



## Life in the surf-zone: Variations of faunal assemblage structure in temperate sandy beaches of the Southwestern Atlantic coast

Sandra M. Fiori<sup>a,b,\*</sup>, Andrea Lopez Cazorla<sup>a</sup>, Ana Martínez<sup>c,d</sup>, M. Cecilia Carcedo<sup>a,b</sup>, Gabriela Blasina<sup>a,b</sup>, Juan M. Molina<sup>a,b</sup>, John Garzón Cardona<sup>a,c</sup>, Jessica Moyano<sup>a,c</sup>, M. Clara Menéndez<sup>a</sup>

<sup>a</sup> Instituto Argentino de Oceanografía, (IADO-CONICET-UNS), Florida 8000, B8000FWB, Bahía, Blanca, Argentina

<sup>b</sup> Departamento de Biología, Bioquímica y Farmacia, Universidad Nacional del Sur, San Juan 670, B8000FWB, Bahía, Blanca, Argentina

<sup>c</sup> Departamento de Química, Universidad Nacional del Sur, B8000FWB, Bahía, Blanca, Argentina

<sup>d</sup> Instituto de Química del Sur, INQUISUR-CONICET-UNS, Av. Alem 1253, B8000FWB, Bahía, Blanca, Argentina

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### ABSTRACT

This study explores the changes of biological descriptors -richness, diversity and abundance-of faunal surf-zone assemblage along a temperate coastal fringe. Three mesotidal sandy beaches with different morphodynamic states, adjacent to an estuarine zone, were seasonally sampled during a year. Zooplankton, zoobenthos and fish samples were taken in the surf-zone and a set of potential explanatory environmental variables were measured and/or quantified. Generalized linear models (GLM) were employed to compare environmental and biological variables between beaches and seasons. Beaches varied from tide-dominated flat to tide-modified reflective to intermediate. The assemblage included 108 taxa, of which few were numerically dominant. Richness of each biological group was similar along the shore and higher values of  $\alpha$ -diversity were associated with minimum values of total abundance.  $\beta$ -diversity was mainly a consequence of species turnover, mostly due to changes in zoobenthic and zooplanktonic taxa. Results of GLM test showed that seasons and beaches have an interdependent effect on the abundance of the surf-zone assemblage. All biological groups showed marked seasonal variability in its occurrence, possibly associated with environmental variables, such as temperature and photosynthetic pigment concentrations. Zooplankton and fish groups reached maximum abundance, during autumn and spring respectively, in tide-modified beaches where the surf-zone was well developed and waves reached higher heights. Zoobenthic abundance peaked in beaches with narrower surf-zone and lower wave energy, during autumn, winter and spring, which could be advantageous for those taxa that escape from predators by burying or for species that actively swim near the seafloor. The copepod *Acartia tonsa*, the clupeidae fish *Ramnogaster arcuata* and the mysids *Arthromysis magellanica* and *Neomysis americana* all typical species of the neighboring estuary, were the main responsables for these distribution patterns. The connection of the surf-zone with the adjacent estuarine area is also evident by its role in enriching the dissolved organic matter of surf-waters.

### 1. Introduction

The surf-zone of sandy beaches is considered a semi-closed system and it represents a transition area between the dunes and the open sea, playing an important role in transporting and exchanging organic matter and nutrients between these adjacent environments (McLachlan and Defeo, 2018). Primary productivity of this zone is mainly given by a few species of diatoms, which thrive in variable surf conditions. Surf-zone primary production rates are less well known but are certainly more

variable. They are the base of the food chain in the inshore of the sandy beaches (Odebrecht et al., 2010, 2014).

Surf-zone assemblages are composed of a scarce number of resident species, some of them endemic, as well as transient species that arrive at these waters from neighboring ecosystems (for example offshore zones, estuaries, rivers, etc) taking advantage of the turbulent conditions generated by the waves that allow them to feed, spawn or breed safely from predators (McLachlan and Defeo, 2018). Some species in the surf swim freely into the water column, like zooplankton and fishes, and

\* Corresponding author. Instituto Argentino de Oceanografía, (IADO-CONICET-UNS) Florida 8000, B8000FWB, Bahía Blanca, Argentina.

E-mail address: [sfiori@criba.edu.ar](mailto:sfiori@criba.edu.ar) (S.M. Fiori).

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others are associated with the bottom, like epi and hyperbenthic invertebrates. These two components are linked by interspecific interactions such as predator-prey relationships, which affect community structure (e.g. composition, richness and diversity) and population dynamics parameters (e.g. recruiting, abundance and mortality) (McLachlan and Defeo, 2018). The zooplankton of the surf-zone may include copepods, small prawns and larval stages of some benthic taxa (McLachlan and Defeo, 2018; Menéndez et al., 2019; Baleani et al., 2020, 2021). The ichthyofauna composition in these zones is variable and generally dominated by larval and/or juvenile stages, which could indicate that these are important breeding and nursery areas (Marin Jarrin et al., 2009; Olds et al., 2018). The benthic invertebrates are mainly represented by peracarid crustaceans with the additional presence of decapods, euphausiids, pycnogonids and mollusks (Beyst et al., 2001a; Carcedo et al., 2015).

The dynamics of most marine coastal ecosystems are driven by environmental variables. The surf-zone is no exception: water temperature, precipitations -and their associated changes in salinity- and suspended sediments have been pointed up as the main structuring factors of zooplankton distribution (e.g. Menéndez et al., 2019; Stull et al., 2016). Other events like wind regime and tidal cycle also affect zooplankton dynamics on a shorter time-scale (Baleani et al., 2020, 2021). Research on macrobenthic organisms and fishes has suggested that the compositions of biological assemblages are highly variable, changing with fluctuations in physical parameters as water temperature, hydrodynamic factors such as wave height and turbidity, and the biomass of drifting algae or seagrass (Beyst et al., 2001a,b; Olds et al., 2018) and, as a consequence, they can affect the productivity of these environments (Janssen and Mulder, 2005; Marin Jarrin and Shanks, 2011; Sato et al., 2008).

The turbulent nature of surf-zone waters renders the design of a reliable sampling strategy a significant challenge (Odebrecht et al., 2014). Partly due to these difficulties, this environment has received less attention than other coastal ecosystems worldwide. A handful of studies exist on some aspects or components of the surf-zone of the Atlantic coast of South America. Some address physico-chemical variables (Menéndez et al., 2016), others studied the biotic components, such as phytoplankton (Odebrecht et al., 2010, 2014), zooplanktonic (e.g., Costa et al., 2011; Menéndez et al., 2019), benthic (Carcedo et al., 2015) and fish (Felix-Hackradt et al., 2010) assemblages of the surf-zone fauna. However, a holistic approach to the study of the surf-zone ecosystem, one that encompasses different biotic components, together with environmental variables and their interaction, has not been attempted so far.

The present study was conducted in the littoral fringe of the southwestern Buenos Aires Province (Argentina), a temperate area characterized by a continuum of sandy beaches that vary slightly in their morphodynamic state (Carcedo et al., 2015). Literature suggests that the Bahía Blanca Estuary (BBE), exports warm waters and sediments to the sea around these sandy beaches, turning the adjacent inner shelves into a transitional environment between the estuary and the open beaches located to the north of the Buenos Aires Province (Delgado et al., 2016; Martos and Piccolo, 1988; Menéndez et al., 2015). The objective of the present study was to describe seasonal and spatial variations in the composition and abundance of surf-zone faunal assemblage in beaches with different morphodynamic types/states. We hypothesized that biological descriptors of the assemblages -richness, diversity and abundance-change in relation to a set of potential explanatory environmental variables (photopigments concentrations, dissolved organic matter, nutrients and hydrological characteristic) and the morphodynamic type/state of beaches (wave climate, tidal regime, sedimentological characteristic).

## 2. Materials and methods

### 2.1. Study area

The study area, located in the inner shelf of the northern zone of "El Rincón" (38°–41° S), comprises a 60 km long shoreline between the BBE and the mouth of the Sauce Grande River (Fig. 1A). The area is characterized by wide sandy beaches backed by extensive dunes covered by native grassland or, near touristic centers, fixed by exotic vegetation or replaced by urban constructions (Fig. 1B–D). These beaches have a mesotidal regime with semidiurnal tides with a maximum amplitude of 3.58 m (Servicio de Hidrografía Naval, 2021). Mean wave height in the study area varies between 0.25 and 1.5 m. Maximum wave height occurs in spring and minimum in winter (Bustos, 2012; Delgado et al., 2012). The area has a temperate climate; the average temperatures oscillate between 14 and 20 °C and the mean annual precipitation is 650 mm. Prevailing wind directions came from N, NW and NE, whereas the strongest ones came from the S, SE and SW, especially in spring and summer (Bustos, 2012).

### 2.2. Sampling design

The surf-zone assemblage was sampled seasonally for one year, in November 2015 (spring), February 2016 (summer), May 2016 (autumn) and August 2016 (winter) in three mesotidal oceanic sandy beaches: Punta Tejada (S1), Pehuen C6 (S2) and Monte Hermoso (S3). These beaches are located 18, 28 and 52 km away from the mouth of BBE (point of reference 38° 57' S; 61° 53' W), respectively (Fig. 1A). Beach sampling was performed during light hours, within the same week, and began always at low tide. Due to the difficulties involved in sampling in a highly variable environment such as the surf-zone, wind speed did not exceed 10 km/h during the week previous to the sampling in order to avoid high turbulent conditions.

### 2.3. Morphodynamic type/state of beaches

In each sampling date, beach profiles were made perpendicular to the shoreline using the methodology described in Emery (1961) to determine *Beach Width* (distance from the dune baseline to low tide swash in meters) and the *Tidal Range* (vertical difference between low and high tide levels in meters). *Mean Tide Range* (m) was taken from the Tidal Tables ([http://www.hidro.gov.ar/oceanografia/tmareas/form\\_tmareas.asp](http://www.hidro.gov.ar/oceanografia/tmareas/form_tmareas.asp)). *Surf-zone Width* (m) was estimated by measuring the wave dissipating area on ten images of each beach (one per year) provided by Google Earth, using the measuring tool in Google Earth Pro. *Wave Height* (m) was determined averaging 3 sets of 30 measures of breaking waves. Each measurement was performed with graduated poles against the horizon (McLachlan et al., 2018). Finally, *Wave Period* (s) was estimated during low tide as the time interval between 10 consecutive breaking waves and dividing by 10.

Beach type and state were determined for each studied beach using the model proposed by McLachlan et al. (2018), comprising two steps. The Relative tidal range (*RTR*) index was used to identify the relative importance of tides and waves in controlling beach type (step 1). *RTR* is a dimensionless index that measures the relative importance of the influence of waves and tides in beach morphology (Masselink and Short, 1993) and is defined as:

$$RTR = \frac{Tide}{Hb} \quad (1)$$

where *Tide* is *Mean Tide Range*; and *Hb* is the *Wave Height*. Low values (<3) indicate wave-dominated beaches, values in the range 3–10 indicate tide-modified beaches, and values > 10 indicate tide-dominated beaches (McLachlan et al., 2018). Wave period (s) was used to identify the broad morphodynamic state in swell and sea environments (step

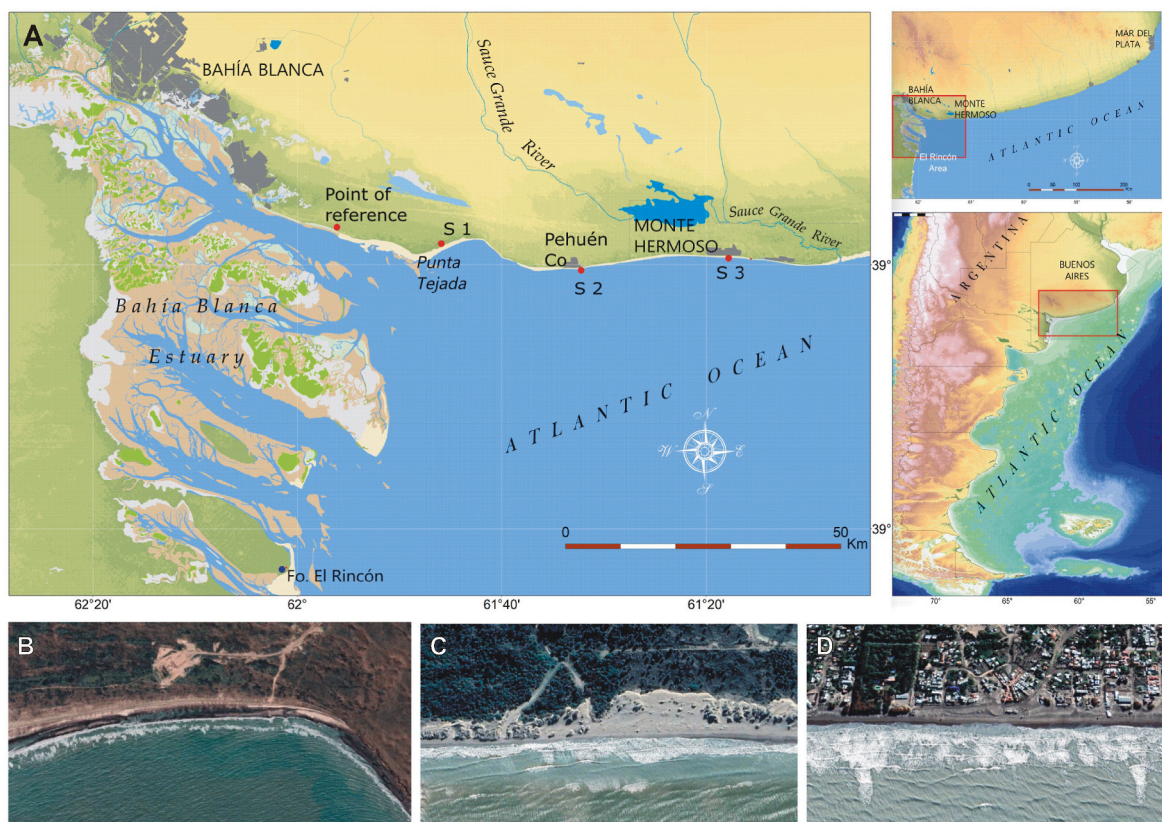


Fig. 1. A) Map of the southeast coast of the Buenos Aires province, showing the beaches where the surf-zone was sampled (A) S1 - Punta Tejada, B) S2 - Pehuén Co., C) S3 - Monte Hermoso). Map made by W. Melo. Images taken from Google Earth.

2). In swell environments, wave action is long period ( $T > 8$  s, typically 10–15 s) and, although variable, comes from the open ocean, while in sea environments wave action is locally generated by local winds and is more intermittent with short wave periods  $< 8$  s (usually 3–5 s) (McLachlan et al., 2018).

Sediment samples ( $n = 12$ ) were taken from the surf-zone with a cylinder of 10 cm diameter and 5 cm depth, and then washed, dried, homogenized and weighted before mechanically sieving through a traditional sieved column. Mean grain size and sorting were classified following the Wentworth scale and computed according to Folk and Ward (1957) and results were expressed as  $\phi$  values ( $\phi = -\log_2$  diameter in mm). The percentage of pelitic fraction, defined as the silt-clay fraction ( $< 63$   $\mu\text{m}$ ) was calculated for each sediment sample. The content of organic matter was estimated by measuring the loss of weight on ignition at 500 °C for 12 hs, after oven-drying to constant weight (15 hs at 105 °C) (Luczak et al., 1997).

#### 2.4. Physicochemical characterization

Water salinity, temperature (°C), pH, dissolved oxygen ( $\text{mgL}^{-1}$ ) and turbidity (NTU) were measured *in situ* with a multiparameter sensor (Horiba U-10). For the photosynthetic pigments, water samples ( $n = 12$ ) were filtered (GF/F, 47 mm, Whatman) and kept frozen ( $-20$  °C) until extraction with acetone:water (9:1) overnight at  $-20$  °C. Chlorophyll-a (Chl-a) and phaeopigment (Pha) were quantified with a fluorometer (Shimadzu RF-5301). Additional filtrates were kept frozen at  $-20$  °C for subsequent inorganic nutrient determinations. Ammonium ( $\text{NH}_4^+$ ), nitrate ( $\text{NO}_3^-$ ), nitrite ( $\text{NO}_2^-$ ), phosphate (DIP) and silicate (Si) were measured according to standard methods (Strickland and Parsons, 1972). The sample aliquots to determine Si were thawed at 4 °C in the dark to ensure the depolymerization process. After thawing was complete, the samples were taken out of the refrigerator, mixed, and kept at

room temperature overnight before analysis (Zhang and Berberian, 1997). Dissolved inorganic nitrogen (DIN) was calculated by the sum of  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and  $\text{NO}_2^-$  concentrations. Dissolved nutrient ratios were calculated (DIN:DIP and Si:DIN) in order to evaluate possible limitations in phytoplankton growth. Fluorescent dissolved organic matter (FDOM) duplicate samples (20 mL) were filtered through combusted GF/F filters (5h, 450 °C) and collected in combusted glass vials (8 h, 450 °C). Samples were brought to room temperature before analyses. Fluorescence spectra were recorded with a spectrofluorometer (Shimadzu RF-5301). The bandpass was set to 5 nm and 2 nm for excitation and emission respectively. Absorbance based inner filter corrections (McKnight et al., 2001), and blank (ultrapure water) subtractions, were applied to all samples before normalization to Raman units (Murphy et al., 2010). Estimation of dissolved humic-like and protein-like substances was carried out at the wavelengths proposed by Coble (1996) (Table S1 of the Supplementary Material) and three fluorescence indices were determined to assess possible sources and diagenetic state of DOM (Table S2 of the Supplementary Material).

#### 2.5. Biological assemblage

Biological sampling was carried out walking and hand-towing the respective gear for 200 m parallel to the shoreline in surf-waters ranging from 0.7 to 1.2 m in depth. Zooplankton samples ( $n = 12$ ) were collected near the surface layer using a conical open-mouth net with a 200- $\mu\text{m}$  mesh size, equipped with a General Oceanic® flow meter. Zoobenthic samples ( $n = 12$ ) were taken with a benthic sledge with a 50  $\times$  20 cm frame, equipped with a 1.5 m length and 500  $\mu\text{m}$  mesh net. This sledge collects the organisms living on the surface of soft-bottom sediments (epibenthos), and those occupying the uppermost benthic layer, swimming at short distances from the bottom (hyperbenthos). Fishes were captured using two types of nets: one with a 1 cm (knot-to-knot) mesh



and the other with a 1000  $\mu\text{m}$  mesh size, and grouped in one sample ( $n = 12$ ). All samples were preserved in 4% formaldehyde and were qualitatively and quantitatively analyzed. Zooplankton samples with high abundances were further sub-sampled (1/10) or in the case of samples with low abundance, the entire sample was examined. Zoobenthos and fish samples were completely analyzed. Organisms were identified to the lowest taxonomic level using the available literature for the area for zooplankton (e.g. Boxshall and Halsey, 2004; Boltovskoy, 1983, 1999; Young et al., 2001), zoobenthos (e.g. Boschi 1964; Bastida and Torti 1967, 1969, 1970, 1973; Boschi et al., 1992; Orenzan 1974; Penchaszadeh 2004; Poore et al., 2009) and fishes (Figueroa 2019).

## 2.6. Data processing and statistical analyses

All biological groups were quantified in terms of abundance. Zooplankton was expressed as individuals per cubic meter ( $\text{ind.m}^{-3}$ ). Fishes and zoobenthos were expressed as individuals per effort unit trawl ( $\text{ind.trawl}^{-1}$  - individuals captured over 200 m). Generalized linear models (GLM) were employed to compare environmental (temperature, salinity, pH, turbidity and dissolved oxygen) and biological (total abundance of each biological group) variables between beaches (S1, S2 and S3), through the four sampled seasons. The effects of both factors were analyzed using a likelihood ratio test (LRT) and Tukey tests for pairwise comparisons. Spearman's correlations were performed to look for associations among the analyzed variables.

The richness and  $\alpha$ -diversity of each biological group were estimated using integrated rarefaction/extrapolation curves based on the first three Hill numbers using the R package iNext (iNterpolation/EXTrapolation) according to Hsieh et al. (2016). Different Hill numbers  $qD$  are defined by their  $q$  "order" (Hill, 1973) as:

$$qD = \left( \sum_{i=1}^S p_i^q \right)^{1/(1-q)} \quad (2)$$

where  $S$  is the number of species in the assemblage and the  $i^{\text{th}}$  species has relative abundance  $p_i$ ,  $i = 1, 2, \dots, S$ . The parameter  $q$  determines the sensitivity of the measure to species relative abundance. When  $q = 0$ , the species relative abundances do not count at all and  ${}^0D$  equals species richness. For  $q = 1$ , referred to here as Shannon entropy, species are weighed in proportion to their frequency, which can be roughly interpreted as the number of "typical species" in the assemblage (Chao et al., 2014). When  $q = 2$  the equation yields Simpson diversity, which can be roughly interpreted as the number of "very abundant species" in the assemblage. To compare the assemblages, data were rarefied, using the maximum reference sample size as the base sample size. All extrapolation curves were used to estimate 95% confidence intervals using a bootstrap method based on 200 replications. These confidence intervals, an alternative to standard statistical testing (Magurran, 2004), were used to analyze the differences between beaches. Non-overlapping 95% confidence intervals, whether rarefied or from extrapolated curves, indicated significant differences at a level of  $<5\%$  (Chao et al., 2014). Additionally,  $\alpha$ -diversity profile curves were constructed, which shows the different Hill numbers as a function of the  $q$  parameter (0, 1 and 2).

In order to analyze the variation in species composition among the three studied beaches, decompositions of  $\beta$ -diversity indices were examined using the approach proposed by Baselga (2010), using the R package *betapart* (Baselga and Orme, 2012).  $\beta$ -diversity was calculated on presence-absence data using the Sorensen dissimilarity measure ( $\beta_{\text{sor}}$ ) and then partitioned into its components of turnover ( $\beta_{\text{sim}}$  - species replacement between sites) and nestedness ( $\beta_{\text{nes}}$  - species loss from site to site).

Non-metric multidimensional scaling (nMDS) analysis was used to assess possible changes in the composition of the biological assemblage among beaches and seasons, through metaMDS function in *vegan* package (Oksanen et al., 2008). The technique was based on a triangular matrix using the Bray Curtis similarity index (Clarke and Warwick,

1994). The assemblage–environment relationships were examined by fitting environmental vectors onto the nMDS ordination using the *envfit* function in the *vegan* package. The significance of the fitted vectors was assessed using a permutation procedure (999 permutations). The effect of beaches and seasons, as well as their interaction, on assemblage composition and the individual species were analyzed using the *manyglm* function in the *mvabund* package (Wang et al., 2012). The *manyglm* was calculated using a negative binomial family. These analyses were performed with R statistical environment (R Core Team, 2021).

## 3. Results

### 3.1. Morphodynamic type/state of beaches

A summary of the physical and sedimentological features of the three sandy beaches is presented in Table 1. Beach Width decreased from S1 to S3, while Surf-zone Width increased gradually from S1 to S3. No surf-zone was found in 50% and 30% of the images analyzed for S1 and S2 respectively (Fig. 1B–D). Images from S3 always had a distinguishable surf-zone (Fig. 1D). In most conditions, spilling type breakers were predominant, with some plunging waves registered sporadically. According to the RTR index, S1 was classified as a tide-dominated beach, while S2 and S3 were classified as tide-modified beaches. S1 always had shorter wave periods, S2 had mean values around the threshold of 8 s, and S3 had longer periods. According to the model proposed by McLachlan et al. (2018), S1 could be classified as tide-dominated flat, S2 and S3 as tide-modified reflective to intermediate beaches. The sediments in the surf-zone of S1 and S2 showed similar features: very fine, moderately selected sand; while sediments in S3 had a larger mean grain size, fine texture and a more uniform grain shape. The pelitic fraction of all sediment samples did not surpass 0.3% and the average concentration of organic matter was below 1.6% loss-on-ignition in S3 and below 1% in S2 and S.

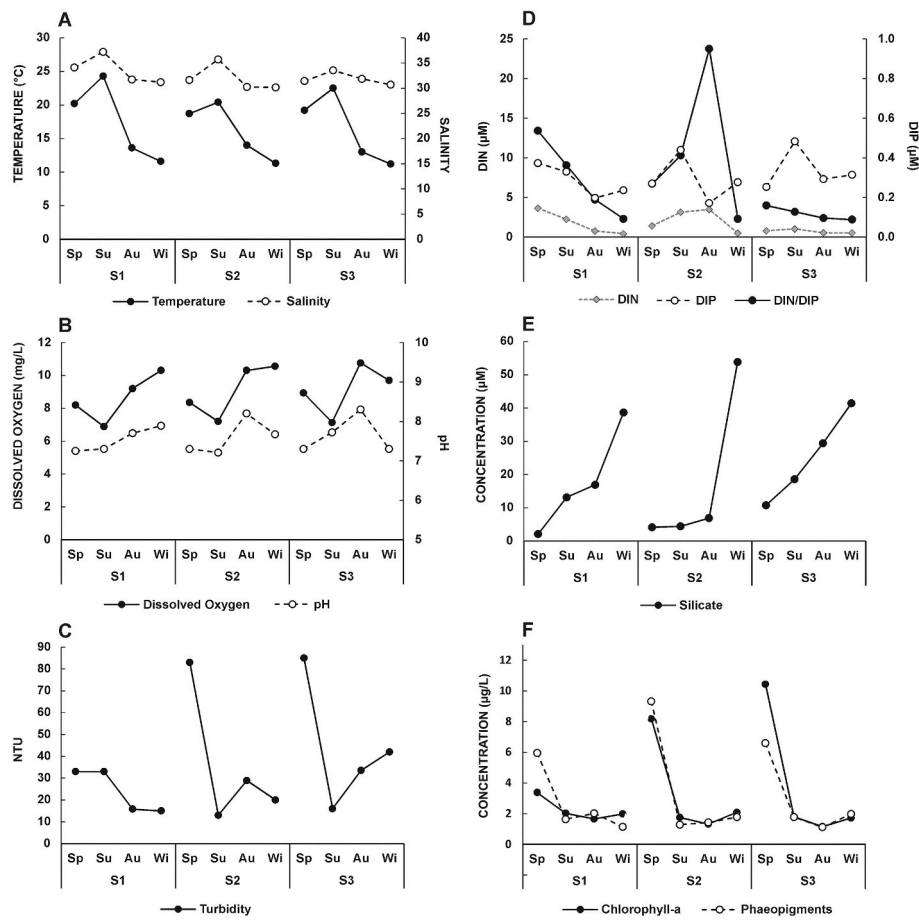
### 3.2. Physicochemical characterization

The mean values of temperature, salinity, pH and dissolved oxygen were similar for the three beaches (LRT,  $p > 0.05$ ), showing significant differences between seasons (Fig. 2A and B). Higher values of

**Table 1**

Summary of physical and sedimentological variables from November 2015 to August 2016 of the surf-zone of each studied beach. Data is provided in means  $\pm$  SD. S1 - Punta Tejada, S2 - Pehuen C3, S3 - Monte Hermoso.

	S1	S2	S3
<b>Beach measures</b>			
Beach Width (m)	141.25 $\pm$ 46.79	111.25 $\pm$ 27.80	120 $\pm$ 34.88
Tidal range (m)	2.83 $\pm$ 0.42	2.41 $\pm$ 0.61	1.88 $\pm$ 0.75
Mean Spring Range (m)	2.41	2.32	2.32
Surf-zone Width (m)	43.40 $\pm$ 46.20	62.86 $\pm$ 41.00	83.17 $\pm$ 34.94
Surf-zone Width Range (m)	0–117	0–114	41–155
<b>Wave</b>			
Height (m)	0.25 $\pm$ 0.22	0.38 $\pm$ 0.16	0.59 $\pm$ 0.76
Height Range (m)	0–0.70	0.20–0.60	0.20–1.00
Period (s)	5.35 $\pm$ 1.41	8.48 $\pm$ 4.06	9.63 $\pm$ 4.32
Period Range (s)	0–6.95	4.80–13.27	5.23–14.29
<b>Sediment of surf zone</b>			
Mean grain size ( $\phi$ )	3.70 $\pm$ 0.34	3.27 $\pm$ 0.42	2.00 $\pm$ 0.13
Sorting ( $\phi$ )	0.31 $\pm$ 0.27	0.38 $\pm$ 0.14	0.97 $\pm$ 0.23
Texture	Very Fine	Very Fine	Fine
Pelitic fraction %	0.19 $\pm$ 0.07	0.29 $\pm$ 0.16	0.08 $\pm$ 0.06
Mean Organic Matter (mg/g)	5.14 $\pm$ 5.03	6.14 $\pm$ 3.77	8.38 $\pm$ 4.99
<b>Beach index</b>			
RTR	19.21 $\pm$ 8.15	7.40 $\pm$ 2.66	3.84 $\pm$ 0.54



**Fig. 2.** Physicochemical variables measured in the surf zone of S1 - Punta Tejada, S2 - Pehuen C o and S3 - Monte Hermoso. A) Temperature and salinity, B) dissolved oxygen and pH, C) turbidity, D) dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphate (DIP), E) chlorophyll-a and phaeopigment and F) Silicate. References: Sp - Spring, Su - Summer, Au - Autumn, Wi - Winter.

temperature were registered during summer, and lower in winter ( $LRT$ ,  $Dev. = 13.91$ ,  $df = 3$ ,  $p = 0.001$ ). Same patterns were registered for salinity ( $LRT$ ,  $Dev. = 1.27$ ,  $df = 3$ ,  $p = 0.039$ ). Dissolved oxygen showed higher values during winter and autumn ( $LRT$ ,  $Dev. = 2.25$ ,  $df = 3$ ,  $p = 0.010$ ), while pH peaked maximum values in autumn ( $LRT$ ,  $Dev. = 0.13$ ,  $df = 3$ ,  $p = 0.030$ ). Mean turbidity did not show a difference between beaches or seasons (Fig. 2C).

Values for DIN did not vary between beaches and seasons ( $LRT$ ,  $Dev. = 3.09$ ,  $df = 2$ ,  $p = 0.22$ ;  $LRT$ ,  $Dev. = 3.90$ ,  $df = 3$ ,  $p = 0.42$ , respectively). The contribution of ammonium to DIN was variable, being less than 50% in S3 and considerably higher in S2 and S1 (up to 90%). DIP were similar in the three beaches ( $LRT$ ,  $Dev. = 0.018$ ,  $df = 2$ ,  $p = 0.219$ ), and showed higher values during summer ( $LRT$ ,  $Dev. = 0.19$ ,  $df = 3$ ,  $p = 0.001$ ) (Fig. 2D). Silicate concentrations showed lower values in spring, than in the rest of the year ( $LRT$ ,  $Dev. = 14.51$ ,  $df = 3$ ,  $p = 0.022$ ) (Fig. 2E). DIP values  $> 0.2 \mu\text{M}$  as well as  $\text{DIN:DIP} < 10$  and  $\text{Si:DIN} > 1$  would indicate N limitation.

Chl-a and Pha showed significant differences between seasons, higher values were registered during spring ( $LRT$ ,  $Dev. = 14.15$ ,  $df = 3$ ,  $p = 0.015$ ;  $LRT$ ,  $Dev. = 16.52$ ,  $df = 3$ ,  $p = 0.007$ , respectively), while during the rest of the year values were significantly lower. During this season of high pigments concentration in surf waters, Chl-a and Pha showed lower values in S1 compared to S2 and S3 respectively (Fig. 2F), showing positive correlations with turbidity ( $r_s: 0.91$ ,  $p < 0.001$ ;  $r_s: 0.84$ ,  $p < 0.001$ , respectively) and negative correlations with Si ( $r_s: -0.62$ ,  $p < 0.05$ ;  $r_s: -0.73$ ,  $p < 0.01$ , respectively).

No significant differences in FDOM values were found between beaches or seasons ( $LRT$ ,  $p > 0.05$ ). The fluorescence signals of the

humic-like groups were identified in all samples and followed the same peak pattern:  $\text{FDOM}_A > \text{FDOM}_M \sim \text{FDOM}_C$ .  $\text{FDOM}_M$  was present in all samples with an intensity similar to  $\text{FDOM}_C$  (Fig. 3A).  $\text{FDOM}_A, C, M$  were negative correlated with Si ( $r_s: -0.66$ ,  $p < 0.05$ ;  $r_s: -0.73$ ,  $p < 0.01$ ;  $r_s: -0.75$ ,  $p < 0.05$ , respectively) and positively correlated with Pha ( $r_s: 0.60$ ,  $p < 0.05$ ;  $r_s: 0.70$ ,  $p < 0.05$ ;  $r_s: 0.76$ ,  $p < 0.01$ , respectively). Also  $\text{FDOM}_{C, M}$  showed a positive correlation with Chl-a ( $r_s: 0.61$ ,  $p < 0.05$ ;  $r_s: 0.69$ ,  $p < 0.05$ , respectively). The  $\text{FDOM}_A/\text{FDOM}_C$  ratio was estimated in the range of 1.39–2.32. Protein-like signals were detected in all samples.  $\text{FDOM}_T$  correlated negatively with Si ( $r_s = -0.70$ ,  $p < 0.05$ ). At S2, mean  $\text{FDOM}_B$  value was almost 1.6 times that of S3, and nearly 2.5 that of S1, suggesting local inputs of protein-like substances (Fig. 3B). FDOM showed a high degree of humification in all beaches ( $\text{HIX} = 3.24 \pm 1.82$ ). For S1, the FDOM is derived mainly from microbial and other biological sources (BIX range 0.94–1.07). For S2 and S3, additional sources might have also contributed to the FDOM values measured (BIX range 0.73–1.14). The FIX ranged between 2.01 and 2.51 with a mean of  $2.33 \pm 0.14$  indicating an aquatic microbial source of FDOM (Fig. 3C).

### 3.3. Biological assemblage

A total of 108 taxa were identified, distributed in 28, 74 and 6 zooplanktonic, zoobenthic, and fish taxonomic categories, respectively (Table S3 of the Supplementary Material). Mean total abundances ( $\pm\text{SD}$ ) of zooplankton, zoobenthos and fish were  $629.50 \pm 812.85 \text{ ind. m}^{-3}$ ,  $1968.42 \pm 2135.68 \text{ ind. trawl}^{-1}$  and  $186.66 \pm 275.02 \text{ ind. trawl}^{-1}$ , respectively; and showed significant interaction effects between seasons and beaches ( $LRT$ ,  $Dev. = 77.04$ ,  $df = 6$ ,  $p = 0.042$ ;  $LRT$ ,  $Dev. = 91.66$ ,

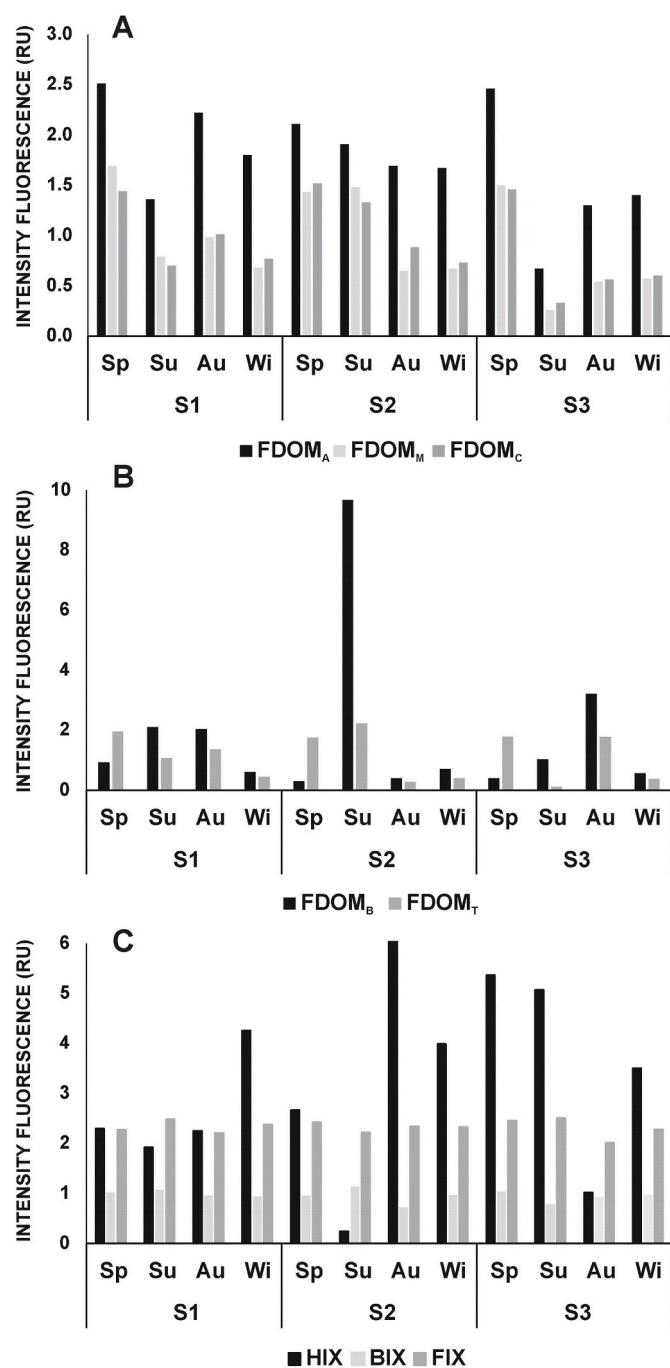


Fig. 3. Variation of mean intensities of the fluorescent components of dissolved organic matter (DOM) A) humik-like; B) protein-like and C) fluorescence indices: Humification Index (HIX), Biological Index (BIX) and Fluorescence Index (FIX) in each studied beach. References: S1- Punta Tejada, S2 - Pehuén Co, S3 - Monte Hermoso, Sp - Spring, Su - Summer, Au - Autumn, Wi - Winter.

$df = 6$ ,  $p = 0.042$ ;  $LRT$ ,  $Dev. = 55.73$ ,  $df = 6$ ,  $p = 0.047$ ; respectively). Therefore, both factors have an interdependent effect on the abundance of the surf-zone assemblage. Zooplankton abundance reached maximum values during summer and autumn, in S2 and S3 respectively (Fig. 4A). For the zoobenthic group, abundance peaked in S1 during spring, and in S2 during autumn and winter (Fig. 4B). During spring, fish group reached maximum abundance in S3 (Fig. 4C).

Within zooplankton, Copepoda was the most important group in relation to the number of taxa (8) followed by Cnidaria (5 taxa) and Decapoda (4 taxa) (Table S3 of the Supplementary Material). The

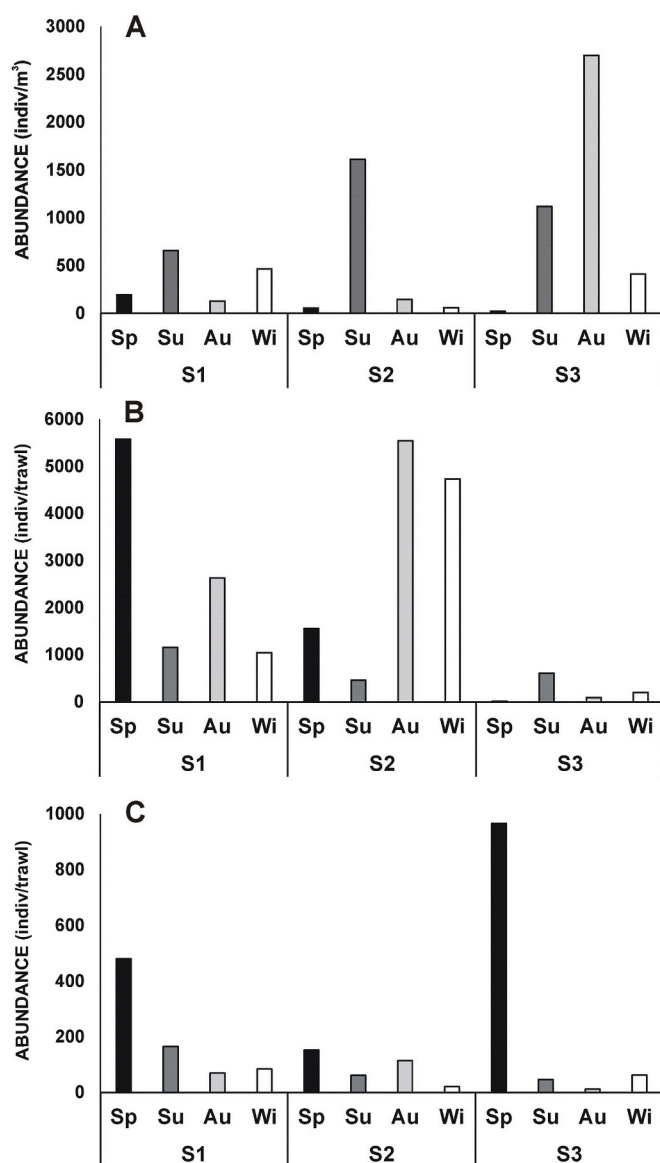


Fig. 4. Abundance of A) zooplankton, B) zoobenthos and C) fishes in each studied beach and season. References: S1- Punta Tejada, S2 - Pehuén Co, S3 - Monte Hermoso, Sp - Spring, Su - Summer, Au - Autumn, Wi - Winter.

copepods *Acartia tonsa* and *Paracalanus parvus* were the most representative in terms of the number of organisms (mean = 473.78 and 107.30  $\text{ind.m}^{-3}$  respectively), representing 67.23 and 15.22% of the total zooplankton abundances. The 97.9% of the total abundance of zoobenthos was represented by peracarid crustaceans, including Isopoda (16 taxa), Amphipoda (12 taxa), Mysida (4 taxa), Cumacea (3 taxa) and Tanaidacea (1 taxa). Other less represented groups were Decapod crustaceans (8 taxa), Ostracoda (1 taxon), Annelida (8 taxa), Cnidaria (4 taxa), Briozoa (9 taxa), Mollusca (5 taxa), Pycnogonida (1 taxon), Equinodermata (1 taxon) and Insecta (1 taxon) (Table S3 of the Supplementary Material). The mysids *Arthromysis magellanica* and *Neomysis americana* were the most representative species in terms of the number of organisms, representing 45.68 and 39.48% of the total benthic abundance (mean = 897.9 and 776.0  $\text{ind.rawl}^{-1}$ , respectively). The 85.97% of the total abundance of fish was represented by clupeids. Six species of teleost fishes, all of them in juvenile stage, were collected from the three sample sites: *Ramnogaster arcuata*, *Odontesthes argentinensis*, *Anchoa mitchilli*, *Brevoortia aurea*, *Pomatomus saltatrix* and *Micropogonias furnieri*. *R. arcuata* was the most abundant species (81.71%) followed by

*O. argentinensis* (13.93%) and *A. maritii* (3.42%) (Table S3 of the Supplementary Material).

The rarefaction curves indicated that zooplankton and fishes were adequately sampled, while the curve of S3 for zoobenthos did not reach an asymptotic value, suggesting that sampling for this group in S3 was not enough (Fig. 5) and therefore excluded from subsequent analysis. Estimated Hill numbers indicated that richness of zooplankton ( $S1 = 18.00 \pm 0.62$ ;  $S2 = 17.00 \pm 0.87$ ;  $S3 = 16.00 \pm 0.83$ ), zoobenthos ( $S1 = 42.12 \pm 6.08$ ;  $S2 = 135.00 \pm 111.55$ ) and fishes ( $S1 = 6.00 \pm 2.19$ ;  $S2 = 4.00 \pm 0.48$ ;  $S3 = 4.00 \pm 0.37$ ) were similar in all beaches, the 95% confidence intervals converged so that point intercepts did not differ significantly. Shannon and Simpson's diversity showed significant differences in all comparisons (except  $^2D$  among S1 and S2 for zoobenthos). Both of them followed the same pattern for each biological group. For zooplankton diversity was maximum in S1 ( $^1D$ :  $S1 = 5.07 \pm 1.18$ ;  $S2 = 1.61 \pm 0.05$ ;  $S3 = 1.94 \pm 0.03$  -  $^2D$ :  $S1 = 3.30 \pm 0.09$ ;  $S2 = 1.21 \pm 0.02$ ;  $S3 = 1.54 \pm 0.02$ ), while zoobenthos diversity was maximum in S3 ( $^1D$ :  $S1 = 3.46 \pm 0.05$ ;  $S2 = 3.05 \pm 0.03$ ;  $S3 = 9.74 \pm 0.44$  -  $^2D$ :  $S1 = 2.25 \pm 0.02$ ;  $S2 = 2.28 \pm 0.02$ ;  $S3 = 5.63 \pm 0.28$ ). Diversity of fishes peaked maximum in S2 ( $^1D$ :  $S1 = 1.93 \pm 0.05$ ;  $S2 = 2.67 \pm 0.08$ ;  $S3 = 1.28 \pm 0.03$  -  $^2D$ :  $S1 = 1.63 \pm 0.05$ ;  $S2 = 2.34 \pm 0.11$ ;  $S3 = 1.12 \pm 0.02$ ).

Dissimilarity value for the total assemblage between beaches was  $\beta_{sor} = 0.47$ , being the turnover ( $\beta_{sim} = 0.45$ ) higher than the nestedness

dissimilarity ( $\beta_{nes} = 0.02$ ). Similar values were obtained for zooplankton ( $\beta_{sor} = 0.46$ ,  $\beta_{sim} = 0.44$ ,  $\beta_{nes} = 0.02$ ) and zoobenthos ( $\beta_{sor} = 0.48$ ,  $\beta_{sim} = 0.46$ ,  $\beta_{nes} = 0.02$ ), while fishes presented the lowest  $\beta$ -diversity values ( $\beta_{sor} = 0.30$ ,  $\beta_{sim} = 0.22$ ,  $\beta_{nes} = 0.08$ ).

Fig. 6 shows the results of the nMDS ordination of the biological samples in a two-dimensional space (stress = 0.12). Variations in surf-zone biological assemblage composition were positively correlated with season sampled (manyglm,  $LRT = 572.7$ ,  $p = 0.014$ ), with the beach sampled (manyglm,  $LRT = 569.8$ ,  $p = 0.001$ ) and across seasons and beaches (manyglm,  $LRT = 797.1$ ,  $p = 0.002$ ). Due to the significant interaction term, both season and beach have an interdependent effect in the structure of the surf-zone assemblages. Mean abundances of 11 taxa were significantly influenced by season and 10 taxa were significantly influenced by beach (Table 2). The vector fitting analysis of environmental variables showed that wave height ( $r^2 = 0.72$ ,  $p < 0.004$ ), turbidity ( $r^2 = 0.70$ ,  $p < 0.005$ ),  $DOM_A$  ( $r^2 = 0.67$ ,  $p < 0.012$ ),  $DOM_M$  ( $r^2 = 0.53$ ,  $p < 0.036$ ),  $DOM_C$  ( $r^2 = 0.65$ ,  $p < 0.016$ ), Chl-a ( $r^2 = 0.71$ ,  $p < 0.009$ ) and Pha ( $r^2 = 0.54$ ,  $p < 0.033$ ) were significantly correlated to the ordination configuration.

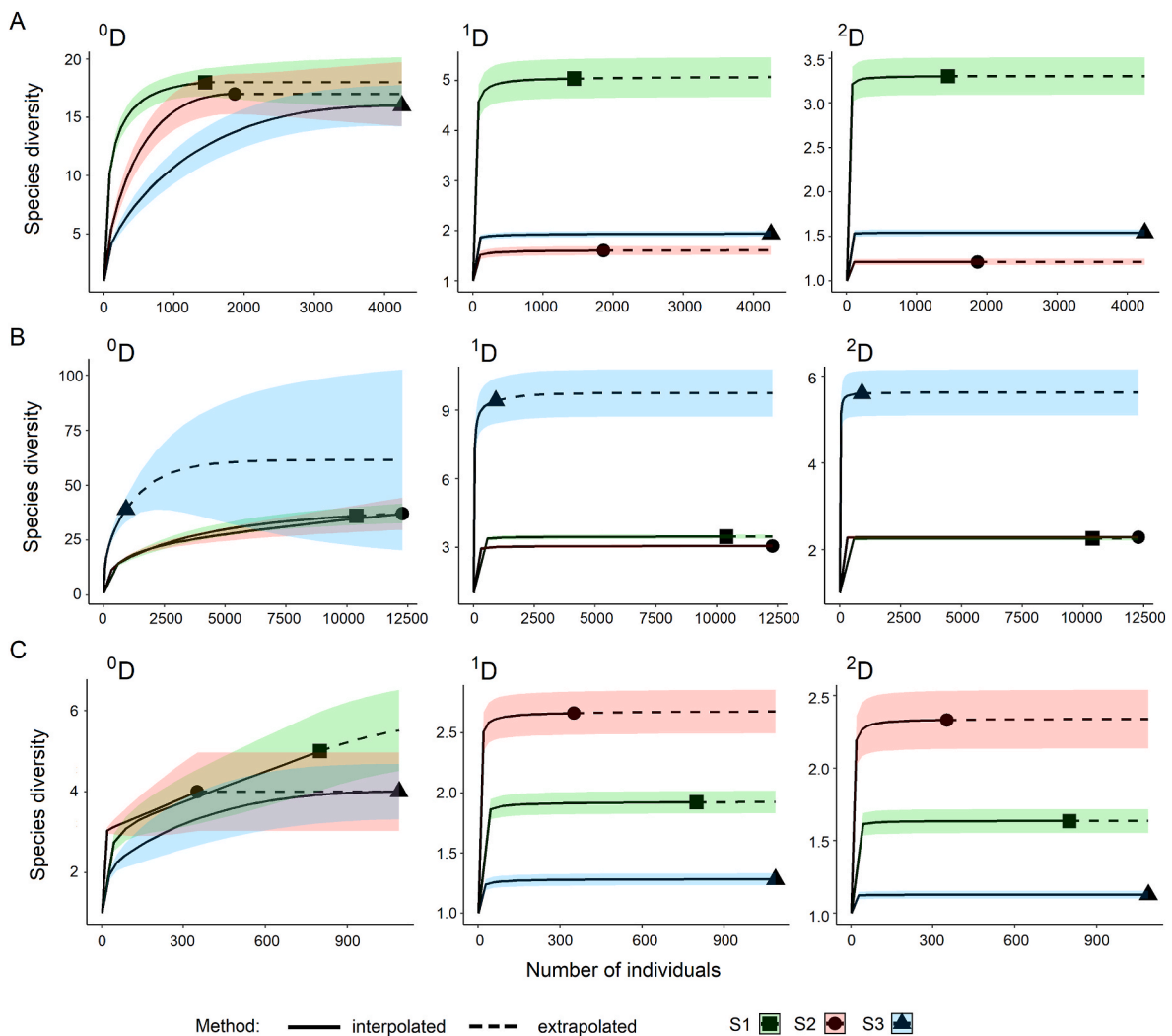
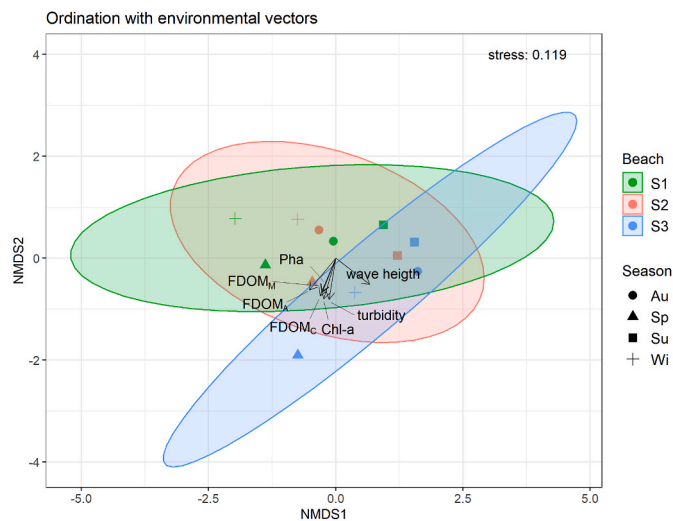


Fig. 5. Hill numbers. Sample-size-based Rarefaction/Extrapolation curves for A) zooplankton, B) zoobenthos and C) fishes. Order  $^0D$  species richness (left panel),  $^1D$  Shannon diversity (middle panel) and  $^2D$  Simpson diversity (right panel). The solid dots represent the reference samples. References: S1- Punta Tejada, S2 - Pehuén Co, S3 - Monte Hermoso.





**Fig. 6.** Non-metric multidimensional scaling (nMDS) ordination of surf-zone assemblage with environmental variables (significant). References: S1- Punta Tejada, S2 - Pehuén Co, S3 - Monte Hermoso, Sp - Spring, Su - Summer, Au - Autumn, Wi - Winter.

## 4. Discussion

### 4.1. Morphodynamic type/state of beaches

The surf-zone width and wave contribution to beach morphology increased from the estuary to the most exposed beach. This pattern agrees with local historical data and the spatial trend detected along the Buenos Aires Province coast, with an increase in mean wave height northwards from the BBE to Mar del Plata (Perez et al., 2017). A long series of wave data registered for S1 and S2, indicated a mean wave height of less than 1 m with periods of 8 s for these beaches (Bustos, 2012; Baleani et al., 2020; Delgado et al., 2012). For S3, wave coastal measurement showed that the more frequent heights were about 1 m, followed by others between 1 and 2 m, reaching up 4 m on some

occasions (Carcedo et al., 2015; Caló et al., 2005). Indeed, Caló et al. (2005) describes S3 as a beach with bi-modal wave period distribution with 38% of the observations greater than 9 s, corresponding to storm waves, and 62% less than 9 s that represents the waves generated locally by the wind. According to the model proposed by McLachlan et al. (2018), used to select the modal morphodynamic type-states of the beaches, and using all available information, S1 could be classified as tide-dominated flat, S2 and S3 as tide-modified reflective to intermediate beaches, and finally S3, during storm periods, as wave-dominated intermediate to dissipative.

### 4.2. Physicochemical characterization of surf-zone

Hydrological characteristics of the surf-zone - salinity, surface temperature, dissolved oxygen, and pH - were in the range of the values registered for the inner shelf waters (e.g. Delgado et al., 2016; Garzón Cardona et al., 2021). In fact, the inner shelf of the southwest of Buenos Aires Province is characterized by temperate (15 °C), highly saline (35), and turbid (37 NTU) waters, with pronounced seasonal variability and homogeneity of the water column all year round (Delgado et al., 2016). These values are related to the plume that comes from the estuary which has a strong seasonal behavior (at least in terms of temperature, salinity, and suspended sediments) (Delgado et al., 2016).

Nitrogen is the limiting nutrient for phytoplankton in temperate regions (Odebrecht et al., 2014), a situation that was particularly evident in S3, where the average DIN concentration was below 2 µM, the theoretical half-saturation constant for uptake (Fisher et al., 1992). DIP values, DIN:DIP and Si:DIN ratios indicated that phosphate concentrations would not limit phytoplankton growth in the study area. The seasonality in the concentration of photosynthetic pigments in the water column, would indicate that phytoplankton biomass peaked during spring. Also, the negative correlation between Chl-a, Pha and dissolved Si suggested that the greatest contribution to the biomass of primary producers would be given mainly by diatoms. The dominance of the phytoplanktonic community by few species of diatoms is a characteristic feature of the surf-zone of exposed sandy beaches (Odebrecht et al., 2014). In the studied beaches, the surf diatom *Attheya armata* has been reported in patches of discolored water reaching up to 60,000 cell/ml (Gayoso and Muglia, 1991). These accumulations are highly variable, in

**Table 2**

Mean abundances of taxa significantly influenced by seasons and beaches and results of likelihood ratio test (LRT). Data is provided in means ± SD. Sp - Spring, Su - Summer, Au - Autumn, Wi - Winter, S1 - Punta Tejada, S2 - Pehuén C6, S3 - Monte Hermoso. Signif. codes: 0.001 '\*\*\*' 0.01 '\*\*'.

TAXA	LTR Dev, p-value	SEASONS				BEACHES		
		Sp	Su	Au	Wi	S1	S2	S3
<b>Zooplankton</b>								
<i>Acartia tonsa</i>	19.39 *	16.0 ± 7.9	1032.0 ± 509.1	794.0 ± 1216.9	53.2 ± 27.3			
<i>Paracalanus parvus</i>	15.36 *	3.3 ± 1.1	40.0 ± 13.0	164.7 ± 247.2	221.3 ± 165.8			
<i>Cyclopoida</i>	4.12 *						0.5 ± 1.0	
<i>Artemesia longinaris (L)</i>	5.02 *							0.7 ± 1.5
<b>Zoobenthos</b>								
<i>Arthromysis magellanica</i>	13.59 *	2060.7 ± 2820.4		287.0 ± 236.6	1244.0 ± 1375.9			
<i>Synidotea marplatensis</i>	9.63 *		47.0 ± 43.5		0.3 ± 0.6			
<i>Pagurus sp.</i>	13.09 **		2.7 ± 2.1					
Ostracoda	11.04 *		3.0 ± 3.5					
Pycnogonida indet.	5.54 *		0.7 ± 0.6					
Briozoo indet. 2	8.32 **		1.0 ± 0.0					
<i>Neomysis americana</i>	26.02 **					586.0 ± 980.8	1739.5 ± 2345.8	2.5 ± 5.0
<i>Leptoserolis bonaerensis</i>	20.63 **					48.0 ± 36.9	17.2 ± 18.7	2.7 ± 1.5
<i>Lyssiamaeidae indet.</i>	12.45 *						2.75 ± 3.2	0.7 ± 1.0
Tanaidacea indet.	8.79 **						1.00 ± 0.8	
<i>Aglaophamus sp.</i>	10.28 *					2.5 ± 4.4		
<i>Brachidontes rodriguezii</i>	14.80 **							2.7 ± 3.1
<b>Fishes</b>								
<i>Ramnogaster arcuata</i>	15.16 *	506.7 ± 442.2	2.3 ± 2.1	49.0 ± 50.6	51.3 ± 2 6.9			
<i>Odontesthes argentinensis</i>	22.00 **	0.3 ± 0.6	83.0 ± 59.7	15.7 ± 6.4	5.0 ± 4.6			
<i>Anchoa marini</i>	11.26 *	25.3 ± 41.3		0.3 ± 0.6		0.2 ± 0.5	18.5 ± 36.3	0.5 ± 1.0
<i>Anchoa marini</i>	15.50 *							
<i>Brevortia aurea</i>	12.59 *					4.2 ± 7.2		1.0 ± 2.0



the short term associated with storm/calm cycles (McLachlan and Defeo, 2018).

The fluorescence intensity peaks and ratios obtained in our samples indicated a marine origin and an allochthonous contribution to the humic-like pool and suggested a predominance of fulvic compounds (FDOM<sub>A</sub>). Numerous studies have reported salt marshes and wetland plants as major sources of DOM to estuarine and coastal waters (Schiebel et al., 2018; Qi et al., 2017). In particular, Zhang et al. (2015) explored the effects of *S. alterniflora* invasion on the structure of DOM components in Yanghe Wetland, and reported that after the invasion the proportions of FDOM<sub>A</sub> increased. These results reinforce the relevance of the influence of the connection between the estuary and the adjacent beaches and show for the first time the role of BBE salt marshes enriching the DOM of the nearby beaches. In addition to the allochthonous contribution, BIX and FIX values suggested that the contribution of aquatic and microbial resources is also important. In our study, protein-like substances were more mutable than humic-like substances. The tryptophan (FDOM<sub>T</sub>) and tyrosine-like (FDOM<sub>B</sub>) fluorophores are considered highly bioavailable materials and are known to be released from phytoplankton activity. FDOM<sub>B</sub> generally has lower fluorescence intensities than of FDOM<sub>T</sub> because it is almost quenched when it occurs in proteins (Lakowicz, 1983). However, our results exhibited this condition only in spring, so the higher intensity of FDOM<sub>B</sub> than of FDOM<sub>T</sub>, being indicative of free tyrosine, is consistent with the presence of highly degraded protein-like material. At S2, the mean fluorescence intensity of FDOM<sub>B</sub> was almost 1.6 times that of S3 and nearly 2.5 that of S1, suggesting that there are local inputs of protein-like substances. In different coastal environments, a major source of FDOM<sub>T</sub> usually is from autochthonous production by phytoplankton (Amaral et al., 2016); however, several compounds of high heterogeneity could contribute to the protein-like signal, particularly in coastal systems of wetlands and estuaries.

#### 4.3. Biological assemblage

The surf-zone assemblage was characterized by many species represented by a low number of individuals and a few dominant, many of them shared with the BBE. High values of  $\alpha$ -diversity registered for each biological group along the studied beaches were associated with low representation of the dominant species. Richness, in terms of the number of species, was similar along the coast, and  $\beta$ -diversity indicated that taxonomic dissimilarity between beaches was around 50%, being mainly a consequence of turnover of low abundant species.

The calanoid copepods *A. tonsa* and *P. parvus*, the species that contributed mostly to the total zooplankton abundance, have been already described as frequent and dominant in surf waters of S2 and S3, showing that they are part of the pool of resident species of the local surf-zones (Menéndez et al., 2019; Baleani et al., 2020). *A. tonsa* showed maximum abundances in summer and autumn, which agrees with previous studies in the region (Menéndez et al., 2019; Baleani et al., 2020). This is an eurytopic species with a cosmopolitan distribution along temperate coastal areas, and plays a pivotal role in the trophic web of the nearby estuary (Lopez Cazorla, 2007; Lopez Cazorla et al., 2011). In estuarine waters of the BBE, *A. tonsa* is found throughout the year with maximum abundances during the summer and minimum ones during winter, when temperature decreases, and the environment becomes unfavorable for the population (Menéndez et al., 2012). On the other hand, *P. parvus* showed the highest abundances in autumn and winter. This agrees in part with previous studies in the study area, where this coastal neritic and small-sized copepod has been mentioned as dominant in winter months, with very low abundances during the rest of the year (Menéndez et al., 2019; Baleani et al., 2020). This species, typical of outer estuarine and inner shelf zones, is one of the primary grazers in terms of biomass and production rate (e.g. Lee et al., 2011) and can ingest ciliates, dino- and nanoflagellates in massive abundances, in addition to phytoplankton (Wu et al., 2010). Species belonging to the

*Paracalanus* genus have already been reported, with similar abundances, in other surf-zones like the Ajuruteua (Brazil) and Matrouh (Egypt) beaches (Costa et al., 2011; Pinheiro et al., 2011, 2013; Aboul Ezz et al., 2014). In all, both copepods are the most abundant species in a coastal fringe of the southwest of Buenos Aires Province, in which total zooplankton abundances seemed to increase toward most exposed beaches. In fact, Menéndez et al. (2019) postulate that food supply accessible to zooplanktonic organisms is apparently higher in the surf-zone near our S3 than in nearby inner-shelf waters, explaining in part the zooplankton abundance patterns obtained in the present study. Beaches with rip currents and deep channels such as S3 in addition to higher wave energy and turbulent conditions, could lead to a retention and concentration of phytoplankton -especially diatom cells- and other low-motility organisms (McLachlan et al., 2018), and a derived-accumulation of zooplanktonic organisms.

The abundance of zoobenthic taxa showed spatial and seasonal variations in the studied coast. The species that most contribute to the higher abundances detected in S1 and S2, the mysid *Neomysis americana*, is widely distributed in the BBE, mainly during warm seasons. This species, together with other mysid found in this study, *Arthromysis magellanica*, migrates from the estuarine area towards the external zone to the area known as “El Rincón” (Cardelli et al., 2006; Viñas and Hoffmeyer, 2016), including the studied sandy beaches located in its northern area. The higher abundances of *A. magellanica* registered during spring and winter, and the absence of organisms during summer, are in coincidence with previous records for the study area (Carcedo et al., 2015) and with the hypothesized migratory pattern for these species.

Another abundant zoobenthic taxa, responsible for the compositional differences among beaches, was the isopod *Leptoserolis bonaerensis*. This species was already described as a member of the surf-zone community of the study area and nearby environments (Carcedo et al., 2015; Escofet et al., 1979; López Gappa et al., 2006), and its higher abundances in beaches near the BBE could be attributed to variations in the physical characteristics of the surf-zone. It has been reported that an increase in sediment grain size caused a significant increase in the burial time of isopods (Griffith and Telford, 1985). Carcedo et al. (2015) proposed that *L. bonaerensis* could avoid coarser sediments because they could entail longer exposure to predators, resulting in the different abundance patterns observed. This is in accordance with the present study, where higher abundances of *L. bonaerensis* were registered in S1 and S2, both beaches with finer sediments in their surf-zones.

It has been suggested that wave action and movements of sediments control the structure of benthic assemblages from surf-zones (Borzzone et al., 1996; Beyst et al., 2001a; Barros et al., 2002), with higher abundance, diversity and richness in beaches subjected to less wave-action. Lower wave energy and less turbulent conditions found in S1 and S2 could be advantageous for species that use burial as a mechanism to escape predation (*L. bonaerensis*) or for free-swimmers that are actively seeking suitable habitat as spawning grounds or feeding zones (*N. americana*), enhancing their abundance in these beaches. These results are in accordance with Beyst et al. (2001a), who found negative correlations between wave height and total benthic invertebrates density, suggesting that under severe weather conditions, good swimmers (e.g. mysids) are capable of leaving the surf-zone and avoiding the turbulence, resulting in a decline of the total density (Colman and Segrove, 1955).

The degree of exposure to wave action is also generally considered to be one of the main structuring factors of fish communities in sandy beaches, with higher teleost abundance as wave exposure decreases (Beyst et al., 2001b; Rodrigues et al., 2015). We did not find a clear spatial pattern associated with wave action; however, seasonal variations seemed to be an important structuring factor. Higher total abundances of fish species were found during spring and summer, which is in accordance with Olds et al. (2018), who mention water temperature as a positive correlator to surf fish abundance. Although we did not find differences in fish richness along the studied coast, the lowest species

diversity driven by highest dominance of *Ramnogaster arcuata* was recorded in S3, the beach with higher levels of wave exposure. Other authors (Rodríguez et al., 2015 and references therein) suggest that an increase in wave energy is generally followed by an increase in dominance of species adapted to these conditions, which could be the case for *R. arcuata*.

Several fish species use surf-zones as nursery areas, feeding grounds and migratory pathways (Bergamino et al., 2011; Olds et al., 2018). *R. arcuata* and *Odontesthes argentinensis*, both with a wide distribution in coastal areas in the Southwestern Atlantic Ocean, could make use of the surf-zones in such ways (Dyer, 2000; Lopez Cazorla et al., 2011). *R. arcuata* is a main functional component of the ecosystem of BBE, where it is one of the most abundant species (Molina et al., 2021). *O. argentinensis* inhabit estuaries and inshore waters, including surf-zone sandy beaches, where it migrates during late spring and summer to reproduce (Beheregaray and Levy, 2000; Molina et al., 2021). These two species have links with BBE, and were the most abundant fish species caught in our study, suggesting either a common distribution along the coast, age-class segregations in different environments, or migrations between BBE and S1-3 (Rodríguez et al., 2015). In our study, all fish were caught at a juvenile stage, which makes it plausible that the surf-zone is acting as a nursery area for these species. Additionally, the seasonal pattern in the abundance of fish found is coincident with the spawning period of the species, another piece of evidence that might support this postulate (Beheregaray and Levy, 2000; Lopez Cazorla & Sidorkewicz, 2009). Additional evidence, such as spawning adults in the proximities, ichthyoplankton studies to confirm the presence and accumulation of larvae in the surf, finding lower densities of juveniles in surrounding environments and site fidelity over time and space (Heupel et al., 2007) would be needed to elucidate the role of these coastal ecosystems as nursery grounds.

#### 4.4. Final remarks

The different morphodynamic type/state of the beaches, given by the different role of waves and tides in the beach morphology, seems to be an important structuring factor for zooplankton and zoobenthic species (higher species turnover) and to a lesser extent, for fishes. All biological groups showed marked seasonal variability in their occurrence, possibly associated with environmental variables, such as temperature and pigment concentrations, and biological traits as the lifecycle and migratory behavior of dominant species. Given the age-class of fish found in the area, the surf-zone of this coast could act as a nursery throughout the year. Many studies have postulated this function for the surf-zone ecosystem, but this has rarely been measured. More work is needed to confirm whether surf-zone represent effective nurseries for juvenile fish (Olds et al., 2018). The connection of the surf-zone with the BBE is not only evident by the number of species shared between both ecosystems, but also by the role of estuarine salt marshes in enriching the dissolved organic matter of surf-waters. Future studies that include estimations of biomass, production, consumption, and trophic relationships of the zoological components inhabiting the surf-zones should be conducted, in order to elucidate biological structuring factors, and how matter and energy flow in this scarcely studied ecosystem.

#### Author contributions

Sandra M. Fiori: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Visualization; Writing - original draft; Writing - review & editing. Andrea Lopez Cazorla: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Supervision; Writing - review & editing. Ana Martínez: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Supervision; Writing - original draft; Writing - review & editing. M. Cecilia Carcedo: Conceptualization; Formal analysis; Methodology; Writing - original draft; Writing - review

& editing. Gabriela Blasina: Conceptualization; Formal analysis; Methodology; Writing - original draft; Writing - review & editing. Juan M. Molina: Conceptualization; Formal analysis; Methodology; Writing - original draft; Writing - review & editing. John Garzón Cardona: Formal analysis; Methodology. Jessica Moyano: Formal analysis; Methodology. M. Clara Menéndez: Formal analysis; Methodology; Writing - original draft; Writing - review & editing.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.csr.2022.104781>.

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