REVIEW

Towards integrated knowledge of climate change in Arctic marine systems: a systematic literature review of multidisciplinary research

Marianne Falardeau and Elena M. Bennett

Abstract: Climate change affects Arctic marine ecosystems, the ecosystem services they provide, and the human well-being that relies on these services. The impacts of climate change in the Arctic and elsewhere involve cascading effects and feedbacks that flow across social-ecological systems (SES), such as when sea ice loss alters food security through changes in the distribution of marine animals. These cascades and feedbacks across social and ecological systems can exacerbate the effects of climate change or lead to surprising outcomes. Identifying where cascades and feedbacks may occur in SES can help anticipate, or even prevent unexpected outcomes of climate change, and lead to improved policy responses. Here, we perform a systematic literature review of multidisciplinary Arctic research to determine the state of knowledge of the impacts of climate change on marine ecosystems. Then, in a case study corresponding to Inuit regions, we use network analysis to integrate research into a SES perspective and identify which linkages have been most versus least studied, and whether some potential cascades and feedbacks have been overlooked. Finally, we propose ways forward to advance knowledge of changing Arctic marine SES, including transdisciplinary approaches involving multiple disciplines and the collaboration of Indigenous and local knowledge holders.

Key words: climate change, marine ecosystem services, social-ecological systems, resilience, transdisciplinary research.

Résumé : Les changements climatiques affectent les écosystèmes marins de l'Arctique, les services écosystémiques qu'ils rendent et le bien-être humain qui dépend de ces services. Les impacts des changements climatiques dans l'Arctique et ailleurs impliquent des effets en cascade et des rétroactions qui circulent à travers les systèmes socioécologiques (SSE), comme lorsque le recul de la glace de mer affecte la sécurité alimentaire à travers des changements dans la distribution des animaux marins. Ces cascades et ces rétroactions à travers les systèmes sociaux et écologiques peuvent exacerber les effets des changements climatiques ou donner lieu à des résultats surprenants. L'identification des endroits où les cascades et les rétroactions peuvent survenir dans les SSE peut aider à anticiper et même prévenir des résultats inattendus des changements climatiques et conduire à une amélioration des interventions. Les autrices ont réalisé une synthèse systématique de la littérature de la recherche interdisciplinaire sur l'Arctique afin de déterminer l'état des connaissances des impacts des changements climatiques sur les écosystèmes marins. Par la suite, dans une étude de cas correspondant aux régions inuites, elles ont utilisé l'analyse

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en réseau pour intégrer la recherche à une perspective SSE et identifier quels sont les liens qui ont été les plus étudiés par rapport à ceux qui ont été le moins étudiés, et si certaines cascades ou rétroactions potentielles ont été négligées. Finalement, elles proposent des moyens de pousser plus loin les connaissances sur les SSE marins de l'Arctique en changement, y compris des approches transdisciplinaires impliquant plusieurs disciplines et la collaboration des détenteurs des savoirs traditionnels autochtones locaux. [Traduit par la Rédaction]

Mots-clés : changements climatiques, services écosystémiques marins, systèmes socioécologiques, résilience, recherche transdisciplinaire.

Introduction

The Arctic Ocean is at the forefront of climate change due to complex feedback processes that cause Arctic warming to be more rapid than the global mean (ACIA 2004; IPCC 2014). Fast warming of the Arctic region triggers multiple, often unexpected, changes in the marine environment (Larsen et al. 2014). Among those changes, loss of the Arctic ice cover is a major concern because sea ice supports unique ecosystems and provides key ecosystem services locally (including a platform for transportation and cultural activities; ICC-Canada 2008; Eicken et al. 2009) and globally (including the regulation of the planet's climate; Chapin et al. 2005; Euskirchen et al. 2013; CAFF 2015).

The impacts of climate change in the Arctic affect people around the planet, but especially those who live in the North (Huntington et al. 2013; CAFF 2015; Ford et al. 2015). Many Arctic communities rely on marine resources to support mixed economies in which subsistence activities have strong cultural importance and supplement, or even substitute for, participating in the labor market (Larsen and Fondahl 2015; AMAP 2017). These communities, which often include Indigenous groups, may be disproportionately impacted by climate change, especially when the speed of change exceeds their ability to adapt (Larsen et al. 2014; Ford et al. 2015).

Climate change causes cascading effects and feedbacks that can accelerate change and spread impacts through social-ecological systems (SES) (ACIA 2004; Carmack et al. 2012; Larsen et al. 2014; Petrov et al. 2016) — such as the cascading effects of sea ice loss on cultural values (e.g., ICC-Canada 2008; Eicken et al. 2009; ICC 2010), that of shifting marine food webs on commercial fisheries (Arctic Council 2016), or the feedbacks caused by the interactions of climate change with shipping and pollution (e.g., Bennett et al. 2015; Larsen and Fondahl 2015). Such cascades can provoke surprising outcomes (Adger et al. 2005) that may erode resilience (the capacity of ecosystems and people to buffer and adapt to shocks, such as climate change and other human-caused pressures; e.g., Biggs et al. 2012; Carmack et al. 2012; Arctic Council 2016). Grappling with cascades and feedbacks where they occur can help to build resilience through purposeful action (Adger et al. 2005; Biggs et al. 2009, 2012), such as diversifying livelihood strategies (e.g., encouraging tourism or art, Arctic Council 2016; Leu 2019) and fisheries (e.g., targeting a diversity of species, Anderson et al. 2017).

There is growing evidence that cascading effects and feedbacks are not effectively captured when ecosystems and social systems are studied separately (Liu et al. 2007; Arctic Council 2016; IPBES 2016; Guerrero et al. 2018). Indeed, by focusing on only ecological or only social elements rather than on the linkages that connect them, we may miss those parts of SES where cascades and feedbacks can exacerbate the impacts of climate change (Leenhardt et al. 2015; Guerrero et al. 2018). For this reason, high-level international organizations have expressed the urgent need for integrated knowledge of Arctic climate change (e.g., ICC 2010; Larsen et al. 2014; CAFF 2015; Larsen and Fondahl 2015; Arctic Council 2016;

ARAF 2017). In particular, the Arctic Council — the leading intergovernmental forum on Arctic issues — has called for interdisciplinary and transdisciplinary science (i.e., which crosses disciplinary boundaries (interdisciplinary) and involves non-academic knowledge systems (transdisciplinary), both considered as integrative; Tress et al. 2005) that reflects the intertwined nature of Arctic SES for guiding adaptation, management, and resilience building (PAME 2014, 2017; CAFF 2015; Arctic Council 2016; SEI and SRC 2017). However, such integrative science is impeded by the lack of a common framework to reconcile the multiple terminologies and methods used to study the impacts of climate change on Arctic ecosystems and peoples (Arctic Council 2016; Petrov et al. 2016).

Ecosystem service (ES) approaches are often used to develop integrated knowledge of SES (e.g., MA 2005; de Groot et al. 2010; TEEB 2010; Costanza et al. 2017). They offer a common language to bridge information from across disciplines and ways of knowing to study problems that involve complex feedbacks (e.g., Granek et al. 2010). We suggest that an ES lens could advance our understanding of the social-ecological interactions related to Arctic climate change (Huntington et al. 2013; PAME 2014, 2017; CAFF 2015; Arctic Council 2016, 2017).

Here, we used an ES framework to integrate peer-reviewed Arctic climate change research (ACCR) from across academic disciplines of the natural and social sciences into social-ecological knowledge, focusing on a case study SES corresponding to Inuit regions. We focus on Inuit because they use, and deeply connect to, marine ecosystems for their livelihoods and well-being (e.g., ICC-Canada 2008; Larsen and Fondahl 2015; AMAP 2017), and because they are one of the most populous and widespread Indigenous people of the Arctic, living across Canada, Alaska, Greenland, and Russia (Ahlenius et al. 2005; Larsen and Fondahl 2015). The study objectives were to:

1. Provide an overview at the circumpolar scale of the most and least studied impacts of climate change on marine ecosystem processes and their ES implications.
2. Integrate multidisciplinary ACCR into a comprehensive picture of the reported impacts of climate change in a case study SES corresponding to Inuit regions.
3. Identify the most and least studied cascading effects and feedbacks of climate change in Inuit regions and explore whether social-ecological linkages might have been overlooked.
4. Evaluate the outcomes from the first three objectives and suggest ways forward to advance integrative Arctic research about the ongoing and future impacts of climate change in the marine Arctic and other complex SES.

Methods

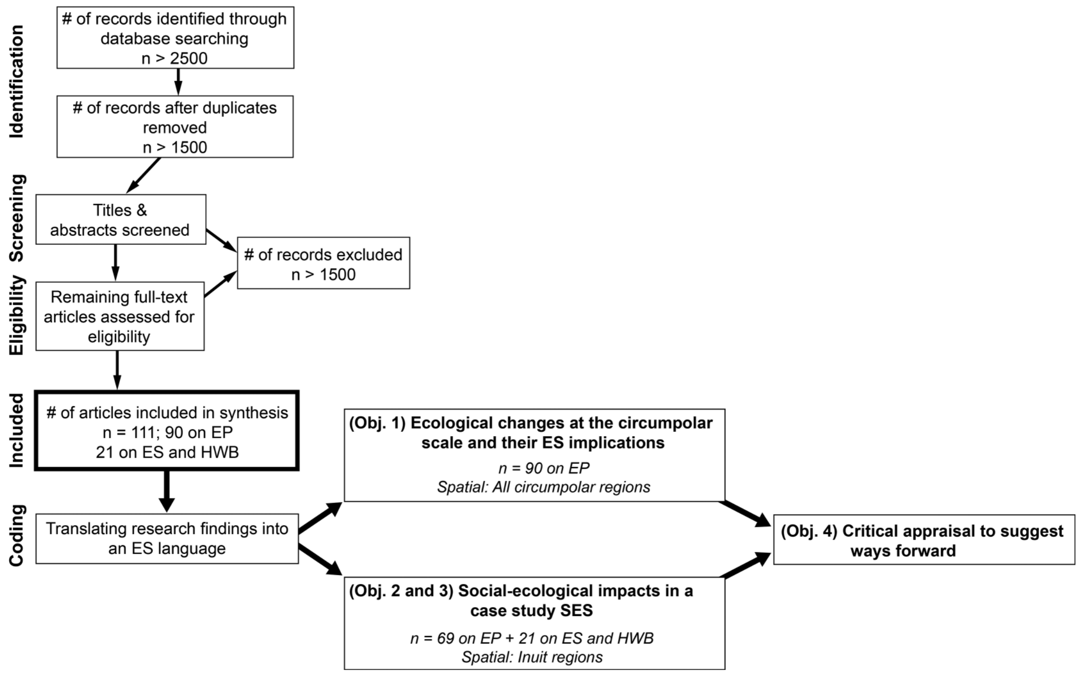
We combined a systematic review (identification, screening, eligibility assessment, and coding of articles based on an Arctic ES framework) with network analysis to assemble, and integrate across, ACCR (Fig. 1).

Assembling and organizing ACCR

We gathered peer-reviewed literature on the impacts of climate change on Arctic marine systems using an approach inspired by systematic review techniques (Moher et al. 2009; Ford et al. 2012, 2014; Berrang-Ford et al. 2015). We developed ten search strings to select relevant peer-reviewed articles from the ISI Web of Science and Scopus (Supplementary Tables S1–S3[1]) published between 1 January 2013 and 2016. The initial searches generated over 2500 potentially relevant articles. After removing duplicates, we screened titles and abstracts,

[1]Supplementary material is available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/as-2019-0006.

Fig. 1. Flow diagram of the review approach adapted from the preferred reporting items for systematic reviews and meta-analyses (PRISMA) methodology (Moher et al. 2009) followed by the steps for achieving the four study objectives. Of the 111 articles included in the review, 90 focused on ecosystem processes (EP), all spatial and temporal scales taken together, and were used to provide an overview of circumpolar research (objective 1), and 21 focused on ecosystem services and human well-being (ES and HWB) in Inuit regions. These 21 articles were merged with a subset of 69 articles from the 90 articles gathered on ecosystem processes, only retaining those with scales relevant to Inuit regions, for a total of 90 articles used to perform a full social-ecological systems integration and address objectives 2 and 3 of the study. In the end, we critically appraised the outcomes from our first three objectives to pursue objective 4 of the study.

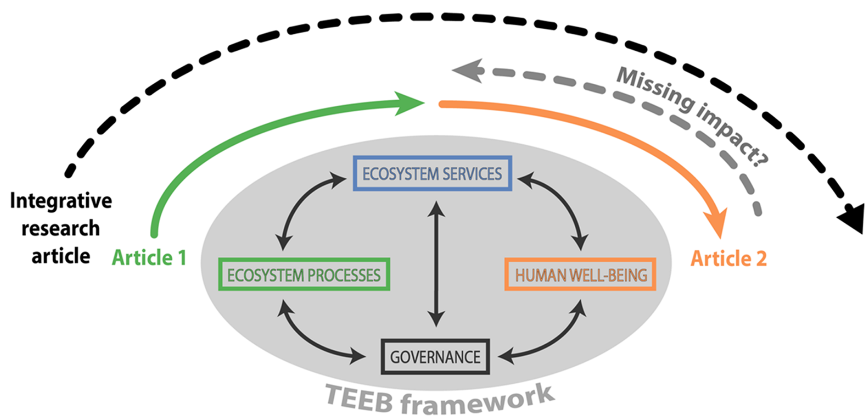


selecting relevant articles following inclusion criteria (Supplementary Table S3[1]). We then scanned the full texts of remaining articles to further assess eligibility, ultimately retaining 111 articles for full review (Supplementary Table S4[1]).

After identifying and selecting 111 relevant articles, we divided them based on their primary focus and scales (temporal and spatial) to achieve our different study objectives (Fig. 1). The primary focus of articles could either be on ecosystem processes (to be used for the analysis of objective 1), or ES and Inuit well-being (to be used for the analysis of objectives 2 and 3). We also categorized articles by the scale of research: temporal scale, observed (1970–2015) or future impacts (after 2015; temporal scale categories were non-exclusive as a few articles covered both present and future impacts); and spatial scale, either local, large scale, or pan-Arctic. We examined articles on the impacts of climate change on ecosystem processes at the circumpolar scale for objective 1 and focused on Inuit regions only when examining articles on ES and human well-being (to achieve objectives 2 and 3). This focus was chosen because it was clear that producing a coherent SES study on the impacts of climate change would require scaling down to a particular human population, as impacts on ES and human well-being are experienced differently by distinct Indigenous and non-indigenous groups (Larsen and Fondahl 2015). Inuit have lived across more than half of the Arctic for thousands of years and are one of the most populous Indigenous people of the circumpolar North (ICC-Canada 2008; Larsen and Fondahl 2015). Thus, scaling

Box 1. TEEB framework to collate ACCR and identify the “missing impacts” of climate change.

We used the adapted *The Economics of Ecosystems and Biodiversity* (TEEB) ecosystem services (ES) framework (greyed out zone) to translate research findings from peer-reviewed Arctic climate change research (ACCR) articles into chains of impacts and see which parts of the framework were and were not studied. Most articles looked only at parts of the framework (either ecosystem processes, ES, or human well-being; governance is outside the scope of this study); few looked at all parts of the framework. In the example below, Article 1 (in green) studied changes in an ecosystem process that directly influenced an ES, whereas Article 2 (in orange) focused on changes in human well-being as related to alteration of an ES due to climate change. An integrative research article that looked at how the impacts of climate change flow from ecosystem processes, to ES and human well-being, is indicated with a black dashed arrow. By collating a large amount of research, we were able to connect those multiple pieces of the puzzle into a synthetic picture of the reported impacts of climate change on an Arctic marine social-ecological systems corresponding to Inuit regions. However, some “missing impacts” (places where impacts or feedbacks most likely occur — based on the linkages (black arrows in the greyed out zone) of the Arctic-adapted TEEB framework — but that were not studied in our sample of peer-reviewed articles) are likely, for example feedbacks from changes in human well-being conditions that could alter people’s capacity to obtain ES.



our analysis to a case study SES corresponding to Inuit regions gave us the ability to capture a broad spectrum of change, while remaining focused on a group with a shared cultural approach to interacting with ecosystems (ICC-Canada 2008).

Building an Arctic ES framework

ES frameworks have the ability to link changes in ecosystem processes to changes in ES and human well-being outcomes, thus providing guidance to translate existing research into social-ecological information (Granek et al. 2010). We used *The Economics of Ecosystems and Biodiversity* (TEEB) (de Groot et al. 2010; TEEB 2010; CAFF 2015) ES framework to link ACCR, focusing on three components of the TEEB framework: ecosystem processes, ES, and human well-being (Box 1). We adapted the framework to the study context (i.e., to Arctic marine ecosystems, Inuit as ES beneficiaries, and climate change as the main driver of change) by building on existing literature (MA 2005; ICC-Canada 2008; Eicken et al. 2009; de Groot et al. 2010; TEEB 2010; Wassmann et al. 2011; Böhnke-Henrichs et al. 2013; Cubasch et al. 2013; Huntington et al. 2013; Pörtner et al. 2014; CAFF 2015; O’Garra 2017) and through an iterative review of all the 111 selected articles. Our iterative process revealed Arctic- and Inuit-specific examples to fit under the TEEB framework components, as well as new ES and human well-being constituents that are not typically represented in the general marine ES literature. In particular, we added the ES of sea ice platform, shipping routes, and new species to harvest, as well as important Inuit notions as related to human

Table 1. General definitions of key concepts used in this study, specific definitions of Arctic marine and coastal ecosystem services and human well-being constituents, and specific examples (adapted from MA 2005; ICC-Canada 2008; Eicken et al. 2009; de Groot et al. 2010; TEEB 2010; Böhnke-Henrichs et al. 2013; Huntington et al. 2013; CAFF 2015; O'Garra 2017).

	General definitions
Social-ecological system	The ecological and social systems located within defined spatial boundaries that are intertwined through the tight interactions of ecological and social components.
Ecosystem processes	Structure and processes generated by vegetal and animal organisms and their interactions with biotic and abiotic materials, such as photosynthesis and species interactions.
Ecosystem services	The direct and indirect contributions of ecosystems to human well-being. Ecosystem services are co-produced through interactions between humans and their environment.
Provisioning services	The goods that humans obtain from ecosystems such as food, water, and raw materials.
Regulating services	The benefits derived from the regulation of the biosphere by ecosystem processes, such as carbon sequestration.
Cultural services	The non-material benefits that humans obtain from ecosystems including recreation and spiritual experience.
Human well-being	A context-and situation-dependent state that consists of five main constituents: basic material for good life, health, good social relations, security, and freedom of choice (not assessed in this review study).

		Specific definitions	Example
Regulating services	Biological control	The contribution of marine/coastal ecosystems to healthy population dynamics and ecosystem resilience through food web structure and dynamics.	The maintenance of energy flows from phytoplankton to apex predators.
	Carbon sequestration	The role of marine/coastal ecosystems in the ocean biological pump.	The absorption of carbon dioxide by phytoplankton and its sedimentation to the ocean floor.
	Climate regulation	The influence of biological and sea ice processes on the climate.	The reflection of sun radiation by Arctic sea ice and its cooling effect.
Provisioning services	Marine and coastal food	All available marine life fished, hunted, or harvested from marine/coastal environments for the specific purpose of human consumption as food.	Clams, fishes, marine mammals, and seabirds.
	Shipping routes	Routes for the shipping of food and other goods.	The Northwest passage as a route for pleasure crafts, cruise ships, and cargo ships.
	Sea ice platform	Platform for a range of land-based and ice-based activities.	Travelling on the sea ice to access hunting and fishing grounds.
	New species to harvest	All marine fauna and flora expanding their range from southern latitudes that could be consumed by humans as food.	Salmon, tuna, killer whales.

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		Specific definitions	Example
Cultural services	Sense of place, identity, and heritage	The importance of marine/coastal environments for Inuit identity, cultural traditions, and history.	Cultural traditions and sense of identity associated with marine mammal hunting.
	Recreation and tourism	The contribution of marine/coastal environments to recreation and tourism.	Arctic marine mammal sight-seeing, recreational fishing.
	Spirituality	The contribution of marine/coastal ecosystems to spiritual experiences.	Healing benefits associated with spending time on the ocean.
	Knowledge systems	The contribution of marine/coastal environments to knowledge systems, including Inuit knowledge.	Local knowledge about hunting and fishing techniques.
Human well-being	Basic material for good life	The ability of people to access resources to sustain their livelihood, food security, and basic needs. For Inuit, this includes access to land-, marine- and ice-based activities.	Revenue, physical access to harvest grounds.
	Health	The maintenance of nutrition, defense against disease, and overall health (physical and mental).	Nutritional benefits of food, and mental wellness associated with land-, marine- and ice-based activities.
	Security	The maintenance of personal safety, secure resource access, and security from disasters.	Ability to have safe and stable ice conditions for hunting.
	Good social relations	The maintenance of social cohesion, community relations, and mutual respect.	Healthy relationships with family and relatives.

Note: The ecosystem service of climate regulation is beyond the scope of this review. Marine/coastal includes offshore, inshore, and littoral ecosystems, but not freshwater ecosystems.

Table 2. The percentage of peer-reviewed Arctic climate change research in our sample that studied the response of each ecosystem process to climate change, along with the ecosystem services affected by reported changes (% of articles, $n = 90$ articles from across the Arctic).

Ecosystem processes	Observed impacts	Future impacts
Abundance	12%	**21%**
Contaminant levels	2%	**0%**
Distribution	16%	**24%**
Food web structure and dynamics	3%	9%
Species invasion	**22%**	**33%**
Metabolism, condition, and growth	12%	6%
Parasitism	2%	0%
Phenology	5%	6%
Primary production	**24%**	**42%**
Reproduction	5%	3%
Secondary production	5%	**21%**
Sedimentation	5%	3%
Survival	3%	3%
Trophic ecology	**26%**	9%
Ecosystem service affected		
Biological control	57%	55%
Carbon sequestration	22%	48%
Marine and coastal food	50%	24%
New species to harvest	17%	21%
No. articles	**58**	**33**

Note: Percentages are not cumulative — a single article could report impacts on more than one ecosystem process. Ecosystem processes reported as impacted in more than 20% of the articles are in bold.

well-being, such as safe access to ice-based activities (Table 1). Once we had developed an Arctic-adapted TEEB framework (see Table 1 for the ES and human well-being constituents, and Table 2 for the ecosystem processes), it served as a common language to bring together ACCR articles from different disciplines (Box 1), each with their unique sets of terminologies and methods. Because ES terminology was particularly scarce in the articles we analyzed, we accepted a range of terms to code impacts on ES (Supplementary Table S5[1]).

Synthesizing research on the impacts of climate change on marine ecosystem processes and ES across the Arctic

To provide a broad overview of the most studied impacts of climate change on marine ecosystem processes and how these changes have affected Arctic ES (objective 1), we gathered all articles with a primary focus on ecosystem processes ($n = 90$ articles with spatial scales ranging from local to circumpolar, including areas outside Inuit regions, such as the Barents Sea; Fig. 1). We first identified the ecological level of focus in each article, from species to whole ecosystems, highlighting the principal level of interest (one per article). Then, we listed all ecosystem processes studied (more than one per article), and any reported change in processes due to climate change. Finally, we assessed the implications of reported changes for ES that are tightly linked to ecosystem processes — biological control, carbon sequestration, marine and coastal food, and new species to harvest — as impacts on these ES could plausibly be assumed from the ecological research reviewed (Supplementary Table S5[1]). For example, if an article mentioned change in primary production, we inferred effects on carbon sequestration based on existing studies making this link (Anderson and Totterdell 2002; Riebesell et al. 2007); or, if any article mentioned change in the distribution of seal populations, we linked this to changes in the ES of "marine and coastal food" as seal is an important food item for Inuit (Priest and Usher 2004).

Integrating ACCR into knowledge of the social-ecological impacts of climate change in Inuit regions

We then shifted from research on ecological impacts alone to those studies that also included social and social-ecological impacts. At the same time, we limited our geographical range to Inuit regions to focus on a single coherent SES. Narrowing down to the 90 articles relevant to objectives 2 and 3, we used network analysis to produce two networks of SES impacts in Inuit regions: observed impacts of climate change and future impacts of climate change.

Network analysis is widely used to study questions that involve complex relationships among elements, as it breaks down data into nodes (sets of concepts) and their connections (called edges; e.g., Janssen et al. 2006; Baggio et al. 2016). Here, network analysis facilitated integration as it allowed us to develop connections between separate articles spanning different disciplines across both natural and social sciences. We used network analysis to show how impacts of climate change measured across the 90 articles interact with one another, and to identify cascading effects and feedbacks that might have been absent from the ACCR analyzed. We refer to these as "missing impacts" and unmasked them based on the Arctic-adapted TEEB framework: linkages known as important based on the framework, but unstudied by ACCR, were considered as "missing impacts" (Box 1). We first transcribed research findings from each article into chains of impacts (Carter et al. 1994) using coding schemes based on the adapted TEEB framework (Supplementary Table S5[1]). For example, linking sea ice decline to change in polar bear distribution, and in turn, to the availability of marine and coastal food. We did not include null results of studies that found no impacts. We then integrated chains of impacts from across articles with the network analysis software *Gephi* (Bastian et al. 2009).

In our networks, nodes represent climatic drivers (e.g., sea ice decline) or impacted ecosystem processes, ES, or human well-being constituents (e.g., animal distribution, marine and coastal food, or food security), whereas edges represent actual impacts that flow in the SES (e.g., the impact that occurs when sea ice decline affects animal distribution). Chains of impacts coded from articles translate into series of edges that start from one or a few climatic drivers and link impacted SES components. Each edge, or impact, has a weight that is proportional to the number of times a specific impact (i.e., the portion of a chain of impacts) was reported in articles, which we used to identify most and least studied impacts. We also used the weighted degree centrality — a proxy that highlights the nodes with the most connections — to identify the climatic drivers and SES components that have been studied the most. We further separated centrality into: in-degree centrality, the number of inbound connections, which in this study indicates the degree to which a SES component is shown to be impacted by climate change; and out-degree centrality, the number of outbound connections, which in this study indicates a climatic driver or a SES component that was reported to funnel impacts to other nodes.

Critical appraisal to suggest ways forward for integrated ACCR

Finally, we critically appraised the outcomes from our first three research objectives to identify whether some research gaps may limit comprehensive understanding of climate change (objective 4). We attribute these research gaps to challenges experienced during our post-hoc integration of peer-reviewed ACCR, and from similar gaps being identified in major circumpolar assessments. To further understand features that may have challenged our integration of ACCR into SES information, we explored the level of SES integration of single ACCR studies, whether they considered drivers' interactions, such as the interaction of climate change with shipping or pollution, as well as the methods and scales (temporal and spatial) most commonly used. For the level of SES integration, we considered articles

Table 3. Main ecological levels at which the impacts of Arctic climate change on marine ecosystem processes were assessed (% of articles, $n = 90$ articles from across the Arctic).

Ecological level	Observed impacts	Future impacts
Biodiversity	0%	6%
Ecological community	3%	3%
Ecosystem	2%	6%
Food web	2%	9%
Primary production	17%	**21%**
Sedimentation	5%	3%
Species	**57%**	**24%**
Species group	14%	**27%**
No. articles analyzed	**58**	**33**

Note: Percentages have been rounded and may not equal 100%. Ecological levels studied in more than 20% of the articles are in bold.

that addressed the three different SES components (ecosystem processes, ES, and human well-being) to be more integrative, and those that did not to be less integrative. We compared the outcomes from our gap assessment to gaps previously reported in major circumpolar assessments as impeding the development of integrated knowledge of Arctic climate change (Supplementary Table S6[1] for a list of the reports assessed).

Results

Objective 1: research on ecosystem change at the circumpolar scale

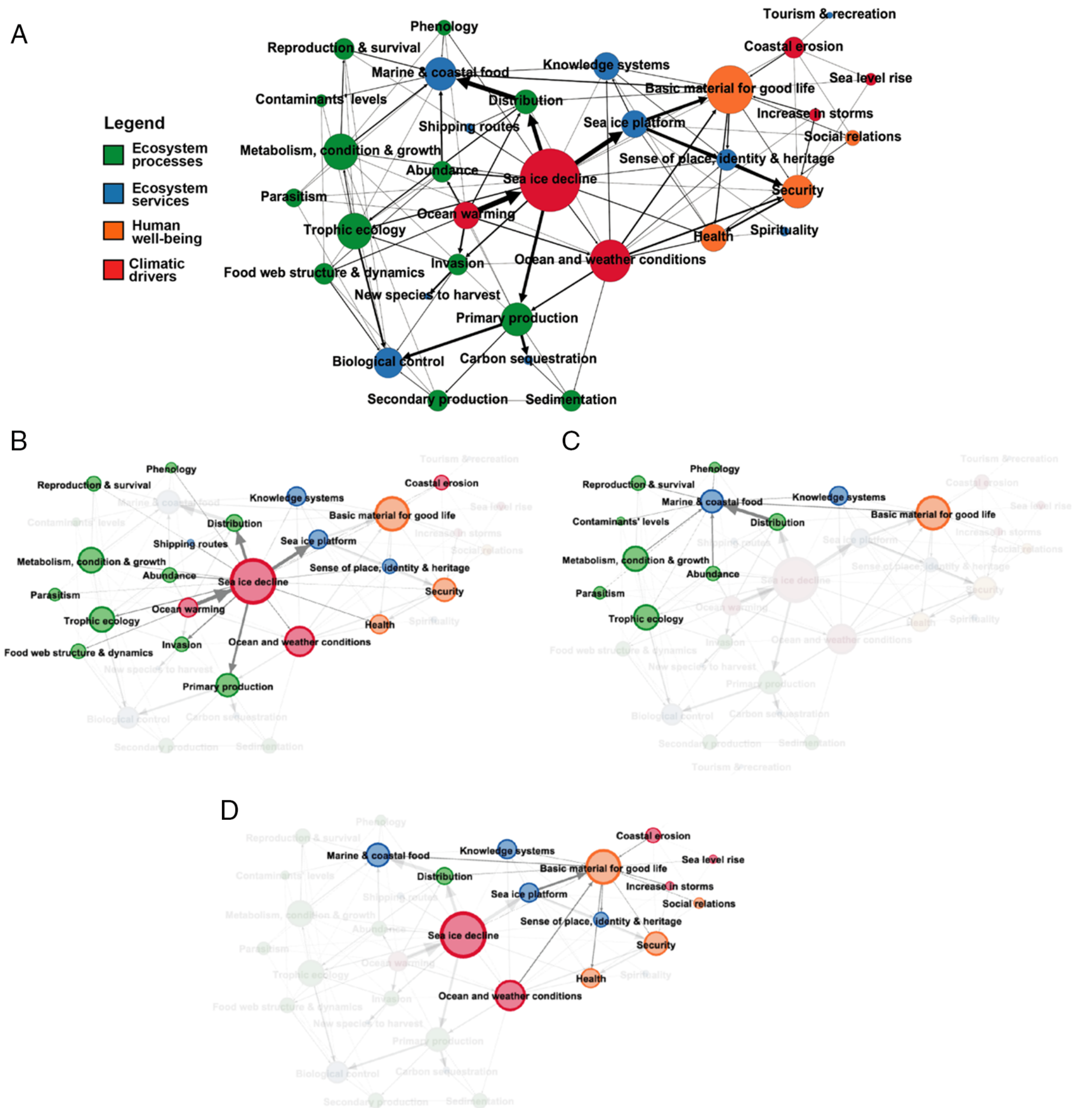
The impacts of climate change on marine ecosystems reported in our sample of peer-reviewed ACCR were complex and diverse, affecting ecosystem processes at a range of ecological levels, with implications for both the present and future provision of ES (Tables 2 and 3). Notwithstanding the wide range of impacts reported, some ecosystem changes were more studied than others. Articles on the observed impacts of climate change on ecosystem processes focused on changes in trophic ecology (i.e., feeding relationships between species; 26%), primary production (24%), invasion of species from southern latitudes (22%), and changes in Arctic species distribution (16%; Table 2). The most frequently studied impacts on ES were on marine and coastal food (50%) and biological control (57%). Studies of the future of Arctic marine ecosystems often focused on the impacts of climate change on primary production (42%), the northward expansion of boreal and temperate species (33%), as well as changes in the distribution and abundance of Arctic marine species (24% and 21% respectively). The most studied impacts of future ecosystem change on ES were on biological control (55%) and carbon sequestration (48%; Table 2). Overall, we found that impacts on single species and groups of species were more frequently studied than whole ecosystems' responses to climate change (Table 3). We additionally identified that species invasion into the Arctic is of great interest to the scientific community. At the circumpolar scale, 19% of studies observed or projected the northward expansion of marine species that could be of interest for human consumption, such as salmon from both the Pacific and Atlantic Oceans (e.g., Jensen et al. 2014; Logerwell et al. 2015).

Objectives 2 and 3: case study of Inuit regions

Observed impacts of climate change on the SES

The network of observed impacts of climate change that we developed for the SES of Inuit regions is composed of 33 nodes, including six climatic drivers, 13 ecosystem processes, 10 ES, and four human well-being constituents (Fig. 2A). All the ES and human well-being constituents from the adapted Arctic ES framework (Box 1) appear as nodes in the

Fig. 2. (A) Social-ecological network of the observed impacts of climate change in Inuit regions ($n = 63$ articles; 43 with a primary focus on ecosystem processes and 20 on ES and human well-being). The size of the nodes is proportional to their weighted degree centrality. The thickness of the edges represents their weight and is proportional to the number of times an impact was reported. In (B), (C), and (D), we highlighted three nodes (sea ice decline, marine and coastal food, and basic material for good life) with particularly high degree centrality measures. The rest of the network is greyed out to highlight the direct connections of each of these three nodes. (B) Highlight on the node with the highest weighted degree centrality, sea ice decline (91; out-degree = 74), and its direct connections; (C) highlight on the ES with the highest weighted in-degree, marine and coastal food (33), and its direct connections; (D) highlight on the human well-being constituents with the highest weighted in-degree, basic material for good life (32), and its direct connections.



final network, confirming our sense that existing studies of climate change explore a breadth of ecological, socio-economic, and cultural impacts.

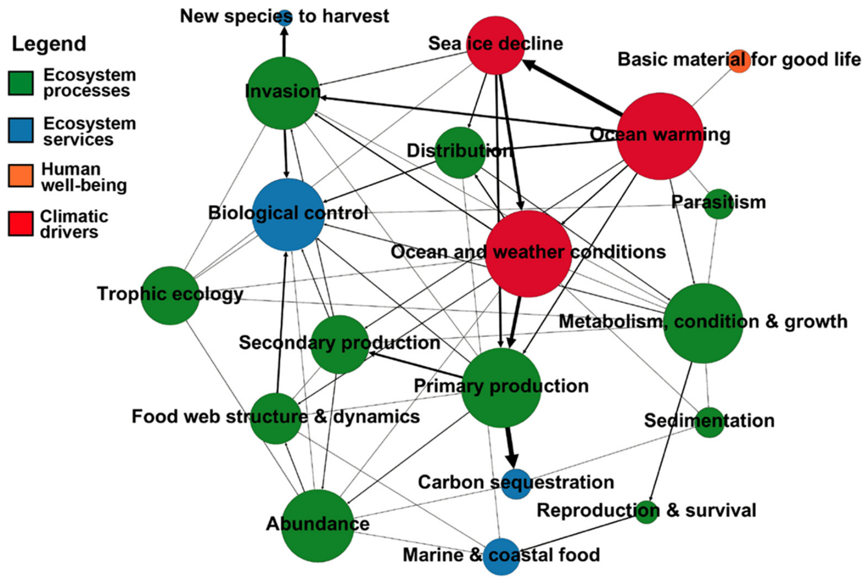
In Inuit regions, the climatic changes most studied by the scientific community are sea ice decline, warming temperatures, and changes in ocean and weather conditions (measured by the weighted degree centrality; Fig. 2A). The research analyzed shows that climatic changes impact marine ecosystem processes, with a focus on the distribution of marine animals, primary production, and trophic ecology. In turn, climatic and ecological changes alter ES, with the sea ice platform being most studied, followed by marine and coastal food, biological control, sense of place, identity and heritage, and knowledge systems. Finally, the reported impacts of climate change are shown to affect Inuit well-being, with research efforts focusing on basic material for good life, followed by security and health. Mapping ACCR with network analysis also allowed us to identify the most studied cascading effects of climate change. In particular, sea ice decline affects 58% of the nodes (Fig. 2B), with direct impacts spanning all three categories of SES components (ecosystem processes, ES, and human well-being) and cascading onto most of the other SES nodes (Fig. 2A). Changes in the distribution of marine animals in response to sea ice loss were reported most often, with cascading effects on marine and coastal food (Fig. 2C). For example, sea ice melt in Alaska impacted walrus' distribution and migrations, which affected hunters, who must now travel to new and potentially more dangerous locations to harvest animals (Fidel et al. 2014). The impacts of sea ice loss on ES and human well-being, especially the sea ice platform, marine and coastal food, knowledge systems, and security, were also shown to have cascading effects onto basic material for good life (53% of the inbound connections; Fig. 2D).

Although a large breadth of SES components (represented as nodes in the network) are studied in response to climate change, and a few edges, or impacts, have large weight (seven edges with a weight $\geq$10), we found that, overall, most impacts were weakly studied (99 edges with a weight $\leq$5; that is 88% of the edges), and some are most likely unstudied. These "missing impacts" are places where cascading effects or feedbacks most likely occur, but that were not studied in our sample of peer-reviewed articles (Box 1). For example, we found a lot of research on the effects of climate change, and especially changing sea ice conditions, on the distribution of marine animals that are harvested for human consumption (edges' weight = 13 between sea ice decline and animals' distribution, and 15 from animals' distribution to marine and coastal food). However, the cascading effects of changing marine food species on cultural services and Inuit well-being were only weakly studied. In particular, only the effects of changing food on knowledge systems (edge weight = 2) and basic material for good life (edge weight = 4) were reported, whereas the potential effects of changing Arctic marine food on the cultural service of sense of place and identity was not studied (Fig. 2C). Other potential "missing impacts" are the cascading effects of harvestable marine species expanding North on human dimensions. These were not studied at all in our sample of articles, although new harvestable species have been reported in Inuit regions (in-degree = 6; Fig. 2). Cultural services were generally less studied than other ES, especially spirituality (in-degree = 2), and tourism and recreation (in-degree = 1), as well as their interactions with other types of ES, as only 1% of articles used for the case study SES considered all three types of ES.

Projected impacts of climate change on the SES

Research on the future impacts of climate change was primarily biophysical (Fig. 3). The network included 19 nodes: three climatic changes, 11 ecosystem processes, four ES (provisioning and regulating) and only one well-being constituent — basic material for good life — from a study on the economic implications of sea ice loss (Euskirchen et al. 2013). The future climatic changes in Inuit regions most studied in our ACCR sample were ocean warming, changes in ocean and weather conditions, and sea ice decline. This differs from the network on observed impacts in which the node of sea ice decline was the most studied of all climatic changes (Fig. 2B). In part, the broader set of climatic changes

Fig. 3. Social-ecological network of the future impacts of climate change in Inuit regions ($n = 28$ articles; 27 with a primary focus on ecosystem processes and 1 on ES and Inuit well-being). The size of the nodes is proportional to their weighted degree centrality. The thickness of the edges represents their weight and is proportional to the number of times an impact was reported.



considered in research on the future might be because 96% of these articles featured quantitative modelling approaches that incorporate multiple climate proxies, whereas research on present impacts often focused on sea ice data as a proxy for climate change.

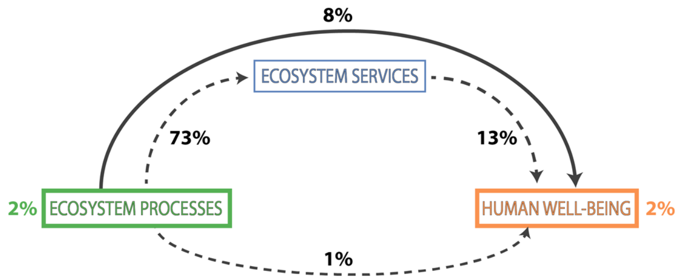
Changing primary production was a highly studied future ecosystem change, followed by species invasions. We found that 59% of primary production's connections are outbound, meaning that it is projected to funnel impacts, especially to carbon sequestration and secondary production, but also to ocean's temperature (further accelerating ocean's warming through a positive feedback; Park et al. 2015), food webs, species' abundance, and biological control. There was no research assessing the future impacts of climate change on cultural services and non-economic aspects of Inuit well-being.

Discussion

ACCR is a rapidly growing field that provides invaluable information on changing Arctic marine systems. Bringing together multiple empirical studies from across disciplines and translating findings using a common language highlights not only which aspects of climate change have been most and least frequently studied in the Arctic, but also how the reported impacts are interconnected, and which cascading effects and feedbacks have received most attention. This integration effort allowed us to identify research gaps that may limit comprehensive understanding of climate change in Arctic marine SES. In particular, we found that:

1. There were limited studies about how impacts flow from ecosystem processes to ES and Inuit well-being (8% of articles; Fig. 4). Some cascading effects and feedbacks were understudied, and "missing impacts" are likely (Box 1).
2. Research exploring cumulative impacts, that is, the interactions of climate change with other anthropogenic drivers, was uncommon (featured in just 13% of the 111 articles synthesized).

Fig. 4. Social-ecological components affected by the reported and projected impacts of climate change in the case study social-ecological system of Inuit regions ($n = 90$ articles). Percentages have been rounded and may not equal 100%.



3. Research with a primary focus on ecosystem processes tended to feature both present (64%) and future (36%) impacts of climate change, whereas research on human dimensions of climate change in Inuit regions focused primarily on the present (95%).
4. Areas researched were spatially heterogeneous; there were some research hotspots, including the Hudson Bay, and the Barents, Beaufort, Chukchi and Bering seas, and other areas that were studied relatively infrequently (Fig. 5).

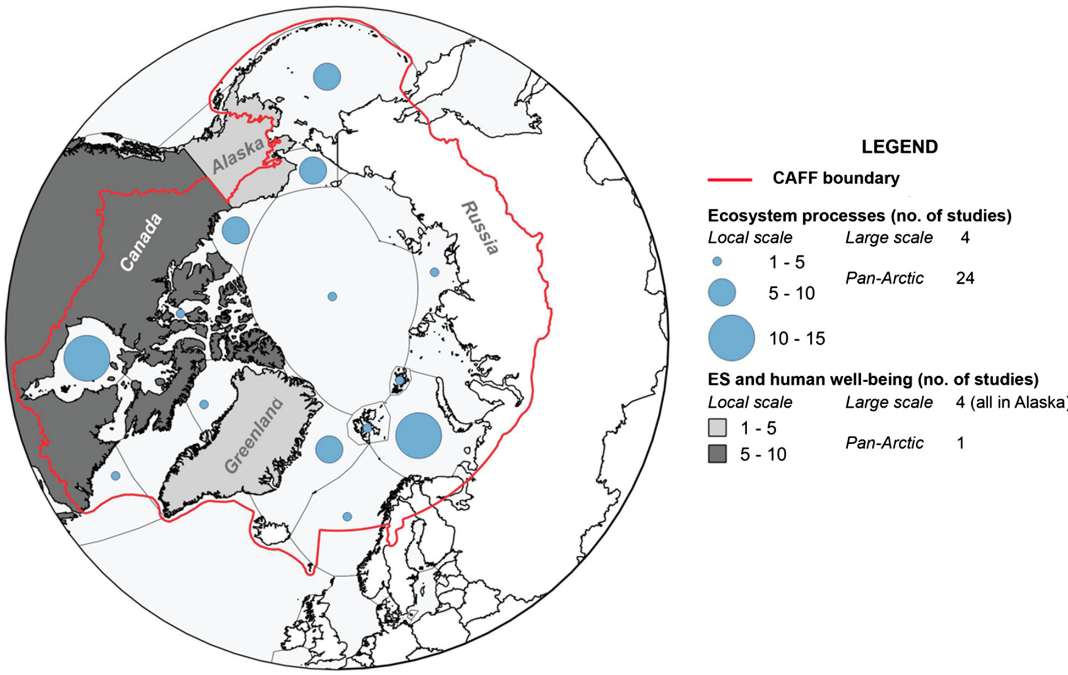
Below, we discuss each of these gaps and suggest possible ways forward to expand research on the social-ecological impacts of climate change in the marine Arctic.

Truly integrative research on Arctic marine SES is rare

Although we know that social-ecological linkages are key drivers in many systems around the world (Liu et al. 2007; Biggs et al. 2009; Guerrero et al. 2018), our systematic review of the Arctic revealed that integrated studies of social-ecological impacts in Inuit regions were not common. Articles typically focused on either ecological or social impacts of climate change, but rarely on both. Research with a primary focus on ecological impacts dominated (81%) and generally featured chains of impacts flowing from climatic changes to ecosystem processes and ES. Research on the human dimensions tended to focus on the direct effects of climate change on Inuit culture and livelihoods, but often without examining how impacts are funneled through marine ecosystem processes and ES.

Nonetheless, some integrative research has been done (Fig. 4) and this provided critical information on cascading effects and feedbacks that would have been difficult to capture with a disciplinary lens (Liu et al. 2007; Leenhardt et al. 2015). Interestingly, all the articles that we categorized as integrative were transdisciplinary, as they used consultative processes with Indigenous and local knowledge (ILK) holders (Tress et al. 2005). This emphasizes how ILK can contribute critically important information for detecting climatic changes and understanding their social-ecological implications (e.g., Fidel et al. 2014; Rosales and Chapman 2015). Integrative articles detailed both direct and indirect effects of climate change on Inuit communities, such as how sea ice loss directly caused losses to resource access, personal safety, physical health, and Inuit knowledge, or how it altered animals' distribution, abundance, or condition, and in turn affected Inuit who sustain important aspects of their well-being by harvesting Arctic marine wildlife (e.g., Gadamus 2013; Fidel et al. 2014; Voorhees et al. 2014; Rosales and Chapman 2015). Fidel et al. (2014) explored the linkages between walruses and traditions, proposing that climate-related changes in walrus distribution might have implications for traditional culture, as some people shifted to other subsistence activities or food sources in response to changing walrus movement patterns. Rosales and Chapman (2015) suggested that the erosion of Arctic coasts might lead

Fig. 5. Circumpolar overview of the Arctic climate change research compiled in this study ($n = 111$ articles). Inuit regions include Greenland, Canada, Alaska (U.S.), and the Chukotka region of Russia (in the Russian Far East). Research effort is divided by the primary focus of articles: ecosystem processes ($n = 90$ articles), or ecosystem services (ES) and human well-being ($n = 21$ articles). At the local scale, articles on ecosystem processes were spatially categorized by sea (blue circles), whereas articles on ES and human well-being were sorted based on the country of the Inuit communities where research was based (research based in one to five communities qualified as local; grey shades). Large and pan-Arctic scale articles are indicated in the legend only. Large scale articles on ecosystem processes are those covering more than three seas, whereas those on ES and human well-being covered more than five communities. Pan-Arctic research covers all areas above the conservation of Arctic flora and fauna (CAFF) Arctic boundary. The map was created in QGIS 2.18.20 (version 2.18.20; QGIS Development Team 2018). It includes three layers: the CAFF Arctic boundary (CAFF 2017), the marine regions' boundaries (Flanders Marine Institute 2012), and the world's borders (Thematic Mapping API 2009).



to the loss of areas used for travel, recreation, and traditional gatherings. This means that the effects of coastal erosion go beyond physical safety and infrastructure — they can cascade into impacts on important cultural services. Finally, only a few integrative articles examined the effects of climate change on intangible aspects of Inuit well-being. For example, sense of place and mental wellness of some harvesters have been affected by limited access to harvest grounds due to unsafe sea ice conditions, which altered their ability to maintain healthy relationships with their relatives (Cunsolo Willox et al. 2013).

Although our analysis disentangled some of the cascading effects and feedbacks that cause climate change impacts to move across the case study SES, we found that many linkages were hardly studied, with "missing impacts" likely (linkages from the adapted TEEB framework that are unstudied in the marine Arctic; Box 1), such as the implications of changing marine ecosystems for cultural services. These less- or un-studied social-ecological linkages are likely to influence how coastal communities experience climate change; for instance, the ability to access areas for fishing and hunting Arctic marine animals, and Arctic biodiversity in itself, are linked to intangible cultural values that underpin adaptive capacity, such as knowledge systems, identity and cultural survival of Indigenous peoples

(Ford et al. 2013; Huntington et al. 2013; Arctic Council 2016). These social-ecological linkages may, thus, constitute weak points where impacts can erode people's resilience (Arctic Council 2016). In contrast, some linkages may create opportunities for coastal communities, like the opening of new commercial and subsistence fisheries due to increased ocean productivity and the northward expansion of boreal species (CAFF 2015; Pecl et al. 2017). More research into these types of social-ecological linkages could help avoid unforeseen consequences and even prevent regime shifts, such as rapid socio-cultural shifts that can erode resilience, and take advantage of potential opportunities (Arctic Council 2016).

Interacting drivers and their cumulative impacts are infrequently studied in the Arctic

Climate change in the Arctic is known to exacerbate other anthropogenic drivers; for example, by allowing for more shipping and port development, in turn leading to increased pollution (e.g., Bennett et al. 2015). In addition, climate change is embedded in complex social-ecological contexts, where it is often one stressor among many others — for instance in communities that are facing pressing social issues (e.g., communities of Nunavut facing high food insecurity rates; Beaumier et al. 2015; Huntington et al. 2019), in places where social dynamics lead to different groups of people being affected differently (e.g., children, women, and Elders; Ford et al. 2012), or in regions with industrial developments (e.g., oil extraction in Alaska and the Russian Arctic; Bennett et al. 2015; Larsen and Fondahl 2015).

We found that ACCR exploring the cumulative impacts of climate change with other drivers was uncommon (only explored in 13% of all the articles synthesized). Yet, the articles that did examine drivers' interactions provided important insights on linkages where impacts may be exacerbated. For instance, marine wildlife in the Bering and Chukchi seas has been affected by the synergistic impacts of shipping and sea ice melt (Gadamus 2013; Gadamus et al. 2015), and polar bear's exposition to contaminants in East Greenland is likely influenced by both emissions (and regulations of) contaminants and climate-related shifts in their diet toward more contaminated subarctic prey (McKinney et al. 2013). How these drivers' interactions will ultimately impact the provision of ES and human well-being needs further investigation to avoid surprising outcomes (Larsen et al. 2014; CAFF 2015; ICC-Alaska 2015; Arctic Council 2016; AMAP 2017).

Current impacts to cultural services and human well-being are far more studied than their future conditions

Understanding how future changes in Arctic marine ecosystems will affect cultural services and human well-being is critical to planning for resilience (CAFF 2015; Ford et al. 2015; Arctic Council 2016). However, such research is extremely limited in ACCR, as future impacts of climate change on human dimensions were featured only in 1% of the articles used for full SES integration. The majority of research on future impacts instead focused on ecosystem processes by using quantitative statistics and modelling (93%). Those methods are powerful for studying biophysical processes but have their limits in terms of connecting to human dimensions of change (Fulton 2010; Österblom et al. 2013).

Methods designed to explore, and even model, future social-ecological changes and feedbacks could help tackle the temporal mismatch. In particular, scenarios — plausible narratives about the future — are powerful for foreseeing the future impacts of anthropogenic drivers on SES (e.g., Oteros-Rozas et al. 2015; IPBES 2016). Scenario planning, which functions as a type of "soft systems modelling" that often combines quantitative and qualitative information, has been used extensively around the world to explore alternative futures for SES (e.g., Bennett et al. 2003; MA 2005; Biggs et al. 2007). Scenarios are also often used to link ILK to scientific expertise (IPBES 2016) and might help anticipate how Arctic marine SES will respond to future climate change. The use of scenarios is nascent in the Arctic, although recently increasing, indicating that interest in this type of integrative method is growing among Arctic researchers (CAFF 2015; AMAP 2017; Flynn et al. 2018; Falardeau et al. 2019).

ACCR efforts are spatially heterogeneous

The Arctic is known to be fragmented into a multiplicity of socio-economic and cultural contexts that deeply affect the way humans depend on ES and are influenced by ecosystem change (Larsen et al. 2014; CAFF 2015; Larsen and Fondahl 2015; Arctic Council 2016). Thus, research on the impacts of climate change on ecosystem processes, ES, human well-being, and their linkages that span different geographic areas and scales is important to seize the diversity of social-ecological responses that can arise across the Arctic. However, we found that the availability of English peer-reviewed ACCR was spatially heterogeneous, with clear research hotspots for both research on ecosystem processes (especially the Hudson Bay and the Barents Sea), and that on ES and human well-being (the Canadian Arctic), versus many areas with limited research (including the Baffin Bay, the Laptev Sea, and the Central Arctic Ocean; Fig. 5). It is also noteworthy that Alaska was a hotspot of integrative research, as 88% of the integrative articles synthesized were based there.

Uneven research efforts across space, coupled with little integrative research (Gap 1), make large-scale integration difficult and perhaps incomplete (Huntington et al. 2013; Larsen et al. 2014; CAFF 2015; Larsen and Fondahl 2015; Arctic Council 2016). In particular, making assumptions about social-ecological linkages at the pan-Arctic scale by collating studies (both disciplinary and integrative) from only a few areas risks missing the influence of local contexts on the way climate change impacts ecosystems, and, in turn, is experienced by Arctic Indigenous and non-Indigenous peoples (Larsen et al. 2014; CAFF 2015; Arctic Council 2016). This is why we decided to limit our full SES integration to Inuit regions, to collate ACCR into a coherent SES, focused on one Indigenous group with a shared culture and way of life (ICC-Canada 2008). Nonetheless, our SES integration entailed some limitations, including fewer studies on the human than the ecological dimensions of climate change, which augments the risk of missing divergent responses among Inuit communities, and the use of different indicators and methods, which challenges integration (Larsen and Fondahl 2015). Ultimately, coordinated efforts to monitor and model the different SES components and their linkages across many Arctic regions and communities, and at multiple spatial scales, will help to improve integrated assessments of Arctic change (Larsen et al. 2014; CAFF 2015; SEI and SRC 2017).

Ways forward for transdisciplinary research on Arctic climate change

Unprecedented and rapid climatic changes in the Arctic are thought to create a high risk for social-ecological surprises (Arctic Council 2016). Given this context, a priority should be to study cascades and feedbacks that may lead to unforeseen consequences, and even regime shifts, in Arctic marine SES (e.g., Larsen et al. 2014; CAFF 2015; Arctic Council 2016; SEI and SRC 2017). But how can Arctic research study those impacts of climate change that move from ecological to social parts of SES and back?

Disciplinary research is no doubt essential to develop an in-depth understanding of climate change impacts in the Arctic. However, post-hoc integration of disciplinary research has important limitations that interdisciplinary and transdisciplinary research do not have (Leenhardt et al. 2015; Bourgeron et al. 2018; Guerrero et al. 2018). In particular, the aim of disciplinary research is generally to study a specific part of an SES, such as the physiological response of a fish species to warming temperatures or the effects of sea ice decline on a community's cultural values, often without attention to the linkages between these different types of impacts. Here, we identified some linkages in the Arctic-adapted TEEB framework that were under- or un-studied, which suggests that our post-hoc integration effort — mainly based on ACCR on either ecological or human dimensions of change — left some blind spots where important cascading effects and feedbacks are likely poorly understood.

Interdisciplinary and especially transdisciplinary research approaches can help to tackle these blind spots, simply because one of their goals is to assess social-ecological linkages (Liu et al. 2007; Leenhardt et al. 2015; IPBES 2016; Petrov et al. 2016; Bourgeron et al. 2018; Guerrero et al. 2018). Indeed, grappling complex SES linkages is most effective when different methods, disciplines and knowledge systems collaborate. In particular, crossing disciplinary and academic boundaries can generate new knowledge of social-ecological dynamics, such as how they operate in specific contexts, while recognizing the worldviews, needs, and priorities of rights holders (IPBES 2016; Petrov et al. 2016; Balvanera et al. 2017*a*; Tengö et al. 2017). Transdisciplinary research approaches are in line with new paradigms in Arctic research, where ILK holders are increasingly involved (CAFF 2015; Larsen and Fondahl 2015; Forbes et al. 2016; Petrov et al. 2016; AMAP 2017; Huntington et al. 2019). Although studying SES responses to anthropogenic drivers remains a great challenge in systems worldwide, interdisciplinary and transdisciplinary approaches are in rapid expansion and there are several methods that Arctic science could build upon (e.g., Cook et al. 2014; IPBES 2016; Balvanera et al. 2017*b*; Calvin and Bond-Lamberty 2018; Guerrero et al. 2018).

Assessing social-ecological dynamics at large scales is challenging given the diversity of circumpolar contexts and patchy availability of data (e.g., Larsen et al. 2014; CAFF 2015; Larsen and Fondahl 2015). Nonetheless, attempts to look into large scales should be pursued to gain insights into the breadth of ongoing and future social-ecological changes, and to detect whether changes happening in one place, might spread elsewhere (Arctic Council 2016). To this end, methods do exist (e.g., see IPBES 2016; Calvin and Bond-Lamberty 2018) and could be adapted to the Arctic (Arctic Council 2016). For instance, global or regional climate models can be combined with data (both quantitative and qualitative) on ecological and social dynamics to understand SES responses to climate change, as in Tyler et al. (2007), who studied how reindeer pastoralism may be impacted by climate change in northern Norway. More recently, an Arctic Ocean Health Index (AOHI) has been developed to assess social-ecological status of marine regions across the Arctic (Burgass et al. 2019). Although the AOHI is a promising first attempt to quantify the status of marine SES at a pan-Arctic scale, this kind of assessment is currently limited by the scarcity of primary data (Larsen et al. 2014; Burgass et al. 2019). Sometimes such large-scale integration efforts can be scaled down to regions where sufficient primary data exist, such as Alaska, where our integration was eased due to a large amount of research on the different SES components and their connections.

Interdisciplinary and transdisciplinary studies at small scales are thus important. These small-scale efforts would ideally be coordinated to use methods and indicators that are compatible for full SES integration and scale up into larger assessments (Arctic Council 2016; Bourgeron et al. 2018). Place-based integrative research, which aims at studying how social-ecological dynamics operate at small scales, includes several methods that could be applied to the Arctic (Balvanera et al. 2017*b*). For instance, expert elicitation is suited to bring together insights from ILK holders and scientists into information on SES responses to climate change and other cumulative anthropogenic drivers (e.g., see Cook et al. 2014; Singh et al. 2017). Community-based observatories also offer a small-scale solution to data collection (Burgass et al. 2019). These observatories could continuously monitor, in partnership with local communities, a range of social-ecological indicators that reflect the status of Arctic marine SES and their responses to drivers, such as data on ES and human well-being, like harvested marine mammals, the status of iconic and culturally important Arctic species, and the state of knowledge systems and food security, in parallel with climatic data

(Huntington et al. 2013; Fidel et al. 2014; CAFF 2015; Larsen and Fondahl 2015; Arctic Council 2016).

Conclusion

Knowledge of the coupled nature of Arctic marine SES has advanced tremendously in recent years (Arctic Council 2016; Petrov et al. 2016). Our synthesis of peer-reviewed ACCR shows that the impacts of climate change on Arctic marine ecosystems are diverse, with complex implications for ES and human well-being in Inuit regions. However, some social-ecological linkages are likely still overlooked or understudied, including the effects of changing marine ecosystems for cultural services that underpin people's adaptive capacity. Such linkages may play a significant role in the way coastal communities experience climate change, but we know little about them or how they function. We highlight some challenges inherent to post-hoc integration of disciplinary research that might augment the likelihood of missing important social-ecological linkages, and thus, the risk for surprises. Understanding how the impacts of climate change interact in Arctic marine SES, and the range of outcomes — both tangible and intangible — for coastal communities, is a difficult endeavour but a critical one that will require crossing disciplinary and academic boundaries. Collaborations among ILK holders and researchers from different disciplines can produce new knowledge and untangle the complexity of Arctic climate change.

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