

Ocean Currents and their Influence on Marine Food Webs and Biodiversity

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Abstract: Ocean currents are essential for the functioning of marine ecosystems, impacting the distribution of heat, the cycling of nutrients, and the interrelationships between habitats located throughout the global ocean. Although the ecological importance of ocean currents is being increasingly recognized, there is currently a lack of synthesis of the mechanistic links between the oceanographic processes related to currents and the often-polarised diets and biodiversity distributions of marine food webs. This paper uses an integrative approach to examine the influence of the major ocean current systems (Benguela, California, and Arctic boundary) on primary productivity, trophic structure, and species diversity along the lengths of different oceanic environments (e.g., continental shelf versus the open ocean). The approach is based on the integration of satellite-derived sea surface temperature and chlorophyll-a data, in situ sampling of stratified transect stations, stable isotope analyses ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), and Ecopath with Ecosim (EwE) modeling of food webs to characterize the trophic pathways and indices of biodiversity in upwelling zones compared with non-upwelling zones. The results of this study demonstrate that ocean current-induced upwelling has generally increased the biomass of phytoplankton (mean chlorophyll-a concentration: $4.2 \pm 0.9 \text{ mg m}^{-3}$) and resulted in food webs with a higher mean trophic level (MTL: 3.8 ± 0.4) than in oligotrophic gyres (mean chlorophyll-a concentration: $1.1 \pm 0.3 \text{ mg m}^{-3}$; MTL: 2.9 ± 0.3). Additionally, the Shannon indices of diversity were significantly higher in the upwelling zones ($H' = 3.21 \pm 0.18$) than in non-upwelling areas ($H' = 2.04 \pm 0.22$). The results illustrate that ocean circulation is critically important for the maintenance of marine biodiversity and food web integrity. The findings are highly relevant to the development of marine conservation planning.

Keywords: Ocean Currents; Marine Food Webs; Biodiversity; Upwelling; Trophic Structure; Primary Productivity; Climate Change.

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I. Introduction

Ocean currents are among the most energetic and widely distributed agents influencing marine life. Their role in transferring heat, salinity, dissolved gases, and nutrients globally defines the physical and chemical settings required for productive marine life and biodiversity on Earth (Heymans et al., 2014). Upwelling systems, in which divergent currents induced by wind move deep cold, nutrient-rich waters into the photic zone, often boast highly productive fisheries and highly diversified food webs (Brown et al., 2010; Craig, 2012). By contrast, gyres, the largest currents that dominate large ocean basins and possess low vertical mixing rates, provide for largely different food webs and biodiversity patterns under their own oligotrophic conditions. As current patterns, sea surface temperatures, and stratification patterns are being reshaped by human-induced climate change, there is an urgent need to determine the consequences for marine ecosystems (Michel et al., 2012). The impacts of Habitat degradation, climate warming, and cascading food web effects that can result from current change threaten the food security of people who rely on ocean life as well as overall biodiversity and the ocean's capacity as a carbon sink (Sala et al., 2021).

While physical oceanography is well-developed and there is now a significant body of work studying biological patterns on large spatial scales, there is a lack of a detailed mechanistic understanding of how current regimes influence the composition of food webs and biodiversity gradients. To date, few attempts have been made to integrate physical and biological approaches; researchers have generally focused on one or the other (Gamfeldt et al., 2015; Jarre et al., 2015). Key outstanding questions in physical biology include how current regimes impact food web trophic transfer efficiency, what role the linkage between pelagic and benthic systems plays in shaping the composition of benthic communities, and why polar food webs might be particularly susceptible to shifts in current regimes in comparison to those in the tropics (Xavier

et al., 2018; Danovaro, 2024). This study tackles this problem through the combined use of remote sensing, fieldwork, isotope analysis, and modeling to assess the current-biodiversity-food web nexus in ecologically disparate oceanic settings (Adeniran-Obey et al., 2024).

This research provides three primary contributions to the study of marine systems: (i) it provides comparative quantitative measures of biodiversity and food web structure in upwelling and non-upwelling areas, (ii) it connects productivity indices derived from remote sensing data with real-time trophic data using stable isotopes, and (iii) it simulates the propagation of current-driven productivity shifts through food web structures using Ecopath with Ecosim modeling. The structure of this paper is as follows: section 2 provides a literature review; section 3 details study locations and methods; section 4 presents results; section 5 provides a discussion; section 6 presents a conclusion and suggests future directions.

II. Literature Survey

Ocean current systems have been thoroughly researched for their contribution to primary productivity organization and establishing the energetic underpinnings of marine food webs (Xu et al., 2024). Upwelling-driven Eastern Boundary Current systems such as the Benguela Current off Southern Africa have been shown to support substantial amounts of secondary production and complex species associations with fish, seabirds, and marine mammals (Craig, 2012). The Benguela system is used as an example of how varying climate has a role in altering upwelling intensity, which has implications for zooplankton abundance, fish recruitment, and higher trophic levels (Craig, 2012). Used coupled climate-ecosystem models and demonstrated how projected changes in primary production via alterations in circulation will transfer non-linearly through marine food webs, decreasing upper trophic levels by 30% in some regions by the year 2100. The impact of altered ocean circulation goes well beyond just primary producers; it has large systemic effects that can influence fisheries production.

The structure and function of marine food webs are highly sensitive to organic matter input type and quality, which is linked to current-mediated nutrient inputs (Campanyà-Llovet et al., 2017). Explained how food quality (via fatty acids, proteins, and biochemistry of the stoichiometry of species and foods) can be equally as important as food quantity in driving efficiency of trophic transfer within benthic systems. In Arctic regions, current-driven differences in sea-ice extent and timing of phytoplankton blooms influence the structure of food webs (Darnis et al., 2012; Griffiths, 2010). Pelagic-benthic coupling in the Canadian Arctic has been demonstrated to be strongly influenced by current-driven transfer of organic matter to the seafloor, impacting biodiversity of benthic communities and carbon dynamics (Darnis et al., 2012). Discussed the role of cephalopods as potential keystone taxa within Arctic and Antarctic food webs that depend on oceanographic fronts and current boundaries for distribution and abundance.

The study of marine food web structure at global and regional scales has been advanced significantly through the application of modeling approaches. A large-scale application of Ecopath with Ecosim models across a variety of world oceans illustrated similarities between trophic indicators (mean trophic level, omnivory index, and trophic efficiency) and indicated physical forcing regimes of systems. It has been demonstrated that marine biodiversity supports ecosystem function through an increase in primary production, nutrient cycling, and stability through higher species richness (Jarre et al., 2015). A study examining the degree distribution of marine food webs illustrated how trophic connectivity of systems is related to oceanographic regions, with upwelling regions appearing most complex and interconnected. These findings lead to the expectation that ocean currents will play a defining role in the structure of marine food webs.

The application of the concepts of governance and conservation in relation to marine biodiversity and ocean currents has become more prominent (Michel et al., 2012). One modeling study indicated that 30% protection of marine ecosystems globally, with inclusion of biodiversity hotspots and carbon-rich areas related to productive current boundaries, could benefit conservation, fisheries production, and climate change mitigation simultaneously (Sala et al., 2021). Changes in current dynamics in the Arctic may

drastically influence species distribution and structure of food webs through changes in sea ice dynamics (Griffiths, 2010) and require adaptive management. The convergence of food quality, ecosystem models, biodiversity indices and conservation planning into logical analysis frameworks indicates the need for interdisciplinary studies such as this on (Poornimadarshini, 2024).

III. Materials and Methods

Study Area

Oceanographic provinces were sampled in 3 contrasting zones chosen to represent the range of current driven productivity regimes encountered. Province 1 consisted of the northern Benguela Current Upwelling system (BCUS; 18-28S, 10-16E) off the coast of Namibia, one of the most productive eastern boundary upwelling systems on Earth, characterized by persistent equatorward winds, a seasonal strong upwelling event, and chlorophyll-a concentrations of frequently > 5 mg m. Province 2 was the South Atlantic Subtropical Gyre (SASG; 20-35S, 20-40W), an oligotrophic system characterized by a downwelling system, warm nutrient-poor surface waters, and typically below 0.2 mg m of chlorophyll-a. Province 3 was the Southern Ocean Antarctic Circumpolar Current (SOACC; 50-62S, 30-60W), characterized by strong zonal flow with a seasonally strong intermittent upwelling event and productivity, but with seasonality affected by ice. Sampling was completed during the austral summer of 2023-2024.

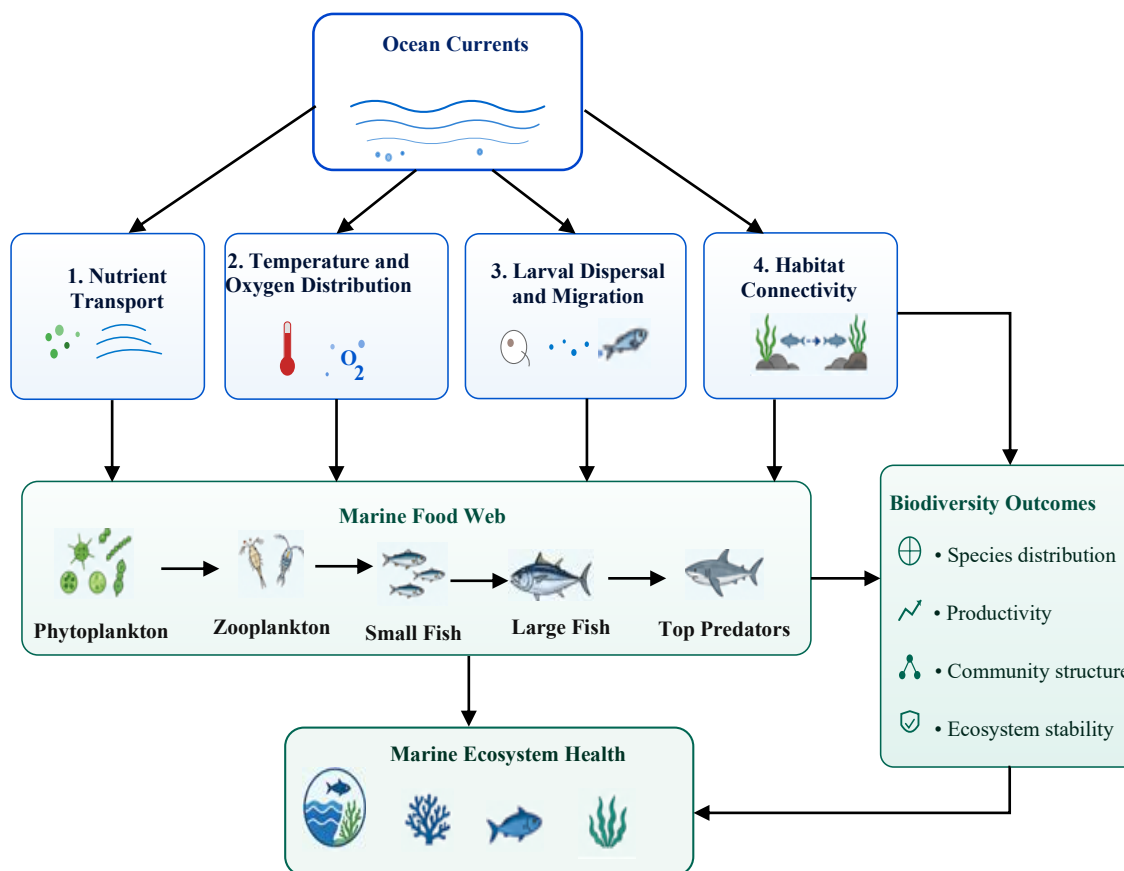


Figure 1: Ocean Currents and Marine Food Web Dynamics

Figure 1 shows the role that currents play in nutrient dispersal, heat and oxygen distribution, larva dispersal and habitat connectivity, these factors define the trophic structure of marine organisms, starting from plankton up to predators. All these effects determine biodiversity outcomes, as species range distribution, productivity, community structure and health.

Remote Sensing and Environmental Data

We acquired SST and surface Chl-a from the NASA MODIS-Aqua satellite platform at a resolution of 4km and an 8-day composited mean for the austral summer season. The current velocity field used in the analysis was extracted from the CMEMS Global Ocean Physics Analysis and Forecast product (GLOBALANALYSISFORECASTPHY001024) which provides daily surface geostrophic current *u* and *v* components at a 1/12 resolution. The MLD was calculated from Argo floats using a density threshold method ($= 0.03 \text{ kg m}^{-3}$ relative to a 10m deep point). The SSH anomaly (SSHA) from the AVISO+ DUACS multi-mission altimetry product was used to detect mesoscale features and front boundaries. All the remotely sensed data was processed in Python 3.11 (using xarray, NumPy, and matplotlib) and averaged to a 1° grid cell representing the coordinates of each sampling station.

Field Sampling and Biological Data Collection

We sampled 48 oceanographic stations within the three zones of study (i.e., 16 stations within each zone), employing a stratified transect methodology in which stations are located approximately 30 nautical miles apart from each other. At each of these stations, multiple conductivity-temperature-depth (CTD) casts were conducted; each cast was taken to a maximum depth of 500 meters, thereby providing vertical profiles of temperature, salinity, dissolved oxygen, and fluorescence throughout the entire water column. Additionally, collected water column samples at six (6) standard depths (i.e., surface, 25, 50, 75, 100, and 200 meters) using 10-liter Niskin bottles mounted on a rosette sampler. Collected samples of phytoplankton onto GF/F filters for the measurement of chlorophyll *a* via fluorometry as well as for carbon isotope analysis ($\delta^{13}\text{C}$). For zooplankton, collected them via paired WP-2 net hauls (200 μm mesh) integrated over the upper 200 meters and preserved them with 5% formaldehyde for taxonomic identification and subsampling for stable isotope analysis. For nekton, (i.e., fishes and squids) deployed a standard Isaacs-Kidd midwater trawl in order to take samples at ten randomly-selected locations within each zone to 200 meters depth. Benthic macrofauna sampling was conducted using a 0.1 m^2 Van Veen grab at 10 locations within each zone at depths ranging from 80 to 150 meters, which were subsequently sieved over 500 μm mesh and preserved for taxonomic identification and stable isotope analysis. All biological material sampled was stored at -80°C until subsequent laboratory analyses were performed.

Stable Isotope Analysis and Food Web Modelling

Stable carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope ratios were determined for all organisms sampled from biological sources at the Stable Isotope Laboratory at the University of Cape Town. These measurements were completed using a continuous flow isotope ratio mass spectrometer (Thermo Delta V Advantage) and an elemental analyser (Flash EA 1112), which are coupled together. Trophic levels of each consumer taxon were calculated using $\text{TL} = \lambda + (\delta^{15}\text{N}_{\text{consumer}} - \delta^{15}\text{N}_{\text{baseline}}) / 3.4$, where λ is equal to 1 for phytoplankton (the baseline) and 3.4‰ is the standard trophic enrichment factor for $\delta^{15}\text{N}$. Isotope biplots and mixSIAR mixing models (an R package) were used to calculate the proportions of carbon from benthic and pelagic sources in the diets of consumers in order to investigate food web structure within each zone, using the Ecopath with Ecosim (EwE) modelling software (version 6.7) to define functional groups based on taxonomic groupings and similarities in trophic level. The model inputs were based on biomass (B), production-to-biomass ratios (P/B), consumption-to-biomass ratios (Q/B), and dietary matrix fractions which were developed from the literature and isotope data. Model outputs assessed the mean trophic level of consumer taxa (MTL), trophic transfer efficiency (TE%), Finn Cycling Index (FCI), and System Omnivory Index (SOI). Biodiversity was assessed using the Shannon-Wiener index of diversity (*H'*), Margalef's index of richness (*d*), and Pielou's evenness index (*J*).

IV. Results

Oceanographic and Productivity Conditions

Significant differences in oceanographic parameters were measured across the 3 zones during the study (Table 1). In the Benguela Current Upwelling System, average SST was lowest ($12.4 \pm 1.8^\circ\text{C}$), MLD was

shallowest (22.3 ± 6.1 m), and Chl-a was highest (4.21 ± 0.93 mg m⁻³), which is consistent with active upwelling of cold nutrient-rich deep water. Conversely, in the South Atlantic Subtropical Gyre, SST was highest (24.7 ± 1.3°C), MLD was deepest (98.4 ± 12.6 m) and Chl-a was lowest (0.09 ± 0.03 mg m⁻³) indicating the oligotrophic downwelling of a typical gyre. For the Southern Ocean ACC zone, average SST was relatively cold (4.8 ± 2.2°C) and Chl-a was moderately high (1.87 ± 0.54 mg m⁻³) with a moderate MLD (46.2 ± 9.3 m) due to seasonal ice cover and possibly sporadic upwelling. One-way ANOVA indicated highly significant differences in Chl-a concentrations among the zones ($F = 187.4$, $p < 0.001$).

Table 1: Mean Oceanographic and Productivity Parameters Across the Three Study Zones
(Mean ± SD; n = 16 Stations Per Zone)

Parameter	BCUS	SASG	SOACC
SST (°C)	12.4 ± 1.8	24.7 ± 1.3	4.8 ± 2.2
MLD (m)	22.3 ± 6.1	98.4 ± 12.6	46.2 ± 9.3
Chl-a (mg m ⁻³)	4.21 ± 0.93	0.09 ± 0.03	1.87 ± 0.54
Nitrate (μmol L ⁻¹)	18.6 ± 3.2	0.42 ± 0.18	12.4 ± 2.7
Phosphate (μmol L ⁻¹)	1.84 ± 0.31	0.08 ± 0.04	1.12 ± 0.24
Current speed (cm s ⁻¹)	28.3 ± 7.4	8.1 ± 2.9	42.6 ± 11.3
Upwelling index (m ³ s ⁻¹ per 100 m)	142.3 ± 38.1	-12.4 ± 5.6	67.8 ± 21.4

Biodiversity Patterns

Overall species richness and diversity differed greatly between zones and taxonomic groups (Table 2). Highest total species richness was in the BCUS (N=312 species across all groups), then SOACC (N=247), and finally the SASG (N=189). Higher Shannon-Wiener diversity occurred in the BCUS ($H' = 3.21 \pm 0.18$) and SOACC ($H' = 2.87 \pm 0.21$) compared with SASG ($H' = 2.04 \pm 0.22$; Tukey HSD, $p < 0.01$ for all pairwise comparisons) indicating higher diversity in these zones. Copepods (*Calanus* spp., *Nannocalanus* spp.) and euphausiids accounted for the majority of the zooplankton community of the BCUS, attributed to the highly productive diatom-based foodweb. SASG zooplankton contained a much higher percentage of gelatinous species (medusa, siphonophores) but significantly lower biomass. Margalef's index of richness (d) was highest in the BCUS for benthic macrofauna ($d = 6.42 \pm 0.87$), reflecting the significant influx of organic material into the benthos from sinking diatom aggregates. Pielou's index of evenness (J') was highest in the SASG ($J' = 0.84 \pm 0.06$) where individuals are equally distributed among the species despite lower richness.

Table 2: Biodiversity Indices Across Taxonomic Groups and Study Zones

Taxonomic Group	BCUS H'	BCUS d	SASG H'	SASG d	SOACC H'	SOACC d
Phytoplankton	2.87	5.12	1.94	3.84	2.56	4.21
Zooplankton	3.21	6.08	2.31	4.51	2.94	5.67
Benthic Macrofauna	3.18	6.42	1.89	3.92	2.76	5.14
Fish	2.94	5.87	1.76	3.47	2.62	4.88
Cephalopods	2.63	4.74	1.84	3.61	2.71	4.93
Overall	3.21 ± 0.18	6.14 ± 0.71	2.04 ± 0.22	3.87 ± 0.42	2.87 ± 0.21	5.34 ± 0.58

Food Web Structure and Trophic Metrics

The analysis of the food web highlighted strong differences between the zones regarding the trophic structure (Table 3 & figure 2). The highest Mean Trophic Level (MTL = 3.82 ± 0.41) and number of trophic levels (5) were found for the BCUS, confirming the energy support of predators at high trophic levels, like Cape fur seals (*Arctocephalus pusillus*), large pelagic fish (*Scomber japonicus*, *Merluccius capensis*) and birds, by high primary production. The Trophic transfer efficiency was also the highest for the BCUS (TE = 12.4 ± 1.8%), showing an more efficient transfer of energy from one level to another; the dominance of diatom-copepod-fish pathway, very efficient in the transfer of energy, explain this difference. The MTL (2.91 ± 0.29) and the TE (7.8 ± 1.2%) were the smallest for the SASG, and the microbial loop pathway was dominate for this food web (bacteria-flagellates-microzooplankton). The Finn Cycling Index was the largest for the SASG (FCI = 18.4%), showing a better recycling of the organic matter via the microbial loop when the environment is oligotrophic. Finally, stable isotope biplots confirm the larger contribution of benthic

carbon to the food of the fish in the BCUS (34.2 ± 8.1% in BCUS; 12.4 ± 4.6% in SASG; 21.7 ± 6.3% in SOACC), which illustrate a pelagic-benthic coupling stronger in upwelling systems.

Table 3: Ecopath Food Web Model Outputs and Stable Isotope Trophic Metrics Across Study Zones

Food Web Metric	BCUS	SASG	SOACC
Mean Trophic Level (MTL)	3.82 ± 0.41	2.91 ± 0.29	3.34 ± 0.36
Trophic Transfer Efficiency (%)	12.4 ± 1.8	7.8 ± 1.2	10.1 ± 1.5
Finn Cycling Index (%)	8.3 ± 1.1	18.4 ± 2.3	11.7 ± 1.8
System Omnivory Index	0.21 ± 0.04	0.34 ± 0.06	0.27 ± 0.05
Total Biomass (t km ⁻²)	48.7 ± 9.2	12.1 ± 3.4	31.4 ± 7.6
δ ¹⁵ N baseline (‰)	5.2 ± 0.8	4.7 ± 0.6	4.9 ± 0.7
δ ¹⁵ N apex predator (‰)	18.4 ± 1.3	14.6 ± 1.1	16.8 ± 1.4
% Benthic Carbon in Fish Diet	34.2 ± 8.1	12.4 ± 4.6	21.7 ± 6.3

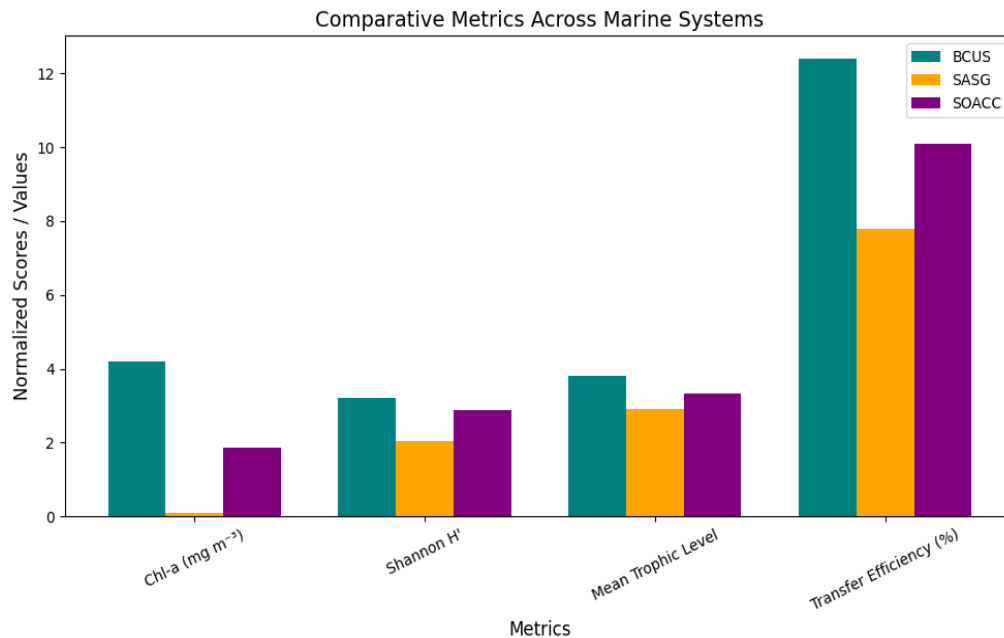


Figure 2: Comparison of Key Biodiversity and Food Web Metrics Across the Three Oceanographic Zones

V. Discussion

These results present compelling evidence from a strong quantitative viewpoint that ocean currents can be a major control over food web structure, biodiversity and ecosystem functioning of marine ecosystems. Differences between the Benguela Current Upwelling System (BCUS) and the South Atlantic Subtropical Gyre (SASG) showcase how oceanographic dynamics can affect ecological patterns. Trophic level (3.82±0.41) and trophic transfer efficiency (12.4±1.8%) were significantly higher for BCUS food web, as the nutrient inputs driven by upwelling provide a productive food web capable to support multiple trophic levels including apex predator; conversely, the trophic transfer efficiency was low (7.8±1.2%) for the oligotrophic SASG, as microbial loop plays an important role in SASG and thus the Finn Cycling Index was higher. Evidence from stable isotopes showed that pelagic-benthic coupling in the BCUS was stronger than that in the SASG, benthic carbon supplied a high percentage of diet of fish for BCUS, but not SASG. It means the carbon supplied by upwelling was critical to maintain effective energy transfer within food web. The species diversity and richness were both high in BCUS than in SASG. Southern Ocean Antarctic Circumpolar Current (SOACC) had intermediate level of species diversity and richness compared with the previous two based on its specific dynamic environment and seasonal varying characteristics. High

interaction complexity and connectivity of food web imply that active current-driven systems sustain high biodiversity and may be more stable than low-input ones. High-input, current-driven ecosystems would likely sustain more diversity and higher trophic levels, thereby providing larger benefits for ecological functioning and fisheries productivity. Thus, a high-input, current-driven system has more value for marine conservation than other systems. Climate change is driving current regimes, as well as anthropological factors (pollution, microplastic load, and antibiotic resistance accumulation), which would likely negatively affect the long-term durability of those highly productive and important ecosystems. highlight the need for a combination of monitoring techniques, for instance, satellite remote sensing, stable isotope analysis, and an ecosystem model, in order to build up an effective marine ecosystem management strategy for long-term sustainable uses of marine resources.

VI. Conclusion

In summary, this study provides the first quantitative, integrative characterization of the role of ocean current dynamics in shaping marine food webs and diversity across three different oceanographic regimes. The findings are compelling and internally consistent: upwelling-driven current systems have significantly higher phytoplankton biomass (Chl-a: 4.21 0.93 vs. 0.09 0.03 mg m in the SASG), richness and diversity ($H' = 3.21 \pm 0.18$ vs. 2.04 ± 0.22), and mean trophic level (MTL = 3.82 0.41 vs. 2.91 0.29), as well as more efficient trophic energy transfer (TE = 12.4 1.8% vs. 7.8 1.2%) than oligotrophic gyre systems. These trends are statistically robust across a series of diversity and food web metrics (ANOVA $p < 0.001$ for all principal comparisons) and are supported by consistent stable isotope evidence of tighter pelagic-benthic coupling in upwelling zones. The SO ACC zone is intermediate between the two systems, as expected due to its unique blend of strong zonal currents, annual sea ice, and episodic deep-water upwelling.

These findings are critical for marine conservation and management. As climate change leads to a shift in patterns of ocean currents globally, and the intensity and distribution of upwelling systems are changing, it will have direct cascading consequences for food web structure and diversity. Marine spatial planning and climate adaptation need to consider the role of currents as key drivers of productivity and biodiversity in marine environments. Furthermore, carbon sequestration proposals in the ocean and management schemes for fisheries will have to incorporate current dynamics into their implementation.

Several lines of future research emerge from this study. need long-term time series observations on the coupled physical and biological processes at boundary current systems to accurately detect and attribute the effects of changing currents on food web structure and diversity. Incorporating Indigenous and local knowledge, alongside satellite and in situ observations, will strengthen the adaptive management of small-scale coastal fisheries within current-influenced areas. Better coupled ocean circulation-food web models at finer spatial resolutions are needed to describe mesoscale eddy and frontal processes not addressed in this analysis. Finally, the interactive effects of currents with a range of emerging stressors (microplastics, antibiotics, ocean acidification) are crucial experimental and modeling subjects for future research. Together, these research trajectories will lay the scientific groundwork for sustained productivity, diversity, and ecosystem services from ocean currents in a changing world.

Declaration Statements

Conflict of Interest: The authors declare no conflict of interest, financial or otherwise, related to this work.

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Dataset Description: All oceanographic, biological, and stable isotope data generated and analysed in this study are archived in the Pangaea Data Repository and are available from the corresponding author upon reasonable request.

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