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RESEARCH ARTICLE

Fuzzy cognitive mapping as a tool to assess the relative cumulative effects of environmental stressors on an Arctic seabird population to identify conservation action and research priorities

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Abstract

1. In the Arctic, chemical contaminants, shipping, oil pollution, plastic pollution, changing habitats in relation to climate change and fisheries have been identified as environmental stressors to seabirds such as *Fulmarus glacialis* (northern fulmar; qaqulluk; ᖃᖅᑯᓪᓗᒃ), but rarely have these stressors been considered within a cumulative effects framework in this species which is currently showing a declining populations trend.
2. As a novel tool to understand cumulative effects within a conservation context, we applied a fuzzy cognitive mapping (FCM) approach that allows experts to arrange key factors and their interrelationships, organizing their understanding of the components of a complex issue into a graphical representation; a 'cognitive map'.
3. This process was grounded in local environment concerns as documented in several Nunavut-specific reports and discussions, and worked with western-trained seabird experts with knowledge of northern fulmar populations to assess the inter-related environmental threats to fulmars as a way to combine these stressors in a cumulative effects framework and identify conservation actions and knowledge gaps.
4. We found strong agreement that the main stressors affecting northern fulmar populations in Canada include pollution (11% total influence (TI)), shipping activities (16% TI), hunting and fishing (18% TI) and mining/oil and gas exploitation activities (22% TI).
5. The indirect influence of threats on northern fulmar population size (57% TI) exceeded the total direct influence (43% TI), emphasizing the value of cognitive

mapping in cumulative effects assessment for a more holistic understanding of interacting stressors.
6. Participants expressed substantial uncertainty regarding the strong relationships leading from the concepts, commercial fishing activity in the BBDS and the North Atlantic fisheries activity, indicating that these potential stressors require more research.
7. Similarly, uncertainty was expressed about the potential effects of zodiac traffic, ship strikes of northern fulmar, number of oil spills and magnitude of oil spills on northern fulmar.
8. By characterizing individual factors as manageable or not, we determined that stressors are largely manageable with enforcement of existing policies (58% TI)—importantly, fishing activities were both highly influential on fulmars and deemed manageable, which will inform ongoing co-management planning in the region.

KEYWORDS
Arctic, best professional judgement, expert opinion, fuzzy cognitive mapping, seabirds, wildlife management

1 | INTRODUCTION

The early 21st century is not a great time for birds: The size of many avian populations is in decline, with notable losses of an estimated three billion birds in North America during the past five decades (Kim et al., 2021; Rosenberg et al., 2019). This pattern has been well established for many of the seabird species (Paleczny et al., 2015), which are among the most threatened of all bird groups (Dias et al., 2019). Specifically, Croxall et al. (2012) reviewed many of the causes for seabird declines, which are numerous and diverse, and identified that key threats include negative interactions with fisheries, pollution, introduction of invasive species, climate change, habitat loss and disturbance from humans.

Environmental change in its myriad forms, usually anthropogenically driven, is a key factor influencing seabird population change. In the Arctic, environmental changes are happening rapidly. The Arctic has long been known as a sink for pollution from long-range sources, which yield deleterious, sublethal effects on breeding seabirds (e.g. Dietz et al., 2019; Tartu et al., 2014). The Arctic region is also warming at a rate double that of the rest of the planet (Cohen et al., 2014), resulting in potential fisheries expanding concomitant with reduced sea-ice cover (Tai et al., 2019), and in many parts of the Arctic, increasing shipping traffic (Pizzolato et al., 2014). Collectively, the marine environment that supports Arctic seabirds is changing, and doing so physically (Stroeve et al., 2007), chemically (McPhee et al., 2009) and biologically (Tremblay et al., 2011). In turn, these changes may be influencing the range of seabird species, with observations of the 'Atlantification' of formerly Arctic areas (e.g. northward shift of prey and seabird species; Vihtakari et al., 2018), including in the eastern Canadian Arctic (Gaston & Woo, 2008). Indeed, while much of the evidence of climate change on Arctic seabirds has been shown in Svalbard colonies where changes are pronounced (e.g. Grémillet et al., 2015), the vast colonies in Nunavut (Arctic Canada) are also at risk (Mallory et al., 2019).

In the circumpolar Arctic, one of the many seabird bioindicators is the northern fulmar (*Fulmarus glacialis*; Figure 1) (Mallory et al., 2006; Mallory & Braune, 2012; Mallory, Hatch, et al., 2020). It is a medium-sized petrel that is distributed from boreal waters to the high Arctic, breeds in cliff colonies of up to tens of thousands of birds, forages at the ocean's surface on a diverse array of prey and may travel >500 km from its breeding colony to find those prey (reviewed in Mallory, Dey, et al., 2020). Fulmars are particularly suitable as biomonitors for an Arctic environmental assessment because they are influenced by many anthropogenic stressors in the marine environment, and generally respond more to these stressors than most sympatric seabirds (e.g. Ellis et al., 2013). In particular, they are exposed to considerable chemical contamination in their diet (Braune et al., 2016, 2019; Provencher et al., 2020), are highly susceptible to ingesting plastic debris in the ocean (van Franeker et al., 2021) and are vulnerable to negative interactions with fisheries (e.g. Bærum et al., 2019; Colston-Nepali et al., 2020; Figure 1). While fulmars are relatively well studied in the Canadian Arctic as compared to some species, most studies to date have been undertaken in thematic silos; there is relatively no work to date that examines the environmental stressors in fulmars in relation to each other.

In the Baffin Bay–Davis Strait (BBDS) marine region lying between Greenland and Nunavut (Canada), there are two major seabird colonies (Akpait and Qaqulluit National Wildlife Areas) that are co-managed by Environment and Climate Change Canada (ECCC) and the community of Qikiqtarjuaq (Mallory et al., 2022). These colonies

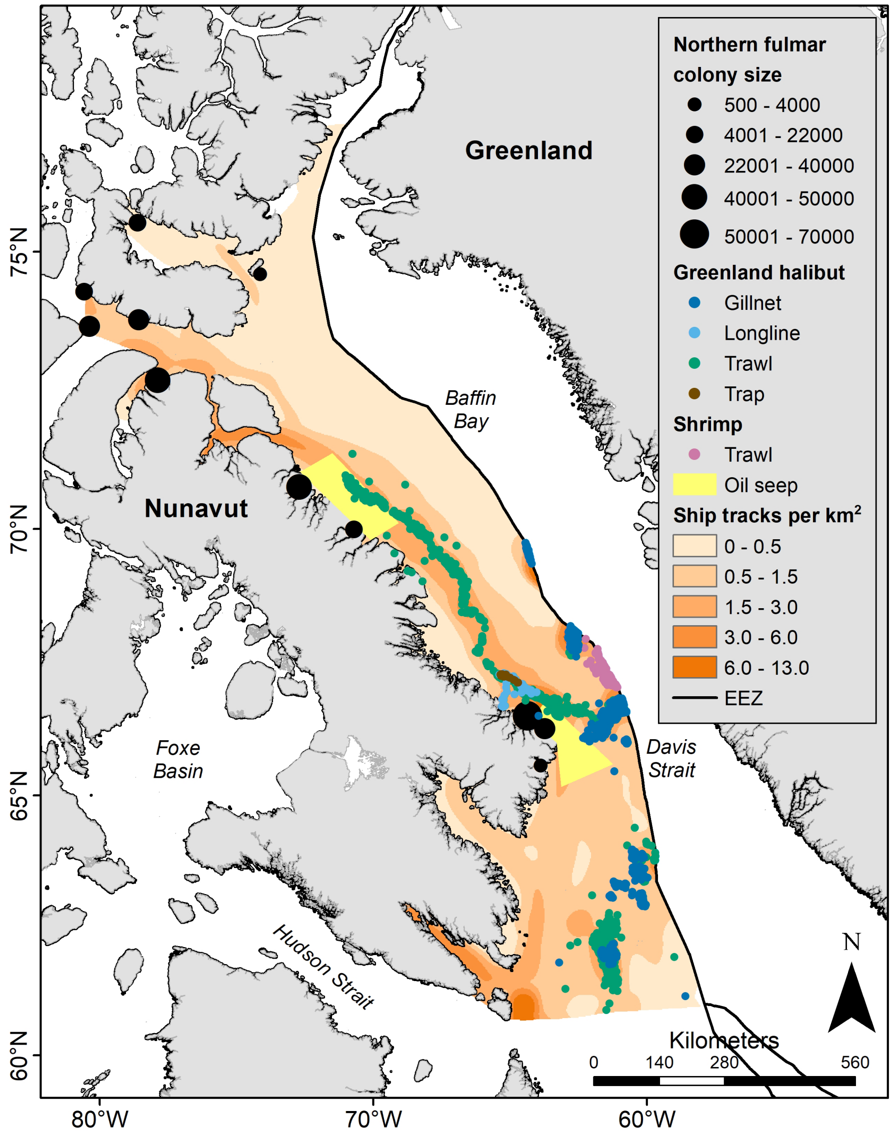

FIGURE 1 Multiple stressors in the Baffin Bay–Davis Strait (BBDS) region (to the Canadian Exclusive Economic Zone), including oil and gas seeps, shipping traffic density and fishing in relation to the northern fulmar colonies in the region. Seabird location and size data are from ECCC-CWS colony database, fisheries data are unpublished data from DFO and shipping data are based on AIS that tracks vessels globally. Base map used was from https://gadm.org/. The Economic Exclusion Zone (EEZ) border is shown dividing the BBDS region, and is from Flanders Marine Institute (2014). Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 8. Available online at https://www.marineregions.org/ and https://doi.org/10.14284/386.

are home to several species of seabirds, including northern fulmars (Figure 1). The Sululiit Area Co-Management Committee (ACMC) is co-chaired by ECCC and a community member from Qikiqtarjuaq, and is tasked with the management of the seabirds in the Akpait and Qaqulluit National Wildlife Areas (Mallory et al., 2022). In collaboration with both the Sululiit ACMC and the Nattivak Hunter and Trapper Organization (HTO) in Qikiqtarjuaq, there has been work focusing on migratory birds and stressors in the region (e.g. Hamilton et al., 2021; Mallory et al., 2004). In Nunavut, there are several groups that co-manage wildlife, set priorities for migratory bird research and support research on these topics. This includes the Canadian Wildlife Service (CWS), the Nunavut Wildlife Management Board and the Northern Contaminants Program. Fisheries, pollution, habitat degradation and wildlife disturbance have all been highlighted as stressors in the BBDS region (Figure 1), where more knowledge is needed on the interactions and indirect effects of these stressors to understand their impacts on migratory birds and other species. While studies have addressed a range of environmental stressors in the region, ongoing discussions with both the Nattivak HTO and the Sululiit ACMC have emphasized the need to assess these different stressors in the region in relation to each other to better inform management discussions.

The management of migratory birds can present jurisdictional, logistic and often cultural challenges (e.g. variation in international legal protection, costs of monitoring, hunting versus conservation; Elmberg et al., 2006; Johnson et al., 2018). Notably, while seabirds have been managed by Indigenous Peoples around the world since time immemorial, and co-management is now legally enshrined in some regions (e.g. Mallory et al., 2022), there is a lack of Indigenous perspectives in seabird management and research studies to date (Alexander, Provencher, Henri, Taylor, Lloren, et al., 2019), although there are some excellent recent contributions to this field (Henri et al., 2020; Henri, Martinez-Levasseur, et al., 2020). For migratory species, and especially those in remote regions, scientists increasingly recognize that typical wildlife monitoring programmes, such as aerial or ground surveys, are often impractical to acquire sufficient data on population status, trends or threats. Thus, alternative methods of information should be incorporated in management, such as local ecological knowledge (Gilchrist et al., 2005), citizen science (Tulloch et al., 2013) and expert opinion (Drescher et al., 2013). In particular, expert opinion can be a powerful tool both to develop and to validate wildlife–habitat models (e.g. Hurley et al., 2009; Swihart et al., 2020). Such an approach is also important considering the many different stressors that seabirds are exposed to, and the likelihood of interactive effects. Consideration of indirect pathways of effect and interactions among stressors is typically lacking in the literature reporting empirical data on seabird populations, including northern fulmar. Additionally, because cumulative effects can be antagonistic, additive or synergistic, a more holistic view of the threats can inform how a variety of management actions may influence populations. Seabird populations must be managed in this context, and there is a need to take a more cumulative effects approach to better understand complex ecological systems that are affected by multiple stressors. Moreover, because the diverse threats to seabirds are varied, an understanding of how these threats can be managed and reduced is critical to seabird conservation. Only through a cumulative effects framework can we conceive of the ramifications of candidate conservation actions.

Fuzzy cognitive mapping (FCM) is a form of modelling that allows experts to arrange key factors and their interrelationships, organizing their understanding of the components of a complex issue into a graphical representation of the system that we call a *cognitive map* (sensu Kosko, 1986). The cognitive maps apply standardized regression coefficients to the relationships among factors that allow us to compute the outcome of the maps, making them semiquantitative. This is analogous to path analysis or structural equation modelling, except that the standardized regression coefficients are assigned to each bivariate relationship by the experts, based on their expert opinion rather than based on covariance among measured variables (reviewed in Papageorgiou & Kontogianni, 2012). The main benefits of the FCM approach that make it valuable in conservation biology are that it: (1) enables us to incorporate latent and composite variables, providing we clearly define them (Özesmi & Özesmi, 2004); (2) allows us to model relationships, including indirect relationships, for which there are scarce data and quantifiable uncertainty (Hobbs et al., 2002); (3) permits us to compare and combine knowledge derived from different types of experts or different ways of knowing (Bosma et al., 2017); and (4) allows us to investigate different management scenarios or policy options in complex systems (e.g. Pluchinotta et al., 2019). Given the many environmental threats that fulmars are exposed to, and the lack of cumulative effects' assessments on fulmars, FCM was identified by our group as a useful tool to understand the interactive stressors. In particular, it would allow us to interrogate indirect relationships, tracing the capability of management actions to influence fulmar population size and warning of potential unintended outcomes (Larrosa et al., 2016; Wootton, 1994). This is particularly important when managing multiple threats as action on one threat may lead to changes in a related threat, which could have unintended consequences for the wildlife population of concern.

As part of a larger project focusing on fulmar conservation, we used the FCM approach to develop a model of the main factors influencing the size of the northern fulmar population in the BBDS region of Canada. We used this process of formalizing expert opinion with FCM to identify areas of scientific debate or research gaps that could advance our management and monitoring goals in the BBDS. Based on conversations with partners, we defined our main objectives as: (1) to investigate the relative individual importance and potential cumulative effects of key threats to northern fulmar; and to (2) to assess to what extent the population size is subject to management based on the proportion of driving factors deemed manageable, weighted by their relative importance. To inform the future management of northern fulmar in the region, we also sought (3) to identify any useful indicators that could predict impending change to the northern fulmar population size and (4) identify areas of certainty and uncertainty in relation to environmental threats to help prioritize areas for conservation concern in the BBDS.

2 | MATERIALS AND METHODS

2.1 | Origin of this project

The project reported on here is nested within the larger research programme aimed at the conservation of northern fulmars in Canada within the co-management structure of Nunavut, Canada (see Mallory et al., 2022). Specifically, the Sululiit Area Co-Management Committee (ACMC) has directed ECCC personnel to adopt a cumulative effects perspective in the region when assessing seabird populations, and encouraged the approach reported on here (Sululiit ACMC Meetings, Qikiqtarjuaq, Nunavut, March 2020 and 2021).

With the onset of the global pandemic in 2020, the ACMC decided to delay their involvement until the FCM workshops could be held in person. Meanwhile, partners encouraged us to undertake this approach with the western trained scientists to 'do our homework' in preparation for future activities and learn from the process. Within this context, we report here on a process that was specifically designed for western-trained scientists to take part and share their knowledge in an entirely online set of workshops. For context, a parallel process is being undertaken with Indigenous Knowledge holders (the Sululiit ACMC) that is co-designed with the ACMC to reflect how they would like to structure their workshops and sharing sessions that fit their needs. Recent work reporting on FCM with Inuit partners demonstrates how these processes can be community specific (Dubos et al., 2023). A future paper will report on this parallel process in the future. This separate, but parallel process, as supported by the Sululiit ACMC, aims to respectfully carry out work on fulmar conservation that is directed by partners. This effort recognizes that the respectful weaving of knowledge systems requires a process that is specifically designed and implemented with Indigenous partners at all stages of the research, a critical aspect of respecting and valuing Indigenous partner values, knowledge and resources (Baker, 2021; Beausoleil et al., 2022; Brunet et al., 2020; Wong et al., 2020).

2.2 | Origin of concepts

To ensure that our efforts complemented the ongoing co-management of seabird colonies in the Akpait and Qaqulluit National Wildlife Areas, we used several ongoing efforts and recent Nunavut-specific reports that include Inuit Knowledge as the focal lens for the work. This includes a recent environmental assessment undertaken in the BBDS region by the Nunavut Impact Review Board, Crown Indigenous Relations and Northern Affairs Canada, the Government of Nunavut and the Qikiqtani Inuit Association. To ground the work in regional concerns, we derived our preliminary list of key concepts (threats, stressors and response variables pertinent to northern fulmar populations in the BBDS) from the draft Sululiit ACMC management plan (in prep) and the Strategic Environmental Assessment's Indigenous Knowledge study (Klein, 2018; QIA, 2019). The Indigenous Knowledge study process and report highlighted key threats from fisheries, pollution and shipping identified by the 10 communities in the environmental assessment region (Klein, 2018). In further discussions with the members of the Qikiqtarjuaq community (one of the 10 communities), they highlighted plastic pollution and oil-related contaminants as priorities.

We then adapted the core concepts from the above documents and meetings to meet certain criteria necessary for application in an FCM and drafted definitions for each (Supplementary Information 1). After incorporating feedback from the expert participants, our glossary included 58 concepts. For organizational purposes, we grouped the concepts under seven themes, though some factors crossed themes. Themes included: (1) hunting and fishing, (2) research, (3) shipping, (4) mining, oil and gas exploitation, (5) pollution, (6) climate change and (7) interactions with other species.

2.3 | Selection of experts

As the first component of this process, we invited all members of the Environment and Climate Change Canada Seabird Technical Committee (Canadian) and the CAFF CBird group (pan-Arctic) with expertise in research, monitoring or management of northern fulmar populations breeding in the BBDS to participate in an FCM workshop. All of the original nine invitations were accepted, with all participants based in Canada; experience ranged from 1 to 21 years working on seabird populations in Arctic Canada. All experts involved in this project belong to one or both of the above organizations and are co-authors of this paper. As part of the invitation (Supplementary Information 2), we provided each participant with a glossary of key concepts and their definitions. As a part of the planning for this process and in dialogue with the Sululiit ACMC, the next component of this process will be to conduct a similar FCM workshop with local Indigenous experts (ACMC members) in locally based workshops. The FCMs based on scientific expertise and those based on local expertise will be used to facilitate dialogue among partners to seek key areas of commonality, and identify knowledge gaps that can lead to future collaborative work in the region.

2.4 | Expert workshop

Prior to the workshop, each participant reviewed the glossary (Supplementary Information 1) and provided feedback. This ensured that when participants begin creating their individual FCMs, each was working from a common set of candidate factors and with a common and thorough understanding of their meaning (recommended by Hobbs et al., 2002). Each participant was provided with: (1) an instructional manual on how to build their fuzzy cognitive map in yEd graph editor (yEd_Graph_Editor, 2020); (2) an instructional video on the steps covered in the manual; and (3) a graphml file with the key concepts they would use to build their individual fuzzy cognitive maps (yEd_Graph_Editor, 2020). Our objective was to remove technological barriers to participation, which we anticipated could prove a challenge because COVID-19 precluded meeting in person.

We hosted a virtual workshop in November 2020 (Supplementary Information 3). During this, we gave an overview of the objectives, a presentation to review northern fulmar ecology in the region and an overview of the application of FCMs in conservation biology. We then described the process of FCM development, illustrated the application of the yEd graph editor (yEd_Graph_Editor, 2020) and addressed any questions that arose. For 3 days following the workshop, participants worked individually from the graphml file template to: (1) select the concepts from the vetted list that they considered crucial to northern fulmar populations in the BBDS region; (2) connect the selected concepts to illustrate causal relationships among them that lead back to the keystone concept of northern fulmar population size; and (3) assign both the strength and uncertainty scores to each relationship.

To understand the relative impact on fulmars of the different environmental stressors, we defined *strength* as a standardized regression coefficient that quantifies how much of an influence one concept has on another according to an arbitrary scale of −10 to 10. A negative strength value meant that an increase in the magnitude of the first term would cause a decrease in the magnitude of the second term (i.e. they are inversely related). Conversely, a positive value indicated that they were directly proportional, and an increase in the first term would cause an increase in the second term. These relationships could be non-linear, as long as they were monotonic. The *uncertainty* attribute qualified how confident we were in the strength we assigned to the relationship on a scale of 1–10, with 1 being extremely confident and 10 being entirely speculative. It is important to note that these results are based on subjective estimates on an arbitrary scale, rather than actual empirically measured impacts on fulmar population. We met again to address any questions from participants and to assess whether changes to the glossary were needed (i.e. addition, deletion or revision of concepts).

This process led to several revisions to our glossary (Supplementary Information 4).

To assess how manageable the fulmar populations are within current policy frameworks, participants submitted their individual fuzzy cognitive maps and categorized whether or not each concept was manageable. We defined manageability as any concept at least partially sensitive to changes in legislation, policy, regulation or best management practices under national or regional jurisdiction (i.e. Canada or Provincial or Territorial) that are currently in place (i.e. the policy tools already exist and need to be implemented, enforced, enacted etc.). Importantly, political will was not considered a factor—we defined manageability within the existing policy space, not the will to enact the policies. Manageability considered jurisdiction, temporal and spatial scales of consideration and the existence of effective policy, regulation or technology that would allow the prevention of impact. This excluded off-setting that would be applied after an impact, which is sometimes called 'mitigation'. We asked experts to '*consider whether the threat can be prevented or its impact reduced via prevention. Is it technically feasible, does Canada have jurisdiction, is the threat operating at a spatial scale that is aligned with Canada's jurisdiction, is the threat operating over a temporal scale where time lags won't prevent any management action from having a measurable effect within the next 5–10 years*'.

After the individual FCMs were submitted, we met virtually again to discuss any discrepancies in expert participant manageability ($n=2$), and to present the consensus FCM (see below). Participants were given the opportunity to revise their manageability categorizations after the group discussion, with these revised categorizations of concepts used in final analyses.

2.5 | Statistical analysis of adjacency matrices

We averaged the nine individual FCMs to generate a consensus FCM using the FCMmapper package (Dikopoulou & Papageorgiou, 2017) in R (RCoreTeam, 2020). Specifically, we converted each individual FCM to an uncertainty and strength matrix. Then, we rescaled values in each uncertainty and strength matrix to range between 0 and 1 and built a consensus matrix for each by finding the mean across the nine individual maps. Thus, we had two consensus maps: one for strength and one for uncertainty.

We used the concept.indices function in FCMmapper to estimate the concept-level indices for our strength consensus map. These indices (reviewed in Özesmi & Özesmi, 2004) included (1) whether a concept was a transmitter, receiver or ordinary (concepts not connected to at least one other concept by a relationship were excluded from consideration); and (2) the in-degree, out-degree and centrality of a concept. Concepts that are transmitters only originate relationship arrows, whereas receivers only have relationship arrows directed towards them. Ordinary concepts have both incoming and outgoing relationship arrows. Concepts with high in-degree have a large sum of relationship strengths for incoming arrows and may be integrative indicators of the system state, whereas high out-degree concepts have a large sum of relationship strengths as arrows originating from them exert disproportionate influence on the system state. Centrality is the sum of in-degree and out-degree. These indices can highlight candidate indicator concepts (objective 3), as well as reflect the relative importance of concepts and their themes (objective 1).

We used our expert-derived classification of concepts as manageable or not to quantify the fraction of total influence (TI) of all concepts on northern fulmar that was deemed sensitive to management actions (objective 2). Where experts disagreed on manageability of a concept, we took the majority decision, which was 6/9 or more in agreement in all cases ($n=58$ concepts). Those manageable concepts with high total influence were identified as those that could enable best management practices, policy or legislative change to influence northern fulmar in the BBDS. We calculated the total fraction of threats considered manageable by summing the total influence of all manageable concepts on northern fulmar and dividing this by the sum of total influences on northern fulmar for all concepts incorporated into the consensus FCM. More details on the statistical computation can be found in Supporting Information.

Last, we used the uncertainty matrix to identify knowledge gaps (objective 4). We considered relationships with mean uncertainty values <3 as low uncertainty, values 3–7 as moderate uncertainty and >7 as high uncertainty. Relationships combining high absolute value strength with high uncertainty, we considered in need of additional research. We also examined the degree of ubiquity among concepts from the nine individual FCMs to elucidate any areas of disagreement or inconsistency among our expert participants. Concepts present in fewer than 4/9 FCMs or more than 6/9 FCMs were considered to be viewed consistently among experts, but concepts with ubiquity between four and six were also identified as candidates for additional study.

2.6 | Visualizations

The full consensus map was interrogated for analyses (found in Supplemental Information 6) but was difficult to interpret visually. To filter the concepts and relationships to focus the final map on the strongest relationships and the concepts most influencing the population size of northern fulmar, we first eliminated the positive strength relationships that fell below the top 10 percent of average strength values. Second, we eliminated the negative strength relationships that fell below the bottom 10% of average strength values. In other words, we retained only the 10% strongest relationships, both positive and negative. We then imported all concepts that were linked by these strongest relationships. Finally, we confirmed that this focus on relationships did not exclude any concepts with important indirect influence on northern fulmar population size by checking that the resulting map included all concepts within the upper 25% of total influence scores. Importantly, quantitative analyses were carried out on the full dataset and this simplified dataset was used to help visualize the most important concepts and relationships.

We symbolized the arrows to represent the average strength, direction and uncertainty assigned by the participants to each relationship. We then sized each concept's symbol to represent its total influence (direct + indirect) on northern fulmar population size. We coloured the concept symbols to highlight the influence of (1) different themes, (2) the level of ubiquity among concepts and (3) their manageability. In each version of the simplified consensus map, we modified the symbol for northern fulmar population size to be a pie chart depicting the percent of total influence on northern fulmar population size exerted by concepts categorized these three ways.

All analyses were carried out on the full consensus map (Supplementary Information 5), but to facilitate visual interpretation of the consensus map, we created a simplified map including only 40 concepts and 60 relationships (i.e. edges) linking them. Because some of these 40 key concepts were connected by relatively weak relationships (<10% strength value), this left them 'floating' and disconnected from the simplified map. We rectified this by adding back the strongest relationship connecting any floating concepts back to the simplified map, yielding a simplified map for the purposes of visualization with 67 relationships (Figures 3–5).

3 | RESULTS

3.1 | Consensus map

The individual FCMs generated by the nine participants (Supplementary Information 5) exhibited a high level of agreement. For example, 41% of the 59 concepts were either included in all nine FCMs ($n = 20$, including the northern fulmar population size), or included in none of the nine FCMs ($n = 4$), resulting in a consensus map (Supplementary Information 6) with a high level of ubiquity (56% of the 59 concepts were in seven or more of the nine FCMs). This consensus map included 55 concepts connected by 330 relationships, with an average six connections per concept.

Most concepts had both inward and outward pointing relationships ($n = 49$ ordinary concepts). Only three concepts were receivers (only receiving arrows directed towards them), including the *Northern Fulmar population size*, and five were transmitters (only originate relationship arrows with no concept included here influencing them). The in-degree, out-degree and centrality of all concepts included in the consensus map are presented in Supplementary Information 7. Unsurprisingly, the concept with the top in-degree value (most arrows pointing toward it) was the *Northern Fulmar population size* (57.83). This was followed by *Larger vessel traffic* (21.55),

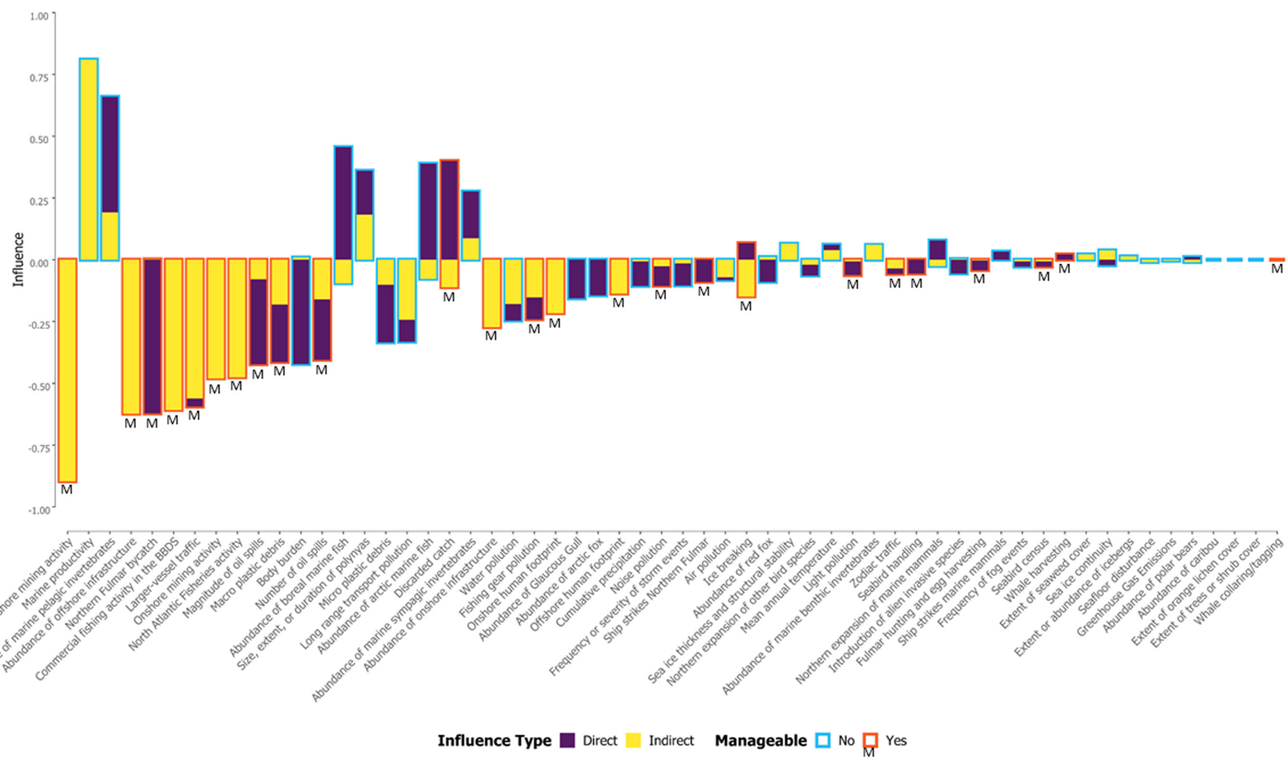

FIGURE 2 Total influence of all concepts mapped by experts in northern fulmar populations in the BBDS region, ordered from most to least influential. Positive influence values indicate the concept is positively correlated with northern fulmar population size, whereas negative influence values indicate that the concept is negatively correlated with northern fulmar population size. Influence bars are split to indicate the total direct (purple) and indirect (yellow) influence of each concept on the northern fulmar population size. Bars highlighted by teal outlines were deemed by experts to be manageable concepts, whereas bars outlined in navy blue are considered not manageable. Manageability was defined for this exercise as concepts that it was technically feasible to influence that operated at spatial scale under the jurisdiction of Canada and where measurable effects would result from management actions within 5–10 years.

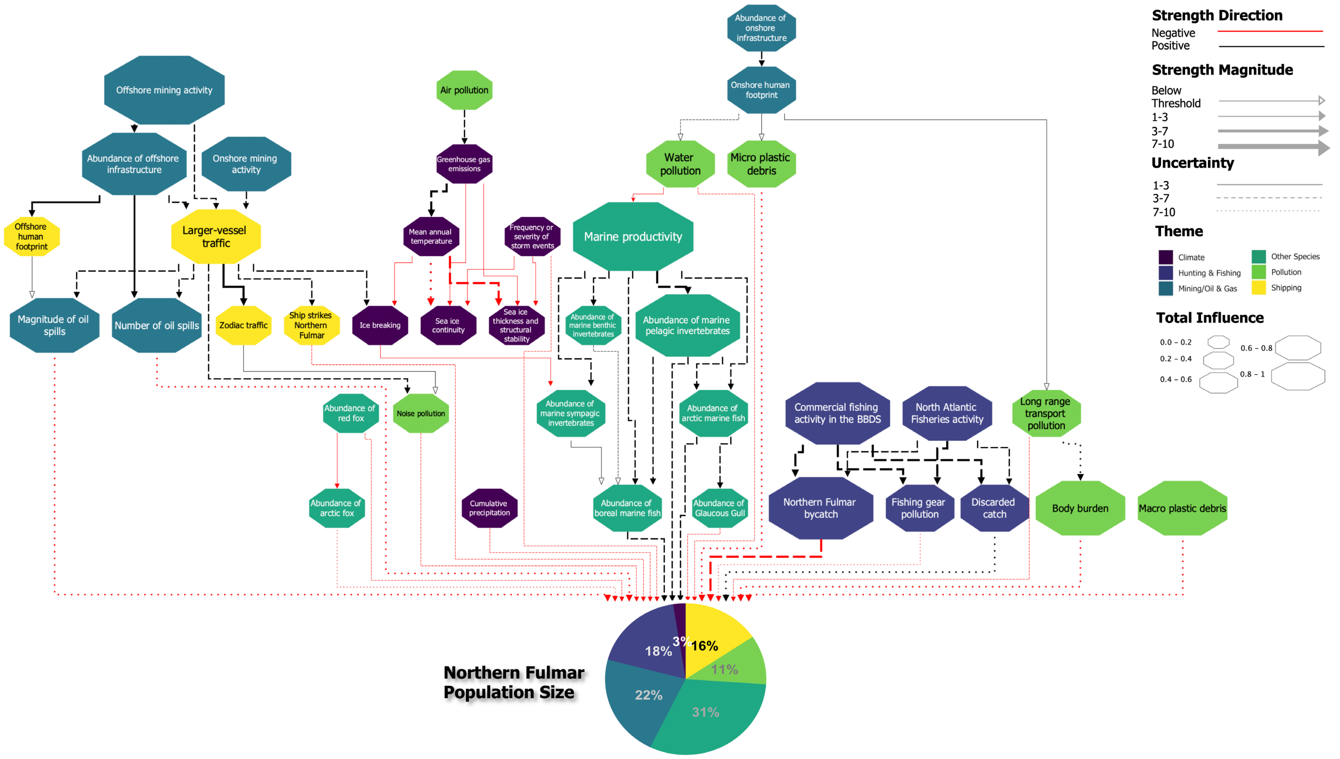

FIGURE 3 Simplified consensus map emphasizing the total influence of concepts on northern fulmar population size, grouped by theme. The size of the concept represents the strength of its total influence on northern fulmar population size and the relative influence by theme is expressed in the pie chart symbolizing the concept of northern fulmar population size. Arrows are coloured by whether the originating concept exerts a negative or positive influence on the receiving concept. The width of the arrows indicates the average strength of that influence and the arrow solidity indicates the average level of certainty that individuals ascribed to that relationship.

Light pollution (16.66) and the *Abundance of Arctic marine fish* (16.66). Concepts with the highest out-degree (most arrows originating from them) included *Larger vessel traffic* (33.66), *Commercial fishing activity in the BBDS* (27.89), *Offshore mining activity* (23.89), *North Atlantic fisheries activity* (21.11), the *Abundance of offshore infrastructure* (20.55) and *Onshore mining activity* (16.67), reflecting shipping, hunting/fishing and mining/oil and gas exploitation themes. *Mean annual temperature* (25.45) and *Sea ice continuity* (13.22) were also among the top 10 out-degree concepts, reflecting the potential influence of climate change (Supplementary Information 7).

3.2 | Total influence on northern fulmar population size

Our focus was on better understanding the drivers of *Northern Fulmar population size* in the BBDS. The absolute value of total influence (direct + indirect) of the mapped concepts on northern fulmar population size exhibited a skewed distribution (Figure 2). The top 10 concepts comprise 49.5% of the total influence and the top 21 concepts comprise 79.8% of total influence on northern fulmar population size. These values varied from the extreme negative weight of −0.896 (constituting 7.2% of absolute total influence on northern fulmar population size) for the offshore mining activity concept to the extreme positive weight of +0.810 (constituting 6.5% of absolute total influence on northern fulmar population size) for the marine productivity concept. Yet, most concepts ($n = 37$) exerted a negative influence on northern fulmar, amounting to 72.7% of the total influence on northern fulmar population size (Supplementary Information 7). Relatively few ($n = 17$) concepts exerted a net positive influence on northern fulmar population size, amounting to 27.3% of the total influence. Moreover, the majority of concepts exerted indirect influence on northern fulmar population size ($n = 48$ concepts, cumulatively accounting for 56.7% of total influence), rather than direct ($n = 39$ concepts, cumulatively accounting for 43.3% of total influence), and several of the most influential concepts exerted exclusively indirect influence on northern fulmar population size (Figure 2).

3.3 | Themes

The pie chart representing the concept of northern fulmar population size in the simplified consensus map depicts the relative influence of each theme (Figure 3). The single theme most influential on *Northern fulmar population size* was 'other species,' with 31% of TI grouped under this theme. This influence was due mainly to *Marine productivity*, which supports the base of the northern fulmar's food web. The theme of 'mining, oil and gas' exerted the second greatest TI on northern fulmar population size (22% TI), mainly through the influence of *Offshore*

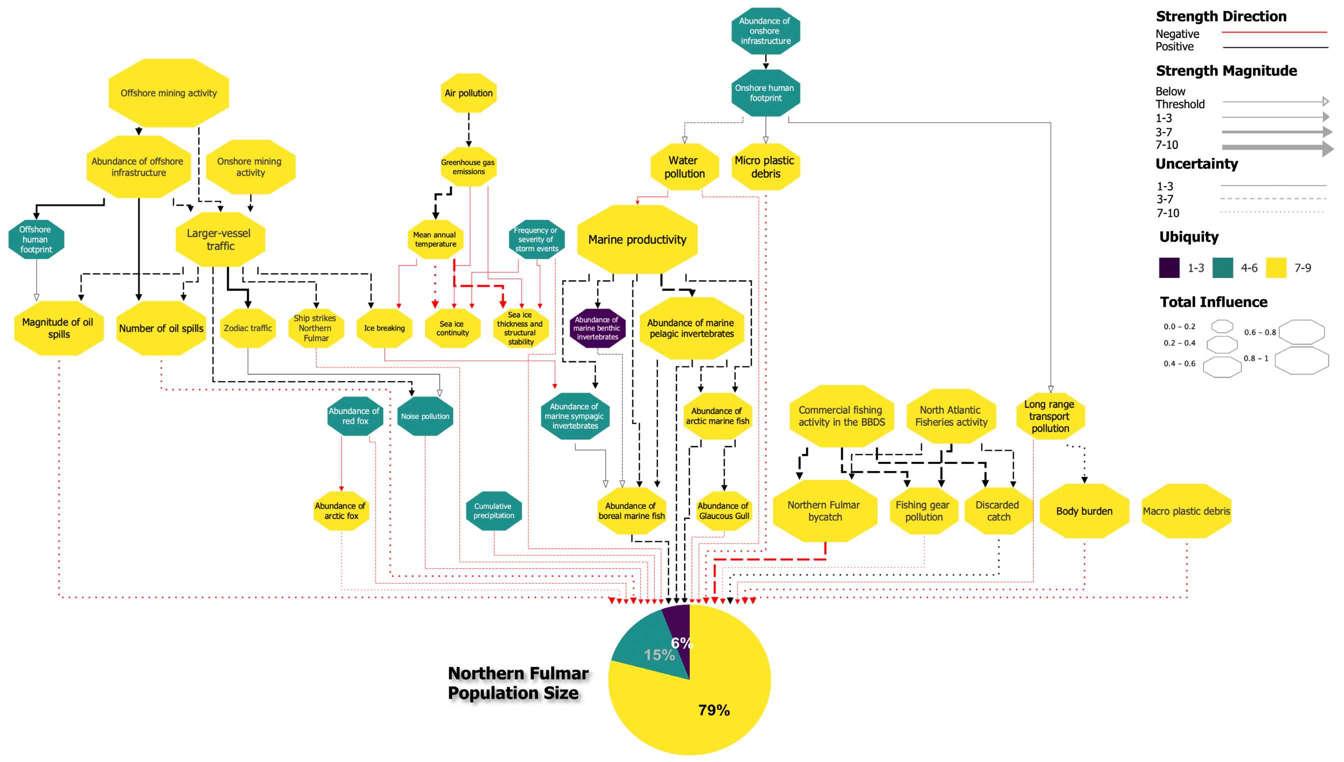

FIGURE 4 Simplified consensus map emphasizing the total influence of concepts on northern fulmar population size, grouped by ubiquity. The size of the concept represents the strength of its total influence on northern fulmar population size and the relative influence by ubiquity category is expressed in the pie chart symbolizing the concept of northern fulmar population size. Arrows are coloured by whether the originating concept exerts a negative or positive influence on the receiving concept. The width of the arrows indicates the average strength of that influence and the arrow solidity indicates the average level of certainty that individuals ascribed to that relationship.

mining activity and the *Abundance of offshore infrastructure*, which not only led to a greater effect of *Number of oil spills* and *Magnitude of oil spills* but also greater *Larger vessel traffic*. Consequently, the theme 'shipping' exerted 16% TI on *Northern fulmar population size*. The total influence on *Northern fulmar population size* in the theme 'hunting and fishing' (18% TI), with *North Atlantic fisheries activity* and *Commercial fishing activity in the BBDS* resulting in *Northern fulmar bycatch* as well as generating *Fishing gear pollution*. Other concepts grouped under the 'pollution' theme also contributed importantly (11%), with *Macroplastic debris* and *Microplastic debris* singled out as key contaminants and other contaminants grouped by vector, including *Air pollution*, *Water pollution*, *Noise pollution* and *Light pollution*.

3.4 | Uncertainty and ubiquity

There was a high degree of ubiquity in which concepts were included in the individual maps (Figure 4), with 79% of the total influence on *Northern fulmar population size* in the consensus map originating from concepts present in at least seven of the nine individual maps. Similarly, there was a high level of agreement among experts regarding which concepts were unimportant: 15 of the 59 concepts defined in the glossary were present on three or fewer of the nine individual maps and contributed only 6% total influence to *Northern fulmar population size* (Supplementary Information 1). Only one of these concepts (*Abundance of marine benthic invertebrates*) was deemed to exert a strong enough influence on the *Northern fulmar population size* to warrant inclusion in the simplified map. This was due to the strong influence of *Marine productivity*, which feeds into *Abundance of marine benthic invertebrates* (Figure 4). Generally, relationships deemed strong were also assigned low uncertainty, but not universally. For example, the direct influence of *Mean annual temperature* on *Sea ice continuity* was strong but uncertain, whereas the influence of *Mean annual temperature* on *Ice breaking activity* was highly certain but not very strong (Figure 4).

Concepts with intermediate ubiquity can indicate a lack of agreement among experts regarding that concept's influence on *Northern fulmar population size* and may point to areas of scientific debate. For example, intermediate levels of ubiquity can indicate disagreement between experts, such as *Onshore human footprint*, which some considered influential while others did not. However, intermediate ubiquity concepts contributed a relatively small amount (15%) of the total influence on *Northern fulmar population size* (Figure 4). Even the most influential concepts with intermediate ubiquity (*Abundance of onshore infrastructure*, the *Onshore human footprint* and the *Abundance of marine sympagic invertebrates*) were deemed weak, with total influence on *Northern fulmar population size* less than |0.28| out of a maximum of |1.0|.

Participants revealed that they assigned uncertainty to the relationships based on three sources: (1) the answer was known, but

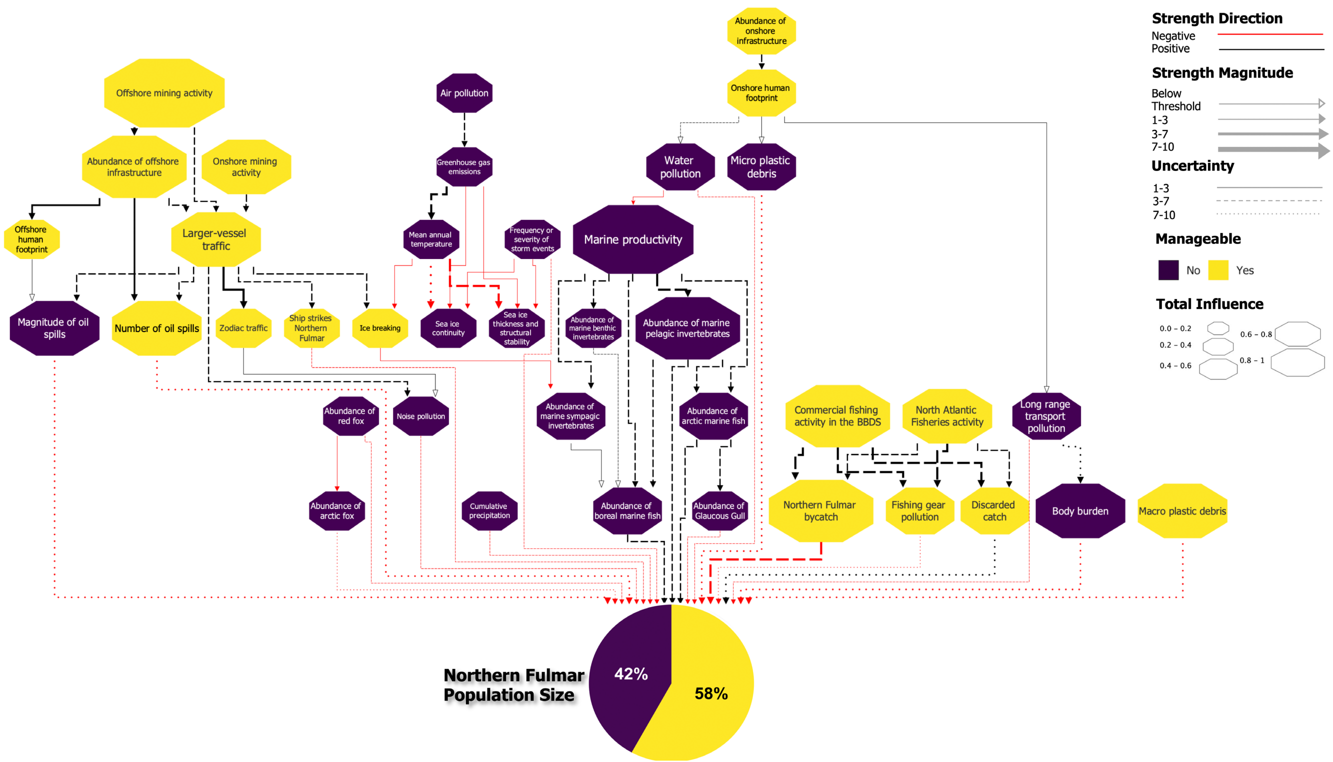

FIGURE 5 Simplified consensus map emphasizing the total influence of concepts on northern fulmar population size, grouped by manageability: Manageable is yellow and unmanageable is purple. The size of the concept represents the strength of its total influence on northern fulmar population size and the relative influence by manageability category is expressed in the pie chart symbolizing the concept of northern fulmar population size. Arrows are coloured by whether the originating concept exerts a negative or positive influence on the receiving concept. The width of the arrows indicates the average strength of that influence and the arrow solidity indicates the average level of certainty that individuals ascribed to that relationship.

not by the individual expert; (2) the topic was adequately studied, but the literature conflicted on the direction or strength of the relationship; or (3) the topic was not adequately studied and additional research is needed to substantiate the hypothesized direction or strength of the relationship. Consequently, relationships assigned high uncertainty are not necessarily research gaps, depending on their estimated influence. Relationships considered influential but uncertain should be prioritized for research. Overall, there was substantial uncertainty expressed regarding the strong relationships leading from *Commercial fishing activity in the BBDS* and the *North Atlantic fisheries activity*. In contrast, the strong relationships leading from *Onshore mining activity* and *Offshore mining activity* were deemed more certain (Figure 4). Interestingly, though the effects of mining activities on *Zodiac traffic*, *Ship strikes of northern fulmar*, *Number of oil spills* and *Magnitude of oil spills* were relatively certain, the consequences for northern fulmar were less certain.

3.5 | Manageability

Of the total influence on northern fulmar population size, 58% was deemed by the experts to originate from concepts deemed manageable (Figure 5). The concepts exerting the greatest total influence on northern fulmar population size that were considered manageable included *Offshore mining activity*, *Abundance of offshore infrastructure*, *Northern Fulmar bycatch*, *Commercial fishing activity in the BBDS*, *Larger vessel traffic*, *Onshore mining activity*, *North Atlantic fisheries activity*, *Macroplastic debris* and *Number of oil spills*, which all had total influence values less than −0.4. The most influential concepts that were deemed unmanageable included *Marine productivity* and *Abundance of marine pelagic invertebrates*, which both had total influence values greater than 0.65, and *Magnitude of oil spills* and *Body burden (of contaminants)*, which both had total influence values less than −0.4.

We found that the concepts under a single theme were often deemed to have similar manageability. For example, none of the *Climate Change*-related stressors were deemed to be manageable by the definition used here, and similarly all of the concepts in the *Hunting and Fishing* theme were deemed manageable. The theme of *Pollution* was the exception—10 of the 17 concepts in the pollution theme were deemed manageable.

4 | DISCUSSION

Given the many ways in which seabirds are affected by anthropogenic activities at different stages of their annual cycle (e.g. Croxall et al., 2012), it is important to consider cumulative effects when examining the threats to species. In the BBDS region, cumulative effects are a priority for several of the groups tasked with managing wildlife populations and protected areas (https://www.nirb.ca/content/strategic-environmental-assessment), including the Sululiit ACMC (Mallory et al., 2022). In this project, we leveraged the opinion of recognized western-trained scientific experts with a goal of modelling the relative cumulative effects of perceived stressors on northern fulmars in the BBDS to evaluate the degree to which northern fulmar population size could be managed under existing policies. We explored which stressors were most likely proxies of fulmar population size, given that large-scale population monitoring in the region is logistically impractical.

Experts generally agreed that factors which had the greatest negative influences on fulmars in the BBDS were principally anthropogenic activities—offshore mining, fisheries and vessel traffic—and these tended to have strong out-degree values (strong influence on northern fulmar populations). This accords well with literature showing that fulmars follow vessels (Camphuysen & Garthe, 1997), including those lit at night (Dupuis et al., 2021), and get caught in nets and on longlines (Anderson et al., 2018; Hedd et al., 2016), but the high value of offshore mining was somewhat surprising. This type of threat to fulmars was not identified as a significant factor in recent reviews of the species' status (Mallory, Hatch, et al., 2020). Because offshore mining inherently increases habitat degradation, lighting, vessel traffic and oil spill risk in the fulmar foraging range, experts concluded it had high potential for strong direct and indirect effects on fulmar. This was reflected in the uncertainty analysis; experts had high uncertainty linking direct effects of mining-related activities to fulmar numbers, yet they had low uncertainty in linking mining-related activities to threats like ship strikes and oil spills. Consequently, these indirect effects demand additional research.

Effects of pollution (oil spills, plastic debris and chemical contamination) were also considered strong, direct negative influences on northern fulmar. This finding is consistent with this species' well-established propensity for accruing various types of pollution (Dietz et al., 2019; van Franeker et al., 2021), although many other seabird species may be more sensitive to oil spills than fulmars (Lorentsen & Anker-Nilssen, 1993; Waugh et al., 2022). Moreover, we noted that all of these direct effects were considered to have smaller influence than the predominant, direct negative effect of fisheries bycatch (Anderson et al., 2018).

When considering what conservation actions to focus on for a species or in a region, it is the interplay between the strength of the influence a threat may have on a species and its manageability that is important to consider. Addressing challenging threats that are highly influential on a species, but are beyond the control of any current policy or regulation, outside the jurisdiction of relevant authorities or subject to temporal lags is still important, but may require exploring relevant policy levers, rather than management actions. These are longer term actions that need to be considered. A threat that is influential for a species that is deemed manageable may be a better focus for conservation efforts, even if it is not the largest relative threat. Importantly, most of the threats that were thought to have a strong negative effect on northern fulmars in the BBDS region were deemed to be manageable, that is, government regulations, policy and enforcement either exist or could be developed to reduce the effects of these threats. These include the broad categories of pollution, fisheries and natural resources extraction (oil and gas exploitation/mining). With all the concepts for *Hunting and Fishing* deemed manageable, and fishing-related concepts found to have a high level of influence on *Northern Fulmar Populations*, this suggests reducing fulmars impacts from fisheries is an area where conservation gains may be made relatively easily within existing frameworks. In our results, it is interesting to note the climate change had both a lower relative overall influence on *Northern Fulmars populations*, and these concepts were also deemed all unmanageable. This finding is surprising given that many seabird species have been shown to be highly sensitive to shifts in marine species associated with climate change (Descamps et al., 2019; Dias et al., 2019; Pratte et al., 2019; Vihtakari et al., 2018; Wauchope et al., 2017). Only through the combined relative evaluation of these stressors in relation to each other can such relationships be identified to highlight what themes should be the focus of conservation efforts as management levers that are most likely to be easily implemented.

Despite that most of the drivers identified as influencing northern fulmars were negative, notably the effect of fisheries and bycatch, the theme considered to have the greatest influence on fulmar population size was ‘other species’ (31% TI), which was principally a reflection of marine productivity and abundance of fish prey. This is consistent with the established relationship that seabird populations are tightly coupled with annual marine food supplies (Cairns, 1988), at least at a coarse level (e.g. Piatt et al., 2007) and may be particularly good indicators in the Arctic, a region of a highly pulsed availability of food (Ramírez et al., 2017). Interestingly, Camphuysen and Garthe (1997) have previously shown that the assumed importance of North Sea fisheries on fulmar distribution was overestimated, and that in fact factors which influenced productivity and fish distribution better explained fulmar distribution at sea. However, in a more recent analysis, Darby et al. (2021) found that the distribution of fisheries activity was the best predictor of fulmar distribution in the waters around the United Kingdom, better than standardly used metrics like bathymetry and chlorophyll concentration. They attributed the relationship to the tendency for fulmars to scavenge offal from fisheries vessels. Fulmar distribution in Alaska was also tied closely to fishing effort (Renner et al., 2013). Both of those studies were undertaken in regions with much greater fishing history, year-round duration and intensity than in the BBDS. Consequently, the extent to which these relationships may apply in the BBDS is unknown. Nonetheless, with their potentially large, negative impacts, themes of ‘shipping’ and ‘hunting and fishing’ combined had approximately the same influence (34% TI) as ‘other species’. This suggests that researchers should explore how these concepts may be used as indicators to monitor fulmar population size, by better understanding how closely these themes are tied to bird numbers. This will require additional research to compare colony numbers or reproductive effort and success to some of these environmental metrics (e.g.

shipping numbers, chlorophyll *a* concentration, fishing intensity). In particular, enhanced efforts in tracking large vessels in the region at a finer scale, and in the regions most used by northern fulmars, should be a priority to understand direct and indirect effects on fulmar populations. We are only at the early stages of this research in the Arctic region (Halliday et al., 2022; Wong et al., 2018).

Scientific experts within this exercise suggested that the bulk of influence on fulmars was indirect (i.e. seven of the top 10 drivers; Figure 2), emphasizing the importance of a cumulative effects perspective as asked for by the Sululiit ACMC. What this means is that understanding or having control over the variables or concepts with *direct* influence on fulmars would not be adequate to predict most changes in northern fulmar population size, because the importance of ultimate drivers is not necessarily proximately related to the number of northern fulmars. For example, even if we could reduce the levels of bycatch, minimize oil spills and reduce the exposure to pollution, all presumably to benefit fulmar populations, fulmar numbers could still decline in response to marine productivity or other offshore industrial activities, or even in response to stressors outside the BBDS. The effects of climate change on the timing and amounts of food supplies, as well as breeding phenology and success, can play an important role in annual success of Arctic fulmars (Descamps et al., 2019; Gaston et al., 2005; Gutowsky et al., 2022). However, in the absence of additional focused study, our ongoing lack of knowledge on the indirect effects of many of these factors on Arctic bird populations will continue to preclude our ability to make reliable predictions about future trends in population health.

We recognize that while our focus was northern fulmar populations in the BBDS region, the experts that were able to participate in this project were exclusively from Canada. Northern fulmars in particular have a circumboreal range that includes the entire North Atlantic in their annual range, with fulmars from European colonies using North American waters and vice versa (Mallory, Hatch, et al., 2020). Recent genetic analyses have shown that in fact there is little genetic differentiation between fulmar colonies across the North Atlantic, and recommends that conservation efforts for fulmars need to be collaborative across the region given the likely links between populations (Colston-Nepali et al., 2020). As a result of the annual movements of northern fulmars in the North Atlantic, we recognize that there are likely a number of threats beyond the borders, jurisdiction and management practices of Canada.

When interpreting these results, it is important to consider that fulmars are far-ranging generalists (Mallory, Hatch, et al., 2020). This aspect of their ecology may make them better at compensating for change in one particular site (e.g. disturbance/mine) or one particular prey species (e.g. changes in prey species). How this species responds to stressors is very different from other sympathetic species in the region that are short-range foragers with more specialized diets (e.g. murres, terns, kittiwakes and eider ducks). Thus, while this process is an important tool to conservation planning tool, we see this as a species-specific model of understanding that should be taken into consideration along with other information. We also do not consider this an exercise in informing general seabird conservation actions, as that would require additional considerations and information. However, the FCM process could be effectively used to visualize and interrogate expert knowledge about other seabird species.

The use of expert opinion clearly has both strengths and limitations (Drescher et al., 2013), and this similarly applies to using experts in an FCM process. A strength of the FCM approach to understanding cumulative effects is that it can include expert opinion on a variety of topics in relation to each other. We actively sought out participants that brought expertise to the process which covered a range of topics relevant to the area, including research at land, at sea (e.g. Wong et al., 2014), with industrial interactions (e.g. Hedd et al., 2016) and over decades (e.g. Gutowsky et al., 2022). In the end, we were pleased that the expert group included most of the lead western-trained scientists conducting research on northern fulmars in Canada in the last 20 years; we are confident that this group had a robust and practical perspective on fulmar ecology and management. Of course, a limitation of the project is that all expert opinions were based on the best available knowledge, which for fulmars in the BBDS region is patchy, with a limited number of direct observations/studies of the interactions between fulmars and their at-sea stressors. This was reflected and accounted for in the certainty values discussed above. While there are many species breeding in the Canadian Arctic that are annually monitored and have extensive efforts to track seasonal and annual movements (e.g. thick-billed murres *Uria lomvia* Gaston et al., 2011; common eiders *Somateria mollissima* Mosbech et al., 2006), northern fulmars have been little studied to date in the same way. In the BBDS region, fulmar colonies are found on remote cliffs, often far from communities, and as the species is not widely harvested, population monitoring is not carried out regularly. A recent population census updated colony counts that were over 30 years old in some cases (Mallory, Dey, et al., 2020), and tracking efforts of northern fulmars in the Canadian Arctic are limited to a handful of individuals (Mallory et al., 2008). Notably, experts could only include relationships in the FCM models that they had reason to expect. There are likely interactions between the environmental stressors, and potentially other environmental stressors that have not been identified here due to knowledge limitations. Therefore, the maps produced here should not be considered finalized concept maps, but tools to explore how stressors may interact in the BBDS region, and what actions may be needed to conserve northern fulmars breeding in northern Canada.

Importantly, we recognize this FCM exercise with western-trained seabird experts as the first step in a larger project that is underway (as outlined above in the project origin section). As highlighted in recent works, there are many reasons for examining research questions through multiple knowledge systems (Goodchild, 2021; McGregor, 2021). Specifically, the weaving of Indigenous Knowledge Systems (IKS) and western-based science have been examined as a way to further explore research on biodiversity in coastal ecosystems (Alexander et al., 2021; Alexander, Provencher, Henri, Taylor, Lloren, et al., 2019). The need to respectively weave or braid IKS is increasingly recognized in policy and legislation, both at the national and international level. In Canada, many federal government departments have a mandate to consider and, respectively, include IKS in research and decision-making processes (Alexander, Provencher, Henri, Taylor, & Cooke, 2019; Henri et al., 2021). For example, the value of IKS for biodiversity conservation and sustainability has been highlighted in several United Nations (UN) fora, and through the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP; UN, 2008). Therefore, the next phases of this research program will work directly with the Sululiit ACMC under a similar process co-developed and co-implemented with IKS experts (see Mallory et al., 2022) to explore the influence of environmental stressors on northern fulmar populations in the region. We hope this approach will help identify management tools, as well as future areas of research to be collaboratively developed with partners in the region.

AUTHOR CONTRIBUTIONS

Rebecca Rooney, Jennifer Provencher and Mark Mallory conceived the ideas, designed the project, designed methodology, implemented the data collection, analysed the data and drafted the original text; Jody Daniel and Jess Ives helped to design the analytical methods, collected the data, processed the data, created the figures and reviewed and edited the final text; April Hedd, Grant Gilchrist, Carina Gjerdrum, Greg Robertson, Rob Ronconi, Kirsten Wilcox and Sarah Wong all contributed to outlining the methods and terms, contributed to the expert workshops, interpreted and discussed the data and figures produced and contributed to writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors do not have any conflicts of interest to report in relation to this manuscript.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

All the data and methods for this manuscript are contained within the methods and supplemental materials.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Supplementary Information S1: Original Glossary 5 November 2020.

Supplementary Information 2: Invitation & participant list.

Supplementary Information 3: Agenda from 9 November 2020.

Supplementary Information 4: Revised Glossary 13 November 2020.

Supplementary Information 5: The 9 individual FCMs.

Supplementary Information 6: The complete consensus map.

Supplementary Information 7: Table of concept in-degree, out-degree and centrality.

Supplementary Information 8: Table of consensus edges with strength, ubiquity and variance measures.

Supplementary Information 9: Statistical methods.

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