Oceanologia, 67 (1)/2025, 67111
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Institute of Oceanology

https://doi.org/10.5697/USFE4011

Climate change and its effects on the marine food web with a concentration on the pelagic fishery in the northern Arabian Sea

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Abstract

The northern Arabian Sea, a vital ecosystem that sustains a significant population through its fisheries is increasingly threatened by climate change, overharvest, and coastal pollution. To evaluate the combined effects of these pressures on fishery health, microplankton, fish bycatch, and coastal environment data were examined between 2019 and 2023 from key hotspots. Using the time-cumulated indicator (TCI) and efficiency cumulated indicator (ECI) approaches, we aimed to determine broader spectrum of energy flow in the ecosystem. The findings revealed a delicate equilibrium in the ecosystem. Although average temperatures remained stable, variations in rainfall patterns suggested potential changes in salinity and dissolved oxygen levels, signaling subtle climate change influences. Biological indicators highlighted dynamic shifts: species diversity fluctuated, suggesting community restructuring, while increased evenness implied potential ecological stabilization. The production and biomass (P/B) ratio was higher in 2019, reflecting faster biomass production compared to the slower rate observed in 2023. This instability may be attributed to environmental changes, altered species composition, and a steady increase in fishing pressure. Notably, consistent fish catches amidst relatively stable species diversity suggest complex population dynamics. In terms of energy flow and transformation, a significant rise in TCI, suggests accelerated energy transfer, likely driven by a decline in predator population. Additionally, the instability in Residence Time (RT) underscores intricate food web interactions. Our findings highlight the delicate equilibrium of the northern Arabian Sea, as revealed by the overall data and assessment. Understanding these intricate dynamics is crucial for developing effective conservation strategies and promoting sustainable fishing practices.

Keywords

Equivalent black carbon; Climate change; Ecosystem dynamics; Energy transformation; Food web dynamics; Pelagic fishery; Northern Arabian Sea

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Received: 20 August 2024; **revised:** 12 December 2024; **accepted**: 7 January 2025

1. Introduction

Climate change has cast a long shadow on our oceans, threatening marine ecosystems and fisheries. This threat is multifaceted, with direct impacts such as overfishing and indirect effects like changes to primary production, which is the foundation of the food web. Biodiversity loss and population shifts are key drivers of global change. Additionally, global warming is dramatically altering the distribution and abundance of fisheries resources (Simpson et al., 2011; McKenzie et al., 2021). The scientific community overwhelmingly agrees on the urgent need to address these challenges to prevent unforeseen consequences for ecosystems (Jochum et al., 2012; Rall et al., 2012).

Adapting to global changes in fish production is challenging when considering the entire ecosystem. Identification, physiological needs, preferred conditions, habitats, life spans, and interactions among diverse species vary in different environments, which poses a challenge in accurately predicting future fish production. Overfishing and other anthropogenic drivers contribute to global warming, leading to changes in species abundance, diversity, and trophic exchange, ultimately affecting marine food webs. A trophodynamic approach is required to assess the impact of anthropogenic activities and the resulting changes in global biomass parameters within the food web. Factors such as important habitats, anthropogenic activities, invasive species, and global changes can disrupt marine species' ecosystems and alter the patterns and performance of their food webs (Britten et al., 2016). Rapid changes in global fisheries production have been associated with decreased predator biomass (Tremblay-Boyer et al., 2011; Christensen et al., 2014), primarily due to overfishing, which reduces fish production and disturbs marine habitats. These alterations affect ecosystem structure and functions, affecting species size, growth, production, distribution, and interrelationships. Understanding these pressures is crucial for developing fisheries production and ecosystem-based management.

Besides ecosystem-based management and trophodynamic models, traditional species-specific approaches to fisheries management are increasingly inadequate. While climate envelope models offer a simplified predictive tool (Cheung et al., 2010), they overlook the intricate dynamics of marine ecosystems. To address this, a trait-based approach is emerging (Gleiber et al., 2024), focusing on key pelagic fish families (Leiognathidae, Clupeidae, Pristigasteridae, Scombridae, Carangidae, Scatophagidae, and Siganidae). These species, pivotal to the marine food web, undergo dietary shifts from plankton to a broader prey base as they mature. By analyzing population trends and feeding habits, we can gain crucial insights into the overall health of the pelagic ecosystem.

Ecosystems are intricate networks where energy flows upward through trophic levels. Anthropogenic activities, particularly overfishing, disrupt these delicate balances, influencing species behavior, population dynamics, and ultimately food web structure. Fishing pressure often targets larger individuals, leading to size-based shifts and reduced biomass transfer (Olsen et al., 2004; Perry et al., 2010). To quantify energy flow, we employed trophic transfer efficiency and biomass residence time as described by Maureaud et al. (2017). These metrics, combined with size-based analyses (Jennings and Collingridge, 2015; McKenzie et al., 2021), provide insights into energy pathways and ecosystem responses. For pelagic systems, dynamic size-spectrum models offer additional tools to understand population dynamics (Law et al., 2009).

Thus, this study aims to integrate trophic dynamic data, climate change trends, and analysis of pelagic fishery, Plankton community, and coastal pollution to identify broader patterns of energy flow and develop a deeper understanding of these pressures, thereby promoting sustainable fisheries management and strengthening ecosystem resilience.

2. Material and methods

The study examined pelagic fishery bycatch data from specific locations between 2019 and 2023 to improve understanding of the pelagic food web along the coastal belts of Sindh and Balochistan, in the northern Arabian Sea. Further, the study determines anthropogenic activities, environmental conditions, and plankton diversity variations on the pelagic fish populations across different geographical areas along the coast.

2.1 Sample collection details

Samples were collected from eight locations along the coast including Jiwani, Gwadar, Pasni, and Sonmiani (Balochistan coast); and Mubarak village, Hawks Bay, Korangi, and Keti Bandar (Sindh coast) (Figure 1). These sites exhibit variations in topography, bathymetry, substrate structure, biodiversity, and anthropogenic activities.

Microplankton were collected using two different nets. A Neuton phytoplankton net, 30 µm mesh size, was towed vertically from the surface to a 100-m depth for 20 minutes. A Bongo zooplankton net: 25 cm mouth diameter, 300 µm mesh size was towed obliquely from the surface to a depth of 100 m for 20 minutes. Duplicate samples were collected at each site, and one sample was preserved in 5% formalin for species identification. The second sample was preserved on ice and later stored in the freezer for metal concentration.

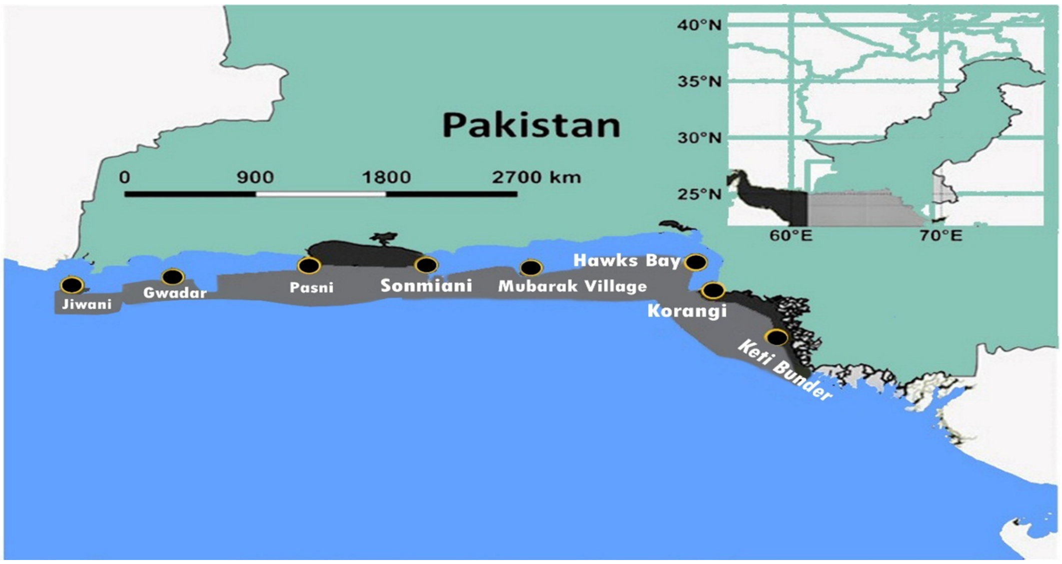

Figure 1. Study sites along Balochistan and Sindh coastlines, northern Arabian Sea.

Fish samples were collected by bycatch using a 100 m long and 60 m wide gill net with a 2.5 cm mesh size. Each trip had a one-hour hauling time. The collected ichthyofaunas were stored in an ice box and retrieved from the CEMB Fisheries laboratory for identification and data analysis.

2.2 Sample processing and identification

All samples were carefully sorted and identified to the lowest taxonomic level possible, using a combination of field identification guides (e.g., Fischer et al., 1990; Carpenter and Niem, 2001; Psomadakis, 2015), online repositories; such as FishBase (www.fshbase.org), SeaLifeBase (www.sealifebase.ca), Google Images (www.images.google.com), bibliographic databases; Google Scholar (www.scholar.google.com), and Web of Science (www.webofscience), were searched, in addition to the original literature. Only 0.2% of the bycatch data were excluded due to taxonomic uncertainties or ambiguous species behavior. We carefully assessed the excluded data for potential biases and ensured minimal impact on the overall analysis.

2.3 Calculation of biomass transformation

The rate of biomass flow between trophic layers in the food web was estimated by assessing the speed of shifting biomass using the production-to-biomass ratio, as described by the empirical equation proposed by Gascuel et al. (2008) and Maureaud et al. (2017) using the formula of

$$(\mathrm{P/B})_{\mathrm{i,j}} = 1.06 \times e^{0.018\times \mathrm{T_j}} \times \mathrm{K}_{\mathrm{i,j}}^{0.75} \tag{1}$$

where P represents production, B represents biomass, $(\mathrm{P/B})_{\mathrm{i,j}}$ represents the speed of shifting or flow between trophic layers, $\mathrm{T_j}$ is the mean temperature, and $\mathrm{K_{i,j}}$ is the von Bertalanffy growth model.

We followed four steps to estimate biomass flow: (i) the trophic transfer efficiency was determined using catch data collected over five years from 2019 to 2023. (ii) We analyzed time-series data on reciprocated factors that influence the ecosystem's trophic layers in the food web. (iii) We investigated the temporal dynamics of these variables and their relationship to variations in fishing and climate conditions. (iv) Finally, we conducted cluster analyses to identify the intervariability inter variability in trends among different ecosystems, grouping those with similar trends. In conclusion, this study provides a comprehensive understanding of ecosystem characteristics and how they change within individual clusters and are influenced by both natural and anthropogenic factors in marine food webs.

2.4 Trophodynamic transformation

The shifting/flow of species-specific values within trophic layers is critically important for the functioning of the food web because it involves different adaptations and variations in the food web structure. To analyze these variations, we examined the tropic spectra based on the total species values per trophic level.

By studying the trophic spectrums, we gained insights into how different species contribute and interact within each trophic level. This analysis helps us understand the energy flow, feeding relationships, and ecological dynamics of food webs. The drift of species-specific values into various trophic layers affects the general stability and complexity of the food web, which also affects how resources and energy are distributed among different organisms.

2.5 Data analysis

Multiple metrics, including average ecosystem parameters, primary productivity, salinity, temperature, and oxygen levels, were employed to evaluate the impacts of climate change. Mean values were used to differentiate between exclusive ecosystems at the different study sites. Cluster analysis was used to group ecosystems with similar characteristics, particularly those that had been most disturbed or damaged (with the highest mean percentage). By employing cluster analysis and integrating various indicators, we identified patterns affected by variables like overfishing and climate change.

2.6 Statistical analysis

Data were analyzed using SPSS version 27, with statistical significance set at $p < 0.05$. The von Bertalanffy growth coefficient (K) was estimated using FiSAT version 1.2.2. Initial data management and organization were conducted in Microsoft Excel 2016 version 2312.

3. Results

The northern Arabian Sea ecosystem underwent significant changes over the five-year study. The physical pa-

Table 1. The average (± STD) physical parameters recorded at various sampling stations along the coasts of Baluchistan and Sindh, northern Arabian Sea.

Year	2019	2020	2021	2022	2023
Temp	27.1 ± 0.53	26.2 ± 0.66	27.4 ± 0.62	26.4 ± 0.44	26.8 ± 0.62
Salinity	32.33 ± 1.18	32.36 ± 1.02	32.37 ± 1.11	32.33 ± 0.08	32.34 ± 1.13
PH	8.45 ± 0.06	8.44 ± 0.06	8.45 ± 0.02	8.43 ± 0.03	8.44 ± 0.04
TDS	31.94 ± 3.02	31.91 ± 3.12	31.89 ± 3.05	31.91 ± 3.18	31.92 ± 3.07
DO	6.36 ± 1.04	6.33 ± 1.06	6.3 ± 1.01	6.32 ± 1.13	6.33 ± 1.04

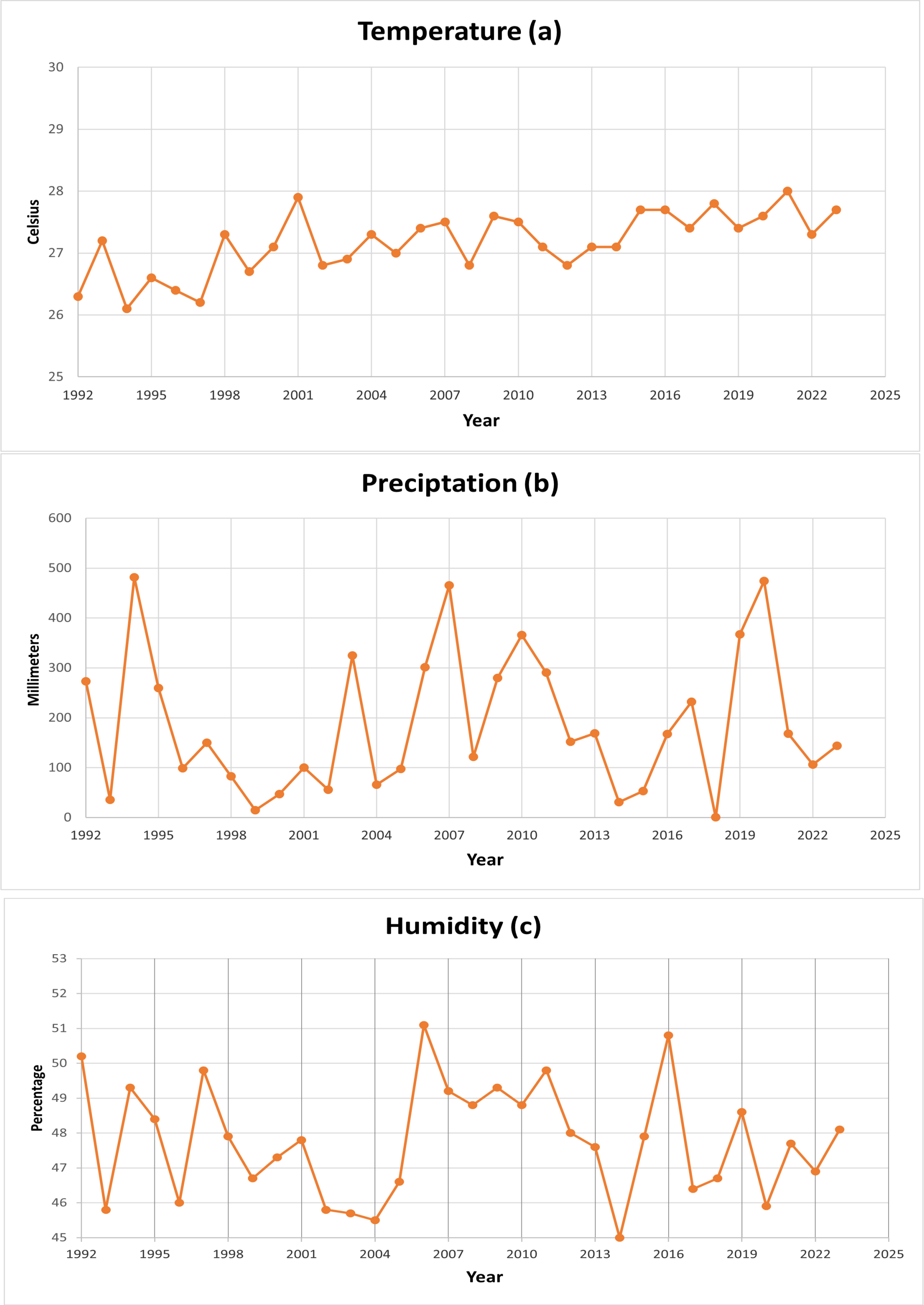

Figure 2. Metrological data spanning 32 years record the essential components of climate influence on the northern Arabian Sea coastal zone.

rameters like mean temperature across was 26.78, with a range of ±1.2°C (Figure 2a). This indicates that over five years temperature has little influence or fluctuates due to climate change. However, a significant variation in seasonal patterns and rainfall was observed radically (Figure 2b,c). This variability may be a major consequence of climate change, but it may also partially offset the effects of climate change on the temperature and salinity

Table 2. Valuable insights into the dynamics of diversity, evenness, richness, and population size in the observed community over five-year period.

Year	2019	2020	2021	2022	2023
Shannon's diversity index	2.36	2.69	3.24	2.48	3.17
Evenness	0.63	0.73	0.75	0.64	0.84
Total number of individuals	416	323	562	432	232
Average population size	10	8.1	14	11	11.1

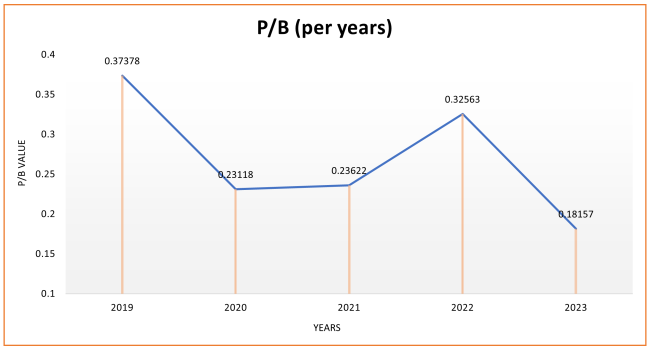

Figure 3. Speed of flow P/B trophic spectrum constructed from catch data.

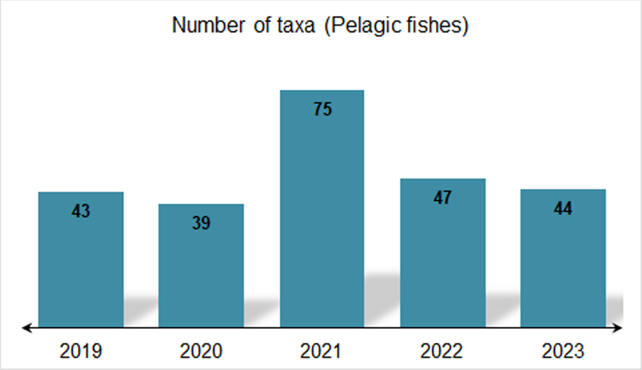

Figure 4. The fluctuations in fish species diversity within the north Arabian Sea over five years were measured using the total annual catch.

range across different trophic levels. The salinity throughout the study remained constant with an average of 32.35 (Table 1). The other parameters, such as pH, TDS, and DO, were 8.442, 31.89, and 6.30, respectively, in the range of ±2.02.

The analysis of the biodiversity data revealed intriguing trends: the Shannon index fluctuated, with diversity peaking in 2021 (3.24) and 2023 (3.17) before dipping in 2019 (2.36). This suggests potential shifts in community composition within ecosystems. Notably, evenness shows a steady increase across years, from 0.63 in 2019 to 0.84 in 2023. This indicates a more balanced distribution of individuals among species, representing potential environmental improvements or community stabilization. The average population size per species generally declined over the study period, with the highest value occurring in 2021 (14) and the lowest in 2020 (8.1) (Table 2). Despite fluctuations in the total number of individuals, this decrease warrants further investigation. Such information and data provide key insights into the interplay between different species and the overall health of the NAS ecosystem.

The P/B ratio varies across the five years, ranging from a high of 0.374 in 2019 to a low of 0.182 in 2023. This indicates changes in the rate of biomass production relative to the existing biomass over the studied timeframe (Figure 3). Higher P/B ratios (such as those in 2019) indicated faster biomass turnover, meaning that new biomass is produced at a higher rate than existing biomass lost. This could be due to factors like rapid growth, favorable environmental conditions, and high reproduction rates. Nevertheless, lower P/B ratios (such as in 2023) showed the opposite turnover, where new biomass production is slower than biomass loss. However, fluctuations in the P/B ratio could be related to various factors, such as the following:

- Variation in environmental factors (e.g., temperature, nutrient availability).
- Variations in species composition and community dynamics.
- Disturbance events (e.g., storms, overfishing).

Furthermore, fish species composition displayed remarkable stability across the five-year study period, with approximately 80–90% species consistency. However, species richness differed significantly from year to year. Biodiversity exhibited inconsistency from a low of 39 species in 2020 to a high of 75 species in 2021 (Figure 4). The overall trend suggests a relatively stable fish community.

The diversity and abundance of primary productions (phytoplankton) in the NAS were very high, with approximately 34 individual species identified. *Ceratiumfurca* was was the most dominant species followed by *Cyclotella*, *Protocentrum*, and *Pyrophacusstenii* at 35%, 29%, 9%, and 2.2%, respectively (Figure 5a). In terms of secondary production (zooplankton), there were 23 identified species in which *Calonoid* were the most abundant, followed by jellyfish, copepods, and amphipods at 49%, 25%, 15%, and 2%, respectively (Figure 5b). The effects of climate change on these ecosystems are much more important in terms of individual-specific species abundance and distribution. Nevertheless, the overall ecosystem of the NAS is diverse and unique, with severe rainfall, minimum oxygen zones, upwelling, and seismic faults. Hitherto, the flow of food energy from one tropic to another is a remarkably eco-balanced system.

Our analysis revealed a statistically significant ($p < 0.05$) increase in the time cumulated indicator (TCI) over the 5-year. TCI values ranged from approximately 0%

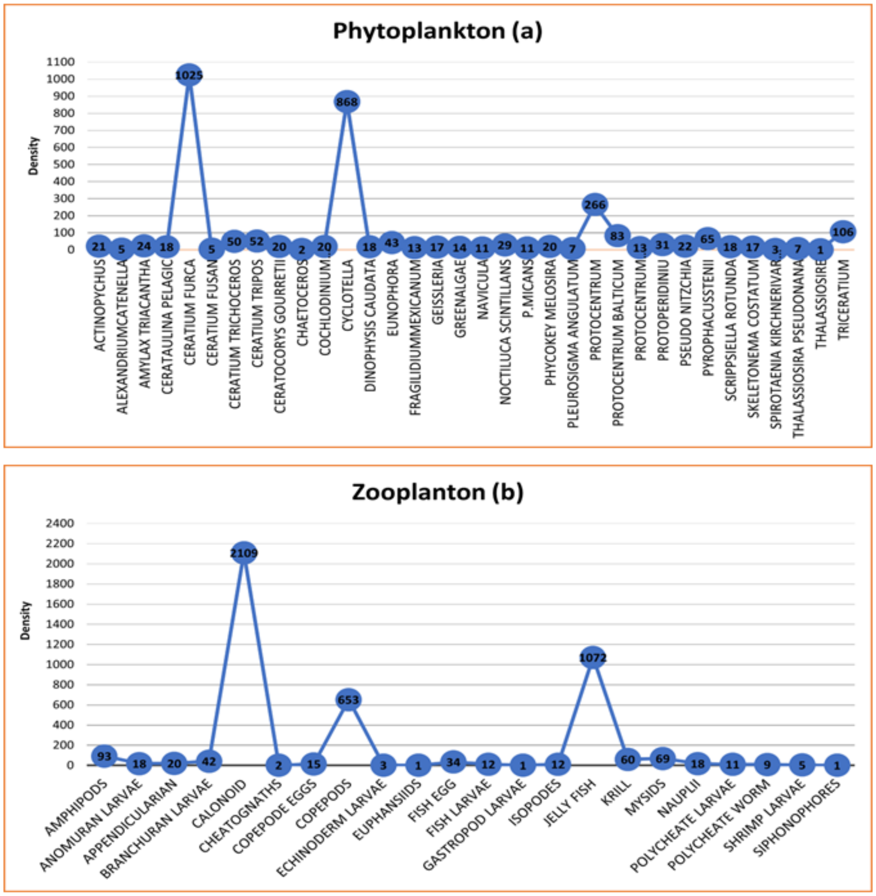

Figure 5. Primary and secondary production, Phyto (a) and Zooplankton (b) biodiversity and their respective abundance within the NAS.

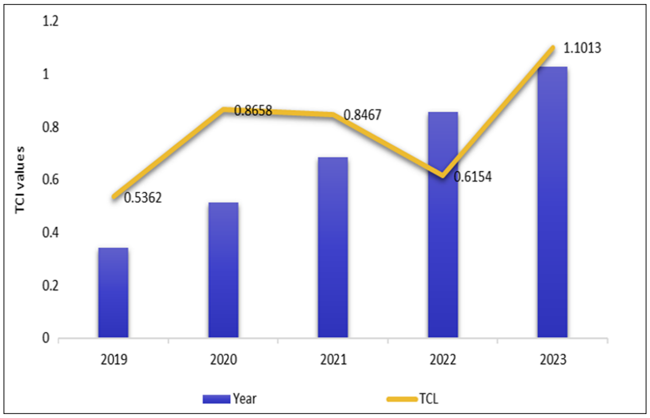

Figure 6. Evaluating the impact of trophic level resistance time on biomass turnover dynamics in ecosystem processes.

to 1.2%, with a gradual upward trend. Residence Time (RT), on the other hand, exhibited fluctuations throughout the span, lacking a clear directional trend (Figure 6). Fluctuations in TCI and RT may be linked to changes in fish population dynamics. Fishing pressure and environmental factors can disrupt predator-prey relationships, influencing energy flow. For example, a decline in predator populations can lead to increased prey biomass and extended residence times within lower trophic levels.

Climate change, manifested in altered rainfall, temperature, and nutrient levels within the NAS, can significantly influence TCI and RT. These environmental shifts impact organism growth rates and feeding behaviors, consequently affecting food web dynamics. Anthropogenic activities further exacerbate these impacts. Generally, higher trophic levels exhibit longer life spans, resulting in elevated TCI values. This is attributed to the cumulative biomass acquired from lower trophic levels over extended periods. For instance, apex predators like cartilaginous fishes (Elasmobranchii) possess substantially higher TCI values compared to their prey due to their longer life spans and accumulated biomass.

4. Discussion

This study represents the first comprehensive synthesis of pelagic fauna assemblages, their vulnerability status, and conservation methods for coastal habitats throughout the region. Five years of sampling in the NAS resulted in 75 individual species with maximum richness of *Ilisha striatula* (40%), *Equulites lineolatus* (25%), *Sardinella longiceps* (22%), and *Karalla daura* (16%). The richness of fishes was comparable to that reported by Li et al. (2023), but the organisms they caught included fish, mammals, reptiles, cetaceans, and birds. Our bycatch results were also similar to those of Gleiber et al. (2024), who caught 529 pelagic fish in a season. According to the study, the special roles that coastal habitats play for these species as breeding grounds, havens, rest stops, and/or feeding locations (Sievers et al., 2019; Lefcheck et al., 2019). Notably, a high diversity of pelagic fauna (*Ilisha striatula*, *Equulites lineolatus*, *Sardinella longiceps*, and *Karalla daura* species) is highly supported by the NAS coastal environments, including coastal waters, soft sediments, and firm bottoms.

In ecosystem functioning, dominant species frequently play key roles. Total biomass is increased by abundant species. Variations in biomass may indicate changes in community composition. A high population density may be a sign of favorable circumstances, such as an abundance of resources. Low density may indicate competition, stress, or habitat deterioration. The specific environmental conditions or health of an ecosystem are indicated by specific species. Their availability or shortage sheds light on ecosystem stability and health. For example, fish, amphibians, and some plants can act as markers of changes in habitats and water quality (Vergés et al., 2014). The combined effects of climate change and human activities on the coastal ecosystem, are the nursery ground for many pelagic fish (He and Silliman, 2019).

Typically, pelagic fish, such as Family Leiognathidae, Clupeidae, Pristigasteridae, Carangidae, Scatophagidae, and Siganidae, are small (average;18 cm in length, 38 g in weight), but some species like *L. equulus*, *A. fasciata*, and *L. splendens*, grow rapidly. In the initial stage, these pelagic species primarily feed on diatoms, copepods, protozoans, and veligers, while in the more mature stage, they prefer copepods, nauplii, lucifers, cirripeds, adult crabs, prawn Mysis, amphipods, polychaetes, fish eggs, algae, cladocerans, and detritus, however, some species exclusively feed on copepods and phytoplankton (Fanelli et al., 2023; Hetherington et al., 2024). Their size and mouth elasticity determine the type of plankton upon which they prey. Usually, small fish consume chlorophyta, copepods, and small crustaceans, while larger fish prey on polychaetes, amphipods, and detritus (Fanelli et al., 2023). A seminal study by Farooq et al. (2017) characterized feeding strategy and potential competition in marine species revealing a significant diet overlap attributed to monsoon-induced changes, which play a crucial role in influencing temperature, migration patterns, and the abundance of fish and shellfish in the northern Arabian Sea ecosystem.

Climate change significantly affects marine ecosystems, changing their physical and chemical makeup. Temperature variations, ocean acidification, hypoxia, shifts in species range, coral reef decline, sea level rise, extreme events, impacts on fisheries and communities, and overfishing threaten fish stocks. Climate change disrupts marine ecosystems, causing shifts in fish distribution. This threat not only threatens marine biodiversity but also the livelihoods and cultural practices of fishing communities, including those that rely on subsistence fishing methods and indigenous customs. These zones (the coastal ecosystem of Hawks Bay) are rapidly deteriorating due to a confluence of natural and human-induced factors, such as extreme weather events, rising sea levels, and metal pollution and these factors disrupt the food chain across multiple trophic levels, affecting organisms from base to the apex of the food web (Jan et al., 2022). Urgent mitigation efforts are crucial to protecting our oceans and the life they sustain. By monitoring these changes, we can gain critical insights into conservation strategies and advocate for stricter regulations.

Multiple studies have demonstrated that trophodynamic indicators can be used to assess the impacts of fisheries and ecosystem changes (Cury et al., 2005). The study further highlights the utility of marine ecosystem indicators in supporting an ecosystem approach to fisheries and facilitating international comparisons. The study of Walumona et al. (2024) reported a low trophic transfer efficiency (6.4%–0.49%), based on a 3-year dataset. However, our study, with its comprehensive and up-to-date data, provides a more robust approach to ecological network analysis. This analysis is essential for evaluating the ecological functioning of the system in the context of climate change and anthropogenic activities. Climate change can impact fisheries species at various life history stages, such as spawning and feeding (Eduardo et al., 2024), which are often characterized by distinct environmental preferences. For instance, changes in temperature and precipitation patterns can alter the distribution and abundance of prey species, affecting the feeding success of fisheries species. Similarly, shifts in ocean currents and temperature can impact spawning success and larval development. Additionally, variations in water quality can influence the phenotypic characteristics of fish populations (Kashani and Panhwar, 2023), while environmental variation can affect marine organisms' biodiversity and population (Kachhi et al., 2024). Understanding these stage-specific responses to climate change is crucial for predicting population-level impacts and developing effective management strategies. Furthermore, the heterogeneous distribution of fisheries areas throughout the annual cycle can lead to bias in the analysis (Zhai et al., 2024). To address these limitations, future studies could employ more advanced statistical models that explicitly account for the spatial and temporal structure of the data. Moreover, integrating independent data sources, such as fisheries-independent surveys or remote sensing data, could help reduce errors and provide a more comprehensive understanding of the relationships between fisheries species and their environment.

Plankton abundance exhibited a 12% fluctuation during the study period (2019–2023), comparable to findings by Panhwar and Mairaj (2022). While our species-based model offers valuable insights into overall fishery fluctuations in the NAS unknowingly their complete contribution to the ecosystem. Besides, the species-based model provides valuable information about the overall fishery in the NAS, allowing us to track these fluctuations in tandem with global changes. The Arabian Sea, with its unique characteristics, hosts one of the most intense open ocean Oxygen Minimum Zones (OMZs). This perennial OMZ significantly impacts adjacent coastal fisheries and ecosystems. However, the fate of the Arabian Sea, OMZ under climate change scenarios remains elusive. Recent research has indicated that the Arabian Sea OMZ is projected to shrink due to climate change (Vallivattathillam et al., 2023). Deoxygenation in the northern Arabian Sea may alter the distribution and behaviors of pelagic fish. Reduced oxygen levels can impact fish physiology, migration patterns, and reproductive success. However, to investigate the consequences of global change and the NAS eco-modal paradigm, this research focused on the impact of climate change and the critical role of plankton and fish resources. Phytoplankton, the base of the food chain enriches the environment and provides carbon to higher trophic levels, especially during blooms (Trombetta et al., 2020). Additionally, it makes a major contribution to dissolved organic carbon through cell death and exudation (Dafner and Wangersky, 2002). This pool of organic matter is further supported by grazer cross-feeding, which promotes the growth of bacteria and phytoplankton (Morris et al., 2013). Elevations in water temperatures tend to favor heterotrophic flagellates and smaller phytoplankton, impeding the effective transfer of energy to higher trophic levels (Peter and Sommer, 2012; Moustaka-Gouni et al., 2016). This warming triggers trophic cascades, shifting control from bottom-up (nutrient-driven) to top-down (predator-driven) regulation within the food web. Warmer temperatures increase microbial respiration, oxygen consumption, and grazing rates (Chen et al., 2012). These modifications affect the composition and operation of microbial networks, which may have an impact on the flow of energy to higher levels during and after bloom (Aberle et al., 2012). The main types of plankton in the NAS are dinoflagellates, diatoms, and algae. They use various feeding methods, including autotrophic, heterotrophic, and phagotrophic, to ingest pico- and nanoplankton (Kamiyama, 2015). They are important to both the open ocean's intricate microbial food web and the simpler classical food web of coastal regions. In spite of the secondary producer's microzooplankton populations can reach millions of individuals per litter under favorable conditions, they are often associated with specific co-existing species or blooms (Asha Devi et al., 2024). Microzooplankton Jellyfish abundance or blooms can vary significantly due to many factors, such as seasonal changes, nutrient availability, and environmental conditions (Gibbons and Richardson, 2009). Similarly, copepods and amphipods, two types of microcrustaceans, appear to be more prevalent in the NAS food web. Their ability to adjust to shifting food availability is impressive (D-Alelio et al., 2016). Although there has been a long history of microbial research in marine food webs (Shao et al., 2023), most of the data are still insufficient to fully understand the ecosystem. Wetzel et al. (1972) proposed a general model that emphasizes the importance of microorganisms in natural water and demonstrated how they utilize primary production to shape pelagic ecosystems. Compared to a simple food chain, the relationships between plankton in a food web are more intricate. In contrast to the number of top predators in a linear food chain, the hierarchical structure of the food web produces fewer top predators. Dissolved Organic Material (DOM), which higher species cannot directly use, is consumed by bacteria within the microbial loop. DOM is made up of the cytoplasm released from phytoplankton cells and liquid waste from zooplankton (Reiss et al., 2009). Microflagellates and ciliates feed on bacteria and zooplankton then consume these smaller drifting organisms, recycling organic matter back into the marine food web. A symbiotic relationship exists between phytoplankton and bacteria, as bacteria facilitate growth and survival by leaching nutrients into the ecosystem. Besides viruses, plankton are the second most abundant microorganisms that produce DOM and release nutrients into marine life (Stawiarski et al., 2016). Water currents, depth, seasonality, and temperature significantly influence plankton communities (Shi et al., 2020). Our study in the NAS confirmed this, with seasonal rainfall (monsoon) exerting a pronounced impact on salinity, turbidity, and dissolved oxygen, which in turn affected plankton composition. Understanding the intricate interplay between plankton, pelagic fish, and environmental factors is crucial for effective conservation and management of the NAS ecosystem.

The ocean's future health hinges on our ability to navigate this intricate interplay of factors. By integrating long-term monitoring, advanced modeling techniques, and interdisciplinary collaboration, we can enhance our ability to predict and mitigate the impacts of climate change and human activities on this vital marine ecosystem.

5. Conclusion

Climate change is fundamentally altering marine ecosystems, with profound implications for fish communities and fisheries. Understanding these community-level impacts is crucial because they influence how the food web functions and ultimately determine fisheries yield. By providing a comprehensive assessment of pelagic fauna in the NAS, we highlight the need for a holistic approach to understanding and mitigating these impacts. Our research underscores the synergistic effects of climate change and human activities, such as overfishing, on the structure and function of marine food webs. By understanding these phenomena, we can gain a deeper understanding of the entire marine ecosystem and develop more effective conservation strategies. The findings illuminate the current state of marine ecosystems and the potential consequences of combined changes on the efficiency and stability of food webs at a broader scale.

Acknowledgments

The Higher Education Commission of Pakistan (HECP) is greatly acknowledged for funding under NRPU-17461 to SKP.

Author Contribution Statement

IK conducted the sampling, data handling, species identification, and writing and editing original draft; SKP contributed to the study conception, funding acquisition, and project administration and edited the subsequent draft of the manuscript; and KKK contributed to the sampling data interpretation and discussion.

Conflict of interest

None declared.

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