



The importance of a functional approach on benthic communities for aquaculture environmental assessment: Trophic groups – A polychaete view

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ABSTRACT

Polychaetes were studied to assess the effect of aquaculture activity on the seafloor. Very high biodiversity of species was recorded associated with aquaculture centres with Cirratulidae, Spionidae and Paraonidae families being the most diverse and abundant families. The spatial distribution of polychaete trophic groups was the best descriptor for detecting changes on the benthos. Surface and subsurface deposit-feeding species dominated the sites closest to the rafts cages, highlighting *Capitella capitata* and *Cirratulus cirratus* as opportunistic species. While replacement and species succession were observed with increasing presence of carnivores and omnivores in sites further away from the salmon cages and experiencing less impact. Analyses based on the distance of feeding modes and ecological groups from the disturbance source were better indicators of the impact that the traditional community approach or sediment biogeochemistry. Therefore, functional traits studies should always be considered on environmental assessments of benthic systems impacted by aquaculture.

1. Introduction

The aquaculture activity in coastal marine ecosystems is highly harmful and has a negative impact on marine environments around the world (e.g. Weston, 1990; Klinger and Naylor, 2012; Tičina et al., 2020; Dauvin et al., 2020). Direct impacts of open-water aquaculture in different parts of the world have been observed on the seabed under and in the near vicinity of the fish farms where particulate organic waste settles (Stagličić et al., 2017; Jansen et al., 2019) or spreads under different hydrodynamic regimes (Valdemarsen et al., 2015). These inputs cause seafloor organic enrichment and hence change the structure and function of benthic communities and the biogeochemical functioning of the sediment (Tomassetti and Porrello, 2005; Kutti et al., 2007; Edgar et al., 2010; Bannister et al., 2014; Tomassetti et al., 2016). Most of the consequences of this activity on the benthic environment were first recorded in European countries, however, aquaculture is also widespread in Chilean Patagonia where similar impacts on benthos have been reported (Buschmann et al., 2009; Niklitschek et al., 2013; Quiñones et al., 2019).

Shifts in benthic macrofauna from organic enrichment systems, such as succession or colonization events, have been widely described in coastal ecosystems (Pearson and Rosenberg, 1978; Nilsson and Rosenberg, 2000; Rosenberg, 2001). These authors describe that the zone with highest organic pollution is anoxic, and hence without oxygen and fauna. Then, there will be a polluted zone dominated by high abundance of small size animals, termed “opportunistic species” e.g. *Capitella capitata*, a polychaete commonly found in organic-enriched sediments (Grassle and Grassle, 1976; Blake, 2009; Riera et al., 2011; Fernández-Rodríguez and Londoño-Mesa, 2015). Next, there will be a transition zone with a few species and low abundance and biomass and, finally, there will be a “normal population” with richness, diversity, biomass and abundance levels similar to non-impacted sites. This is the classic Pearson and Rosenberg model (Pearson and Rosenberg, 1978), however, variations may be observed according to different responses shown by species.

Polychaetes are a conspicuous and dominant element of benthic communities and their spatial distribution patterns have been investigated widely about environmental variables (Gilberto et al., 2004; Tyler

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and Kowalewski, 2018). Their broad distribution in marine habitats often contributes critically to total macrofaunal diversity and standing stock abundance in benthic marine and estuarine sediments (Manokaran et al., 2013). Polychaetes assemblages show changes in standing stock and function as a response to different environmental variables, with the increase of sediment organic content being one of the most important consequences of anthropogenic activities (Pearson and Rosenberg, 1978; Rosenberg, 2001; Dauvin et al., 2016; Álvarez-Aguilar et al., 2017). Indeed, in polychaetes, these responses reflect different tolerance levels due to size, mobility, growth rates and reproduction (Dauer, 1993; Rivero et al., 2005), but also the great variety of feeding modes (Fauchoald and Jumars, 1979; Jumars et al., 2015). For example, species of the Spionidae can switch their feeding mode depending on food availability, which enables their distributions to be related to organic enrichment (Jumars et al., 2015). Analysis of polychaete trophic structure allows a functional approach, providing a better understanding of the complexity and compositional shifts of these communities (Weston, 1990; Gaston et al., 1998; Pagliosa, 2005; Cheung et al., 2008). These analyses are useful approaches to assess distribution patterns and environmental impacts by aquaculture (Domínguez Castanedo et al., 2012). Changes on functional traits in a far-field component can be used to determine the ecological footprint left by this activity (Wang et al., 2017). In fact, there is growing evidence that grouping polychaete species into feeding groups can highlight information that may be hidden by taxonomic approaches (Cheung et al., 2008; Shuai et al., 2014) and hence shifts in trophic structure may be interpreted as disturbance indicators (Gaston et al., 1998; Domínguez Castanedo et al., 2012).

Polychaetes are particularly good bioindicators of organic pollution (Dean, 2008; Neave et al., 2013; Mangion et al., 2017) because of their high diversity, abundance, and functional significance. Polychaetes can show a quick response due to their short life-cycles. Their wide tolerance to contaminants often means that they are in the first colonization stages after disturbance by organic enrichment (Giangrande et al., 2005; Rivero et al., 2005; Dean, 2008; Quiroga et al., 2012; Mangion et al., 2014). They are often used to define ecological groups (Grall and Glémarec, 1997) as part of biotic indexes employed to understand the environmental-health status of benthic communities (Borja et al., 2000, 2014). Although some indices use all macrobenthic community (Borja et al., 2009), studies show that polychaetes may be used as surrogates for total macrobenthic diversity (Olgard et al., 2003; Olgard and Somerfield, 2000). This reflects a pattern from the species to the order level along with both natural (Włodarska-Kowalczyk and Kędra, 2007) and pollution disturbance gradients (Olgard and Somerfield, 2000).

Despite the importance of functional approach (Gaston et al., 1998; Bremner et al., 2003), in Chile, the aquaculture environmental regulations do not consider trophic structure as disturbance indicators. The importance of marine biotic indexes have also been suggested but studies exploring their use are limited (Quiroga et al., 2013; Borja et al., 2014; Pino et al., 2015). However, the species composition and community structure remain as the main ecological parameters used to indicate environmental conditions on the seafloor. This research analyses the polychaete assemblages standing stock and also considers functional traits for a better understanding of spatial distribution and relationships with environmental parameters. The comparison of functional traits distribution will allow us to know if polychaete feeding modes are good indicators to assess the impacts and the ecological footprint of aquaculture activity at different spatial scales. The scale of impacts on benthos will be defined by values of reference associated with the organic content of sediments, composition, abundance and diversity of polychaete assemblage and the presence or absence of feeding modes and ecological groups (AMBI index) (Wang et al., 2017; Klootwijk et al., 2021).

Therefore, this study analyses if trophic group variations explain the spatial distribution of polychaete communities compared with traditional environmental and geochemistry methodologies. This study will investigate whether sediment composition, organic content and distance

from fish farms determine the polychaetes ecology. Finally, authors aim to highlight the relevance of functional traits as organic pollution descriptors by aquaculture activity in the northern Chilean Patagonia.

2. Materials and methods

2.1. Study area

The study site was located in the inner marine areas of Chiloé and Aysén, Chilean Patagonia, southern Chile (Fig. 1). Four zones were selected at differing distances from salmon farming centres (SFC). Zone 1 belongs to eighteen stations located <670 m from SFC in the Archipiélago de Las Guaitecas and Archipiélago de Los Chonos areas, Aysén region. Zone 2 belongs to six stations located 3200 m from SFC, Zone 3 with six stations, 5900 m from SFC and Zone 4 with twenty-four stations located >10,000 m from SFC. Zones 2, 3 and 4 were located on the southeastern margin of the inner sea of Chiloé Island (Corcovado Gulf), south from Palena River mouth (43°46' – 43°51'S), inside the jurisdiction of Pitipalena-Añihué Coastal Marine Protected Multiple Use Area N° 13/2014 (Ministerio del Medio Ambiente, 2015). The distance from farms for each sampling station and its depth was measured with a Samsung GPS Echo Sounder.

2.2. Oceanographic background

In the inner sea of Chiloé, the local circulation in channels and fjords is influenced by tidal currents and topography that can be important in the distribution of particulate organic matter (Sobarzo et al., 2018). Overall, the surface water has low nutrient content and high availability of dissolved oxygen, while more homogeneous nutrients levels, characterized by high concentrations, are found in deeper waters (Silva and Guzmán, 2006). On temporal variability, the hydrographic conditions appear to be highly influenced by large-scale processes such as tidal currents, which control the changes in the chlorophyll-a, dissolved oxygen and temperature, even in the small channels and bays (Narváez et al., 2019). Also, the influence of freshwater provided by fjords and subantarctic water masses produces a typical estuarine circulation, defining saline fronts throughout the fjords region and supporting retention areas where the biological productivity is enhanced (Sobarzo, 2009). The study area is characterized by complex marine-terrestrial interactions that result in high primary production, and pools of high concentrations of dissolved and particulate organic matter (González et al., 2019). In this region, the most important sources of particulate material associated with surface waters, are fluvial runoff and coastal erosion, contributing to 25–50% of the surface primary productivity reaching the seafloor (Sobarzo, 2009; Zapata-Hernández et al., 2016; González et al., 2019).

2.3. Sediment sampling

Oceanographic samplings for environmental data and fauna were carried out in summer, autumn and spring seasons during 2017. Surface sediment samples from each station were collected using a van Veen grab (0.1 m²). From each sample grain size and total organic matter (TOM) content were determined using 150 g of sediment. Sediment subsamples for chemical analysis were taken immediately after recovery, labelled with the date, depth and station number information and then stored frozen at –20 °C before analysis. Organic matter content was determined by loss of weight on ignition at 475–500 °C for 5 h and calculated as a percentage (Byers et al., 1978). The grain size was determined using the surface layers of each sediment sample. After a homogenizing process, the sample was mixed with 100 ml sodium hexametaphosphate solution and washed on 0.063 mm sieve. The finest fraction was determined through the weigh difference between the removed fraction from 0,063 mm sieve (4 φ Wentworth scale) (silt and clays) and total. Particle grain size data were analysed following the Folk

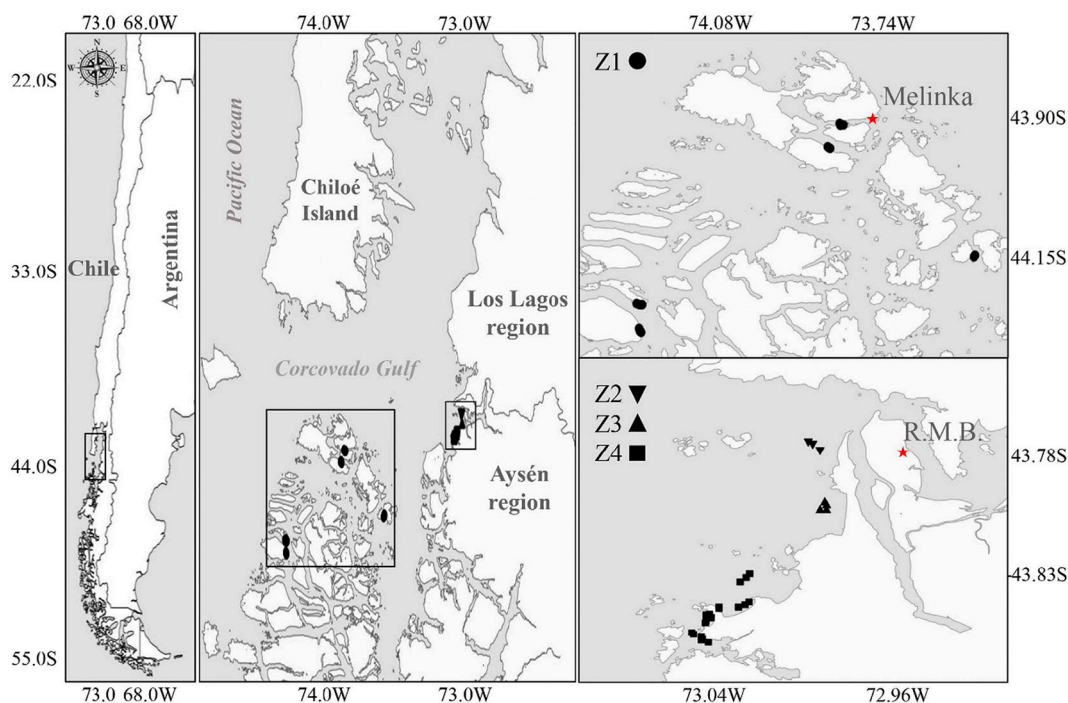


Fig. 1. Location of the sampling stations and zones in the study area (Z1 \leq 100 m to 670 m; Z2 = 3200 m, Z3 = 5900 m and Z4 = 10,200 m of distance from farm). R. M.B. = Raúl Marín Balmaceda.

and Ward scale (Blott and Pye, 2001). Further information about sampling stations is provided in Supplementary data, Table 1.

2.4. Polychaetes

Sediment samples for macrofauna analysis were collected using a van Veen grab (0.1 m^2). Three replicates were taken on each sampling station for this purpose. The sediment was sieved through a $500 \mu\text{m}$ mesh size screen and latterly on 1 mm mesh size for sorting the polychaete fauna. The biological material was fixed in a 70% ethanol-seawater solution. Polychaete fauna was identified at species level using a NIKON SMZ 800 stereomicroscope and light microscope NIKON eclipse E200 with the support of several taxonomic keys. Polychaetes were also counted to estimate abundance (number of individuals) and weighed as wet weight to calculate biomass in grams using an analytical scale with a precision of 0.1 mg . All these procedures were carried out at the Benthos laboratory of the Universidad de Valparaíso, Chile.

2.5. Functional traits

Each species was classified for overall feeding modes using the feeding guilds for polychaete families proposed by Fauchald and Jumars (1979) in the “Diet of worms” work and its later update by Jumars et al.

Table 1

Summary of environmental data (mean and standard deviation) in each zone for the study area.

Location	Distance (m)	No. stations	Depth (m)	%Mud	%MOT
Z1	81–670	18	42.7 (\pm)	14.2 (\pm)	1.4 (\pm)
			12.4	15.9	1.0
Z2	3230	6	46.4 (\pm)	37.3 (\pm)	2.3 (\pm)
			6.7	7.1	0.7
Z3	5920	6	30.8 (\pm)	21.8 (\pm)	1.0 (\pm)
			9.3	15.9	0.3
Z4	10,200–13,000	24	28.4 (\pm)	24.7 (\pm)	1.1 (\pm)
			19.6	25.0	0.4

(2015). Accordingly, polychaete species were divided into five feeding modes: carnivores (C), omnivores (O), surface deposit feeders (S), sub-surface deposit feeders (or burrowers) (B) and suspension feeders (or filters) (F). This classification also considers three categories of motility: motile (M), discreetly motile (D) and sessile (S); and three morphological structures used in feeding: jawed (J), tentaculate (T) and other structures (X). Feeding subcategories (feeding guilds in practice) were defined using the species' mobility and morphological structures associated with feeding. For the assignment of ecological groups, each polychaete species was also classified according to a schema proposed by Grall and Glémarec (1997), which is based on an organism's sensitivity to stress, such as organic enrichment. Therefore, each species was assigned to one of the following ecological groups: EG I: Sensitive species present on normal conditions; EG II: Indifferent species with low densities; EG III: Tolerant species stimulated by organic enrichment; EG IV: Second-degree opportunistic species and, EG V: First-degree opportunistic species. To assign these ecological groups the free access library of the AZTI's Marine Biotic Index (AMBI) v5 software was used (<https://ambi.azti.es/es/>) as well as the knowledge of local experts and the authors, who have extensive experience on this issue. This tool is also used to generate the AMBI index, providing an estimate of the disturbance level on benthic communities. The assignment of feeding categories and ecological groups are detailed in Table 2.

2.6. Data analysis

The abundance and biomass data obtained in each replicate were standardized by area as individuals per m^2 and then used to determine means and standard deviations per zone. Additionally, the mean individual body size (mg wet mass) was calculated as the total macrofauna community biomass divided by total macrofauna community density per zone. Community structure was described using traditional diversity indexes such as Species richness (S'), Shannon-Weaver ($H' \text{Log}2$), Sanders-Hurlbert rarefaction ($ES_{(10)}$), Simpson dominance (D'), and Evenness ($J' = 1-D$). The similarity matrix was calculated using the Bray Curtis index. SIMPER analyses were performed to describe the contribution of feeding subcategories (feeding guilds) to similarities within

Table 2

List of the polychaete species, family, feeding modes, feeding subcategories, ecological groups (AMBI) and total abundance (individuals per m^{-2}) by zone, recorded in the study area. Feeding modes; SDF, surface deposit feeder; SSDF, subsurface deposit feeder; CR, carnivore; OM, omnivore; FF, filter-suspension feeder. Feeding subcategories; first letter, B, subsurface deposit feeder (burrowing); S, surface deposit feeder; C, carnivore; O, omnivore; F, filter feeder. Second letter, M, motile; D, discretely motile; S, sessile. Third letter, J, jawed; T, tentaculate; X, other structures. Na: not assigned.

Taxa	Family	Feeding modes	Feeding subcategory	Ecological group	Z1	Z2	Z3	Z4
<i>Ampharete kerguelensis</i>	Ampharetidae	SDF	SDT	III	93	7	10	73
<i>Ampharete</i> sp.		SDF	SDT	I	47			7
<i>Melinna cristata</i>		SDF	SDT	II				13
<i>Pareurythoe chilensis</i>	Amphinomidae	CR	CMX	I	20			83
<i>Capitella capitata</i>	Capitellidae	SSDF	BMX	V	1137		3	
<i>Capitellidae</i> nd.		SSDF	BMX	V	3			
<i>Notomastus chilensis</i>		SSDF	BMX	III				253
<i>Notomastus</i> sp.		SSDF	BMX	III	30	3		363
<i>Caulleriella cristata</i>	Cirratulidae	SDF	SDT	IV	167	297		997
<i>Caulleriella</i> sp1.		SDF	SDT	III	917	473	3	590
<i>Caulleriella</i> sp2.		SDF	SDT	III		143		50
<i>Caulleriella</i> sp3.		SDF	SDT	III		110	13	
<i>Chaetozone curvata</i>		SDF	SDT	IV	57	3	10	593
<i>Chaetozone setosa</i>		SDF	SDT	IV	870	10	3	2603
<i>Chaetozone</i> sp1.		SDF	SDT	IV	880	140	83	283
<i>Chaetozone</i> sp2.		SDF	SDT	IV	387	193	170	1343
<i>Chaetozone</i> sp3.		SDF	SDT	IV	477	163	53	133
<i>Chaetozone</i> sp4.		SDF	SDT	IV	707	3		
<i>Cirratulus cirratus</i>		SDF	SDT	IV	4307			
<i>Cirratulus</i> sp1.		SDF	SDT	IV	1187			
<i>Cirratulus</i> sp2.		SDF	SDT	IV	963	40		
<i>Cirriformia</i> sp.		SDF	SDT	IV	3			
<i>Dodecaceria multifiligera</i>		SDF	SDT	III	70			17
<i>Kirkegaardia</i> sp1.		SDF	SDT	IV	413	380	40	1040
<i>Kirkegaardia</i> sp2.		SDF	SDT	IV	60			277
<i>Kirkegaardia</i> sp3.		SDF	SDT	IV				47
<i>Cossura</i> sp.	Cossuridae	SSDF	BMX	IV	510	10		77
<i>Ctenodrilus</i> sp.	Ctenodrilidae	SSDF	BMX	III				10
<i>Dorvillea</i> sp.	Dorvilleidae	OM	OMJ	II	13	3		
<i>Schistomeringos chilensis</i>		SSDF	BMX	IV				7
<i>Schistomeringos longicornis</i>		SSDF	BMX	II	23			
<i>Lamispina gymnopapillata</i>	Flabelligeridae	SDF	SDT	I	23			
<i>Pherusa</i> sp.		SDF	SDT	I				30
<i>Glycera capitata</i>	Glyceridae	CR	CDJ	II	403			107
<i>Glycera</i> sp.		CR	CDJ	II				193
<i>Hemipodia simplex</i>		CR	CDJ	II	197	17	43	1617
<i>Glycinde armata</i>	Goniadidae	CR	CDJ	II	337	173	27	243
<i>Goniada</i> sp.		CR	CMJ	II				23
<i>Dalhousiella ancuda</i>	Hesionidae	OM	OMJ	II				3
<i>Gyptis</i> sp.		OM	OMJ	II	3			
<i>Hesionella</i> sp.		OM	OMJ	II				10
<i>Hesionides</i> sp.		OM	OMJ	III		3	3	53
<i>Leocratides</i> sp.		OM	OMJ	II	10	3	10	83
<i>Lacydonia</i> sp.	Lacydoniidae	SSDF	BMX	Na	3			
<i>Eranno chilensis</i>	Lumbrineridae	CR	CMJ	II	833	37	67	327
<i>Lumbrinerides</i> sp1.		CR	CMJ	II	7			27
<i>Lumbrinerides</i> sp2.		CR	CMJ	II				3
<i>Lumbrinerides</i> sp3.		CR	CMJ	II				3
<i>Lumbrineris cingulata</i>		CR	CMJ	II				13
<i>Lumbrineris</i> sp.		CR	CMJ	II	23	40	7	43
<i>Ninoe leptognatha</i>		CR	CMJ	II	220	710	70	237
<i>Ninoe</i> sp.		CR	CMJ	II	30			33
<i>Magelona annulata</i>	Magelonidae	SDF	SDT	I	63	3	3	100
<i>Asychis</i> sp.	Maldanidae	SSDF	BDX	II			23	3
<i>Clymenella minor</i>		SSDF	BDX	I				13
<i>Euclymene</i> sp.		SSDF	BDX	II	17		120	253
<i>Maldane sarsi</i>		SSDF	BDX	II	113		3	87
<i>Nicomache</i> sp.		SSDF	BDX	II	23			
<i>Praxillella</i> sp.		SSDF	BDX	III	13		7	90
<i>Aglaophamus peruana</i>	Nephtyidae	CR	CMJ	II	900	167	103	1203
<i>Nephtys ferruginea</i>		CR	CMJ	I		10		
<i>Nephtys magellanica</i>		CR	CMJ	III	197	40	10	393
<i>Nephtys</i> sp.		CR	CMJ	II			3	
<i>Nereis callaona</i>	Nereididae	OM	OMJ	II	10			
<i>Nereis eugeniae</i>		OM	OMJ	II	30	27		40
<i>Nereis</i> sp.		OM	OMJ	III				3
<i>Drilonereis</i> sp.	Oeonidae	OM	OMJ	II				7
<i>Onuphis pseudoiridescens</i>	Onuphidae	OM	OMJ	I	13		7	3
<i>Ophelia</i> sp.	Ophelidae	SSDF	BMX	I		3		37
<i>Leitoscoloplos chilensis</i>	Orbiniidae	SSDF	BMX	IV	30		7	50
<i>Leitoscoloplos</i> sp.		SSDF	BMX	IV	7			33

(continued on next page)

Table 2 (continued)

Taxa	Family	Feeding modes	Feeding subcategory	Ecological group	Z1	Z2	Z3	Z4
<i>Leodamas</i> sp.		SSDF	BMX	I	13		7	153
<i>Naineris chilensis</i>		SSDF	BMX	I				20
<i>Phylo felix</i>		SSDF	BMX	I				3
<i>Aricidea (Aedicira) antarctica</i>	Paraonidae	SDF	SMX	III	373	37		613
<i>Aricidea (Acmira) finitima</i>		SDF	SMX	III	1043	73	10	3817
<i>Aricidea (Acmira) strelzovi</i>		SDF	SMX	II				17
<i>Aricidea</i> sp.		SDF	SMX	II				7
<i>Cirrophorus</i> sp1.		SDF	SMX	II				67
<i>Cirrophorus</i> sp2.		SDF	SMX	II	33	37	17	80
<i>Cirrophorus</i> sp3.		SDF	SMX	II	3			10
<i>Levinnesia antarctica</i>		SDF	SMX	III	1223	13	13	1690
<i>Paradoneis</i> sp.		SDF	SMX	III				17
<i>Paraonides</i> sp.		SDF	SMX	III				3
<i>Paraonis</i> sp.		SDF	SMX	III		3		
<i>Cistenides ehlersi</i>	Pectinoridae	SSDF	BDX	II	10			3
<i>Eteone sculpta</i>	Phyllodoceidae	CR	CMX	II	13	7	10	17
<i>Eteone</i> sp1.		CR	CMX	II				20
<i>Eteone</i> sp2.		CR	CMX	I	10			3
<i>Eulalia</i> sp.		CR	CMX	II	27	143	7	43
<i>Paranaitis</i> sp.		CR	CMX	II				7
<i>Phyllodoce</i> sp1.		CR	CMX	II	63			60
<i>Phyllodoce</i> sp2.		CR	CMX	II	10			
<i>Ancistrostylis</i> sp.	Pilargidae	CR	CMJ	III				10
<i>Halosydna patagonica</i>	Polynoidae	CR	CMJ	II				7
<i>Harmothoe exanthema</i>		CR	CMJ	II	37			47
<i>Harmothoe patagonica</i>		CR	CMJ	II			3	
<i>Harmothoe</i> sp.		CR	CMJ	II	20	7		13
<i>Harmothoe spinosa</i>		CR	CMJ	II	13	23	3	67
<i>Hermadion magalhaensi</i>		CR	CMJ	II	10			
<i>Acromegalomma pigmentum</i>	Sabellidae	FF	FST	III				7
<i>Amphicorina</i> sp.		FF	FST	II				3
<i>Chone striata</i>		FF	FST	II	30		3	7
<i>Parasabella</i> sp.		FF	FST	III	7			3
<i>Sabellidae</i> nd.		FF	FST	I				3
<i>Scalibregma inflatum</i>	Scalibregmatidae	SSDF	BMX	III	17	3		37
<i>Apomatus</i> sp.	Serpulidae	FF	FST	I	3			
<i>Leanira quaterfagesi</i>	Sigalionidae	CR	CMJ	II	13	47	63	227
<i>Sigalion</i> sp.		CR	CMJ	II				3
<i>Sthenelais helenae</i>		CR	CMJ	II			10	
<i>Boccardia</i> sp.	Spionidae	SDF	SDT	IV				13
<i>Boccardia polybranchia</i>		SDF	SDT	IV				3
<i>Dipolydora socialis</i>		SDF	SDT	IV	10			147
<i>Dispio uncinata</i>		SDF	SDT	III	3	7		7
<i>Laonice</i> sp.		SDF	SDT	III	30			
<i>Prionospio ehlersi</i>		SDF	SDT	IV	3			60
<i>Prionospio orensanzii</i>		SDF	SDT	IV	20			360
<i>Prionospio patagonica</i>		SDF	SDT	IV	37		3	130
<i>Prionospio peruana</i>		SDF	SDT	IV	10			
<i>Prionospio</i> sp1.		SDF	SDT	III				30
<i>Prionospio</i> sp2.		SDF	SDT	III				13
<i>Prionospio steenstrupi</i>		SDF	SDT	IV				7
<i>Scolecopsis chilensis</i>		SDF	SDT	IV	3			
<i>Spiophanes bombyx</i>		SDF	SDT	III	110	3	20	477
<i>Spiophanes duplex</i>		SDF	SDT	III	10			3
<i>Sternaspis scutata</i>	Sternapsidae	SSDF	BMX	III			10	
<i>Sternaspis</i> sp.		SSDF	BMX	III				3
<i>Erinaceusyllis</i> sp.	Syllidae	OM	OMJ	II				3
<i>Exogone</i> sp1.		OM	OMJ	I	3			7
<i>Exogone</i> sp2.		OM	OMJ	I				7
<i>Exogoninae</i> nd.		OM	OMJ	II				7
<i>Paraehlersia</i> sp.		OM	OMJ	II				3
<i>Parapionosyllis</i> sp.		OM	OMJ	II				207
<i>Parapionosyllis brevicirra</i>		OM	OMJ	II	7			
<i>Parexogone</i> sp.		OM	OMJ	II	17			87
<i>Salvatoria</i> sp.		OM	OMJ	II	3			3
<i>Syllinae</i> sp.		OM	OMJ	II				7
<i>Syllis</i> sp.		OM	OMJ	II				3
<i>Amaeana occidentalis</i>	Terebellidae	SDF	SDT	II				7
<i>Amphitrite</i> sp.		SDF	SDT	II	7			
<i>Artacama valparaisiensis</i>		SDF	SDT	III	33	10	13	13
<i>Loimia</i> sp.		SDF	SDT	II	17			7
<i>Streblosoma bairdi</i>		SDF	SDT	I		10	3	
<i>Streblosoma</i> sp.		SDF	SST	I				3
<i>Terebella plagiostoma</i>		SDF	SST	II				7
<i>Thelepus</i> sp.		SDF	SDT	II	7			23
<i>Travisia chiloensis</i>	Travisiidae	SSDF	BDX	I	3			27
<i>Travisia</i> sp.		SSDF	BDX	I				7

and dissimilarities between groups. The species abundance data matrix was transformed ($y = \sqrt{x}$) for the ordination method nonmetric multidimensional scaling (nMDS) analysis (Clarke and Gorley, 2006). We then tested for significant differences among stations and sampling sites using 1 or 2-way permutational multivariate analysis of variance (PERMANOVA) (Anderson, 2001). To relate the trophic structure and environmental variables, a Canonical Correspondence Analysis (CCA) was realized (Jongman et al., 1987). Additionally, Spearman correlations were made including ecological parameters where biological and environmental data were transformed according to Zar (1999). All statistical analyses were carried out using both Primer-e v6 (Clarke and Gorley, 2006) and Past v4 (Hammer et al., 2001) statistical software.

3. Results

3.1. Environmental parameters of the sediment

The TOM content varied between 0.41 and 4.95% between zones with mean values lower than 2.35%. Highest values were recorded in Z1 (4.95%) and Z2 (3.64%). The sediment grain size was dominated by sandy fractions with mean values always above 60%, while mud mean values were lower at 38%. The highest individual sample values for mud were recorded in Z4 (up 70%), however, the overall average for this zone was lower ($24.7\% \pm 25.0$), indicating a high heterogeneity for the study site. In Z2 mud concentrations were 37.3% on average, while in Z3 a decrease in mud content was recorded with a mean value of 21.8%. The lowest mean mud content was recorded at Z1 with just 14.2%. Depths on sampling stations varied between 1.8 and 64 m, with Z1 and Z2 being the deepest (>40 m) and Z3 and Z4 the shallowest on average (further information in Table 1 and Supplementary data).

3.2. Composition, abundance, diversity and biomass of polychaete assemblage

A total of 14,364 polychaetes were collected in the current study, corresponding to 35 families, 95 genera and 148 species of polychaetes. The total abundance was 47,880 (indiv. m^{-2}) with Cirratulidae and Paraonidae as the most abundant families with 21,770 (45%) and 9200 (19%) individuals per m^{-2} , respectively. Cirratulidae, Spionidae, Syllidae and Paraonidae were the families with the highest number of

species with 18, 15, 11 and 11, respectively. The five species with the largest abundances were *Aricidea finitima* (Paraonidae) (4943 indiv. m^{-2}), *Cirratulus cirratus* (Cirratulidae) (4307 indiv. m^{-2}), *Chaetozone setosa* (Cirratulidae) (3487 indiv. m^{-2}), *Levinsenia antarctica* (Paraonidae) (2940 indiv. m^{-2}) and *Aglaophamus peruana* (Nephtyidae) (2373 indiv. m^{-2}). This last species also showed the highest occurrence in the study being recorded at 89% of sampling stations (details in Table 2).

The different zones showed variations in the number of species and individuals. Z1 and Z4 recorded the highest number of species with mean values over 20 species, while the lowest mean values were recorded at Z3 (Fig. 2). The total number of species per sampling station showed higher differences with values between 5 and 39 species (Supplementary data). The mean number of individuals recorded the highest value at Z1 and the lowest value at Z3 (Fig. 2), showing a range from 1120 individuals per m^{-2} to 183 individuals per m^{-2} . However, the total number of individuals was higher at Z4 with 22,990 individuals per m^{-2} and lower at Z3 with 1100 individuals per m^{-2} . Data are summarized in Fig. 2 and Supplementary data.

A subtle spatial pattern was observed on Shannon diversity (H'), Expected number of species (ES_{10}), Dominance (D') and Evenness (J'). H' , ES_{10} and J' slightly increased with increasing distance from aquaculture centres, while D' decreased (Fig. 2). Mean values showed high variability between zones. Z1 recorded the highest dominance (D') (0.26 ± 0.15) but the lowest ES_{10} (4.98 ± 1.34) and J' (0.74 ± 0.15). Z2 recorded the higher ES_{10} (5.94 ± 0.37) and J' (0.87 ± 0.03), but lowest D' (0.13 ± 0.03). Z3 recorded the lowest H' (2.72 ± 0.65), while Z4 the highest H' (3.25 ± 0.5) (Fig. 2).

Biomass (wet weight) was highly variable between zones with total values per station from 0.1 $g m^{-2}$ to 21 $g m^{-2}$ (Supplementary data). Mean values recorded less variation ranging from 3 to 6 $g m^{-2}$. This variability was characterized by lower values in Z1 and Z2, and higher values in Z3 and Z4, furthest from farms (Fig. 2 and Supplementary data). Mean animal body size varied from 4 to 47 wet mg $indiv^{-1}$ at the Z1 and Z3, respectively (Fig. 2). In Z1 and Z2, a higher number of small-bodied polychaetes were found, while large-bodied size polychaetes were more abundant in zones further away from farms. Since small-size species dominated the current study the presence of large-size species such as *Aglaophamus peruana* (Nephtyidae), *Glycinde armata* (Goniadidae), *Ninoe leptognatha* (Lumbrineridae), *Euclymene* sp. (Maldanidae), *Leanira quatrefagesi* (Sigalionidae) and *Cirratulus cirratus* (Cirratulidae)

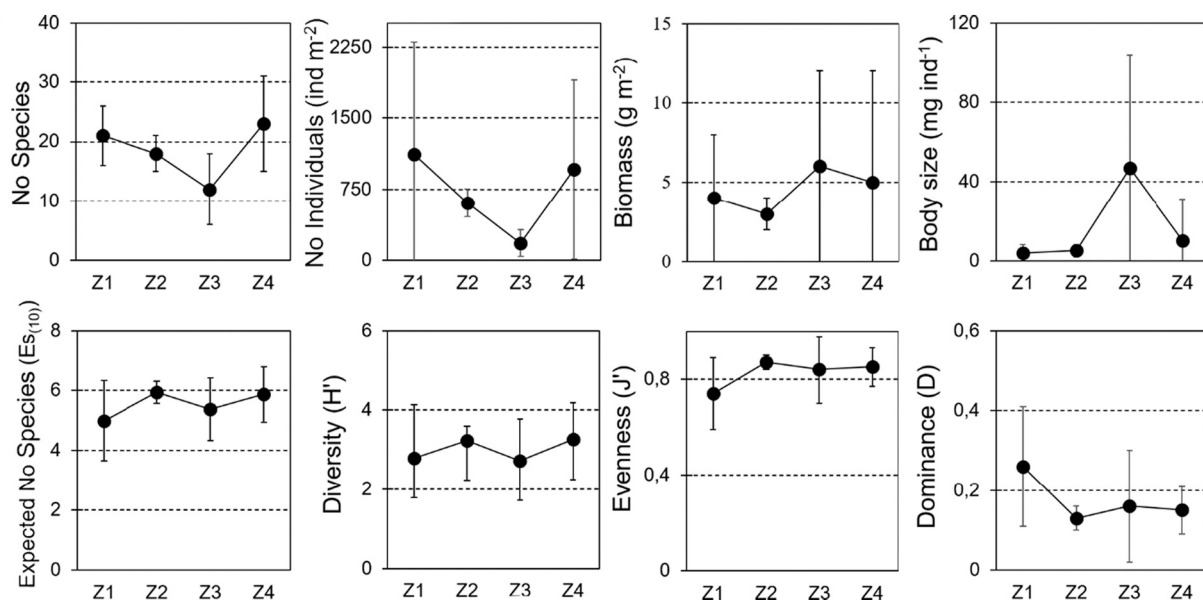


Fig. 2. Distribution per zone of the number of species (S), number of individuals (ind. m^{-2}), biomass ($g m^{-2}$), body size (mg ind^{-1}), expected number of species (ES_{10}), diversity (H'), evenness (J') and dominance (D) in the study area. Mean and standard deviation values are shown.

contributed to increases in the biomass from some specific sampling stations (see Table 2).

3.3. Feeding modes and ecological groups

Five feeding modes and ten subcategories (feeding guilds) were identified in polychaete assemblage (Table 2). Surface deposit feeders (SDF), which includes the subcategories SMX and SDT, was the most frequent feeding mode followed by carnivores (subcategories CMJ and CDJ) and sub-surface deposit feeders (SSDF). These three feeding modes dominated all study zones (Table 2). Omnivores and filter feeders were also recorded but with less frequency. Concerning mobility, both motile and discretely motile organisms represented 99% of the polychaete assemblage (41 and 58%, respectively). About morphological structures associated with feeding, tentaculate polychaetes were the most common with 50% followed by non-jawed polychaetes (28%) and, finally, jawed polychaetes (21%).

The trophic structure distribution shown by nMDS ordination allowed us to identify four groups in the four studied zones (Fig. 3) (PERMANOVA, $p < 0.05$). A first group (a) exclusively associated with the influence of salmon farming activity (Z1) and was characterized by a dominance of burrowing sub-surface deposit feeders (BMX) represented by *Capitella* cf. *capitata* (Capitellidae). A second group (b) was formed by one sampling station from Z4 characterized by the dominance of surface deposit feeder species *Kirkegaardia* sp. and *Chaetozone* sp.2 (SDT) and by the carnivore *Hemipodia simplex* (CDJ) but this last species showed less overall dominance. The third group was formed by deposit feeders and carnivores families (Cirratulidae; SDT, Paraonidae; SMX, Lumbrineridae and Nephtyidae; CMJ, Glyceridae and Goniadidae; CDJ) and was recorded from Z1 (close to salmon farming) to Z4 (far from salmon farming; >10 km), representing 83% of sampling stations. Lastly, a fourth group where suspension-subsurface deposit feeding (Maldanidae; BDX) and carnivore polychaetes (Sigalionidae and Nephtyidae; CMJ) were dominant in five sampling stations from Z3 and Z4 (Fig. 3).

The ecological group analysis identified that in sampling stations close to salmon farming centres, there were higher numbers of first-degree opportunistic species (e.g. *Capitella capitata*, EG: V) and second-degree opportunistic species (*Cirratulus cirratus*, *Cirratulus* sp. 1

and *Cirratulus* sp. 2, EG: IV). Zones farthest from aquaculture centres the polychaete assemblage was mainly formed of second-degree opportunistic species (EG: IV), tolerant species (EG: II) and indifferent species (EG: III). These three ecological groups were widely represented in 90% of sampling stations due to their high abundance. Sensitive species (EG: I), common under natural conditions, represented less than 1,5% of the overall total, recording a very low percentage (2,5%) at Z4 with species like *Leodamas* sp. (Orbiniidae) and *Magelona annulata* (Magelonidae) (Fig. 4). Species unassigned to any ecological group were mainly found at Z3 with values less than 10% and highlighting the presence of *Euclymene* sp. (BDX).

Results obtained from SIMPER analysis (Figs. 3 and 4c) demonstrated that stations located at zones closer to the aquaculture centres were dominated by a low number of species belonging mainly to Capitellidae and Cirratulidae families. While zones further away were characterized by more species which were recorded with high abundance and distributed among several families such as Paraonidae, Lumbrineridae, Cirratulidae, Maldanidae, Sigalionidae and Glyceridae.

3.4. Relationships between environmental and biological data

The Spearman correlation analysis showed significant positive correlations ($p < 0.05$) for distance from farms with the expected number of species ($r = 0.36$), diversity ($r = 0.35$) and evenness ($r = 0.34$), respectively. Meanwhile, negative correlations with dominance and the ecological group V were observed. Depth exhibited a negative correlation with CDJ ($r = -0.35$). In contrast, mud percentage was positively related with CDJ ($r = 0.37$), but negatively related to CMJ ($r = -0.27$) trophic subcategories. The TOM in sediment did not show a significant relationship with biological variables ($p > 0.05$) (further information is provided in Table 3).

The results of the CCA are shown in Fig. 5. This analysis showed that there were four environmental variables, which explained most of the variance (i.e. distance from farms, depth, TOM and mud%). The first two CCA axis eigenvalues accounted for 87% of the total variance. For the functional traits, the first axis indicated that distance from farms, depth, and TOM were the most important variables, while the percentage of mud explained better the variance along the second axis (Fig. 5, $p <$

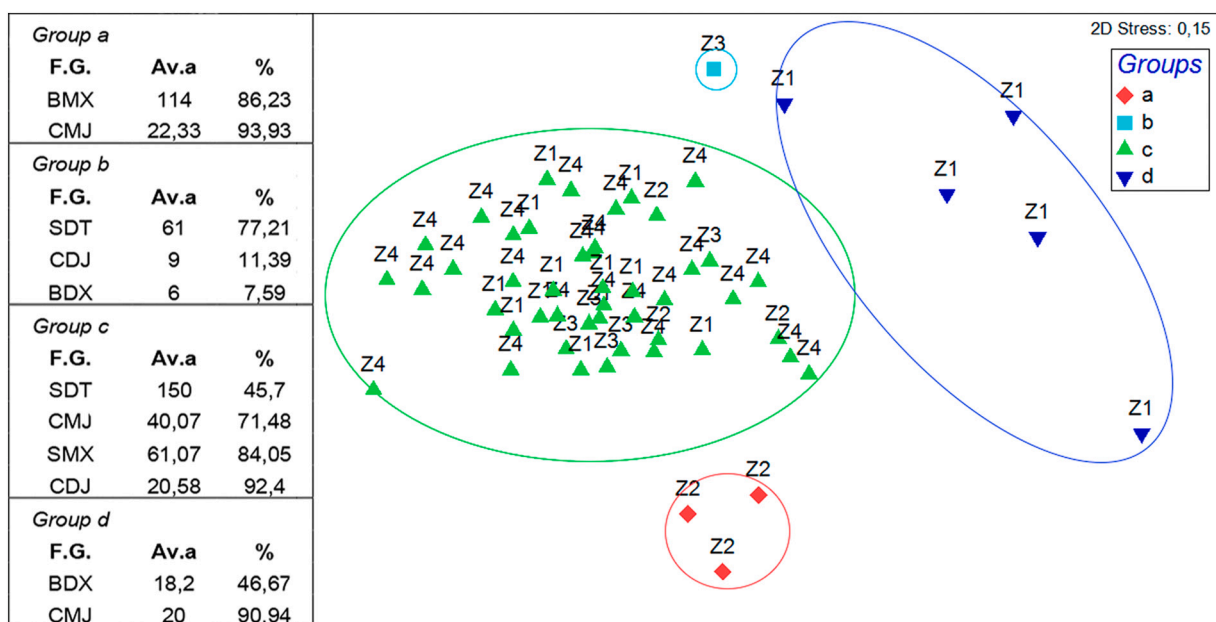


Fig. 3. Non-metric multidimensional scaling (nMDS) ordination plot for polychaete assemblages based on feeding subcategories. Percentage of similarity is shown for every group.

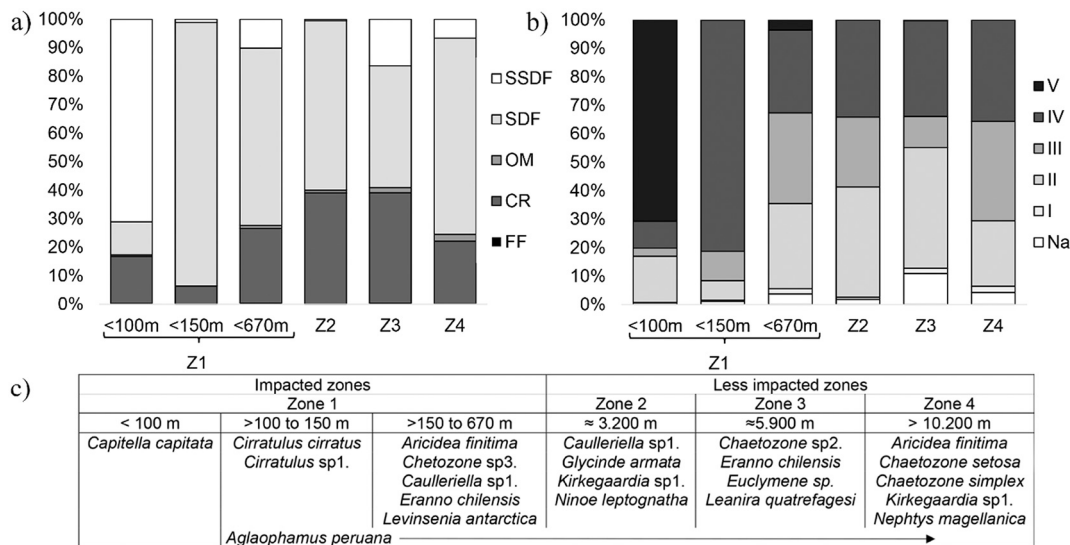


Fig. 4. Upper panel: percentage contribution of feeding mode (a) and ecological groups (b) (I, II, III, IV and V) for the different zones. Lower panel: dominant polychaete species for impacted zones and less impacted zones (70% similarity) (c). SSDF: sub-surface deposit feeders, SDF: surface deposit feeders, OM: omnivores, CR: carnivores and FF: filter-suspension feeders.

0.05). The stations close to the salmon farming (Z1 and Z2) appear to be related with higher TOM and depth, in turn, associated with BMX (Capitellidae) and SDT (Cirratulidae) trophic subcategories. It is important to note that CDJ was related to sampling stations in Z1 with shallow depths (Fig. 5). In contrast, the sampling stations in Z3 and Z4 were related to distance from farms and associated with CDJ, OMJ and SMX. These results were consistent with Spearman correlation analysis (Table 3; Fig. 5).

4. Discussion

4.1. High polychaetes biodiversity associated with aquaculture centres

The analysis of aquaculture impacts on marine sediments and the identification of pollution indicator species have been widely developed (e.g. Borja et al., 2014; Keeley et al., 2014; Martínez-García et al., 2015, 2019). However, Chile despite being one of the most important countries in this activity, with 1409 centres (723 at Aysén region) (<https://mapas.subpesca.cl/ideviewer/>), lacks studies that analyse the impact on benthic communities and the associated time-spatial variability (Niklitschek et al., 2013; Quiroga et al., 2013). Most studies have a social-economic approach and do not consider the benthos on their environmental assessments (Quiñones et al., 2019). Therefore, the current research is a relevant contribution to understanding these impacts taking as an example the polychaete assemblage. Despite these organisms are important indicators of the benthic ecosystem health, little is known about their ecology. This knowledge will serve to understand the effects of different activities such as aquaculture, overfishing or conservation.

The study zone was characterized by high abundance, species number and diversity. The number of species recorded - 148 species - representing a quarter of the polychaete fauna described for Chile to date (Rozbaczylo et al., 2017). These numbers could increase as several taxa have not yet been identified or classified. Studies recently published (Blake, 2018) and "in progress" on bitentaculate cirratulids would indicate the presence of more morphotypes than currently recognized (Soto EH, Personal Communication). The polychaete assemblages were

dominated by small-size organisms with short life-history. Species belonging to the Cirratulidae and Paraonidae families were the most abundant. These findings are similar to those reported for soft-bottom environments from Chilean Patagonia (Thatje and Brown, 2009; Montiel et al., 2011; Quiroga et al., 2012, 2013). However, such a high polychaete diversity is not usual for a small geographic area (Pabis et al., 2015; Wouters et al., 2018).

The anthropogenic pressure originated from marine fish farming causes an increased load of organic matter and nutrients (e.g. Johansen et al., 2018; Keeley et al., 2019; Klootwijk et al., 2021). In general, lower values of the expected number of species and diversity in the stations at Z1 were registered, their values increasing gradually with increasing distance to the farms. Besides, values of evenness and dominance of the polychaete assemblages exhibited a converse pattern, characterized by low values evenness and high values of dominance in the stations at Z1. It is important to note that the number of individuals, biomass and body size were highly variable about the distance from farms, in particular those stations at Z3 and Z4 (Fig. 2). We found a low number of individuals at Z3, which were dominated by large-bodied size polychaetes as *Euclymene* sp. and *Maldane sarsi* (Family Maldanidae); by contrast in the stations at Z4 there was a high number of individuals with small-bodied size. This heterogeneity may be related to the influence of allochthonous OM or too high spatial variability in grain size in the study area. The influence of rivers such as the Palena River maybe affects the macrobenthic composition and community structure as has been observed in other locations in Chilean Patagonia (Quiroga et al., 2012, 2016).

Overall hydrodynamic conditions result in the transport of fine particles and organic matter (Dauvin et al., 2020). In our study area, TOM concentrations were similar to those reported by Silva (2006) but without evidence of organic enrichment in the sediments, however, Stead et al. (2011) have reported higher mean values (~3%) on sites near our study area. There was no clear spatial pattern with distance despite what was expected and there were higher organic matter values in sampling stations from different zones regardless of their distance from aquaculture centres. Z1 did not show the highest mean organic matter value despite its closeness to aquaculture centres, recording

lower mean concentrations than those commonly observed from sediments close to this type of activity – often >5% (Shakouri and Auðunsson, 2006; Neofitou et al., 2010; Huang et al., 2012). Overall concentrations recorded in this study were widely below the limits established by environmental authorities (<9%) (Resolución Exenta 1508-2014/SUBPESCA). Some studies have reported that the impacted area by aquaculture activities would be restricted to sediments located under rafts cages and up to 500 m around the cages (Kutti et al., 2007; Huang et al., 2012; Zhulay et al., 2015). In the current research there were no sites under raft cages. Such an area would receive the different inputs from aquaculture centre and the degree of impact would be related to several factors, for example, the exported organic matter, water column depth, distance between rafts cages, winds, currents and benthic processes (Tomassetti and Porrello, 2005; 2016; Huang et al., 2012; Keeley et al., 2013). We suggest that in our study area the deposition of organic matter is related to local hydrodynamic conditions transporting particulate organic matter far from the farms (Sobarzo et al., 2018), thus explaining some of the variations in observed organic matter values. Large variations on the tidal regime are common on study sites and could also explain the low accumulation of organic matter around cages as reported by Dauvin et al. (2020) for Cherbourg, France.

Our results would indicate that disturbances of polychaete assemblages associated with aquaculture activities were mainly observed at sites located up to 150 m from rafts cages because the main replacements of the dominant species and trophic groups were recorded at these distances. It is expected that the organic content of sediments should be determining the composition, abundance and diversity in benthic polychaetes. However, despite there was no significant correlation observed the analysis of organic matter, as well as grain size, have proven to be conclusive to assess the benthic community response to aquaculture effects (Kutti et al., 2007; Neofitou et al., 2010; Keeley et al., 2014; Huang et al., 2012; Dauvin et al., 2020).

This study does not originally consider the study of benthic polychaetes under farms. However studies made on nearby sites report a similar trophic groups composition, lower diversity and abundance under farm cages. In addition, deposit feeders (SSDF and SDF feeding modes) were widely dominant in abundance and number of species highlighting Cirratulidae, Capitellidae and Paraonidae families. The higher level of occurrence on sites was observed in Capitellidae species such as *Mediomastus branchiferus* and *Capitella capitata*, while several species were recorded on one or two sites (Muñoz and Quiroga, 2018).

Physically the sediments were characterized by a higher proportion of sand with just a few stations at Z4 showing higher mud. These results are similar to those reported by Stead et al. (2011) though these authors record a higher mud percentage in only one site close to Z1. Coastal sedimentation processes determined by high riverine inputs (Palena River) may explain the higher content of sandy sediments mainly at Z2, Z3 and Z4 since these stations were located close to the river mouth. The sediment conditions at Z1 could be explained by oceanic inputs and downward transport from the water column.

Sediment grain size distribution did not show a clear spatial pattern related to distance from farms, demonstrating the high heterogeneity of studied sediments. This sediment heterogeneity was also recorded by Dauvin et al. (2020) on Rade de Cherbourg, English Channel, with a

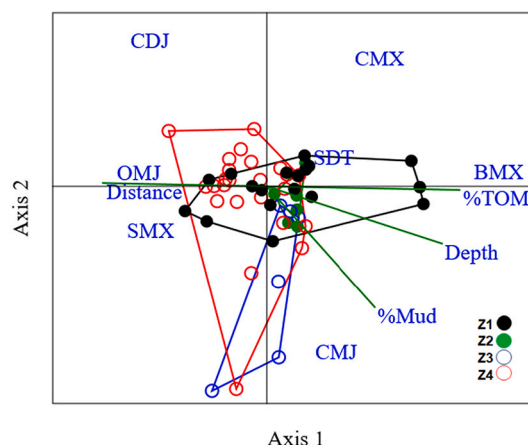


Fig. 5. Correspondence canonical analysis (CCA) ordination plot of feeding subcategories and environmental variables by sampling zones.

lower percentage of fine particles around cages but with similar indicator species such as *Capitella minima*. In a semi-enclosed Gulf in Greece, the Mediterranean Sea, Neofitou et al. (2010) recorded sediments mainly composed of sand (62–79%) at the farm stations. These results may be compared to our study, coinciding with a higher presence of carnivore species such as *Nephtys hystrix* on sediments with a higher content of sand (49–60%). In this study, sediment grain size variations between zones were recorded although mean mud percentages were always lower than 38%. The effects of these changes would be related to the presence or dominance of specific trophic groups such as deposit-feeders or carnivores.

The dominance of sandy bottoms also would explain the regular and abundant occurrence of some carnivore polychaetes found by this study as demonstrated by correlation analysis (Spearman correlation, $r = -0.27$, $p < 0.05$, Table 3), as well as the presence of filter feeders and omnivorous. In soft-bottom benthic ecology, a higher presence of carnivores and hence a less impacted benthic community has been associated with sandy sediments (Gray and Elliot, 2009). Finer sediments usually hold higher organic matter (Tomassetti et al., 2016), however in this study sediments with low organic matter content were mainly found. While the proportion of mud was negatively correlated with depth (Spearman correlation, $r = -0.35$, $p < 0.05$, Table 3), overall depth was not an important parameter to explain polychaete distributions.

The main parameter correlated with the polychaetes response and that could be used to detect the influence of aquaculture was the distance from the disturbance source. The analysis of this parameter was particularly useful to identify whether and what groups changed due to specific environmental conditions. This approach is suitable in assessing the changes in functional diversity caused by aquaculture impacts (Tomassetti and Porrello, 2005; Dimitriadis and Koutsoubas, 2011; Riera et al., 2015) and other anthropogenic pressures (Manokaran et al., 2013; Punzo et al., 2015).

Table 3

Spearman correlation analysis for diversity parameters and feeding subcategories with environmental variables (distance from farms, depth, mud% and TOM%) for the study area. Bold letter = $p < 0.05$ statistical significance.

	D'	ES ₍₁₀₎	H'	J'	CDJ	CMJ	OMJ	EGV
Distance (m)	-0.35	0.36	0.35	0.34	0.33	-0.05	0.34	-0.49
Depth (m)	0.09	-0.1	-0.04	-0.08	-0.35	0.11	-0.15	0.13
Mud (%)	0.07	0.04	0.04	-0.06	0.37	-0.27	-0.05	0.06
TOM (%)	0.02	0.02	0.05	-0.01	0.15	-0.1	0.01	-0.09

4.2. The importance of a functional view on benthos environmental assessment

Surface deposit feeder (mostly Cirratulidae and Paraonidae) and carnivore (mostly Nephtyidae, Lumbrineridae and Polynoidae) polychaetes were the main feeding modes. It is probably that the great amount and variety of food supply reaching the seabed favoured the surface deposit feeders and hence, with the increase of prey, the carnivore species too (Iken et al., 2010; Bluhm et al., 2011). However, this trophic composition is also recorded on soft-bottom systems without organic inputs by anthropogenic activity (Paiva, 1993; Mattos et al., 2012).

Studies made by different authors have highlighted the close relationship between deposit feeder polychaetes and organic matter content (Quiroga et al., 2013; Zhulay et al., 2015). In our study area, deposit feeders and also carnivore polychaetes appear to prefer sandy sediments rather than muddy ones. They may take advantage of the sediment interstitial spaces where there is more food available together with high availability of preys (Muniz and Pires, 1999; Domínguez Castanedo et al., 2012). Nevertheless, both feeding modes may be found in sandy and muddy bottoms (Jumars et al., 2015). Discretely motile carnivore polychaetes (CDJ) were positively correlated with mud % variable, where sandy sediments dominated in this study ($r = 0.37$). Despite muddy bottoms were not dominant a higher abundance of glycerid polychaetes (*Hemipodia simplex*) at zones 1 and 4 would be explained by a higher content of sand (Table 2). Manokaran et al. (2013) also recorded the presence of carnivore polychaetes but on sediment with a higher proportion of mud (<50%). It would appear that carnivore polychaetes inhabit soft sediments as mentioned before.

nMDS analysis of trophic groups per zones is shown in Fig. 3, indicating that the burrower deposit feeders (BMX), characterized mainly by high densities of *Capitella capitata* (Capitellidae), were important in stations close to farming centres (<100 m). *C. capitata* was one of the most abundant species at Z1 which had some of the highest organic matter concentrations (4.95 and 3.19%). Also, CCA confirmed the close relationship between *C. capitata* and organic matter content (Fig. 5). This species is widely known as an important ecological indicator due to its high densities in polluted ecosystems (Albano et al., 2013) and appears to benefit from organically enriched sediments with low dissolved oxygen levels (Tsutsumi et al., 1990; Weston, 1990). In our study, *C. capitata* showed high density very close to the rafts cages however this high density likely corresponds to a complex of distinct species of Capitella genus (Silva et al., 2017).

An analysis at Z1 (Fig. 4a) showed a clear replacement of dominant species. *C. capitata* dominated at sites located <100 m from farms, however, disappeared totally at sites >100 m and <150 m, where cirratulid species (SDT) dominated like *Cirratulus cirratus*. On these sites both species contributed over 70% of the abundance, explaining their dominance. Cirratulids are considered second-degree opportunist species (EG IV) and *C. cirratus* has been recognized as a bioindicator of polluted environments (Bellan, 1980) associated with aquaculture centres (Elías et al., 2003; Tomassetti et al., 2016). On sites furthest from the farms (<670 m), the dominance of surface deposit feeders was not so evident and a more diverse trophic structure was observed. Paraonid polychaetes (BMX) and carnivores (CMJ and CDJ) mainly colonized these sites with high abundance indicating better environmental conditions (Pagliosa, 2005; Cheung et al., 2008). Families commonly associated with low pollution like Terebellidae and Syllidae (Giangrande et al., 2005; Dean, 2008) were also found. Even on those sites where the trophic structure was completely different, as shown by nMDS (Fig. 3, groups "a" and "c"), the presence of carnivores (*Eranno chilensis*) and specially maldanids (*Euclymene* sp., *Maldane sarsi*) would indicate a clear transition zone. Toward less impacted zones further from aquaculture centres, assemblage succession was evident with the colonization by other species. Functional traits described here agree with the Pearson-Rosenberg conceptual model (Pearson and Rosenberg, 1978)

describing a generalized pattern of response for benthic communities in relation to organic enrichment.

The oceanographic and hydrodynamic settings outlined above may have resulted in an increase of species belonging to ecological groups II and III, mainly carnivores (e.g. *Ninoe leptognatha*) and bitentaculate cirratulids together with the presence of species of the group I, explaining the succession indicated in Fig. 4b and c. At Z4 successional change is still more evident with the record of omnivores, suspension and filter feeder polychaetes contributing to a higher diversity of species and trophic groups. Finally, the polychaete assemblage is again dominated by surface deposit feeders reaching an apparent condition of ecological stability (Fig. 4a).

In this study, the trophic structure was dominated by deposit feeders. According to Rivero et al. (2005) and Hossain (2018), this feeding mode would be generally associated with environments under stress with the presence of opportunists species. However, not all deposit feeder polychaetes are pollution indicators. Some of these species have been widely recorded in zones without apparent perturbation demonstrating a variable response to environmental conditions. This is the case of *Chaetozone setosa* and *Aricidea (Acmira) finitima*, which recorded high densities at Z4 (Table 2) and so they could not be associated with opportunistic behaviour caused by anthropogenic disturbances.

The diversity of feeding modes and subcategories observed would indicate abundant food supply with detritus. In the study area, high levels of primary productivity have been reported (Silva et al., 2011; Vargas et al., 2011). This food source originated from the surface ultimately sinks and reaches the seabed supporting diverse and heterogeneous benthic communities (Zapata-Hernández et al., 2016; Cari et al., 2020). However, it is not the only food source influencing this diversity since high particulate material (enriched organically) from aquaculture centres and terrigenous inputs from Palena River are also present.

The analysis of the spatial distribution of functional groups was a key factor in gaining a better understanding of the influence of aquaculture on polychaete assemblages ecology. This approach, focused mainly on trophic structure, elucidated ecological patterns that usually are less evident under a structural methodology as reported by several authors (Domínguez Castanedo et al., 2012; Cheung et al., 2008). Our results also confirmed the relevance of using trophic subcategories such as feeding guilds (Pagliosa, 2005), because they showed correlations with key environmental parameters. The practical importance of functional approach is increasingly relevant. Authors consider functional diversity not only as a component of biodiversity also as an indicator of ecosystem functioning (Heemsbergen et al., 2004; Hooper et al., 2005). Pacheco et al. (2011) mention that the analysis of functional traits should be considered in traditional studies related to species diversity because they provide indicators of ecosystem stress.

5. Conclusions

The analysis of the structure and function of polychaete assemblages showed the impact of aquaculture activity on the benthic community. This impact was more evident on trophic groups revealing a gradient of species succession mainly determined by the distance from the disturbance source. We suggest that *Cirratulus cirratus* (surface deposit feeder) be considered an indicator of zones impacted by aquaculture at Chilean Patagonia. We also recommend monitoring the ecology of *Chaetozone setosa* (Cirratulidae), *Aricidea (Acmira) finitima* and *Levinsonia antarctica* (both Paraonidae). These species were shown to be tolerant in impacted zones but dominants in the farthest zones of aquaculture centres. These species could be selected as pollution indicators with further evidence.

The current study represents a relevant contribution to a greater understanding of soft-bottom polychaete biodiversity of the northern Patagonia area. The high diversity of polychaetes should be highlighted, considering that the area is under strong and permanent anthropogenic threats (aquaculture, pollution, fisheries, global change) that contribute to the loss of biodiversity. We suggest that the biological information

provided on this study should be used for supporting conservation and management strategies mainly on those areas where multiple uses take place. It is worth noting that in the area there are two coastal marine protected areas (Tic-Toc and Pitipalena-Añihué), a marine reserve (Las Guaitecas National Reserve) and all northern Patagonia region is being proposed like a global Ecologically and Biologically Significant Area (EBSA N° 20; West Wind Drift Convergence; CBD Report, June 2013).

Finally, the functional traits approach presented in this research revealed the environmental condition of the benthos that may not have been recorded with the information only provided by sediment geochemistry. Therefore, we suggest that functional traits studies on benthic communities must be considered as part of environmental assessments associated with aquaculture activities complementing traditional methods. This study has demonstrated that trophic and ecological attributes are good proxies which can detect impacts and additionally may provide relevant information on ecosystem functioning and services in areas influenced by aquaculture at Chilean Patagonia. The uncontrolled expansion of aquaculture toward more southern areas forces the development of better and more precise tools for a more complete environmental evaluation of marine ecosystems.

CRedit authorship contribution statement

Carlos Sanchis: Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Eulogio H. Soto:** Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Eduardo Quiroga:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization.

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.marpolbul.2021.112309>.

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