region are attributed to distinct habitats, contingent upon the time of year. Environmental alteration can influence these organisms' abundance, diversity, and variety (Zhang *et al.,* 2024). Identifying the elements that elucidate the array of bycatch populations in pocket seine fisheries is crucial for efficiently handling exploited assets and protecting the most endangered animals. Most research examining pelagic tropical species' environmental proclivities has primarily relied on catch information and effort from tuna fishing vehicles, particularly longline Catch Per Unit of Effort (CPUE) information, while seldom utilizing observer data from purse-seine fisheries. Therefore, an in-depth knowledge of the relationships among oceanic species and their surroundings must be established to ensure the correct execution of Ecosystem-Based Fishery Management (EBFM) before executing any conservation strategy.

Materials and Methods

Research Locale

The study area was situated in the southwestern Atlantic Ocean, spanning from 36°W to 17°E and from 21°N to 16°S. The Atlantic tides exhibit elevated levels of salt and oxygen that are dissolved. The yearly mean Sea Surface Temperature (SST) exceeds 25°C for most regions and falls below 21°C after significant upwelling episodes, such as the equatorial summertime rise. The Intertropical Convergence Zone (ITCZ), where the northeastern and southeastern trade winds meet, is situated north of the equator at about 6°N, particularly in the Pacific Ocean. It is correlated with reduced sea surface saltiness and elevated temperatures at the bottom. The equator rising delineates a seasonal phenomenon resulting from the dynamics of trade winds. Tropical upwelling commences in the boreal springtime, attaining peak levels of chlorophyll in the summertime. Significant oceanic processes influencing the ecology are the Guinea and Angola thermal domes, located at about 11°N-14°W and 13°S-10°E. These phenomena are marked by an elevation of the thermocline due to a dome-like accumulation of chilled water from deeper layers, occurring on either side of the equator throughout the winter and summer.

Data on Bycatch

The European Union (EU) academic observer system for tropical fish such as tuna purse-seine aquaculture in the Atlantic and Indian Oceans, encompassing roughly 12% of the trips from 2000 to 2025, is administered by French and Spanish scientific organizations (Ergüden *et al.*, 2022). Observers collected information encompassing trip details, fishing operations (set kind, geographical coordinates of the set, day and time of the set), and accidental capture species groupings (in terms of mass or species count). Bycatch animals are categorized into groups: billfishes, sharks, fish with bones, rays, sea turtles, and primates. Bycatch organisms are often identified at the species level, although they are sometimes classified at the genus or category level.

The fishing group was designated the specimen unit and classified into related sets (FADs) and free-swimming collection (Free School groups). Related sets are found on various floating items, including logs, flotsam, deceased and living whale sharks, and data flags. The natural objects (logs) and assemblages linked to whale sharks were incorporated into the analysis as FADs, regarded as connected assemblages. Organic and synthetic floating things were presumed to exert comparable positive and negative impacts on bycatch. Sets linked to whales (mysticetes) were categorized as Free Schools sets due to the potential cohabitation of dolphins and tunas in feeding zones targeting the same victims, with whales serving as indicators for the vessels to locate fish educational institutions, hence classifying them as free-swimming clumps. Between 2000 and 2025, 1.6k sets were recorded in the Spanish and French purse seiner fleets, comprising 578 Free Academy sets and 1.1k FAD sets.

Selection of Taxonomic Groups

Nine groups (five FAD sets and four Open Schools sets) only identified species at the bycatch taxonomic grouping level. Hence, they were excluded from further analyses. Additionally, six inaccurately labeled Free School groups were removed to prevent bias in the selection technique. For recordings of higher taxonomic levels (species, relatives, order, and others), species counts and abundances were determined based on the species makeup of the appropriate category (e.g., species and parent) within the same region for that specific year. Due to the inability to identify species-level classifications, these were regarded as morphospecies categories, identifiable by morphology and regarded as a single species in biodiversity assessments.

Ecological Data

For each fishing batch (date and location), oceanographic parameters were supplied by Collecte Localisation Spacecraft (CLS) with worldwide geographical maps for every factor. Data on the environment preceding this information were unavailable. The global circulation of the ocean system provides information about temperatures at depths of 25, 35, 55, and 70 meters; the depth and gradients of the thermocline; saltiness at 25, 35, 55, and 70 meters; and total ocean current velocity, with an accuracy of 20 kilometers and a rate of every 2 to 3 days. Sea Surface Temperatures (SST; in °C) were obtained from satellite imagery with an accuracy of 5 km, sourced, etc. Chlorophyll intensity on the actual day of the fishery set and 12 days prior, with a 5-km resolution, was obtained from satellite data. The water level anomalies and geostrophic current speed derived from altimetry were accessible at a resolution of 20 kilometers.

Biodiversity Metrics

Two distinct diversity indexes were calculated to assess the diversity of bycatch collections across fishing modes: the Animal Richness Ranking, representing the total count of species in a given area, and the Shannon Diversification Ranking, which integrates aspects of both wealth and evenness (the proportional abundance of each kind) and is the most widely utilized method for measuring diversity. Animal accumulation graphs were generated for each trawling method to illustrate the total number of animals documented as a function of the amount of sampling (i.e., number of data points). This technique generates a smooth curve by repeatedly adding specimens to the accumulating curve. It displays the mean of these variations from random information arrangements, often represented as a value of 100. All potential species are identified in the purse-seine fisheries' research region after the curve's asymptote is attained. The non-parametric Kruskal-Wallis examination of variances was employed to identify significant variations in two independent, non-normally distributed measurements.

The rank/abundance plot or dominance curves can quantify the proportional abundance of various species in a region (uniformity). The vertical axis represents the square root of plenty, whilst the horizontal axis denotes the number of animals. The log-abundance graphs illustrate the relative number of species, ranging from the most abundant to the rarest. The amount of each species was derived from the log-abundance charts corresponding to each fishing method.

Geographic and Ecological Attributes of Bycatch Collections

Generalized additive Simulations were developed to ascertain the time, space, and ecological features of bycatch collections concerning biodiversity of species and the Shannon variation of diversity in both angling methods in the eastern Pacific Ocean from 2000 to 2025, due to the inconsistent accessibility of oceanographic data before 2000 across all factors. The research executed the model using 630 data points for FAD settings and 400 samples for Free Schools sets. The analysis incorporated spatial (longitude and length), temporal (month), relationship type, and oceanic factors.

Chlorophyll is integral to marine environments, serving as a reservoir of energy that permeates trophic levels and indicates prey abundance. This study identified intriguing correlations between inferred chlorophyll-a levels measured 15 days prior and the quantity of free-swimming tuna in the Indian Ocean. This factor has been examined in the Caribbean Sea to investigate the links between environmental variables and tuna patterns in DFAD sets.

Associations among oceanographic parameters were examined to identify potential collinearities. In instances of substantial interaction among the two factors (Pearson correlations $r > 0.56$), only one parameter was incorporated into the final model. To assess the model's efficacy with an independent a database, the data was divided into two segments: one segment utilized for model fitting (82% of the information), referred to as the training information, and the other employed for evaluating predictions, termed the testing information (25% of the information). The present research used a k-fold segmentation method ($k = 5$) to generate testing information (25%) and learning information (70%) from observer recordings. Regional prediction mappings for both diversity scores and by set type were generated utilizing the complete dataset. Trimestral predictions were disregarded owing to the insufficient size of the sample.

Description of the Ecosystem

Flow charts illustrating trophic levels and relationships among functional categories delineated the food web's framework. The Total System Throughput (TST) in the 1995s approach comprised 41% trash flows, 37% exports of goods, 14% use, and 8% respiratory. Despite TST declining to 4995 t km^2y^1 in the 2010s and 4494 t km^2y^1 in the 2020s, the flow proportions remained analogous to those in the 1995s scenario. From the 1995s to the 2015s, the relative ratio of the method's ascendency rose from 52% to 58%, while its overhead (resiliency) declined from 48% to 42%. The total system energy (except detritus) diminished from 57.3 t km-2 in the 1995s to 47.4 t km-2 in the 2010s (a reduction of 12%) and further declined to 37.5 t km-2 in the 2015s (a loss of 38%). The average trophic level of the population (> 2) was 3.83 in the 1995s, 3.73 in the 2010s, and 3.49 in the 2015s.

Ecological Functions of Functional Collections

Mesozooplankton (MP) and benthic insects, tiny pelagic fishes such as anchovy, and apex predators like hake and bluefish exerted considerable impact directly and indirectly across the food chain. MP exhibited the most significant relative total impact and served as the primary species in the 1995s, followed by anchovies in both keystoneness and comparative total effect. Invertebrates living in the sea ranked second in the 1995s regarding their keystone status and overall influence. The trophic processes began to alter following this decade's end. The proportional overall effect of MP diminished from 1.0 in the initial decade to 0.92 in the 2005s and 0.7 in the 2015s, while anchovies exhibited the most significant relative overall impact in the 2015s. Throughout all times, MP was the keystone species in the biological community, next to anchovies. The keystoneness and percentage overall effect of bluefish rose dramatically from -0.6 in the 1995s to -0.4 in the 2015s.

Impacts of Fishing

The total capture rose from 4.1 t km^2y^1 in the 1995s to 4.5 t km^2y^1 in the 2010s, declining to 3.7 t km^2y^1 in the 2015s. The 2005 model yielded the highest cumulative effectiveness (4.1) and gross effectiveness (0.003), which is associated with the danger of overpopulation in an environment. Exploration rates of functional categories peaked in the 2000s, except tresses and whiting, which attained their most significant levels in the 1995s, and anchovies and pilchard, which peaked in the following decade.

The gillnet fishing exhibited a positive balanced trophic effect on whiting during the 2005s (0.052) and 2015s (0.041) as the indirect impacts outweighed the immediate negative consequences of exploitation, specifically through the predation of whiting's enemies, including turbot, thornback ray, and select dogfish. The purse seine fishing adversely affected anchovy populations in all decades, with impacts of -0.048 in the 1995s, 0.071 in the 2005s, and -0.24 in the 2015s. Gillnetters significantly affected bluefish, bonito, berries, turbot, thornback ray, and dogfish across all timeframes. Laser trawlers adversely affected thornback rays, selected dogfish, and turbot, with a pronounced detrimental influence on deep water flower shrimp across all eras. Gillnetters exerted an indirect favorable influence on mullets by diminishing the populations of their enemies.

Conclusion

This study has enhanced the comprehension of the composition and variety of bycatch groups in the eastern Atlantic Ocean. It has disclosed several correlations between biodiversity and the principal oceanographic features of the Atlantic Ocean for both fishery methods. The results indicated that FAD sets can accumulate more bycatch organisms and exhibit greater variety than Free School sets. Diversity fluctuates by region and season, depending on fishing methods, indicating the necessity of integrating information from both modalities to enhance understanding of the geographic spread of these species groupings. The analysis provides novel insights into the many environmental aspects of the bycatch populations. Biodiversity research is essential for enhancing comprehension of ecological processes and the kinds of organisms residing within them, and fulfilling the model's goals.

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