

Article

Structure and Spatio-Temporal Dynamics of Marine Communities Associated with the Kelp Forests at Cape Froward, Strait of Magellan

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Abstract

Giant kelp forests, *Macrocystis pyrifera*, dominate the coasts of southern Patagonia and are particularly abundant in the coastal ecosystems of Cape Froward, where they play a key role in biodiversity conservation and the provision of multiple ecosystem services, establishing themselves as one of the most resilient kelp forest ecosystems on the planet. This study constitutes one of the first spatiotemporal assessments of the diverse components inhabiting kelp forests in the Strait of Magellan (Cape Froward). In total, 238 taxa belonging to zooplankton, benthic invertebrates, fish, and understory of macroalgae inhabiting the understory were identified in these ecosystems, including species that are key to the coastal communities of the Magellan region. In general terms, the results show that the coastal ecosystems of Cape Froward support highly diverse, dynamic, and complex communities, with characteristics representative of ecological systems of regional and global significance. In this regard, the present study provides a solid scientific basis for promoting conservation measures for these ecosystems at the southern tip of Patagonia.

Keywords: Patagonia; Magellan region; *Macrocystis*; foundational species; biodiversity; marine conservation

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1. Introduction

Strait of Magellan (54° S) is the result of a series of geodynamic, tectonic, and glacial events that affected southern South America during the Last Glacial Maximum (LGM), between 23,000 and 19,000 years ago, a period during which the largest glacial ice sheets in South American Patagonia were recorded [1–3]. Currently, this extensive geographic area forms part

of the Patagonian Fjords and Channels System (PFCS), which extends between 42° and 56° S. It is characterized by a distinctive geomorphology, including fjords, channels, and islands, with a marked glacial influence on the water bodies [4]. This condition results in the region exhibiting notable environmental heterogeneity, where temperature, salinity, tidal range, and circulation patterns are strongly influenced by water masses originating from the southeastern Pacific [5]. These water masses define its thermohaline characteristics, which are modulated by freshwater inflows, the tidal regime, and winds [6].

In the southernmost segment of the Strait of Magellan, Cape Froward stands out. It forms part of the central sub-basin that extends from Carlos III Island to Segunda Angostura. This area is characterized by estuarine and brackish waters [7]. Furthermore, it has been described as a zone of upwelling, resulting from the differences in depth between Carlos III Island (~60 m) and Cape Froward (>500 m) [8]. Due to these conditions, Cape Froward and its surroundings constitute a rich marine ecosystem. These oceanographic and geomorphological characteristics have allowed for a wide variety of habitats and biotopes in this region of Southern Patagonia [9], where the substrate is highly variable, ranging from soft-bottom areas to rocky reef systems [10]. Key ecosystem components include extensive kelp forests, primarily giant kelp *Macrocystis pyrifera* (Linnaeus) C. Agardh 1820. This species is described as a keystone species [11] and is considered the most resilient kelp species on the planet, with a stability for almost 200 years in Patagonia [12].

The *M. pyrifera* forests in southern Patagonia have been identified as marine biodiversity hotspots [13–16]. In fact, Darwin, upon his first encounter with the Southern Ocean, recognized and highlighted their importance in the coastal marine ecosystem [17]. This significance is directly linked to their three-dimensional morphology and highly plastic, adaptable physiological characteristics [18]. The heterogeneous structure that these forests form in the environment determines relevant physicochemical and hydrological properties in the coastal setting [19–22]. This feedback has implications for ecological processes within the forest, where important community attributes—such as structure, diversity, dominance, food web dynamics, and productivity [11]—can vary significantly depending on the architectural and functional traits of the kelp forest [20,23–26].

Much of the research on the components of the marine ecosystem in the Cape Froward area has been limited to descriptions of the abundance, richness, and spatial variation in the macro-benthic community [27–29], as well as specific studies of pico- and nanophytoplankton assemblages [30]. In addition, some studies have examined specific taxa, such as the 14 species of echinoderms described by Mutschke and Ríos [31], and others have aimed to describe the trophic structure in the area, including Cape Froward, which identifies the interactions among 135 taxa of marine organisms [32]. On the other hand, there are only isolated studies that partially describe the population dynamics and morpho-functional aspects of *M. pyrifera* forest ecosystems, as well as the diversity of macroinvertebrates and macroalgae associated with them in the Águila bay area [33], leaving much of the eastern section of the Brunswick Peninsula, including Cape Froward, without data. However, despite the fragmented nature of the available data, in other areas of southern Patagonia, the structural role of kelp forests on certain components of these marine ecosystems—such as macroinvertebrates and fish—has been documented [34–36], without including others such as zooplankton and macroalgae.

It is well known that the highly heterogeneous composition of benthic systems in the PFCS results in strong gradients in physical disturbances, including changes in water column optics and movement, substrate type, depth, and seasonality, which affect biological processes and interactions within kelp forests [18,37–42]. Given this background, it is particularly important to understand the composition of the biota associated with these southern ecosystems and their spatiotemporal changes, not only by focusing on specific components but also by seeking to expand this knowledge. Therefore, assessing whether

the population structure of the kelp forest overlaps with abiotic engineering processes regarding the structuring of associated assemblages of zooplankton, macroinvertebrates, fish, and macroalgae [25,43,44] is a line of research that has been explored little in high-latitude ecosystems in the Southern Hemisphere.

This study presents one of the first spatio-temporal assessments of various components of the kelp forest ecosystems of southern Patagonia and aims to highlight their structural role in an area of the Strait of Magellan (Cape Froward) that has been identified as a major marine ecosystem critical for biodiversity conservation and with a great potential to mitigate the effects of global climate change. For all the reasons outlined above, the objective of this study is to characterize the biodiversity of the communities comprising zooplankton, invertebrates, fish, and understory macroalgae, as well as their spatiotemporal variation in the marine ecosystems of Cape Froward, which are dominated by *M. pyrifera* forests. We hypothesize that biodiversity and community structure of zooplankton, benthic invertebrates, fish, and understory macroalgae that inhabit the *M. pyrifera* forests at Cape Froward exhibit spatio-temporal variation. Our study will provide background information on the role of the kelp forests at Cape Froward and Strait of Magellan as keystone species [11], capable of providing refuge, food resources, and reproductive areas for numerous marine species [45], thereby modulating the composition and structure of these communities.

2. Materials and Methods

2.1. Study Site and Data Collection

Two field surveys were conducted nearby and inside shallow forests of giant kelp, *M. pyrifera*, located in Cape Froward area, Magellan Strait, southern Chilean Patagonia. The first survey was carried out from 5–11 November 2024 (spring), and the second from 14–20 May 2025 (autumn). A total of 12 stations per season were surveyed (Figure 1). Sampling sites were selected to represent the spatial variability of the study area along the western side of the Strait of Magellan, with stations classified as west, central, and east, according to the Cape Froward area.

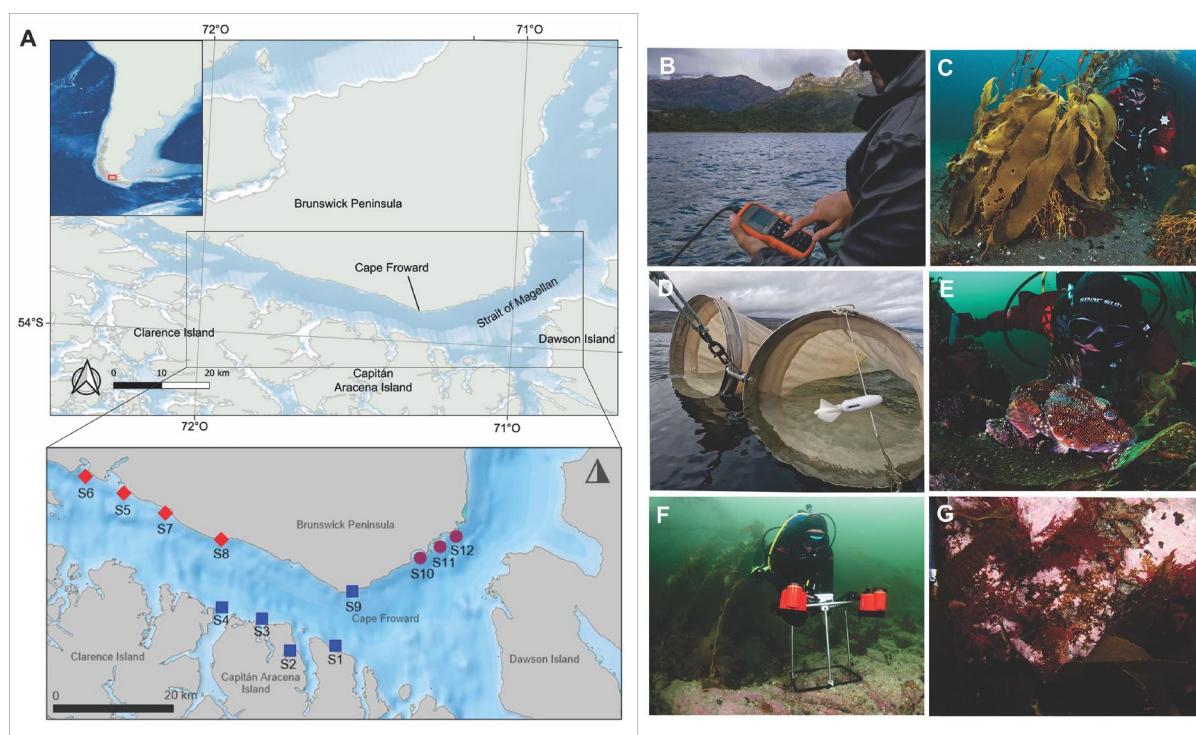


Figure 1. Geographic location of the study area at Cape Froward, Brunswick Peninsula in the Strait of Magellan (red rectangle), showing the sampling stations (S). (A) The sampling stations in the

figure are represented by geometric shapes of different colors located relative to Cape Froward; red (diamonds) represent stations on the west coast, blue (squares) represent stations on the central coast, and deep violet (circles) represent stations on the east coast. (B) Recording of abiotic variables in the water column, (C) population monitoring of giant kelp forests *M. pyrifera*, (D) Zooplankton sampling with a bongo net, (E) visual fish census along a sampling transect, (F,G) photo-quadrat surveys of benthic invertebrate diversity and macroalgal understory. Photos: (B,D) Nicolas Muñoz, (G) Mariano Rodríguez, (C,E,F) Eduardo Sorensen (Fundación Rewilding Chile).

Prior to each survey, temperature ($^{\circ}\text{C}$), salinity (psu) and dissolved oxygen ($\text{mg}\cdot\text{L}^{-1}$) measurements were taken at a depth of 5 m below the surface using a Hanna Instruments HI98494 multiparameter probe (Hanna Instruments, Inc., Smithfield, RI, USA), and a Secchi disk was used to measure water transparency (m).

2.2. Abundance and Density of Kelp Forests

To estimate wet biomass (kg ind^{-1}), we collected whole *M. pyrifera* individuals across a representative range of size classes (>20 per sector). For everyone, we recorded the maximum holdfast diameter (cm), maximum holdfast height (cm), number of stipites, total length (m), and individual wet biomass (kg) to develop an allometric model for estimating individual wet biomass. To identify the most robust morphometric variable for individual wet biomass (kg ind^{-1}), we applied a stepwise multiple regression analysis [46]. The regression models were fitted using linear least squares, forced to pass through the origin ($b_0 = 0$), and evaluated using analysis of variance (ANOVA). Next, individual wet biomass (kg) was estimated using a power-law allometric relationship; $\text{wet biomass} = \alpha \times \text{model}_b$, where α represents the predictor variable, model_b is the multiplicative scaling constant derived from the regression analysis. This allometric approach is standard practice for estimating individual biomass in large brown algae [33,47,48].

Each 25 m transect was then surveyed by a diver, who covered a 1 m wide area on either side of the line, resulting in a total sampled area of 50 m^2 per transect ($n = 2$ transects at each station). For each transect, we recorded the density of *M. pyrifera* individuals per m^2 and the morphometric variable identified as an estimator of wet biomass (e.g., diameter and height of holdfast, or number of stipites) estimated from the regression models. After recording the morphometric variable that best describes the wet biomass of *M. pyrifera*, we estimated biomass at the individual level (kg ind^{-1}) and then quantified biomass per unit area (kg m^{-2}). This analysis was conducted at the level of the 50 m^2 transect, allowing estimation of the density and abundance of *M. pyrifera* per m^2 .

2.3. Marine Communities Associated with the Kelp Forests

2.3.1. Zooplankton

At each of the 12 stations, oblique tows were conducted from a maximum depth of 20–30 m to the surface, at a distance of 20–30 m from the kelp forest. A standard Bongo net (60 cm in diameter, $300 \mu\text{m}$ mesh size) equipped with a Hydro-Bios flowmeter was used to estimate the volume of filtered seawater. The tows lasted 20–35 min, depending on the site's depth. Samples were fixed using 5% formalin buffered with sodium borate. Each sample was examined thoroughly under a Leica EZ4 stereomicroscope (Leica Microsystems, Wetzlar, Germany). All organisms were counted and identified to the lowest possible taxonomic level, using specialized literature [49,50].

2.3.2. Visual Kelp Forest Fish Census

Subtidal transects were surveyed at each of the stations where kelp forests were present during the spring and autumn surveys. At each study site, a diver identified and counted all fish species within 1 m on either side of a 25 m transect line (50 m^2) ($n = 2$

transects at each station). Since most fish species are benthic and cryptic, the transects were conducted by the same diver between 0.5 and 1 m above the sea floor at a uniformly slow swimming speed of 2 m min⁻¹ [36,51]. The transects were conducted parallel to the shoreline.

2.3.3. Invertebrates and Macroalgae of the Understory

After completing the fish survey in the 25 m transect (50 m²), a second diver photographed a 0.06 m² quadrant ($n = 40$) in situ, alternating between both sides of the transect within 1 m on either side, recording the presence of invertebrates and understory vegetation inhabiting the kelp forest. To ensure complete coverage of each quadrant, the camera was kept approximately 1 m above the substrate. The photo-transects were conducted using an Olympus TG-7 camera (OM Digital Solutions Corporation, Hachioji-City, Tokyo) in an Ikelite waterproof housing, a wide-angle lens, and two Inon strobes at approximately 1 m above the benthos. Identification of invertebrates and the understory components was performed at the lowest possible taxonomic level, using specialized literature.

2.4. Statistical Analysis

2.4.1. Abiotic and Biotic Factors

Environmental variables (temperature (°C), salinity (psu), dissolved oxygen (mg L⁻¹) and transparency (m)) and structural characteristics of the *M. pyrifera* forest, represented by density (ind. m⁻²) and biomass (kg m⁻²), were first evaluated in terms of their distribution using the Shapiro–Wilk normality test. Based on these results, relationships between *M. pyrifera* density and wet biomass and environmental variables were explored using bivariate correlation analyses, applying Pearson's correlation coefficient for normally distributed variables and Spearman's rank correlation otherwise. All multivariate analyses were conducted in PRIMER-e v7 [52], while diversity calculations were performed in PAST v4.03 [53].

2.4.2. Structure and Diversity of Marine Communities

Richness was interpreted as mixed-level taxonomic [54], rather than strict species richness, due to the identification of taxa at different hierarchical levels. Taxon accumulation curves were generated based on presence/absence data to assess the representativeness of the sampling effort. Additionally, expected richness was estimated using the non-parametric Chao2 estimator [55], which is appropriate for incidence data and accounts for the frequency of rare taxa (i.e., those occurring in one or two samples). This approach allowed the evaluation of sampling completeness and the potential underestimation of observed richness. These analyses were conducted using the EstimateS v9.1 software [56].

To assess spatial and temporal patterns in community composition, a two-way PERMANOVA was first applied based on a Jaccard similarity matrix derived from presence/absence data, evaluating differences among spatial sectors (west, central and east coast) and seasons (spring and autumn). Subsequently, a similarity percentage analysis (SIMPER) was conducted to decompose community variability and identify the taxa contributing most to significant differences among groups. Patterns in assemblage structure were then visualized using non-metric multidimensional scaling (nMDS), hierarchical clustering (CLUSTER), and clustered heatmaps. In addition, richness maps were generated to represent spatial patterns of taxonomic richness across sampling events.

3. Results

3.1. General Observations

Environmental conditions showed low variability between sampling periods. Temperature ranged from 7.2 to 8.4 °C in spring 2024 and from 7.3 to 8.5 °C in autumn 2025. During spring, slightly higher values were recorded in the central sector (7.3–8.4 °C), whereas the eastern sector showed lower values (7.2–7.4 °C). In autumn, the highest temperatures were observed in the western sector (8.1–8.5 °C), while the remaining sectors showed similar values. Salinity remained stable across all stations and sampling periods, ranging between 28.2 and 28.9 psu, with no clear spatial differences (Table 1).

Table 1. Geographic position station depths (m) within the forests of *M. pyrifera*, and environmental variables (temperature (°C), salinity (psu), dissolved oxygen (O₂, mg L⁻¹) and transparency (m)) recorded at each sampling station in Cape Froward, Strait of Magellan, during spring 2024 and autumn 2025. Values represent the median of replicate measurements per station and sampling period. Abbreviations: Station (S), Sal. (Salinity), Temp. (Temperature), Trans. (Transparency), and n.d. (no data).

Sector	Station	Lat. (°S)	Lon. (°W)	Depth (m)	Spring 2024				Autumn 2025			
					Temp. (°C)	Sal. (psu)	O ₂ (mg/L ⁻¹)	Trans. (m)	Temp. (°C)	Sal. (psu)	O ₂ (mg L ⁻¹)	Trans. (m)
Central	S1	−53.986	−71.333	4.6	8.4	28.9	9.3	5.5	7.8	28.7	6.7	15
	S2	−53.999	−71.446	5.6	7.7	28.6	7.9	6.0	7.7	28.7	5.5	13
	S3	−53.942	−71.533	6.8	7.3	28.7	8.1	5.0	7.9	28.2	6.7	15
	S4	−53.921	−71.638	5.0	7.3	28.6	8.1	6.0	7.3	28.7	6.7	14
	S9	−53.892	−71.276	5.0	7.4	28.7	8.6	7.0	7.6	28.8	7.5	13
West	S5	−53.739	−71.886	5.3	7.7	28.7	7.6	5.0	8.1	28.7	6.3	16
	S6	−53.705	−71.989	6.1	7.5	28.8	7.4	6.0	8.2	28.3	5.8	18
	S7	−53.766	−71.777	4.9	7.5	28.8	7.5	9.0	n.d.	n.d.	n.d.	n.d.
	S8	−53.813	−71.631	6.0	7.5	28.8	7.2	7.5	8.5	28.8	6.3	15
East	S10	−53.842	−71.097	6.5	7.3	28.4	7.2	7.0	7.7	28.7	7.4	15
	S11	−53.822	−71.037	6.0	7.2	28.6	8	6.5	7.6	28.3	7.5	14
	S12	−53.804	−70.997	5.5	7.4	28.6	7.6	4.5	7.7	28.7	7.6	16

The main seasonal differences were observed in dissolved oxygen and water transparency. During spring 2024, oxygen concentrations ranged between 7.2 and 9.3 mg L⁻¹, with relatively similar values among sectors, while transparency was low (4.5–9 m). In autumn 2025, dissolved oxygen concentrations ranged between 5.5 and 7.6 mg L⁻¹, whereas transparency increased markedly across the study area, reaching up to 18 m in the western sector and between 13 and 16 m in the central and eastern sectors (Table 1).

The wet biomass and density of the kelp forests showed spatial variation; however, regarding seasonal patterns, it was not possible to identify clear patterns of change across the entire study area. During spring 2024, the western sector recorded the highest biomass values, with S5 reaching the maximum of the entire dataset (4.5 kg m⁻²), while the remaining stations in this sector showed considerably lower values (S6: 0.3 kg m⁻²; S7–S8: 0.6 kg m⁻²). The central sector presented intermediate biomass (1.0–2.9 kg m⁻²), with S2 as the most productive station (2.9 kg m⁻²), whereas the western sector recorded the lowest overall values (0.8–1.9 kg m⁻²). Density followed a similar spatial pattern, ranging from 0.10 ind. m⁻² (S4) to 0.37 ind. m⁻² (S5) across all sectors (Table A1). In autumn of 2025, wet biomass increased at most stations compared to the spring, along with a change in the spatial pattern of abundance. The central and eastern sectors showed more homogeneous values (1.1–2.3 kg m⁻²), with S10 and S12 reaching the highest values of the season (2.0 and

2.3 kg m⁻², respectively), while the eastern sector recorded the lowest abundance in the kelp forests, particularly in S6 (0.6 kg m⁻²). Density also decreased across all sectors during autumn, with values ranging from 0.09 ind. m⁻² (S11) to 0.23 ind. m⁻² (S9), with the lowest densities recorded in the eastern sector (Table A1).

3.2. Richness Composition

3.2.1. Zooplankton

A marked seasonal shift in zooplankton composition was observed, with a total of 106 taxonomic groups recorded and a clear decline from spring (95 taxa) to autumn (62 taxa). During spring, 30 taxa were identified, whereas this number decreased to 14 in autumn. The spring assemblage was occurrence by early larval stages of cirripedes (Cirripedia nauplii: 100%; Table 2), along with the presence of ophiuroid larvae (Ophiura larvae: 100%) and bryozoan larvae (Cyphonaute larvae: 100%). In contrast, autumn was mainly characterized by the predominance of bryozoan larvae (Cyphonaute larvae: 100%) and the persistence of *Muggiaea atlantica* (Cunningham, 1892) (92%). Additionally, a higher diversity of early crustacean stages was observed in spring, including brachyuran zoeae (100%) and cirripede nauplii (100%), whereas in autumn, this diversity declined considerably, being largely restricted to cypris larvae (8%). Regarding ichthyoplankton, eight taxonomic groups were recorded in spring (fish eggs: 100%), whereas only one group was detected in autumn. Accordingly, both meroplankton and ichthyoplankton showed higher proportions in spring (24.7% and 0.7%, respectively), decreasing markedly in autumn (2.4% and 0.001%).

Table 2. Frequency of occurrence (Freq., %) of the main zooplankton taxonomic groups recorded during the spring and autumn sampling periods. Frequency of occurrence was calculated as the percentage of stations where each taxon was present relative to the total number of stations sampled in each period. Only taxa reaching frequencies higher than 80% in at least one of the sampling periods are included.

Phylum	Family	Taxa	Freq. (%)	
			Spring	Autumn
Cnidaria	Diphyidae	<i>Muggiaea atlantica</i>	75	92
	Bougainvilliidae	<i>Bougainvilla</i> spp.	92	0
Arthropoda	Euphausiidae	Euphausiidae nauplii	100	0
	Euphausiidae	Calyptopis	100	8
	Calanidae	<i>Calanoides</i> sp.	100	92
	Clausocalanidae	<i>Clausocalanus</i> sp.	92	100
	Centropagidae	<i>Centropages</i> sp.	100	25
	Metridinidae	<i>Metridia lucens</i>	50	50
	Scolecitrichidae	<i>Scolecithricella</i> sp.	58	92
	Oithonidae	<i>Oithona</i> sp.	100	92
	Rhincalanidae	<i>Rhincalanus nasutus</i>	83	25
	Podonidae	<i>Podon leuckarti</i>	83	0
	Podonidae	<i>Eoadne tergespina</i>	100	8
	Hyperiididae	<i>Hyperietta dilatata</i>	50	83
	Hyperiididae	<i>Themisto gaudichaudii</i>	0	100
		Brachiura zoea	100	0
		Cirripedia nauplii	100	0
		Cypris larvae	92	8
Chaetognatha	Sagittidae	<i>Serratosagitta tasmanica</i>	33	92
Chordata	Clupeidae	<i>Sprattus fueguensis</i>	83	0
		Appendicularia	100	92

	Fish egg	100	0
Bryozoa	Ciphonauta larvae	100	100
	Larva Equinoidea	83	0
Echinodermata	Larva Asteroidea	83	0
	Ophiura larvae	100	0

The spatiotemporal distribution of taxonomic richness decreased consistently across all sampling stations toward autumn 2025. During spring, richness exhibited a longitudinal gradient along the study area (Figure 2A,B). The highest values were concentrated in the western sector, particularly at stations S5–S7, where 51–56 taxa were recorded, while the eastern sector showed intermediate values (38–41 taxa) and the central sector displayed greater variability (21–50 taxa; Figure 2A,B). In contrast, during autumn, species richness was considerably lower and more homogeneous, ranging between 17 and 26 taxa. During this period, the longitudinal gradient disappeared, with an overall reduction in maximum values and lower spatial differentiation among stations.

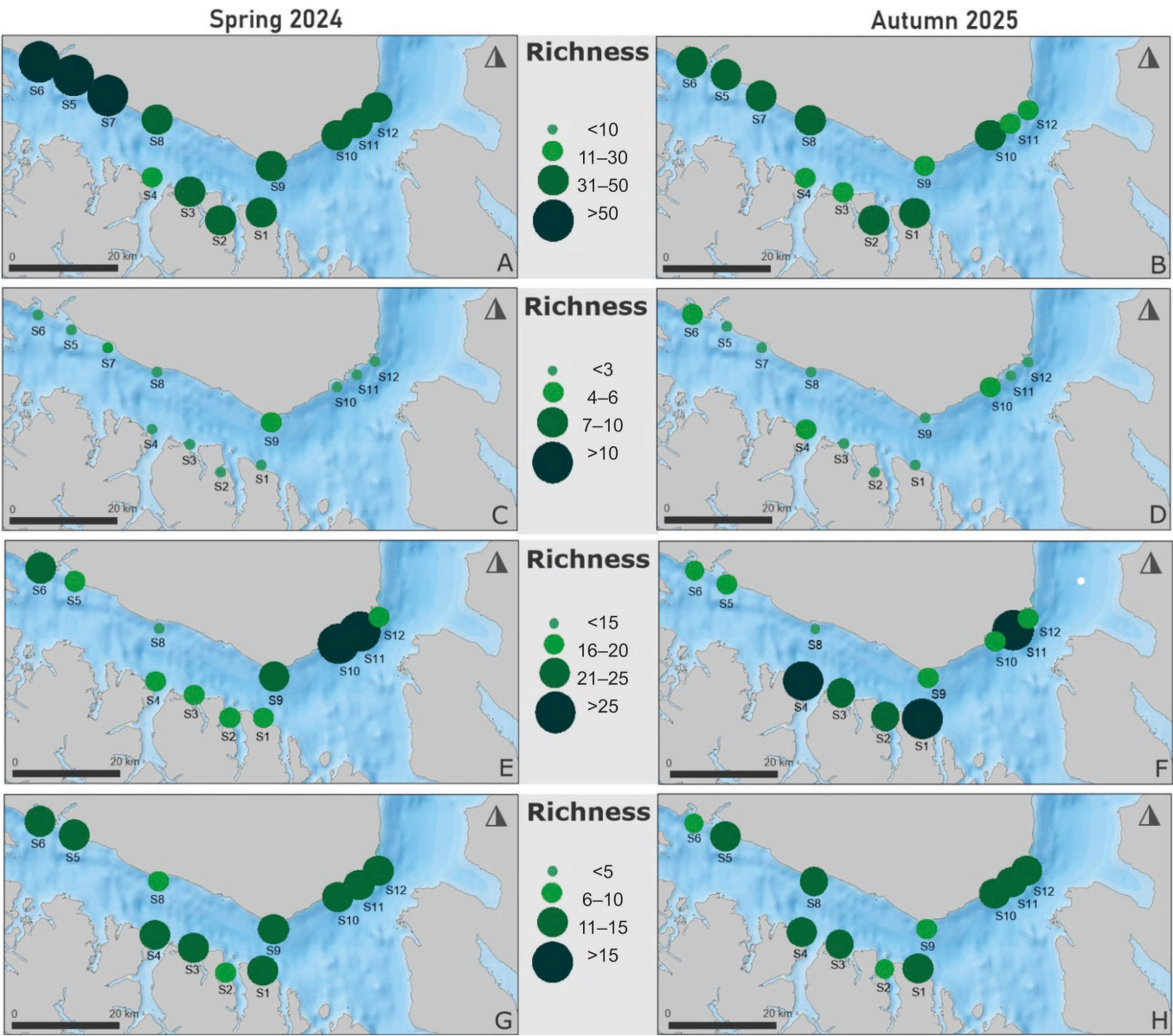


Figure 2. Spatial distribution of taxonomic richness across different biological assemblages during spring 2024 (left panels) and autumn 2025 (right panels) in the Cape Froward area, Strait of Magellan. Panels (A,B) correspond to zooplankton, (C,D) to kelp forest fish, (E,F) to benthic invertebrates,

and (G,H) to understory of macroalgae. Circle size represents the richness recorded at each sampling station, according to the categories defined in the legend.

In the early stages of sampling, zooplankton showed a rapid increase in observed richness, followed by a more gradual rise without reaching a clear asymptote in either season. In spring, observed richness approached 90–95 taxa toward the final samples, while the Chao2 estimator stabilized around 100–105 taxa, maintaining a consistent difference from observed richness. In autumn, observed richness increased to 60–65 taxa, whereas Chao2 reached values close to 75–80 taxa, remaining higher than observed values throughout the sampling effort. The lack of convergence between observed richness and Chao2 indicates that additional taxa could be recorded with increased sampling effort (Figure A1A,B).

Significant relationships were found between zooplankton richness and several abiotic variables. Richness was strongly and negatively correlated with water transparency (m; $r_s = -0.57$, $p = 0.01$), while showing a positive association with dissolved oxygen concentration (mg L^{-1} ; $r_s = 0.51$, $p = 0.01$). No significant trends were found with temperature ($^{\circ}\text{C}$; $r_s = -0.08$, $p = 0.73$) or salinity (psu; $r_s = 0.29$, $p = 0.17$). Zooplankton richness was also not significantly correlated with kelp forest structure, including biomass ($r_s = -0.16$, $p = 0.46$) and density ($r_s = 0.35$, $p = 0.09$) (Table A6).

3.2.2. Kelp Forest Fish

A total of 12 fish species were recorded during the study, half of which (6 species) belong to the family Nototheniidae, representing 50% of the total assemblage richness. In spring, 10 species were identified, with *Patagonotothen tessellata* (Richardson, 1845) being the most frequent (75%), followed by *Patagonotothen cornucola* (Richardson, 1844) and *Patagonotothen* spp. (both 50%), all of them broadly distributed across sampling stations. Of these, about 67% are fish in the invertebrate-feeding group, while only 33% are piscivorous and invertebrate-feeding. (Table 3). By autumn, richness increased slightly to 11 species. During this period, *Patagonotothen* spp. became the most frequent taxon (83%), while *P. cornucola* remained relatively common (58%), and *P. tessellata* decreased in frequency (33%). Seasonal changes were also evident in the occurrence of less frequent species. For instance, *Pogonolychus marinae* (Lloris, 1988) and *Patagonotothen longipes* (Steindachner, 1876) (0–17%) were only recorded in autumn, whereas *Myxine* sp. was restricted to spring (8–0%). In contrast, species such as *Cottoperca trigloides* (Forster, 1801), *Austrolycus depressiceps* (Regan, 1913), and *Leptonotus blainvillanus* (Eydoux & Gervais, 1837) showed similar frequencies between seasons, although their overall occurrence remained low (Table 3).

Table 3. Frequency of occurrence (Freq., %) of the main taxonomic groups of fishes recorded during the spring and autumn sampling periods. Frequency of occurrence was calculated as the percentage of stations at which each taxon was present relative to the total number of stations sampled in each period. Trophic group classification according to Friedlander et al. [35]. Abbreviations: Pisc. = piscivore, Inv. = invertivore.

Family	Taxa	Trophic Group	Freq. (%)	
			Spring	Autumn
Myxinidae	<i>Myxine</i> sp.	Pisc., Inv.	8	0
Agonidae	<i>Agonopsis chiloensis</i>	Inv.	17	8
Bovichtidae	<i>Cottoperca trigloides</i>	Pisc., Inv.	17	17
Nototheniidae	<i>Patagonotothen</i> spp.	Inv.	50	83
	<i>Patagonotothen tessellata</i>	Inv.	75	33
	<i>Patagonotothen cornucola</i>	Inv.	50	58
	<i>Patagonotothen squamiceps</i>	Inv.	25	17

	<i>Patagonotothen longipes</i>	Inv.	0	17
	<i>Paranotothenia magellanica</i>	Inv.	25	17
Zoarcidae	<i>Austrolycus depressiceps</i>	Pisc., Inv.	8	8
	<i>Pogonolycus marinae</i>	Pisc., Inv.	0	17
Syngnathidae	<i>Leptonotus blainvillanus</i>	Inv.	8	8

Spatially, fish richness displayed a relatively homogeneous pattern between spring 2024 and autumn 2025, with no clear differences along the longitudinal gradient of the strait (Figure 2C,D). During spring, richness ranged from 1 to 4 species per station, with slightly higher values at central and eastern stations (e.g., S9–S10). In autumn, richness varied between 0 and 4 species, maintaining a similar spatial structure but with greater variability, particularly in the western sector, where both low and relatively high values were observed (Figure 2C,D).

In both seasons, species accumulation curves for fish taxa showed a gradual increase in observed richness, approaching an asymptote toward the final samples. In spring, observed richness approached ~12 taxa, and the Chao2 estimator, after an early peak (16–17 taxa), declined and overlapped with observed values around ~12–13 taxa. In autumn, observed richness increased progressively to ~11–12 taxa, while Chao2 reached ~14–15 taxa at intermediate sampling effort and then decreased slightly toward ~12–13 taxa, also reducing the difference toward the end. These patterns indicate good sampling representativeness, with a low proportion of undetected species, particularly in spring (Figure A1C,D).

Spearman rank correlations did not reveal significant relationships between fish richness and abiotic variables, including temperature (T°C; $r_s = 1.00$, $p = 0.40$), salinity (psu; $r_s = -0.03$, $p = 0.90$), dissolved oxygen (mg L⁻¹; $r_s = -0.30$, $p = 0.15$), and water transparency (m; $r_s = 0.27$, $p = 0.21$). In contrast, fish richness showed significant negative associations with kelp forest structure, including biomass ($r_s = -0.54$, $p = 0.01$) and density ($r_s = -0.46$, $p = 0.02$), indicating a decrease in fish richness as the kelp forest increases (Table A6).

3.2.3. Benthic Invertebrates

During spring 2024, a total of 76 benthic invertebrate taxa associated with the *M. pyrifera* forest were recorded at Cape Froward. The assemblage was dominated by Mollusca (21 taxa; 27.6%), followed by Echinodermata (15 taxa; 19.7%), Arthropoda (12 taxa; 15.8%), Cnidaria (8 taxa; 10.5%), and Porifera (6 taxa; 7.9%) (Table 4). Together, these groups accounted for more than 80% of the total recorded taxa. Within these dominant groups, Gastropoda and Decapoda contributed the highest taxonomic richness. The most frequent taxa, recorded across multiple stations, included *Nacella* spp., *Cosmasterias lurida* (Philippi, 1858), *Pseudechinus magellanicus* (Philippi, 1857), and representatives of Holothuroidea. In autumn 2025, the benthic invertebrate assemblage at Cape Froward comprised 75 taxa. As in spring, Mollusca was the dominant group (20 taxa; 26.7%), followed by Echinodermata (14 taxa; 18.7%), Arthropoda (12 taxa; 16.0%), Cnidaria (7 taxa; 9.3%), and Annelida (5 taxa; 6.7%). Together, these groups accounted for more than 75% of the total recorded taxa (Table 4).

Table 4. Frequency of occurrence (Freq., %) of the main taxonomic groups of benthic invertebrates recorded during the spring and autumn sampling periods. Frequency of occurrence was calculated as the percentage of stations at which each taxon was present relative to the total number of stations sampled in each period. Only taxa reaching frequencies higher than 50% in at least one of the sampling periods are included.

Phylum	Family	Taxa	Freq. (%)	
			Spring	Autumn
Cnidaria		Actinaria	58	58
		Hydrozoa	58	42
Annelida	Chaetopteridae	<i>Chaetopterus variopedatus</i>	42	58
		Polychaeta	67	83
Mollusca	Fissurellidae	<i>Fissurella</i> sp.	50	50
		Gastropoda	83	83
	Calliostomatidae	<i>Margarella violacea</i>	42	50
	Nacellidae	<i>Nacella</i> sp.	83	75
	Nacellidae	<i>Nacella deaurata</i>	58	42
		Nudibranchia	75	58
		Polyplacophora	50	42
		Cirripedia	83	92
Arthropoda	Paguridae	<i>Pagurus comptus</i>	58	33
	Lithodidae	<i>Lithodes santolla</i>	75	67
Echinodermata		Asteroidea	75	58
	Asteriidae	<i>Anasterias antarctica</i>	50	42
	Asteriidae	<i>Cosmasterias lurida</i>	83	92
	Arbaciidae	<i>Arbacia dufresnii</i>	42	50
	Temnopleuridae	<i>Pseudoechinus magellanicus</i>	75	42
		Holothuroidea	75	67
		Ophiuroidea	42	75
Chordata	Didemnidae	<i>Didemnum studeri</i>	42	50

At the species level, several taxa exhibited marked differences in frequency between seasons, while others remained relatively constant. During spring, high frequencies were observed for Actiniaria (58%), Hydrozoa (58%), *Nacella* spp. (83%), Cirripedia (83%), *C. lurida* (83%), and *P. magellanicus* (75%), many of which were recorded in more than 75% of the stations. In contrast, during autumn, taxa such as Porifera (92%), Polychaeta (83%), Cirripedia (92%), and *C. lurida* (92%) increased in frequency, with some reaching values above 80–90%, indicating a broader spatial occurrence during this period. Conversely, species such as *Pagurus comptus* (White, 1847) (58% to 33%) and *Nacella deaurata* (Gmelin, 1791) (58% to 42%) showed a decrease in frequency from spring to autumn. A subset of taxa displayed relatively stable frequencies across both seasons, including Actiniaria (58% in both periods), *Fissurella* sp. (50% in both periods), and Gastropoda (83% in both periods), suggesting temporal persistence in their spatial distribution (Table 4).

During spring, the highest richness values were recorded at stations located in the eastern sector of the fjord (S10 and S11), both with 35 taxa. Intermediate richness values were observed at stations S6 and S9 (23 taxa), whereas the lowest richness was recorded at station S8, with only 7 taxa (Figure 2E). In contrast, during autumn, the spatial pattern shifted, with the highest richness recorded at station S4 (36 taxa), followed by S11 (28 taxa). In addition, stations S6 and S9 exhibited decreases in richness of more than 20% relative to spring season (Figure 2F).

The Chao2 estimator was higher than observed richness in both spring and autumn, suggesting that additional species could be recorded (Figure A1E,F). However, differences

in the shape of the curves were observed between seasons. In spring, observed richness did not reach a clear asymptote, maintaining an increasing trend toward the final samples (~80 taxa), whereas the Chao2 estimator tended to stabilize in the last samples at around 95–100 taxa, maintaining a gap with observed richness. In autumn, observed richness also continued to increase progressively (~65–70 taxa), without reaching full stabilization, while the Chao2 estimator reached maximum values close to 95–100 taxa in the intermediate samples, remaining relatively stable toward the end.

A significant negative relationship was found between benthic invertebrate richness and temperature ($r_s = -0.43$, $p = 0.03$), indicating a decrease in richness with increasing temperature. No significant relationships were detected with other abiotic variables, including salinity ($r_s = -0.14$, $p = 0.51$), dissolved oxygen (mg L^{-1} ; $r_s = -0.02$, $p = 0.92$), and water transparency ($r_s = -0.04$, $p = 0.87$). Similarly, benthic richness showed no significant association with kelp forest structure, including biomass ($r_s = -0.25$, $p = 0.25$) and density ($r_s = -0.11$, $p = 0.60$) (Table A6).

3.2.4. Understory of Macroalgae

During the sampling, a total of 27 understories of macroalgal taxa associated with kelp forests were recorded. In spring, 25 taxa were identified, dominated by Rhodophyta (60%), followed by Ochrophyta (28%) and Chlorophyta (12%), whereas 24 taxa were recorded in autumn (Table 5). Differences in the frequency of occurrence of several taxa were observed between seasons. Some species showed high frequency in both periods, including *Ulva* sp. (spring–autumn; 75–82%), *Codium* sp. (60–64%), and *Desmarestia confervoides* (Bory) M.E. Ramírez & A.F. Peters 1993 (91–82%), suggesting their role as persistent components of the assemblage. In contrast, several taxa increased their frequency during autumn, notably crustose red algae (75–100%), *Desmarestia ligulata* (Stackhouse) J.V. Lamouroux 1813 (33–64%), *Sarcopeltis skottsbergii* (Setchell & N.L. Gardner) Hommersand, Hughey, Leister & P.W. Gabrielson 2020 (33–82%), *Corallina* sp. (67–91%), and *Ptilonia magellanica* (Montagne) J. Agardh 1852 (42–90%). On the other hand, some taxa showed a marked decrease or absence in autumn, such as *Iridaea cordata* (Turner) Bory 1826 (50–0%), *Phycodrys rubens* (Linnaeus) Batters 1902 (68–0%), *Plocamium secundatum* (Kützinger) Kützinger 1866 (58–9%), and *Palmaria* sp. (50–9%), evidencing a seasonal turnover in macroalgal assemblage composition (Table 5).

Table 5. Frequency of occurrence (Freq., %) of the main taxonomic groups of understory of macroalgae recorded during the spring and autumn sampling periods. Frequency of occurrence was calculated as the percentage of stations at which each taxon was present relative to the total number of stations sampled in each period.

Phylum	Family	Taxa	Freq. (%)	
			Spring	Autumn
Chlorophyta	Ulveaceae	Chlorophyta	90	82
		<i>Ulva</i> sp.	75	82
		<i>Codium</i> sp.	60	64
Ochrophyta	Desmarestiaceae	Ochrophyta	90	91
		Crusty algae	75	100
		<i>Desmarestia confervoides</i>	91	82
		<i>Desmarestia ligulata</i>	33	64
Rhodophyta	Corallinaceae	Rhodophyta	82	82
		<i>Corallina</i> sp.	67	91
		<i>Callophyllis</i> sp.	92	73
	Kallymeniaceae	<i>Callophyllis variegata</i>	83	45
		<i>Callophyllis atrosanguinea</i>	50	36

Gigartinaceae	<i>Sarcopeltis skottsbergii</i>	33	82
Delesseriaceae	<i>Lophurella hookeriana</i>	50	55
Gigartinaceae	<i>Iridaea cordata</i>	50	0
Rhodymeniaceae	<i>Rhodymenia coccocarpa</i>	50	10
Palmariaceae	<i>Palmaria</i> sp.	50	9
Delesseriaceae	Delesseriaceae	42	82
	<i>Phycodrys rubens</i>	68	0
Plocamiaceae	<i>Plocamium secundatum</i>	58	9
Ceramaceae	<i>Ptilonia magellanica</i>	42	90
Rhodomelaceae	<i>Polysiphonia</i> sp.	50	9

Richness exhibited a consistent spatial pattern between spring 2024 and autumn 2025, maintaining an overall structure along the longitudinal gradient (Figure 2G,H). During spring, mean richness was approximately ~13 taxa in the western sector, compared to ~10.8 taxa in the central sector and ~10.7 taxa in the eastern sector of Cape Froward. In contrast, during autumn, although the general spatial structure was maintained, differences among sectors tended to decrease, with mean values of ~12.3 taxa in the eastern sector, ~12 taxa in the central sector, and ~8.5 taxa in the western sector (Figure 2G,H). The latter also showed higher variability, including extreme values that increased dispersion among stations.

Observed richness increased gradually with sampling effort in both seasons, approaching an asymptote toward the final samples. In spring, observed richness tended to stabilize between samples 8–11, reaching values close to 22 taxa, while the Chao2 estimator converged around 25–27 taxa. In autumn, stabilization occurred earlier, approximately from sample 6 onward, with similar observed richness values (22–24 taxa) and Chao2 estimates close to 24–26 taxa (Figure A1G,H). The Chao2 estimator was consistently higher than observed richness, particularly at early sampling stages, but tended to converge with observed values as sampling effort increased.

Regarding environmental conditions, Spearman rank correlations revealed no significant relationships between macroalgal taxonomic richness and abiotic variables, including temperature ($^{\circ}\text{C}$; $r_s = -0.22$, $p = 0.30$), salinity (psu; $r_s = -0.37$, $p = 0.08$), dissolved oxygen (mg L^{-1} ; $r_s = 0.14$, $p = 0.52$), and water transparency (m; $r_s = -0.04$, $p = 0.84$), although a marginal negative trend was observed with salinity. Additionally, local variability in *M. pyrifera* does not directly explain patterns of richness across sampling sites, as richness showed no significant association with kelp forest structure, including biomass ($r_s = -0.09$, $p = 0.68$) and density ($r_s = -0.02$, $p = 0.93$) (Table A6).

3.3. Spatial and Temporal Patterns

3.3.1. Zooplankton

Zooplankton assemblage composition did not show significant differences among sectors (central, western, and eastern; PERMANOVA, pseudo-F = 0.927, $p = 0.437$). Pairwise comparisons confirmed the absence of differences between all sector combinations (central vs. western: $p = 0.316$; central vs. eastern: $p = 0.801$; western vs. eastern: $p = 0.134$), indicating a lack of spatial structuring in assemblage composition. In contrast, assemblage composition differed significantly between sampling periods (spring and autumn; PERMANOVA, pseudo-F = 14.96, $p < 0.001$). Pairwise comparisons confirmed these differences ($p < 0.001$), indicating a marked temporal shift in zooplankton assemblage structure. The SIMPER analysis indicated an overall average dissimilarity of 69.55% between spring and autumn zooplankton assemblages (Table A2). This dissimilarity was mainly explained by a set of taxa with relatively low individual contributions. The taxa contributing most to the observed differences included *Ctenocalanus citer* (Heron & Bowman, 1971) (cumulative

contribution: 13.0%), followed by fish eggs (15.1%), *Themisto gaudichaudii* (Guérin, 1825) (17.2%), Ophiuroidea larvae (19.3%), cirripede nauplii (21.4%), brachyuran zoea (23.5%), and euphausiid nauplii (25.6%). Additional contributions were provided by *Bougainvillia* spp. (27.6%), *Calyptopis* stages (29.5%), and *Evadne tergestina* (Claus, 1864) (31.4%; Table A2).

The nMDS ordination revealed a clear separation between spring and autumn zooplankton samples, forming two well-defined clusters (Figure 3A). Spring samples were tightly grouped, indicating relatively high similarity among stations, whereas autumn samples showed a more dispersed distribution. The grouping pattern was supported by similarity contours, with most samples within each season clustering at approximately 40–50% similarity (Figure 3A).

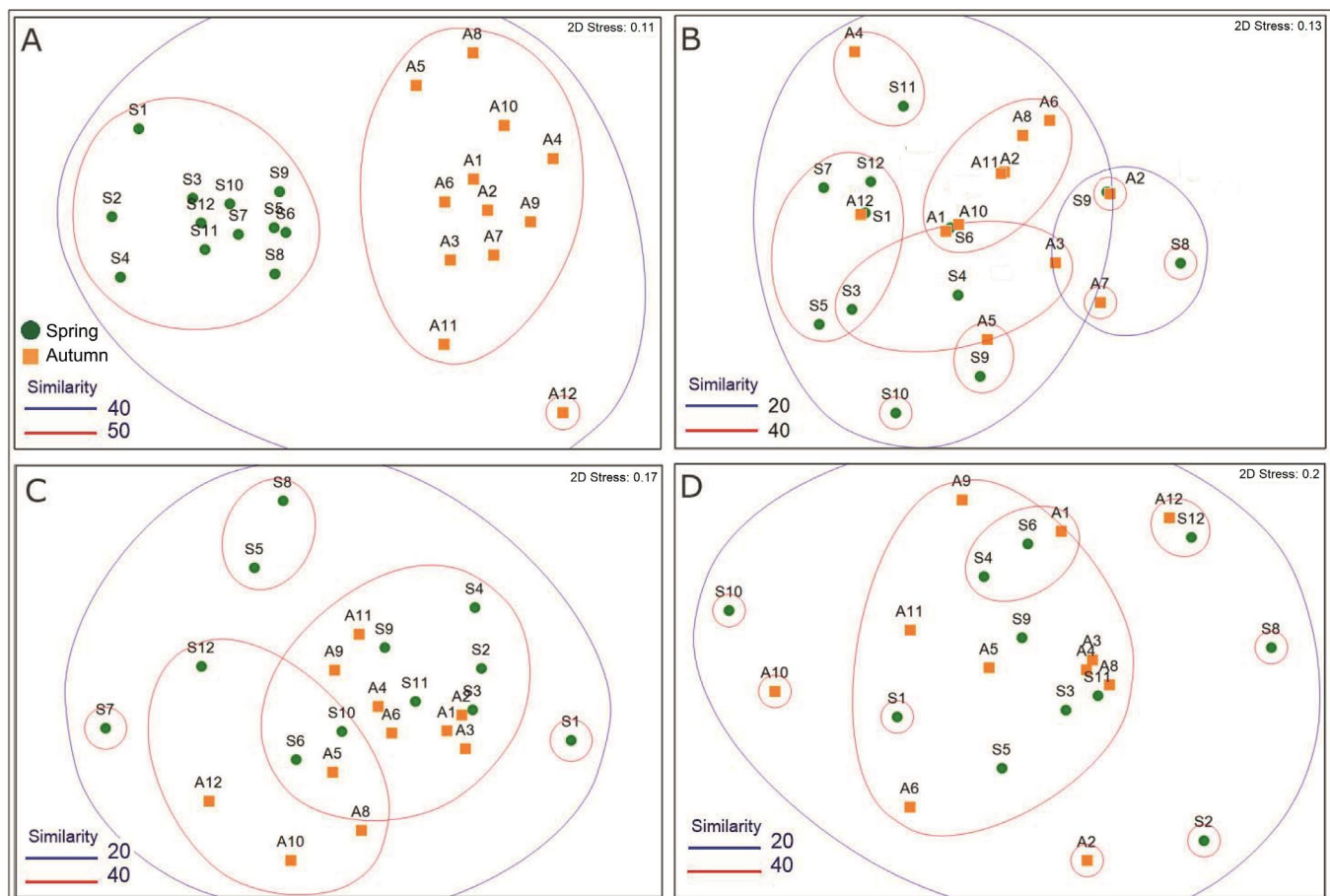


Figure 3. Non-metric multidimensional scaling (nMDS) ordination based on a Jaccard similarity matrix constructed from presence/absence data for the different biological assemblages in the Cape Froward area, Strait of Magellan. Panels correspond to (A) zooplankton, (B) kelp fish forest, (C) benthic invertebrates, and (D) understory of macroalgae. Points represent sampling stations, differentiated by season (spring and autumn). Ellipses indicate similarity levels among samples (20–50%), and stress values are shown in each panel.

The clustered heatmap revealed distinct zooplankton assemblages associated with each sampling period. Three main groups of taxa were identified based on their occurrence patterns; the first group, located in the upper cluster, included taxa such as *Rhopalomena velatum* (Gegenbaur, 1857), *Calycopsis* sp., *Paraeuchaeta* spp., *Euphausia vallentini* (Stebbing, 1900), *T. gaudichaudii*, and *Thysanoessa* sp., which were predominantly associated with autumn samples. These taxa showed low or absent occurrence in spring and increased presence across multiple autumn stations, contributing to the separation

between periods. A second group of taxa, forming a central and dense cluster, was widely distributed across spring samples and included copepods and larval forms such as *Oithona* sp., *Calanoides* sp., *Clausocalanus* sp., and bryozoan larvae. These taxa were consistently present across most spring stations, generating a homogeneous assemblage with high similarity. A third group, located in the lower cluster, was also primarily associated with spring samples and included taxa such as *Rhincalanus nasutus* (Giesbrecht, 1888), *E. tergestina*, *Calyptopsis* sp., euphausiid nauplii, *Bougainvillia* spp., and *C. citer*. In contrast to the central group, these taxa showed a more variable distribution among stations but remained predominantly present in spring and showed limited occurrence in autumn (Figure A2).

3.3.2. Kelp Forest Fish

Fish assemblage composition was similar between spring and autumn (PERMANOVA, pseudo-F = 2.013, $p = 0.057$). A similar pattern was observed across sectors (central, western, and eastern; PERMANOVA, pseudo-F = 1.337, $p = 0.186$), suggesting a relatively homogeneous spatial structure. Pairwise comparisons further supported this pattern, with p -values of 0.289 (central vs. western), 0.182 (central vs. eastern), and 0.249 (western vs. eastern).

The nMDS ordination of fish assemblages showed broad and overlapping groupings between seasons, indicating low temporal differentiation (Figure 3B). This pattern was consistent with the cluster analysis, which showed associations between spring and autumn stations within the same similarity groups, without clear segregation by season. However, greater dispersion of spring stations was observed in the nMDS space compared to autumn stations, which tended to cluster more tightly, suggesting higher heterogeneity in assemblage composition during spring (Figure 3B).

Consistently, the heatmap revealed a heterogeneous distribution of species across seasons, without clear patterns of seasonal dominance, supporting the high overlap in assemblage composition. Nevertheless, some differences in species occurrence frequency were observed. During spring, the assemblage was dominated by *P. tessellata* and *P. cornucola*. In contrast, during autumn, a higher presence of species such as *Patagonothoten* spp., *P. longipes*, and *P. marinae* was recorded, reflecting a more heterogeneous assemblage. Some species, including *P. magellanica*, *P. squamiceps*, and *L. blainvillianus*, were present in both periods with similar frequency (Figure A3).

3.3.3. Benthic Invertebrates

Benthic invertebrate assemblage composition did not show significant differences between spring and autumn (PERMANOVA, pseudo-F = 0.818, $p = 0.787$). Pairwise comparisons confirmed the absence of differences between both periods ($p = 0.794$), suggesting high temporal stability in assemblage structure. In contrast, assemblage composition differed significantly among sectors (central, western, and eastern; PERMANOVA, pseudo-F = 1.838, $p = 0.002$). Pairwise comparisons showed that the central sector was significantly different from both the western ($p = 0.002$) and eastern sectors ($p = 0.013$), while no differences were detected between the western and eastern sectors ($p = 0.272$), indicating a spatially differentiated assemblage structure, particularly in the central sector. The SIMPER analysis indicated that the average dissimilarity between the central and western sectors was 59.83%, explained by a broad set of taxa with low and relatively homogeneous individual contributions (Table A3). The main contributing taxa, including Polychaeta, *Margarella violacea* (P. P. King, 1832), *Anasterias antarctica* (Lütken, 1857), and *Arbacia dufresnii* (Blainville, 1825), jointly accounted for 13.2% of the total dissimilarity. The cumulative contribution of the first ten taxa reached 28.9%, while the first twenty taxa explained approximately 50.8% of the dissimilarity. For the comparison between the central and eastern

sectors, the SIMPER analysis indicated that the overall average dissimilarity between the central and eastern sectors was 56.03%, explained by a broad set of taxa with low and relatively homogeneous individual contributions (Table A4). The main contributing taxa included *M. violacea* (cumulative contribution: 2.56%), *P. magellanicus* (5.10%), *P. comptus* (7.61%), Nudibranchia (10.05%), and *A. antarctica* (12.48%). Additional contributions were provided by Ophiuroidea (14.74%), Asteroidea (16.96%), *Antholoba achates* (Drayton in Dana, 1846) (19.19%), and Polychaeta (21.26%). The cumulative contribution of the first ten taxa reached 21.26%, while the first twenty taxa explained approximately 40.28% of the total dissimilarity. The first twenty-five taxa accounted for 50.05% of the dissimilarity, indicating that differences between sectors were driven by the combined contribution of multiple taxa rather than a few dominant species.

The nMDS ordination of benthic invertebrate assemblages showed a broad overlap between spring and autumn samples, with no clearly separated groups in either period. However, similar to fish, the spring stations were more dispersed in the ordination space than those from autumn, which tended to cluster into two main groups with similarity levels around 40% (Figure 3C). This pattern was supported by the cluster analysis (Figure A4), as stations from both spring and autumn were intermixed within different similarity groups, without consistent segregation by sampling period or geographic sector. Although some spring stations formed closer groupings (e.g., western stations S6, S7, S8), the overall pattern indicates a high compositional overlap between periods and a weak spatial structure along the longitudinal gradient.

The heatmap showed a heterogeneous distribution of taxa across stations, with no exclusive dominance of groups restricted to a single period (Figure A4). However, differences in the recurrence of some taxa were observed. During spring, several records were associated with taxa such as Hydrozoa, *Margarella antarctica* (E. Lamy, 1906), *N. deaurata*, Isopoda, and some echinoderms, although with a more irregular distribution among stations. In contrast, during autumn, a higher recurrence of widely distributed groups such as Porifera, Cirripedia, Gastropoda, Polychaeta, Holothuroidea, and Ophiuroidea were observed, all of which were present across multiple stations. Some taxa, including Gastropoda, Cirripedia, Porifera, and Polychaeta, occurred in both periods and contributed to the observed compositional overlap.

3.3.4. Understory of Macroalgae

No significant differences in assemblage composition were detected between spring and autumn (PERMANOVA, pseudo- $F = 0.659$, $p = 0.789$). Similarly, no overall differences were found among sectors (central, western, and eastern; PERMANOVA, pseudo- $F = 1.29$, $p = 0.164$). Pairwise comparisons suggested a potential difference between the central and western sectors ($p = 0.014$), whereas no differences were detected between the central and eastern sectors ($p = 0.183$) or between the western and eastern sectors ($p = 0.811$). The SIMPER analysis indicated that the dissimilarity in assemblage composition between the central and western sectors was primarily driven by *Codium* sp. (8.44%), *D. ligulata* (6.16%), *Callophyllis variegata* (Bory) Kützinger 1843 (6.07%), *Ulva* sp. (5.78%), *Lophurella hookeriana* (J. Agardh) Falkenberg 1901 (5.58%), and *S. skottsbergii* (5.58%). Additional contributions were provided by *Callophyllis atrosanguinea* (Hooker f. & Harvey) Hariot 1887 (5.44%), *D. confervoides* (4.61%), and crustose algae (4.31%), which together accounted for more than 50% of the total dissimilarity (Table A5). The nMDS analysis showed no clear separation between spring and autumn samples, with stations grouping in a mixed manner and indicating a high degree of compositional overlap between both periods, with similarities equal to or greater than 60% (Figure 3D).

The clusterized heatmap reveals the presence of a central macroalgal assemblage widely distributed across both sampling periods, composed of taxa that dominate

community structure, such as Ochrophyta, Rhodophyta, *Corallina* sp., crustose red algae, *D. confervoides*, *Callophyllis* sp., Delesseriaceae, and Chlorophyta. According to the cluster analysis, only stations S7 and S10 from spring formed a distinct group, characterized by low similarity with the remaining stations (<40%; Figure A5), and representing some of the few stations where *D. confervoides* and *D. ligulata* were absent. Despite this general pattern, subsets of taxa with seasonal affinity were identified. In spring, species with more restricted distributions were observed, such as *I. cordata*, *Durvillaea antarctica* (Chamisso) Hariot 1892, and *Adenocystis utricularis* (Bory) Skottsberg 1907. In contrast, the autumn assemblage was characterized by a higher frequency and broader occurrence of taxa such as *S. skottsbergii*, *D. ligulata*, and *L. hookeriana* (Figure A5).

Overall, the results indicate that assemblages are structured around a common core of shared taxa, whereas seasonal differences are mainly expressed as variations in the frequency of occurrence of certain species, rather than as a complete turnover in composition.

4. Discussion

4.1. Habitat Characteristics

Our observations did not reveal any significant differences in the abiotic characteristics of the surface water column associated with the kelp forests, likely because the surveys were conducted during transitional seasonal periods. However, small spatial variations in temperature and salinity were detected, caused by the inflow of cold, low-salinity water from continental currents in the Cape Froward area [57], mainly in the eastern part of the Strait of Magellan [58], characteristic of an area dominated by low-salinity, low-density waters, with weak vertical gradients and limited deep-water turnover [59]. These observations are consistent with previous descriptions of the water column, which indicate that this area of the strait has low-salinity waters [60] of an estuarine nature [61], along with relatively homogeneous and low temperatures in spring (7.0–7.5 °C; [62]). Regarding dissolved oxygen concentration in the water column (~6.0 m), the values recorded in spring remained within the ranges reported by other studies; for example, Valdenegro and Silva [7] report concentrations of 6.5–7.0 mL·L⁻¹. Transparency was the variable that showed the greatest spatiotemporal differences during the study, especially in the eastern zone. In this area, average transparency in spring did not exceed 6.0 m, a value that corresponds to the increase in effluents with high sediment concentrations entering the system [58].

Regarding the biotic component of the Cape Froward area, it should be noted that the kelp forests do not exhibit seasonal patterns in abundance and density that differ from those previously described in other studies of the Magellan region [63]. In general, differences in wet biomass (kg·m⁻²) were observed among the stations studied, and in both seasons, the central sector of the study area exhibited the highest biomass. This pattern of spatiotemporal differentiation was less evident in density, a common characteristic of annuals kelp forests at south of Chile [64]. The spatial differences, primarily related to wet biomass, may have been influenced by the intense oceanographic dynamics in the central sector, which corresponds to the most exposed section of the Strait of Magellan. This scenario had already been described by Plana et al. [65], who documented that the exposed populations of *M. pyrifera* in Tierra del Fuego showed the highest abundance compared to those located inside Porvenir Bay, arguing that in exposed environments, nutrient concentrations increase, favoring the vegetative development of plants, as noted by Wheeler [66] and Gerard [67].

4.2. Marine Components of the Kelp Forest Ecosystem

4.2.1. Zooplankton

Various reports on southern Patagonia region indicate that much of the variation in zooplankton abundance, composition, and ecological characteristics is driven by seasonal variability [68]. For example, Landaeta et al. [69] observed these variations in the vicinity of the Pedro Channel, the Dyneley Strait, and the Cockburn Channel, recording 65 taxonomic groups in summer (early March 2020) and 50 in winter (June 2020). This pattern has also been reported in kelp forests of the northern Hemisphere, where 34–54 unique taxa have been described in these ecosystems [70,71], far less than those observed in the kelp forests of southern Patagonia. In this sense, the increase in zooplankton abundance during warm periods (southern summer) correlates with an increase in net phytoplankton concentration [60], which becomes available on the food web. In this context, although no marked differences in surface water temperature were observed between spring and autumn in our study area, small differences in salinity were observed across sectors, especially in the eastern sector (S10–S12) and the central sector (S1–S4) around Cape Froward. In both sectors, these lower salinities may partially modulate zooplankton communities and decrease abundance indices during the autumn. This period precedes the southern summer, when the highest freshwater discharges into the system are recorded in the Strait of Magellan, which can reach in some areas in spring ($36.5 \text{ m}^3 \text{ s}^{-1}$ in September) [58]. These inflows generate osmotic stress, which can lead to zooplankton mortality because they are unable to evade low-salinity water masses in environments characterized by intense turbulent mixing [72]. In general terms, our results confirmed the high frequency of early life stages of crustaceans and fish in spring, compared to autumn. This pattern had already been described by other authors, who confirm that in much of the Patagonian region, there is a synchronization of spawning periods during the southern spring, coinciding with the increase in phytoplankton blooms in spring, which can reach an increase of ~64% in their components compared to winter periods in this region [73]. This synchronization ensures the survival of the larval stages and early developmental stages of numerous species that utilize kelp forests, including those of commercial interest (e.g., king crab, snow crab, southern scallop; [74–76]), as key areas for their life cycles, thanks to the availability of an abundant and nutritious food supply [77]. Although it is widely documented that the spatiotemporal dynamics of zooplankton in this region are governed primarily by abiotic variables (e.g., salinity, temperature, turbidity) that in turn depend on seasonal variations in irradiance [78], the biotic component, such as kelp forests, apparently does not exert a direct influence on these dynamics. However, aspects of the coverage and spatial extent of these ecosystems (Mora-Soto et al. in review) that are not addressed in this study could influence zooplankton dynamics around Cape Froward. This aspect is particularly relevant for populations in the eastern sector (S6–S8), where the definition of “kelp forests” is more evident, as the largest dimensions in the entire study area are recorded there [79].

4.2.2. Kelp Forest Fish

The 12 fish taxa recorded in this spatiotemporal study do not differ significantly from other reports in the region, where between 14 and 18 species associated with kelp forests have been identified [34,80]. In recent years, sampling efforts in Southern Patagonia have focused primarily on continental fjord systems [35]. In contrast, studies conducted in sub-Antarctic systems influenced by the ocean demonstrate that the structural complexity of kelp forests supports a significantly greater richness of fish species—up to twice that recorded in inland channel environments—due to the stability of oceanographic conditions [34,81]. In this regard, studies covering a wide latitudinal range and a variety of kelp forest-dominated environments in southern Patagonia have documented up to 25 fish

species [36]. Regarding the structure of the fish community, most studies indicate that more than 40% of the total species richness observed in kelp forests belongs to the family Nototheniidae, with the genus *Patagonotothen* spp. being the most common [34–36,80]. Approximately 67% of the total identified fish taxa exhibit invertivore feeding habits common in high-latitude kelp forest ecosystems [35,80]. These fish, found in rocky reefs—where most kelp forests are located—play an important role as mesograzers predators, thereby benefiting these ecosystems [82]. Although environmental heterogeneity in the Cape Froward area is evident—where protected, semi-protected, and exposed coastal ecosystems converge—this variability is not sufficiently pronounced to generate substantial changes in the population structure of kelp forests (Palacios et al. in review). Consequently, the subsequent effects on fish assemblages are limited, unlike those described in other studies covering a wider latitudinal range, in which the spatial structure of fish communities is determined primarily by the characteristics of the habitats in which these ecosystems occur (Hüne et al. in review). Similarly, the homogeneity in fish species richness observed between spring and autumn in this study may be related to the seasonal transition periods during which sampling took place. In studies that include assessments in summer and winter (extreme seasonal periods), marked changes in the diversity and abundance of fish species associated with kelp forests have been recorded. These patterns are primarily linked to temperature, recognized as the factor with the greatest influence on fish communities [83], as it regulates different stages of their life cycle and exerts indirect effects on the ecosystem by influencing its productivity, structure, and population composition [84]. Likewise, the increased activity of mobile fauna during warmer temperatures typical of summer helps explain the greater diversity and abundance observed during that season [85].

4.2.3. Benthic Invertebrates

In the marine ecosystems of southern Patagonia, numerous studies have highlighted the ecosystemic role of kelp forests [13–16,35,36,39,86], primarily in relation to bioengineering functions [87] capable of modifying abiotic conditions and supporting a complex diversity of associated organisms, facilitating their biological processes. In our study, approximately 76 invertebrate taxa were recorded in kelp forests at different stations around Cape Froward, with no significant variations observed between spring and autumn. In both seasonal periods, the dominant groups were Mollusca, Echinodermata, and Arthropoda. These observations are consistent with research conducted in giant kelp forests in the central part of the Strait of Magellan, which identifies these ecosystems as refuges for various trophic groups, primarily herbivores, including the green sea urchin *A. dufresnii*, several species of mollusks of the order Chitonida, and *Fissurella* sp. [88,89]. Although the temporal composition of the taxa did not show notable variation, the relative frequencies of some groups differed markedly between seasons across the study area. Our study did not address the architecture of kelp forests in detail, focusing instead on their population abundance and density. However, it is well documented that this architecture acts as a filter for key abiotic variables (e.g., light and temperature), allowing for the presence of different groups of invertebrates. In dense canopies, particle retention and water dynamics tend to limit herbivore abundance and favor deposit- and suspension-feeding organisms. This situation is intensified in shallow communities, where the shade from dense canopies extends to the first few meters of the water column [90]. Canopy shading can also have positive effects on some sessile invertebrates by improving spatial competition conditions [91]. Although the sampling methodology used (photo-quadrat) allowed for the census of most invertebrate species present in seaweed forests, it has spatial and structural limitations that prevent accounting for certain relevant taxa, which contribute significantly to the diversity of these ecosystems. For example, the unique architecture of the

attachment disc of *M. pyrifera* provides a specific niche for a wide range of marine organisms; up to 114 invertebrate species have been recorded in its holdfasts [16]. Additionally, our study was conducted during a seasonal transition period between extremes (summer and winter). There is evidence indicating that currents and waves generated by wind or storms, which are more intense during the southern summer, can influence both the structure of giant kelp forests [92] and the biological interactions occurring within them [93]. In fact, since much of the algal biomass is concentrated in the floating canopy, the fronds are exposed to strong drag forces that can dislodge entire plants, in some cases stripping extensive areas of algae [94], thereby altering diversity patterns in these ecosystems. In summary, although it was not possible to establish a direct relationship between benthic invertebrate richness and the presence of kelp forests, it is important to note that our study examined only one spatial dimension of the diversity associated with these ecosystems. Kelp forests are characterized by the creation of different climatic niches across multiple spatial scales [95], which allows them to support a rich and diverse biodiversity throughout southern Patagonia.

4.2.4. Understory of Macroalgae

To date, no studies have described the understory communities associated with kelp forests in this region of southern Patagonia; this study represents the first investigation of this ecosystem component, which has been little explored in relation to its connection with *M. pyrifera*. Most of the available studies have focused on descriptions of the macroalgal components present in different areas of this vast region [13,96–103], as well as in specific studies highlighting *M. pyrifera* forests as areas of high phycological diversity [104], where knowledge of this diversity continues to expand [45]. However, beyond the number of taxa in the understory and the status of *M. pyrifera* as a keystone species [11], our observations indicate that the proportions of macroalgal phyla remain consistent with those reported by other studies in the region. In fact, the community is dominated by red macroalgae, followed by brown algae and, to a lesser extent, green algae, which are found mainly in shallow areas of the marine ecosystems of the Strait of Magellan. Although the 27 macroalgal taxa identified in the understory may be considered a small number compared to other studies that have described more than 70 taxa in different areas of the strait [63,104], it is important to note that this study focused exclusively on the macroalgal groups occurring within the inside margins of the kelp forest, excluding those species inhabiting the shallower and intertidal zones of the rocky coastal ecosystem around Cape Froward. Seasonal variations in understory richness were not pronounced, maintaining spatiotemporal stability in species richness. However, the frequency of occurrence (%) of the main taxonomic groups in the macroalgal understory recorded in spring and autumn showed distinct patterns of variation: some groups increased from spring to autumn, while others decreased over the same period. This behavior could be interpreted as an indicator of system stability, beyond the obvious limitations imposed by seasonal effects and the forest's own structure on solar radiation. Thus, in well-established forests, the shading caused by dense canopies can significantly attenuate incident light throughout the first few meters of the water column [90], for example, by 36% just 20 cm below the canopy [105], while light at the bottom can be reduced almost completely [106,107]. However, this light limitation reflects the different requirements of macroalgae throughout an annual cycle that, in regions of southern Chile, are highly seasonal [108], indicating seasonal turnover in the composition of the macroalgal community. Within this context, and in light of our results, we validate the hypothesis proposed in this study, as we observed spatiotemporal variations in several components of the communities associated with these kelp forests at Cape Froward and in the vicinity of the Strait of Magellan.

5. Conclusions

This study represents the most comprehensive assessment to date of certain components of marine biodiversity associated with the kelp forests at Cape Froward, Strait of Magellan. This analysis enabled the spatiotemporal structure of the zooplankton, fish, invertebrates, and macroalgae that make up the understory of these kelp forests to be described. Overall, the results show that the coastal ecosystems of Cape Froward support a highly diverse and complex community, with characteristics representative of ecological systems of global and regional significance.

Regarding seasonal changes in these ecosystems, most components showed an increase in taxonomic richness during the spring. Seasonality is the primary factor structuring the zooplankton community, leading to clear shifts in its composition throughout the year. For the fish community, seasonal changes influence the presence and relative abundance of cryptic species, which are typical of ecologically structured natural environments and cold waters where kelp forests serve as key habitats. These seasonal shifts result in temporal variations in species distribution across both communities. Regarding the benthic invertebrate community, a stable, spatially heterogeneous structure was observed across the sampling stations, determined primarily by local habitat conditions rather than by seasonal changes. Likewise, the understory macroalgal community exhibited high diversity in association with *M. pyrifera* forests, especially during the southern spring.

These results demonstrate that Cape Froward constitutes a unique ecosystem within the southernmost part of Chile and the American continent. Its high taxonomic richness, the presence of dense *Macrocystis* forests, the diversity of invertebrates and fish, and the specific zooplankton records reinforce the ecological importance of this area. This study provides a solid scientific basis for advancing the protection of kelp forests in southern Chile and, at the same time, raises new questions about the ecological functioning of this ecosystem in Patagonia.

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Abbreviations

LGM	Last Glacial Maximum
PFCS	Patagonian Fjords and Channels System
ANOVA	Analysis of Variance
SIMPER	Similarity Percentage Analysis
nMDS	Metric Multidimensional Scaling
CLUSTER	Hierarchical Clustering
S	Station
Sal.	Salinity
Temp.	Temperature
Trans.	Transparency
n.d.	No data
Freq.	Frequency
Pisc.	Piscivore
Inv.	Invertivore
WB	Wet biomass
S.p.	Spring
A.	Autumn
C.	Central
W.	Western
E.	Eastern

Appendix A

Table A1. Geographic coordinates and values of wet biomass (W.B., kg m⁻²) and density (ind. m⁻²) of *M. pyrifera* beds recorded at each sampling station in Cape Froward, Strait of Magellan, during spring 2024 and autumn 2025. Values correspond to the median of measurements taken at each station for each sampling period.

Sector	Station	Lat. (° S)	Lon. (° W)	Spring 2024		Autumn 2025	
				W.B. (kg m ⁻²)	Density (Ind. m ⁻²)	W.B. (kg m ⁻²)	Density (Ind. m ⁻²)
Central	S1	−53.986	−71.333	2.0	0.3	1.5	0.2
	S2	−53.999	−71.446	2.9	0.2	2.3	0.2
	S3	−53.942	−71.533	2.6	0.3	1.6	0.1
	S4	−53.921	−71.638	1.0	0.1	1.6	0.2
	S9	−53.892	−71.276	1.7	0.3	2.1	0.2
West	S5	−53.739	−71.886	4.5	0.4	1.8	0.2
	S6	−53.705	−71.989	0.3	0.2	0.6	0.2
	S7	−53.766	−71.777	0.6	0.2	1.7	0.2
	S8	−53.813	−71.631	0.6	0.1	1.3	0.1
East	S10	−53.842	−71.097	1.3	0.2	2.0	0.2
	S11	−53.822	−71.037	0.8	0.2	1.1	0.1
	S12	−53.804	−70.997	1.9	0.2	2.3	0.2

Table A2. SIMPER results showing the main zooplankton taxa contributing to assemblage dissimilarity (>50% cumulative) between spring (S.p.) and autumn (A.), based on transformed abundance data. Values include average dissimilarity, percentage contribution, cumulative contribution, and mean abundance per period.

Taxon	Av. Dissim	Contrib. %	Cumulative %	Mean S.p.	Mean A.
<i>Ctenocalanus citer</i>	9.0	13.0	13.0	0.3	1.8
Fish eggs	1.5	2.1	15.1	1.0	0.0
<i>Themisto gaudichaudii</i>	1.5	2.1	17.2	0.0	1.0

Ophiura larvae	1.5	2.1	19.3	1.0	0.0
Cirripedia nauplii	1.5	2.1	21.4	1.0	0.0
Zoea Brachiura NI	1.5	2.1	23.5	1.0	0.0
Nauplio Euphausidae	1.5	2.1	25.6	1.0	0.0
<i>Bougainvilla</i> spp.	1.4	2.0	27.6	0.9	0.0
Calyptopis stages	1.3	1.9	29.5	1.0	0.1
<i>Evadne tergespina</i>	1.3	1.9	31.4	1.0	0.1
Gastropoda larvae	1.2	1.8	33.2	0.8	0.0
Asteroidea larvae	1.2	1.7	34.9	0.8	0.0
Cypris larvae	1.2	1.7	36.6	0.9	0.1
Equinoidea	1.2	1.7	38.3	0.8	0.0
<i>Podon leuckarti</i>	1.2	1.7	40.0	0.8	0.0
<i>Sprattus fueguensis</i>	1.1	1.7	41.7	0.8	0.0
<i>Thysanoessa</i> sp.	1.1	1.6	43.2	0.0	0.8
<i>Centropages</i> sp.	1.1	1.5	44.8	1.0	0.3
<i>Heterorhabdus</i> sp.	1.1	1.5	46.3	0.0	0.8
Pinnotheridae zoea	1.0	1.5	47.8	0.8	0.0
<i>Rhincalanus nasutus</i>	1.0	1.4	49.2	0.8	0.3
<i>Serratosagitta tasmanica</i>	1.0	1.4	50.7	0.3	0.9

Table A3. Results of the SIMPER (Similarity Percentage) analysis identifying the main benthic invertebrate taxa responsible for the dissimilarity in assemblage composition (>50% cumulative) between the central (C.) and western (W.) sectors, based on transformed abundance data. Shown are the average dissimilarity (Av. dissim), percentage contribution (Contrib. %), cumulative contribution (Cumul. %), and mean abundance per sector (Mean C. and Mean W.).

Taxon	Av. Dissim	Contrib. (%)	Cumul. (%)	Mean C.	Mean W.
Polychaeta	2.3	3.8	3.8	1.0	0.1
<i>Margarella violacea</i>	1.9	3.1	7.0	0.3	1.0
<i>Anasterias antarctica</i>	1.9	3.1	10.2	0.8	0.1
<i>Arbacia dufresnii</i>	1.8	3.0	13.2	0.7	0.0
Nudibranchia	1.7	2.8	16.1	0.1	0.7
<i>Nacella deaurata</i>	1.6	2.6	18.8	0.7	0.3
<i>Chaetopterus</i> sp.	1.5	2.6	21.4	0.7	0.3
Ophiuroidea	1.5	2.5	24.0	0.7	0.3
<i>Pagurus</i> sp.	1.5	2.5	26.5	0.0	0.6
Polyplacophora	1.4	2.3	28.9	0.7	0.4
Asteroidea	1.4	2.3	31.3	1.0	0.4
<i>Pseudoechinus magellanicus</i>	1.4	2.3	33.6	0.7	0.4
<i>Pagurus comptus</i>	1.3	2.2	35.9	0.3	0.6
<i>Fissurella</i> sp.	1.3	2.2	38.1	0.5	0.4
Hydrozoa	1.3	2.2	40.4	0.5	0.6
Actinaria	1.3	2.2	42.6	0.6	0.6
<i>Didemnum studeri</i>	1.2	2.1	44.7	0.4	0.4
<i>Lithodes santolla</i>	1.2	2.1	46.8	0.2	0.4
Porifera	1.2	2.1	48.9	0.8	0.6
Cirripedia	1.1	1.9	50.8	0.7	0.7

Table A4. Results of the SIMPER (Similarity Percentage) analysis identifying the main benthic invertebrate taxa responsible for the dissimilarity in assemblage composition (>50% cumulative) between the central (C.) and eastern (E.) sectors, based on transformed abundance data. Shown are the average dissimilarity (Av. dissim), percentage contribution (Contrib. %), cumulative contribution (Cumul. %), and mean abundance per sector (Mean C. and Mean E.).

Taxon	Av. Dissim	Contrib. %	Cumulative %	Mean C.	Mean E.
<i>Margarella violacea</i>	1.4	2.6	2.6	0.3	0.8
<i>Pseudoechinus magellanicus</i>	1.4	2.5	5.1	0.7	0.2
<i>Pagurus comptus</i>	1.4	2.5	7.6	0.3	0.8
Nudibranchia	1.4	2.4	10.1	0.1	0.7
<i>Anasterias antarctica</i>	1.4	2.4	12.5	0.8	0.3
Ophiuroidea	1.3	2.3	14.7	0.7	0.3
Asteroidea	1.2	2.2	17.0	1.0	0.5
<i>Antholoba achates</i>	1.2	2.2	19.2	0.0	0.5
Polychaeta	1.2	2.1	21.3	1.0	0.5
<i>Didemnum studeri</i>	1.2	2.0	23.3	0.4	0.7
<i>Chaetopterus variopedatus</i>	1.1	2.0	25.3	0.7	0.5
<i>Eurypodius latreillei</i>	1.1	2.0	27.2	0.3	0.5
<i>Fissurella</i> sp.	1.1	1.9	29.2	0.5	0.7
Hydrozoa	1.1	1.9	31.1	0.5	0.5
<i>Psolus</i> sp	1.0	1.9	33.0	0.2	0.5
Pycnogonida	1.0	1.9	34.8	0.2	0.5
<i>Creppipatella</i> sp.	1.0	1.8	36.7	0.1	0.5
Actinaria	1.0	1.8	38.5	0.6	0.7
Polyplacophora	1.0	1.8	40.3	0.7	0.7
<i>Arbacia dufresnii</i>	1.0	1.8	42.1	0.7	0.7
Holothuroidea	0.9	1.7	43.7	0.8	0.7
Ascidacea	0.9	1.6	45.4	0.4	0.2
Decapoda	0.9	1.6	47.0	0.1	0.3
<i>Munida gregaria</i>	0.9	1.6	48.6	0.1	0.3
<i>Trophon geversianus</i>	0.8	1.5	50.1	0.0	0.3

Table A5. Results of the SIMPER (Similarity Percentage) analysis identifying the main taxa responsible for the dissimilarity in assemblage composition (>50% cumulative) between the central (C.) and western (W.) sectors. For each taxon, average dissimilarity (Av. dissim), percentage contribution to total dissimilarity (Contrib. %), cumulative contribution (Cumulative %), and mean frequency of occurrence in each sector are reported.

Taxa	Av. Dissim	Contrib. %	Cumulative %	Mean C.	Mean W.
<i>Codium</i> sp.	2.9	8.4	8.4	0.7	0.1
<i>Desmarestia ligulata</i>	2.1	6.2	14.6	0.4	0.4
<i>Callophyllis variegata</i>	2.1	6.1	20.7	0.1	0.4
<i>Ulva</i> sp.	2.0	5.8	26.5	0.6	0.9
<i>Lophurella hookeriana</i>	1.9	5.6	32.0	0.1	0.4
<i>Sarcopeltis skottsbergii</i>	1.9	5.6	37.6	0.7	0.7
<i>Callophyllis atosanguinea</i>	1.9	5.4	43.1	0.4	0.1
<i>Desmarestia confervoides</i>	1.6	4.6	47.7	0.9	0.7
Crustly algae	1.5	4.3	52.0	1.0	0.7

Table A6. Spearman's rank correlation coefficients (r_s) and associated p -values describing the relationships between environmental variables and species richness (S) of zooplankton, benthic invertebrates, fishes, and macroalgae understory in kelp forests of Cape Froward, Strait of Magellan. Values in each cell are presented as r_s , p . (*) Significant correlations ($p < 0.05$) are indicated in bold. Normality was assessed using the Shapiro–Wilk test prior to correlation analyses, and because one or both variables did not meet the assumption of normality, Spearman's rank correlation was used.

	Normality	Zooplankton (S) (r_s , p -Value)	Kelp Forest Fish (S) (r_s , p -Value)	Benthic Invertebrates (S) (r_s , p -Value)	Macroalgae Understory (S) (r_s , p -Value)
Temperature (°C)	No	−0.08, 0.73	1.00, 0.40	−0.43, 0.03	−0.22, 0.30
Salinity (psu)	No	0.29, 0.17	−0.03, 0.90	−0.14, 0.51	−0.37, 0.08
Dissolved oxygen (mg L ^{−1})	No	0.51, 0.01 *	−0.30, 0.15	−0.02, 0.92	0.14, 0.52
Water transparency (m)	No	−0.57, 0.01 *	0.27, 0.21	−0.04, 0.87	−0.04, 0.84
Wet biomass (kg m ^{−2})	No	−0.16, 0.46	−0.54, 0.01 *	−0.25, 0.25	−0.09, 0.68
Density (ind. m ^{−2})	No	0.35, 0.09	−0.46, 0.02 *	−0.11, 0.60	−0.02, 0.93

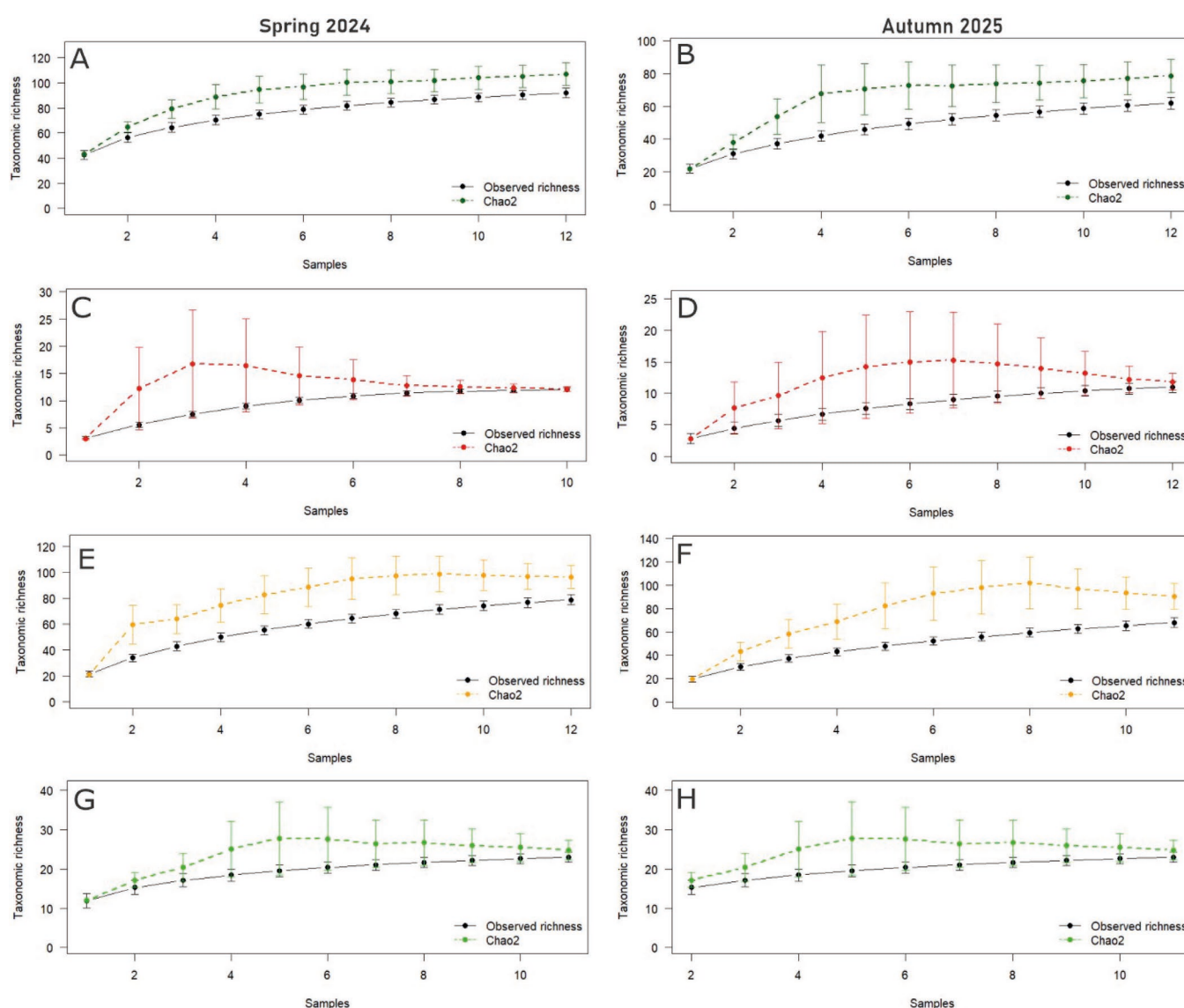


Figure A1. Species accumulation curves of marine communities associated with *M. pyrifera* recorded at Cape Forward, based on observed species and the expected number of species on stations (Chao2 estimator; error bars = standard error). (A,B) Zooplankton; (C,D) Kelp forest fish, (E,F) benthic invertebrates, and (G,H) understory of macroalgae.

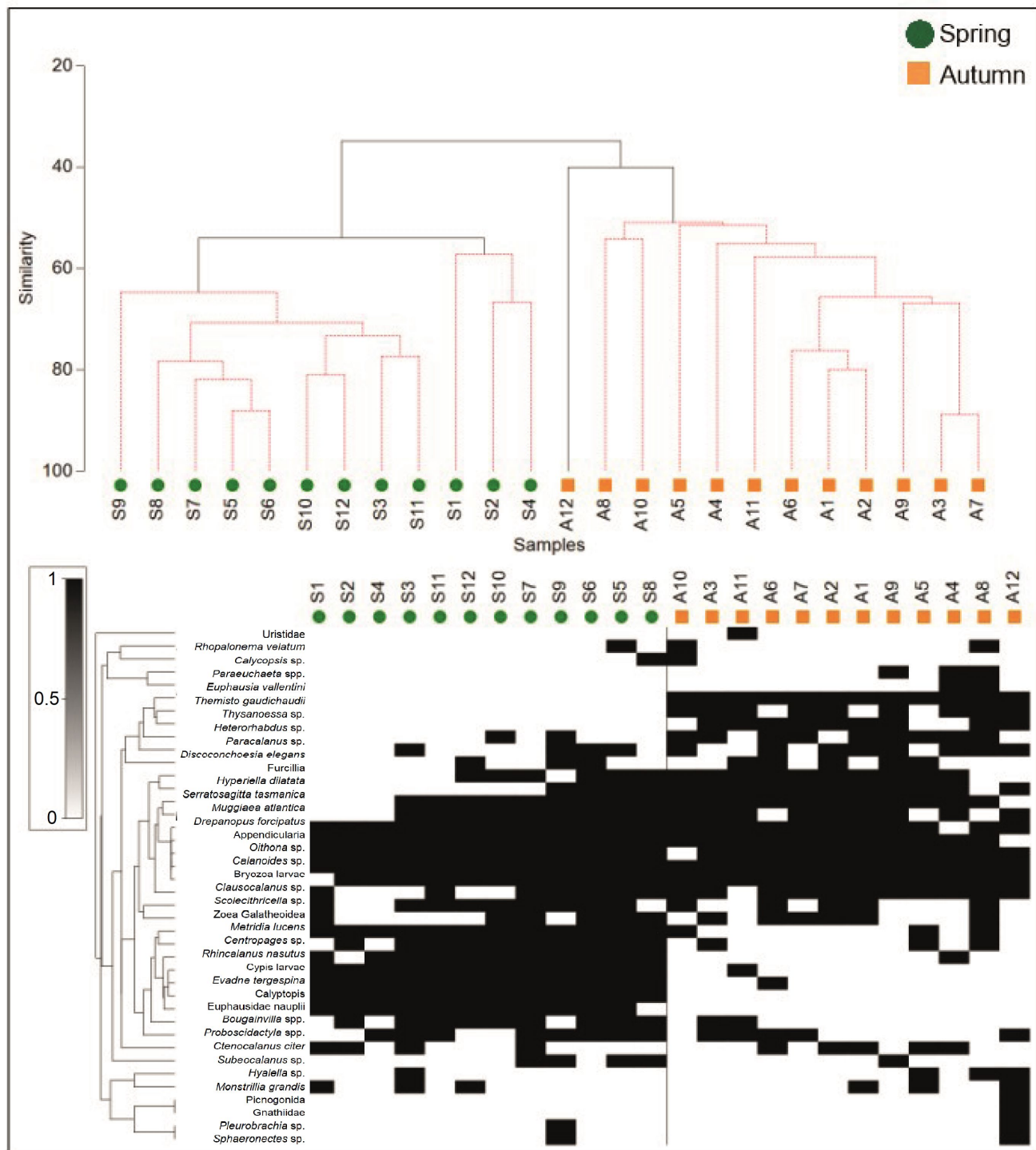


Figure A2. Clustered shadow diagram representing the presence/absence matrix of zooplankton taxa across stations between spring and autumn. White spaces indicate the absence of species in the corresponding transect, while black marks represent the presence of the taxon. The dendrogram on the left illustrates the hierarchical clustering of the identified species.

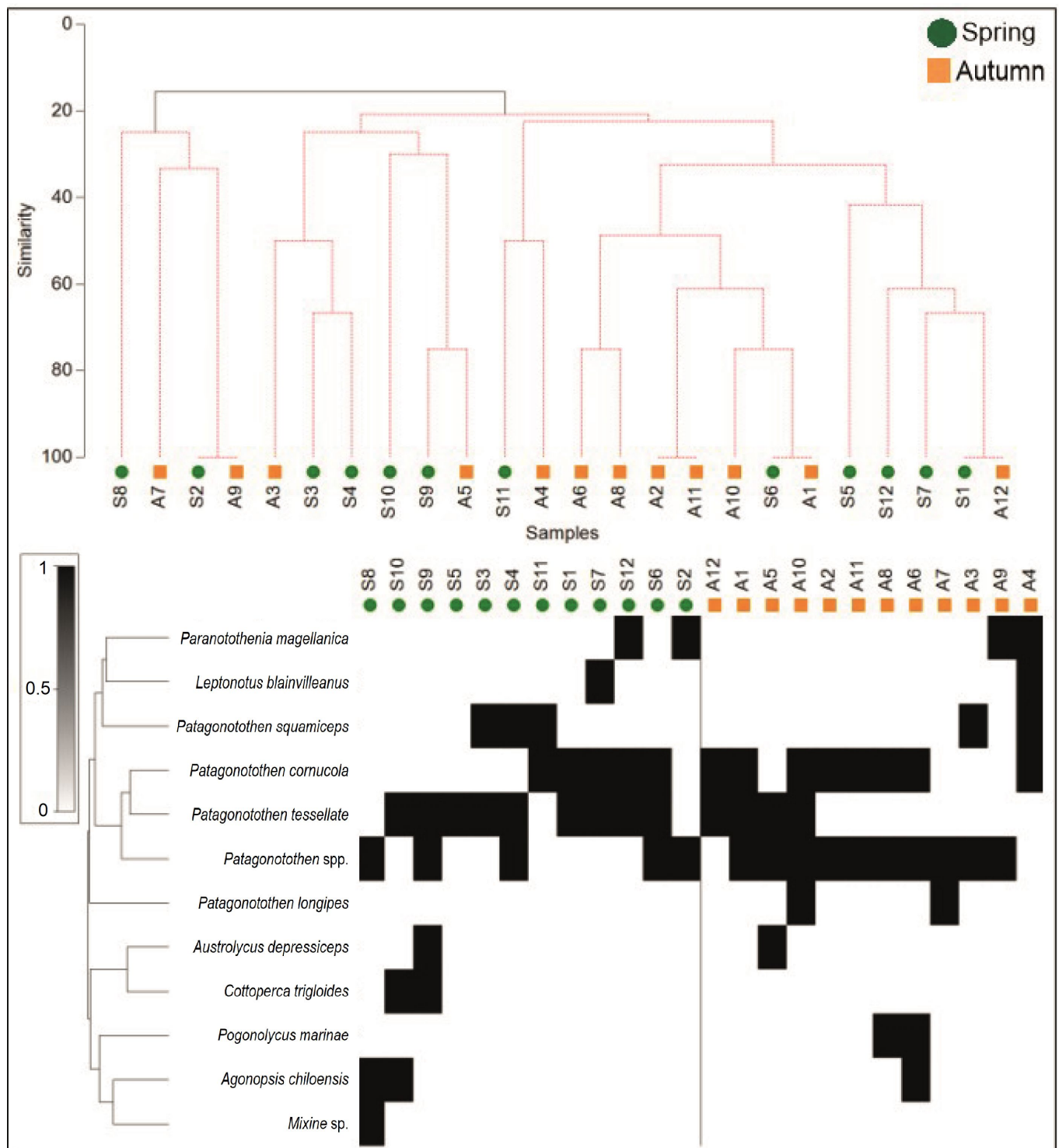


Figure A3. Clustered shadow diagram representing the presence/absence matrix of fish's taxa across stations between spring and autumn. White spaces indicate the absence of species in the corresponding transect, while black marks represent the presence of the taxon. The dendrogram on the left illustrates the hierarchical clustering of the identified species.

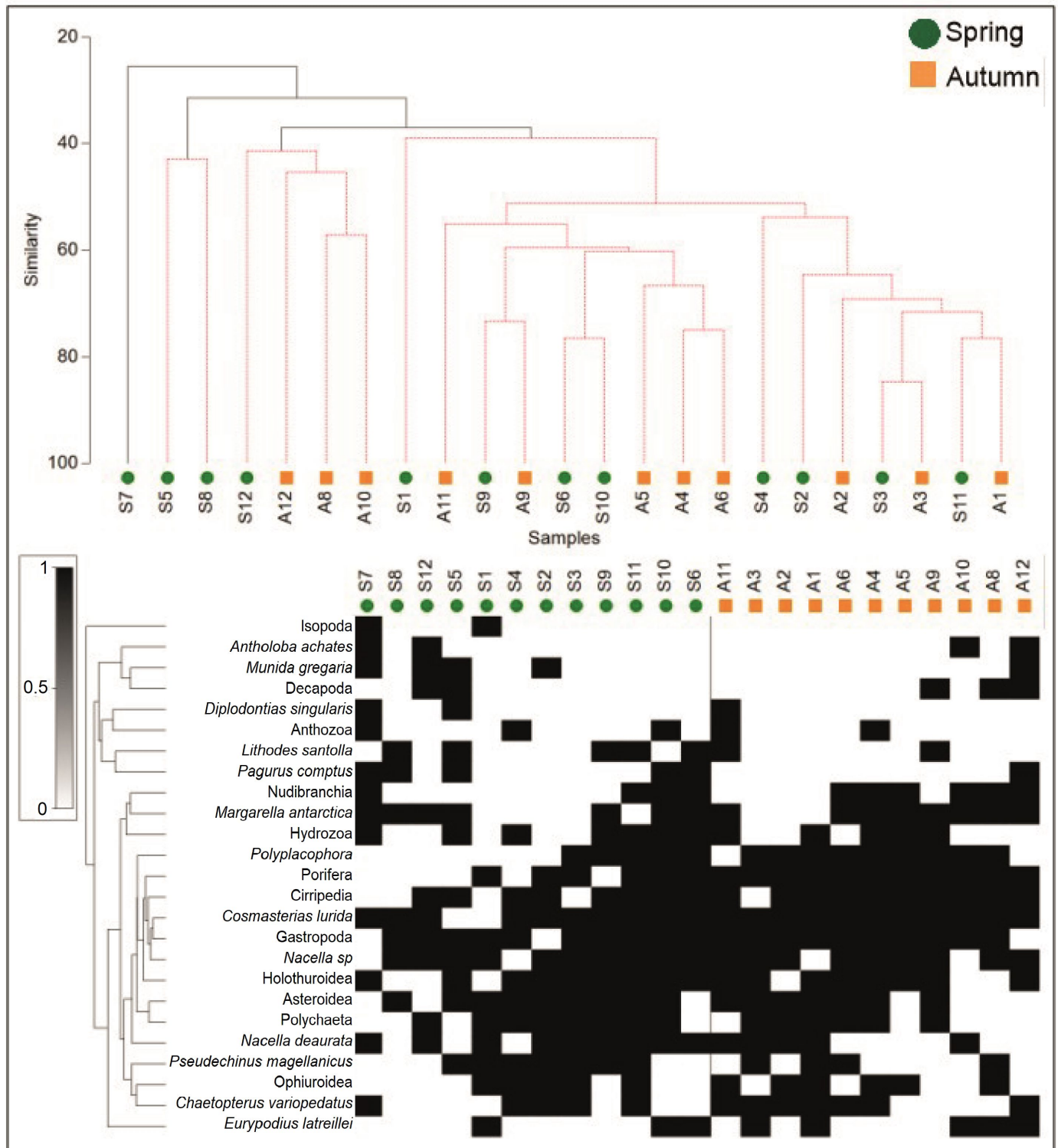


Figure A4. Clustered shadow diagram representing the presence/absence matrix of benthic invertebrates taxa across stations between spring and autumn. White spaces indicate the absence of species in the corresponding transect, while black marks represent the presence of the taxon. The dendrogram on the left illustrates the hierarchical clustering of the identified species.

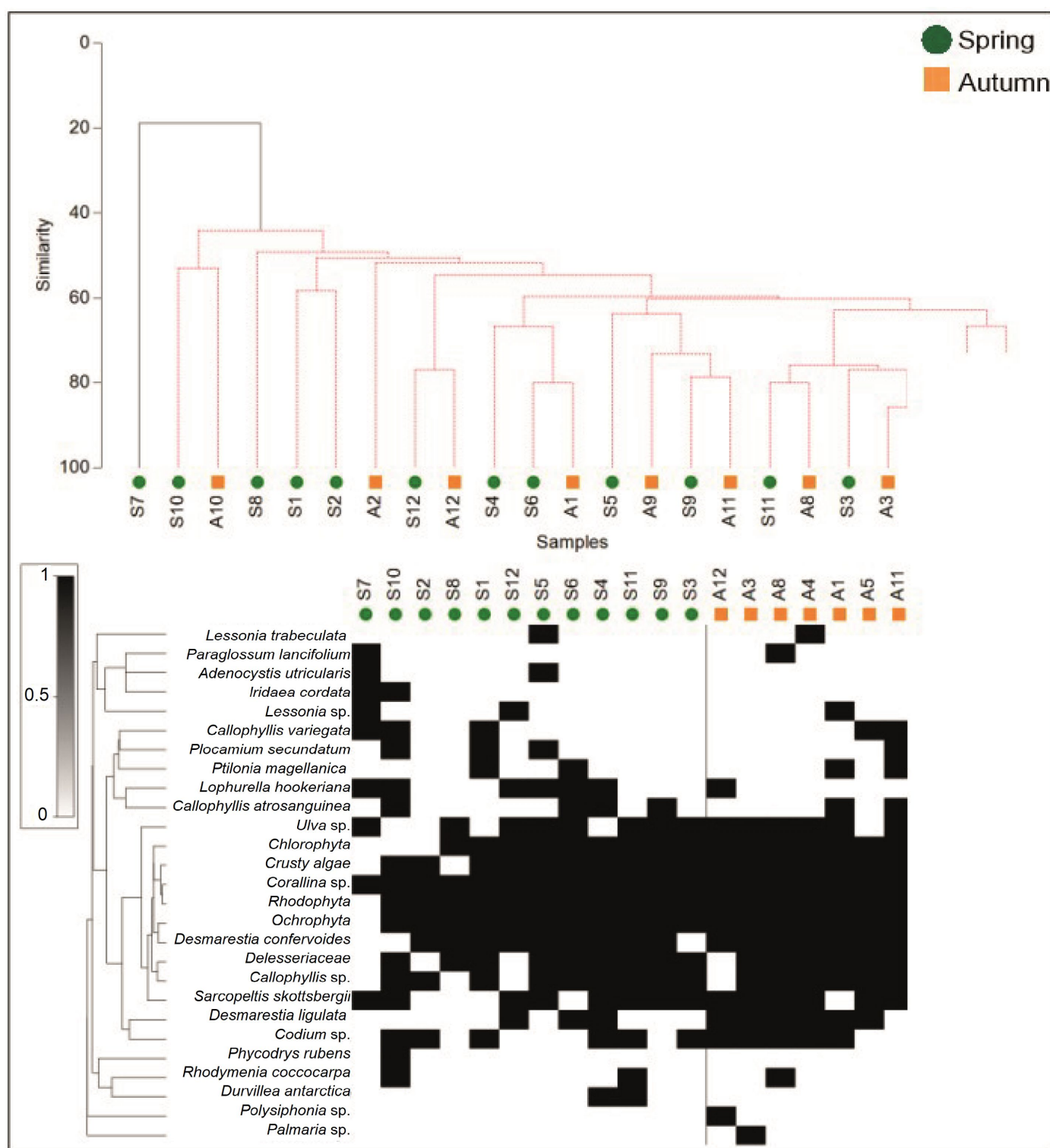


Figure A5. Clustered shadow diagram representing the presence/absence matrix of understory of macroalgae assemblage's taxa across localities between spring and autumn. White spaces indicate the absence of species in the corresponding transect, while black marks represent the presence of the taxon. The dendrogram on the left illustrates the hierarchical clustering of the identified species.

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