



# A systematic review of indicators and methods used to assess coastal to offshore marine ecosystems in the western Canadian Arctic

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## Abstract

Integration and coordination among monitoring programs are needed to better assess the impacts of climate change on Arctic marine ecosystems. The use of common indicators and methods could facilitate this comprehensive understanding. We completed a systematic review of published marine research in the western Canadian Arctic from 1962 to 2021 to identify the commonalities in methods and indicators present in assessments of coastal and offshore ecosystems. Most abundant in our sample were indicators addressing the environmental context, followed by indicators concerning trophic webs and biological organisms, and finally indicators associated with anthropogenic stressors and threats. Ship-based studies located far offshore were by far the most common and focused on indicators that characterized the physical environment and lower trophic levels. Commonalities in data collection methods suggest possibilities for standardization among programs for some parameters. Differences and data gaps highlighted areas for future coordination and the potential to integrate among indicators, especially as some indicators may span coastal to offshore ecosystems whereas individual monitoring programs may not. The results of this review could be used to identify and gather data into broad-spanning datasets. Overall, this systematic review highlights opportunities to link indicators and methods among coastal to offshore programs and will therefore facilitate connectivity and coordination of ecological research and monitoring in the western Canadian Arctic.

**Keywords** Ecosystems · Climate change · Systematic review · Arctic · Methods · Indicators

## Introduction

Rapid Arctic change is occurring (IPCC 2013; Arctic Council 2016), impacting Arctic marine ecosystems at various temporal and spatial scales (Wassman et al. 2011; Niemi et al. 2019). Within the Canadian Arctic, there are recognized regional differences in the nature and extent of these changes due to the extensive variation present across Arctic features and ecosystems (summarized in Niemi et al. 2019). The western Canadian Arctic, for instance, is characterized by the deep Canada Basin and the sea floor rise to the

Polar Continental Shelf, with the presence and depth of sills throughout the Arctic archipelago influencing water flow (Niemi et al. 2019). It is also uniquely positioned to receive both nutrient-rich inflow from the Pacific Ocean and freshwater input from the Mackenzie River (Carmack et al. 2015), which is also the largest single source of sediments in the Arctic (Rachold et al. 2000). Recent environmental change in the western Canadian Arctic includes warming temperatures and an increase in easterly winds, together leading to a dramatic reduction in sea ice (Wood et al. 2013). Sea-level rise and coastal erosion are a concern for nearshore areas because this reduction in the extent and duration of sea ice cover is paired with low coastal elevation, an increase in storm variability, and a shift in wind direction (Small et al. 2011), resulting in an increasing frequency of storm surges (Harper et al. 1988; Pisaric et al. 2011). The resulting impacts are affecting coastal communities and culturally important sites (Colette 2007).

A coordinated approach to monitoring is needed across the Arctic to document this environmental change and understand the resulting impacts to Arctic ecosystems, especially

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amidst their underlying inherent variability (Niemi et al. 2019). To achieve international integration and reporting, monitoring plans developed for the Arctic recommend the identification and use of common indicators (e.g., Conservation of Arctic Flora and Fauna (CAFF) Arctic Marine Biodiversity Monitoring Plan, Gill et al. 2011) or groups of ecologically related coastal species, called focal ecosystem components (FECs) (CAFF Arctic Coastal Biodiversity Monitoring Plan, Jones et al. 2019). As part of an adapted ecosystem-based approach to monitoring, the Circumpolar Biodiversity Monitoring Plan outlines an iterative process to bring together available knowledge across ecosystems, species, and their interactions (Christensen et al. 2021). While desirable, it is also difficult to transition the considerable recent effort toward Arctic research (e.g., International Polar Year) into a coordinated approach to monitoring (Gill et al. 2011). As a result, there is not yet the level of comprehensive knowledge needed to support ecosystem-level management (Michel et al. 2013; Niemi et al. 2019).

Here, we contribute a synthesis of published literature regarding western Canadian Arctic marine research and monitoring, focused not on the research results needed to assess ecosystem change or stability, but instead on the monitoring targets (indicators or focal ecosystem components, FECs) and methods used to assess them. By doing so, we build a platform that identifies common methodological approaches and links methods with indicators to span coastal to offshore ecosystems. While applicable Arctic-wide, we focus here on the western Canadian Arctic to provide a regionally specific synthesis, which could highlight important differences in approaches related to physical features or other variables. Therefore, our objectives here are to (1) document the methods used in studying important marine indicators in the western Canadian Arctic, with a focus on identifying commonalities, and (2) find methodological links across coastal and offshore ecosystem assessments. This synthesis is intended to contribute to existing monitoring plans, facilitate the identification of connections among coastal and offshore ecosystems, and lead to improved coordination and collaboration across more robust monitoring programs.

## Methods

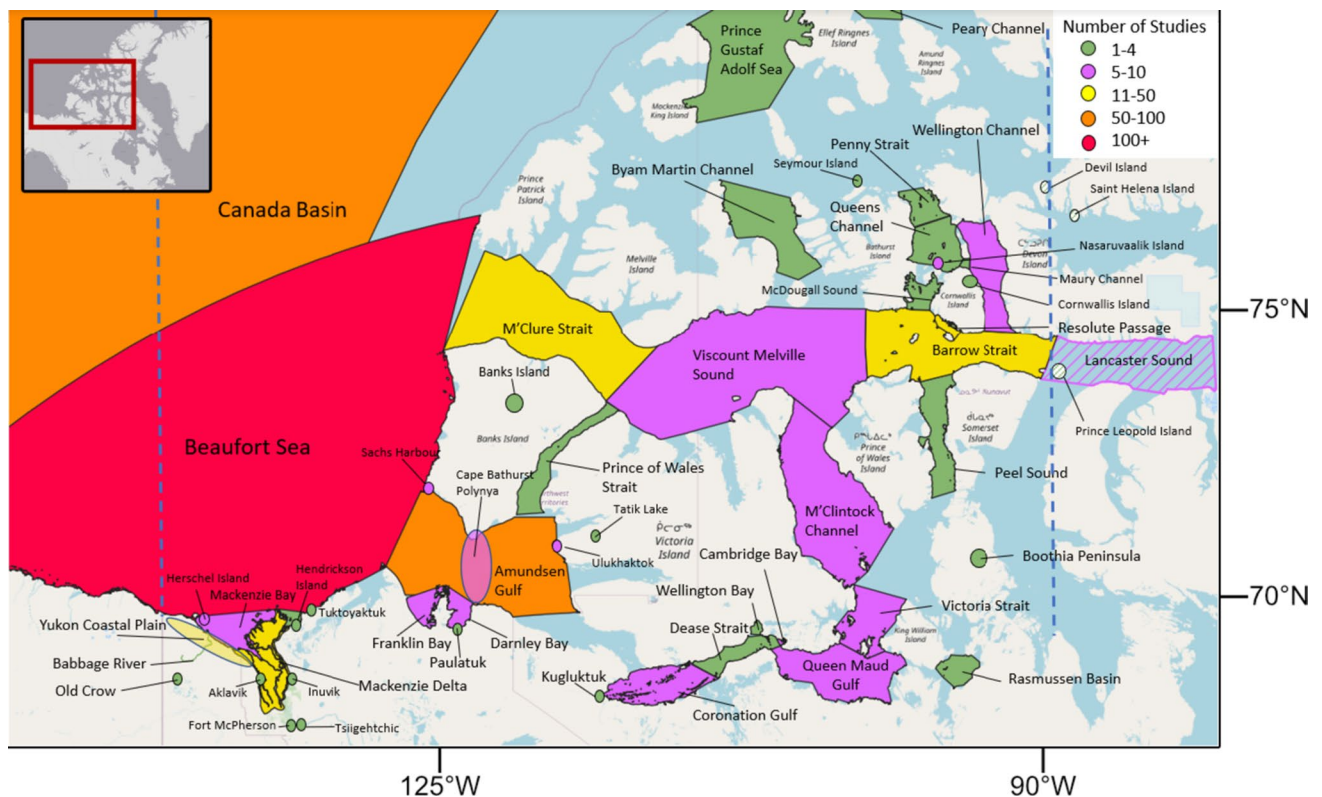
### Systematic review

We used a systematic literature review approach to obtain a thorough appraisal of indicators and the methods used to study them in western Canadian Arctic marine research and monitoring. We defined the western Canadian Arctic as the marine waters west of the Boothia Peninsula and the Somerset, Devon, Ellesmere, and Axel Heiberg islands, to the

Exclusive Economic Zone (EEZ) boundary ending at the Alaskan border (Fig. 1). A systematic literature review is characterized by an explicit and rigorous methodology which differs from that of traditional reviews in its use of transparent, objective criteria. The search terms (Online Resource 1) and subsequent coding questions (Online Resource 2) were derived from the indicators outlined in Ehrman et al. (2022). Here and in Ehrman et al. (2022), indicators are defined as ecosystem components that respond to anthropogenic stressors or environmental drivers in a way that can be measured to evaluate whether conservation objectives are being met. Originally developed specifically for the Anguniqvia Niqiqyuam Marine Protected Area (ANMPA), located near Paulatuk, Northwest Territories in the western Canadian Arctic, these indicators were selected for their ability to identify ecosystem changes with respect to conservation objectives (Ehrman et al. 2022). They were chosen based on available scientific information and published Indigenous knowledge, with consideration of literature regarding environmental indicator selection and examples from other monitoring programs (Ehrman et al. 2022). The indicators were then peer-reviewed by over 20 government and non-government scientists as part of a Canadian Science Advisory Secretariat (CSAS) process supporting the development of a monitoring plan for the ANMPA (DFO 2022). The indicators were grouped into three broad categories in Ehrman et al. (2022), which were maintained for this review in order to facilitate identifying linkages among responses in upper trophic level species and their ecosystems to the drivers of change. These categories are (1) indicators that provide environmental context, (2) indicators of biological and food web integrity, and (3) indicators of anthropogenic stressors and threats.

Once the search terms were compiled into a search string, appropriate databases were selected. Web of Science was chosen due to its broader temporal coverage compared to Scopus (Arezoo et al. 2013). The final search occurred on May 5th, 2021, using the search terms outlined in Online Resource 1. A similar search of the Fisheries and Oceans Collection on the Federal Science Libraries Network was conducted to obtain peer-reviewed literature relevant to our research objectives that was not published in academic journals (Online Resource 3). The search terms were the same, with the search string modified to account for syntax differences between the two search engines.

The combined searches returned 1395 papers, which were then subjected to a series of screenings (Fig. 2). The initial screening involved assessing the title and abstract for our inclusion/exclusion criteria (i.e., geographic scope, language, focus, ecosystem, publication type, temporal scope, and the presence of a methods section) and excluding those papers that did not meet our criteria. This title and abstract screening left 523 papers, which were then assessed



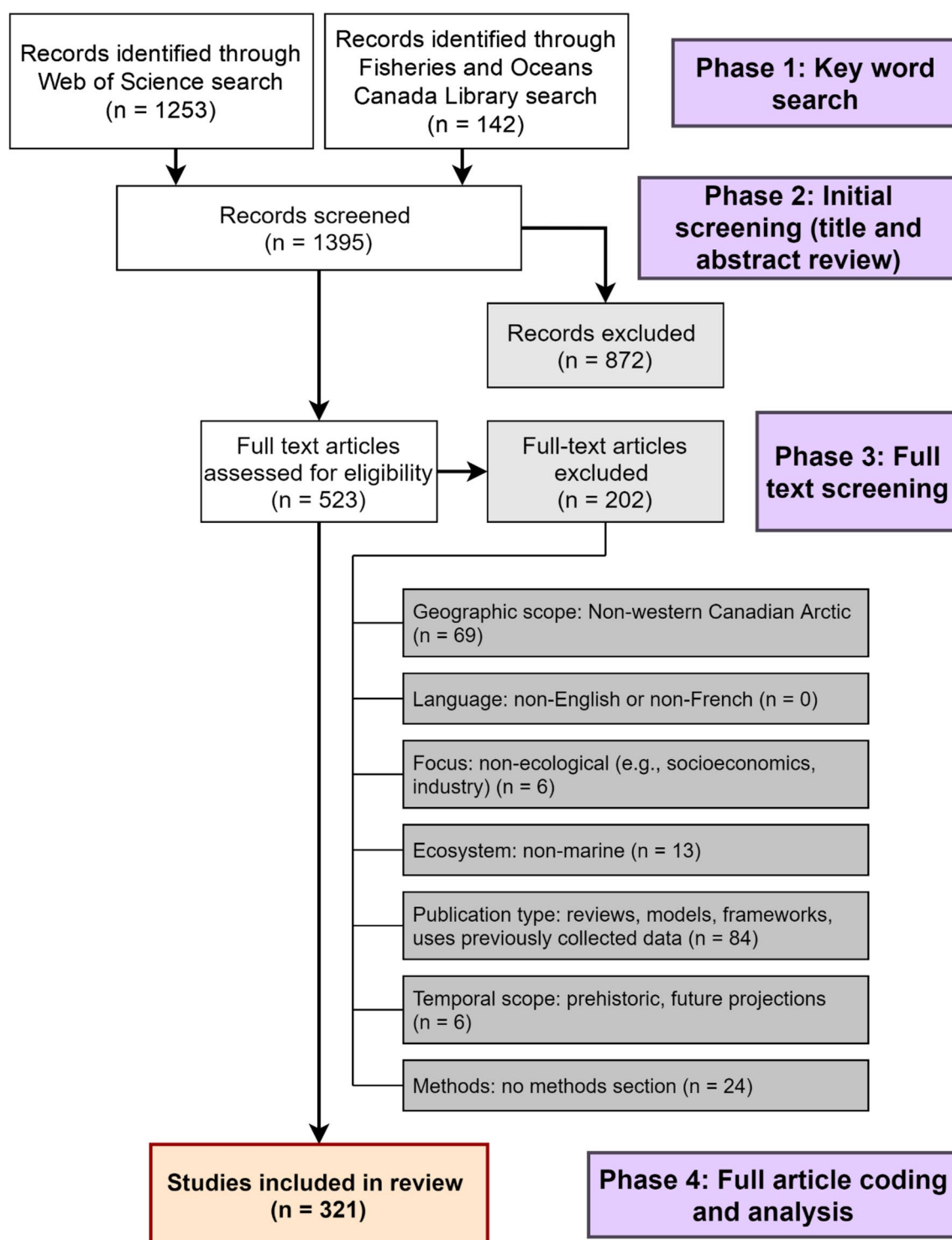
**Fig. 1** Heatmap of the number of papers that took place in the 59 study areas identified in our sample during coding. Marine areas are outlined with distinct shapes; non-marine areas (specific communities, islands, etc.) are marked with dots. Blue areas indicate no

studies. Resolute Bay is not visible at this scale but was host to four studies. Boundaries of the western Canadian Arctic as defined in this review are marked by the dotted blue lines. Created in QGIS

to extract information pertaining to the indicators studied and the methods of data collection. This information was coded into a database by two independent coders (MB & KW). During this coding process, a further 202 publications were excluded. Of those 202 exclusions, the majority were because of publication type ( $n=84$ ) and geographic scope ( $n=69$ ). Other reasons for exclusion included a lack of methods section ( $n=24$ ), ecosystem focus ( $n=13$ ), paper focus ( $n=6$ ), and temporal scope ( $n=6$ ) (Fig. 2). In total, 321 papers were included in our final sample; a full list of these papers can be found in Online Resource 4. See Online Resource 5 for the inclusion and exclusion criteria used to assess all papers.

Following the screening process, information relevant to our objectives was extracted from the 321 papers using 82 coding questions divided into 6 sections (Online Resource 2). Sections 1 to 3 focused on the broad indicator categories being studied (environmental, biological, and anthropogenic stressors) and defined the specific parameters used for each indicator group. We use Ehrman et al. (2022)'s definition of a parameter, which is a measurement or aggregate of measurements used to assess the status of an indicator; multiple parameters can be used to measure

a single indicator. "Primary production" in Sect. 1 refers to production in a chemical sense, whereas "primary producers" in Sect. 2 refers to organisms themselves. Section 4 categorized papers based on study duration (Online Resource 2). Section 5 (the methodologies associated with each indicator type) and its subsections were created using a preliminary assessment of common methodologies from monitoring programs described in Ehrman et al. (2022) and including other categories as relevant. Section 6 was developed to categorize papers between coastal and offshore sampling. Studies were designated as coastal nearshore, coastal offshore, far offshore, or offshore tender based on the type and size of vessel, if one was used, or based on water depth at the location where the data were collected if a vessel was not used (e.g., for moorings) (Table 1). If water depth was not provided, it was estimated from the International Bathymetric Chart of the Arctic Ocean (IBCAO). Some papers could not be categorized by these definitions ( $n=22$ ); this was due to either insufficient data provided by the paper, or the use of only satellites in the methods (i.e., satellite data were categorized by scale, not coastal versus offshore location).



**Fig. 2** PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram

### Data analysis

Data were analyzed using descriptive statistics and correlational tests. Descriptive statistics were computed using Excel (2016) to provide a base understanding of the data

and identify any readily visible outliers and potential issues during coding (e.g., incorrect or abnormal entries). Correlational tests were performed in R 4.1.2; two-proportion Z-tests and Fisher's exact test (depending on sample size) were used to assess the relationships between different

**Table 1** Location categories of where the studies took place and their definitions

Category	Definition
Coastal nearshore	Studies done onshore, from shore-launched boats or at a depth of less than 20 m
Coastal offshore	Studies done from coastal vessels of less than 80' or at depths of 21–100 m
Far offshore	Studies done from large oceangoing vessels over 80' long or at depths of over 100 m
Coastal nearshore ice	Studies performed through the ice at depths of less than 20 m
Coastal offshore ice	Studies performed through the ice at depths between 21 and 100 m
Far offshore ice	Studies performed through the ice at depths greater than 100 m
Offshore tender	Studies that utilize a small vessel launched from an offshore ship to access shallower waters (e.g., ships' boats or RHIBs)

categories of data (e.g., determining if methods differed significantly between coastal and offshore studies).

A heatmap was created to demonstrate the number of papers across the marine areas and communities in the western Canadian Arctic (Fig. 1). This was done in QGIS 3.14, using data taken from the Canadian Geographical Names Database (CGNDB). The marine areas studied in the papers were recorded during coding and the appropriate KML file for each area was downloaded from the CGNDB and then converted into a QGIS shapefile. The different map polygons denoting marine areas were color-coded according to the number of studies performed in those locations. Studies that took place at specific communities, islands, or other terrestrial locations are denoted with dots, which follow the same colour-code.

## Results

### Descriptive statistics

Publication year ranged from 1963 to 2021; 83% of papers were published in 2010 or later. Fifteen countries were represented based on lead author affiliations, with over half of all papers affiliated with Canadian institutions. Academic institutions (based on first author affiliation) represented 64% of the sample, government institutions represented 25%, and various other institution types (e.g., non-governmental organizations, various non-profits, private companies) represented the rest. The spatial scope (the geographic breadth of the study area) of papers was most commonly restricted to an area within the western Canadian Arctic and classified as “Regional” (60%). The remainder of the papers were either classified as “Arctic,” which had study areas that included the western Canadian Arctic but also extended into the eastern Canadian Arctic or non-Canadian Arctic (27%), or “Local,” which were small-scale studies only concerning a single location or one or several communities (13%).

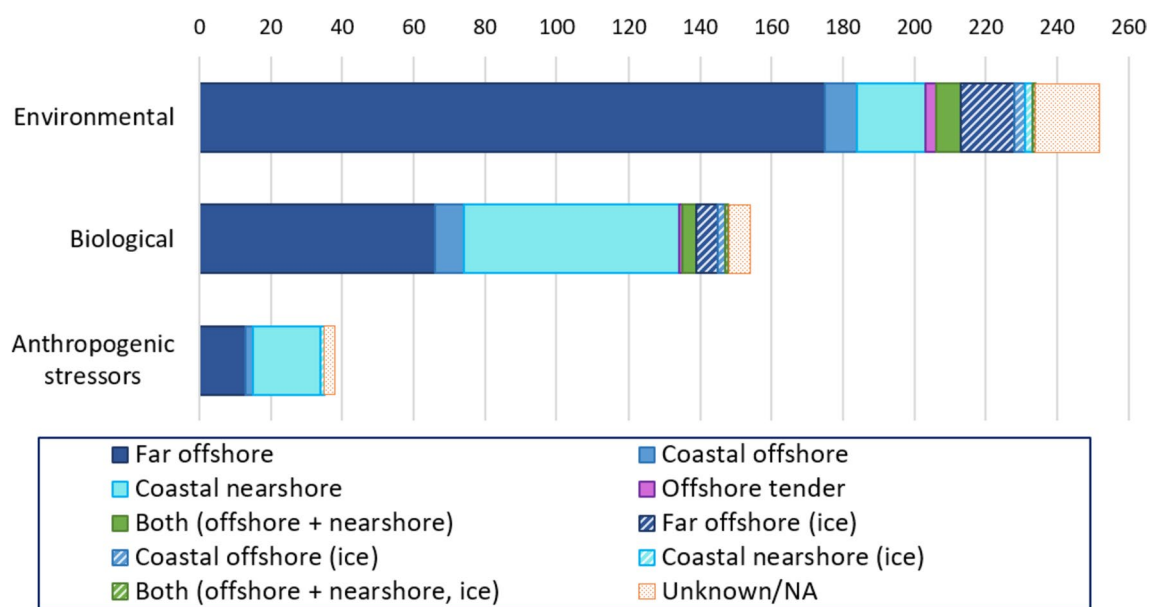
There were 59 marine and terrestrial (i.e., for studies of marine indicators at terrestrial locations) areas studied at

least once in our dataset. The most commonly studied area in the western Canadian Arctic was the Beaufort Sea, followed by the Amundsen Gulf and Canada Basin (Fig. 1). The Mackenzie Delta and Yukon Coastal Plain were both also heavily studied. Fewer papers were focused on more northern areas of the archipelago, where most studies took place in the Parry Channel (particularly the M'Clure and Barrow straits) and Resolute Passage. Many studies took place in multiple areas, e.g., Kirk et al. (2008) took samples from many locations, including Queen Maud Gulf and Peel Sound (Fig. 1). Areas without data in Fig. 1 (i.e., those in blue) demonstrate that many parts of the northern archipelago have had no published research. Non-marine study areas such as coastal communities (e.g., Waugh et al. 2018) and marine bird breeding grounds (e.g., Mallory et al. 2018) were included to encompass community-based Indigenous knowledge studies as well as biological indicators such as seabirds that are frequently studied in their terrestrial habitat.

### Indicators and methods

#### Indicators

In total, 86% of papers collected data on indicators that provided environmental context, 46% collected data on indicators of biological and food web integrity, and 12% collected data on indicators of anthropogenic stressors and threats (Fig. 3). A total of 35% of papers included more than one category of indicator, the most common combination being environmental and biological indicators. Over half of all papers (63%) measured various oceanographic parameters; of these, salinity, temperature, and nutrients were most common (Fig. 4). Of the oceanographic parameters included in the “other” category, total alkalinity ( $n = 19$ ) and inorganic carbon ( $n = 15$ ) were most commonly included, though these were still less common than all other core oceanographic parameters (Fig. 4). Papers that measured coastal change were extremely rare (2%) (Fig. 4a). Papers relating to sea ice and snow were more common, comprising 30% of included papers (Fig. 4). Sea ice parameters in the



**Fig. 3** Counts of papers grouped by inclusions of indicator categories (i.e., physical and chemical environmental context, biological and food web integrity, and anthropogenic stressors and threats)

“other” category included ice motion and various physical and chemical parameters (e.g., temperature, salinity, nutrient concentrations), among others. Seafloor data were recorded in 12 papers (4%). Of those, one focused on bathymetry (Paull et al. 2015) and the remaining 11 collected data on benthic habitats and sediments. Primary producers were the most frequently studied indicator within papers that focused on biological and food web integrity, followed by marine mammals and then anadromous fishes (Fig. 5). No papers covering invasive or colonizing species were present in our sample. The most common types of anthropogenic stressor represented in our sample were contaminants, especially methylmercury, followed by anthropogenic noise (Fig. 6).

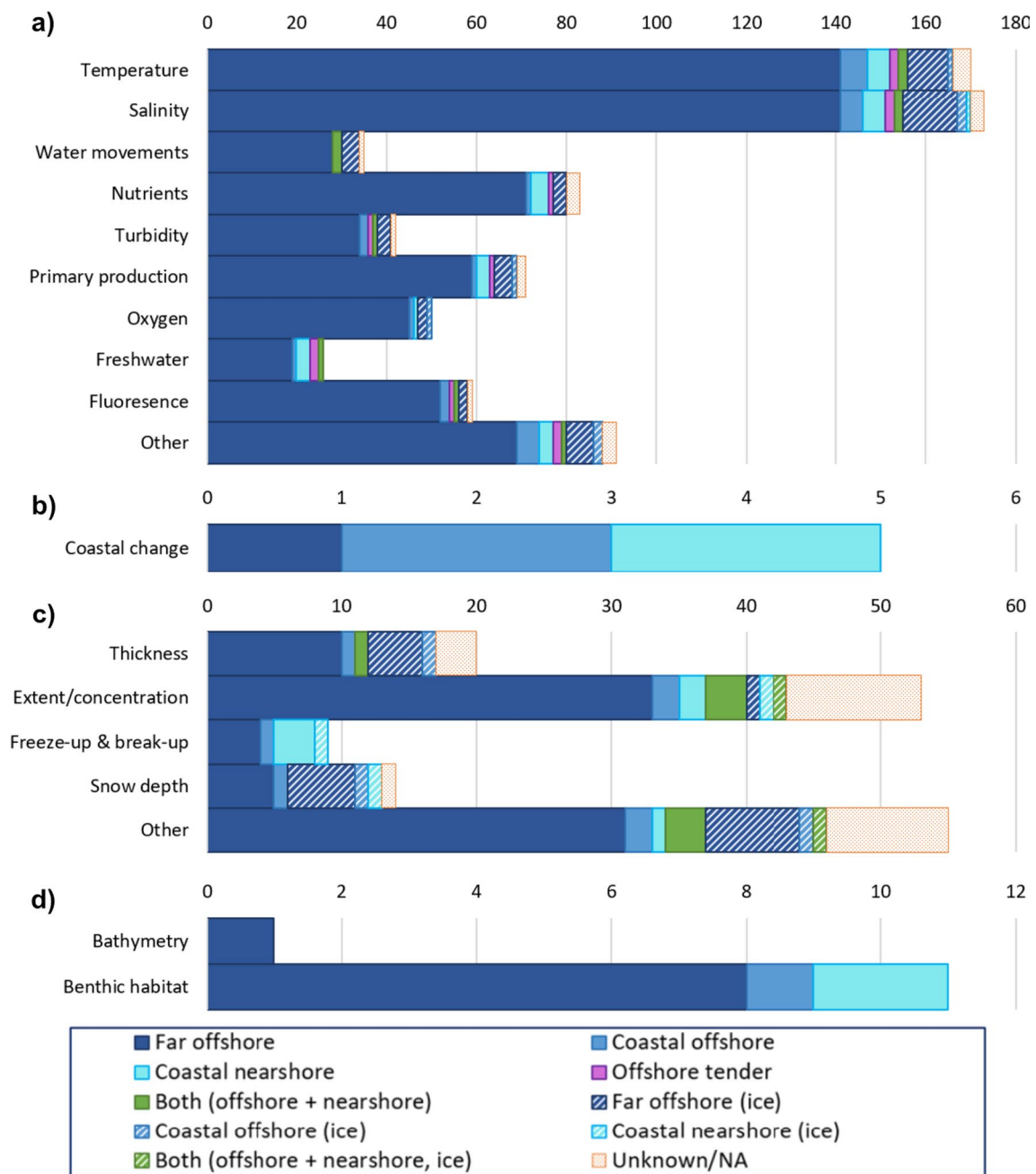
Across location categories, far offshore studies were highly associated with environmental indicators (92% of far offshore studies), coastal offshore studies were associated with both environmental and biological indicators (75% and 58% of coastal offshore studies, respectively), and coastal nearshore studies were most frequently associated with biological indicators (86% of coastal nearshore studies) (Fig. 3). Studies that occurred in both offshore and coastal locations were most frequently concerned with environmental indicators (78% of studies in both coastal and offshore locations) (Fig. 3). For studies that occurred at ice camps, all included data collection for environmental indicators. Studies at ice camps were also associated with biological indicators (40% of far offshore studies, 67% of coastal offshore studies) and anthropogenic indicators (50% of coastal nearshore studies), but these associations were from very small sample sizes (far offshore:  $n = 15$ ; coastal offshore:  $n = 3$ ; coastal

nearshore:  $n = 2$ ) (Fig. 3). Only two studies located at ice camps occurred in both coastal and offshore locations, and these were concerned with environmental and biological indicators, respectively.

## Methods

Rosette casts, typically equipped with conductivity-temperature-depth (CTD) sensors and other instruments, were the most commonly used method in papers that researched physical and chemical indicators, followed by satellite data and moorings. For research focusing on biological indicators, collections from tissue sampling or water sampling were most common followed by collections through several types of netting (i.e., trawling, gill netting, seine netting, and plankton MultiNets). Other common methods for collecting biological data included harvest records and acoustic recordings. The specific parameters studied across biological indicators varied widely but the most commonly measured were basic biological and morphological measurements (e.g., mass, length, age, maturity, sex), diversity and community structure, and abundances or count data of organisms (Fig. 7). Most anthropogenic data were collected from tissue samples (46%) and water samples (30%).

Across location categories, far offshore studies ( $n = 144$ ) and studies using offshore tender ( $n = 3$ ) were most commonly associated with CTD profiling and rosette casts, whereas coastal nearshore studies were most frequently associated with various types of biological collections



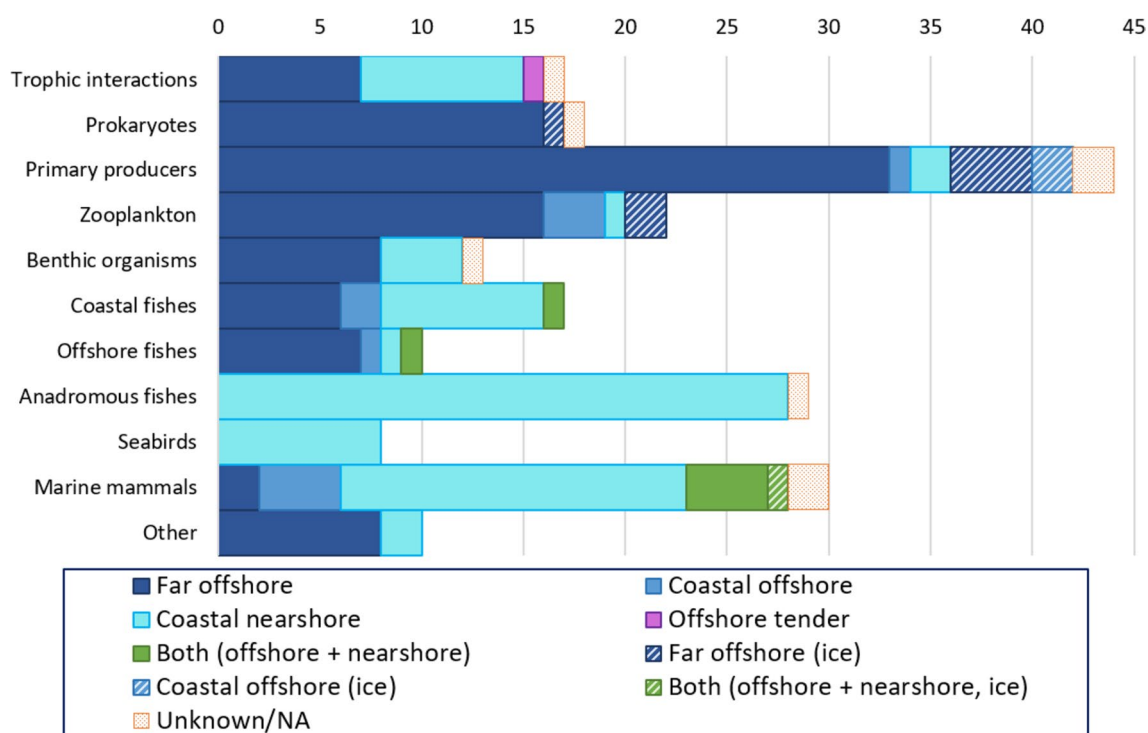
**Fig. 4** Total count of all papers that include indicators that provide environmental context: **A** Core oceanography ( $n=203$ ), **B** Coastal change ( $n=5$ ), **C** Sea ice and snow ( $n=97$ ), **D** Bathymetry ( $n=12$ ).

These are separated by measurement parameter, where applicable, and are grouped by coastal/offshore sampling location categories

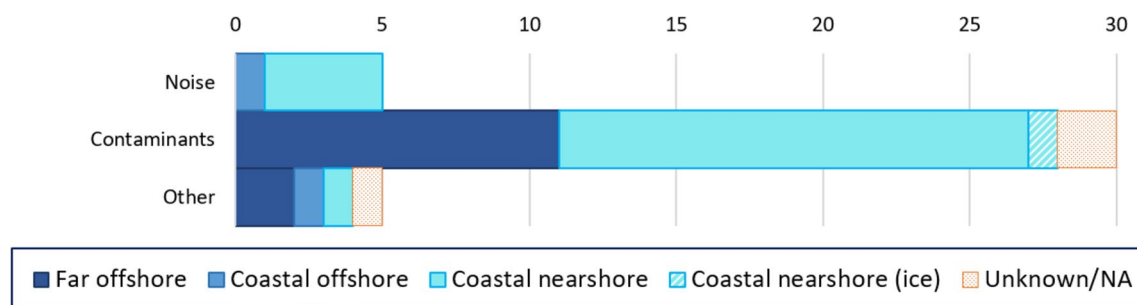
( $n=42$ ) (Fig. 8). Studies that occurred at far offshore ice camps used methods for measuring physical and chemical indicators categorized as “other” most frequently ( $n=12$ ) (Fig. 8); often these were ice corers (e.g., Campbell et al. 2018). All other location categories (Table 1) did not show any strong associations with particular methods.

### Study duration

A broad range of study durations were observed across papers in the sample. Studies that lasted from two to five years were most common (17%), whereas studies lasting between six months and one year were least common (8%) (Fig. 9). Abundances of all other duration categories were



**Fig. 5** Total count of all papers that include indicators of biological and food web integrity ( $n=148$ ), grouped by coastal offshore sampling location categories



**Fig. 6** Total count of all papers that include indicators of anthropogenic stressors and threats ( $n=37$ ), grouped by coastal offshore sampling location categories

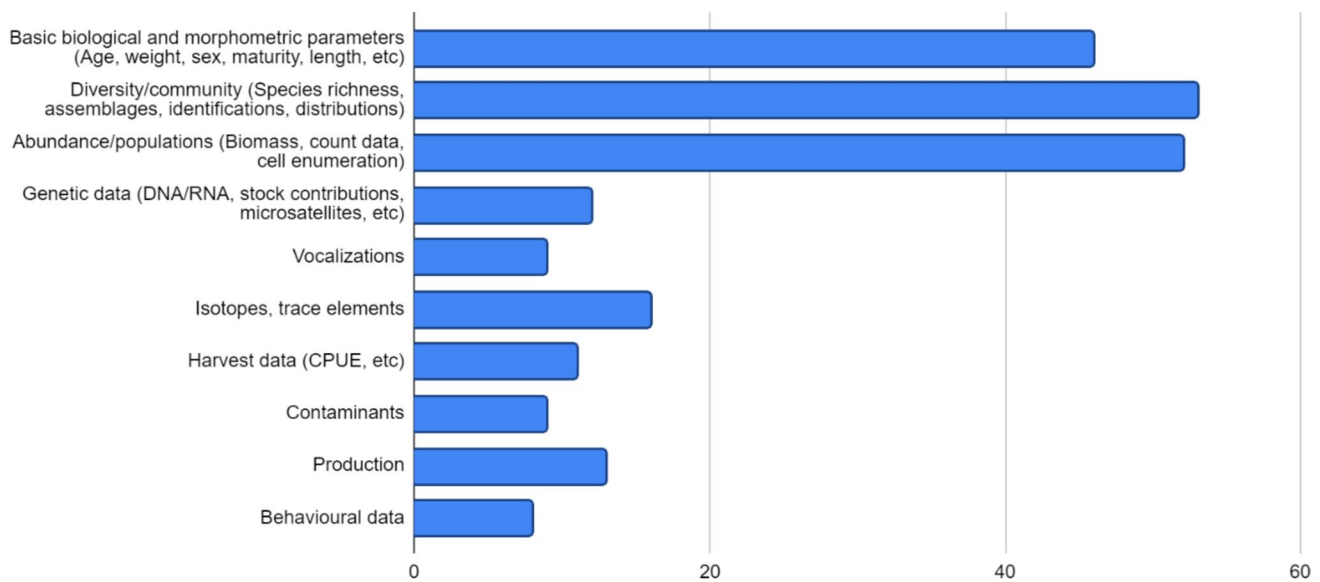
within 1% of one another (Fig. 9). All indicator categories had studies lasting from less than or equal to a month, up to  $\geq 10$  years, with two exceptions (Table 2). Studies focusing on coastal change ( $n=5$ ) never lasted less than two years, whereas studies focusing on the seafloor (i.e., bathymetry and bottom sediment) only included duration categories longer than one month but shorter than 10 years (Table 2). Papers including physical and chemical indicators ( $n=245$ ) were most commonly studied for a duration of one to six months, whereas papers including biological indicators ( $n=148$ ) and anthropogenic indicators ( $n=37$ ) were most commonly studied for durations between two and five years (Table 2). Nineteen papers were unable to

be categorized based on study duration, primarily due to insufficient information (e.g., Alkire et al. 2010; Finke et al. 2017) or a complete lack of sampling duration provided in the paper or supplementary files (e.g., Smethie et al. 2000; Lemes et al. 2011).

## Coastal and offshore links

### Indicators

The majority of indicators were associated with both coastal and offshore studies, though studies located far offshore were most common in our sample (64%). Studies of bathymetry



**Fig. 7** Frequencies of basic biological parameters in studies using biological indicators

and prokaryotes occurred exclusively offshore (Figs. 4, 5). Studies of anadromous fishes and seabirds occurred exclusively in coastal areas (Fig. 5).

Significant differences in indicator prevalence were observed among the location categories (Figs. 4, 5, 6). Indicators that were studied significantly more in papers focusing on far offshore locations included all oceanographic parameters (including the two most common parameters in the “other” category, i.e., total alkalinity and inorganic carbon) ( $p < 0.0001$ ), ice thickness ( $p = 0.0003$ ), ice extent and concentration ( $p < 0.0001$ ), other ice-related parameters ( $p < 0.0001$ ), benthic habitat ( $p = 0.0041$ ), prokaryotes ( $p < 0.0001$ ), primary producers ( $p < 0.0001$ ), zooplankton ( $p < 0.0001$ ), and offshore fishes ( $p = 0.0035$ ). Papers that focused on coastal locations included marine mammals ( $p < 0.0001$ ) and contaminants ( $p = 0.0001$ ) as indicators significantly more than papers focusing on other location categories. All other differences were not significant.

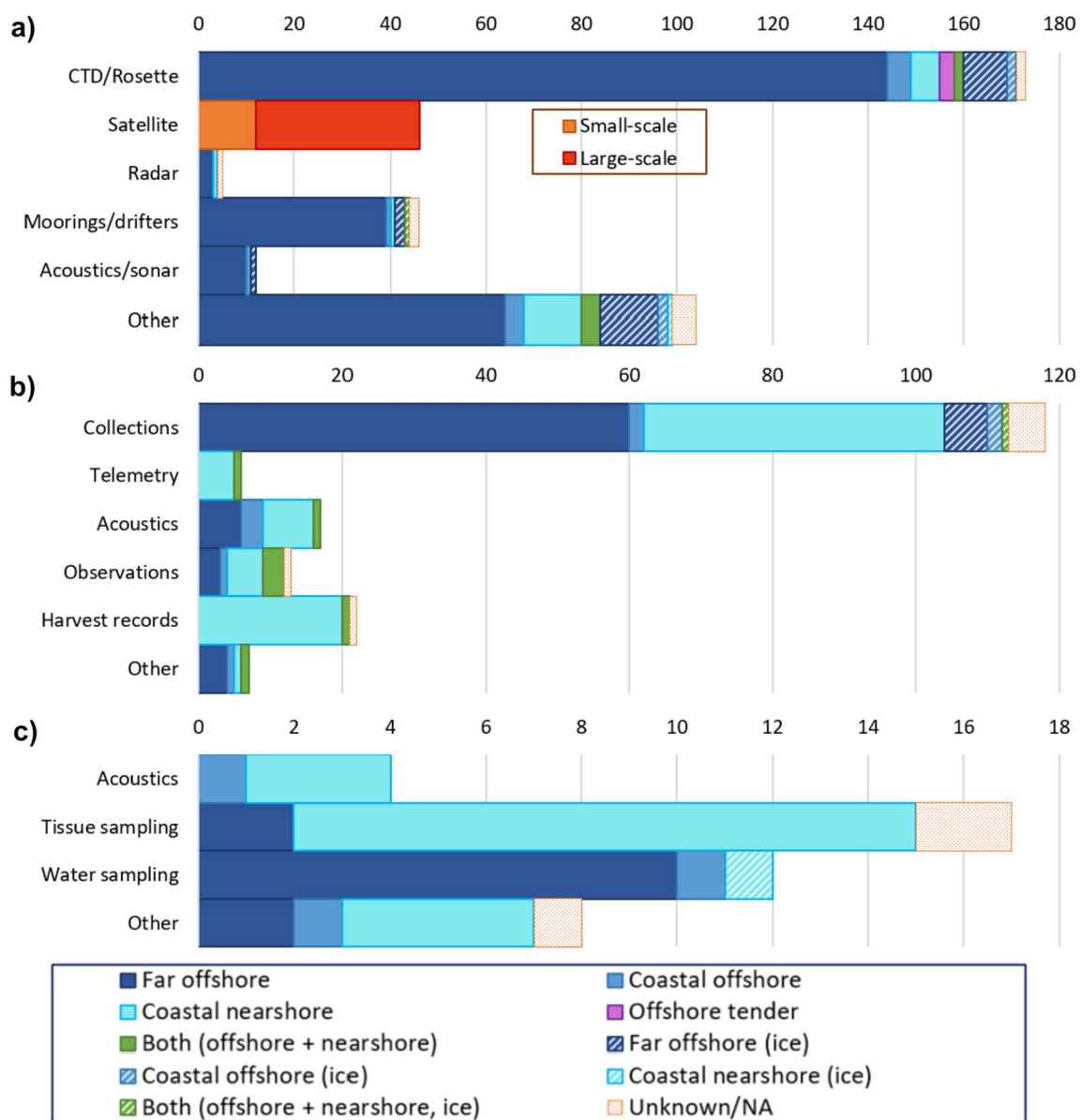
## Methods

Significant methodology differences were observed between coastal and offshore studies (Fig. 8). Far offshore studies included significantly more CTD and rosette sampling ( $p < 0.0001$ ), moorings and drifters ( $p < 0.0001$ ), acoustics and sonar ( $p < 0.0001$ ), other physical and chemical sampling methods ( $p < 0.0001$ ), biological collections ( $p < 0.0001$ ), and water sampling for anthropogenic indicators ( $p < 0.0001$ ). Coastal studies included significantly more harvest records ( $p < 0.0001$ ) and tissue sampling for anthropogenic indicators ( $p = 0.0006$ ). All other differences in method use between location categories were not significant.

Only eight papers collected data in both offshore and coastal locations, with only one of these describing methodological differences between locations (i.e., Doxaran et al. (2012) used CTD casts to sample offshore stations, but not the stations designated “river transects”).

## Discussion

This review aimed to provide a thorough description of research and monitoring in the western Canadian Arctic, with a particular focus on documenting the methods used to study important indicators and highlighting methodological linkages between coastal and offshore study areas. A total of 321 peer-reviewed articles and reports were included in the final sample. Studies focusing on far offshore areas represented 64% of the sample, whereas studies focusing on coastal offshore and coastal nearshore areas represented 6% and 23%, respectively. Parameters used to assess the core oceanography indicator were the most commonly measured ( $n = 203$ ), followed by those to assess biological indicators ( $n = 148$ ), and parameters related to the sea ice and snow indicator ( $n = 97$ ). Over half of all papers had study locations in the Beaufort Sea, Canada Basin, or Amundsen Gulf, which indicates both the accessibility and the importance of these marine regions, and corresponds to the extensive far offshore research programs in these areas (e.g., CASES, BREA-MFP, CBS-MEA) (Fig. 1). This may also indicate that these areas are more readily accessible to research vessels when compared to areas further east, which can have longer durations of ice cover (Niemi et al. 2019) and are further from the



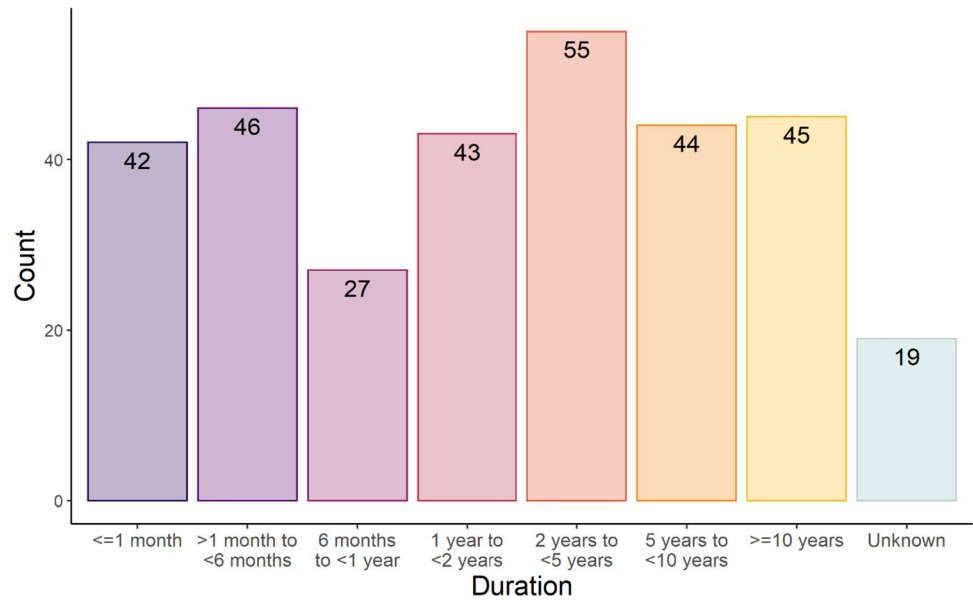
**Fig. 8** Count of papers grouped by the use of various data collection methods in **A** papers focusing on physical and chemical indicators ( $n=243$ ), **B** papers focusing on biological indicators ( $n=148$ ), and

**C** papers focusing on anthropogenic indicators ( $n=37$ ). Satellite use is categorized as large scale (regional or pan-Arctic) or small scale (local)

Arctic ports. Other systematic reviews discussing methods and indicators have focused on temperature effects of green infrastructure (Koc et al. 2018), sustainability (Visentin et al. 2020), and ecosystem services (Czúcz et al. 2018), among others. However, systematic reviews specifically focusing on documenting the methods of all research and monitoring programs in a given area, particularly in fields related to ecology, are not present in the literature. Thus, this review is necessary to highlight commonalities in indicators and methods in marine research, which can facilitate linking research and monitoring efforts across coastal to offshore ecosystems.

### Methods and indicators in western Canadian Arctic research

Large differences were observed in the research frequency of various indicators. By far, the most frequently researched indicators were those related to the physical and chemical environment, likely due to the importance of environmental conditions in influencing all levels of the marine ecosystem (Ehrman et al. 2022). This ubiquity may also highlight a relative ease of consistent or repeated measurement (e.g., underway or multiple-site water sampling onboard research vessels, Barber et al. 2010; continuous satellite data of ice

**Fig. 9** Study duration of all papers included in the sample ( $n = 321$ )**Table 2** Distribution of study durations by indicator type. Many papers included multiple indicator types; thus, these numbers do not indicate the total paper inclusions

Indicator type	≤ 1 month	> 1 to < 6 months	6 months to < 1 year	1 to < 2 years	2 to < 5 years	5 to < 10 years	≥ 10 years
Environmental	38	41	23	31	37	35	29
Biological	16	23	11	24	27	17	22
Anthropogenic stressors	3	7	2	2	8	5	2

conditions, Parkinson et al. 1999). Marine mammals were also frequently studied, likely because of their importance as a subsistence resource and cultural touchstone in northern communities (Lockhart et al. 2005) and also their role as marine sentinel species that serve as indicators for ecosystem health (Bossart 2011). Indeed, multiple monitoring programs focus on marine mammals and highlight their importance as subsistence species and indicators of change (e.g., the Beluga Health Research and Monitoring Program, Harwood et al. 2015; the Fish and Marine Mammal Community Monitoring Program, Ostertag et al. 2018).

Though a broad range of methodologies was documented in the sample, some commonalities were apparent. For instance, across all location categories, oceanographic parameters such as temperature, salinity, and nutrient concentrations were often measured by rosette water samplers equipped with CTD instruments and, in many cases, the same brand of instruments (i.e., Niskin bottles and “Seabird SBE” CTD instruments). In addition, satellite data collected by organizations such as the National Snow and Ice Data Center (NSIDC) are readily accessible and may contribute to the frequency of satellite imagery as a method in our sample (e.g., Parkinson et al. 1999; Agnew et al. 2008; Ma

et al. 2017). These commonalities allow for more accurate comparison of results across different studies and can aid in developing a more complete understanding of the Arctic’s coastal and marine ecosystems. For this reason, standardized or semi-standardized sampling methods should be a consideration in all future research and monitoring programs. However, not all methods are suitable across all locations; for example, satellite imagery may not be available at a suitable resolution to support small-scale analyses (Gully et al. 2022), and location-specific physical features may complicate satellite analyses (Mustapha et al. 2012).

Differences in methodologies across coastal and offshore location categories highlight potential difficulties with linking research in these ecosystems. The disproportionate use of certain methods far offshore, e.g., CTD profiles and rosette casts, is likely linked to the repeated use of these methods when associated with offshore ships (Barber et al. 2010; Toole et al. 2010). The vast majority of CTD profiles are conducted using Seabird SBE profilers, highlighting a relative standardization across offshore ship-based studies. Moorings and drifters were used almost exclusively offshore, due to the association of these tools with either ice sheets (e.g., Krishfield et al. 2008) or the open ocean

(e.g., Kemp et al. 2005). In addition, many oceanographic moorings are located far offshore to avoid being damaged or destroyed by sea ice. The singular example in our sample with moorings deployed in coastal waters was focused on a soundscape used by beluga whales (*Delphinapterus leucas*), where acoustic recorders were fixed to moorings deployed only during summer months (Halliday et al. 2020). While moorings are extremely useful for continuous, consistent monitoring of diverse data, as they can be equipped with various measuring instruments and samplers and are often deployed for long periods, their use in nearshore areas is limited by the presence of potentially damaging sea ice. This may preclude the long-term use of moorings for monitoring in coastal areas, limiting this as a potential avenue for data collection and connection across coastal and offshore ecosystems. The near-exclusive use of harvest records and surveys in coastal nearshore locations is directly related to the high association of these methods with coastal Arctic communities, and their ubiquity in association with subsistence harvesting and traditional knowledge (Lockhart et al. 2005; Kruse 2011). Tissue sampling for anthropogenic stressors was likely more associated with coastal studies for these same reasons, i.e., these tissue samples are often taken from harvested animals, in collaboration with community partners (Lockhart et al. 2005; Verreault et al. 2005). Differences outlined above may illustrate potential difficulties associated with linking coastal and offshore work, particularly in terms of shared methodologies.

While differences in methodology as outlined above highlight possible barriers to developing linkages between coastal and offshore research and monitoring, the results of this systematic review may also offer opportunities to link coastal and offshore work using existing data. As an example, acoustic monitoring for vocalizations of marine mammals already shows some level of standardization across coastal nearshore (Halliday et al. 2019, 2020) and coastal offshore (Halliday et al. 2017; Heimrich et al. 2021) locations, with these studies utilizing “Wildlife Acoustics” model SM2M and model SM3M instruments to collect vocalization data. Continued use of these methods will facilitate ongoing collection of comparable data across coastal and offshore ecosystems; discussions of how to collect comparable data in far offshore locations (e.g., from offshore moorings as in Lockhart et al. (2016) or from a large offshore vessel during stationary periods as in Whitt et al. (2023)) could use these existing studies as reference. Few other opportunities for connecting existing methodologies were identified here; as such, this review hopes to prompt discussions of ways to standardize certain data collections (e.g., standardized trawls and grabs for benthic invertebrates) across coastal and offshore research.

Only a small percentage of papers were categorized as occurring in both the nearshore and the offshore, providing

a minimal sample to discuss existing linkages. Most of these papers described no methodological differences between coastal and offshore areas. In some cases, these methodological similarities were due to one method being used across a broad study area (e.g., the use of aerial surveys by Stirling et al. (2008)), while others used the same methods in study areas delineated between coastal and offshore by the authors (e.g., Reimnitz et al. (1993) used different vessels to access coastal and offshore areas, but the same methods). These similarities in methods demonstrate a precedent for connecting coastal and offshore domains in terms of research and monitoring. However, filling data gaps will likely be necessary. For example, the huge proportion of far offshore CTD profiles in comparison with nearshore areas could indicate a need for similar sampling in coastal areas, as was done in Galindo et al. (2016). Use of CTD profiles from rosette samplers may be limited in coastal sampling, as the deployment systems of rosettes are often too large and cumbersome for smaller shore-based vessels. However, similar measurements using standardized profiling instruments and water collections could be conducted from coastal vessels with more size-appropriate collection methods (e.g., buckets, handheld probes) that would allow for comparison across coastal and offshore research despite the differences in methodology. Initiating conversations between coastal and offshore researchers is vital to determining how best to facilitate linkages in research and develop a more holistic understanding of the Arctic marine ecosystem. Because of linkages between coastal and offshore ecosystems (Eriksson et al. 2011), and the use of both coastal and offshore waters by many species (e.g., Dolly Varden, *Salvelinus malma*; Courtney et al. 2018), connecting research and monitoring in these domains are necessary to better understand and predict changes in the vulnerable Canadian Arctic.

## Gaps and future research

This systematic review allows us to identify gaps in geographic coverage for research and monitoring efforts in the western Canadian Arctic (Fig. 1), as well as gaps in the assessment of key indicators. For instance, all seabird data in our sample were located in the eastern region of the western Canadian Arctic. There are reviews summarizing the status of seabirds in the Beaufort Sea area (Dickson and Gilchrist 2002) and in several migratory bird sanctuaries in the Northwest Territories (Latour et al. 2008). Our criteria excluded reviews and we did not search the Environment and Canada Climate Change (ECCC) library, however, possibly contributing to the lack of Beaufort-focused seabird studies in our sample. Similarly, studies addressing invasive species were entirely absent from our sample. While this may highlight an issue related to terminology, as “invasive species” was not included as a search term (we expected

that papers including colonizing or invasive species would be caught by the other biological indicator search terms) and potentially colonizing species may not necessarily be described as “invasive” (e.g., Pacific salmon, *Oncorhynchus* spp., Dunmall et al. 2013), it is also possible that this represents a knowledge gap. This is an important area for future study as a reduction of sea ice due to climate change is predicted to increase Arctic shipping traffic and will bring an increased risk of ship-mediated invasive species (Miller and Ruiz 2014; Goldsmit et al 2018). A solution for these discrepancies in future reviews would be to conduct a back-check of the literature (i.e., assessing the sample of publications for gaps in key research areas) to ensure that our sample is representative and that our search criteria did not miss or exclude publications on certain topics. This would allow for a better assessment of the literature and would highlight where search methods could be improved in future reviews. Though benthic habitat was identified as an important indicator in Ehrman et al. (2022), it was poorly represented in our sample. This, combined with a lack of basic biological data relating to Arctic benthic organisms (Renaud et al. 2019) and the environmental factors governing their distribution (Roy et al. 2014), precludes understanding of how benthic habitats and benthic organisms may respond to future change, and thus represents an important knowledge gap. Further research on anthropogenic stressors in the western Canadian Arctic is required; papers focusing on this type of indicator were minimal in our sample (12%), and those were mostly contaminant studies that focused on organisms most immediately important to humans (anadromous fishes and marine mammals). Few studies focusing on anthropogenic noise in the western Canadian Arctic were identified in the literature, despite increasing vessel traffic associated with decreasing sea ice (Dawson et al. 2018), highlighting a need for further research to assess impacts on the culturally, economically, and ecologically important marine mammals in this region (McWhinnie et al. 2018). Expanding contaminant studies to include other types of biological indicators as well as being responsive to newly identified anthropogenic stressors (e.g., offshore and nearshore industry) and incorporating them into research and monitoring (Ehrman et al. 2022) will better allow us to predict how all parts of the ecosystem are being affected by human activity.

Long-term monitoring is necessary to assess change in the Arctic marine environment, where climate change is impacting all levels of the ecosystem (Wassman et al. 2011). Almost half of all studies in our sample lasted for less than two years; while useful in providing information on how conditions change depending on time of year, or how conditions change from year to year, these studies provide little information on how climate change affects conditions in Arctic marine ecosystems over a longer term. Almost all indicators identified in this review were included in at

least one study lasting over five years, however, indicating that long-term monitoring is being implemented across all levels of the Arctic marine ecosystem. Long-term research was especially prevalent in studies focusing on sea ice concentration, anadromous fishes, and marine mammals, likely due to long-running satellite databases and harvest monitoring programs (Harwood et al. 2014; Gallagher et al. 2020; Peng et al. 2020). Further efforts at long-term monitoring in the western Canadian Arctic should be made to increase our understanding of baseline Arctic processes and to identify changes associated with ongoing anthropogenic warming. However, the logistics of long-term monitoring are complicated in the Canadian Arctic, with cost and access both heavily impacted by harsh environmental conditions and inaccessibility associated with sea ice and remoteness (Henson 2014). In addition, while data gaps as presented in this review may highlight opportunities to conduct further research and connect ecosystems, filling these gaps may be logistically infeasible or unnecessary. For example, moorings are rarely used in coastal locations due to potential damage from sea ice, whereas harvest records are almost exclusive to coastal nearshore studies by their nature, and thus the lack of this method in offshore studies does not represent a gap that needs filling. Due to the inherent variability of Arctic ecosystems (Niemi et al. 2019), certain baselines may be especially difficult or even impractical to ultimately create. Additionally, while it would be ideal to fill all data gaps identified in this review and focus monitoring efforts on each of these indicators, this is not always possible. More realistic is to identify the rightsholder priorities, stakeholder interests, and community needs, and focus research on those areas. This review emphasizes all levels of the ecosystem with the understanding that studying them consistently is not always feasible; instead, all of these indicators should at least be considered when designing monitoring programs, and efforts can be made to investigate indicators that are proxies for multiple different parameters (e.g., snow thickness also relates to seal habitat and under-ice PAR and production; Ehrman et al. 2022). In addition to climate change, other variables that may be derived from both anthropogenic and/or natural sources (e.g., noise, ocean acidification) must be considered. This issue is particularly acute in the Arctic as access to and passage through the Arctic increases and as increasing carbon dioxide contributes to further ocean acidification in the Arctic, both of which are contributing to the cumulative effects of change with relatively unknown broader implications (Insley et al. 2017; Niemi et al. 2021).

The results of this review could be used to identify the existing data and gather those data into long-term or wide-spanning datasets concerning Canadian Arctic marine ecosystems. This compilation of data would align well with the concept of Essential Variables, which are variables broadly agreed to be sufficient and necessary for ongoing global

monitoring of biodiversity and climate (Pereira et al. 2013; Miloslavich et al. 2018). Many of the indicators identified by Ehrman et al. (2022) and investigated in this review overlap with Essential Ocean Variables and Essential Biodiversity Variables (Muller-Karger et al. 2018), suggesting an opportunity to use this review and the Essential Variable concept in tandem to highlight the areas of important future research and monitoring. The Essential Ocean Variables are very similar to the parameters that make up the core oceanography indicator as well as several biological indicators (e.g., phytoplankton, marine mammals) identified by Ehrman et al. (2022), doubly highlighting the importance of these indicators for the understanding and management of marine ecosystems. Essential Variables are monitored across methods of measurement (e.g., IOCCP 2017), which would allow research connections even where methods have historically been different or where other factors (e.g., the sampling environment) necessitate unequal methods.

Integrating information across indicators will help with assessing climate change-related stressors (e.g., increased vessel traffic and industry in newly accessible areas, competition, and exclusion resulting from northward range expansions; ACIA 2004), which will be important given the rapid rate of change in the Arctic (IPCC 2013; Arctic Council 2016). Integrating across indicators will also help to assess other stressors and drivers of Arctic change as well (e.g., linking zooplankton and oceanographic data to assess ocean acidification; Niemi et al. 2021). Indeed, the need to connect among research and monitoring efforts, integrate among species and knowledge systems, and link coastal to offshore ecosystems is apparent in order to understand the effects of these changes on ecosystem stability and to predict future change. The synthesis provided here highlights the commonalities in the use of indicators and methods and opportunities to further link ship-based offshore to shore-based coastal programs, thus contributing a fundamental layer to inform existing monitoring plans and future programs and facilitate improved coordination moving forward.

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**Data availability** The data underlying this article are available in the article and in its online supplementary material.

## Declarations

**Conflict of interest** The authors have declared that no competing interests exist.

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