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Emerging studies

Global ecological and economic connections in Arctic and sub-Arctic crab markets

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ABSTRACT

High latitude marine systems are experiencing climate change and other human-induced impacts that outpace global averages. Communities dependent on these systems are also undergoing complex economic and socio-ecological changes. Ecological, economic, market and community developments in Arctic and sub-Arctic crab fisheries are increasingly complex and uncertain. These escalating risks and complexities threaten well-being, social and ecological integrity of dependent communities and ecosystems. Through interdisciplinary and transdisciplinary collaboration, we examine the escalation to illustrate how global ecological and economic connections are co-evolving between nature, society, and industry. The article demonstrates how informal, integrative cooperation with broad stakeholder participation at a global scale, focused on information sharing and scientific cooperation, addresses local and regional dynamic markets and ecosystems for improved economic and ecological outcomes.

1. Introduction

The productive capacities of earth's ecosystems are changing. Both climate change and more direct human activities are drivers [1,2]. High latitude systems are experiencing the most rapid climate change [3]. Concomitantly, these regions are also experiencing complex economic and social changes, including access to and use of marine resources [4]. Economic changes are intertwined with ecological ones. Responses to

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economic and ecological changes will determine their net impacts [5]. This article lays out details and consequences of ongoing ecological and economic changes affecting Arctic and sub-Arctic crab fisheries at the global level. The aim of doing so is to illustrate how broadening scientific cooperation to include disciplines, stakeholders, and decision-makers that are relevant across the commodity supply chain can improve well-being in many diverse economic and ecological dimensions.

Coordination of scientific and managerial activities across these socio-ecological dimensions can reduce negative impacts to communities from uncertainty resulting from increasingly dynamic changes to markets and ecosystems. Fisheries-related institutional development or investments that focus on static or historical measures of competition and markets will fail to provide for potentially catastrophic ecological-economic disruptions [6–8]. This paper illustrates by example how informal, integrative institutions can and should form through broad stakeholder participation focused on information sharing and scientific cooperation to address increasingly dynamic changes to markets and ecosystems.

Traditionally productive marine ecosystems are experiencing species depletions, while the same species that are declining in established fishing areas are becoming biological invaders elsewhere [9]. Options for natural resource management depend on economic conditions relating to various ecosystem components, including uncertainty [10]. Natural resource industries often lend themselves to industrial concentration, in part to reduce such uncertainties [11], with potentially mixed consequences for both social welfare and ecosystems [12]. Positive consequences from increased cooperation amongst natural resource firms and/or governments may include greater control over product safety and quality. In the case of international natural resource commodities like crabs, reductions in overharvesting of common property resources and improved supply traceability can be benefits [11,13]. Broad stakeholder engagement typically facilitates positive socio-ecological consequences. As the economic scale of Arctic and sub-Arctic fisheries has become global, a best management strategy is to broaden stakeholder engagement to the global scale. The global inter-disciplinary collaboration presented herein to better understand factors affecting these fisheries, and the dynamic changes and uncertainties they are facing, allows for a bellwether study on global-scale ecological and economic connections co-evolving between nature and industry.

Industry costs and biological reproduction dynamics are highly differentiated across locations harvesting crabs of the same species. Regional differences in transportation capacity, costs, expectations, and incentives to exploit crab resources are increasing competition and uncertainty in these industries and increasing product prices are feeding overfishing pressures [14]. The large physical, industrial and disciplinary distances amongst stakeholders have historically deterred development of global-scale analysis and cooperation that could increase sustainable behaviors in resource exploitation. The dynamics of sustainable exploitation behaviors improve with coordination, information, and planning [6,15], highlighting the need for such coordination as presented herein.

On multiple occasions in 2017–2019, the authors of this initiative met in-full or in sub-groups in the field Alaska (2017), Japan (2017, 2019), South Korea (2017, 2019), Norway (2017, 2018, 2019), and for workshops at the headquarters for the International Council for Exploration of the Sea (ICES) in Copenhagen, Denmark (December 2017), in Seattle, WA (U.S.A.) (January 2019), and in Tromsø, Norway (November 2019). The authors, a group of diverse global stakeholders, ecologists, economists, resource and conservation managers, fish harvesters and industry representatives, used the meetings to identify priorities for understanding, and reducing, intertwined ecological and market risks in the fisheries and the ecosystems upon which they depend.

To be most effective, information sharing and joint research agendas that promote vital positive aspects of cooperation should focus on: 1) fostering integrated understanding of climate-related impacts on fisheries viability; 2) management options for smoothing ecological uncertainties across time and space; 3) diversifying risks (international agreements, cooperative research, cost-effective stock enhancement and by-product uses); and 4) sustainability and transparency in supply chains, domestic and international markets, infrastructure and other investment decisions.

The authors view the Arctic and sub-Arctic crab fisheries as harbingers of change. They are exemplar species through which to study the effects of climate change in addition to more direct market and ecological forces. Northern crab species typically have limited temperature tolerance ranges and move slowly across regions, resulting in high levels of localized adaptation [16]. Two species of these crabs - *Paralithodes camtschaticus (red king crab)* and *Chionoecetes opilio (snow crab)* – are recently established bio-invasions in the Barents Sea (i.e. northern Norway / western Russia), bringing considerable ecological, economic and institutional change to the region [17,18]. In some of their known native ranges, on the other hand, the red king crab and snow crab stocks are facing substantial declines, with accompanying economic and ecological concerns [19], though these have been at least temporarily offset by increasing prices. The disruptions happening globally on these focal species exemplify present and future impacts from climate change. Increasing rates of species distributional range shifts coupled with declining transportation challenges and increasing economic harvest incentives are leading to rapid transformation of longstanding ecological and economic relationships.

2. Current limitations in sustainable decision-making

The ability to act upon changes affecting northern crab resources is limited by fragmented and uncertain information. The current species ranges are imperfectly understood, particularly at the global scale. In recognition of this, projects such as AquaMaps, OBIS: the Ocean Biogeographic Information System, and/or the Sea Around Us now build models to generate predicted habitats, primarily for conservation purposes [20]. Maps created using available ecological information from these databases, built upon existing scientific observation and parameters, are shown in (Fig. 1). These maps highlight the spatial scale of existing knowledge gaps and identify how information sharing can improve these gaps.

The data obtained from AquaMaps on crab species range distributions provide estimated relative probabilities of species occurrences for the crabs alongside observed and recorded occurrence data, but they are incomplete. These maps use parameters with broad ranges for depth, temperature, salinity, primary production, ice coverage, and distance from land to establish probabilities [22] of suitable habitat and do not provide full information on known or suspected populations in Arctic and sub-Arctic waters. In the Barents Sea for example, where both focal species of crabs have recently established and their range of distribution continues to expand, invasion data are particularly absent. We have supplemented this gap in the invasive species range with the latest available information from regional agencies, including the Institute of Marine Research in Norway.

At least two type of additional available information relating to real-time activities highlight the benefits of increased communication and sharing within the industry and across nations. Fish harvesters themselves, for example, can share information to indicate where distributions of invading species are prominent (e.g. the initiative to detail where crab pots are fished in Norway through Barents Watch (www.barentswatch.no)), generating both increased safety information for vessels and gear, and first-hand information about where dense aggregations of the crabs are verified or suspected to be. Beyond regional information, Global Fishing Watch (www.globalfishingwatch.org) provides visualization and traceability in the industry that harvesters, NGOs and governments alike can use to understand how fishing vessels catch

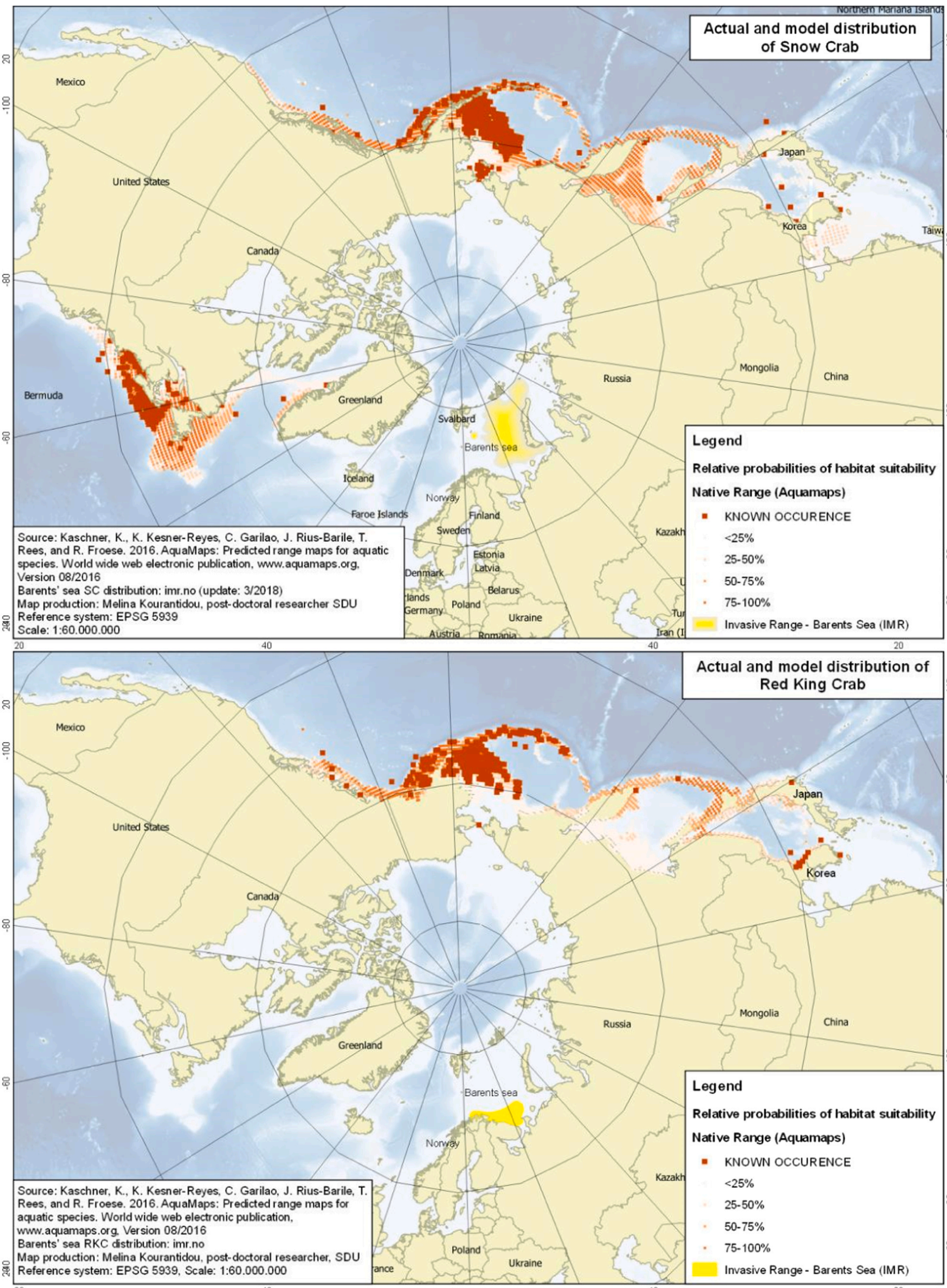

Fig. 1. Panel A: Global Distribution of Snow Crab. Panel B: Global Distributions of Red King Crab. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Sources: Invasive Ranges (Barents Sea), in yellow: Institute of Marine Research (IMR), Tromsø, Norway [21], Native Ranges: in red: AquaMaps [22], Ocean Biogeographic Information System [23].

and transport their products. With Global Fishing Watch, users must be able to associate vessels with the species they are catching. These mapping tools identify how cooperative information sharing amongst firms and other industry players can add value to both the industry in new frontiers, and our ability to monitor and regulate it.

Data are also absent for the pan-Arctic waters north of the Bering Strait all the way through to the North Atlantic, including the Beaufort, East Siberian, and Laptev Seas, where recently verified or increasing snow crab presences are associated with rising temperatures [24,25], as well as with primary production and salinity shifts resulting from shrinking ice coverage [26]. Further, there are known presences of both snow crab [25] and red king crab [26] in the White and Kara Seas [27] and the snow crab has now been confirmed in waters adjacent to Svalbard [28]. Evidence suggests rapid changes in distributions of these species, but lack of routine monitoring in new frontiers compromises the ability to make strong quantitative links between rates of climate change and rates of species redistributions, and therefore predictive assessments that could be built upon them.

As Arctic and sub-Arctic waters undergo significant ecological change, challenges loom for local and regional management of profitable Arctic and sub-Arctic crab species in the US, Canada, Greenland, Norway, Russia, Korea and Japan. The variation between the determined priorities for production, available industrial structures, market size, distance to market, and potential profitability are combined with the different considerations for ecosystems and ecosystem services, and ultimately reflected in the degree of regulation and harvest of these crabs.

3. A global perspective on evolving trends

With challenges associated with rapid changes in distributions of lucrative northern crab species in mind, a group of international participants working in natural sciences, social sciences, management and the fishing industry met as an expert group of the International Council for the Exploration of the Sea (ICES) in December 2017, with continuing communication thereafter, to jointly consider ecological, commercial, community and sustainability angles. The participants identified key areas in which international and interdisciplinary research could provide efficiencies and gains to all parties. In particular, they found that both the inherently competitive interests of regional suppliers and the consumers who benefit from this competition could be made better off through improved cooperation in understanding the ecological-economic dynamics affecting local communities. This improvement in welfare comes in part from better collective understanding of the individual steps that coastal communities have taken to respond to global shifts in markets and environmental conditions.

The invasion of Arctic and sub-Arctic crab species to new waters simultaneously occurs as existing fish and shellfish stocks face declines due to overexploitation and environmental changes. The crabs in their non-native areas of distribution therefore represent not only invasive species problems, but also valuable commodities in a world of depleting stocks [18,29–31]. Accompanying global rising incomes, increased demand for seafood [32,33] and improved transportation logistics that bring buyers and sellers closer together are shifting the structure of the global industry in harvest and trade in these species. These shifts are complex, creating new beneficiaries and new costs both directly in the fisheries and indirectly through changes in ecosystem characteristics. These latter impacts are particularly poorly understood, though the changes in the fisheries themselves are also hard to decompose and analyze without the global perspective gathered and presented here.

4. Climate and economy related impacts on fisheries viability and management

Over time, the total global catch of snow crab and red king crab has oscillated with an overall upward trend, and it has been generally increasing since the beginning of the millennium, as illustrated in (Fig. 2, Panel A. Fig. 2, Panel A) and (Fig. 3) together illustrate how production has grown and shifted amongst nations and species since the middle of the past century. In the 1960s and 1970s Japan dominated global catch, in the 1980s and 1990s the US led production, and today Canada is the leading producer of the large, internationally marketed crabs.

S. Korea does not separate *C. opilio* (the internationally traded snow crab) from *C. japonicus* in the Food and Agriculture Organization (FAO) data used in the graphs. *C. japonicus* is mostly consumed domestically or regionally, so that the country's large harvests in recent years reflect mainly increased catch of the smaller *C. japonicus*, though the total value of the two harvests is similar [34]. There has been a prominent shift from king crabs (*Paralithodes spp.*) to snow crabs (*Chionoecetes spp.*) after the mid-1970s, shown in (Fig. 2, Panel B) and (Fig. 3 (king crabs in red shades, snow crabs in blue shades)). In addition, the rise in Japan and S. Korea of snow crab catch is mainly the less valuable *C. japonicus*. The extent to which this may be a 'fishing down the food chain' concern versus a market response to income and price shifts from one product type to another is unclear [35,36]. The question represents the type of concern our call for interdisciplinary, international cooperation can address.

The very small relative catches for Norway illustrate how the addition of commercial species to the Barents, which has created significant disruption and change in Northern Norway [18,38] has only slightly added to global stocks to date. At the same time, there are both high expectations and high uncertainty about the future spread of snow crab in particular [39]. Better estimates of Norway's potential productivity can come from analyzing the wider set of ecological and economic data achieved by pooling information across fisheries and regions. This group is currently pursuing exactly such work.

Information sharing across the fisheries on management can also benefit a wide range of stakeholders. The economic and management characteristics of the crab fisheries generating the global catches shown in (Figs. 2 and 3) range widely over time and space. Current management characteristics are summarized in (Table 1), for species engaged in international trade. Information over time on management conditions and their changes within fisheries or regions that could be used to explore the dynamics illustrated in (Fig. 3) has proven difficult to collate, as vocabularies, management concepts, and responsible agencies are not consistent across countries or time; this valuable effort is left for future work.

The challenges of compiling (Table 1), and adding a temporal dimension, provide further insight into the benefits of cooperation and communication. Some countries, like Canada, have formal integrated management plans that differ across regions, all easily accessible [40], but no national overview or easily understood timeline of management changes. Many Canadian and other fisheries have specific gear restrictions for different fleets, and fisheries may be subsistence, indigenous, artisanal or commercial. They have generally evolved over time toward greater co-management, with a notable shift in management philosophy following the collapse of east coast groundfish stocks in the early 1990s [41], but beyond this notable event there is a lack of clear timelines as to when, how, or why, management strategies have evolved.

C. japonicus is not included here in the overview of regulations; the species is, however, subject to various local fishing community

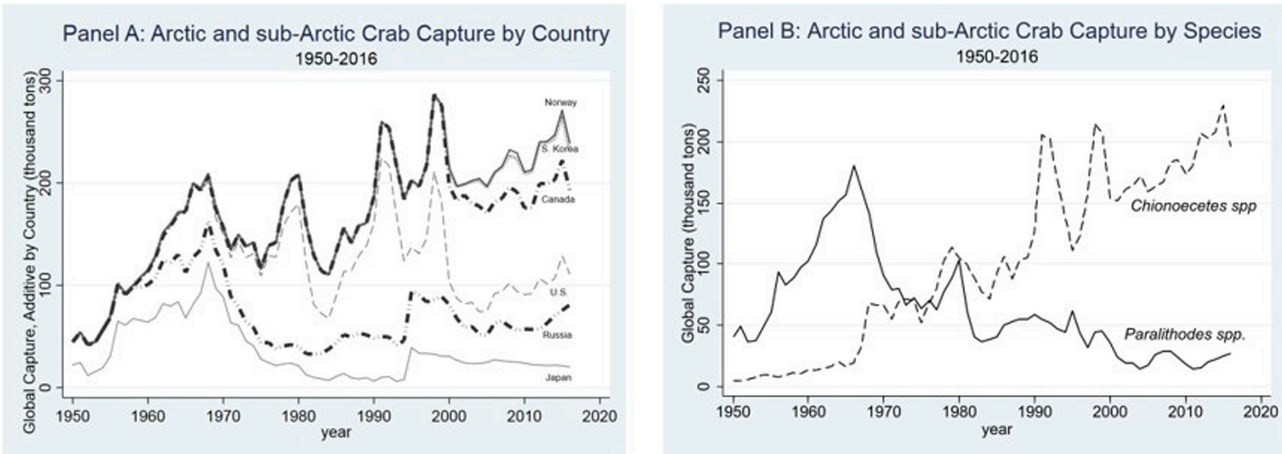

Fig. 2. Panel A: Global capture of major Arctic and sub-Arctic species by country of capture, 1950–2016. Panel B: Global capture by genus, 1950–2016.
Source: [37].

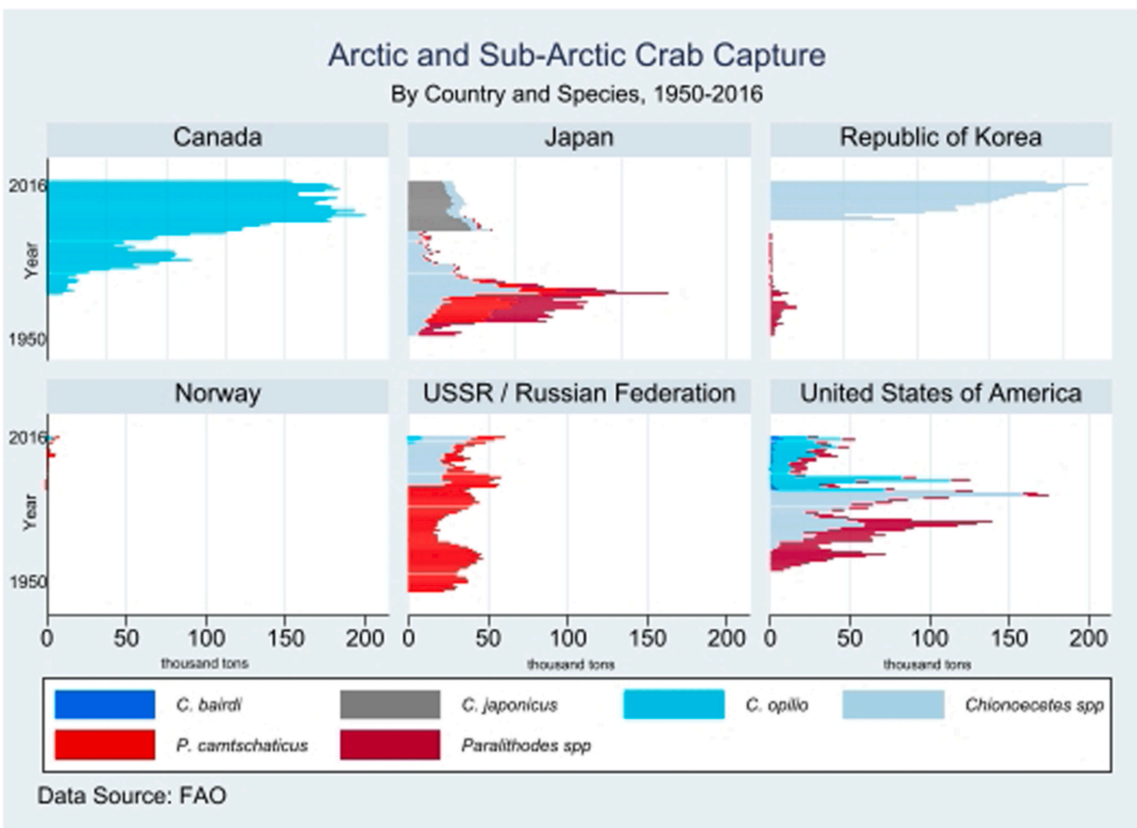

Fig. 3. Arctic and Sub-Arctic Crab Harvests by Country and Species, 1950–2016. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
Source: [37].

regulations in Japan and S. Korea. In S. Korea the species is regulated within a total allowable catch (TAC) system allocated based on acceptable biological catch (ABC), like *C. opilio* [34]. Fishing pressures on *C. japonicus* are high and can be expected to increase overall as the generally preferred substitute, *C. opilio*, becomes more expensive. The significant price gap between the two species also drives economic incentives to promote fraud, which can be reduced through biological testing [42]. A similar relationship exists between *C. opilio* and *C. bairdi*, the latter generally commanding a higher price. Interdisciplinary information sharing and cooperation benefits society in this case by, among other things, maintaining product quality.

In Japan, offshore trawl vessels operate in both nearshore prefecture- and offshore ministry- managed waters [43,44], with additional gear possibilities, e.g. nearshore pots, under various local fishery management association rules. In Norway, the fisheries include both small-vessel coastal (red king crab) and larger vessel offshore (snow crab) fisheries. Russian and Alaskan crab fisheries are both large-scale offshore commercial operations with pots or trawls and, at times,

Table 1
Management efforts for main Arctic/sub-Arctic crab species in international trade.

Country (Area)	Species	Management Goals (private or public)	Regulatory levels	Regulatory Environment	Assessment Effort
USA (Pacific)	RKC	MSY	State/Federal	Rationalization, TAC	H
			State (AK)	TAC, Closed areas, 3-S	H
USA (Pacific)	SC	MSY	State/Federal	Rationalization, 3-S	H
USA (Atlantic)	*no commercial fisheries for RKC or SC*				
Canada (Pacific)	*no commercial fisheries for RKC or SC*				
Canada (Atlantic)	SC	Part MSC Certified[a]	Federal	Rationalization	
			4 regions[b]	Closed areas, 3-S	H
Greenland	SC	Goal setting in progress	National	Annual TAC, area quotas	M
Norway	RKC	Containment (OAA)	National	Open access	M
		Long term fishery (QRA)	District (Finnmark)	2-S	H
				Personal quota[c]	
Norway	SC	Sustainable fishery	National	Vessel license[d]	H
Russia (Pacific)	RKC	MSY, ABC	National	TAC, Closed areas, 3-S	H
Russia (Pacific)	SC	MSY, ABC	National	TAC, Closed areas, 3-S	H
Russia (Barents)	RKC	MSC Certified	National	TAC, Closed areas, 3-S	H
Russia (Barents)	SC	ABC	National	TAC, Closed areas, 3-S	H
S. Korea	SC	ABC	National	TAC[e], 3-S	M
Japan	RKC	No formally stated goal	Federal	2-S	L
			State (HKD)	Additional restrictions	
Japan	SC	ABC	Federal	2-S	M
			State	TAC differentials	

Abbreviations:
2-S: Size and Sex restrictions on harvest
3-S: Size, Sex and Seasonal restrictions on harvest
ABC: Allowable Biological Catch
MSC: Marine Stewardship Council
MSY: Maximum Sustainable Yield
OAA: Open Access Area
QRA: Quota Regulated Area
RKC: Red King Crab (P. Kamtchaticus)
SC: Snow Crab (C. opilio and C. bairdi)
TAC: Total Allowable Catch allocations
VMS: Vessel Monitoring System
Notes:
Assessment Effort, Annual Stock:
H (High): Annual trawl & pot surveys, Annual Science Advisory Reports, Historical catch data driven (Logbooks, Landing Statistics), VMS and observer data, additional episodic scientific research
M (Moderate): Primarily annual survey and/or catch data assessment
L (Low): No formal assessment
[a] Precautionary approach primary when stocks incaution zone; socio-economic forces, when stocks in healthy zone.
[b] Canadian SC regions: Gulf of St. Lawrence, Newfoundland/Labrador, Maritimes, Quebec.
[c] Personal quota connected to value of additional fisheries activities by individual.
[d] Vessel license requires quota holdings in other Barents fisheries.
[e] One quarter of TAC allocated to individual vessels in the major fisheries of inshore gill-net, and inshore trap.

on-board freezer processing, where the same vessels may be used for both species. The Canadian fisheries are conducted in small vessels separated into a mixture of fleet sectors ranging from smallest (< 35 ft) vessels in coastal areas to largest (65–90 ft) vessels in offshore areas and are only prosecuted using pots [45]. Better understanding of the trade-offs inherent in the profitability and distribution of socio-economic gains across these different fisheries prosecution strategies can inform on fisheries dependent community development strategies, for example downstream processing regulations found in Alaska or Greenland.

The range of monitoring and management systems across countries spans from very little, if any, accounting for stocks to annual assessment and consultation meetings incorporating industry stakeholders, scientists and regulators. Under-investments in monitoring both economic and ecological spaces make cooperative agreements for reducing Illegal, Undocumented and Unregulated (IUU) fishing or for fending off the spread of invasive species more difficult.

Resource surveys and biological accounting systems for the crabs, and the use of those data to generate stock assessments, range widely as well. Overall, the effects of climate shifts on crab stocks are not well understood and have not been studied to a large extent in the scholarly literature. Part of the 'cyclicality' visible in [Fig. 2 (Panel A)] can be explained by changes in fishing pressure; for example, management and governance changes such as the creation and enforcement of Exclusive Economic Zones over the past decades. EEZs have enabled a wide variety of additional governance actions that restricted open access, increased the tractability of international environmental agreements, and led to recovery in some overexploited stocks [46].

Some changes in global capture, however, can be directly related to a combination of economic activity and ecological change. The increase in Canadian harvests beginning in the 1980s and growing significantly through the late 1990s reflects both increased abundance and increased economic interest in snow crab following the collapse of groundfish fisheries and their supporting ecosystem [47,48]. A closer account of the evolution of the Newfoundland and Labrador snow crab fishery, for example, can be found in its Integrated Fisheries Management Plan. The plan directly addresses the interdependency of the ecological conditions for crab and the management actions that have been and will be taken for both inshore and offshore snow crab fisheries [49].

The sustained, increased output in Canada over almost two decades now faces growing uncertainty over price, quantity, and other key variables not only from availability of crab but also from wide ramifications from the novel coronavirus' impacts on maritime safety, crab processing and markets. These latter uncertainties are not limited to Canada and highlight the interconnected market forces. The virus, for example, delayed the start of the fisheries' 2020 seasons and it was speculated that it would affect production of catch and processing up to 30% for some portions of Newfoundland and Labrador and Gulf of St Lawrence regions [50,51], though this concern did not materialize. At the same time, market highs for prices at the beginning of 2020 [52] have been replaced by deep price drops for virtually all cold water crab species as luxury food markets decline [53]. The global expectation and norm in the marketplace have been growth in Canadian supply for two decades alongside Alaskan declines, as shown in (Fig. 3) [54]; this is now replaced with both demand- and supply- side shifts whose long-term impacts are highly uncertain. Outlooks and planning in the local fisheries will benefit from a more global perspective achieved through broader engagement at this level.

Our global approach seeks to deepen the understanding of economic and physical determinants of the global crab capture and production. In this context, the various stages of industry development are viewed as a continuum of opportunities and challenges in real time. This variation stems from both the new populations resulting from species invasions and new management structures imposed to curb overharvesting and overcapitalization. A systems approach to problems posed and solutions attempted with different conditions is improving the information flow amongst stakeholders and those implementing regulation and governance in ways that may yield more efficient societal outcomes from global crab populations in a context of the 'fisheries ecosystem'.

5. Risk diversifying strategies through cooperative research

Focal points for cooperation include acknowledgment of how increased diversification strategies, intended to smooth climate uncertainties, might require international and regional agreements to enable cooperation for global sustainability.

Furthermore, diversification and risk mitigation might be enabled through industry and interdisciplinary scientific research in addition to policy channels, particularly with respect to information sharing among different regions where crabs are commercially fished (and marketed), and across disciplines, particularly where results from individual disciplines can feed into each other to improve overall understanding and decision-making.

Information exchange and sharing may include building a joint understanding of (a) ecological challenges across space, ranging from invasion in the Barents Sea, to shifting recruitment and stock patterns in the Bering Sea [55,56] or declining recruitment and stock fluctuations in Newfoundland and Labrador [49] to possible climate driven stock shifts as well as (b) socioeconomic and management challenges associated with illegal, unreported and unregulated (IUU) fishing [13], management efficiency, measures and trade-offs between implementing a precautionary approach and sustaining livelihoods in coastal communities that are dependent on the crab fisheries.

Cooperative research across space and disciplines is key in diversifying risk. It can help address socio-ecological issues not commonly explored in coastal and marine research for the study of the same species produced in different regions. Interdisciplinary efforts, such as our meetings, can address how shifting anthropogenic landscapes influence the dynamics within coastal communities and the effects on fishing mortality, stocks and compliance with management measures. The participants agreed at the December 2017 ICES group meeting that safeguarding social interests and achieving long-term sustainable management of stocks requires that social and economic behaviors of actors involved are considered alongside the study of climate shifts and ecological dynamics. Interdisciplinary and transdisciplinary efforts that integrate social and ecological systems can help build successful holistic resource management. The need for (a) transcending traditional disciplinary boundaries and (b) broadly including societal collaborators as well as academics in decision-making is widely recognized when addressing marine resource management challenges [57,58]. Such efforts are currently absent for many fisheries around the world, including the crab fisheries we examine in this paper. The approach proposed by the ICES group focuses on intersecting biology, ecology and economics for optimal management of native and invasive crab fisheries at a global level.

5.1. Stock enhancement and recovery

Cooperative research can also seek to enhance regional efforts to understand the potential for stock recovery and enhancement efforts such as those underway in Alaska [59] and Russia [60]. By integrating information from the ecological processes of the invasions in the Barents Sea, scientists may be able to improve outcomes from large scale hatchery releases. Currently, questions regarding how successful hatchery rearing might occur at higher density, and therefore become more cost effective, remain [61]. This research would also expand naturally to better understanding of the potential and actual climate-driven changes in ocean and coastal conditions, affecting marine living organisms (including the snow crab), which are also underway in Atlantic Canada [62,63].

5.2. Understanding market conditions

Better information sharing about harvest conditions can improve connections between sellers and buyers, including implementations of sustainability measures and efforts to reduce IUU fisheries [13]. Whether demand for sustainable crab catches is strong enough to cover additional costs remains an unanswered question, although preliminary evidence from Norwegian enterprises involved in origin-to-plate supply chain tracking [64] indicates consumer willingness to pay a premium for high quality live-crab with sustainability certification.

Some further mixed evidence comes from recent Marine Stewardship Council (MSC) certification changes in crab fisheries. The costly certification endeavor can be considered an investment to recoup through higher prices; without the potential for higher prices, or with high compliance costs, fisheries are unlikely to certify. While several snow crab fisheries have become certified (Russian Barents, two regional Canadian fisheries), the only certified red king crab fishery is the one operated by the small Russian Barents Crab Catchers of North fleet, which became certified in 2018 [29]. The Quebec (Canada) AQIP snow crab trap fishery is currently under assessment. The Gulf of St. Lawrence snow crab fishery certification was suspended in 2018 due to gear entanglements with marine mammals, while the Kyoto Danish Seine Fishery Federation's flounder and snow crab fleet – the first and only Japanese fishery of any sort to be MSC certified, in 2008 – has recently been withdrawn from re-certification (in 2019) after suspension in 2017 due to conflicting management goals [65]. The lack of consensus regarding the net benefits of certification further underscores the fluctuating conditions for the crab fisheries and the need for multidisciplinary, international understanding of the ecological and economic conditions.

Lower-cost live crabs delivered to Asian markets by ship from Eastern Russia have been increasingly supplemented by higher cost live crabs from the Norwegian Barents Sea. Fallout impacts from the novel coronavirus may reverse these trends, however, and reinforce the marginality of the Norwegian supply [66]. The growing success in long-distance export of high value crabs to traditional Asian crab markets in Japan and S. Korea has led to the setup of infrastructure for American trial efforts to deliver live crab to Shanghai [67]. The need for a constant supply of high-quality products is expanding the investment in infrastructure and advances in fisheries science for international suppliers across geographical locations. Investments in certification are increasing. There are also significantly different preferences for live, fresh or frozen crab products, regardless of certification, which are important for both regional management and profitability and investment decisions.

These differences in consumer preferences, along with different shelf lives and/or packaging and transport conditions for live, fresh and frozen crab, create natural segmentation of the markets for crab. Generic crab species have been shown to be generally both income and price elastic in Japan [68], while for the US, they have been shown to be inelastic [69], or price inelastic but income elastic [70,71]. On the other hand, more specific estimates of demand elasticity for Alaskan red king crab are high, indicating significant substitutability [72]. The substitutability in the consumer market does not equate to substitutability in production, however, ecologically or economically; the Barents Sea crabs' status as invaders and market newcomers create quite distinct impacts in comparison to those of the long-established crab populations and markets in the rest of the Arctic and sub-Arctic.

Norway's quick shift from frozen red king crab products to live products in the last decade has brought significant price increases per kilogram across the supply chain, and snow crab harvesters are hoping to replicate these gains if they can solve live storage needs that differ between the two species [73]. This interdisciplinary biological and economic challenge is one of many where the market and infrastructure conditions create path dependencies that will determine the long run interest and viability of the fishery. Failure to maintain viable market conditions for the crabs in the Barents, for example, will mean that alternatives to markets should be considered for responding to the invasive aspects of their presence there, and in particular the threats that the species may move into new ecosystems and/or jurisdictions [18].

Norway has also exploited the rapid growth of the invasive species in responding to the existing seasonal constraints on competitor's supplies from Alaska and Russia. The country has opened the red king crab fishery year-round [73], whereas the Pacific supplies are generally limited to fall and winter. The effectiveness of this change in market profitability will depend on the willingness of consumers to consume the crabs outside of the traditional seasons, which is in turn a factor of the quality characteristics of the crab. The potential consequences in terms of managing the resource as both an invasive species and a commercially desirable commodity is an intriguing unknown; year-round pressure may e.g. reduce recruitment, favoring invasive species management over commercial management. Quality, processing capability, and marketability are expected to be lower for at least part of the time that the fisheries are closed elsewhere, due to molting [74,75]. Through the process of trying to market live crabs year-round in South Korea, Norway is slowly learning that market conditions consist of more than selling to the highest anonymous bidder; greater understanding of market behaviors and strategies is needed for long term sustainability [76].

5.3. Developing by-product uses

It is estimated that 30% of captured crab biomass is available for by-products after processing [77,78]. As of today, most by-products from the Norwegian crab fisheries are discarded or dumped at sea [73]. In Alaska some snow crab and red king crab processors produce fishmeal from the waste, while some grind and discard the waste at sea or close to shore [79], often resulting in additional costs to the producers [80]. Research has shown potentially valuable products in crab tails, roe and fish sauce from gills [78,81]. Furthermore, processed by-product potential has been shown in omega-3 rich oil, chitin, minerals, shell meal and proteinaceous compounds [77,80,82–84]. Before either of these products can be used in an economically sustainable way, there are research challenges that must be solved. These include market demand and possibilities to expand demand, processing, and economic assessment that includes investment- and processing costs. Overcoming these challenges is expected to deliver on a great potential valorization of by-products from red king and snow crabs, and by combining biotechnological processes with scaling-up possibilities and market knowledge, a new by-product derived industry has a high profitability potential [73].

Norway's small catch levels, which result in 'every crab counting,' combined with societal interest and investment in fisheries make the country a natural leader in these developments and research, from which all countries' fisheries stand to gain. Cooperative research can broaden and hasten results in this sector.

5.4. Sustainable investment decisions

Through the multidisciplinary academic, governance and stakeholder ICES group, new and unexpected questions of scale and scope can also be addressed. For example, given the evidence provided from recent rising prices and lowered costs in recent years up through 2019, it was not ecologically realistic to imagine that Norway's small-scale fisheries for crab could grow to meet demands sufficiently without significant impacts to the Barents' benthos. In Russian waters of the Barents Sea, the invasive snow crab has been deemed the biggest contributor to top-down regulation of the benthic community [85]. Impacts from the novel coronavirus, however, have changed the short run outlook and highlighted many ecological and economic interdependencies as well as the importance of interdisciplinary risk management. The virus's impacts may require more flexible thinking about measurement and management of catch in 2020 and 2021, at the very least.

Despite current and unknown short-term ramifications of the coronavirus, long run expectations for high pressures on crab populations have not changed significantly at this point, though conversations are turning more seriously to how to shorten and localize supply chains in food commodities [86], which, if taken up by crab consumers, would have dramatic long term impacts on these Arctic and sub-Arctic fisheries. Alternative strategies for harvest, transport and trade that can deepen and broaden the productivity of the natural capital can benefit the long and short runs and increase overall resilience. Such strategies could potentially take the form of increased aquaculture through stock enhancement at the post-larval stage [59,61]. The choices made regarding investments require extensive dialog between industry and science to identify the combined ecological and economic stumbling blocks to progress.

Choices surrounding production methods should also reflect flexibility and diversification. For example, investments in stock enhancement of the crabs that are carefully tuned to life-cycle vulnerabilities may need further adjustments over time as climate change and related impacts such as ocean acidification change the framework conditions for ecosystem productivity.

6. Missing elements for improved analysis and implications for future markets

Representation within the ICES group covered all of the producing and most of the major consumer nations, with the exception of China, where crab consumption has been rapidly rising. Continuous expansion of China's domestic consumption has the potential to change the established market dynamics for both international suppliers and neighboring Asian markets [87].

Market dynamics in Asia have recently relied on South Korea as a distribution hub for international supply (re-exports) to other countries. Almost 40% of the live red king crab that enters the South Korean market is re-exported to other countries, 40% of which is redistributed to China, Hong Kong and Macau, another 40% to the US and Canada and 10% to other Asian countries [88]. Although most of the product is considered to be from certified Russian origins, there remain concerns regarding the commercialization of potentially undetected IUU Russian or North Korean catch, in spite of the 2009 Korea-Russia agreement to prevent IUU fishing [89] by utilizing origin certificates for crab products re-exported from South Korea [13,90]. In an effort to increase transparency, China and Russia, which also have had an IUU fishing agreement since 2012 [91], are developing closer distribution methods.

Changes in market dynamics are expected to show that Chinese domestic markets for red king and snow crabs will directly absorb a large share of the increased export volumes from Russia by replacing previous imports from US and Japan for 2018 [92]. The growth in Chinese markets stems from an overall rapid expansion in consumption of international seafood products to supplement domestic production and high seas catches [93]. At the same time, Russian exports have become more competitive through e.g. higher 2018 TACs [92] and a redistribution of quota allocations [94] that has increased the availability of Russian products for Chinese consumers.

Another mechanism bringing higher volume directly to China is a new bypass of the South Korean wholesale business, expanding the market. In contrast, US-China trade disruptions due to tariff escalations are moving Chinese customers away from US seafood product by increasing the price in a highly price sensitive market; substitute producers and species, like American lobster from (*Homarus americanus*) from Canadian waters, are filling the gaps. Such changes in the markets highlight the fast response of both consumers and suppliers to assess risks and explore available opportunities.

Understanding these global market dynamics through integrated, cross-disciplinary efforts and collaboration is paramount to sustainable long-term crab fisheries management. Without this understanding, uncertainties on crab production and optimal stocks, which could be reduced, may persist and that management actions may not yield the expected socioeconomic welfare.

7. Conclusions

We should anticipate that the same global shifts happening in the crab industry will develop in many fisheries as climate change and related impacts, or human interventions in ecosystem productivity, affect the distributions and abundances of species. The lessons the ICES group identified as key for research needs and policy guidance include better understanding of how:

- decision-making at various scales affects the dynamics of ecosystem productivity;
- investments in physical capital, including both fleet and on-shore investments, feed back into decisions that impact natural capital and its resource flows;
- segmented market demands and high substitutability may make these investments less resilient to ecosystem and economic change;
- spatial and product differentiation may alleviate some of these concerns.

Increases in resilience to both climatic and market shifts may be especially aided by greater cooperation amongst scientists and across scientific fields, as well as better communication between resource managers and resource users. The group's work, which is a first attempt to piece together sustainability challenges in production and supply of Arctic and sub-Arctic crabs, aims to contribute to interdisciplinary efforts that address how regional changes in marine environments and market shifts influence the global dynamics of socio-ecological systems.

Management decisions at the local level are expected to have increasingly global spillover effects as stocks move in response to climate impetus. The feedback effects of shifting transactions costs in world markets will also increase the ways in which decisions in one fishing community will influence outcomes in another. New marketing approaches including branding and investments in product quality may serve to better meet the needs of demand segmented based on quality ranging from live, individualized deliveries to market to large scale industrial production's supply chain transparency. These approaches will benefit from increased global perspective that aims to reduce instabilities in supply from changes in ecosystem and economic productivity.

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