Estuarine, Coastal and Shelf Science 313 (2025) 109119

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Long-term impact of dredging and beach nourishment works on benthic communities

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ARTICLE INFO

Keywords:
Dredging
Benthic recovery
Macrofauna
Megafauna
Sediments
Timer series
Arcachon bay

ABSTRACT

Dredging and rainbowing techniques are commonly used to replenish sandy beaches and protect the coast against erosion. Since 2003, such operations have been conducted every other year on Pyla Beach, Arcachon Bay (French Atlantic Coast). The evolution of macrobenthic communities subjected to regular disturbance was analyzed once in springtime at dredging and disposal sites, as well as in a control area, over 21 years. The overall benthic community was dominated by the same few species. The dredged area harbors a benthic community whose characteristics suggest the maintenance of a disturbed status, compared to the control area, whose community follows a trajectory possibly influenced by the general decrease of organic matter in the sediment. Regarding the disposal site, species richness is slowly declining. In both disturbed areas, the community was dominated by species able to recolonize rapidly (polychaetes, peracarid crustaceans), while the control area rather favored bivalves.

1. Introduction

Erosion of sandy coasts is a global phenomenon that could result in the extinction of almost fifty percent of the world's sandy beaches by the end of the 21st century (Vousdoukas et al., 2020). This trend is often correlated with climate change affecting waves and storm surges, largely exacerbated by the intense increase in the global mean sea level since the end of the last century (Dong et al., 2024; Nerem et al., 2018; Oppenheimer et al., 2019). Facing this coastal vulnerability and the simultaneous increase in human population in these areas, various measures are implemented: the use of soft or hard coastal defenses, retreat or relocation, and accommodation by accepting a higher risk of flooding (Almeida Neves, 2019; Saengsupavanich, 2022). In response to erosion issues, beach nourishment is being developed in many coastal countries to create or expand existing beaches and to fuel their socio-economic benefits (Bax et al., 2024). The effects of these operations on the environment lead to controversial conclusions, depending on the kinds of organisms (plankton, nekton, benthos) or habitats (seagrass, coral reef, naked sediments) on which they were tested (Lalèyè et al., 2020; Saengsupavanich et al., 2023). Also, the intensity and/or frequency of the works lead to different impacts. Four years after dredging cessation off the east of Felixstowe (southeast of England), values of benthic macrofauna abundance and species richness were lower in an area exposed to more intense dredging activity, compared with values from an area with low intensity and those from a control site. The same conclusion was reached regarding the structure of macrofauna assemblages in this area (Boyd et al., 2003; Wan Hussin et al., 2012). Another (relative) consensus is that in high-energy conditions and/or clean sand, macrofauna communities exhibit the most rapid and complete recovery rate after disturbance, compared to muddier communities (Chauvel et al., 2024; Dernie et al., 2003; Van Dolah et al., 1984). An experimental approach with trays settled on the floor in San Felipe Channel (Ceuta, North Africa) revealed that recolonization of benthic macrofauna occurred within approximately 15 days and indicated the importance of the bedload transport of juveniles and adults (Guerra-García and García-Gómez, 2006). Similar observations were made in such environments characterized by high energy (current, waves), although recovery time could be longer, ranging from a few months (Guerra-García et al., 2003; Newell et al., 1998; Van Dolah et al., 1984; Vivan et al., 2009) to a few years (generally <10 yr after works

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https://doi.org/10.1016/j.ecss.2024.109119
Received 4 September 2024; Received in revised form 30 December 2024; Accepted 30 December 2024
Available online 31 December 2024
0272-7714/

cessation) (Sánchez-Moyano et al., 2004; Wan Hussin et al., 2012). Indeed, different reviews demonstrated a wide range of recovery times among studies (Bolam and Rees, 2003; Wilber et al., 2008). The capacity of the system to re-establish depends, among other factors (besides works intensity and sediment grain size), on the types of community in the impacted area, on the dredging/nourishment season, on the gear penetration (dredging) or sediment layer thickness (beach replenishment), on the life cycles and feeding strategies of species, etc. (Sánchez-Moyano et al., 2004). Another observed alternative conclusion was the lack of recovery in macrofauna assemblages, at least at the scale of the monitoring (Boyd et al., 2005; McLaverty et al., 2020; Mielck et al., 2021; Wijsman et al., 2023), with the rarest species having difficulties coming back (Kenny and Rees, 1996).

Thus, a key limitation of most studies in drawing conclusive results is the insufficient duration of monitoring programs, with an average length of only 15 months for beach ecology-nourishment impact studies over the past two decades (Paris et al., 2023). Long-term studies (approximately 10 years or more) remain rare (Wan Hussin et al., 2012) and are often focused on a limited number of taxa (Leewis et al., 2012; Paris et al., 2023). In contrast, the present study is based on a unique 21-year dataset comprising quantitative macrofauna data collected in a continuously human-perturbed environment. In southwestern France, the issue of coastal erosion is particularly significant due to the 200-km long sandy beach stretching from the Gironde Estuary to the Basque Country (Delangue and Teillac-Deschamps, 2018) (Fig. 1). Arcachon Bay, a 180-km^2 lagoon, interrupts this straight coast. The entrance of the lagoon is also composed of sandy beaches threatened by sea-level rise, which could reach 0.5–1.0 m by 2100 (Le Treut, 2013) and 3 m in the worst-case scenario by 2300 (Oppenheimer et al., 2019). On the eastern coast, the three-km long beach of Pyla is protected by a seawall. However, due to rising sea levels and a deficit of upstream sediment supply, erosion became a significant concern by 1980 when the steel sheet pile wall, supporting the base of the concrete seawall, became apparent. Beach nourishment was used to protect public beaches and coastal property. However, until 2002, only a small quantity of fine aeolian sand was transported to the beach by trucks. Due to its fine grain size and aeolian origin, this sand quickly dispersed, and after a few weeks, the beach recovered its initial profile. In 2003, 11×10^5 m^3 of median sand (the same grain size as the destination site) from an adjacent shallow area was deposited along this coast. Since then, only sand from this adjacent area was utilized, and approximately 1.5×10^5 m^3 has been added every other year to maintain a beach profile allowing for coastal protection.

The present study assessed the impact of these maintenance works on the benthic macrofauna over 21 years, at the dredging site and the disposal site, compared to a control area nearby. Additionally, former studies demonstrated that different conclusions could be reached depending on whether sampling was performed with a dredge (0.5 to 1-cm mesh size) or with a grab (1-mm mesh sieve) and that both methods can be complementary (de Montaudouin et al., 2023; Wijsman et al., 2022). Thus, both gears were simultaneously used, except in intertidal areas where the dredge could not be used for technical reasons. Due to the type of habitat (high-energy site, medium sands) and previous studies, little impact on small macrofauna (sampled with the grab) was expected because of fast recolonization facilitated by dispersion through current and bedload transport (Robinson et al., 2005; van Dalfsen et al., 2000; Van Dolah et al., 1984). Conversely, there could be an impact on larger, long-lived invertebrates sampled with the dredge at a longer temporal scale (Newell et al., 1998; Wilber et al., 2008).

2. Material and methods

2.1. Study site

The studied area is at the entrance of Arcachon Bay, a 180-km^2 lagoon on the French northeastern Atlantic coast (Fig. 1). This channel (approximately 20 km^2) connects the lagoon to the Atlantic Ocean, exchanging volumes of water ranging from 370 to 400 $\times 10^6$ m^3 for spring tide to 130 to 200 $\times 10^6$ m^3 for neap tide at each tide (Bouchet, 1968). Tidal amplitude ranges from 0.9 to 4.9 m, following tide coefficient and location in the lagoon (Gassiat, 1989). In this ocean-influenced part of the lagoon, mean sea temperature varies seasonally between 5 °C

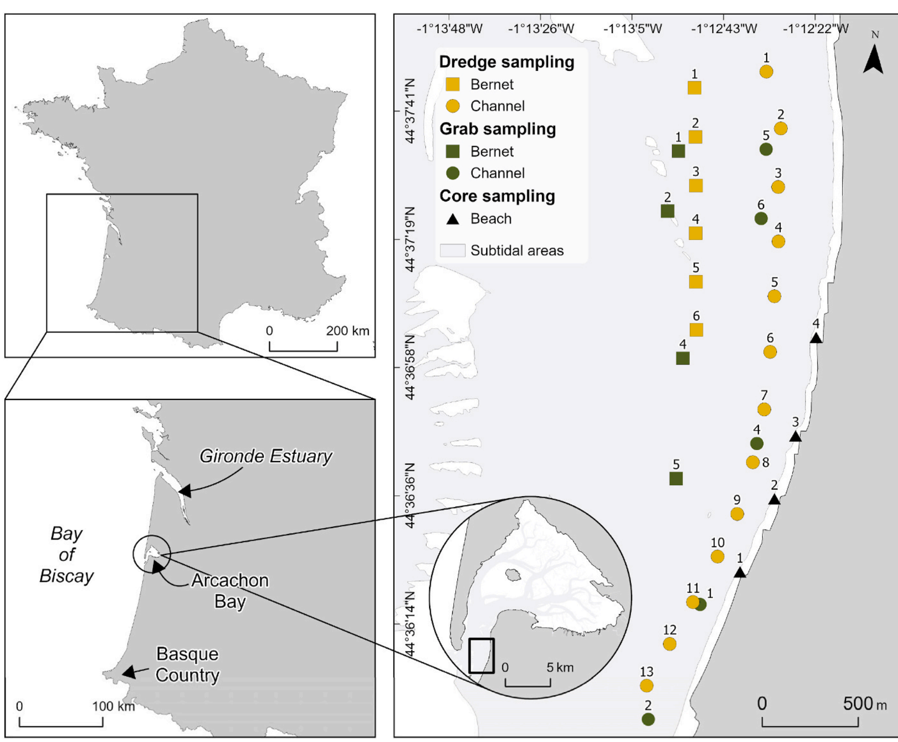


Fig. 1. Location of the sampling sites in Arcachon Bay, specifying the gear (dredge, grab, or corer) in Bernet channel (dredging site), Pyla channel (control site), and Pyla beach (disposal site).

and 23 °C, while salinity ranges from 27 to 35. The works that began in 2003, involved collecting sand from a shallow area to deposit these sediments along the coast. The project focused on three areas (Fig. 1) named as follows: (1) "Bernet channel", the dredged site. Bernet channel is a short channel of approximately 1 km long and 0.5 km wide (the dredged area ranged between 0.4 and 0.8 km^2 and covered the entire Bernet Channel), with a depth ranging from 4 to 9 m. (2) "Pyla channel", the control site nearby. Pyla channel extends for 5 km. Along the Pyla channel, the depth increases from the north (10 m) to the south (15 m), and maximum currents (with a tide coefficient >100) can reach 1.4 m s^{-1} (3) "Pyla Beach", the disposal area where the collected sediments were disposed of. (Fig. 1). Pyla Beach is approximately 3 km long and is divided by a dozen perpendicular artificial rocky piers designed to reduce erosion. Additionally, the coast is protected by a continuous concrete seawall.

The entire area consists of medium sands with a median grain size of approximately 300 μm (SOGREAH, 2001). Even during storm events, the ocean swell is usually less than 1 m (with a period of less than 8 s), and the relatively sheltered situation results in choppy seas with a height of 0.2–0.4 m. Nevertheless, this situation, coupled with sea-level rising, winter offshore sand migration resulting in a net annual deficit, and the occurrence of intense storms, contributes to chronic coastal erosion.

2.2. Dredging and disposal works

When monitoring began in 2003, the Bernet channel had never been dredged before, nor had the Pyla channel. However, Pyla Beach had already undergone regular beach nourishment by terrestrial means (see introduction). Beach nourishment using marine sands from Bernet started in 2003 and was conducted almost every other year, typically in January for 2–4 weeks (2003, 2005, 2007, 2010, 2012, 2014, 2016, 2018, 2020, and 2022). The rainbowing method was applied, in which a dredging ship excavated the sediment in the shallow waters above Bernet channel (4 to 9-m deep), mixing it with a large quantity of water to create a mixture called "slurry," which was ejected onto the channel and beach of Pyla through the air (Fig. 2). In the first year (2003), a total of 11×10^5 m^3 was disposed. Afterward, the volume was reduced to 1.4-1.8×10^5 m^3 per working year to maintain the beach. This volume was extracted from a 0.4–0.8 km^2 zone corresponding to the entire Bernet channel. Additionally, the entirety of Pyla Beach was involved in the replenishment works, which prevented any comparison with a control intertidal area.

2.3. Sampling

The dredged area (Bernet channel) was compared with a control area (Pyla channel). The reference area benefited from its proximity to the dredged area, ensuring similar sediment, depth, and water body characteristics. However, the disadvantage was that the control area is located between the dredged and the disposal areas (Fig. 1) and could therefore be subjected to indirect impacts (*e.g.,* turbidity, bedload transport modification, etc.). Regarding the intertidal area affected by the nourishment operation, the entire beach was involved, with no designated control area. It is also important to remember that the entire beach had already been disturbed before 2003 by the disposal of eolian sands using terrestrial methods (trucks). However, the volume of sand was negligible compared to that associated with beach nourishment in 2003 and afterward.

Macrofauna and sediment sampling was performed each year in April or May. This period was chosen for practical reasons, such as improved navigability outside the summer tourist season and the windy winter months, as well as ecological considerations, including avoiding the peak invertebrate recruitment period and ensuring that the sampled fauna represented a settled adult community rather than transient juvenile populations. Stations were systematically distributed within each site (channels, and beach). Firstly, in the Bernet channel (N = 4 stations, 2 replicates) and the Pyla channel (N = 5 stations, 2 replicates), sediment was sampled with a Van Veen grab (0.1 m^2). In compliance with the guidelines provided by ISO 16665, each sample was washed on a 1-mm mesh sieve, fixed in 4% neutral buffered formalin, and stained with Rose Bengal. The same protocol was followed for the beach (N = 4 stations, 4 replicates), but sampling was performed at a low tide level of high coefficient (>90) with a 0.09 m^2 corer. Individuals were sorted and identified at the lowest possible taxonomic level (Suppl. 1). Biomass was measured in terms of ash-free dry weight calculated as the difference between dry weight (60 °C, 48 h) and ash weight (450 °C, 4 h). A

Fig. 2. Dredger "Côte de Bretagne" rainbowing in 2007 at Pyla sur Mer, France.

supplementary sample was taken to characterize sediments. Sediment median grain size was determined after sieving pre-weighted dried sediment through a wet column of sieves with decreasing aperture (1000 μm, 500 μm, 250 μm, 125 μm, and 63 μm). The percentage of organic matter in the sediment was assessed after ignition (450 °C, 4 h) of a dried aliquot of sediment. Secondly, the fauna was sampled again in the Bernet channel (N = 6 stations, 1 replicate) and the Pyla channel (N = 13 stations, 1 replicate) using a dredge with a 1 m width opening, a 20 cm height, and a 1 cm mesh net. Each sample length (on average 250 m) was controlled with a GPS. Individuals were counted, identified, and released into the sea (no biomass).

2.4. Data analysis

Apart from a technical report on the fauna in this area from 2001 (de Montaudouin and Raigné, 2001), no reliable data were available before 2003, when large-scale dredging and beach nourishment operations began. Therefore, the presented results pertain to the period 2003 to 2023, covering 21 annual sampling campaigns.

2.4.1. Characterization of the associated benthic community

A Hierarchical Clustering Analysis (HCA) completed by the Similarity Profile routine SIMPROF (Clarke et al., 2008) was performed on the Hellinger-transformed median abundances at each site and for each year ($n_{perm} = 9999$) using the Ward clustering method and the Hellinger distance ($p_{\text{threshold}} = 0.01$). This data transformation allowed to compare fauna retrieved using slightly different sampling surfaces (0.1 m^2 grab and 0.09 m^2 cores). This analysis was performed on R© version 4.2.0 (R-Core-Team, 2022) using the *clustsig* package (Whitaker and Christman, 2014). For each group identified by the SIMPROF routine, indicator species were identified using the IndVal procedure from the *labdsv* R package (Roberts, 2019). This analysis relies on the concepts of species fidelity (*i.e.*, the species is present in every element of a group) and specificity (*i.e.* the species is exclusively present in one group)

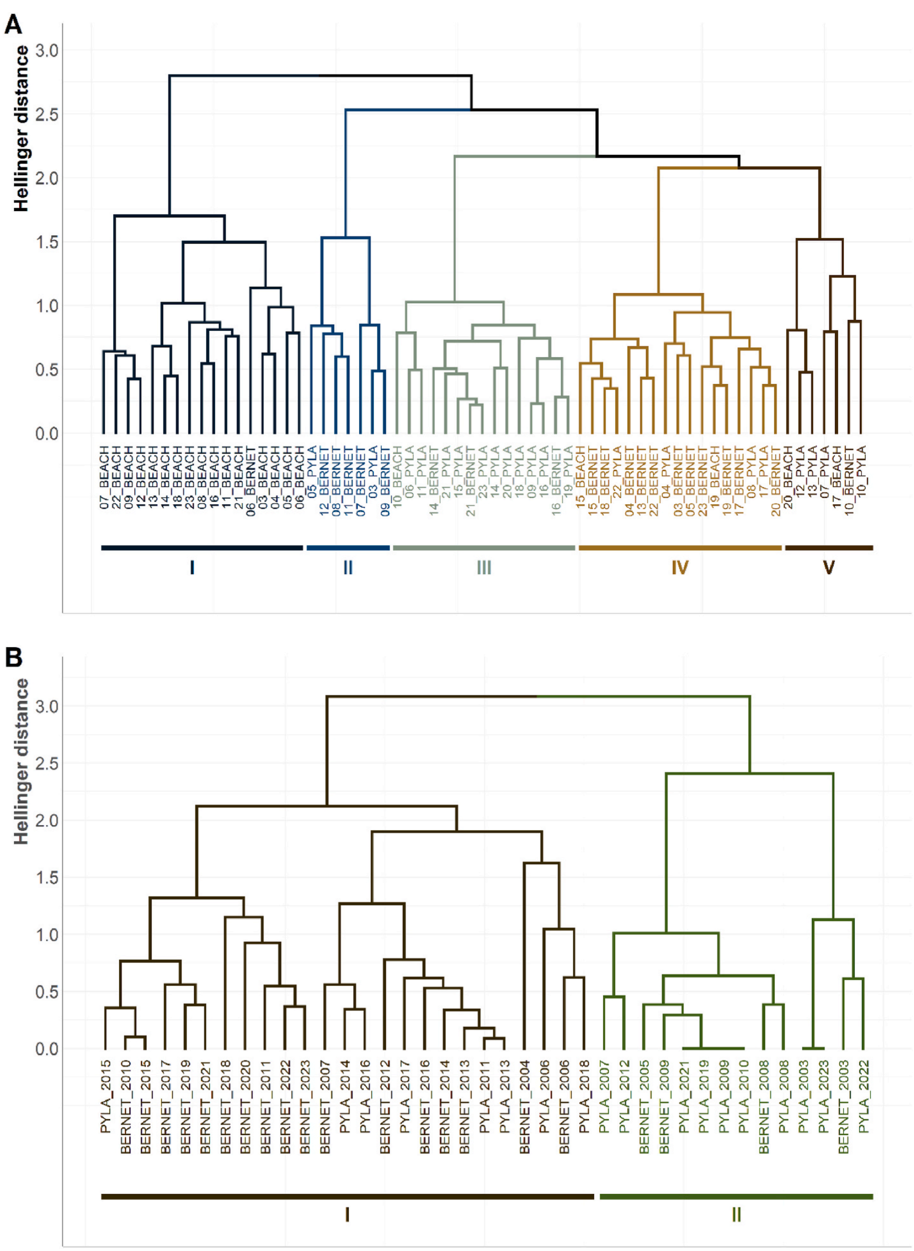


Fig. 3. Hierarchical Clustering Analysis (HCA) performed on the Hellinger-transformed annual median abundances of the organisms sampled with the Van Veen grab (A) and with the dredge (B).

(Dufrêne and Legendre, 1997).

2.4.2. Long time-scale trend (21 yr, 2003–2023)

To investigate the existence of temporal trends, a Mann-Kendall test (Yue and Wang, 2004), a well-suited test to detect trends in time series as it accounts for possible serial correlation in the data, was used. Tested variables were (1) for the sediment: median grain size and organic matter content and (2) for the fauna: abundance, biomass (only for 1-mm mesh sieved fauna), infauna proportion (in number of individuals), and species richness. Due to multiple comparisons and to avoid type-I error, the Bonferroni correction was applied to determine the significant p-value threshold ($p = 0.0031$). The analyses were performed on R© version 4.2.0 using the *modifiedmk* package (Patakamuri and O'Brien, 2021).

3. Results

The term "campaign" will be used to refer to a "site × year" sampling occasion.

3.1. Clustering analysis on the entire area

The clustering analysis performed on grab samples discriminated five groups for a 2.0 Hellinger distance (Fig. 3A) described hereafter from the largest to the smallest. Group I gathered 16 out of 21 intertidal sampling campaigns (Pyla Beach). It was characterized by four taxa (Table 1). The five other intertidal campaigns (2010, 2015, 2017, 2019, 2020) were dispersed in the remaining clusters, with no relation to the temporal proximity of the disposal works. Group IV discriminated the same number of sampling campaigns (17) and gathered 11 out of the 21 campaigns at the dredging site (Bernet) (Fig. 3A). It was characterized by the amphipods *Bathyporeia* spp. (Table 1). Most of the other campaigns of this cluster concerned the Pyla channel. In size, the third cluster was Group 3 which gathered 11 of the 15 campaigns (*e.g.*, half of the totality of the Pyla channel campaigns) (Fig. 3A). Group III was characterized by a single species, the mysid *G. spinifer* (Table 1). Finally, the smaller groups, group II characterized by four taxa (Melitidae, *Mytilus* spp., *Magelona* spp., and *Tritia reticulata*) and group V characterized by the amphipod *Hippomedon denticulatus*, mixed campaigns in Bernet and Pyla channel, before 2013 (Table 1, Suppl. 1).

The clustering analysis performed on dredge samples discriminated two groups for a 2.5 Hellinger distance (Fig. 3B). Group 1 included 17 out of the 21 campaigns at the dredging site (Bernet) and was characterized by *T. reticulata* (gastropod) and *Diogenes curvimanus* (hermit crab) (Table 1). The four remaining Bernet campaigns in the 2nd group were characterized by the large bivalve *Mactra glauca.* Campaigns in the subtidal disposal site (Pyla channel) were equally distributed between both clusters.

Table 1
Indicator species based on the faunal groups discriminated by the clustering analysis, for grab and dredge-sampled fauna (Fig. 6). A: Annelida; B: Bivalvia; CD: Crustacea Decapoda; CP: Crustacea Peracarida; G: Gastropoda.

GROUP	TAXA	IndVal	p-value	Sign.
	GRAB-SAMPLED FAUNA			
Group I	*Haustorius arenarius* (CP)	0.754	0.001	***
	Eurydice spp. (CP)	0.394	0.006	**
	Ophelia neglecta (A)	0.370	0.015	*
	Sphaeroma spp. (CP)	0.235	0.037	*
Group II	*Magelona* spp. (A)	0.493	0.001	***
	Tritia reticulate (G)	0.421	0.002	**
	Heteromastus filiformis (A)	0.259	0.024	*
	Capitella minima (A)	0.257	0.021	*
	Phoronida	0.247	0.026	*
	Ophiuridae	0.242	0.014	*
Group III	*Gastrosaccus spinifer* (CP)	0.446	0.011	*
Group IV	*Bathyporeia* spp. (CP)	0.458	0.004	**
Group V	*Hippomedon denticulatus* (CP)	0.373	0.024	*
	DREDGE-SAMPLED FAUNA			
Group I	*Tritia reticulata* (G)	0.831	0.001	***
	Diogenes curvimanus (CD)	0.657	0.002	**
Group II	*Mactra glauca* (B)	0.655	0.012	*

3.2. Bernet channel (subtidal dredged area)

At the dredging site of Bernet channel, the median grain size of sediments remained stable over the years (at approximately 340 μm (Suppl. 2). In contrast, the organic matter content significantly declined, decreasing from approximately 0.4%–0.2% of the dry sediment weight (Table 2, Suppl. 2). A total of 94 and 25 taxa were sampled with the grab and the dredge, respectively (Suppl. 1-A & B). The median abundance per year of the fauna sampled with a 1-mm mesh (grab) ranged from 83 ind.m^{-2} to 567 ind.m^{-2} (Fig. 4A), with a mean of 202 ind.m^{-2}. More than 94% of the individuals belonged to the infauna. The median biomass per year ranged from 0.2 gAFDW.m^{-2} to 10.2 gAFDW.m^{-2}, with a mean of 1.3 gAFDW.m^{-2} (Fig. 4B). The median species richness per year ranged from 4 to 12 taxa, with a mean of 7 taxa (Fig. 4C). There was no significant decrease in abundance, biomass, or species richness from 2003 to 2023 (Table 2). Six taxa from grab-sampled fauna (*Bathyporeia* spp., *Gastrosaccus spinifer*, *H. denticulatus, Macomangulus tenuis, Nephtys cirrosa*, and *Urothoe* spp.) were retrieved in over 80% of the 21 years and represented 45% of the collected individuals (Suppl. 1-A). Between 2003 and 2012, these species represented on average 35% of the total abundance, with high interannual variability, ranging from 13% to 80%. In the following years, from 2013 to 2023, they accounted on average for 79% of the total abundance (ranging from 42% to 96%) (Fig. 4D).

The median annual abundance of the fauna sampled with a 1-cm mesh dredge ranged between 0.002 and 0.082 ind.m^{-2} (Fig. 4E), while species richness ranged from 1 to 6 species (Fig. 4F). Both parameters showed no significant decrease over the years (Table 2). Three taxa from dredge-sampled fauna (*D. curvimanus*, *M. glauca* and *T. reticulata*) were retrieved in over 80% out of the 21 years (and represented 56% of the collected individuals) (Suppl. 1-B).

3.3. Pyla channel (subtidal control)

A similar trend to that observed at the Bernet channel was noted at

Table 2
Mann-Kendall correlation parameters testing the relation between time (from 2003 to 2023) and macrofauna parameters (median of abundance, biomass, and species richness), and time and sediment characteristics (organic matter (OM) content in the sediment in %), according to the type of work (DR.ber: dredging; C.pyl: Control in Pyla channel, no direct impact; DI.bea: Disposal on the beach) and the type of sampling gear (N = 21). *tau* is the coefficient of Mann-Kendall. p-value is compared to 0.05/16 = 0.0031 (Bonferroni correction). Significant correlations are in bold.

Work	Gear	Variable	tau	p-value
DR.ber	grab	Abundance	−0.13	0.0950
DR.ber	grab	Biomass	−0.01	0.9540
DR.ber	grab	Species richness	−0.01	0.9390
DR.ber	dredge	Abundance	−0.08	0.2930
DR.ber	dredge	Species richness	−0.08	0.3920
DR ber	**grab**	**Sediment OM**	**−0.63**	**<0.0001**
C.pyl	**grab**	**Abundance**	**−0.22**	**<0.0001**
C.pyl	grab	Biomass	−0.19	0.0090
C.pyl	grab	Species richness	−0.22	0.0350
C.pyl	**dredge**	**Abundance**	**−0.65**	**<0.0001**
C.pyl	dredge	Species richness	−0.27	0.0120
C.pyl	**grab**	**Sediment OM**	**−0.58**	**<0.0001**
DI.bea	corer	Abundance	−0.02	0.8680
DI.bea	corer	Biomass	−0.18	0.0190
DI.bea	**corer**	**Species richness**	**−0.23**	**0.0002**
DI.bea	**corer**	**Sediment OM**	**−0.38**	**<0.0001**

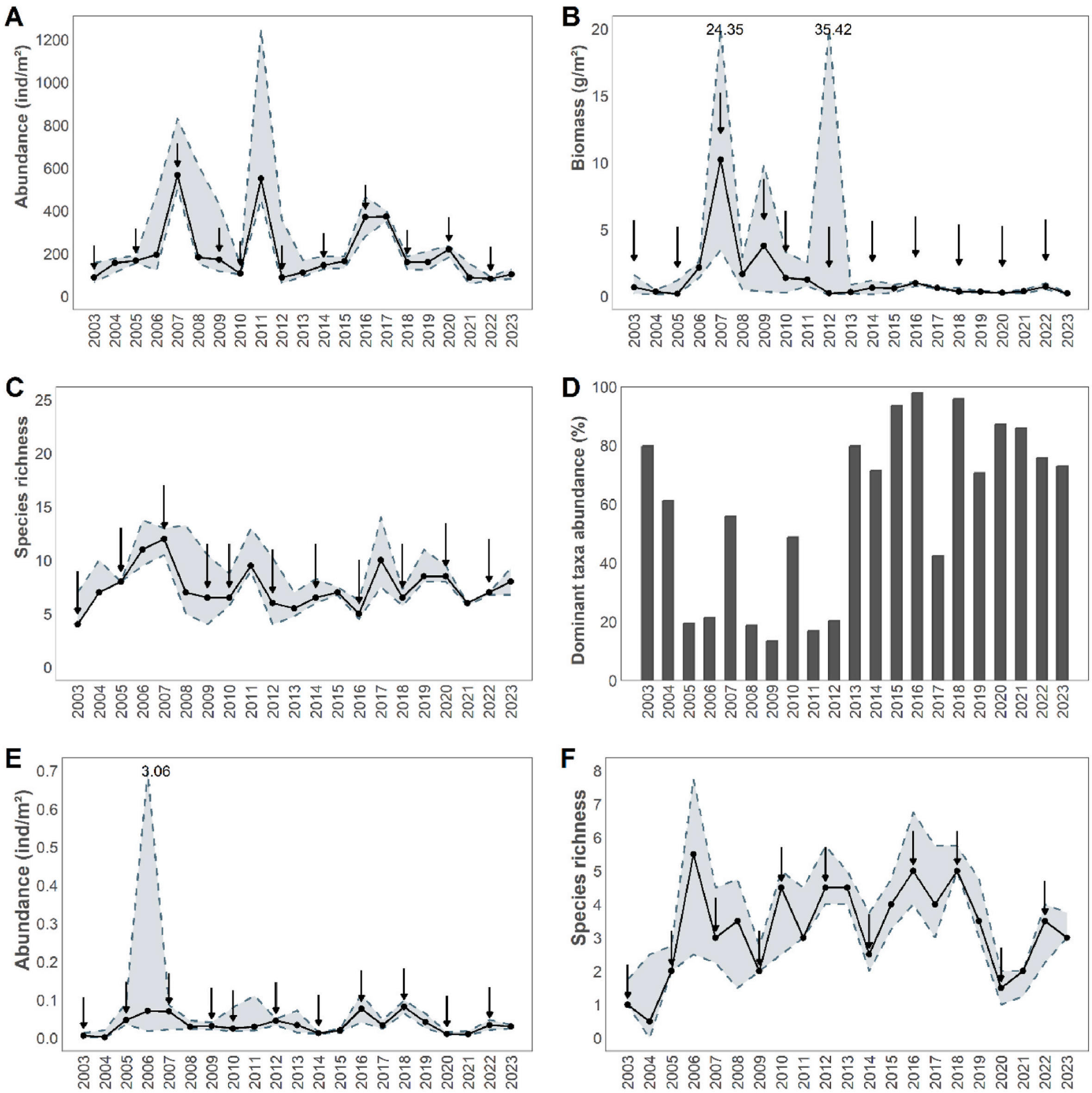


Fig. 4. Median macrofauna abundance (A), biomass(B), and species richness (C) per sample (the grey area represents the range from the first to the third quartile), collected with the grab and sieved on a 1-mm mesh sieve, in Bernet (dredging site). Arrows indicate the periods of dredging and replenishment. (D) illustrates the percentage of the 6 dominant taxa (*Bathyporeia* spp., *Gastrosaccus spinifer*, *Hippomedon denticulatus, Macomangulus tenuis, Nephtys cirrosa*, and *Urothoe* spp.), in terms of abundance, per year. Median megafauna abundance (E) and species richness (F) per sample (the grey area represents the range from the first to the third quartile), collected with the dredge and sieved on a 1-cm mesh sieve, in Bernet channel (subtidal dredging site). Extreme values are indicated as text for readability purposes.

the Pyla channel regarding the sediment. Indeed, the sediment median grain size remained stable over the years (*ca.* 340 μm) while the organic matter content significantly declined by *ca.* 0.4%–0.2% of the dry sediment weight from 2003 to 2023 (Table 2, Suppl. 2). A total of 112 and 38 taxa were sampled with the grab and the dredge, respectively (Suppl. 1-C & D). The median abundance per year of the fauna sampled with a 1-mm mesh (grab) ranged from 56 ind.m^{-2} to 517 ind.m^{-2} (Fig. 5A), with a mean of 212 ind.m^{-2}, showing a significant decrease over the years (Table 2). The median biomass varied from 0.1 gAFDW. m^{-2} to 2.3 gAFDW.m^{-2}, with a mean of 0.7 gAFDW.m^{-2} (Fig. 5B). The median species richness varied from 4 to 13 taxa, with a mean of 8 (Fig. 5C). More than 97% of the individuals belonged to the infauna. Five taxa (*Bathyporeia* spp., *Gastrosaccus spinifer*, *H. denticulatus, Nephtys cirrosa*, and *Urothoe* spp.) were retrieved in over 80% (i.e., 17 years) out of the 21 years (Suppl. 1-C). Over the years, and despite interannual fluctuations, these taxa accounted for 38% of the total abundance in the first decade and 70% in the second decade (Fig. 5D).

The median annual abundance of the fauna sampled with a 1-cm mesh dredge ranged from 0.004 to 0.056 ind.m^{-2} (Fig. 5E) showing a significant decrease over the years (Table 2), while species richness ranged from 1 to 5 species (Fig. 5F) with no significant decrease over the years (Table 2). Five taxa (*Atelecyclus undecimdentatus*, *D. curvimanus*, *Echinocardium cordatum*, *M. glauca*, *T. reticulata*) were retrieved in over 80% out of the 21 years (and represented 55% of the collected individuals) (Suppl. 1-D).

3.4. Pyla Beach (intertidal disposal)

A similar trend to that observed at the two subtidal sites was noted regarding the beach sediment. The median grain size of the sediment remained stable over the years at approximately 340 μm, and the organic matter content significantly declined by *ca.* 0.35%–0.20% of the dry sediment weight (Table 2, Suppl. 2). The yearly median abundance of the fauna sampled with a 1-mm mesh (corer) ranged from 64 ind.m^{-2}

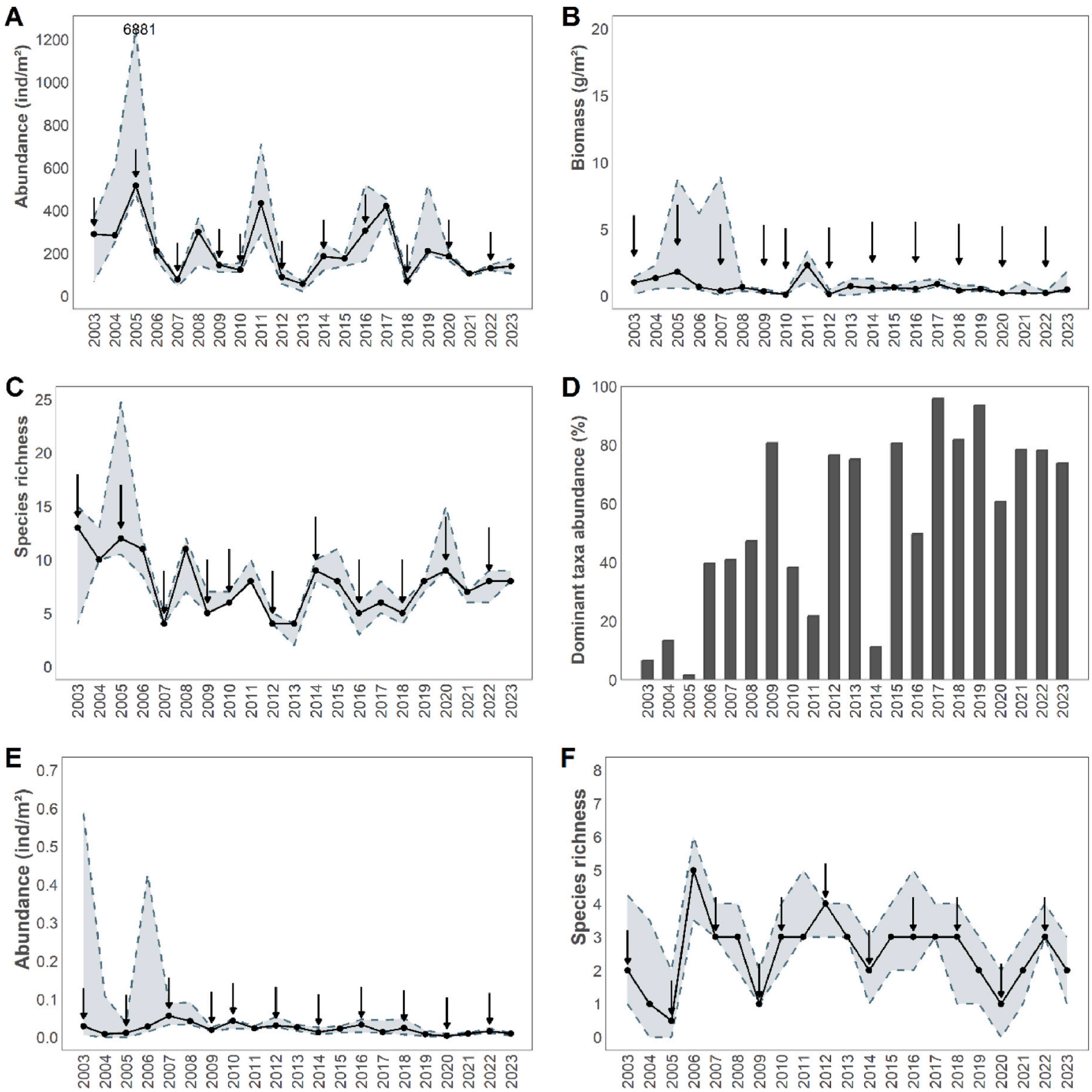


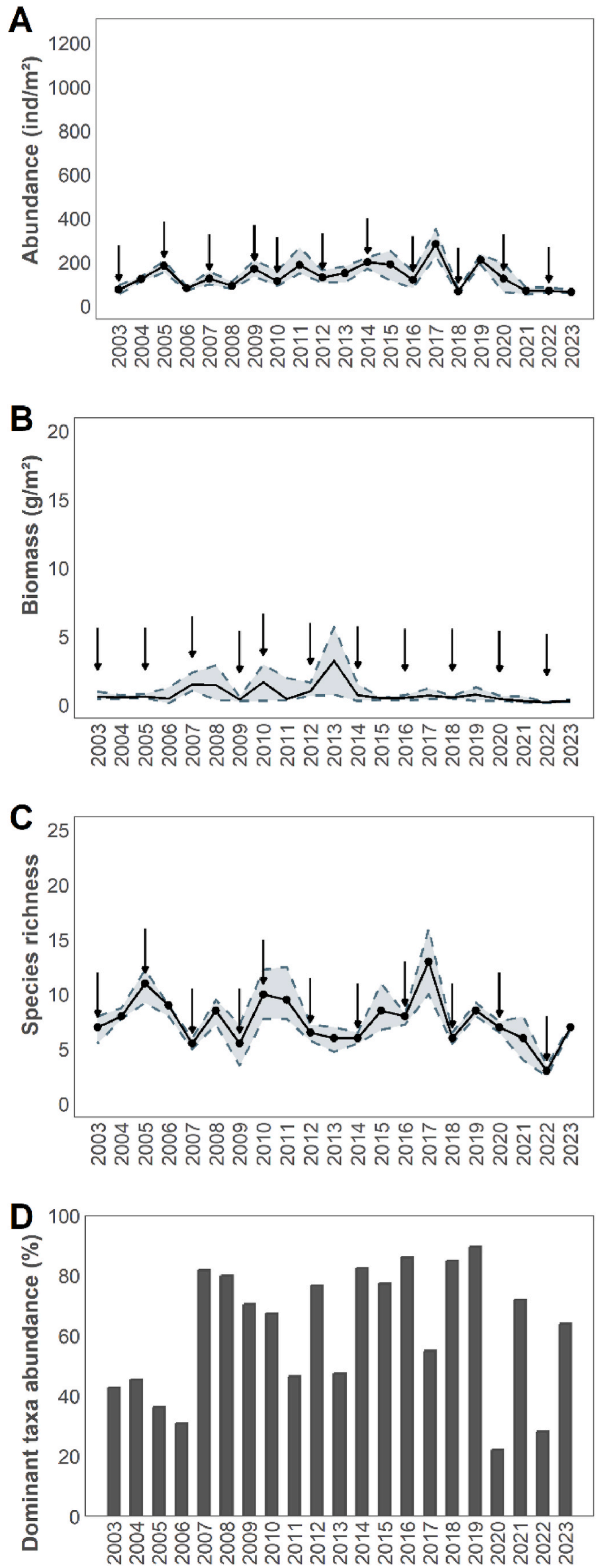
Fig. 5. Median macrofauna abundance (A), biomass(B), and species richness (C) per sample (the grey area represents the range from the first to the third quartile), collected with the grab and sieved on a 1-mm mesh sieve, in Pyla channel (subtidal disposal site). Arrows indicate the periods of dredging and replenishment. (D) illustrates the percentage of the 5 dominant taxa (*Bathyporeia* spp., *Gastrosaccus spinifer*, *Hippomedon denticulatus, Nephtys cirrosa*, and *Urothoe* spp.), in terms of abundance, per year. Median megafauna abundance (E) and species richness (F) per sample (the grey area represents the range from the first to the third quartile), collected with the dredge and sieved on a 1-cm mesh sieve, in Pyla channel (subtidal control site). Extreme values are indicated as text for readability purposes.

to 283 ind.m^{-2} (Fig. 6A), with a mean of 134 ind.m^{-2}. Over 96% of the individuals belonged to the infauna (Suppl. 1-E). The median biomass per year ranged from 0.2 gAFDW.m^{-2} to 3.2 gAFDW.m^{-2} (Fig. 6B), with a mean of 0.8 gAFDW.m^{-2}. The median species richness per year ranged from 3 to 13 taxa, with a mean of 8 taxa (Fig. 6C), and showed a significant decrease over the years (Table 2). Seven taxa from the core-sampled fauna (*Bathyporeia* spp., *G. spinifer*, *M. tenuis,* Nemertea, *N. cirrosa, Ophelia neglecta*, and *Urothoe* spp.) were retrieved in over 80% out of the 21 years (and represented 60% of the collected individuals) (Suppl. 1-E). Between 2003 and 2023, these species represented between 22% and 90% of the total abundance, with no obvious temporal trend (Fig. 6D).

4. Discussion

Many studies describe modifications of benthic community parameters shortly after works (van der Wal et al., 2011; Vivan et al., 2009) or refer to "recovery" after the cessation of works. In sandy bottoms, they often show a global recovery within a few months (Guerra-García et al., 2003; Newell et al., 1998; Wilber et al., 2008), or four years (Boyd et al., 2005; Wan Hussin et al., 2012). Published results referring to ongoing works, *i.e.*, repeated disturbances over a multi-decadal period, are scarcer and underscore the fact that "recovery" implies a return to preplacement ecological conditions, which may not be practically achievable in this case (Wilber et al., 2008). Moreover, differences in recolonization processes of benthic assemblages are also related to the intensity of dredging operations in terms of frequency and volume (La Porta et al., 2009; McLaverty et al., 2020), partly explaining the contrasting results from different study sites (Bolam and Rees, 2003). This 21-yr time series raises questions about the effect of regular sand extraction and beach nourishment operations (occurring every other year) on benthic community structure in medium sands, compared to a control area with no direct impact.

A lack of data before the works, apart from a unique sampling



(caption on next column)

Fig. 6. Median macrofauna abundance (A), biomass(B), and species richness (C) per sample (the grey area represents the range from the first to the third quartile), collected with the grab and sieved on a 1-mm mesh sieve, in Pyla beach (intertidal disposal site). Arrows indicate the periods of dredging and replenishment. (D) illustrates the percentage of the 5 dominant taxa (*Bathyporeia* spp., *G. spinifer*, *M. tenuis,* Nemertea, *N. cirrosa, Ophelia neglecta*, and *Urothoe* spp.), in terms of abundance, per year.

campaign in 2001 (de Montaudouin and Raigné, 2001), hindered a comprehensive assessment of the impact of the works relative to the initial conditions (*i.e.,* baseline data), particularly due to the significant interannual variability displayed by benthic communities. It is common for impact studies to encounter challenges due to imbalances in sampling effort before and after the works (Boyd et al., 2003; Sánchez-Moyano et al., 2004; Vivan et al., 2009). Consequently, this study did not focus on comparing benthic communities before and after the works. Instead, it concentrated on the impact of a continuous sediment disturbance (2003–2023), caused by dredging and beach nourishment, on benthic fauna.

4.1. The global benthic communities, combining disturbed and control areas

The clustering analysis (HCA) based on the grab samples showed poor discrimination between years, whether it was a year with dredging/replenishment or not, due to the high homogeneity and stability of the species composition across sites. In the three investigated areas, the grab-sampled fauna was dominated by infauna (>90% of total abundance). Four taxa were abundant, frequent, and shared by all three sites (*Bathyporeia* spp., *G. spinifer*, *N. cirrosa,* and *Urothoe* spp.). These taxa are all characteristic of clean medium sand, in shallow oceanic bottoms of this geographic area and were also retrieved in this lagoon in 1988 and 2002, before the start of these dredging and beach nourishment operations (Blanchet et al., 2005). Dredge-sampled fauna was dominated by epifauna (>75%). Bernet and Pyla channel shared three species (*D. curvimanus*, *M. glauca*, *T. reticulata*) which are also characteristic of this habitat (habitat codes 7141 and 2574, on the classification of European Union Habitat Directive (92/43/EEC) (Grall and Tauran, 2020; Lutrand et al., 2020) and may display a high resilience when facing physical stress (*D. curvimanus, T. reticulata*) (Dolbeth et al., 2006; Gaspar et al., 2001). Rapid re-colonization was possible due to the biological traits of these species (mobility, pelagic larvae and/or juveniles) is also facilitated by the similarity between native and fill sands (Paris et al., 2023). An important consequence is that in such environments, where interannual and seasonal variability is high, short-term impacts (a few months after the works) are difficult to detect. This often leads to the conclusion that fauna recovery is achieved in less than 2–3 years (Chauvel et al., 2024; Leewis et al., 2012), provided that sediment characteristics remain stable (Wijsman et al., 2023). However, the present study demonstrated that long-term monitoring may yield different conclusions.

4.2. Intertidal vs. subtidal benthic communities

Out of the 144 taxa identified, 48 taxa, representing 83% of all collected individuals, were shared across all three sites (Suppl. 1-A, C & E). The most notable pattern observed was the distinct difference in benthic community composition between the intertidal (disposal) and subtidal sites (dredged and control): almost all intertidal taxa were also present in subtidal sites (60 out of 69), conversely, it represented only half of the subtidal taxa, the other half containing fewer peracarid crustaceans and more bivalves (Suppl. 1-A, C & E). The lower proportion of bivalves and the higher proportion of peracarid crustaceans in the intertidal zone suggest that peracarid crustaceans may adapt more readily to intertidal conditions due to their motility, whereas bivalves, which can only recolonize through their (post-)larval stage, require more stable conditions found in the subtidal zones. Additionally, the intertidal area was entirely affected by the works (*i.e.* there was no control beach nearby). While rapid recolonization by opportunistic species was observed within less than four months, the benthic community structure in this area continued to evolve over the years, with a significant reduction in species richness and a non-significant reduction in biomass (but $p = 0.019$). In sandy and unstable substrates like those examined in the present study, results align with numerous previous studies indicating a rapid recolonization process (de Montaudouin et al., 2023; Newell et al., 1998). Consensus is lacking regarding the duration of the impact of beach nourishment on sandy beach intertidal benthic communities and key environmental variables (Wooldridge et al., 2016). Some authors have highlighted rapid recovery in clean sand communities (Danovaro et al., 2018; Dernie et al., 2003; Guerra-García and García-Gómez, 2006; van Dalfsen and Essink, 2001) while others have indicated long-term impacts or even the absence of complete recovery (Boyd et al., 2003; Wooldridge et al., 2016).

4.3. Dredged vs. control subtidal communities

In the subtidal area, the clustering analysis (HCA) performed on grab- or dredge-sampled macrofauna did not clearly separate the control area (Pyla channel) from the dredged area (Bernet channel). These two areas shared 72 taxa (out of 113 taxa at Pyla and 93 taxa at Bernet) (Suppl. 1 A & C). At the dredged area, all quantitative parameters (abundance, biomass, species richness) remained stable over the years. However, in the last decade, five taxa accounted for 80% of the total abundance, compared to 35% before 2013, suggesting that ongoing works are impoverishing the benthic community diversity (Kenny and Rees, 1996). These five taxa (*Bathyporeia* spp., *G. spinifer*, *H. denticulatus, N. cirrosa*, and *Urothoe* spp.) are motile and have a dispersal larval stage, making them well-adapted to hydrodynamically disturbed environments. Moreover, the recovery process benefits significantly from the presence of undisturbed surrounding areas, which act as 'refuge areas' for many species (van Dalfsen et al., 2000). These findings align with several similar studies that report rapid recovery (within a few months) following dredging activities (de Montaudouin et al., 2023; Robinson et al., 2005; Sánchez-Moyano et al., 2004), provided that sediment characteristics remain unaltered (Chauvel et al., 2024; Cooper et al., 2011; Mielck et al., 2021; Wijsman et al., 2023). The control area (Pyla channel) was very similar in terms of abundance, biomass, species richness, and species composition. Like the Bernet channel, it was not disturbed before 2003. The main difference is that the dominance of the five taxa increased progressively over the years, while total abundance slightly decreased over time, regardless of the sampling gear used, along with non-significant negative trends for all other parameters (with p-value<0.05, but not significant with the Bonferroni correction) (Table 1**)**. The decrease in abundance could be related to the overall reduction in organic matter in the sediment, which may be due to the indirect effects of the works (dredging westward and disposal eastward) or other trends related to global change such as the increase in the number of storms per year: 10 during 2003–2013 and 31 during 2014–2023 (BRGM, 2024). The impoverishment of organic matter related to continuous works and degradation of labile compounds has been documented and is known to persist over the years even after works cessation (Paradis et al., 2021). Also, disturbances or habitat loss leading to habitat fragmentation do not necessarily alter species composition due to the potential for recolonization from adjacent areas. However, they can result in a decline in species abundance, likely due to the scarcity of a key resource (*e.g.*, organic matter in the present study) (Do et al., 2013).

4.4. Disturbed intertidal benthic communities

The outcome of beach nourishment is not limited to the addition of sand at a specific site; it also induces broader environmental modifications. Added sand influences currents, waves, and sediment transport, eventually redistributing over months in cross-shore and longshore directions (de Schipper et al., 2021). In our study, involving repeated works, the habitat remains in a persistently unstable state. In such contexts, characterized by significant temporal and spatial variability, short-term or small-scale monitoring is insufficient to capture subtle changes in benthic communities (Danovaro et al., 2018; Paris et al., 2023; van Dalfsen and Essink, 2001). Conversely, extending the spatial scale to multiple beaches (Leewis et al., 2012; Wooldridge et al., 2016) or monitoring duration to over 10 years (this study) can reveal negative effects on biodiversity. Although beach species are adapted to high-energy environments with rapidly changing conditions, this does not ensure that all species are resilient to nourishment-induced changes (de Schipper et al., 2021). In this study, beach nourishment favored clades capable of rapid recolonization, such as polychaete annelids and peracarid crustaceans. The combined proportion of these clades was 81% of the community abundance, compared to just 15% for molluscs (Suppl. 1–E). Generally, opportunistic (r-selected) species facilitate rapid recovery (Chauvel et al., 2024; Leewis et al., 2012), whereas slow-developing (K-selected) species are most adversely affected. However, the cumulative impact of continuous disturbance over an extended period (21 years) resulted in a net loss of macroinvertebrate species richness. While this decrease was moderate, it was statistically significant and would have gone undetected with a shorter monitoring duration."

5. Conclusion

While small-scale beach nourishment is often perceived as an eco-sustainable approach to counter coastal erosion, its impacts are highly site-specific and strongly influenced by the total amount of sediment used and local environmental conditions (Danovaro et al., 2018). Each site and dredging experience contributes valuable knowledge, but deriving generalized conclusions remains challenging (de Schipper et al., 2021). Public priorities frequently appear contradictory, as they simultaneously aim to preserve beaches while ensuring high biodiversity along the coast (Bax et al., 2024). However, the presumed innocuity of beach nourishment concerning benthic diversity and higher trophic levels, such as fish and birds, is highly debatable. Our findings contribute to the growing need to critically reconsider the sustainability of nourishment as a 'soft' coastal management measure (Staudt et al., 2021).

CRediT authorship contribution statement

Adeline Tauran: Writing – review & editing, Writing – original draft, Methodology, Data curation. **Nicolas Lavesque:** Methodology, Data curation. **Hugues Blanchet:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Vaéa Bujan:** Methodology. **Benoît Gouillieux:** Methodology. **Suzie Humbert:** Methodology. **Bastien Lamarque:** Methodology. **Lise Latry:** Methodology. **Xavier de Montaudouin:** Writing – review & editing, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Funding

These studies were partly financed by Syndicat Intercommunal du Bassin d'Arcachon (SIBA), F-33120 Arcachon.

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.

Acknowledgements

Authors express gratitude to all colleagues and students working in the "biodiversity platform" of UMR EPOC, at the marine station in Arcachon. Sampling was conducted with the assistance of the staff and ships Planula III and IV provided by University Bordeaux 1 and CNRS/INSU (Flotte Océanographique Française), respectively. Thanks also to previous Referees.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2024.109119.

Data availability

Data will be made available on request.

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