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RESEARCH ARTICLE

Multiple human activities in coastal benthic ecosystems: Introducing a metric of cumulative exposure

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Co-occurring anthropogenic activities influence coastal ecosystems around the world. Notions of ecological exposure are promising indicators to better understand environmental status and enhance ecosystem protection. This study characterized anthropogenic exposure in the context of multiple human activities on coastal benthic ecosystems at a scale of <100 km. Using a particle diffusion model and fishing event data, we developed an exposure index for seven human activities (aquaculture, artificial structures, dredging, fisheries, runoff, sewers and shipping) in a Canadian industrial harbour area. A generally low cumulative exposure was obtained, with the highest values observed directly in front of the city and industrial areas. Derived exposure indices explained a portion of the benthic community structure ($R^2 = 0.22$), suggesting an ecological link between the exposure of species and their vulnerability to human activities. Such tools are relevant in data-poor environments where proxies are required to assess the state of an ecosystem, facilitating the application of ecosystem-based management.

Keywords: Anthropogenic influence, Exposure indices, Coastal benthos, Macrofauna, Gulf of St. Lawrence

1. Introduction

Management of coastal marine ecosystems requires efficient monitoring of ecosystem components, including human activities, in order to accurately guide environmental conservation initiatives. This need is especially true in the face of intensifying and ever diversifying human activities in marine ecosystems, with the omnipresence of their impacts (Halpern et al., 2019). Environmental assessments should thus consider the cumulative effects of multiple co-occurring human activities to best describe the current and anticipated states of marine ecosystems (Crain et al., 2008; Brown et al., 2014; Côté et al., 2016). With 40% of humanity living less than 100 km from coasts (Socioeconomic Data and Applications Center, 2020), coastal habitats and communities are influenced by a wide variety of human activities from terrestrial, freshwater and marine realms (Feist and Levin, 2016; Micheli et al., 2016). There is thus an urgent need to better understand how these ecosystems may by impacted by anthropogenic influences to accurately support their protection.

Integrative approaches, such as ecosystem-based management and marine spatial planning, are important tools for assessing, monitoring and managing human activities in coastal ecosystems (Margules and Pressey, 2000; Link, 2002; Pikitch et al., 2004; Levin et al., 2009; Santos et al., 2019). Ecosystems are complex entities composed of interconnected components, including biological communities, habitats and human activities, each governed by their own dynamics. An attempt to capture the complexity of this network of interactions has been made with the description of socio-ecological systems, often used to address community resilience issues (Berkes et al., 2000; Redman et al., 2004; Young et al., 2006; Díaz et al., 2011; Glaser et al., 2012). However, efficient environmental monitoring, particularly in the context of multiple human activities, is still a challenge and requires new tools to improve management capacity (Crain et al., 2008; Darling

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and Côté, 2008; Séguin et al., 2014; Piggott et al., 2015; Galic et al., 2018; Hodgson et al., 2019; Carrier-Belleau et al., 2021).

Many studies have focused on the influence of cumulative impacts on ecosystems around the globe (Korpinen and Andersen, 2016), including in-situ field studies (e.g., Ocaña et al., 2019; D'Alessandro et al., 2020), geospatial modelling (e.g., Ban et al., 2010; Stelzenmüller et al., 2010; Parravicini et al., 2012; Okey et al., 2015; Beauchesne et al., 2020) and experimental manipulations (e.g., Beermann et al., 2018; Carrier-Belleau et al., 2022). In particular, Halpern et al. (2008), later updated by Halpern et al. (2019), proposed a comprehensive cumulative impact score for marine ecosystems. This score was calculated by combining spatial data on the *exposure* (co-occurrence between ecosystems and human pressures) and *vulnerability* (how ecosystem components react to this pressure) of ecosystems to 17 human activities (Wilson et al., 2005; Halpern et al., 2007, 2008). The various facets of this score represent important addition to the cumulative impacts literature, highlighting a ubiquitous anthropogenic footprint on marine ecosystems (Halpern et al., 2019). However, several limitations have been identified in these studies, such as the inclusion of very diverse pressures in a common metric, the proper assessment of spatial and temporal variability, the description of how ecosystem components respond to impacts, the inclusion of non-additive effects and the establishment of non-impacted reference conditions (Halpern and Fujita, 2013; Korpinen and Andersen, 2016; Hodgson et al., 2019).

Relating exposure with ecological indicators at a fine spatial resolution is a way to overcome some of these challenges and to address some shortcomings of cumulative impacts studies, especially ecosystem responses to pressure and possible emergent effects. Many relationships between biodiversity and local anthropogenic influence have been observed worldwide (Millenniun Environmental Assessment, 2005; Andersen et al., 2015; Solan and Whiteley, 2016; Ellis et al., 2017), such that ecological indicators provide relevant insights to understand the effects of human activities on the environment. As defined by Pinto et al. (2009), indicators describe ecosystems to determine a status with quantitative data, for example by using key habitat variables or the abundance of characteristic species (Borja et al., 2012; Teixeira et al., 2016). Macrobenthic invertebrates, a highly diverse biological component whose links with human activities have been described in a variety of ecosystems, may serve as ecological indicators (Pearson and Rosenberg, 1978; Grall and Glémarec, 1997; Teixeira et al., 2016). Various benthic species are characterized by a sedentary lifestyle and a relatively long lifespan which tends to reflect medium-term environmental conditions, resulting in adaptation or local extinction when disturbed (e.g., Dauer, 1993; Borja et al., 2000; Wei et al., 2020).

Linking cumulative pressure and biodiversity assessments at a spatial extent below 100 km, this study evaluates the influence of anthropogenic activities on local coastal ecosystems. In this context, the specific objectives of this study are to (i) model the exposure of benthic ecosystems to multiple anthropogenic activities at a local scale and (ii) evaluate how well this index reflects benthic conditions. We expect that the structure of biological communities within high exposure areas ("anthropogenic hotspots") will present evidence of disturbance, such as lower diversity and the presence of opportunistic species, compared to the rest of the study area.

2. Materials and methods

2.1. Study area

As a case study, we focused on the industrial harbour area of Sept-Îles (Québec, Canada; **Figure 1**). Located in the Gulf of St. Lawrence, a priority management area identified by Fisheries and Oceans Canada and a major economic region for Québec (Department of Fisheries and Oceans, 2009; Beauchesne et al., 2016; Daigle et al., 2017; Schloss et al., 2017), Sept-Îles is the fourth largest Canadian port in terms of total exchanged goods and the second largest in Québec in 2020 (Statistics Canada, 2011; Binkley, 2020; Ferrario et al., 2021; Port de Sept-Îles, 2021). Available ecological data on coastal ecosystems in this region were limited, which supported the need to characterize benthic ecosystems and their relation to coastal human activities (Snelgrove et al., 2012; Carrière, 2018; Dreujou et al., 2020b, 2021).

The area includes Baie des Sept Îles and the archipelago at its entrance, covering approximately 200 km^2 (**Figure 1**). Bathymetry is shallow within the bay, with a maximum depth of 50 m at its entrance, then becoming deeper (up to 200 m) in the archipelago (Dutil et al., 2012). The general sediment profile is sandy-silty, with a small fraction of gravel. Benthic communities are diverse with a high density of annelids, arthropods and mollusks (Dreujou et al., 2020b). This region has sub-Arctic environmental conditions, with sea ice formation in November–December

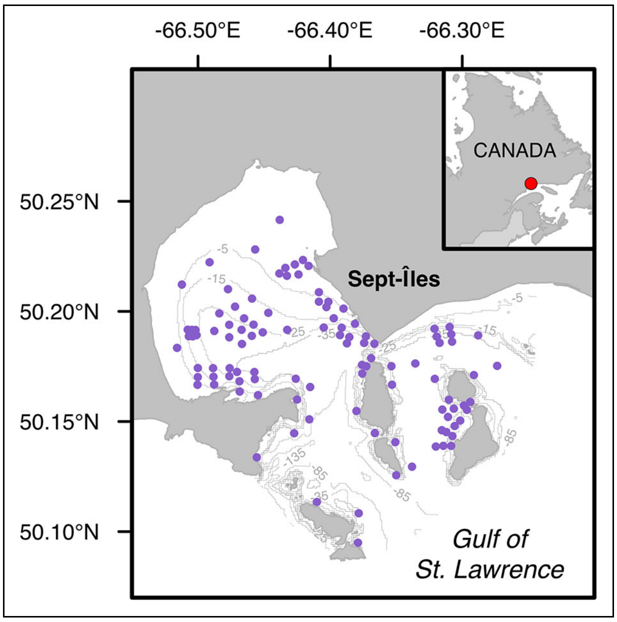

Figure 1. Map of stations sampled in Baie des Sept Îles (Canada). Isolines correspond to the regional bathymetry (depth in meters).

and substantial freshwater runoff due to snowmelt in April (Demers et al., 2018). The area is characterized by strong tidal currents, resulting in an estuarine circulation within the bay, along with freshwater inputs from multiple streams (Shaw, 2019).

Local industrial operations include aluminium production in plants at the Pointe-Noire sector and the southeastern part of the city of Sept-Îles, international shipping of iron ore through bulk carriers (reaching 33.1 MT in 2020) and coastal fisheries targeting fishes (Atlantic herring *Clupea harengus*, Atlantic cod *Gadus morhua*), crustaceans (snow crab *Chionoecetes opilio*, rock crab *Cancer irroratus*, northern shrimp *Pandalus borealis*) and mollusks (whelk *Buccinum* sp, Arctic surf clam *Mactromeris polynyma*; Department of Fisheries and Oceans, 2019; Port de Sept-Îles, 2021).

2.2. Sources of anthropogenic activities

Relevant human activities were identified through a literature review and a compilation of data from local organizations (Port de Sept-Îles, Ville de Sept-Îles and Institut Nordique de Recherche en Environnement et en Santé au Travail) and integrative databases (Beauchesne et al., 2020). This data screening process identified seven relevant human activities: mussel aquaculture, dredging of sediment, city and industrial runoff, sewer discharge, commercial vessel movements and operations (shipping), artificial structures and commercial fisheries.

The distribution and intensity of human activities were characterized using R v4.2 and packages raster and sf (Pebesma, 2018; Hijmans, 2020; R Core Team, 2022). Data for anthropogenic sources consisted of spatial objects (multipoints, multilines and multipolygons), where the relative importance of each component was determined by comparing sources metadata, such as water discharge volume or number of fishing events, to grant standardized weighting coefficients. Data were handled according to confidentiality policies of each source provider.

2.3. Exposure of ecosystems to anthropogenic activities

Because characterization of vulnerability requires extensive data on the physiological responses of species and how *influence* translates to *impact*, we focused on the exposure of benthic communities to human activities (i.e., component $S_{j,x}$ in the score by Halpern et al., 2019). We thus developed an index of exposure E for each considered human activity to describe the anthropogenic footprint in the study area. A "static" environment without spatial or temporal dynamics was considered, such that the index represents a "snapshot of exposure." E was computed differently for land/sea-based activities and for fisheries, as explained below.

2.3.1. Land/sea-based human activities

Indices of exposure for aquaculture, dredging, runoff, sewers, shipping and structures were obtained using a diffusion model, implemented in the absence of a complete circulation model for the Baie des Sept Îles. We developed a unique model that uses theoretical particles set to diffuse within a defined area. These particles result from an activity (such as contaminants or sediment) introduced by point or line sources in the environment. The length of the journey from the source(s) of activity to a location D was used as a proxy of exposure: when D is low, particle density is high (being close to the source), thus indicating a high exposure of the ecosystem to this activity, and vice versa. We identified 11 sources of human activity in the study area, from punctual sources, e.g., sewer drains, to diffuse sources, e.g., coastal runoff from the city (**Figure 2**), acting as sources of particles in the diffusion model.

Distance D was obtained using package gdistance (van Etten, 2017). A 100 × 100 m grid was created for the study area, where we established a connectivity matrix in a chess queen configuration (each cell to its eight direct neighbours using horizontal, vertical and diagonal directions). The cost of moving from one cell to another was computed with two constraints: (i) particles only diffuse in the marine environment and (ii) particles sink according to gravity and settle on the seafloor. To implement these aspects of the model, we used coastlines as boundaries (cost to select land cells is infinite) and bathymetry (movement of particles is primarily downward, while upward movement is secondary and hindered by topography) in the transition function. A least-cost pathfinding algorithm computed distance D from the source(s) of human activity to a specific grid cell (Dijkstra, 1959; van Etten, 2017).

Exposure indices E were calculated for each cell using D and a Gaussian kernel function (exponential quadratic relationship) to account for dispersion in a 2D environment while reducing the contribution of the highest values. The equation for E is thus:

$$E_{ij} = exp\left(\frac{A_j.(D_{ij})^2}{r}\right)$$

where i is a cell, j is a human activity, A is the decay coefficient and r is the spatial extent of the grid.

As the considered human activities do not have the same relative influence on ecosystems, we simulated dispersion patterns with different relationships between distance and exposure by tuning a parameter in the function, the decay coefficient A. Five unique behaviour profiles for particles were established, from very localized (Type I) to ubiquitous (Type V; Figure S1). We performed a literature review to identify physical, chemical and biological pressures to assign behaviour profiles to human activities, considering a Sept-Îles context (**Table 1**). A pressure is defined here as a consequence of a driver (being natural or anthropogenic) affecting the ecosystem, following the Driver-Pressure-State-Impact-Response (DPSIR) framework (European Environmental Agency, 1999; Gari et al., 2015; Judd et al., 2015; Oesterwind et al., 2016). We queried articles and reviews from dedicated scientific studies about each pressure to obtain spatial and temporal ranges, allowing to select a profile type based on the decision table shown in Figure S2. Finally, the most prevalent behaviour profile between pressures was assigned to the corresponding human activity (**Tables 1** and S1).

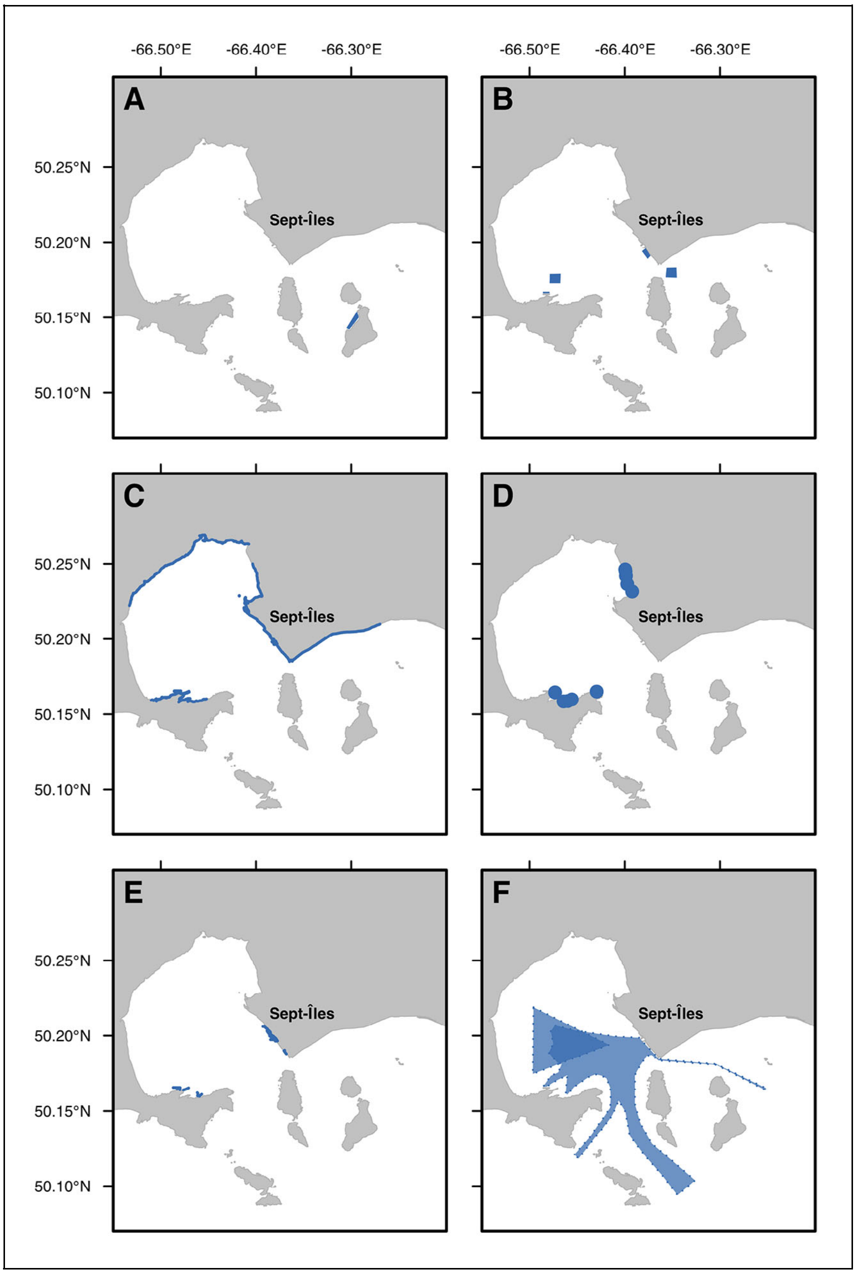

Figure 2. Maps of the considered sources of land- and sea-based human activities in the study area. The human activities (in blue) are (A) aquaculture, (B) dredging, (C) runoff, (D) sewers, (E) structures, and (F) shipping.

2.3.2. Fisheries

The exposure index E for fisheries was calculated by considering the number of fishing events by gear type: areas with a high number of events indicate a high exposure, and vice versa. Data were extracted from the eDrivers platform in the industrial harbour area of Sept-Îles for events recorded between 2010 and 2015 (Beauchesne et al., 2020). Fishing events were compiled in a raster file for four types of fishing gear: traps, bottom-trawls, nets and dredges. We averaged the number of events to obtain a proxy of fishing intensity per gear G. We obtained the exposure index E by combining G from the four gear types using the following equation:

$$E_i = \frac{\sum_k G_{ik}}{4}$$

where i is a cell and k is a gear type.

2.3.3. Cumulative exposure

The seven indices of exposure described above were standardized between 0 (lowest exposure) and 1 (highest exposure) then summed to provide a cumulative exposure score C. Because the relative importance between human activities is unknown for our study area, we considered each activity in the cumulative score to be of equivalent importance (i.e., no weighting parameters). The equation for C is thus:

$$C_i = \sum_j E_{ij}$$

where i is a cell and j is a human activity.

2.4. Habitat and biological samples

To understand how the calculated exposure indices relate to benthic ecosystems, we used several ecological datasets

Table 1. Description of human activities and related pressures considered in this study

Human Activity	Pressures	Description	Main References
Exploitation of mussel farms	Increase in organic matter concentration	Introduced from mussel metabolism and related bacterial activity	Christensen et al. (2003); Crawford et al. (2003); Richard et al. (2007); Callier et al. (2009); McKindsey et al. (2011); Heery et al. (2017); Lacoste et al. (2019)
	Modification of particulate matter	Changes in composition of POM from farm operation and organism degradation	Crawford et al. (2003); McKindsey et al. (2011); Wilding and Nickell (2013); Gallardi (2014)
	Increase in nutrient concentrations	Related to metabolism of mussels and associated species	Christensen et al. (2003); Cranford et al. (2003); McKindsey et al. (2011); Wilding and Nickell (2013); Gallardi (2014)
	Decrease in dissolved oxygen and sediment redox potential	Related to metabolism of mussels, bacteria and associated species	Wilding and Nickell (2013); Tičina et al. (2020)
	Introduction of shellfish diseases	Inherent or emerging diseases from mussels or related organisms	Tičina et al. (2020)
	Introduction of alien species	Parasites, bacteria, viruses and other organisms linked to mussels	Gallardi (2014); Tičina et al. (2020)
Collection and dumping of sediment material	Modification of sediment grain-size	Related to currents and hydrodynamics induced by dredging operations	Desprez (2000)
	Modification of sediment topography	Changes in local sediment slope and bathymetry	Desprez (2000); International Council for the Exploration of the Sea (2001)
	Resuspension of sediments	Related to movement of dredged material	Desprez (2000); International Council for the Exploration of the Sea (2001)
	Modification of chemical concentrations	Chemical elements buried in sediment released back to water column	International Council for the Exploration of the Sea (2001)
	Decrease in dissolved oxygen	Related to metabolism induced by chemical release from sediment	International Council for the Exploration of the Sea (2001)
	Transportation and destruction of organisms	Related to sediment modification	Desprez (2000); International Council for the Exploration of the Sea (2001)
Runoff from city and industries	Increase in nutrient concentrations	Introduced by terrigenous inputs and biological activity from coastal settlements and facilities	Müller et al. (2020)
	Increase in heavy metal concentrations	Introduced by terrigenous inputs and biological activity from coastal settlements and facilities	Müller et al. (2020)
	Increase in organic matter concentration	Introduced by terrigenous inputs and biological activity from coastal settlements and facilities	Müller et al. (2020)
	Modification of salinity gradients	Related to freshwater inputs	Müller et al. (2020)
	Increase in nutrient concentrations	Introduced by wastewater management facilities	Cotano and Villate (2006); Bertocci et al. (2019); Culhane et al. (2019)

(continued)

Table 1. *(continued)*

Human Activity	Pressures	Description	Main References
Wastewater and rainwater from sewers	Increase in heavy metal concentrations	Introduced by wastewater management facilities	Bertocci et al. (2019); Culhane et al. (2019)
	Increase in organic matter concentration	Introduced by wastewater management facilities and related to bacterial activity	Cotano and Villate (2006); Bertocci et al. (2019); Culhane et al. (2019)
	Introduction of exogenic compounds (e.g., drugs)	Introduced by wastewater management facilities	Islam and Tanaka (2004); Culhane et al. (2019)
	Modification of particulate matter	Related to solid and dissolved matter in wastewater outputs	Oviatt et al. (1987)
	Decrease in dissolved oxygen	Related to bacterial activity	Culhane et al. (2019)
	Modification of temperature gradients	Related to freshwater inputs	Bertocci et al. (2019); Culhane et al. (2019)
	Modification of salinity gradients	Related to freshwater inputs	Bertocci et al. (2019); Culhane et al. (2019)
	Increase in biological activity	Bacteria, viruses and other organisms present in wastewaters	Islam and Tanaka (2004); Müller et al. (2020)
Artificial structures (piers, marina)	Modification of hydrodynamics	Related to addition of solid structures	Bulleri and Chapman (2010); Heery et al. (2017)
	Increase in anthropogenic noise	Produced from shipping operations and machinery	Heery et al. (2017)
	Increase in artificial light	Produced by dedicated structures	Bulleri and Chapman (2010); Heery et al. (2017)
	Modification of electromagnetic fields	Produced by underwater cables	Heery et al. (2017)
	Increase in turbidity	Related to sediment resuspension from increased hydrodynamics	Mineur et al. (2012); Heery et al. (2017)
	Introduction of exogenic compounds	Dilution from paints or materials used	Heery et al. (2017)
	Increase in organic matter concentration	Related to accumulation of sediments	Heery et al. (2017)
	Introduction of alien species	Settlement rate increased on solid structures	Bulleri and Chapman (2010); Mineur et al. (2012); Heery et al. (2017)
	Modification of species communities	Linked to new habitats provided by solid structures and to changes in connectivity	Bulleri and Chapman (2010); Bishop et al. (2017); Heery et al. (2017); Momota and Hosokawa (2021)
Commercial vessels anchoring, movement and operation	Introduction of exogenic compounds	Dilution from hull paints	Jägerbrand et al. (2019); Byrnes and Dunn (2020)
	Increase in hydrocarbons	Produced from onboard systems, potential spills and cargo hauling operations	Jägerbrand et al. (2019); Byrnes and Dunn (2020)
	Increase in heavy metal concentrations	Linked to cargo hauling operations	Jägerbrand et al. (2019); Byrnes and Dunn (2020)
	Introduction of marine litter	Plastics and other wastes	Jägerbrand et al. (2019); Byrnes and Dunn (2020)

(continued)

Table 1. *(continued)*

Human Activity	Pressures	Description	Main References
	Increase in coastal erosion	Disturbance of coastal topography by waves	Jägerbrand et al. (2019); Byrnes and Dunn (2020)
	Increase in anthropogenic noise	Produced from engine and ship machinery operation	Jägerbrand et al. (2019)
	Increase in artificial light	Produced from onboard systems	Jägerbrand et al. (2019); Byrnes and Dunn (2020)
	Introduction of alien species	Non-indigenous species present in ballast waters or fouling external surfaces	Jägerbrand et al. (2019); Byrnes and Dunn (2020)
	Modification of sediment topography	Use of anchor systems	Davis et al. (2018); Jägerbrand et al. (2019); Byrnes and Dunn (2020)
	Resuspension of sediments	Use of anchor systems	Davis et al. (2018); Byrnes and Dunn (2020); World Wildlife Fund (2020)

in the study area from Dreujou et al. (2021). Samples were collected in July 2017 within the bay and archipelago of Sept-Îles, where a total of 108 stations were selected using a semi-randomization algorithm. Stations were constrained between depths of 0 m and 80 m with an increased sampling effort in areas where sources of human activities were present (**Figure 1**).

Station depth was obtained from a navigation sonar, then corrected with respect to tide height at the time of sampling. A Ponar grab (0.05 m^2) was deployed at each station from a boat with two independent casts. This first cast collected sediment samples for chemical and physical analyses while sediment from the second cast was sieved on a 0.5 mm mesh size for macrofauna identification. This approach allowed the collection of data on organic matter content, sediment grain-size percentages (gravel, sand, silt, clay), heavy-metal concentrations (arsenic, cadmium, chromium, copper, iron, manganese, mercury, lead, zinc), and the density and wet biomass for each taxon identified.

2.5. Statistical analyses

Correlation between exposure indices and habitat parameters was assessed using Spearman's rank coefficient (Quinn and Keough, 2002). Building on the concept of the Ecological Quality Ratio by van de Bund and Solimini (2007), we computed an exposure ratio ER at each sampled station based on their cumulative exposure score. This ratio compares the value of the score to its extrema to provide integrative information on the severity of the cumulative exposure:

$$ER = \frac{C_i - R_{high}}{R_{low} - R_{high}}$$

where C_i is the cumulative exposure score at station i, R_{high} is the reference value for a high exposure (here, 7) and R_{low} is the reference value for a low exposure (here, 0). Using ER, we assigned an exposure status to each station: a low status corresponds to a high exposure ratio and a high status to a low exposure ratio. Five categories were defined for this status, similar to those used for the Ecological Quality Status: "bad," "low," "moderate," "good" and "high" status (van de Bund and Solimini, 2007).

Characteristic taxa were assessed for each exposure status by computing the indicator value score on benthic assemblages (IndVal, 1000 randomization iterations; Dufrêne and Legendre, 1997). We used benthic community descriptors and environmental indicators calculated by Dreujou et al. (2021): total density, total biomass, taxa richness, Shannon index (base *e* logarithm), Pielou evenness, Multivariate AZTI Marine Biotic Index (M-AMBI), BENTIX score and Benthic Opportunistic Polychaete/Amphipod ratio (BOPA; Legendre and Legendre, 1998; Simboura and Zenetos, 2002; Dauvin and Ruellet, 2007; Muxika et al., 2007; Magurran and McGill, 2011; Dauvin et al., 2016). M-AMBI, BENTIX and BOPA are calculated using relative abundance of species groups, established based on tolerance to perturbation. Phylum mean density and mean biomass were calculated for each exposure status to evaluate their relative variation.

Relationships between exposure indices (predictors) and benthic descriptors (independent variables) were evaluated using multiple regression models. Variables were transformed (log(x + 1) or square root) if the assumptions of normality and homoscedasticity were not respected (Quinn and Keough, 2002). We also explored relationships between the taxa assemblage and exposure indices using non-parametric multivariate regression with distance-based linear modelling (DistLM, 9,999 permutations; McArdle and Anderson, 2001). In both regression analyses, we added depth as a covariate to account for bathymetric variation between stations. Statistical analyses were done using R v4.2 with package vegan and PRIMER-E v6 software (Clarke and Gorley, 2006; Oksanen et al., 2022; R Core Team, 2022).

3. Results

3.1. Exposure indices

Our literature review highlighted 25 unique pressures linked to human activities in the Baie des Sept Îles (**Table 1**), including biological, physical and chemical effects on ecosystems. Most pressures were associated with a localized profile (Type II, 17), followed by diffused (Type III, 12) and very diffused (Type IV, 9) profiles.

Overall, bay-wide average exposure indices were low to moderate, varying between 0.05 (fisheries) and 0.6 (sewers). Only stations close to sources of activity presented high index values, with a limited area of influence for each human activity (**Figure 3**). The fisheries exposure index was highly localized, similar to those for aquaculture and dredging (**Figure 3**). Sewers had the most extensive footprint in the bay, with a highest exposure index at the intersection of the zone of influence of multiple sewer drains. Exposure due to runoff and shipping both decreased with increasing distance from their sources (**Figure 3**). Correlation tests on exposure indices showed positive relationships between runoff and structures (correlation coefficient $\rho = 0.87$), dredging and runoff ($\rho = 0.76$), sewers and shipping ($\rho = 0.74$); all other pairwise tests showed low to moderate relationships ($0.28 < |\rho| < 0.7$).

The cumulative exposure score calculated at each station varied between 0.383 and 3.698 across the bay, with an average of 1.865 (standard error of 0.08, theoretical maximum value of 7; **Figure 4A**). The highest values were detected close to the main industrial and urban activity sources, especially in front of the city of Sept-Îles and the Pointe-Noire sector (**Figure 4A**). The vast majority of the stations sampled for macrofauna were assigned an exposure status of "high" ($n = 40$) or "good" ($n = 50$), while 18 presented a "moderate" status (**Figure 4B**).

3.2. Relationships with benthic ecosystems

Correlations between exposure indices and habitat parameters are summarized in **Table 2**. Overall, sediment parameters had lower correlations with exposure indices than did heavy metals. Organic matter showed positive relationships with sewers ($\rho = 0.42$) and shipping ($\rho = 0.37$) and a negative one with fisheries ($\rho = -0.49$). Sand and silt presented relationships for fisheries, runoff, sewers and shipping, with low to moderate coefficients ($0.19 < |\rho| < 0.38$). Notably, gravel was poorly related to fisheries and shipping, while all correlations for clay were nonsignificant. Concerning heavy metals, three patterns were observed: aquaculture and fisheries had moderate to high negative coefficients for all heavy metals ($-0.24 < \rho < -0.61$); dredging and structures had moderate positive coefficients for some metals ($0.23 < \rho < 0.57$); and sewers and shipping had moderate to high positive coefficients for all metals ($0.27 < \rho < 0.75$). For environmental indicators, most coefficients were not significant but some low relationships ($|\rho| < 0.25$) were evident. Finally, the cumulative exposure score showed low to moderate positive relationships with organic matter and most heavy metals ($0.19 < \rho < 0.58$).

The analysis of phylum mean density and mean biomass varied by exposure status (**Figure 5**). The biomass of annelids was greatest for lower status classes, increasing from 3.7% in "high" status to 38.9% in "moderate" status, while density stayed between 28% and 40% of the total community. Arthropod density peaked at "good" status (53.3%) and was also quite high at "high" and "moderate" status (30.3% and 40.2%, respectively), whereas biomass proportion did not exceed 3%. Mollusc biomass also peaked at "good" status (40.8%) then dropped to 16.9% at "moderate" status and 8.6% at "high" status. Mollusc density stayed around 15% for each status. Echinoderm biomass and nematode density were highest at "high" status stations (86% and 20.3%, respectively) then dropped significantly at "moderate" status stations (as low as 32.7% and 0%, respectively).

The calculation of IndVal yielded few significant characteristic taxa for each exposure status. Stations with a "high" status presented four characteristic taxa: Nematoda ($p < 0.001$), the gastropod *Ameritella agilis* ($p = 0.011$), Nephtyidae polychaetes ($p = 0.021$) and the amphipod *Byblis gaimardii* ($p = 0.033$). Only harpacticoid copepods were identified as significant for stations with a "good" status ($p = 0.029$), while no characteristic taxa were related to stations with a "moderate" status.

Multiple regression analyses between exposure indices and benthic descriptors showed that predictive power was highest for Shannon index (adjusted $R^2 = 0.29$) followed by taxa richness (adjusted $R^2 = 0.16$) and Pielou evenness (adjusted $R^2 = 0.14$). Predictive power for total density and biomass was quite low (adjusted $R^2 < 0.04$) (**Table 3**). Marginal tests for depth indicated statistically significant relationships for Shannon index (standardized coefficient = 0.54), Pielou evenness (0.46) and taxa richness (0.25). Exposure indices mostly showed positive effects on total density, taxa richness, Shannon index and Pielou evenness, with coefficients seldom going over 0.15 (**Table 3**). Different patterns were detected for total biomass, where most activities had negative effects, especially sewers (–0.58) and runoff (–0.48), while structures presented a strong positive effect (0.54). Post-analysis diagnostics for homoscedasticity, normality of residuals and independence were quite robust, especially for taxa richness, Shannon index and Pielou evenness.

DistLM regression on the taxa assemblage had an R^2 of 0.22, and the ancillary constrained ordination is shown on **Figure 6**. The first two axes explained 14.9% of the variance, where two negatively correlated groups of exposure indices were obtained: sewers/shipping to one side, aquaculture/fisheries/runoff to the other (dredging and structures had lower influence). Interestingly, depth did not correlate with exposure indices, although it correlated strongly with benthic community structure, as expected. No structure may be described based on the similarity between stations, except for a group of stations with a higher cumulative exposure score at the centre of the biplot (**Figure 6**).

4. Discussion

This study presents a modelling framework to study anthropogenic influences on coastal benthic ecosystems at a local scale of <100 km using proxies such as distance from sources of activity and fishing events. This tool represents a relevant addition for environmental managers by providing a way to estimate exposure to human activities that may be related to existing ecological data and by

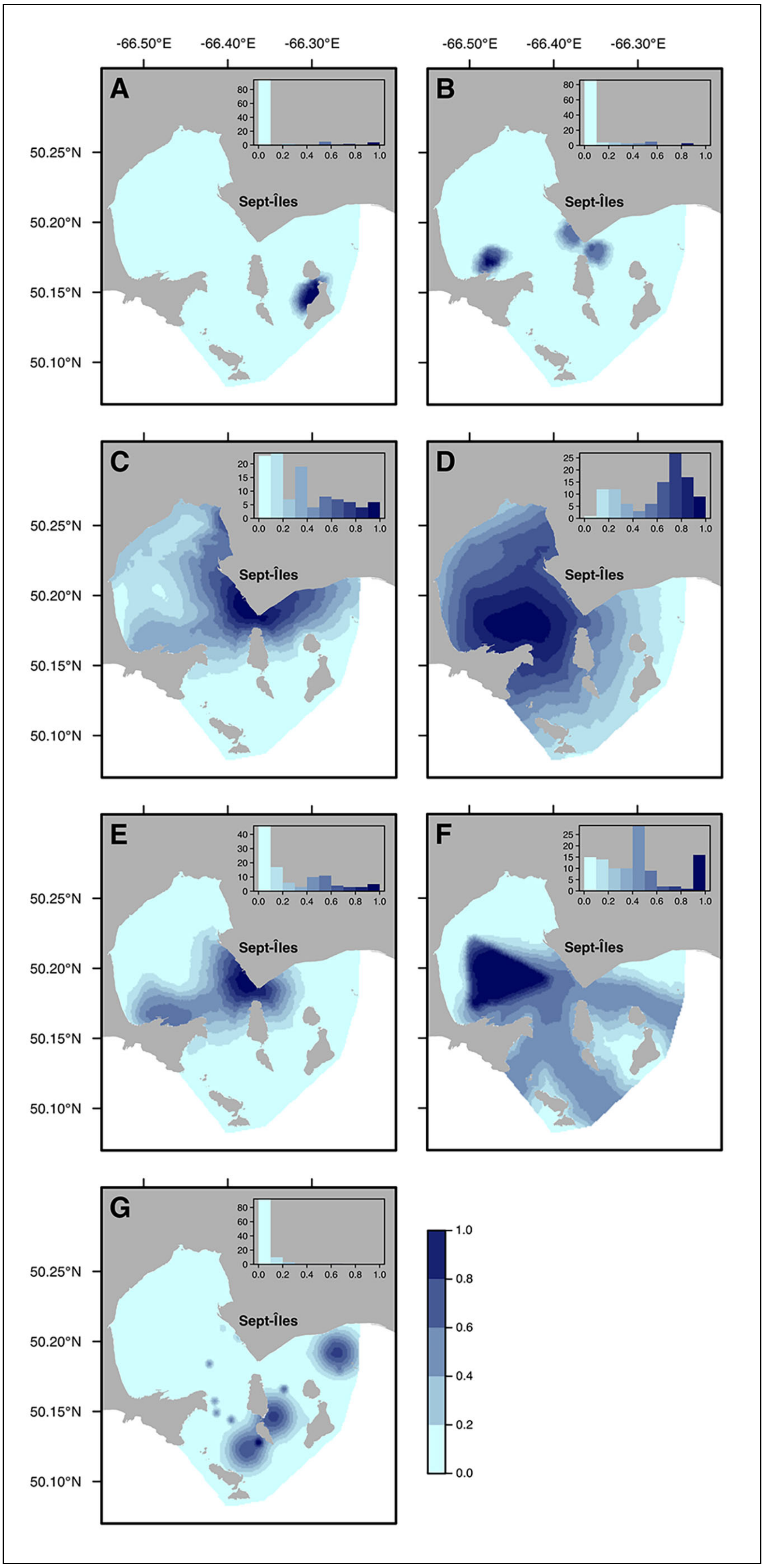

Figure 3. Exposure indices calculated in the study area for each human activity. Histograms represent the number of stations along the value of the index, and colours correspond to exposure classes, from low (0.0) to high (1.0). The human activities considered are (A) aquaculture, (B) dredging, (C) runoff, (D) sewers, (E) structures, (F) shipping, and (G) fisheries.

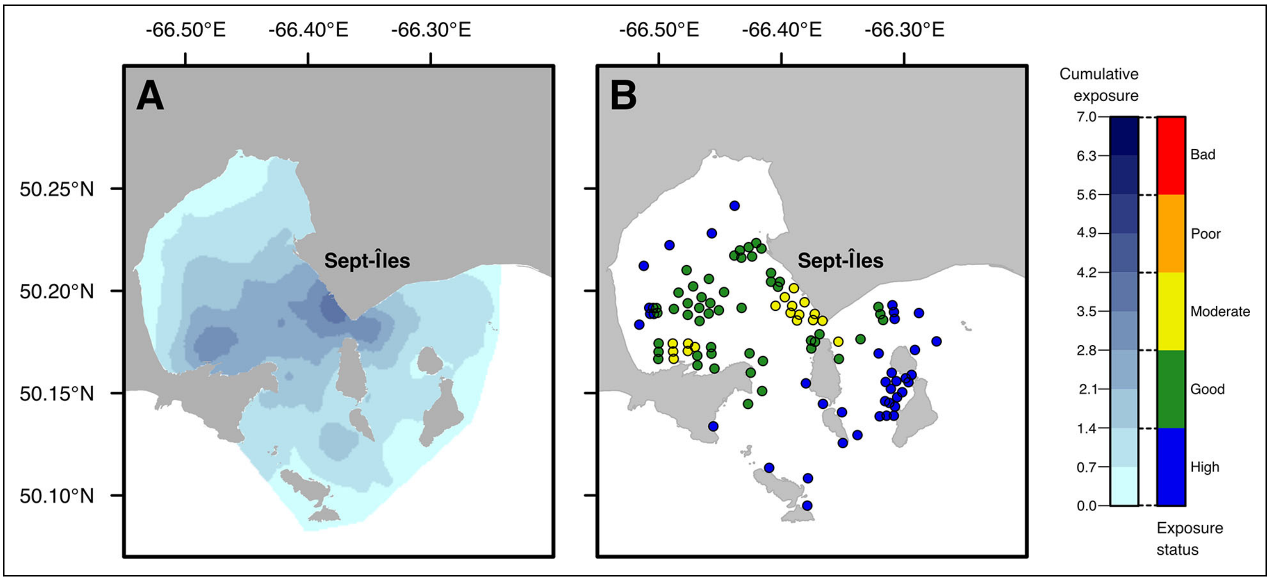

Figure 4. Values of the cumulative exposure score in the study area. (A) Bay-scale variability of the score and (B) exposure status obtained at each station based on this score.

Table 2. Spearman rank correlation coefficients between human activity exposure scores and ecological variables[a]

	Human Activities[b]							
Ecological Variables	**Aq**	**Dr**	**Fi**	**Ru**	**Se**	**Sh**	**St**	**CE**
Sediment parameters								
Organic matter	–	0.24	–0.49	–	0.42	0.37	–	0.28
Gravel	–	–	0.2	–	–	–0.22	–	–
Sand	–	–	0.38	0.3	–0.39	–0.23	–	–
Silt	–	–	–0.38	–0.19	0.34	0.24	–	–
Clay	–	–	–	–	–	–	–	–
Heavy metal concentrations								
Arsenic	–0.28	–	–0.57	–	0.64	0.42	–	0.19
Cadmium	–0.24	–	–0.54	–	0.59	0.27	–	–
Chromium	–0.34	0.23	–0.55	–	0.69	0.46	0.28	0.36
Copper	–0.48	0.37	–0.61	0.3	0.75	0.57	0.47	0.57
Iron	–0.48	0.57	–0.58	0.28	0.67	0.57	0.51	0.58
Manganese	–0.48	0.37	–0.59	–	0.76	0.55	0.4	0.47
Mercury	–0.27	–	–0.54	–	0.64	0.41	–	0.2
Lead	–0.27	–	–0.56	–	0.71	0.42	–	0.3
Zinc	–0.41	0.28	–0.61	–	0.74	0.54	0.33	0.45
Environmental indicators								
M-AMBI	–	–	0.2	–	–	–	–	–
BENTIX	–	–	–0.23	–	0.21	0.23	–	–
BOPA	–0.19	–	–	–	0.25	–	–	–

[a]Only significant relationships are presented.

[b]Aquaculture (Aq), dredging (Dr), fisheries (Fi), runoff (Ru), sewers (Se), shipping (Sh), structures (St), cumulative exposure (CE), Multivariate AZTI Marine Biotic Index (M-AMBI), Benthic Opportunistic Polychaete/Amphipod ratio (BOPA).

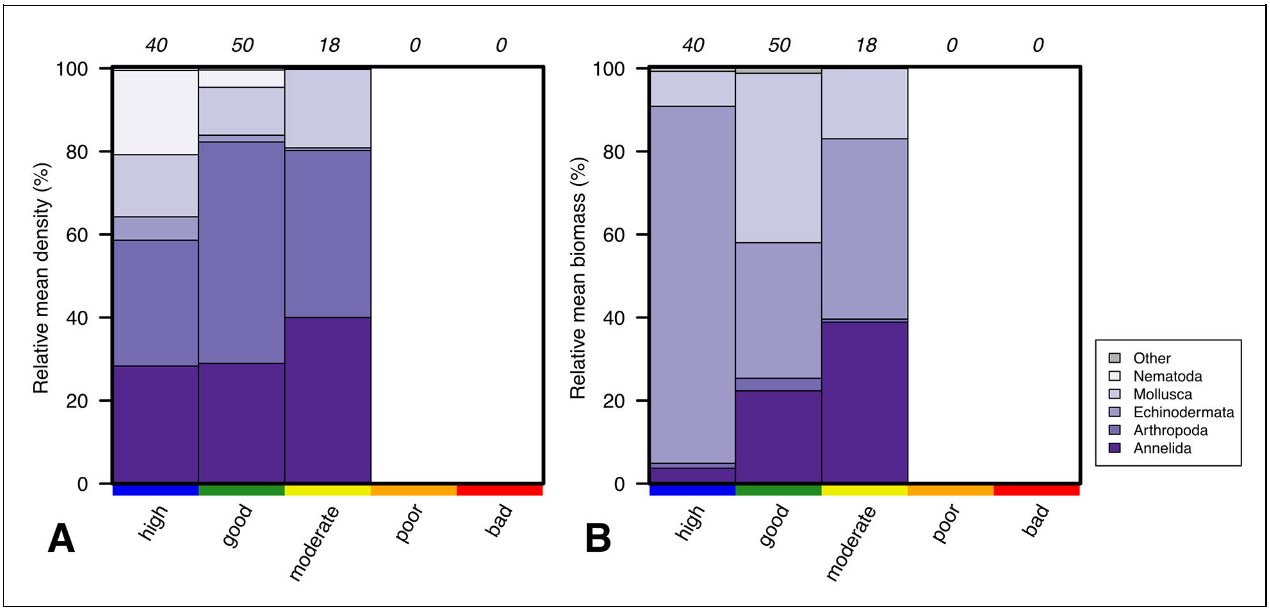

Figure 5. Proportions of each phylum for the five exposure statuses. Proportions are based on (A) mean density and (B) mean biomass of each phylum (colour-coded, inset legend). Numbers on top of each bar correspond to the number of stations in each status.

Table 3. Standardized predictor coefficients (and standard error) from multiple linear regression models between depth and human activity exposure indices and benthic community descriptors

Community Descriptors[a]	Depth	Human Activities[b] Aq	Dr	Fi	Ru	Se	Sh	St	R^2_{adj}[c]
N	–0.19 (0.11)	0.05 (0.14)	–0.12 (0.13)	0.12 (0.12)	0.19 (0.22)	0.15 (0.19)	–0.09 (0.13)	–0.18 (0.25)	0.02
p-value	0.1024	0.6995	0.3483	0.2918	0.3952	0.4198	0.4884	0.4879	
B	–0.21 (0.11)	–0.25 (0.13)	–0.01 (0.13)	–0.1 (0.11)	–0.48 (0.22)	–0.58 (0.18)	0.09 (0.13)	0.54 (0.25)	0.04
p-value	0.0659	0.0598	0.9393	0.3936	**0.0301**[d]	**0.0022**	0.4761	**0.034**	
S	0.25 (0.1)	0.14 (0.12)	–0.18 (0.12)	0.2 (0.1)	0.26 (0.2)	–0.16 (0.17)	0.24 (0.12)	–0.15 (0.23)	0.20
p-value	**0.0172**	0.2602	0.1297	0.0531	0.1994	0.3362	**0.0459**	0.5159	
H	0.54 (0.1)	0.17 (0.12)	0.01 (0.11)	0.03 (0.1)	0.41 (0.19)	0.01 (0.16)	0.11 (0.11)	–0.34 (0.22)	0.29
p-value	<**0.0001**	0.1499	0.9584	0.7924	**0.0287**	0.9877	0.3289	0.1150	
J	0.46 (0.11)	0.07 (0.13)	0.14 (0.12)	–0.13 (0.11)	0.32 (0.21)	0.07 (0.17)	–0.05 (0.12)	–0.33 (0.23)	0.14
p-value	<**0.0001**	0.6073	0.2627	0.2378	0.1236	0.7013	0.7063	0.1715	

[a]Total density (N), total biomass (B), taxa richness (S), Shannon index (H), Pielou evenness (J).

[b]Aquaculture (Aq), dredging (Dr), fisheries (Fi), runoff (Ru), sewers (Se), shipping (Sh), structures (St).

[c]Adjusted R squared (R^2adj) of the model.

[d]Significant p-values of marginal tests on predictors are highlighted in bold.

covering a spatial resolution that is usually less investigated in the cumulative impact literature.

We detected patterns between benthic communities and exposure indices for seven human activities: mussel aquaculture, dredging of sediment, runoff from city and industries, sewer discharge, commercial vessels movement and operation, artificial structures and commercial fisheries. When studying benthic species assemblages, characteristic species and phylum composition changed along a cumulative exposure gradient. The most striking result is an increase of annelid mean biomass in stations with a higher cumulative exposure score, with the dominance of *Nephtys insica*, *Praxillella praetermissa* and *Maldanidae* spp. Many studies have highlighted the use of certain species to indicate ecological status, providing useful indicators on the state of disturbance (Pearson and Rosenberg, 1978; Grall and Glémarec, 1997; Borja et al., 2000). When classifying species according to Borja et al. (2000),

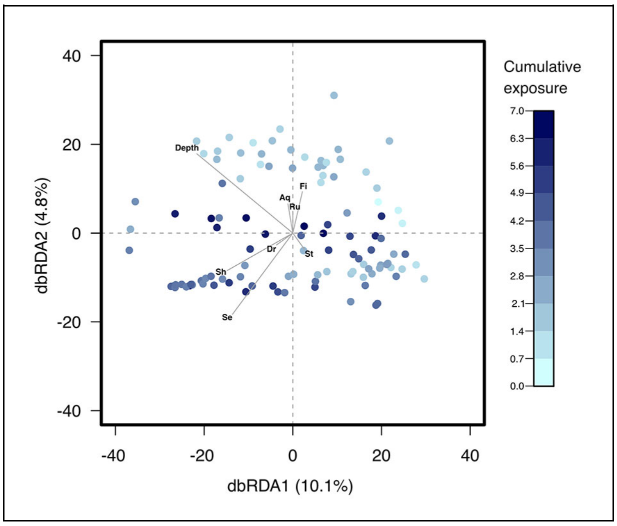

Figure 6. Constrained ordination with a distance-based Redundancy Analysis on the taxa assemblage. Axes percentages are the proportion of variance explained, and colours correspond to the cumulative exposure score. Grey lines indicate depth and human activities: aquaculture (Aq), dredging (Dr), fisheries (Fi), runoff (Ru), sewers (Se), shipping (Sh), and structures (St).

abundance of species sensitive to disturbance (Type I) and tolerant to disturbance (Type III) varied between "high" status and "moderate" status stations. However, no significant trend could be detected because of very different sample sizes between conditions. These results suggest a certain link between the station classification based on their cumulative exposure and the detection of possible disturbance effects (highlighted as a proxy of organic matter enrichment; Pearson and Rosenberg, 1978; Borja et al., 2000). An increased sampling effort and the consideration of other pressures would be needed to strengthen this conclusion.

Models explaining community characteristics (i.e., species richness) by environmental variables and exposure indices provided valuable information on anthropogenic influences on benthic communities. While the predictive power of these regressions was moderate with relatively low coefficients, depth was a significant predictor of community composition. This finding is coherent with patterns of biodiversity in marine ecosystems that distribute along a gradient from richest to poorest with increasing depth (Gray and Elliott, 2009; Levinton, 2013; Piacenza et al., 2015). These results advocate for a complementarity of covariates from abiotic and anthropogenic sources in the study of anthropogenic influence, where the explained variance increases when both types of predictors are considered. That being said, community characteristics may not be the best descriptors to properly account for disturbance, in particular because of their univariate nature (Drouin et al., 2011). Previous works in Baie des Sept Îles by Carrière (2018), Dreujou et al. (2021) and Ferrario et al. (2022) used various methods, including ecological indicators to assess the ecological status of the region. These studies showed that the overall ecological status of the bay is high, which may represent another hypothesis to explain the lack of a strong disturbance gradient in the area.

All sampled stations were influenced by at least two different sources of exposure, which reinforces the importance of studying the cumulative effects of human activities in an integrative way (Dreujou et al., 2020a; Carrier-Belleau et al., 2021). Classification based on the cumulative exposure score showed that 83% of the sampled stations were assigned a "high" to "good" status (i.e., $C < 2.8$). This result suggests a relatively low anthropogenic influence in the majority of the Baie des Sept Îles, which is coherent with the state of the benthic communities described above. Stations reaching higher cumulative exposure scores ("moderate," "poor" and "bad" status) can be considered anthropogenic "hotspots" (Crain et al., 2008; Darling and Côté, 2008; Côté et al., 2016; Galic et al., 2018), as co-occurring human activities have an increased probability to produce possible emergent effects. Hotspot identification may guide environmental protection and sustainable development as a way to target conservation areas or to prioritize management resources where they will be the most impactful.

Overall, exposure indices showed a moderate relationship with community composition in multivariate regression models, except concerning a group of stations with a high cumulative exposure score where communities were similar. Interestingly, the same predictive power was obtained when using only environmental parameters ($R^2 = 0.24$), which reinforces the pertinence of the exposure scores to explain benthic communities as complements of the environmental variables. Dominant taxa at stations with high cumulative exposure scores included *Bipalponephtys neotena* and *Macoma calcarea*, species tolerant to disturbance and found within disturbed areas by Dreujou et al. (2020b). These assemblages may indicate a disturbed profile, where sensitive taxa are rare relative to the dominance of disturbance-tolerant taxa without opportunistic species (Pearson and Rosenberg, 1978; Grall and Glémarec, 1997), reinforcing previous conclusions. Most importantly, hotspots of cumulative exposure are located in areas where communities have a moderately disturbed profile, as detected by Dreujou et al. (2020b; stations from cluster A). These results describe a "snapshot" of ecosystem exposure as they do not include seasonal or temporal variation, which may drastically modify the structure of benthic communities (Dreujou et al., 2018). Establishing long-term monitoring protocols will thus be necessary to increase the robustness of the analysis. Furthermore, relative weight of anthropogenic influence and the integration of the functioning of the ecosystem need to be carefully addressed when calculating cumulative indices, using expert opinion and dedicated research.

This study proposes a means to model exposure using relatively few environmental data, mainly spatial information and surveys with local stakeholders (types of human activity present, location and intensity of sources), which is well suited to describe anthropogenic influence in areas where historical ecological data are scarce. While the score from Halpern et al. (2008) is useful for characterizing cumulative effects globally, the global scale of this assessment prevented the use of fine-scale local data from which an environmental assessment would benefit. Focusing on gradients of exposure is promising as it allows the quantification of anthropogenic influences without needing to define reference conditions, which are often biased due to a lack of historical data or pristine ecosystems (Borja et al., 2012; Korpinen and Andersen, 2016). The addition of other relevant activities, such as tourism or recreational boating, or environmental drivers (e.g., freshwater or terrigenous inputs) would greatly increase its general applicability to other regions. Future works should also consider emerging trends, such as antagonistic or synergistic effects (Korpinen and Andersen, 2016; Galic et al., 2018; Carrier-Belleau et al., 2021), as they influence the description of vulnerability and ecosystem responses to perturbation, thus drastically impacting environmental assessment outcomes.

5. Conclusions

Our results contribute to a better understanding of sub-Arctic ecosystems and how multiple human activities may influence them, which is of tremendous importance in the context of global climate change. By including ecological data at a high spatial resolution, we propose a tool that allows direct evaluation of anthropogenic exposure and its possible effects on benthic communities. Such initiatives could increase the efficiency of adaptive environmental management, especially where data are still scarce, by being incorporated within standardized frameworks that are applicable to a wide range of coastal regions.

Data accessibility statement

Data and code used for this study are available online at https://doi.org/10.5683/SP3/5XZKP3.

Supplemental files

The supplemental files for this article can be found as follows:

Figure S1, Figure S2, Table S1.DOCX

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Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author contributions

Contributed to conception and design: ED, DB, RMD, CWM, PA.

Contributed to acquisition of data: ED.

Contributed to analysis and interpretation of data: ED, DB, RMD, FN.

Drafted and/or revised the article: ED, DB, RMD, JC, FN, CWM, PA.

Approved the submitted version for publication: ED, DB, RMD, JC, FN, CWM, PA.

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