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PRACTICE BRIDGE

Holistic environmental monitoring in ports as an opportunity to advance sustainable development, marine science, and social inclusiveness

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Ports play a central role in our society, but they entail potential environmental risks and stressors that may cause detrimental impacts to both neighboring natural ecosystems and human health. Port managers face multiple challenges to mitigate risks and avoid ecosystem impacts and should recognize that ports are embedded in the wider regional coastal ecosystem. Cumulative impacts of anthropogenic stressors have the potential to further burden the existing suite of natural stressors, particularly where ports are located in embayments and estuaries. Environmental monitoring in ports should thus develop a comprehensive, holistic, multilayered approach integrated in the wider ecosystem that will help managers better achieve sustainable development, a major goal of the United Nations' 2030 agenda and Decade of Ocean Science for Sustainable Development (2021–2030). This practice bridge showcases the experience of the second Canadian Healthy Ocean Network (CHONe2) in Baie des Sept Îles (BSI, Quebec; the fourth largest industrial port in Canada) laying the foundations of holistic environmental monitoring in ports. We describe the partnership model (i.e., engaging scientists, local authorities, an independent organization, and local industries), synthesize the multidisciplinary studies that turned environmental monitoring into a systemic investigation of the biological and physical components of BSI, integrate the developed scientific knowledge into a social–ecological–environmental system, present an innovative near real-time monitoring approach, and discuss implications for management and policy. The CHONe2 experience in BSI aligns with the decade's road map for sustainable development and provides elements that could be adapted to other commercial ports. By suggesting a set of best practices (e.g., multidisciplinarity, transparency, inclusivity, participatory modeling), we hope to spark new interest in environmental monitoring as a path to conciliate development and sustainability of ports and other high-use marine areas.

Keywords: Monitoring, Ports, Decade of Ocean Science, Sustainable development, Gulf of St. Lawrence, Multiple stressors, Coastal management

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1. Introduction

The central role of ports in the functioning of our society was abruptly brought to focus when the worldwide crisis triggered by the COVID-19 pandemic disrupted global supply chains (Cullinane and Haralambides, 2021; Millefiori et al., 2021). With about 90% of global trade moved by shipping (International Chamber of Shipping, 2020), modern ports can be thought of as a complex organism where different port operators—either private or public companies—are the vital organs performing the physiological functions (e.g., cargo handling, freight storage, marine services, and port maintenance), while the port authority acts as the brain that oversees the overall port administration, development, and management. Importantly, since ports are often intermodal shipping nodes that connect maritime, terrestrial (i.e., railroading and trucking), and aerial transportation in the global distribution network (Environmental Protection Agency, 2021), they concentrate different infrastructures and traffic within their surroundings. Moreover, ports also support other—more local—commercial (e.g., fishing, tourism) and recreational (e.g., boating, fishing) activities.

While stimulating economic and social growth, the multiple activities revolving around ports entail several potential environmental risks and stressors that may cause detrimental impacts to both the surrounding natural ecosystems (water, air, soil, fauna, and flora) and human health (Borja et al., 2020). For example, as recently summarized by Valdor et al. (2020), shipping traffic, cargo handling, and transshipment of dry and liquid bulk (e.g., iron ore, aluminum, petroleum-related, and other products) can lead to oil spills, loss of dangerous materials (e.g., creating debris) and wastes (e.g., pollutant compounds) in the aquatic system, and the introduction of invasive species, in addition to port dredging for maintenance, which can alter seabeds and increase organic loads and turbidity. Port-related coastal development can increase both urban and industrial discharges in aquatic systems (e.g., biological and chemical contaminants; Valdor et al., 2020), while coastal populations may suffer from increased traffic congestion as well as degraded air quality from industrial and maritime traffic emissions (Valdor et al., 2020; Zheng et al., 2020).

Given the variety of potential threats to the environment posed by port activities, port managers face multiple challenges to mitigate risks and avoid ecosystem impacts. Indeed, multiple stressors—and their potential cumulative impacts (Côté et al., 2016)—should be addressed concurrently. Local biological and physical conditions may influence the effects of stressors, and potential conflicts may arise between stakeholders (e.g., port operators, local communities) following the adoption of environmental policies. These challenges are particularly relevant for the many ports located in embayments and estuaries, some of the most diverse and productive coastal (Archambault and Bourget, 1999; Greenlaw et al., 2011). Within these geomorphological settings, the cumulative impact of anthropogenic stressors could further burden the existing suite of natural stressors (e.g., organic matter loads and salinity variation due to freshwater inputs) typical of these environments (Attrill and Power, 2000; Elliott and Quintino, 2007).

Environmental management should recognize that ports are embedded in the wider regional coastal ecosystem (100s of meters to 10s of kilometers), where anthropogenic stressors are generally increasing in magnitude, extent, and frequency (Ban et al., 2010; Borja, 2014). However, this is not currently the general approach for port environmental monitoring and management, which is still generally aimed at ensuring regulatory compliance for a predefined set of parameters (e.g., pollutant concentration) within a given port. Indeed, a recent survey of monitoring activities undertaken in major commercial ports around the globe (Ferrario et al., 2021a) highlighted that monitoring initiatives directly undertaken by ports are generally limited to processes and variables of primary concern for port operations (e.g., sediment mobility, water levels, currents, and bathymetry). In contrast, systematic monitoring of biological communities and ecosystems was rarely undertaken by ports as their sustainability efforts are generally focused at enhancing logistics (e.g., energetic efficiency, maritime traffic management) and reducing risks of chemical pollution (e.g., reduce greenhouse gas emissions, air pollution, and spills; Ferrario et al., 2021a). The availability of ecological data around ports thus often depends on programs that focus on wider areas, in which ports happen to be (or on specific habitats or ecosystems in proximity to the port) and are operated under the initiative of governmental, nongovernmental, or academic institutions (Ferrario et al., 2021a). Port managers should, in contrast, consider environmental monitoring as an opportunity to develop a comprehensive, multilayered representation of ports integrated in their wider ecosystem context. This holistic environmental monitoring approach could help managers achieve sustainable development—a major goal of the international environmental agenda (United Nations Development Programme, 2021).

As we enter the United Nations' (UN) Decade of Ocean Science for Sustainable Development (Intergovernmental Oceanographic Commission, 2019; Ryabinin et al., 2019), with the motto "The Science We Need for the Ocean We Want," 3 essential elements emerge to create the space for opportunity within which sustainability may be pursued (Ryabinin et al., 2019; Winther et al., 2020). First, scientists need to embrace multidisciplinary research to tackle the complexity, functioning, and services of marine habitats; second, environmental management should integrate science with societal aspirations; and third, society (e.g., not-for-profit organization, industries, and communities) should be engaged to build on positive experiences and goodwill to enhance the acceptability and implementation of science-based solutions (**Figure 1**).

In this practice bridge, we outline the research framework adopted by the second Canadian Healthy Ocean Network (hereafter "CHONe2") and its partners to shape a holistic environmental monitoring program with the overarching goal of laying the foundation for the sustainable development of Baie des Sept Îles (BSI, located on the north shore of the Gulf of St. Lawrence, Quebec, Canada;

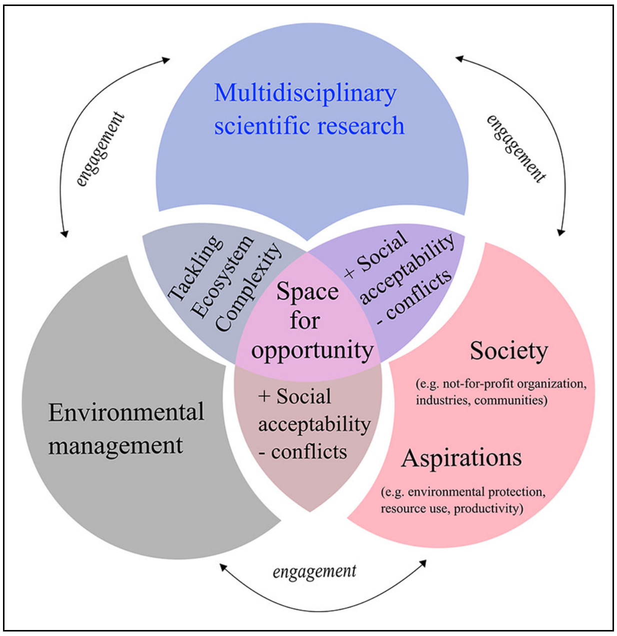

Figure 1. Creating the space for opportunity for sustainability. Multidisciplinary scientific research provides the information needed by environmental managers to implement policies that consider ecosystem complexity. A dialog between environmental managers, scientists, and stakeholders ensures social acceptability of policies and minimizes conflicts by considering the interests and aspirations of society. DOI: https://doi.org/10.1525/elementa.2021.00061.f1

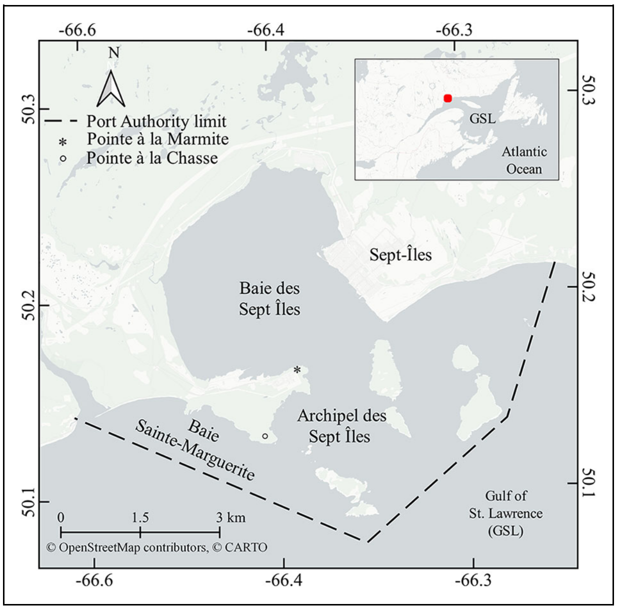

Figure 2. Map of Baie des Sept Îles and its complex. The inset map depicts the position of Baie des Sept Îles (red dot) relative to the North American Atlantic coast and Gulf of St. Lawrence. DOI: https://doi.org/10.1525/elementa.2021.00061.f2

Figure 2) and advance the environmental management of its port. We synthesize CHONe2's partnership model for a BSI case study, highlighting and sharing elements and perspectives that could be adapted to the benefit of other commercial ports and other high use coastal areas.

CHONe2 was a 5-year strategic partnership between Canadian university researchers and government scientists of the Science and Management sectors of the federal Department of Fisheries and Oceans Canada, whose research focused on developing new conservation strategies for Canada's changing oceans. Building on expertise to deliver marine ecosystem-level science on biodiversity and ecosystem science developed during the first iteration of the network (Snelgrove et al., 2012), CHONe2 expanded its participation to include the Port and the City of Sept-Îles and the not-for-profit Northern Institute for Research in Environment and Occupational Health and Safety (INREST) as research partners.

In the second section, we describe the collaborative partnership framework that was established to foster a proactive and socially acceptable approach to sustainable development. In the third section, we synthesize the multidisciplinary studies carried out within CHONe2 to provide a scientifically sound basis for environmental management and decision making in BSI. This ensemble of studies resolved the current ecological and physical conditions of BSI and addressed how natural and anthropogenic stressors could interact to affect benthic communities. The last 2 sections demonstrate how the CHONe2 partnership model can generate a holistic view of the BSI system and present a way forward to transfer this approach to other situations. The fourth section presents how to integrate the developed scientific knowledge into a social–ecological–environmental system (SEES). Finally, a fifth section presents an innovative approach to help prevent environmental degradation in light of current trends in environmental monitoring in harbor areas, while discussing inclusiveness in policymaking.

2. The BSI case study

2.1. Sept-Îles and its port

The City of Sept-Îles was founded in the mid-20th century and has a current population of around 30,000 inhabitants. The bay's coastal area sustains recreational activities such as boating, fishing, diving, kayaking, and marine mammal and bird watching. Because of its geographic setting, BSI hosts one of the largest marine port areas in Canada, ranking fourth among Canadian ports for tonnage handled in 2019 (29,324,703 tons; Binkley, 2020; Port of Sept-Îles, 2021). The port hosts cruise liners and many other local economic activities. Several commercial fisheries and 1 mariculture farm are supported by the bay and its surrounding archipelago and are vital for local communities, including the Innu-takuaikan Uashat mak Mani-utenam Indigenous community. The region is also home to several world-class industries including the aluminum processing company Aluminerie Alouette, the mining companies Iron Ore Company of Canada-Rio Tinto, and the Société ferroviaire et portuaire de Pointe-Noire. These activities expose the greater Sept-Îles area to potential environmental risks.

Over the years, the social context of Sept-Îles proved to be sensitive to environmental issues. The Port of Sept-Îles,

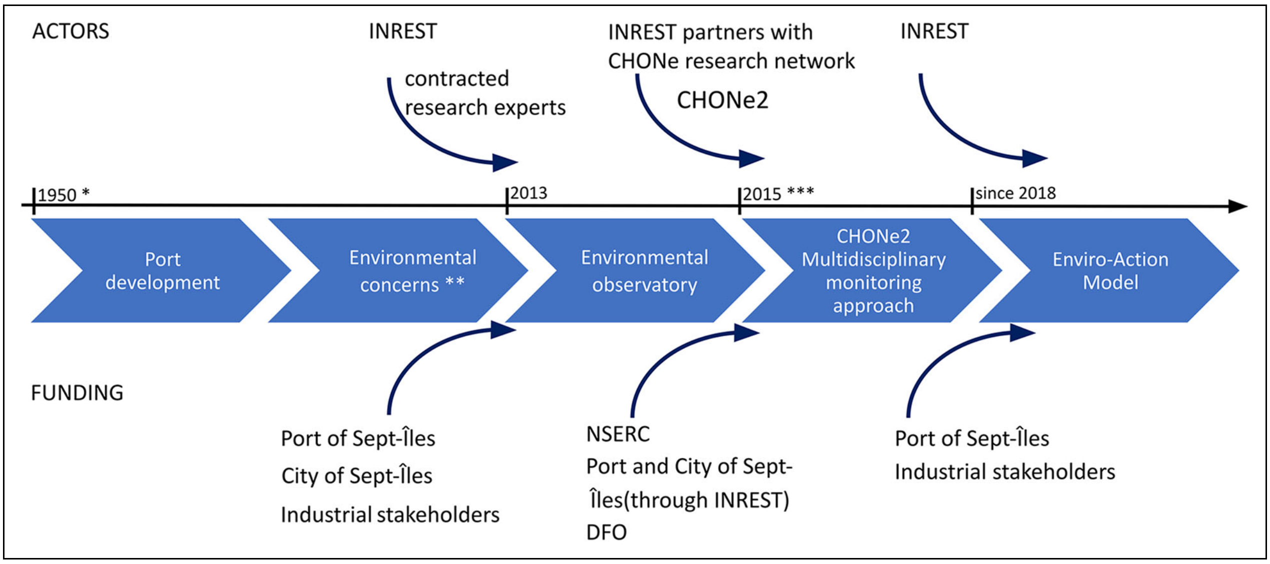

Figure 3. Time line of the development of environmental monitoring programs in Sept-Îles and of related partnerships. Text boxes below the time line highlight key moments in Baie des Sept Îles and their sequential relationship. Black arrows connect specific initiatives to the major actors involved, above the time line, and to funding partners, below the time line. Marks are not spaced proportionally (*: beginning of port industrial development; **: the Port commissioned environmental studies and impact compensation projects before 2013; ***: CHONe2 activity spanned from 2015 to 2021 including a 1-year extension because of the COVID-19 pandemic). DOI: https://doi.org/10.1525/elementa.2021.00061.f3

aware that its projects could impact the environment, acted as a leader representing the local industrial community and businesses located in the port zone and adopted a management strategy to prioritize the preservation of the local ecosystem and promote its sustainable development. In 2013, the independent research organization INREST was created to connect the environmental needs of remote communities—such as that of Sept-Îles—with academic expertise located in major centers (**Figure 3**). Since then, the Port and INREST have engaged academic organizations in several studies to augment knowledge on local ecosystems and develop tools adapted to port realities. Concurrently, INREST has also worked to enhance the engagement of the local Innu-takuaikan Uashat mak Mani-utenam Indigenous community in ecosystem sustainability projects. Over the last decade, this context favored undertaking several environmental monitoring initiatives, including the development of the BSI environmental observatory (Section 2.2), the CHONe2 multidisciplinary program, and the Mishta-Shipu River (east of the BSI) monitoring program, a partnership including the Indigenous community and several regional actors (Section 5.2).

2.2. An environmental observatory: A strategy to enhance social acceptability

Despite over 70 years of industrial activity in the BSI area (Carrière, 2018), very few independent studies have assessed (a) the overall state of the water and sediments, (b) potential environmental impacts, and (c) multiple effects of this activity on BSI's environment. While some local industries and the Port have undertaken various privately commissioned studies in this regard over time, the trustworthiness and social acceptability of these have generally been undermined by their perceived lack of scientific independence. This paucity of environmental data and scientific research is commonly found in other ports around the world (Ferrario et al., 2021a).

In Sept-Îles, the Port Authority, the City, and its corporations, in addition to their primary role of industrial and economic development, also assumed the stewardship of environmental management. In the context of economic development, the need for socioeconomic aspects to evolve according to the principles of sustainable development was recognized early on. To this end, since 2013, these organizations have supported the creation of an environmental observatory led by INREST to establish environmental baselines, measure and predict environmental impacts, and monitor the evolution of the ecological status of BSI. The main goal of the observatory is to ensure that the development of industrial and port activities is respectful of the BSI environment, limit the increase of pollutants and dust emissions, and minimize changes in water and sediment quality, while guaranteeing scientific independency and transparency to gain the trust of citizen committees and environmental groups.

Three particular elements have been pivotal to ensuring the success of the observatory: (1) All funding partners granted independence to INREST and its collaborators to maintain absolute scientific freedom and ensure transparency for raw data and results, (2) all scientific information is shared with all partners to support the timely development of action plans to address any issue that could potentially be detected, and (3) data transparency policies and practices are adopted to ensure the trust of partners, citizens, and communities (Section 2.3). The approach encourages experts to share scientific results and recommendations from their studies with managers and end users and to work collaboratively and preemptively toward environmental conservation in BSI and with other industrial and port sectors.

Since the beginning, the observatory has been funded through INREST by the Port, the City, and corporations—with a quinquennial revision of their financial involvement (**Figure 3**)—and INREST seeks additional funding from regional, provincial, and federal organizations to ensure the financial sustainability of the initiative. As such, the Sept-Îles environmental observatory grew to encompass approximately 235 km^2 in Sept-Îles' Port zone.

2.3. Expanding the observatory and fostering proactive management in BSI

In 2015, INREST partnered with CHONe2 to benefit from a multidisciplinary team of over 30 scientists and experts, including researchers, graduate students, postdoctoral fellows, and technicians. Prior to this, the observatory focused on assessing water and sediment quality (i.e., physicochemical properties and pollutant concentration) and gathered information on the biological components of the ecosystem (e.g., macrobenthos, submerged vegetation, fish communities, and marine mammals), mainly through bibliographic synthesis. Drawing from the knowledge gaps identified in this initial phase and open discussions between CHONe principal investigators and INREST, the CHONe2 research team was formed to gather the expertise needed in oceanography, ecology, remote sensing, environmental management, and policy from Canadian institutions (Université Laval, Institut des sciences de la mer, Université du Québec à Rimouski, Simon Fraser University, and Fisheries and Oceans Canada) to complement and expand on the research being done by the observatory (Section 3).

The collaboration between INREST and CHONe2 scientists established a structured environmental monitoring process to deepen the environmental portrait of BSI that was initiated by the observatory. As a result, credible environmental baselines were provided to better understand potential environmental impacts and to track the evolution of various physical and biological components over the short, medium, and long term.

A data transparency and openness policy—a proof of scientific independence—was adopted to ensure a wide acceptance of results and foster public trust. The observatory made project results and data freely available to the public, publishing a global report (Carrière, 2018). Similarly, CHONe2 required that all projects contributed to the Scholars Portal Dataverse (www.dataverse.scholarsportal.info/dataverse/chone2), a Canadian research data management and sharing platform, following a standardized data and metadata format requirement that applies the Findability, Accessibility, Interoperability, and Reuse of digital assets principles (GO FAIR, 2022).

CHONe2—in partnership with INREST and in collaboration with managers of the City and Port of Sept-Îles and local businesses—provided an opportunity to demonstrate the region's initiative to preserve the BSI ecosystem, to allow stakeholders to engage in a structured environmental partnership, and to respond to public concerns of transparency to identify and manage socioeconomic concerns and expectations.

The extent and the quality of knowledge acquired in the BSI area and the neighboring Côte-Nord region of the Gulf of St. Lawrence during this research project, as well as the research tools developed through the partnership, are important assets for marine environmental managers in the area who are charged with ensuring the sustainable development and preservation of the bay's environment over the long-term. In particular, the outcomes of CHONe2 enable the Port and City of Sept-Îles to better assess the area's capacity to support development projects that are acceptable and safe for the population and the environment, while also allowing the Port to make informed decisions pertaining to current and future activities, including the Port's Master Plan, the emergency plan (e.g., oil spill prevention and intervention), and other related policies (e.g., regulation of vessel speed in the port area).

3. Portraying the ecosystem

The BSI complex (BSIC) encompasses the BSI, a large, shallow bay of about 100 km^2 with a relatively narrow (5 km) opening to the Gulf of St. Lawrence—where the Sept Îles archipelago provides further shelter ("Archipel des Sept Îles"; **Figure 2**). Four small rivers flow into the bay, providing freshwater, nutrients, and sediments. Within the bay, the tidal amplitude can reach 3.4 m, creating an intertidal zone that encompasses up to 34% of the bay. Approximately 20% of the subtidal zone is located at depths less than 10 m, after which the seafloor gently slopes (<2°) toward the center of the bay, where depths reach 30–50 m (Dutil et al., 2012). Outside of the bay and in the archipelago, the seafloor descends more abruptly and generally forms a terrace between 5 and 10 m followed by a pronounced slope (approximately 4°–10°; Dutil et al., 2012). Water in the bay is forced by tides, winds, and freshwater discharge that produce variations in environmental parameters (e.g., currents, water temperature, and turbidity) over tidal and seasonal cycles.

Within the BSIC, CHONe2 oceanographers described water circulation patterns in the bay to support the development of hydrodynamic models to help predict particle dispersion (e.g., pollutant, sediment, nutrients) and variation in plankton dynamics. By advancing optical remote sensing algorithms, researchers provided tools to complement both oceanographic and biological observations and enhance environmental monitoring capabilities. Ecologists characterized various benthic habitats in BSIC and their biological communities to determine baselines and identify environmental status indices to inform management. Additionally, experimental work determined both lethal and sublethal impacts of multiple natural and anthropogenic stressors on benthic species in the study area to help identify actionable environmental interventions and preventive measures.

3.1. Physical components (water circulation)

As many biological and chemical processes depend on physical environmental conditions, understanding the system's physics is key to predicting the dispersion of particles (e.g., organic/inorganic matter and substances, larvae) and disentangling cyclical variations from long-term trends.

However, available information on basic BSIC physical variables, such as temperature, salinity, and currents, lacked sufficient temporal or spatial resolution to describe tidal and seasonal hydrodynamic cycles within it. The CHONe2 monitoring strategy thus aimed to complement existing information (e.g., tide gauge, atmospheric model outputs) with the necessary data to produce a descriptive summary of hydrodynamic conditions in the bay.

Various techniques, including the deployment of multiple sensors (e.g., drifters, current profilers), allowed the team to describe and better understand several main physical oceanographic characteristics of the BSIC (see Shaw, 2019, for full details of the methodology). For example, it was possible to capture seasonal variations of temperature and salinity profiles that further allowed the description of water masses in the bay that contributed to resolve their evolution from spring to fall (Shaw, 2019). In addition, by deploying both GPS-tracked surface drifters and acoustic Doppler current profilers, it was possible to characterize the bay's estuarine circulation to inform important insights on the pulse and movement of spring freshwater and to produce maps of surface currents along with relevant current speed statistics (Shaw, 2019). In particular, both surface (1–10 m) and deep (10–30 m) currents were evaluated over the inner area of the bay (Shaw, 2019).

The CHONe2 approach to oceanographic monitoring will serve as a basis for future modeling work in the BSIC. For example, the described typical and extreme winds, tides, and river discharge conditions could be used as idealized model forcing conditions. Measured in key locations, the response of currents and stratification to tides and seasonal variations could also serve as model quality benchmarks. This hydrodynamic information for the BSIC will provide a better understanding of the environmental context for biological communities. For example, consequences of management decisions could be evaluated in terms of connectivity between different ecosystem compartments and regions (e.g., import–export flows of organic matter, spores, and larvae), thus allowing the identification of high-risk areas in the event of chemical spills and the development of more refined emergency response plans.

3.2. Biotic components

Benthic habitats dominate this ecosystem due to the shallow nature of the bay. The water column has a great influence on both material transport (e.g., sediments, detritus) and light attenuation, hence contributing to fluctuations in primary productivity. The bay (**Figure 2**) is dominated throughout by soft-sediment habitats, ranging from mud to sand toward the mouth of the bay. Along the northern and western shores, intertidal and shallow subtidal zones are dominated by saltmarshes (*Spartina alterniflora*) and eelgrass (*Zostera marina*) beds to a depth of about 1 m below chart datum (Carrière, 2018). Scattered boulders and cobbles support diverse and abundant macroalgal assemblages within this otherwise unsuitable habitat for macroalgae. Boulder and cobble cover increases in the outer bay area, especially in the archipelago, creating a heterogeneous bottom that supports a benthic community characterized by both soft sediment faunal assemblages and abundant macroalgae and benthic invertebrates usually associated with rocky shores. Grazing by sea urchins, however, limits most fleshy macroalgae to shallow depths in the outer bay area and associated islands (Ferrario, personal observation, August 2018).

Building on research conducted in the BSIC by the observatory and the knowledge gaps it identified, CHONe2 researchers focused their efforts on key, but poorly studied, components of this ecosystem. For planktonic primary producers, water samples from different sectors of the bay were used to quantify several biogeochemical state parameters (e.g., concentrations of algal pigments and lipids, dissolved organic carbon, and total suspended solids) and a host of variables describing the inherent (e.g., absorption and scattering properties) and apparent (e.g., reflectance and attenuation coefficient) optical properties of surface waters (Araújo et al., 2020; Araújo and Bélanger, 2022). The principal phytoplankton assemblages were identified based on pigment content, cell size and cell count (flow cytometry), and taxonomy of field samples, revealing major seasonal signals that reflect changes in physical conditions (e.g., temperature, salinity), light regimes, or nutrients. The composition of the phytoplankton assemblage emerged as the main determinant of the lipid content of organic matter. Lipids provide an indicator of the quality of planktonic food in an ecosystem because these compounds are the densest form of energy available in food webs and contain specific fatty acids (e.g., ecoso or EPA) that are essential for the growth and survival of pelagic and benthic consumers. A comparison of samples obtained over a broad geographical area (Marmillot et al., 2020) with those of the bay indicates that the proportion of EPA in phytoplankton increases with the importance of diatoms in the assemblage, followed by secondary influences of pH and salinity. This suggests that the physical environment in the bay influences the nutritional quality of phytoplankton in 2 ways: (1) directly by pH and the influence of freshwater sources on salinity and (2) indirectly via seasonal shifts in phytoplankton assemblages. Beyond providing a better understanding of the factors controlling the underwater light regime, the bio-optical dataset enabled the development and validation of algorithms for remote sensing (Section 3.3).

The distribution and abundance of seagrasses, a key part of shallow water vegetation in estuarine environments, were assessed by remote sensing. Using very high spatial resolution images (Worldview-2, 2-m spatial resolution), intertidal vegetation and eelgrass meadows were estimated to cover over 25% of inner BSIC (27 km^2), confirming their dominant role as a foundation species in shallower parts of the bay (Araújo et al., 2018; Paquette

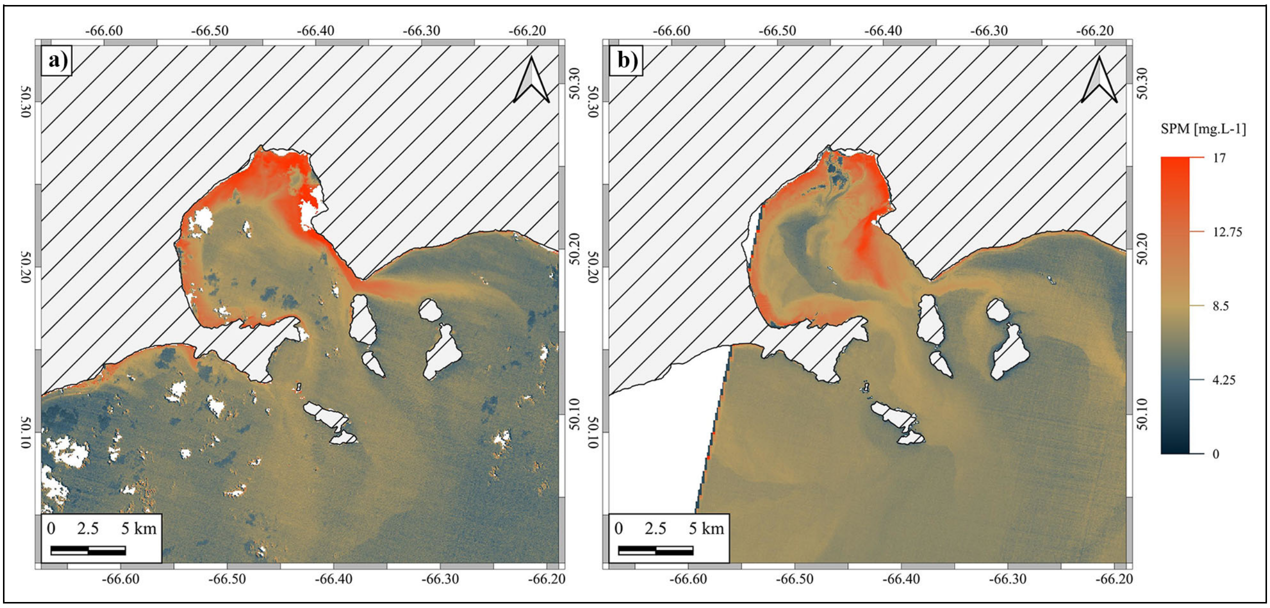

Figure 4. Remote sensing of suspended particulate matter estimation. Example using a regionally tuned algorithm (Mabit et al., 2022) for images acquired with the Sentinel-2A satellite on (a) September 12, 2016, and (b) May 17, 2017. DOI: https://doi.org/10.1525/elementa.2021.00061.f4

et al., 2018). SCUBA (self-contained underwater breathing apparatus) diving surveys assessed vegetation in shallow subtidal waters of the bay and found that macroalgae were very abundant when suitable hard substrata (e.g., boulders) were available (Ferrario and Archambault, 2018). Such assemblages included up to 14 species and were dominated by the kelp *Saccharina latissima* and *Agarum clathratum* within and outside the bay, respectively. However, as is typical for embayments, hard substrata were rare within the bay due to the deposition and accumulation of sediments, such that macroalgae made only a minor contribution to the overall benthic primary production within the bay. Along with macroalgae, the macroepibenthic invertebrate community was monitored as part of a study to assess BSIC ecosystem status (Section 3.5). The biodiversity and distribution of the infaunal macroinvertebrate community was monitored and characterized both within the BSIC and at nearby locations (Dreujou et al., 2020b). A total of 289 taxa were identified, with individuals from 14 phyla, where annelids, arthropods, and mollusks were dominant. Most observed taxa were new mentions for the Sept-Îles region, and no invasive macroinvertebrate species were found, thus contributing significantly to expanding the currently limited ecological baselines for the area.

For an industrial harbor with international connections, CHONe2 monitoring serves as a meaningful checkpoint, although a potential source of uncertainty should be acknowledged. In particular, because of their general scarcity, both ichthyofauna (Ferrario, personal observation, August 2018) and the invertebrates community fouling rocky substrates were not monitored. New and promising approaches, such as environmental DNA (eDNA) and sedimentary DNA, could thus be used in future monitoring to reduce this information gap.

3.3. Development of remote sensing tools for water quality and nearshore vegetated environments monitoring and reconstruction of historical baselines

Satellite imagery provides a synoptic view of the spatio-temporal variation of variables of interest (e.g., water turbidity, suspended particulate matter (SPM), colored dissolved organic matter (CDOM), and chlorophyll *a*; International Ocean Colour Coordinating Group [IOCCG], 2018), providing further opportunities for monitoring. Moreover, satellite archives make it possible to retrospectively evaluate the state of past environmental variables and thus establish a reference state going back several decades.

Within CHONe2, a satellite-based monitoring approach was developed to provide a systematic way to establish a baseline and assess the evolution of several ecosystem proxies over time. A significant effort was made to gather water optical properties in parallel with biogeochemical parameters to facilitate the development, adaptation, and validation of remote sensing algorithms to evaluate SPM, CDOM, and chlorophyll *a* concentration (Section 3.2). For example, water turbidity or SPM (i.e., the dry mass of particles per unit of volume) is a commonly used water quality indicator in most environmental monitoring programs (McCarthy et al., 2017; IOCCG, 2018). Satellite monitoring of SPM can help detect anomalies and assess the potential impacts of human activities in BSIC (e.g., dredging, infrastructure construction, land use change in the watershed, increased wastewater input) much more accurately than sparse in situ data collection approaches. **Figure 4** shows the images acquired by the multispectral instrument on board the Sentinel-2A satellite and corrected for atmospheric effects to retrieve water reflectance following application of a regional algorithm (Mabit et al., 2022). **Figure 4b** clearly shows a plume of SPM in the center of the bay, coming from rivers located west of the city of Sept-Îles; the main source of the plume would not have been detected based on point SPM measurements in the center of the bay. In addition, satellite imagery reveals the shape of the plumes coming from these rivers, providing a better understanding of the dynamics of surface currents in the bay. Such maps can be produced using state-of-the-art algorithms in near real time and delivered to end users through a web portal (under development). Given their increasing availability, satellite optical sensors could also be used to assess SPM at a spatial resolution of ca. 10s of meters on an almost weekly basis.

Using the Landsat Archive at 30-m spatial resolution (a different remote sensing-based approach; U.S. Geological Survey, 2019a, 2019b), the general evolution (1984–2017) of eelgrass meadow coverage through time was assessed. Although inherently limited due to relatively low spectral, radiometric, and spatial resolutions (for some applications), this freely accessible archive provides a unique opportunity to investigate decadal changes of seagrass meadow extent (e.g., Dekker et al., 2005; Calleja et al., 2017). Overall, a 7-fold increase of the meadow extent in BSIC, from around 311 (in 1985) to 2,255 ha (in 2017) was estimated from the Landsat time series. This increasing trend was particularly evident from the late 1990s to early 2000s (Araújo et al., 2018).

The above are convincing examples of the interest and relevance of using a satellite data collection approach when designing monitoring programs in large scale, high use areas, such as ports. Remote sensing should therefore be considered an integral part of any monitoring toolbox and complementary to field data acquisition through in situ sampling or stationary equipment providing groundtruthing (e.g., oceanographic buoys or deep-water fixed stations). When applied, remote sensing can enhance the global or regional spatial context of coastal monitoring by providing more data collection opportunities (spatially and temporally), thus allowing more accurate interpretation when trying to disentangle the dynamic nature of coastal areas from human-induced drivers.

3.4. Guiding management action: Contributions of experimental studies on multiple stressors

Environmental changes resulting from local, regional, or global causes present challenges for managing ecosystems. These changes can act as stressors for organisms, and when multiple stressors—including anthropogenic ones—occur simultaneously, their cumulative effects can be challenging to predict and respond to as they may generate complex interactions that may result in synergies or antagonisms (Folt et al., 1999; Côté et al., 2016; Smith et al., 2019). Concrete actions to respond to environmental changes can, however, be informed by research focused on specific stressors of the system of interest. Based on initial discussions between CHONe2 scientists and partners, 2 projects examined the role of stressors on 2 key biotic groups: bivalves for their relevance as biological indicators and kelp because of their importance as habitat formers.

In the first project, the effects of 2 local stressors (nutrient enrichment and freshwater input) in the context of global warming were investigated in the laboratory (Carrier-Belleau et al., 2021) using 2 bivalve species: the blue mussel *Mytilus* sp. and the Baltic clam *Limecola balthica*. These 2 common species were chosen because their well-known ecology and response to individual environmental stressors (to which they are exposed because they are sedentary) make them good indicators and models to assess the effects of individual and combined stressors (Borja et al., 2000). This project addressed the effects of eutrophication, an emerging stressor in coastal environments (Alsterberg et al., 2012), on benthic communities in estuaries, environments where biodiversity is already impoverished due to decreasing salinity along the hyaline gradient (Attrill and Power, 2000). Attention was focused on 3 aspects considered relevant for management purposes. First, the type of interaction between stressors to help prioritize which stressors to act upon. Indeed, acting directly on a local stressor may result in the greatest ecosystem benefit when effects are synergistic. Conversely, reducing a local stressor may have limited benefits or be detrimental when effects are antagonistic (Brown et al., 2013). Second, the duration of exposure: since the effects of stressors may vary through time (e.g., having beneficial effects on the short term and detrimental effects on the longer term), considering multiple exposure times may guide managers to identify the optimal moment to act upon a stressor. Third, the usefulness of multiple biological metrics (e.g., mortality, bivalve energy content, and shell calcification) as individual and combined stressors will affect different pathways, and focusing on single-level responses could underestimate the effects of stressors in ecosystems. Nutrient enrichment and freshwater input interacted antagonistically on both mortality and shell magnesium content, with nutrient enrichment having a positive effect at moderate levels, thereby counterbalancing negative effects of salinity reduction. Whereas nutrient enrichment had no effect on bivalve energy content in the short term (i.e., 1 month), negative effects increased with greater exposure time. These results speak to the importance of examining the context in which environmental concerns are addressed and the temporal scale over which they are assessed.

The second project examined the distribution and performance of contrasting kelp species within and outside of the bay, using environmental measures of potential stressors and reciprocal transplants to explain current distributions and predict future ones. Kelp are foundation species in many temperate coastal ecosystems, providing both local and regional primary productivity and creating habitat for other flora and fauna (Steneck et al., 2002). In the northern Gulf of St. Lawrence, the most abundant kelp species are *Alaria esculenta* and *Saccharina* sp. (Himmelman, 1991), both of which occur widely within the BSIC. *A. esculenta* was, however, only found around islands outside of the bay. Surprisingly, when transplanted into the bay, it was able to survive and grow there, suggesting that conditions in the bay (higher turbidity and sedimentation) might have greater negative effects on early life stages, especially the microscopic gametophytes, than on the later stages. The other species, *Saccharina* sp., occurred in both habitats, and its dominance and relatively high biomass (918 $\pm$ 435 kg wet mass m^{-2}, mean $\pm$ *SE*, $N = 9$; Ferrario and Archambault, 2018) within the bay is likely due to its greater tolerance to more turbid conditions. Indeed, its abundance within the bay is primarily limited by a lack of suitable substrata, as even small rocks commonly supported several large kelp individuals. However, the ecological performance (e.g., growth and survival) of *Saccharina* sp. was actually greater outside of the bay, suggesting that the bay, with all of its stressors, is a suboptimal habitat (Picard et al., 2022), while other factors, in particular grazing by sea urchins, restricts its abundance and distribution outside of the bay.

These experimental studies exemplify how research targeting key species and stressors can inform environmental managers on which stressors to act upon, how to do so, and when to intervene. The first case illustrates the importance of considering the interactions of stressors over different exposure levels, as they may drastically change (e.g., moving from an antagonistic to a synergistic interaction) beyond a specific intensity. The second case shows how similar species will respond differently to suites of stressors and allows prediction of stress-mediated shifts in the distribution of key species across environmental gradients. Such knowledge is essential for management interventions such as building upon the initial success of artificial reefs to enhance kelp beds within the bay (Johnson et al., unpublished data) to offset losses due to human development and environmental change (Ferrario et al., 2021c).

Overall, distinguishing between local stressors that managers can regulate (e.g., turbidity from dredging) and global ones (e.g., increased temperature) will be critical to prioritize actions as efforts to intervene locally may be useless in the face of global change. Experimental approaches, both in the field and the laboratory, can help inform such decisions. For example, in the above cases, attempts to mediate turbidity or eutrophication may be irrelevant if rising temperatures turn out to be more influential. Finally, CHONe2's work highlights the need to consider multiple biological metrics to account for all possible pathways of the effects of different stressors (Galic et al., 2018).

3.5. Assessing the ecological status of the benthic ecosystem

The BSIC ecosystem is the result of the interconnection between a diverse set of benthic habitats. Benthic invertebrates are involved in several nodes of trophic networks and provide services such as bioturbation, sediment oxygenation, and organic matter cycling (e.g., Ambrose et al., 2001; Defew et al., 2002). Sessile and low-mobility benthic infaunal species may also act as sentinels of environmental perturbation (Pearson and Rosenberg, 1978; Dauer, 1993). The composition and distribution of benthic infauna, its sensitivity to organic matter enrichment (Borja et al., 2000), and relationships with several environmental parameters (e.g., organic matter, photosynthetic pigments, metals, and granulometry) were used to assess the status of the BSIC. Overall, the bay's infaunal community presented similar characteristics (e.g., biodiversity indices) to those in neighboring regions (i.e., within 10s of kilometers) and seemed typical of the wider Gulf of St. Lawrence ecosystem (Dreujou et al., 2020b). Furthermore, 16 environmental indicators calculated based on the infaunal community (including the W-Statistic Index, functional diversity, and the AZTI Marine Biotic Index) indicated generally low perturbation status, with a moderately perturbed profile for some stations close to Sept-Îles and the Pointe-Noire terminal (Dreujou et al., 2021).

However, as the shallow subtidal seafloor ranges from soft to mixed bottoms (i.e., boulders and gravel in a soft-bottom matrix), using only indices based on infauna may overlook the ecosystem heterogeneity that allows species typical of different habitats to co-occur. Therefore, the macroalgal and epibenthic invertebrate communities—including those species which cannot be captured by soft sediment sampling—were also investigated to complement the assessment of the status of the area's ecosystems. By means of an adapted version of the Ecosystem Based Quality Index (EBQI; Ferrario et al., 2021b), BSIC status was evaluated by integrating the known sensitivity of species to stressors with considerations of their functional role in the ecosystem (e.g., predators, herbivores, bioturbators). For example, submerged vegetation not only contributes to primary production but also enhances habitat structural complexity and offers shelter to local species (some of which are of economical relevance), while the presence of predators could help control the abundances of species in lower trophic levels, thus contributing to the maintenance of equilibrium in the system (e.g., control of overgrazing by herbivores). The ecosystem status assessment obtained through the EBQI complemented and confirmed the one based on benthic infauna analysis, while highlighting the relationship between some ecosystem compartments and potential stressors (e.g., predators and trap fishing).

The CHONe2 strategy thus highlights the usefulness and convenience of concurrently adopting multiple indices targeting different biological components to provide a more integral and reliable ecosystem status assessment.

4. The BSI case study as a social—ecological—environmental system

High-use coastal marine ecosystems like BSI are incredibly complex with both anthropogenic and natural drivers of environmental change. To assess causes and consequences related to ecosystem change, various frameworks have been proposed. The Drivers-Pressures-State-Impacts-Response (DPSIR) conceptual framework (Smeets and Weterings, 1999; Lewison et al., 2016) is one such approach that is widely used, but the "human" or social system often is not considered explicitly (but see Swangjang and Kornpiphat, 2021). An alternate but complimentary approach is the SEES framework (Bograd et al., 2019) whereby the social or human system is more integrated with the ecological and environmental systems more commonly considered in many DPSIR applications. This structured approach allows one to identify and understand the linkages between anthropogenic activities (e.g., fishing, shipping, industry), ecosystem responses (including climate change), and societal responses (e.g., community well-being, economic prosperity). Although there is no predetermined "starting" point in the SEES framework (as it is cyclical), one could start with mapping important drivers of ecosystem change, identifying ecosystem components, processes, and/or indicators most likely to be affected by this driver, and then identifying societal implications (e.g., lost fisheries or tourism, management or policy changes). Alternatively, one could start with a noted ecosystem response and then trace this back to potential drivers responsible for this change, either due to environmental or social drivers, while maintaining linkages among all the SEES compartments. The local BSIC marine ecosystem can be affected by multiple human-mediated stressors (Introduction, Section 2.1) which may also interact with climate variability, and the CHONe2 projects developed in and around BSIC can easily be mapped onto this SEES framework (**Figure 5**). Mapping stressors onto the SEES framework can also help visualize which existing regulations or policies and supporting environmental monitoring are contributing to management within BSI; thus, it can be especially helpful for identifying management gaps and monitoring needs (Section 5). Further, quantitative information could allow projections of ecosystem or societal responses to specific perturbations or management actions that could allow actors in the SEES framework to better understand the implications and costs of action or inaction. Finally, it also allows for the inclusion of management scenarios and outcomes, which, if iterative, can serve as the foundation for adaptive ecosystem-based management where the goal is to manage human activities to promote the coexistence of healthy and productive marine ecosystems and the communities that depend on them. Bograd et al. (2019) demonstrate how this framework was applied to 4 case studies of natural and anthropogenically mediated changes in the North Pacific, including interactions with the human system.

Similar to its application to the North Pacific, the SEES framework can be applied to CHONe2's research in BSI in 2 distinct but complementary ways. First, CHONe2 projects and results may be mapped directly onto the SEES framework to better understand the relationships and connections between the different social, ecological, and environmental components. For example, this approach would allow us to relate the observed changes in benthic and macroalgal communities (marine ecosystem components) to changes in the physical environment (via the processes component) and the human system that is likely driving these changes or responsible for making regulatory or policy changes to improve benefits to coastal communities. Further, large-scale drivers such as climate change considered in the climate system can contribute to observed ecosystem changes. As these changes can drastically alter many rate processes in marine ecosystems, this forcing cannot be ignored when considering ecosystem stressors resulting from human activities within the BSI area. For example, increased human activities in BSI could increase SPM and nutrients in the bay. This, in turn, could alter benthic and macroalgal communities, some of which are important for the community of Sept-Îles, either directly as a commercial or recreational fishery resource or indirectly contributing to ecosystem structure and function. Based on this new understanding, management efforts to limit SPM and nutrient additions to the bay should increase the resilience of the BSI system. Monitoring for changes over time would indicate whether management efforts have been effective. Further, while not considered explicitly in CHONe2, this approach can identify which human components could be most influenced by changes in the system which in turn can be used to identify socioeconomic indicators to monitor. For example, monitoring changes in fishery landings or in outdoor recreational activities (e.g., fishing, kayaking, bird-watching, beach going, and SCUBA diving) could provide insights on the ability of the system—or of its management—to yield services to the coastal community in terms of both livelihood and well-being.

The second way in which the SEES framework can be applied to BSI is to evaluate potential desired outcomes for the area. For example, INREST has expressed a desire for greater ecosystem sustainability in light of increased human activities around shipping and industrial development. By mapping specific environmental stressors and management actions in the SEES framework, industry, stakeholders, and local indigenous groups can collectively foresee probable ecosystem responses in a clear and transparent way. Although this in itself does not guarantee uptake by any of the actors within BSI, it is conceptually at the heart of marine spatial planning and comanagement approaches where a common understanding is essential to develop responsible and adaptive management plans and monitoring programs. For example, if shipping were to increase relative to current levels, this framework would allow all interested parties to see what specific changes are likely to occur in each SEES compartment and allow the development of monitoring and mitigation strategies based on existing and new BSI data (**Figure 5b**). Thus, the SEES framework, regularly updated with monitoring observations or experimental studies like the ones undertaken by the CHONe2 network, will allow open and transparent discussions about future management or regulatory decisions. To this end, the framework should be used as an iterative process (as intended) to assess progress toward adaptive ecosystem-based management and adjust management actions accordingly.

5. Adapting the Bay Sept-Îles case to other realities and moving forward

The path that led to the creation of the BSI observatory and its later partnership with CHONe2 might be specific to the academic (i.e., pre-existence of the established research network CHONe), social and political context (e.g., environmental sensibility of local stakeholders, NSERC federal funding programs fostering partnerships between academy and industry) found in Canada and Sept-Îles. However, the need for an independent structure of the observatory, the support from local stakeholders (in

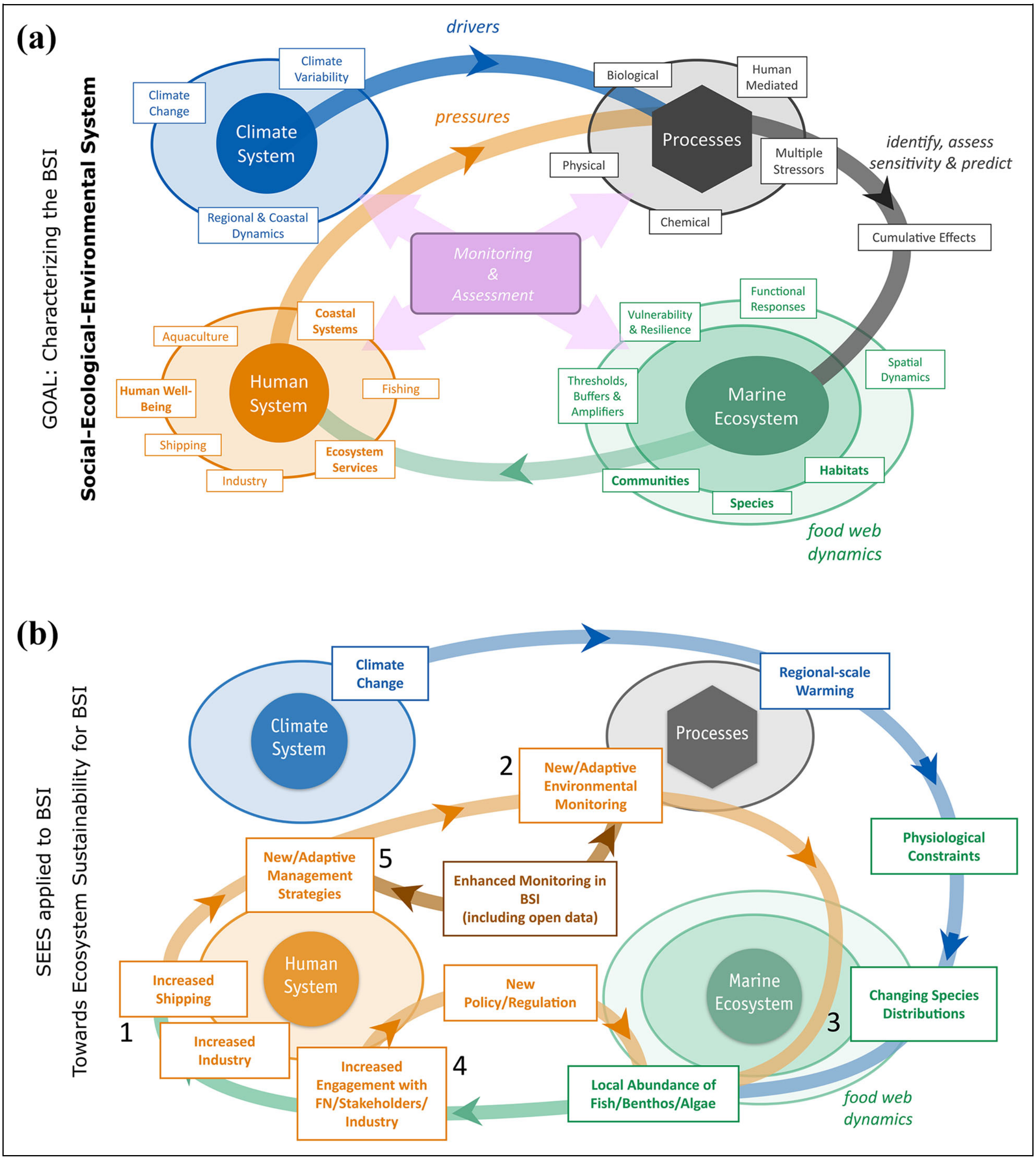

Figure 5. Application of the social–ecological–environmental system framework in Baie des Sept Îles. Diagrams represent (a) key components of the BSI SEES and (b) how this framework can be used to consider planned/potential changes in human use of the BSI system. For example: following an increase in shipping (1), if environmental monitoring (2) detects changes in ecosystem indicators (3), stakeholders could develop or update environmental policies (4), posing the foundation of adaptive management over time (5). DOI: https://doi.org/10.1525/elementa.2021.00061.f5

primis the Port Authority), and the participation of a multidisciplinary team of independent researchers are the 3 elements that form the core of the know-how developed through the establishment of the largest environmental observatory and holistic monitoring in Quebec, Canada. Once these elements are in place, the BSI experience may be adapted to other ports and industrial areas in Canada and abroad and to different geographies by focusing on relevant components—ecological and social—of the specific context. The case of the Port Curtis Integrated Monitoring Program (Gladstone, Australia) is an example that corroborates this view (Australian Institute of Marine Science, 2015): The engagement of stakeholders, government, and research institutions established an

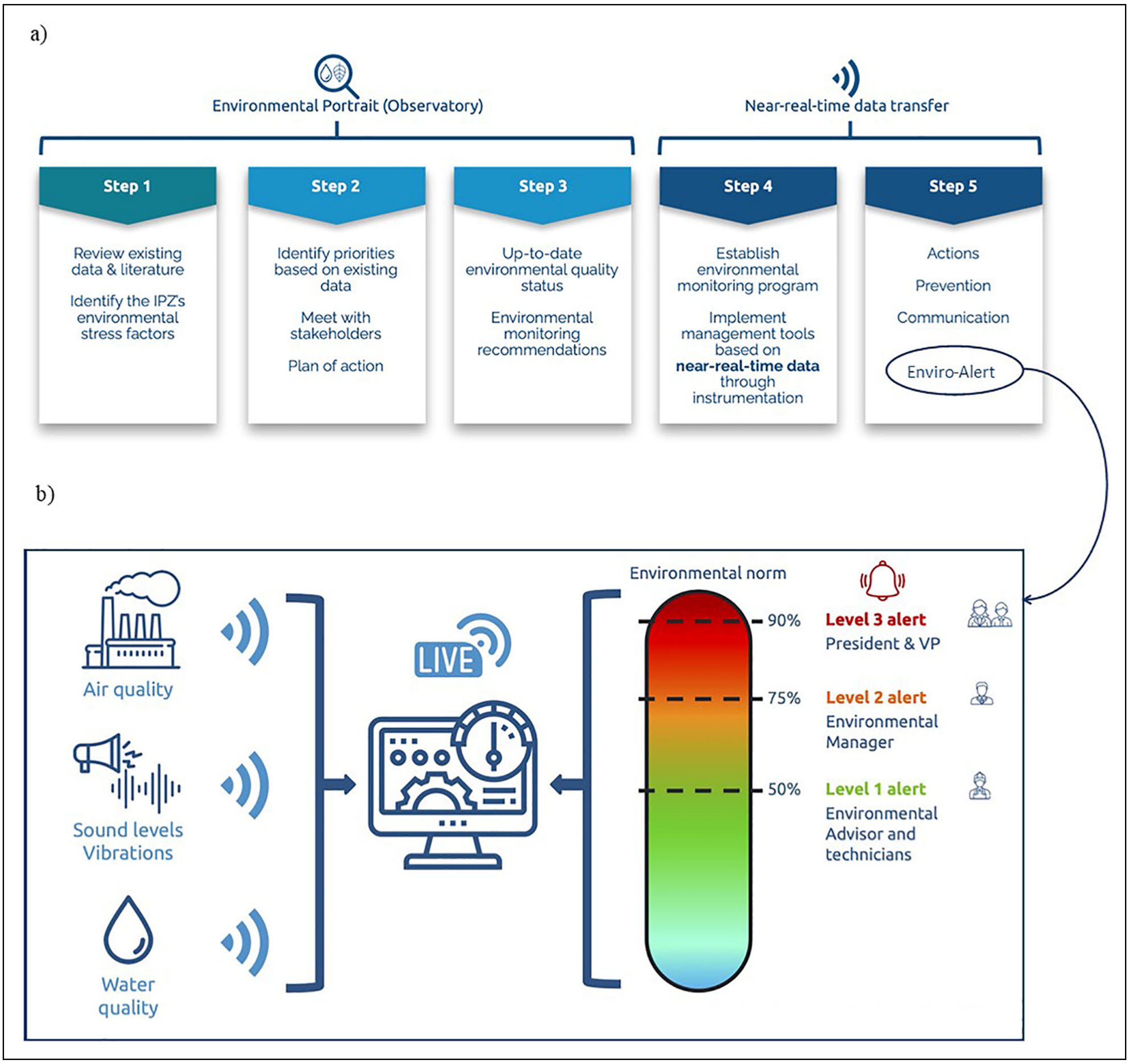

Figure 6. The Enviro-Actions model and Enviro-Alert tool. (a) The Enviro-Actions model is a proactive environmental management model. Steps 1–3 aim to create an environmental observatory to provide an up-to-date environmental portrait of the area under study. Steps 4 and 5 involve near real-time data collection. (b) Transmission of an alarm signal for different parameters to upper management to ensure that preventive actions are taken before contamination, for example, reaches a concentration that could impact the ecosystem. DOI: https://doi.org/10.1525/elementa.2021.00061.f6

independent association ensuring a multidisciplinary monitoring program spanning from air, water, and sediments, to corals, mangroves, and cetaceans. The following subsection will present 3 nonalternative directions that can build on the observatory and CHONe2 experiences.

5.1. A proactive model for environmental management (Enviro-Actions)

Environmental management in the majority of industrial-port zones (IPZs) is currently more reactive than proactive (Ferrario et al., 2021a), such that, because of limitations in monitoring structure (i.e., mainly low temporal frequency and/or coarse spatial resolution), managers are most often only made aware of impacts to the environment after the fact. As such, interventions will be primarily in reaction to events and less capable of preventing impacts. Conversely, it would be desirable that monitoring could detect trends in environmental parameters to provide managers the opportunity to take actions before they lead to impacts. To this end, INREST has developed a new proactive model for environmental management in IPZs called "Enviro-Actions," which consists of 5 steps (**Figure 6a**) with specific objectives:

- *Step 1*: Identify environmental stress factors for the IPZ.
- *Step 2*: Hold meetings with stakeholders to identify priorities for management based on available

environmental data; protocols are recommended, identified, or adapted to measure and predict stressor-driven changes to the IPZ ecosystem; action plans are created in preparation for Step 3.

- *Step 3*: Gather data to establish environmental baselines and assess the current quality status of the IPZ environment.
- *Step 4*: Foster data-based and proactive decision making by establishing an environmental monitoring system that gathers near real-time data on a variety of priority environmental parameters (e.g., water quality, underwater noise, air quality) capable of providing alerts (Enviro-Alert, **Figure 6b**) to response teams.
- *Step 5*: Stakeholders and environmental managers take action to ensure prevention. Near real-time data monitoring can foster communication with the public to reassure and meet the expectations of the community concerning environmental protection and promote social acceptability of port activities.

The first 3 steps of the Enviro-Actions formalize and operationalize the BSI observatory and the CHONe2 multidisciplinary monitoring experiences, and as such, they envisage stakeholder engagement early in the process. The last two expand the BSI experience by developing an alert system, called "Enviro-Alert" (**Figure 6b**), that operates according to a predefined intervention barometer adapted to the levels of risk for a given area within the port. Enviro-Alert is triggered by the early detection of changing trends in levels of environmental stressors from data gathered by the near real-time monitoring system. It will alert progressively higher hierarchical levels of decision making within one or more organizations in the port area to allow appropriate actions to be taken quickly. As such, managers of ports, municipalities, and industries are informed in a timely manner to intervene and prevent a given stressor from exceeding critical thresholds. This proactive approach to ecosystem protection will limit the need to resort solely to response plans after incidents happen, when (usually) standards have already been breached, and quality criteria or recommendations exceeded.

Operationalizing the Enviro-Actions model relies on the involvement of all levels of administration in the organizations that are active in the port area (i.e., the Port, the municipality, and the industries) and focuses on the standards, criteria, or recommendations to be met for the goals of the management system to be achieved. Implementing near real-time monitoring systems that provide a continuous flow of data and an up-to-date portrait of the environmental status will benefit industries particularly by (1) reducing delays often associated with the request of data collection from governmental agencies granting environmental authorizations to development projects and (2) increasing social acceptability and inclusiveness, fostered by neutral scientific data.

The Enviro-Actions model is being implemented in the industrial and port area of Sept-Îles (a team of experts is currently working to prepare and plan the implementation of Step 4), as a pilot case study. Once uniform instrumentation protocols and methodologies have been fully developed, this model will then be applied to other IPZs. The benefit of using the same environmental management protocols and methodologies across ports will be the comparability of data collected between different IPZs and the transfer of knowledge and expertise between research and innovation, as well as between end users and economic and government stakeholders.

5.2. A reliance on relationships around ports

Engagement should always be a key component of any comprehensive sustainable management framework. In particular, in Canada, where Indigenous peoples have a certain level of autonomy in their territories and constitutionally protected rights and title, formal relationships and partnerships often exist between ports and Indigenous communities. Although an active engagement of the local Indigenous community could not be achieved in the context of CHONe2, we recognize that an inclusive decision-making approach should be flexible enough to fit into and augment, rather than replace or replicate, environmental monitoring initiatives led by, co-managed by, or promoted by Indigenous peoples.

A first concrete example of inclusiveness can still be found in Sept-Îles, where the Innu-Takuaikan Uashat Mak Mani-Utenam Indigenous community has been actively engaged in the environmental monitoring of the Mishta-Shipu River, the largest river flowing east of the Port of Sept-Îles area. Following the same philosophy underlying the CHONe2 experience (**Figure 1**), the Innu-Takuaikan Uashat mak Mani-Utenam community joined forces with INREST and partners from Université Laval, industries, and the Quebec government, to establish a monitoring project to complement that of the BSI environmental observatory (e.g., assessment of the water quality and benthic invertebrate community of the river). The Innu community was actively engaged in the Mishta-Shipu River monitoring through Innu students that received Master's level training within the program, which thus represented an opportunity to train a new generation of Innu scientists and environmental managers while preserving the important cultural heritage value of the river for the community. Therefore, as they acquire additional tools and skills from experiences with water, sediment, and benthic monitoring in the area, the Innu community is able to build capacity for ongoing management and preservation of the environment, thereby ensuring increased resilience.

The Tsleil-Waututh Nation (TWN) living along the shores of Burrard Inlet in the heart of the metropolitan Vancouver region (British Columbia, Canada), and the city's primary port area, represents a further example of Indigenous-led sustainable environmental stewardship. Following the closure of shellfish harvest in Burrard Inlet, due to pollution and exceeding cumulative environmental effects of urban, industrial, and port development, TWN has created and is working on the Burrard Inlet Action Plan, a suite of priority actions to improve and restore the environmental health and integrity of the inlet by 2025. The Tsleil-Wauthuth vision for Burrard Inlet includes a place-based and holistic approach to data collection (including in urban areas), updating water quality objectives, installing scientific instruments to monitor water quality, characterizing and reducing pollution from stormwater runoff, mapping nearshore habitats and forage fish spawning beaches, conserving critical nearshore habitat complexes, and recovering shellfish beds.

5.3. Science-policy interface for ports in Canada

The BSI is a good example of how ports and the various levels of government can complement one another's goals. A knowledge-based society emphasizes the importance of sound science advice as a key input to the formulation of policy and decision making about regulations and management both nationally and internationally. There is heightened public interest in science-based issues and discoveries and greater emphasis on public participation in decision making. Concurrently, issues facing governments are increasingly complex and require actions that can have profound impacts on environments, communities, and economies at various scales.

Governmental decision making in Canada aims to be inclusive and consider the widest range of available inputs, integrating all available sources of science, including traditional knowledge, and framed in the context of ecological, social, economic, and cultural considerations.

Particularly in the context of ocean science, there are many opportunities for such assimilation, including building collaborative partnerships with other governments and nongovernment organizations (e.g., academic and environmental groups) and engaging communities and industry stakeholders to share information from their interests in maintaining the health of the natural environment and facilitating the progress of multisectoral development.

When considering science and management in the coastal zone, that is, the traditional location of ports and authorities, the need for integration is even greater as the quantity and intensity of natural and human influences and interests rises substantially. In particular, many ports and other industry stakeholders have embraced the concept of a "blue economy" and have in turn sought participative means to collect information (ecological and other) that can support multidisciplinary and iterative processes (consistent with the SEES framework) to promote sustainable development within their sectors and geographic areas of influence. The shared goal, over the long term, is to balance ecological, economic, social, cultural, and recreational objectives, all within the limits set by natural dynamics.

6. Discussion and conclusion

The approach adopted by CHONe2 in BSI exemplifies how it is possible to realize the foundational concepts of engagement and collaboration for sustainable development at a time when sustainability is at the center of national and international agendas agendas (United Nations, 2018; Intergovernmental Oceanographic Commission, 2019; European Commission, 2021; New Economic Foundation, 2021). The UN Decade of Ocean Science for Sustainable Development aims to address UN Sustainability Development Goal 14 (SDG 14) of the UN 2030 Agenda, whose targets include preventing and significantly reducing marine pollution, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, increase scientific knowledge, and develop research capacity to improve ocean health (SDG 14; United Nations Development Programme, 2021). The UNESCO Intergovernmental Oceanographic Commission is shaping the Decade as an ambitious and unprecedented collaborative framework where scientists, civil society, industrial stakeholders, managers, and policymakers can find matching partners to implement actions and address priorities in ocean science that they themselves can propose (Intergovernmental Oceanographic Commission, 2019).

Canada is embracing this international momentum to become an active leader in transitioning to sustainable development. In this regard, Canada is a member of the High Level Panel for A Sustainable Ocean Economy—a World Resource Institute group of 14 countries representing 40% of the world's coastlines—intended as an ocean policy body to develop and foster an action agenda for transitioning to a sustainable ocean economy (Lubchenco et al., 2020; World Resource Institute, 2021). Furthermore, Canada is moving toward the development of a Blue Economy Strategy recognizing the current contribution of ocean related sectors to the country's economy (Fisheries and Oceans Canada, 2021), joining the European Union (European Commission, 2020) in calling for similar initiatives in other countries such as the United Kingdom (New Economic Foundation, 2021) and the United States (Warren Democrats, 2021). In particular, the IOC's Decade of Ocean Science is drawing a road map toward sustainable development that has its cardinal directions in the following elements (Ryabinin et al., 2019): (1) the enhancement of ocean observations, (2) the sharing of knowledge and data, (3) the promotion of ocean literacy, and (4) the active engagement of all levels of the society (i.e., academia, governments, industrial stakeholders, and private citizens).

The CHONe2 experience in Sept-Îles aligns perfectly with several of these elements and provides evidence that Canada demonstrates the interest and capacity to become a global leader in ocean science and sustainability.

First and foremost, CHONe2 provides a timely demonstration of what collective willpower and vision can achieve. In Sept-Îles, CHONe2 has fostered consensus among stakeholders around the proposed scientific research objectives that has translated into both a substantial financial commitment to the network (Section 2, **Figure 3**) and a collaborative atmosphere between researchers and stakeholders (e.g., support to field campaigns, avoidance of conflicts). CHONe2 thus aligns to calls to drive change by improving science-policy engagement involving governments, the private sector, and civil society (Claudet et al., 2020).

Another step toward meeting SDG 14 of the UN 2030 Agenda is to embrace policies that transcend traditional demarcations (e.g., political boundaries, competency limits of management authorities; United Nations, 2018) in favor of a more holistic management regime in which the effects of decisions are evaluated with respect to the whole ecosystem and its interactions (Carr et al., 2020; Dreujou et al., 2020a; Lubchenco et al., 2020). On a practical level, CHONe2 has made it possible to carry out a monitoring initiative wide enough in scope in BSI to ensure environmental conservation in the area for future generations. Multidisciplinary environmental monitoring in Sept-Îles was intended as a systemic investigation of the integral biological and physical components of the bay, rather than a mere series of unrelated snapshots of disparate parameters. Synthesizing the established baselines and the acquired knowledge of the processes in an SEES framework, CHONe2 represents a significant step toward the holistic management of BSI, favoring ecosystem-based solutions and marine spatial planning.

The network succeeded in building momentum upon which other priorities can be pursued. For example, CHONe2 has created opportunities to increase ocean literacy (Ryabinin et al., 2019; Claudet et al., 2020) in Sept-Îles by bringing ocean science outside classic academic conferences and governmental panels. Indeed, CHONe2 researchers, along with external industrial and transport experts, were invited to present their results and perspectives in person in Sept-Îles during a 3-day convention in 2019 (www.cirsip.ca). In addition, the results and data supporting the environmental observatory and CHONe2 studies were made public (Section 2.3). Making science visible in Sept-Îles helps narrow the gap between citizens and science, as well as encourage constructive interactions with local industries and policymakers.

Alongside holistic monitoring that will support environmental policies, increasing engagement and ocean literacy opportunities will further favor the comprehension of the rationale behind those policies and decrease inertia to change toward sustainability. The Enviro-Actions program is possibly the most evident example of such a change and its implementation is in line with current trends in Ocean-Observing Systems and the call for their improved integration (Claudet et al., 2020; Whitt et al., 2020). Interestingly, several ports around the world are already undertaking a technological evolution based on "Big-data" and the "Internet of Things." For example, in Europe, Antwerp and Rotterdam are "digitizing" their ports to create a virtual 3D copy of their infrastructure and are using artificial intelligence to manage it. By creating a network of sensors to manage port activities (e.g., ship traffic, logistics), these 2 ports are also developing automatic monitoring of air quality and bathymetry (e.g., Port of Antwerp, 2021). Given the magnitude of these efforts, the Enviro-Actions program could readily complement these projects, showing the contribution of CHONe2 in supporting sustainable development through technological innovation.

The port industry works to mitigate risks to the environment and human health by increasingly defining environmental and safety standards through national (e.g., American Association of Port Authorities, Association of Canadian Port Authorities) and international (e.g., International Association of Ports and Harbors, International Maritime Organization, World Association for Waterborne Transport Infrastructure) organizations. Concurrently, academic discussions on the sustainability of port activities have advanced greatly over the last decade, addressing issues, such as port–city interactions, sustainability evaluation, stakeholder involvement, and technological–methodological approaches to promote sustainability (Zheng et al., 2020). The engagement of scientists to provide evidence-based support to sustainability-oriented decision making in ports (worldharbourproject.org; Steinberg et al., 2016) has recently led to the development of a comparative method to assess the environmental risk of ports on aquatic systems globally (Valdor et al., 2020). The primary benefit of Valdor et al.'s (2020) exercise was to produce a census of both the elements of risk (e.g., type and number of port activities, proximity to ecologically valuable areas) and the measures in place to counter risks (e.g., procedures and standards) for each harbor considered. This knowledge is particularly valuable in proactively reducing the occurrence of detrimental conditions and events for the environment, but the need to assess the actual status of the system remains. Specifically, we argue that a holistic approach to ecosystem monitoring and characterization, such as that adopted by CHONe2, is the ideal complement to Valdor et al.'s risk assessment method. Indeed, while a set of monitoring programs could plan to validate the efficacy of measures adopted to avoid impacts (i.e., the realization of a risk), only a comprehensive environmental investigation would additionally be able to identify unmapped risks arising from previously unconsidered elements of the system. Expanding the pool of risks considered is essential to improve the instruments at our disposal (e.g., new protocols, best practices) and to raise port industry standards globally, especially when risk assessment at 1 harbor is evaluated using metrics normalized against the best scoring harbor for a given parameter, as in Valdor et al. (2020).

Some form of monitoring is conducted in virtually all ports, but there is still great variability and inconsistency (Ferrario et al., 2021a)—both nationally and internationally)—regarding which components of the system are targeted (e.g., hydrography, terrestrial/marine ecosystems, and air/aquatic pollution), temporal and spatial resolution of data acquisition, its standardization (e.g., specificity vs. vaguely defined parameters), structure (e.g., occasional vs. regular), and data accessibility (e.g., closed vs. open data). Similar issues may not pertain to monitoring exclusively in ports. For example, biodiversity assessment remains a major gap of environmental monitoring in the Baltic Sea (Kahlert et al., 2020). Monitoring requirements are also better and more consistently defined for other marine industries, such as marine aquaculture, where the need for the homogenization of policies has long been recognized (Read et al., 2001). For example, environmental monitoring for finfish aquaculture in Canada uses guidelines and best practices to conserve benthic quality via the Aquaculture Activities Regulations (Fisheries and Oceans Canada, 2019), rather than imposing a national regulatory framework with rigid threshold values for monitored parameters. This approach allowed for the flexibility required to adapt to the variety of contexts (e.g., geographical settings, type of aquaculture) while promoting comprehensive assessments (e.g., hydrodynamic models, benthic surveys, and chemical analyses). Similarly, port sustainability would benefit from the introduction of best practices or codes of conduct for holistic-oriented environmental monitoring. Indeed, if a network of port authorities and government agencies were keen on establishing common best practices, positive discussions on how to implement comprehensive monitoring would foster harmonization within and between nations. Evidence encouragingly shows that good sustainable development behaviors propagate within a complex regional network of ports (Zhao et al., 2020), while comparative assessment exercises could highlight inspiring models (Valdor et al., 2020).

Lessons learned from the CHONe2 case study in Sept-Îles and of the establishment of the environmental observatory can be summarized into a set of best practices for comprehensive environmental monitoring in ports which include the following:

- Formalize the process through which to identify partnerships. In our experience, the core of the CHONe2 partnership was built by integrating personal connections, largely between members of other multidisciplinary research networks, with select allies that allowed the engagement of local stakeholders. One approach to improve and streamline the CHONe2 experience will be to move beyond personal connections through a systematic, open, and transparent partnership-building process that will ensure inclusiveness and favor multidisciplinarity and diversity of perspectives. Indeed, incorporating human dimensions (e.g., social, economic, and cultural components, including indigenous communities) in ocean governance processes can minimize conflicts and favor acceptance of environmental management measures (Christie et al., 2017). In this regard, one possible way forward could be to increase opportunities for scientists, managers, industrial, and public stakeholders to meet and positively exchange experiences and expectations, following the UN Decade of Ocean Science approach.
- Set the rationale and goals of holistic environmental monitoring using strategies of Participatory Modeling where all partners and stakeholders (representative of as many human dimensions as possible) contribute to the conceptual model of the system underlying the monitoring program (Sterling et al., 2019). In Sept-Îles, discussions with stakeholders were held but not following a structured model; we consider that participatory modeling could improve the CHONe2 approach and present several benefits. For example, it could unlock stakeholders' resources (economic and in-kind) and expertise from nonscientific partners in support of the program. Most importantly, participatory modeling would keep the discussion between all partners open, creating conditions to perpetuate monitoring efforts by securing funding, expanding the extent of monitoring, and identifying new objectives.
- Include a partner credited with intellectual independence, possibly locally connected, to facilitate discussion between partners. This, along with participatory modeling, will enhance social acceptability of environmental management measures potentially adopted in reaction to the monitoring results.
- Monitoring programs should be intended more as a tool to advance the knowledge of a port's natural system rather than solely a confirmatory test to respect legal and standards requirements. While a suite of traditional methods can be adopted for routine monitoring, new technologies and research methods (e.g., eDNA, paleoecology, networks of sensors, real-time data, remote sensing, artificial intelligence, and computer vision) could provide novel insights into the functioning and status of the natural system. Monitoring program partners should thus be open to supporting and favoring innovation.

We hope that the CHONe2 approach summarized here, beyond the specific scientific outcomes generated, will spark new interest in environmental monitoring in ports as a path to conciliate development, sustainability, scientific and technological advancement, and social inclusiveness, both in Canada and internationally.

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Author contributions

- Coordinated and wrote the manuscript: FF.
- Contributed to the conception: FF, PA, JC, LEJ, TWT, NT, EST.
- Drafted the manuscript: FF, CASA, PA, SB, JC, CCB, ED, LEJ, CWM, RM, LO, MMMP, RSL, JLS, EST, NT, TWT, JET.

- Revised the manuscript: FF, PA, JC, LEJ, SKJ, CWM, EST, TWT, TN, MMMP.
- Approved the submitted version: FF, CASA, PA, SB, DB, JC, CCB, ED, LEJ, SKJ, RM, CWM, LO, MMMP, RSL, JLS, EST, NT, TWT, JET.

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