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Report of the 2024 Snow Crab Workshop: Clawing Their Way Back; A Comparative Newfoundland–Alaska Snow Crab Workshop Toward Sustainable Management in Uncertain Times

by

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Alaska Department of Fish and Game Divisions of Sport Fish and Commercial Fisheries

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Weights and measures (metric)	
centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm
Weights and measures (English)	
cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd
Time and temperature	
day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s
Physics and chemistry	
all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

General	
Alaska Administrative Code	AAC
all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.
all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.
at	@
compass directions:	
east	E
north	N
south	S
west	W
copyright	©
corporate suffixes:	
Company	Co.
Corporation	Corp.
Incorporated	Inc.
Limited	Ltd.
District of Columbia	D.C.
et alii (and others)	et al.
et cetera (and so forth)	etc.
exempli gratia (for example)	e.g.
Federal Information Code	FIC
id est (that is)	i.e.
latitude or longitude	lat or long
monetary symbols (U.S.)	$, ¢
months (tables and figures): first three letters	Jan,...,Dec
registered trademark	®
trademark	™
United States (adjective)	U.S.
United States of America (noun)	USA
U.S.C.	United States Code
U.S. state	use two-letter abbreviations (e.g., AK, WA)

Mathematics, statistics	
all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	e
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	E
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	log_2, etc.
minute (angular)	′
not significant	NS
null hypothesis	H_O
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	″
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

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REPORT OF THE 2024 SNOW CRAB WORKSHOP: CLAWING THEIR WAY BACK; A COMPARATIVE NEWFOUNDLAND–ALASKA SNOW CRAB WORKSHOP TOWARD SUSTAINABLE MANAGEMENT IN UNCERTAIN TIMES

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ABSTRACT

An international workshop on snow crabs (*Chionoecetes opilio*) was convened from 29 April through 2 May 2024, in St. John's, Newfoundland, Canada. It was jointly organized by Fisheries and Oceans Canada and the Bering Sea Fisheries Research Foundation (based in Seattle, Washington, USA) and was hosted by the Fisheries and Marine Institute of the Memorial University of Newfoundland. The workshop was convened to allow researchers and industry partners from Atlantic and Pacific regions to share information regarding the dynamics of their stocks, approaches to management, and plan for the future. A catalyst for the workshop was the collapse of the eastern Bering Sea (EBS) snow crab stock during 2018–2021, which caused an economic disaster for fishery stakeholders and fishing communities across the Pacific Northwest and Alaska. US Disaster relief funding is available to support fishers in Alaska, and a portion of these funds are available to fund research. The development of research recommendations formed an important component of the discussions.

Keywords: assessment, biology, *Chionoecetes opilio*, crab, distribution, ecosystem dynamics, fishing mortality, fisheries management, growth, natural mortality, predation, recruitment, research, snow crab, spatial dynamics, workshop

EXECUTIVE SUMMARY

Workshop presentations were organized by topic within 3 primary theme sessions:

- Theme 1: Physical Ecosystem Dynamics included presentations on the dynamics of atmospheric and ocean circulation, air and sea temperatures, and sea ice in the eastern Bering Sea (EBS), Newfoundland and Labrador (NL), Gulf of St. Lawrence (GSL), and Barents Sea, as well as ecosystem approaches for each region.
- Theme 2: Exploratory Population Modeling included presentations on modeling spatial dynamics of snow crab populations and fishing fleets using a variety of different techniques among regions, considerations of predation of snow crab in the eastern Bering Sea and coast of Newfoundland, considerations of skip molting in population models, and an analysis of the formerly strong correlation between NL and EBS stocks of snow crab that has no longer held since 2020.
- Theme 3: Applied Management included talks on innovations in snow crab pots (traps), application of indicators of stock health to fishery management in the EBS and NL, considerations of legal size, precautionary approaches to fishery management, and comparisons of harvest rates and stock outcomes in the EBS and NL.

Research presented during this workshop, including comparisons among North Pacific and North Atlantic stocks, yielded a number of important findings relevant to snow crab fishery management. These included:

THE ROLE OF CLIMATE ON SNOW CRAB PRODUCTIVITY

- Snow crab is an Arctic species that thrives in cold water. In NL, the cold intermediate layer (CIL) is most important to snow crab, whereas in the EBS it is the cold pool. In NL, cold water and sea ice data lags match well with abundance of age-1 snow crab. Most of the NL shelf is dominated by cold water in summer. In the EBS, the bottom cold pool in summer is a function of sea-ice extent the previous winter. A difference across the regions is the presence of the cold arctic-origin Labrador Current in NL.
- Bottom temperatures and sea ice covary with the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices, which describe fluctuations in surface atmospheric pressure that influence the strength and direction of winds and storm tracks in northern latitudes. Fishable snow crab biomass has a 5–9 year lag from fluctuations in the NAO.

- At least 2 mechanisms may be responsible for the relationship between cold temperatures and snow crab productivity: (1) cold temperatures serve as a refuge for small snow crab from groundfish predation; and (2) cold temperatures along with extensive sea ice promote ice-related phytoplankton blooms composed of nutritious diatoms that settle to the seafloor during senescence (old age) where they can be consumed by snow crabs. Interestingly, whereas cold temperatures benefit juvenile snow crab, warm temperatures promote the growth of adult snow crab.
- Historically, the EBS and NL snow crab stocks have generally covaried together. However, since 2020, the correlation between EBS and NL snow crabs has broken down owing to the collapse of the EBS stock and the sustained strong performance of NL stock. The collapse of EBS snow crab over 2018–2021 has been attributed to starvation associated with a regional marine heat wave, leading to high metabolic demands, coupled to high densities of relatively small-sized mature crab. In contrast, the NL snow crab stock varies out of phase with the southern GSL stock depending on the strength of the NAO. In general, a positive-phase NAO leads to a stronger southward-flowing Labrador Current (LC) and cooler conditions on the eastern Newfoundland shelf, whereas relaxation of the NAO allows a larger proportion of the cold LC to flow past the Grand Banks and intrude into the GSL. Thus, the extent of the CIL in NL or the GSL depends on the strength and phase of the NAO, which in turn leads to out-of-phase correlations between NL and southern GSL snow crab.

OTHER ECOLOGICAL FACTORS AFFECTING SNOW CRAB

- Snow crab are often found in the stomachs of cod in both the North Pacific and North Atlantic. However, predation studies have yielded, at best, mixed results about the role of cod predation on snow crab population dynamics. Although some studies have implicated cod in snow crab declines, most have failed to detect such an effect in the EBS, NL, and southern GSL regions. One NL study suggested that predation could be deemed more as a recruitment index than a mortality indicator in stock assessment, particularly given that cod regularly consume a size range of crab that are not well-sampled by survey trawls.
- Bitter crab disease (BCD) is a parasitic infection that gives crab a bitter taste and renders infected crab unmarketable. It is assumed to be fatal in most cases. It has been detected in both North Pacific and North Atlantic snow crab. Current methods that involve sampling of hemolymph (fluid that functions as both blood and lymph in crustaceans) detect BCD with much greater accuracy than former visual detection methods that generally underestimate the prevalence of infection. In the EBS, there was a dramatic increase in BCD over 2015–2017, raising the question whether it contributed to recent population declines in snow crab. Some samples from the northern Bering Sea show prevalence approaching 70%, which is historically high. Because of imprecision of historical visual methods, it is not possible to infer long-term trends in BCD prevalence.

FISHING EFFECTS ON STOCK REPRODUCTIVE HEALTH AND SIZE AT MATURITY

- Harvest rates are similar among EBS and Canadian snow crab fisheries. Although there are differences in their specification, when harvest control rules are expressed using the same "apples-to-apples" metrics (i.e., biomass of males ≥95 mm carapace width, CW), exploitation rates applied in the EBS are quite similar to those used in the southern GSL and Northwest Atlantic Fisheries Organization (NAFO) Divisions 3Ps and 3LNO in NL, but slightly lower than those used in Divisions 3K and 2HJ in NL.

- In NL, a Precautionary Approach (PA) was put into place when the stocks were at low biomass levels and thought to be overexploited. Since the implementation of the PA, stocks have responded very favorably. Discards became low, clutch fullness became high, and CPUE became high. Also, importantly, declining trends in size at maturity ceased in areas of concern once PA management was initiated.
- In the NL PA, harvest control rules are based on estimated biomass but they also consider stock health scores based on predicted fishery CPUE, predicted discards, and female egg clutch size. The primary harvest control rules in the Precautionary Approach allow for up to 42%, 35%, and 20% exploitation rates, with no lower bounds, when the stock is categorized to be in healthy, cautious, and critical zones, respectively.
- EBS male snow crab have been experiencing a concerning long-term decline in size at 50% maturity since 2006, but the causes have not yet been examined. However, similar downward shifts in size of maturity in the NL region were attributed to cold conditions and low densities of large males. Low densities were caused by elevated fishery exploitation rates.
- The mechanism behind the relationship between higher harvest rates and lower size at maturity relates to competition by males for mates. Large males outcompete smaller males for mating opportunities. Large males can deliver large sperm loads to females for fertilization of large egg clutches. Although population densities of large males are high, small immature males tend to continue growing and ultimately reach large sizes that allow them to be reproductively successful. With excessive removal of large males by high fishery exploitation rates, small males undergo terminal molt to maturity sooner because they no longer need to compete with large males for mates. However, they are less competent in mating and multiple small mates may be required for the female to acquire sufficient sperm to fertilize full egg clutches. Also, mating with multiple smaller males causes females to suffer more injuries during mating, due to increased male aggression, and is sometimes fatal.
- In general, female clutch fullness is higher in NL than EBS snow crab: in 2022 just 37% of mature females in the EBS had clutch fullness of 75% full or greater, the lowest on record dating back to 1980.
- Skip-molting is the process by which a crab does not molt in the current year but retains the ability to molt again in subsequent years before attaining terminal molt. In NL, skip-molting occurs most frequently under extreme cold and high population density conditions. This phenomenon has not been fully evaluated in EBS snow crab. It may also be critical in determining the size structure and reproductive dynamics in arctic systems (e.g., Barents, Kara, Chukchi, and Beaufort Seas) into which snow crab are expected to expand their populations as climate change progresses.

Many potential research priorities were identified during workshop discussions. The list of important ones included strengthening future collaborative research, further work on indices of stock reproductive health including changes in size at maturity related to harvest rates, appropriate size limits in light of size at maturity, conduct of a management strategy evaluation for the EBS stock, laboratory studies of crab physiology with respect to temperatures experienced during the 2018–2021 EBS marine heat wave, identification of critical habitats (e.g., nursery areas), impacts of “pelagic” trawls (i.e., as defined for Alaskan fisheries) on crabs, ghost fishing of lost crab pots, gear research to reduce bycatch, and enhancement of our understanding of fisheries as coupled socio-ecological systems including the need for adaptation strategies. The *Discussion* section further elaborates on these and other research topics.

INTRODUCTION

Snow crab (*Chionoecetes opilio*) is a highly valued commercial species that supports important fisheries in both the North Pacific and North Atlantic Oceans. In the North Pacific, snow crab range from the Sea of Japan northeastward through the Bering Sea, supporting fisheries in Korea, Japan, Russia, and the United States. In the western Atlantic, the snow crab's historical range extends from the Canadian Maritimes northeastward to southern Greenland; and in 1996 was first found to have invaded the Barents Sea (Kuzmin et al. 1998), where it currently supports fisheries in western Russia and Norway.

Worldwide, snow crab population status varies considerably among regions. Relatively stable fisheries occur in the Sea of Japan (Zhang et al. 2020); in Canadian waters from the Scotian Shelf (DFO 2021) to the Gulf of St. Lawrence (Surette and Chaseé 2022), and Newfoundland-Labrador (DFO 2023); and northward into Greenland (Hvingel et al. 2021). In contrast, a massive collapse in abundance from 2018–2021 impacted the eastern Bering Sea (EBS) population (Szuwalski 2023), and a large-scale stock failure occurred along the east coast of Japan *circa* 2011, coincident with the Great East Japan Earthquake (Shibata et al. 2021). Meanwhile, the invasive Barents Sea (i.e., Russian and Norwegian) population continues to expand and may not have reached its maximum potential with respect to either spatial or numerical extent (Hogrenning and Eide 2021; Huserbråten et al. 2023). Additionally, snow crabs have been expanding their distribution in the Arctic Ocean, from the Barents Sea eastward into the Kara Sea (Zimina 2014; Zalota et al. 2019), and sea-ice retreat may allow for expansion of the Chukchi-Beaufort population both westward into the East Siberian Sea (Gorbatenko et al. 2023), and eastward within the Beaufort Sea (Bluhm et al. 2015).

In the EBS, Tanner (*Chionoecetes bairdi*) and snow crabs have supported US commercial fisheries since the late 1960s, with peak harvests of snow crab occurring in 1991 at nearly 150,000 metric tons (mt; Nichols et al. 2021). Following a 13-year period (i.e., 1987–1999) during which harvests typically exceeded 45,000 mt annually, catches declined to more modest levels in the 2000s. Over the 21-year period spanning 2000–2020, harvests ranged between 8,600 and 40,300 mt, averaging ~19,200 mt per season. In recent years, this fishery has often represented the most valuable crab fishery in the Bering Sea and Aleutian Islands (BSAI) region, with exvessel values averaging in excess of US$100 million during 2010–2014 (Nichols et al. 2021). From 2017 through 2020, harvests increased from roughly 9,000 mt to more than 20,000 mt, consistent with the progression of a strong year-class into the fishery (Szuwalski 2020). However, this was followed by an 88% decline in harvests during the 2021–2022 fishing season, and the fishery was subsequently closed due to low abundance. This represented the first closure of the EBS snow crab fishery in its 45+ year history and was followed by a second consecutive year of closure. This has caused considerable hardship for an industry that has also seen closures of fisheries for blue king crab (*Paralithodes platypus*) in the Pribilof Islands and St. Matthew Island Districts, as well as closures of the iconic Bristol Bay red king crab (*Paralithodes camtschaticus*) fishery in 2021 and 2022.

In contrast to the EBS, the Canadian snow crab population, while exhibiting decadal-scale cycles in abundance, has continuously supported fisheries without large-scale closures since each regional commercial fishery was first prosecuted, beginning ~50 years ago. Snow crab are harvested in Canada within a series of sub-stocks represented by the Scotian Shelf (DFO 2021), southern Gulf of St. Lawrence (Surette and Chaseé 2022) and northern (DFO 2022) Gulf of St. Lawrence, and Newfoundland and Labrador (DFO 2023). Additionally, this biological population extends northward into east Greenland (Hvingel et al. 2021) and west Greenland (Burmeister 2010). Among these stocks, the Newfoundland-Labrador (NL) stock is the largest, with landings that peaked near 70,000 mt in 1999 and supported fisheries typically in excess of 50,000 mt for more than a decade thereafter (DFO 2023). Following a decline to <30,000 mt in 2018, the fishery again returned to annual harvests in the range of 50,000–60,000 mt, making snow crab the most valuable seafood exported from NL, with exports valued at CDN$781 million in 2022 (NL 2022).

In addition to regional contrasts in stock status, assessment and management approaches also vary globally. Assessments range from formal, carrying-capacity-based numerical modelling (e.g., eastern Japan [Shibata et al. 2021], EBS [Szuwalski 2023], and Barents Sea [Bakanev 2016]), to generalized evaluations of stock status that rely primarily upon observed changes in survey and fishery-based indices of catch per unit effort and "first principles" indicators of stock health such as age structure, sex ratios, and indicators of reproductive success (e.g., Greenland; Burmeister 2010). Such indicators have also been extended to produce formalized multi-indicator harvest controls (e.g., Mullowney and Baker 2023; Mullowney et al. 2024). In US waters, underlying management principles are guided by the Magnuson–Stevens Fishery Conservation and Management Act (MSFCMA), with the specifics for individual species formalized in regional Fishery Management Plans (FMPs). The FMP for BSAI crab stocks prescribes that harvest rates comply to a harvest control rule that is based on stock-specific estimated Maximum Sustainable Yield (MSY), and reduces harvests when estimated stock abundance declines below MSY-based thresholds (NPFMC 2021), whereas annual quotas for each crab stock are set by the Alaska Department of Fish and Game through a co-management agreement established within the FMP (NPFMC 2021). In Canadian waters, the overarching piece of legislation is the Fisheries Act (FA), which, among other strategies, necessitates application of the Precautionary Approach (PA) target-based management. Harvest controls are guided by the PA to fishery management, as implemented through an overarching national framework (Government of Canada 1999; DFO 2006). Although conceptually similar in many respects to the underlying principles of the MSFCMA, the PA Framework ostensibly contains greater flexibility and scope for innovative approaches and has resulted in an array of management structures according to region and species (e.g., Marentette et al. 2021).

The striking contrast between current Alaska and Canadian snow crab stock status, potential variability in approaches to management, and conservation concerns for the species in a backdrop of changing climate and a relative lack of other fishing opportunities for the Alaska fleet, spurred renewed interest in seeking diverse perspectives on the biology and management of this species across international regions. Workshops focusing on various aspects of snow crab biology and assessment have been convened at quasi-regular intervals over the past century (e.g., Kruse et al. 2007; Pengilly et al. 2014), with the most recent series held from 2017 to 2019 (Kaiser et al. 2021). From 29 April through 2 May 2024, this tradition was continued via an international workshop that was convened in St. John's, Newfoundland, Canada, jointly organized by Fisheries and Oceans Canada (DFO) and the Bering Sea Fisheries Research Foundation (BSFRF based in Seattle, Washington) and hosted by the Fisheries and Marine Institute of Memorial University of Newfoundland. The workshop was convened to allow researchers and industry partners representing Atlantic and Pacific harvest regions to share information regarding the dynamics of their stocks and approaches to management and harvest controls, and to plan for a future in which stock variability is expected to increase and in which collaboration is expected to become increasingly important to maintaining sustainable snow crab fisheries. The workshop was chaired by Gordon Kruse and co-chaired by Darrell Mullowney and Scott Goodman. Raquel Ruiz-Diaz served as Rapporteur. The workshop included 41 fishery scientists, managers, industry representatives, graduate students, and others from Canada, United States, Norway, Denmark and France (Appendix A). Participants joined the workshop both in person and by videoconference.

The snow crab workshop was structured into 3 primary Theme Sessions: (1) Physical Ecosystem Dynamics, (2) Exploratory Population Modelling, and (3) Applied Management. Within those themes, presentations were given and participants discussed a variety of specific topics that included large-scale drivers of population productivity and changing ecosystem structure; changes in snow crab distribution under climate change and spatial fleet dynamics, including investigation of alternative spatial analysis techniques; advances in gear technology to allow for effective evaluation of stock status; indicators of population health; evaluation and modelling of molt schedules and skip-molting; and alternative harvest control mechanisms and appropriate scales of management. Summaries of oral presentations are organized in this report by theme and not by chronological order, because some presentations were delivered out of sequence to accommodate speakers' availability as well as the multiple time zones of workshop participants. Discussions were facilitated each day, including a closing session on the last day, to allow for an open discussion regarding Future Outlooks and Research Directions, as well as strategies for developing research and initiating collaborations and partnerships. Discussions over all 3 days were organized together in the final section of this publication.

As is typical of scientific publications, acronyms are defined at their first usage and thereafter only the acronym is used. For convenient lookup, a list of acronyms used in this report appears in Appendix B.

WORKSHOP PRESENTATIONS

THEME 1: PHYSICAL ECOSYSTEM DYNAMICS

Physical Ecosystem Dynamics: Eastern Bering Sea

Elizabeth (Ebett) Siddon – *NOAA Fisheries, Alaska Fisheries Science Center, Juneau*, *Alaska*, *USA*

Atmospheric drivers play a crucial role in shaping the dynamics of the eastern Bering Sea (EBS) ecosystem. Although critical aspects of EBS oceanography have been linked to the El Niño Southern Oscillation (ENSO; e.g., Stabeno et al. 1999), this is not the primary driver of the sea-ice dynamics that are critical to the region's ecosystem structure. Analyses demonstrate little direct relationship between EBS ice extent and the occurrence of El Niño events. In contrast, there are strong relationships between ice coverage and regional atmospheric wind patterns wherein sea ice advances, with very little temporal lag, during periods of northerly winds and retreats during southerly winds. As such, sea-ice dynamics in the EBS are more generally associated with the drivers of wind patterns: namely, variability in the Aleutian Low (AL) pressure system and the location of the upper-atmospheric jet stream that represents a frontal boundary between the AL and the Beaufort high pressure system to its north. Since rigorous data-acquisition began in 1981, considerable interannual variability in mean air temperatures (as recorded at St. Paul Island, near the edge of the EBS continental shelf) has been observed, with a long-term trend of increasing mean temperatures and declining early-season (i.e., forming between 15 October and 15 December) sea-ice extent. Since 1981, mean air temperatures at St. Paul Island have risen by ~0.62°C per decade, with positive temperature anomalies observed during all but three months from 2014 through 2023. The result has been a trend towards increasingly shorter ice seasons that are characterized by relatively thin ice and changes in the extent of the Bering Sea cold pool (i.e., a region of <2º C bottom water; see Kinney et al. 2022) and in salinity gradients that govern vertical water-column stratification. These changes in sea ice dynamics have resulted in a higher proportion of recent spring algal blooms occurring in open water, as opposed to being ice-edge associated. These blooms are less predictable, more dispersed, and more difficult for planktivorous species to exploit effectively. Additionally, increased stratification resulting from increasing salinity has the potential to reduce the vertical overlap between pelagic planktonic food sources, which are distributed above the pycnocline, and benthic consumers. The reduction in the extent of the cold pool has been linked to the northward geographic expansion of predatory species, such as Pacific cod (*Gadus macrocephalus*), at the expense of benthic consumer and prey species, including snow crab. Whereas distributional shifts in cod were probably due to short-term movement (Spies et al. 2020), the rapid decline of snow crab in the EBS is believed to have been a result of mass-mortality (Szuwalski et al. 2023). In addition to the effects of warming events on Pacific cod and snow crab stocks, notable impacts on upper trophic levels included the 2019 die-off of short-tailed shearwaters (*Phoebastria albatrus*) and an "unusual mortality event" for grey whales (*Eschrichtius robustus*) that spanned 2019–2023.

Physical Ecosystem Dynamics: Newfoundland and Labrador

Frédéric Cyr – *Fisheries and Oceans Canada, Northwest Atlantic Fisheries Centre, St. John's*, *Newfoundland*, *Canada*[1]

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The North Atlantic continental shelf is a dynamic system characterized by substantial annual and interannual environmental variability, in which water temperatures below 0°C can often be observed throughout the year. Of critical importance to the dynamics of this region is the Labrador Coastal Current (LCC), a branch of the Labrador Current (LC) system, consisting of cold and fresh Arctic-origin water originating from Baffin Bay and the Hudson Strait. The LCC flows southward along the Labrador coast and along the coast of Newfoundland to the Grand Banks, keeping waters at the seafloor relatively cold and suitable for snow crab.

The main branch of the LC flows parallel to the LCC and transports modified sub-polar waters originating from the West Greenland Current (warmer and saltier than the LCC) south along the Labrador and Newfoundland slope. Near the tail of the Grand Banks, the LC flow is partitioned by a process known as "retroflection" (Jutras et al. 2023) into branches that either continue southward towards the Scotian Shelf and northern Gulf of Maine; or turn eastward to join the Gulf Stream and produce the northeastward-flowing North Atlantic Current. The LC represents the western and southwestern margins of the Subpolar Gyre, an area of cyclonic ocean circulation that is driven by persistent atmospheric low-pressure overlying Greenland, relative to higher atmospheric pressure in the mid-Atlantic Ocean to its south. The location of the "seam" between these 2 pressure cells is subject to decadal-scale variability caused by the Arctic (AO) and North Atlantic (NAO) Oscillations, which cause LC retroflection to shift either northward or southward, depending on the state of these oscillations. In general, positive-phase NAO leads to a stronger LC and cooler conditions on the eastern Newfoundland shelf. In contrast, negative-phase NAO brings warmer waters towards shore and onto the Grand Banks. The overall effects of these oscillations can be summarized in regional climate indices (Cyr and Galbraith 2021), which combine multiple indicators of system status (e.g., winter NAO strength, air and sea temperatures, sea ice extent, and iceberg abundance) to characterize cold versus warm periods. For NL, 1982–1995 represented the coldest period that has been observed over the last 75 years, whereas particularly warm periods were observed from 1964–1971, 2010–2013, and 2020–2024. These thermal cycles have been associated with broadscale changes in productivity that vary depending upon the species considered. For example, Atlantic cod (*Gadus morhua*) and numerous other groundfish stocks–both commercial and noncommercial–have been positively affected by warm phases, whereas cold phases have been linked with stock declines, collapses, and stalled recoveries. Of particular relevance to snow crab, relaxation of the NAO allows a larger proportion of cold Labrador Current system waters (LCC and LC) to flow southward past the Grand Banks and intrude into the Gulf of St. Lawrence (GSL), in turn controlling the extent of the Cold Intermediate Layer (CIL) in both NL and within the GSL. Briefly, the CIL is a layer of water that is produced at intermediate water depths when cold water that was generated during winter becomes trapped between relatively warmer bottom waters and lower-salinity surface waters that are produced from ice-melt, coastal freshwater runoff, and solar heating. Warmer water is important for growth, molting, and mating of adult snow crab (Dawe et al. 2012). whereas cooler waters are hypothesized to enhance survival of early benthic stages by serving as a thermal refuge that excludes key fish predators (Dionne et al. 2003) from snow crab rearing habitat. Thus, snow crab productivity is enhanced when adult habitat is under the influence of warmer waters below the CIL and inshore nursery habitat is encompassed by the CIL. Winter sea-ice coverage serves as an excellent proxy for snow crab recruitment, indexed as the abundance of age-2 crab observed in trawl surveys. Of note, the biomass of exploited crab (i.e., ages 5–9) experienced historical lows during 2016–2018, following warming during 2010–2013. Although stock abundance has recovered and is currently high, concern for upcoming years is warranted given recent warming, low ice coverage, and the observation that 2021 was the warmest year on record.

Physical Ecosystem Dynamics: Southern Gulf of St. Lawrence

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Of interest in the GSL, is the extent to which warming is expected to affect snow crab stock status. Primary hydrographic inputs to the GSL include eastward-flowing sea ice and freshwater from the St. Lawrence River and westward-flowing oceanic inputs arriving through the Strait of Belle Isle to the northeast and northern Cabot Strait (i.e., the Laurentian Channel) to the southeast. These inputs vary in strength on seasonal bases, with highest mean flow rates for all 3 inputs observed from January through March, and slackening thereafter (Galbraith et al. 2023). Overall, the result is persistent southeastward flow through the center of the GSL, along the axis of the Laurentian Channel, with onshore advection to the south of this main flow onto Bradelle Bank and the Magdalen Shallows, northeast of Prince Edward Island, where snow crab are most abundant. Vertical hydrographic structure is characterized by a CIL that varies in strength and geographic coverage depending upon the volume of cold water generated during the winter. This CIL, in turn, intersects adult snow crab habitat at depths of ~50–120 m on the Magdalen Shallows. A variety of metrics including air temperature, sea-surface and bottom-water temperatures, sea ice, and CIL volume, are used to qualitatively evaluate thermal conditions to which the GSL snow crab population is subjected. At centurial scales, air temperatures in the region have been increasing at a rate of approximately 2.2°C per century, with interannual variability of approximately ±2–3°C about the long-term trend; this has translated into increased surface and bottom-water temperatures in recent years. Most of the southern crab grounds experienced warmer September bottom-water temperatures in 2023 than 2022, except along their western and eastern margins (i.e., the Shediac Valley and western Cape Breton, respectively). Average bottom-water temperature increased from 5.2° to 6.0°C in 2023, and no sub-zero temperatures were observed on the crab grounds in September 2023. Low sea-ice volumes have also been observed recently: record-low volume was observed in 2021, and no sea ice was exported to the Scotian Shelf during 2023. The volume of the CIL has experienced a trended decline since ~1992 after having expanded from 1980–1992. The areal habitat index for snow crab, defined as the spatial extent of bottom temperatures between 1° and 3° C, has been below the long-term mean for the last 5 years and 13 of the last 17 years (DFO 2024). Although large volumes of appropriate thermal habitat still exist within the system, capable of supporting robust snow crab populations, the slow declines in both thermal habitat index and total crab abundance are reasons for concern, and the large degree of warming that has been observed in the Laurentian Channel could be particularly troubling. Additionally, concerns have arisen regarding the possibility that anoxic or acidified waters may be advected onshore from the deep waters of the Laurentian Channel, producing episodic or persistent stress to the snow crab population in the future.

Physical Ecosystem Dynamics: Barents Sea

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The Barents Sea is a region undergoing pronounced ecosystem changes and experiences varying temperatures and sea-ice cover throughout the year. Situated between 70° and 82° N, the Barents Sea extends into the Arctic Ocean and is therefore more northerly than either the Bering Sea or the

Newfoundland-Labrador System. The Barents Sea is characterized by its shelf nature, limited to depths of ≤300 m, with complex internal bathymetry composed of a network of shallow banks separated by deeper trenches, and is surrounded by archipelagos including the Svalbard and Franz Joseph Land to the north, and Novaya Zemlya to the east. Oceanographically, the Barents Sea is connected to the abyssal Nansen Basin to the north, and the shallower Norwegian and Kara Seas to the west and east, respectively. Primary inflow is from the North Atlantic Ocean to the southwest, whose relatively warm (> 3° C) and saline (> 35 psu) waters are substantially modified as they flow northeastward through the Barents Sea to exit north of Novaya Zemlya. In winter, large inflows of sea ice occur along the sea's northern boundary, ultimately affecting seasonal ice cover. This dynamic produces 2 oceanographic domains at interplay within the Barents Sea: a warm, well-mixed domain dominated by Atlantic water and a cold, stratified and seasonally ice-dominated Arctic domain to the north. This generates an ecosystem in which the snow crab population, first documented to have invaded the Barents Sea in 1996 (Kuzmin et al. 1998) and hypothesized to have arrived via expansion of the Bering-Chukchi population across the North Pole (Dahle et al. 2022), continues to expand both numerically and spatially; but, within a system that is expected to become increasing less-suitable in the face of climate change. The commercial Barents Sea snow crab fishery was initiated in 2012 and is largely concentrated in the central Barents Sea, with Russian effort extending eastward from the Norwegian-Russian international boundary. Areas of greatest biomass currently occur in Russian waters. As opposed to residing in a CIL, as observed in eastern Canada, snow crab in the Barents Sea are located in somewhat deeper waters and subjected to persistently colder bottom waters. However, the northern Barents Sea has been experiencing reductions in winter sea-ice coverage, an increase in winter heat loss, and an overall warming trend with respect to both air and sea temperatures. Increases in air and sea temperatures observed since 1980 have averaged 2.3°C and 0.2°C per decade, respectively, in conjunction with 14% decadal-scale declines in sea-ice coverage (Gerland et al. 2023). Atmospheric warming is predicted to continue, along with modest decreases in Atlantic inflow, the latter of which is ultimately expected to increase total heat transport due to increases in North Atlantic temperatures that will offset the lower flow rates. These changes are predicted to positively influence numerous finfish species, including gadids and wolffishes (*Anarhichus* spp.). However, effects on snow crab and Arctic cod (*Boreogadus saida*) are expected to be negative (Kjesbu et al. 2022).

Ecosystem Approaches: Alaska

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US fisheries management generally relies upon the numerical assessment of the stock status in which abundance or biomass – and, hence, harvest guidelines – are gauged primarily in terms of the internal stock dynamics, such as recruitment, natural and fishery mortality, and growth. While many of these features of stock function are governed by environmental factors, and management authorities may ultimately seek to conduct Ecosystem-based Fishery Management (EBFM), it is often difficult for stock assessment scientists to explicitly account for external forcing functions that would allow fishery managers to incorporate environmental processes into operational management advice. For EBS fishery stocks, 2 potential "on-ramps" for incorporating external variables into the decision-making process have recently been developed: Ecosystem and Socioeconomic Profiles (ESPs; Shotwell et al. 2023) and their associated Ecosystem Status Reports (ESRs). ESPs use a standardized, stock-specific framework for integrating ecosystem and socioeconomic indicators within the stock assessment and fisheries management process. Once a stock has been prioritized, an ESP is developed, and thereafter, indicators are updated annually with current-year values. On the other hand, ESRs are produced annually and describe each of the large marine ecosystems (in Alaska, the following 7 regions: the southeastern and central Gulf of Alaska; the Aleutian Islands; the eastern and northern Bering Sea; and the Chukchi and Beaufort Seas) within which those stocks reside. Both ESPs and ESRs are intended to provide guidance for setting annual catch levels with regional fishery management councils, the scientific community, and the public as their target audience. Constructing both ESPs and ESRs is reliant upon robust monitoring and process research to provide inputs to the documents, each of which is composed of a diverse suite of indicators selected for their relevance to managed stocks. Data regarding Alaskan snow crab, its fishery, and its ecosystem are primarily derived from fishery monitoring and trawl and pot surveys conducted by the National Marine Fisheries Service (NMFS), Alaska Department of Fish and Game (ADF&G), and regional collaborators. Oceanographic research is conducted by the National Oceanic and Atmospheric Administration, National Weather Service, and academic institutions. Crab research is conducted at the NMFS and ADF&G laboratories in Kodiak, Alaska, and Newport, Oregon, and by academic scientists at various institutions. The Bering Sea ESR includes a broad suite of individual indicators that describe 4 general aspects of the ecosystem: environmental processes, prey sources, predation, and resource competitors. The ESP process is designed to represent a standardized framework for incorporating relevant information into the stock assessment, following an ordered process that: (1) identifies stocks for which ESPs should be constructed; (2) identifies ecosystem pressures and stock vulnerabilities; (3) supports monitoring and analysis of stock-specific status indicators; and (4) reports indicator status to managers and stakeholders. ESPs include both physical (e.g., AO status, cold pool and sea ice extent, pH levels) and biological (e.g., primary productivity, disease prevalence, energetic condition indices) ecosystem indicators, as well as socioeconomic indicators, such as fleet-performance, Total Allowable Catch (TAC) utilization rates, fishery value, and price metrics. The information contained in the ESPs provide a mechanism for monitoring change, i.e., sensitivity of the stock to forcing functions, for scaling and parameterizing relevant factors into numerical stock assessments and alternative models of stock structure. An example would be the creation of time blocks for shifts in snow crab natural mortality to elevated levels in 2018 and 2019 associated with a marine heat wave. Ecosystem indicators are analyzed and presented using a hierarchical approach that ranges from simple "traffic light" tables that characterize the current status of each selected indicator as either low, neutral, or high with respect to their historical average, to complex Bayesian analysis that evaluates indicators for direct incorporation into assessments as discrete covariates. Within the traffic light table, indicators identified as either particularly low or high may be considered as "red flags" capable of causing shifts in stock status and deserving attention with respect to management action or additional research. In 2019, this approach identified numerous red flags that represented precursors to the subsequent EBS snow crab stock collapse. Both ESPs and ESRs can also contribute to the risk tables that are currently used for establishing and evaluating buffers between assessment-derived Overfishing Limits (OFLs) and each year's chosen harvest level (i.e., Acceptable Biological Catch: ABC) and help to identify the most substantial gaps in our understanding of stock function. A broad overview of EBFM applied to BSAI crab fisheries was provided by Kruse et al. (2025).

Ecosystem Approaches: Newfoundland and Labrador

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The term "ecosystem approach" encapsulates a continuum of management approaches defined by an increasing use of ecosystem information and management scope and complexity. Within this continuum we can recognize traditional Single-species Fisheries Management (SSFM) (little to no ecosystem information considered with management focused on a single stock), Ecosystem Approach to Fisheries Management (EAFM) (ecosystem information used, management focused on individual stocks), EBFM (ecosystem information used, management focused on assemblages of interrelated/interconnected stocks) and, ultimately, Ecosystem-based Management (EBM) (ecosystem information used, management focused on multiple sectors, not just fishing, operating in a given ecosystem).

A range of legal instruments currently provides the support for ecosystem approaches in Canada. EAFM is embodied within DFO's Sustainable Fisheries Framework,[2] which articulates fisheries management principles contained in the Fisheries Act[3], whereas other aspects of ecosystem and species conservation are included in the Oceans Act[4] and the Species at Risk Act.[5] At present, there is an active process within DFO to move fisheries management from SSFM into EAFM, with the expectation that this will serve as a stepping stone into EBFM and EBM in the future. In the current context, ecosystem approaches are being designed as a set of tools aimed at addressing biodiversity loss, disturbance, and ecosystem productivity, taking into account ecological, economic, and social sustainability. On the fisheries front, the key to implementing EAFM is recognizing the potentially compounded impacts of multiple fisheries on the ecosystems that sustain their productivity and working to mitigate these impacts. The fisheries management cycle in Canada is explicit and intended to promote adaptive management within its regulatory context (i.e., regulatory structure and potential constraints); EAFM is being embedded within this cycle and implemented at regional scales (e.g., Pepin et al. 2023).

Implementation of ecosystem approaches requires coordination among relevant management authorities and an appropriate legal framework to allow management to be invoked. In NL waters, relevant management authorities include DFO, which manages fishery stocks and associated activities with Canada's 200 nm Exclusive Economic Zone (EEZ); and the North Atlantic Fisheries Organization (NAFO), which represents 13 contracting parties throughout the North Atlantic and whose responsibilities include stocks beyond national EEZs and stocks that straddle international boundaries. NAFO activities are governed by the NAFO Convention and operationally codified within the NAFO Conservation and Enforcement Measures (NAFO 2024). The NAFO Convention includes the call for an ecosystem approach, and the organization has been actively building it up in a stepwise manner for more than a decade (Koen-Alonso et al. 2019).

Because ecosystem approaches require defining the spatial structure of the ecosystems under management, efforts have been made to identify ecosystem areas. In NL waters, DFO and NAFO have formally recognized Bioregions, which represent large marine ecosystems. The EAFM

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2 DFO (Department of Fisheries and Oceans Canada). 2023. Sustainable Fisheries Framework. https://www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/overview-cadre-eng.htm (accessed 07/21/2024).

3 Fisheries Act (R.S.C., 1985, c. F-14): https://laws-lois.justice.gc.ca/PDF/F-14.pdf (accessed 07/21/2024).

4 Oceans Act (S.C. 1996, c. 31): https://laws-lois.justice.gc.ca/PDF/O-2.4.pdf (accessed 07/21/2024).

5 Species at Risk Act (S.C. 2002, c. 29): https://laws.justice.gc.ca/PDF/S-15.3.pdf (accessed 07/21/2024).

implementation in NAFO also includes the definition of Ecosystem Production Units (EPUs) within these Bioregions (Pepin et al., 2014), serving as the functional units for ecosystem summaries and management. Although DFO scientific advice also uses these EPUs for ecological analyses, these have no formal regulatory role within Canada.

Although implementation of EAFM within DFO and NAFO is currently in different states of development, both include the treatment of individual fisheries as well as area-based management measures. With respect to the latter, DFO has established 3 Marine Protected Areas in NL waters through the Oceans Act and an additional 7 Marine Refuges under the Fisheries Act. NAFO has closed 12 submarine seamount systems to bottom fishing, closed 18 areas to protect Vulnerable Marine Ecosystems (e.g., coral and sponge habitat), and continues to evaluate fishing impacts within established Vulnerable Marine Ecosystems for consideration of future action (Koen-Alonso et al. 2019). At the stock level, NAFO has produced Ecosystem Reference Points by harvest guild and EPU, is beginning to generate Ecosystem Summary Sheets and reports of catch sustainability by EPU, and has conducted a multispecies Management Strategy Evaluation (MSE) for Atlantic cod, shrimp (*Pandalus*), and redfish (*Sebastes*) on the Flemish Cap (Pérez-Rodríguez et al. 2017). DFO is currently developing a National Strategic Plan for EAFM, and ongoing EAFM efforts have already led to the incorporation of a variety of ecosystem parameters into individual stock assessments, including the use of prey (capelin, *Mallotus villosus*) indices as a driver of Atlantic cod abundance; and population-dynamic models of shrimp and harp seals (*Pagophilus groenlandicus*) that include environmental parameters. For NL snow crab, the PA is implemented through multi-indicator harvest control (Mullowney and Baker 2023), which not only considers trends in harvest rate and catch per unit effort (CPUE) but also predicts fishery discard rates and the stock's egg-production potential (see the subsequent presentation by K. Baker). Additionally, snow crab management is informed by analyses of relationships between population abundance and environmental drivers, including the AO, NAO, and regional sea-ice extent (e.g., Mullowney et al., 2014), as well as relationships between crab abundance and predators (see subsequent presentations by D. Mullowney and M. Koen-Alonso). Still, shortcomings and challenges remain. For example, management still relies primarily upon single-species approaches and tends to lack mechanistic understanding of the relationships between stock function and environmental drivers.

Ecosystem Linkages: Borealization and the Collapse of Bering Sea Snow Crab

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In the current context, "borealization" is defined as the replacement of subarctic and Arctic marine communities with fauna typically occurring in more southerly locations (*sensu* Orlov and Volvenko 2024); as derived from terrestrial literature in which the term was originally derived to mean the replacement of temperate deciduous forests (e.g., Emmer et al. 1998; Lindbladh et al. 2014) with more-northerly boreal forest (i.e., pine-dominated taiga) and later extended to include the replacement subarctic tundra with boreal taiga, as well (e.g., Roland et al. 2021). An ecotone is an abrupt transition between 2 different biomes. Within the EBS, the presence or absence of sea ice determines the ecotone in which marine communities must function, with the presence of ice defining an Arctic ecotone and the absence of ice a subarctic ecotone. In this context, borealization of the Bering Sea due to anthropogenic atmospheric warming has been long-anticipated. Borealization has been associated with a variety of processes and ecosystem changes, including shifts from ice-associated to open-water spring phytoplankton blooms, reductions in species composition and the mean size of phytoplankton making up those blooms, the magnitude of plankton blooms, warming summertime bottom-water temperatures, and changes in pelagic and benthic productivity. Herein, a Borealization Index was derived for the entirety of the EBS using Dynamic Factor Analysis. This index is composed of 12 time series describing interannual changes in ice cover, bottom temperature, plankton-bloom dynamics, and groundfish and Pacific cod abundance. Over the period from 1972–2022, considerable variability in the Borealization Index has been observed. However, decadal-scale examination suggests relative untrended variability around the mean throughout the 1980s and 1990s; a shift towards arctic conditions from 2006–2013; and generally boreal conditions from 2014–2021, including the highest (i.e., most-boreal) values in the time series having occurred during the 2018–2019 marine heat wave. Bayesian Generalized Additive Modelling (GAM) has been employed to relate snow crab abundance (defined as summertime trawl survey catch per unit effort, CPUE) to the Borealization Index and summertime bottom temperatures. These GAMs suggest that the Borealization Index may be a better predictor of snow crab abundance than bottom temperatures alone, especially for female snow crab. Given that climate analyses based on projected atmospheric carbon levels are consistent in predicting increased warming of both the atmosphere and the EBS, it is reasonable to expect the system to continue to move towards a boreal ecotone and for snow crab abundance to decline as a result. The risk of borealization within the system has increased markedly, and boreal conditions have become increasingly likely. For example, pre-industrial atmospheric conditions were associated with an approximately 56% probability of the EBS experiencing arctic conditions and a <1% chance of boreal conditions in any given year. Following 1.5–2.0°C of marine warming, the incidence is expected to shift to approximately 2% of years in arctic conditions and 19% of years in boreal conditions (i.e., as observed during the 2018–2019 snow crab population collapse [Litzow et al. 2024]). The timing and magnitude of future system reorganization remain unknown, but a fairly conservative estimate based on climate scenario SSP2-4.5 (IPCC 2021) predicts approximately 0.4°C per decade of future warming. Ultimately, rates and outcomes will depend upon future trends in anthropogenic carbon release. However, in the absence of substantial reductions in carbon emissions in the near future, persistence of the EBS snow crab stock and the fishery that relies upon it may depend upon the species' ability to move northward and effectively exploit habitat in the northern Bering Sea and Arctic Ocean. Since the workshop, a paper describing this study has been published (Litzow et al. 2024).

Ecosystem Linkages: Sea Ice and Climate Linkages in American and Canadian Snow Crab Stocks

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Given the potential for climate-driven changes in the productivity and distribution of marine resources, tools for predicting the direction and magnitude of effects may be critical in planning for and reacting to those changes. Snow crab stocks on both sides of North America commonly exhibit abundance fluctuations as a function of recruitment strength and natural mortality. For North America's 3 major stocks – Alaska, the southern GSL, and NL – stock productivity over the last 40 years has fluctuated with roughly decadal-scale oscillations in which Alaska and NL have cycled approximately in phase, and the southern GSL out-of-phase with the other two stocks. In 2019, this pattern was disrupted by the rapid collapse of the Alaska stock (Szuwalski et al. 2023), while NL and overall Atlantic Canadian abundance has remained relatively high. Of particular interest is whether these dynamics may be driven by common atmospheric forcing, such that all 3 stocks might be better understood by identifying their shared sensitivities. Although snow crab occurs in truly Arctic systems, such as the East Siberian, Chukchi, Beaufort, Barents, and Kara

Seas, the stocks in question reside south of the Arctic Circle in regions that are not persistently sea-ice covered. Rather, the highest snow crab biomasses are found where ice-generated cold waters are delivered to their habitats via various oceanographic processes such as advection of water from melting ice down into the water column or transport of ice-generated cold water into a given region via ocean currents. Notably, all 3 of the stocks in question reside in regions that are strongly influenced by the AO. Generally, positive-phase AO is characterized by a relatively stable northern hemisphere polar jet stream, and negative-phase AO results in considerable meandering of the jet stream (Heureux et al. 2017). GAMs were constructed using survey and fishery data collected from 1995–2021 for each stock to identify common teleconnections among stocks that might serve as predictors of future stock performance (Mullowney et al. 2023). Atmospheric teleconnections that were considered included the AO, NAO, ENSO, and the Pacific Decadal Oscillation (PDO). Relationships between snow crab and cod biomass were also investigated within each region. Overall, the AO and sea-ice extent were found to have the greatest relationship with snow crab abundance. The AO tends to govern the generation of sea ice and the transport of ice-derived cold water into snow crab habitat, while, in turn, being governed by anthropogenically derived atmospheric CO_2. To predict future snow crab abundance and habitat availability, 2 predictive models (also GAMs) were constructed: (1) a short-term model in which projected sea-ice extent and the AO Index were chosen as explanatory variables to predict regional snow crab biomass through 2026; and (2) a long-term habitat-availability model in which historical (i.e., 1979–2020) monthly AO and atmospheric CO_2 levels were used to predict monthly sea-ice extent for each region through 2100, which was then converted to hemispheric-level habitat coverage predictions that included areas not currently considered ideal snow crab habitat (e.g., Baffin Bay, Arctic Ocean, Canadian Arctic Archipelago). The effects of climate change are expected to be region-specific, with southern habitats becoming unsuitable as northern regions become increasingly available. Globally, total snow crab biomass and available habitat currently appear to be at or near historical highs. This may reflect a transition-phase in species productivity with warming whereby most historically productive regions are not yet overly affected by habitat loss while new regions concomitantly open as receding seasonal ice becomes more common. In the coming decades, all regions that currently support snow crab stocks are expected to experience reductions in available habitat while Arctic habitat becomes increasingly more available. In the short term, all 3 stocks considered are expected to remain productive, provided that the species is able to move to and exploit new habitats as they become available due to warming. Under the most optimistic emissions scenarios (IPCC projection family B1; Nakićenović et al. 2020), the total habitat available to snow crab may remain relatively stable through 2100. However, under the most pessimistic scenario (IPCC projection A1FI), most regions suffer severe habitat loss beginning ~2050, and relatively little suitable thermal habitat remains by 2100. Still, uncertainties exist. In particular, the specific mechanisms by which sea ice regulates the suitability of habitat remain unknown, and the future strength of the AO and potential changes in ocean current patterns remain uncertain as well. Similarly, the ability of snow crab to move to new habitats and to adapt to changing conditions remains to be seen, as does the response of national governments to the potential regulation of fisheries in presently unexploited regions.

Ecosystem Linkages: Climate Impacts on Grand Banks Snow Crab

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The NL continental shelf can be divided into distinct EPUs, with the Grand Banks being 1 such unit (Pepin et al. 2014). The Grand Banks represent an oceanic plateau, composed of numerous individual fishing banks (e.g., Grand, Green, and St. Pierre Banks) that span an area of over 280,000 km^2, with depths as shallow as 15 m and extending to depths of 200 m. Influenced by the Labrador Current and the Gulf Stream, as well as a CIL, this region experiences dynamic climatic changes on decadal scales. Recent effects of climate change are evident in alterations to heat transfer dynamics, the slowing of the Shelfbreak Jet (Forsyth et al. 2020; Jutras et al. 2023), and weakening of the Atlantic Meridional Overturning Circulation (AMOC; Buckley and Marshall 2016). Notably, the Grand Banks are located within the southeastern edge of Atlantic snow crab distribution, while also representing the species' global southern margin. As a primarily arctic species, data suggest that snow crab distributions are shifting northward, away from the subarctic habitats that they have historically inhabited (Mullowney et al. 2023), likely due to thermal habitat requirements at both the juvenile (Dionne et al. 2003) and adult stages (Ruiz-Diaz et al. 2024b). Snow crab represents the most valuable fishery resource in the NL region, with 59% of the quota currently allocated to the Grand Banks. Understanding how future ocean warming will impact snow crab populations involves employing Species Distribution Models (SDMs). Particularly, we used Spatial and Spatiotemporal SPDE-Based GLMMs with Template Model Builder (sdmTMB)[7] (Anderson et al. 2022). This approach assesses both presence-absence and biomass (using delta-gamma distribution) based on predictor variables such as water depth and temperature, while also accounting for spatial correlations. Using bottom-trawl survey data collected from 1996 to 2019 and a 5 km x 5 km grid of bottom temperature and bathymetry, projections of abundance and distribution were conducted using 3 climate models (IPSL-CM6A-LR: Boucher et al. 2020; GFDL-ESM4: Dunne et al. 2020; Atlantic Canada Model (ACM): Brennan et al. 2016). These models were executed using 3 different global CO_2 emissions scenarios (RCP 2.6, 6.0, and 7.0; Moss et al. 2010), wherein, the IPSL and GFDL models simulated RCPs 2.6 and 7.0 and the ACM was used to simulate RCP 6.0. The first 2 climate models were resolved at 100-km resolution and the ACM at 10-km resolution. Differences in temperature projections were observed among models, with higher-emissions scenarios leading to greater warming, particularly in the IPSL model. Snow crab biomass was projected to decline during the 21st century under both higher-emissions scenarios, with the magnitude and timing of the declines varying according to model-scenario. The GFDL and ACM models projected declines of 15–20% through 2100, while the IPSL suggested a decline of >40%. The IPSL and the ACM projected the initiation of a sharp downward trend beginning in ~2040, whereas in the GFDL, the beginning of the decline was delayed until the early 2080s. Spatial patterns of biomass change indicated that these declines are likely to be most pronounced in the northern part of the Grand Banks, while the deeper waters of the shelf break may experience biomass increases. However, there are uncertainties, especially in nearshore areas, due to limited data. The study provides insights into spatial changes that may be expected to occur as a function of increasing bottom temperatures, but limitations include the inability of SDMs to capture all biotic and abiotic interactions that may modify current and future distributions – thus leading to the assumption that locations at which suitable temperatures occur

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[7] Anderson, S. C., E. J. Ward, P. A. English, L. A. K. Barnett, and J. T. Thorson, 2022. dmTMB: an R package for fast, flexible, and user-friendly generalized linear mixed effect models with spatial and spatiotemporal random fields. (accessed January 1, 2024).

in the future will necessarily be capable of supporting the species. The models also lack functional traits and physiological constraints of the modelled species. Additionally, the spatial random field could impact the estimates of fixed effects due to spatial confounding, which refers to a situation where predictors in the model are correlated with spatial or spatio-temporal effects, potentially leading to an underestimation of the true impacts of ocean warming on the species biomass and distribution. Further details can be found in Ruiz-Diaz et al. (2024a).

THEME 2: EXPLORATORY POPULATION MODELLING

Spatial Considerations: Spatial Fleet Dynamics (Alaska)

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Fishing behavior is an important link between management decisions and bioeconomic outcomes. The diversity in fishers' behavior, motivations, and abilities should inform incentive structures if management aims to consider heterogeneous impacts on and by fishing communities. Modeling human behavior in resource management is important for successful fisheries, especially for fisheries undergoing rapid transformation, such as the Alaska snow crab fishery. Wang et al. (2024) modeled how snow crab fishers choose where to fish in the EBS and examined the diversity of strategies among individuals by fitting a discrete choice random utility model to data on fishing locations using a variety of potential drivers of behavior as covariates. Hypotheses about fishing strategies were developed from interviews with vessel captains in the snow crab fishery. The overall fishing strategy of the snow crab fleet prioritizes revenue and sharing information while minimizing risk, adverse weather conditions, and costs. Specifically, the fleet tends to choose areas with high CPUE at the fleet and vessel levels. High retained catch percentages (i.e., less sorting of bycatch), previous fishing locations in the past two weeks, other vessel effort, and the CPUE of the previous year also increase the likelihood of fishing in an area. Factors that reduce the attractiveness of an area to fishing include distance to the port of landing, ice cover, variance of CPUE at the fleet and vessel levels, and wind speed. Diversity of fishing strategies was driven by differences in spatial footprint of the fleet, vessel size, and ports of landing. Individual strategies were binned into 3 geographic groups: northern, western, and southern regions. These groupings represented fishing grounds either to the north of, within, or adjacent to the western branch of, and southeast of Pribilof Canyon, respectively. Larger vessels ventured farther north, where weather conditions are more extreme; smaller vessels could not adopt this strategy. Those fishing in the southern region were content with lower CPUE because they have close access to ports and their catch rates were good enough to allow them to remain in that region. Despite differences in vessel size, crabbers were spatially adaptive and switched fishing regions depending on the abundance and distribution of crab. In recent years, vessels have increasingly chosen to fish in the northern region, due to the absence of crab in the southern and western regions. Future applications of such spatial fleet dynamics models include the prediction of spatial fishing mortality, informing spatial MSEs, and informing the possibility of a northern Bering Sea fishery despite lower abundance of snow crab compared to the EBS.

Spatial Considerations: State-space Models (Alaska)

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Spatial heterogeneity in population density and fishing effort can produce challenges to stock assessment and fishery management. Although the potential effects of such complexity on assessment results are often acknowledged, data limitations and computational costs typically result in management approaches that invoke simplifying assumptions regarding spatial stock structure and may therefore incompletely represent stock and fishery dynamics. One important question faced by assessment authors is how to account for movement when stock distributions change between the time of survey and the time of harvest. This disconnect can be commonplace for species that undergo seasonal migrations (e.g., snow crab: Mullowney et al. 2018) and in which stock assessment surveys, directed harvest, and bycatch fisheries do not all occur at the same time of year. Spatiotemporal Integrated Population Modelling (IPM) is a tool that allows such processes to be modelled at appropriate scales, enabling the evaluation of the consequences of internal spatial structure. Building upon the framework suggested by Cao et al. (2020), an IPM was constructed for snow crab in the EBS (see Olmos et al. 2023). This model represents an important advancement from Cao et al. (2020) in that it has been fitted to observational data rather than constructed with simulated data with the intent to: (1) understand the regional drivers of snow crab population dynamics and juvenile distribution; and (2) estimate fishing mortality at sub-population scales. With respect to the former, one important question is the degree to which the EBS cold pool might govern the distribution of juvenile snow crab. The snow crab IPM incorporated seasonal information (i.e., to account for temporal mismatch in sampling design) and employed a size-spectrum spatiotemporal population model, controlling for factors including recruitment, growth, natural mortality, fishing mortality, and maturation. The model included spatiotemporal processes as multivariate normal distributions, assumed that underlying population density was homogenous within each spatial cell within the model grid, and modelled the population during 1989–2018 to 4 distinct size classes of crab: 0–40 mm, 40–78 mm, 78–101 mm, and >101 mm CW. For each size class, annual centers of gravity (COGs) were computed for annual survey and commercial catches, allowing interannual patterns and intra-annual divergence (i.e., inferred movement) between survey and catch distributions to be examined. The results demonstrate a relatively restricted annual geographic range for small-sized individuals during warm years and expansion of that range in cold years, consistent with the hypothesis that the EBS cold pool may serve as a refuge from finfish predation, thereby enhancing total recruitment. In general, years of relatively low abundance have been associated with more-northerly population COGs than during years of high abundance. The years in which fishing mortality was lowest have been associated with relatively constrained fishing effort (i.e., smaller overall footprint of the fleet) and with northerly and westerly fleetwide COGs. Model results indicate considerable spatial heterogeneity in fishing mortality and suggest that local exploitation rates can be well above the regional average as estimated from spatially-aggregated models: in some areas, fishing mortality may represent as much as 80% of the estimated underlying population, while in other areas it can be effectively 0. A model of this form could provide the basis for an operating model within an MSE framework, but caution should be exercised with respect to its use for tactical management without further evaluation of model formulation, fitting, and interpretation. In particular, state-space models can, at times, be so flexible that they become prone to "overfitting" the data, even when grossly mis-specified. Future work should include the addition of bycatch and alternative survey data, refined data on growth and molt increments, and the incorporation of environmental factors as covariates that are associated with recruitment and growth, in order to estimate model parameters that are currently pre-specified.

Spatial Considerations: Kriging – Overview of its Origins, Theory, and Use in Fisheries (southern Gulf of St. Lawrence)

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The theoretical development of kriging revolved around the concept of similarity by proximity, with the primary goal to make predictions about quantities of interest at non-sampled areas, as well as their associated uncertainties. The fundamental principle underlying kriging is that "near things are more similar than distant things".

Kriging has long been used to study snow crab populations in the southern GSL, using data from an industry-supported trawl survey that has been performed annually since 1988. Kriging has been used for mapping snow crab distribution, setting exploitation rates and quotas for the following year, as well as standardizing indices.

Kriging operates by modeling the degree of similarity between observations using a variogram, which quantifies how the expected variance between observations varies with their distance of separation. The variogram model is then used to generate a covariance matrix between the set of observations, which is then used as a linear predictor at unsampled locations (kriging is considered a linear regression estimator). Extensions of kriging allow for the incorporation of covariates, such as coordinates, geographic, or environmental variables in the predictions. However, because of the large covariance matrices involved in prediction, approximate methods are generally used to minimize computational demands. Kriging can be used as an interpolation method, or to make statistical inferences about areas of interest.

Although of historical importance, kriging has particularities in its theory and methods that have placed it somewhat outside of mainstream spatial statistics. Current statistical methods generally use Gaussian processes to model spatial correlations, which neatly fit into the wider class of generalized mixed models. This allows for a broader and more accessible range of options for improved local prediction and index standardization.

Comparisons between kriging and sdmTMB were considered, and it was noted that kriging tends to poorly model the patchiness of crab stocks. Transitioning to sdmTMB makes sense if the current survey design changes and/or there is low data availability and low crab presence in some areas. Differences between survey and fishery data were discussed, but it was noted that snow crab movement appears to be limited in this area.

Spatial Considerations: Spatial Fleet Dynamics (Newfoundland)

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Newfoundland was formerly dominated by groundfish fisheries. The first snow crab landings occurred in the late 1960s as bycatch in the groundfish gillnet fisheries. In the 1970s, directed snow crab fisheries developed along the northeast coast, primarily in NAFO Division 3L, eventually spreading into NAFO Division 3K. In area 3Ps, sporadic crab fishing took place in the 1970s but did not occur on a regular basis until the mid-1980s, when fisheries also began in Labrador (NAFO Division 2J). Exploratory fisheries started in 4R in the late 1980s. In 2024 there were 2,183 licenses to fish for snow crab across all Crab Management Areas (CMAs) with smaller quotas assigned to smaller areas fished by inshore fleets and vessels fishing in larger areas offshore receiving larger quotas. The CMAs have no biological basis. The resource is assessed at larger scales, called Assessment Divisions (ADs), which align more closely with NAFO Divisions. This spatial scale of the assessment accommodates different types and amounts of available information among the ADs and better aligns with broad-scale resource status indicators. DFO strives to manage the snow crab fishery based on 3 principles: conservation and sustainable harvest, benefits to stakeholders, and co-management of the crab resource. Despite the disconnect between the spatial scales of resource management and assessment, decision making occurs at the level of the CMAs. It is not possible to predict CPUE for small CMAs. Some fleets are very diversified and hold licenses in other species, such as American lobster (*Homarus americanus*), whose abundance is on an increasing trajectory, providing economic resilience in the event of crab declines. Also, some fleets have chosen to fish more conservatively than prescribed by the harvest control rule; full TACs were not taken in 3K, 3Ps, and 4R3Pn. In 2023, there were increases in TACs and landings in all ADs, except 2HJ and 4R3Pn. Any changes to management, including revision of CMAs, require consultation with stakeholders, highlighting the importance of cooperative management.

Spatial Considerations: Spatial Modelling with sdmTMB (Norway)

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The geographically stratified biomass index is important as a descriptive statistic; however, complications arise when the survey design lacks randomness, impacting the representation of each stratum included within it, or when facing spatio-temporal inconsistencies in survey time series, such as missing coverage in a specific year. Statistical approaches offer a solution by modeling processes, accommodating non-random sampling and spatial structures while addressing uncertainty. This framework encompasses techniques such as kriging, Generalized Linear Mixed Models/Generalized Additive Mixed Models (GLMM/GAMM), and incorporates spatial correlation using Gaussian Markov random fields, including methods like sdmTMB and Integrated Nested Laplace Approximation (INLA). Such a framework has advantages to other, non-parametric, approaches such as kriging, as it allows for a better evaluation of the model performance. Various R[8] packages are available for implementation, including: R-INLA for a Bayesian framework; VAST (Vector-Autoregressive Spatio-Temporal model), which also incorporates multivariate features; and spatio-temporal models categorized as length-based or age-based. Among available R packages, sdmTMB stands out for its user-friendly interface, supporting both regular and spatio-temporal models. The package is well-documented, focusing on familiar features like tweedie, delta-gamma, and delta-lognormal distributions. It facilitates mesh definition, smooths addition, and handles time-varying covariates, interpolation, and forecasting. An application of sdmTMB in building a biomass index for northern shrimp (*Pandalus borealis*) in the Barents Sea (Hvingel and Zimmermann 2023) showcased its utility in addressing gaps and missing data. Various spatio-temporal models were discussed, including those incorporating AR1, RW, IID, spatial, and non-spatial components. It was noted that design-based and model-based indices were similar, and differences mostly emerge where the design-based approach performs poorly because of, for example, missing coverage. The example of snow crab in the Norwegian Sea highlighted the significance of standardizing CPUE and utilizing sdmTMB. The modeling approach significantly affects stock index outcomes as it allows for tracing the expanding distribution of the species in the Barents Sea and accounts for spatial shifts in the fishery. Integrating different data types such as different surveys, incomplete time series, and new vs.

[8] The R project for statistical computing. Version 4.0.4. Vienna, Austria. https://www.R-project.org/.

traditional monitoring techniques is an ongoing challenge. Transition within the fleet to video cameras for onboard catch monitoring and integration of data from different gear types still needs more work. Ongoing work focuses on addressing limitations of video data, incorporating uncertainty estimates in stock assessment, and improving the integration of different data types to enhance understanding and management of marine resources.

Predation: Consumption Index (Alaska)

Kerim Aydin –*NOAA Fisheries, Alaska Fisheries Science Center, Seattle, Washington*, *USA*

The Groundfish Food Habits Program began at the Alaska Fisheries Science Center (NMFS) in 1981 and has been measuring predation on snow crab in the Bering Sea since 1985. Samples are collected from a variety of platforms, but most samples are collected in summer months from bottom trawl surveys in the EBS, Aleutian Islands, and Gulf of Alaska. Methods for all analyses are described in Livingston et al. (2017). Although 159 predator species have been included in the stomach content analysis, analysis focuses on four primary groundfish species: walleye pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*), Pacific halibut (*Hippoglossus stenolepis*), and arrowtooth flounder (*Atheresthes stomias*; Livingston et al. 2017).

In the EBS, the greatest consumers of juvenile (<50 mm CW) snow crab are eelpouts (Zoarcidae), accounting for nearly 50% of all juvenile snow crab predation mortality, although the diets and biomasses of eelpouts are poorly sampled, so this estimate is very uncertain (Aydin et al. 2007). Pacific cod are second, accounting for 11% of consumed juvenile snow crab, followed by sea stars (8%), octopuses (4%), large sculpins (*Cottoidea*; 3%), and yellowfin sole (*Limanda aspera*; 3%). For adult (≥ 50 mm CW) snow crab, the largest known sources of mortality are Pacific cod (17%), crab pots (16%), and skates (*Rajidae*; 2%). However, 63% of snow crab mortality is unexplained, based on the difference between best literature estimates of crab mortality (in 2007) and mortality that is accounted as fishing or predation (Aydin et al. 2007).

Because both juvenile and adult snow crab are often found in the stomachs of Pacific cod, a separate analysis was undertaken to examine the cod consumption of snow crab more thoroughly. Over 57,000 cod stomachs were collected by summer trawl surveys in the EBS and northern Bering Sea during 1985–2022, although the latter has only been sampled in recent years. Consumption of snow crab was estimated by cod length, by geographic stratum (survey area), and by year using: (1) bottom trawl survey estimates of cod; (2) temperature-adjusted daily ration of cod; and (3) percent weight of snow crab in cod stomachs. Findings show that cod begin consuming substantial amounts of juvenile crab when the cod are around 30 cm. The percentage of snow crab in cod diets is higher in smaller cod, whereas larger cod show a shift towards eating walleye pollock in certain areas, but heavily feed on snow crab in other areas. In the EBS, snow crab consumption has fluctuated over time, decreasing around 2010, increasing in 2014–2016, and then decreasing again. Notably, cod between 30–60 cm began consuming more crab around 2014, coinciding with an abundance of 10–20 mm crabs, likely associated with a recruitment event. Future research plans include a project led by Jon Reum (NMFS, AFSC-Seattle) to develop spatiotemporal models to examine crab consumption patterns and develop a crab abundance indicator considering multiple predators. Future plans also include greater coverage in non-summer months by expanding partnerships with the fishing industry and onboard observers.

Predation: Consumption Index (Newfoundland)

Mariano Koen-Alonso – *Fisheries and Oceans Canada, Northwest Atlantic Fisheries Centre, St. John's, Newfoundland, Canada*

Four EPUs are recognized in the Newfoundland-Labrador region, based on food-web dynamics and productivity levels: Labrador shelf (2GH), Newfoundland shelf (2J3K), the Grand Banks (3LNO), and southern Newfoundland (3Ps). The ecological history of this region reflects the history of fishing and climate regime shifts. There has been a very long history of fishing in the region leading up to a post-World War II period of industrial offshore fishing and overfishing. Pre-1990, fisheries were dominated by groundfish (e.g., cod). Post-1990, fisheries have been dominated by shellfish (shrimp and snow crab). Climate regime shifts occurred in the 1920s and 1990s. The 1990s regime shift occurred after the system had been intensively exploited. In the 1990s, there was a significant loss of total biomass in the system, with current biomass estimated at only 30–50% of its pre-collapse levels. In summary, this is a story of a major ecosystem collapse, followed by a significant shift in dominant community structure from finfish to shellfish, and the subsequent slow recovery of groundfish since the collapse. Shellfish, particularly important in the 2J3K region, varies in composition among the EPUs, with higher biomass of northern shrimp (*Pandalus borealis*) in 2J3K and higher biomass of snow crab in 3LNO and 3Ps. Total shellfish biomass has declined in each EPU, with most of the decline due to shrimp.

Diet analysis was initiated in 2008 as part of DFO's Ecosystem Research Program and involves the collection of stomachs during spring surveys in 3LNO and 3Ps, and fall surveys across all regions except 3Ps. The goal of the consumption analysis is to estimate the order of magnitude of food consumption at the scale of relevant fish functional groups. Total food consumption by species is estimated using a range of simple food requirements models, which include: (1) daily rations assumed to be 1–2% of body weight per day based on the literature; (2) bioenergetic-allometric method based on empirical allometric scaling relationships of body weight; and (3) an allometric framework from growth principles based on the von Bertalanffy equation and considering maximum fish length. Consumption estimates for individual species are then aggregated to determine the consumption of functional groups. Individual models are employed to establish a consumption envelope, including median and range values, to characterize the magnitude of total food consumption. Diet composition varies among groundfish species across EPUs, with notable prey items including capelin (especially on the Grand Banks, 3LNO), shrimp (especially on the Newfoundland shelf, 2J3K), and northern sand lance (*Ammodytes dubius*). Snow crab predation by piscivores and large benthivores varies across EPUs. Historically, a crab predation mortality index has been highest in southern Newfoundland (3Ps), intermediate on the Newfoundland shelf (2J3K), and lowest on the Grand Banks (3LNO); all 3 predation indices have been declining and converging in recent years.

Predation: Predation as a Recruitment Index (South Newfoundland Coast, 3Ps)

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In Newfoundland and Labrador, snow crab represent a single genetic stock but occupy 3 separate EPUs: Newfoundland shelf (2J3K), the Grand Banks (3LNO), and southern Newfoundland (3Ps). Each of them has a different fish community structure and oceanographic regime. Atlantic cod are considered as separate stocks in these 3 areas. Groundfish predator stomachs have been collected from bottom trawl surveys for diet analysis since the late 2000s. Cod mostly consume snow crab

≤65 mm CW, with historic research conducted in Newfoundland suggesting that predation is a relatively minor fraction of crab mortality. A predation mortality index was calculated as estimated snow crab consumption divided by the biomass of edible crab (≤65 mm CW males). Low values of the predation mortality index were observed in 2J3K and 3LNO but there were spikes in 3Ps, especially in 2015. This analysis focused on male crab only (relevant to assessment estimates of abundance) in southern Newfoundland (3Ps). The analysis focused on a pulse of small crab that were present in 2009–2011 and that disappeared in survey data with no evidence of mid-sized crabs in the trawl survey after 2011. The loss of this cohort came at a difficult time as estimates of exploitable biomass and recruitment were very low, quotas were already low, and the quotas were not being fully caught. Fishery landings fell to an all-time low in 2016–2018. Concomitantly, another problem was that another source of information, the collaborative trap (pot) survey, did not occur in 2015–2016 because that survey depended on quota being given to crab harvesters conducting the survey and this was not sufficient compensation due to the poor state of the fishery. Another consideration complicating the circumstances surrounding the disappearance of the crab pulse was the low selectivity of the Campelen 1800 shrimp trawl (Dawe et al. 2009) survey gear for mid-sized crab. Interestingly, the predation mortality index was very high during the missing crab period, 2013–2016. Adding further complexity to the situation was the observation that the few crab being caught by the survey trawl were undergoing a lot of skip molting at this time, thus remaining at sizes vulnerable to cod predation for a prolonged period. The confluence of available evidence raised the question: did the fish eat all of the pulse of small crab? Surprisingly, the pre-recruit index increased sharply in 2018–2022, and the exploitable biomass quickly increased to an all-time high in 3Ps, along with TACs, landings, and fishery CPUE. This was not predicted. Amid the various sources of data, the predation mortality index emerged as the sole metric that consistently tracked the recruitment pulse through mid-life stages. Accordingly, discussion arose about whether predation should be deemed more as a recruitment index than a mortality indicator in stock assessment and management, in particular given that cod regularly consume the component of the population that is poorly sampled by the Campelen trawl mid-sized crab.

Considering Skip-molting in Population Modelling of NL Snow Crab

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There are 3 types of molting in snow crab: regular, skip, and terminal. Skip molting refers to the phenomenon where crabs skip a molt stage, leading to delayed growth. Skip molting is identified through a combination of shell condition (subjectively determined) and maturity status (based on chela height to carapace width ratios, Conan and Comeau 1986) assessment, with an "oldshell" immature individual deemed a skip-molter. Skip molting cannot be reliably determined from visual assessments in instars below approximately VIII because young crab molt multiple times per year, with the relatively short inter-molt duration resulting in crab being consistently in a soft/new shell condition. After this instar stage, molting is assumed to follow an annual molting schedule, wherein "oldshell" conditions can occur and skip-molting can be visually determined. In NL and the southern GSL, estimated skip molting incidence averages ~20–40% per year in mid-large size adolescents, with annual maxima reaching up to 60–65% of adolescents in some stage groups in some years. In NL, research has shown that there is an overall positive relationship between skip-molting and individual size, particularly up to approximately 100 mm CW. Cold conditions and high population densities of large males can also increase skip molting. Other potential contributing factors include the availability of food resources, success in mating as an adolescent, sex ratios, population density of adolescents, and density of pre-recruit crab may also play a role in the occurrence of skip molting.

Ignoring skip molting can be an issue, particularly for management systems needing annual advice. Skip molting confounds the accurate development of stage-based transition models, as growth delays are not accounted for. Moreover, the existing literature suggests higher rates of mortality in skip molters relative to regular molters are due to poor physiological condition or greater susceptibility to predation (due to being a smaller size for a longer period). Ignoring skip molting in population models can be a problem because it can lead to overestimation of mature biomass (i.e., assuming all old shell males are mature) or cause advanced cohort progression to larger sizes. Model simulations starting at instar VIII suggest that 23–59% of crab would be delayed by at least 1 year in their transition through the population to legal-size. In areas where skip molting is common, 13–18% of crab may face delays of 2 years. Accordingly, the inclusion of skip molting in population models is essential for accurately estimating growth transition rates and failure to account for it can lead to inaccuracies in recruitment projections. Compounding the issue of inaccurate growth transition assumptions, NL data suggest that mortality in skip molting individuals is high, and thus treating skip molting as regular or terminal molting can significantly impact model outcomes due to mis-specified assumptions about mortality rates.

Overall, the simulations highlight that skip molting is not normally accounted for in population models, but it is an important factor to consider. Skip molting will affect accuracy of growth transition rates in models. Delays of 1–2 years transitioning through the population after ~40 mm CW are relatively common in populations for which moderately high skip-molting rates persist. By extension, legal-size crab, on average, are older than we historically assumed due to skip molting. Populations in which skip molting is high will experience overall truncation in size structure. Without explicitly including skip molting in molt-type outcomes within a multinomial model, assumptions on how to treat skip molters should be based on knowledge of skip-molter mortality in the area. A best-case scenario is either: (1) an assumption of crab being regular molters in a model will match minimal mortality in the wild; or (2) crab being terminal molters in a model will match an assumption of high mortality in the wild. With respect to model projections, models are likely to overestimate recruitment if incorrectly assuming that skip-molting individuals are regular molters and underestimate recruitment if assuming they are terminally molted. Fortunately, improper assumptions in short projections, such as a one-step projection of immediate recruitment into the fishery, have relatively low risk unless skip-molting prevalence is high. Moving forward in developing population models in NL, the best practice would be to include skip molting in modelling, particularly in populations where skip molting is known to be high (such as NAFO Division 3Ps). Given known relationships with contributing factors, it should be possible to incorporate probabilistic-based molt outcomes based on size, temperature, and density into abundance projections. However, further research is warranted to augment existing knowledge on skip-molting contributors. In particular, it is uncertain whether molt history affects current molt decisions.

Desynchronization of Teleconnected Populations: A Case Study of the Bering Sea and Newfoundland Snow Crab

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The 2018–2021 Bering Sea snow crab population collapse is well documented (Szuwalski et al. 2023) and has been featured in US national and international news outlets. An Alaska climate-linked modeling project explored the nature of the population collapse and aimed to address the questions: (1) what happened?; (2) what happens next?; and (3) why did the collapse happen in Alaska? Analyses have explored how mortality associated with the population collapse relates to the environment and have considered temperature, diseases, fishing pressure, cannibalism, population density, and predation by Pacific cod. Results identified temperature and population density of snow crab as significant covariates explaining mortality. Snow crab energetic demands at varying temperatures (Foyle et al. 1989) suggest that the caloric requirements of the population in 2018 were substantially higher than historical levels. The increased metabolic demands, changes in weight-at-size, decreased spatial extent of the population, and body condition suggest that starvation may have played a role in the collapse (Szuwalski et al. 2023).

In trying to predict "what happens next?", a male-only population dynamic model was employed that considered growth and maturity as inputs, fits to survey and fishery abundance and size composition by maturity state, and estimates of recruitment, natural mortality, and fishing mortality. Preliminary results indicated that density dependence and environmental covariates better explain the variability in mortality, recruitment, and maturity than no covariates, and that changes in sea ice coverage have a strong impact on mortality and recruitment. The analysis revealed 2 periods of high recruitment: 1 in the 1980s and 1 in 2010, which both coincided with low AO and high ice cover. Ice cover projections suggested strong impacts on mortality and recruitment, with declining snow crab populations likely to occur as ice continues to retreat.

In trying to understand why the collapse happened in Alaska but not in Canada, Alaska was compared to NL (Mullowney et al. 2023). A high correlation in large-male abundance occurred until 2019, but this correlation declined after 2020. Using Newfoundland data as inputs to the population dynamics model developed for the Bering Sea stock, preliminary fits showed differences in the proportion of each population that has been composed of mature male individuals between NL and the EBS. Generalized Additive Models fit to immature and mature mortality and recruitment, and covariates including fishing mortality, bottom temperature, NAO, and AO, revealed positive relationships with mortality: mature mortality increased with temperature and immature crab density; immature mortality increased with higher temperature, immature density, and fishing mortality; and recruitment increased with NAO and mature density. Recruitment is the primary determining factor for synchronization between the EBS and NL populations, but high EBS mortality, likely linked with the lack of sea ice in 2018–2019, is thought to be the cause of desynchronization in post-2020 years.

In conclusion, even intensively managed populations can collapse due to complex environmental changes. Both NL and Alaska mortality dynamics were linked to ice/temperature and crab density, while recruitment dynamics were related to large-scale indices of environmental variation (NAO, AO). Management reference points should remain unchanged, and managers should exert high fishing pressure on stocks that are flourishing and reduce fishing pressure on stressed stocks to allow time to recover/adapt. Efficacy of protected areas, gear restriction, and effects of bycatch are recommended areas for future research. Similar analyses comparing these stocks to other snow crab populations, such as those near Greenland and Russia, could provide further insights.

THEME 3: APPLIED MANAGEMENT

Advances in Gear Technology

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Past research conducted at Memorial University's Centre for Sustainable Aquatic Resources (CSAR) has focused on increasing the efficiency of snow crab fishing in Newfoundland. Conical snow crab traps are commonly used in NL fisheries and are considered highly efficient. Selectivity curves of pots with different mesh sizes demonstrate improved efficiency as a result of changes in mesh size, hanging ratio, and diamond versus square mesh. Evaluations of circular escape mechanisms revealed that fewer sublegal (<95 mm CW) crab were captured when using escape rings, with no difference in capture efficiency of legal (>95 mm CW) crab (Winger and Walsh 2007, 2011). Although escape mechanisms improve selectivity of legal-size crab and their use is legal, they are not mandatory. Analysis on the utility of plastic collars to deter small crabs from entering pots is in progress. Regarding trap lifespan, cheaper traps priced at $75 CAD can last around 9 years. The process of galvanizing trap frames to prevent corrosion could increase trap lifespan. Research has demonstrated that galvanized traps fish at similar rates as non-galvanized traps, suggesting that, although initially expensive, it is economically favorable to galvanize trap frames (i.e., less effort to replace damaged traps, lower cost over the trap's lifespan, fewer traps sent to the landfill prematurely; Brown et al. 2024). Past work that attempted to develop wire snow crab traps was reviewed. Initial attempts were unsuccessful, but current efforts are evaluating wire snow crab traps with small mesh sizes (100 mm), which are currently illegal but could incorporate escape mechanisms for undersized crabs and increase the lifespan of the traps. The issue of trap loss was discussed: an estimated 27,000 traps are lost in Newfoundland and Labrador each year. Biodegradable escape mechanisms, such as twine, were evaluated (Winger et al. 2015), and as a result, the mandatory use of 96-thread cotton twine began in 2013 to prevent lost traps from ghost-fishing. The potential benefits of artificial light in increasing CPUE have been documented (Nguyen et al. 2017), although concerns have been raised about increased plastic usage and light disturbance. It was noted that artificial light could attract plankton, potentially luring crab, but further research is needed to confirm this. Other gear innovations that were discussed included glow-in-the-dark nets with UV-excited fiber (Frank et al. 2024) and alternative baits (Araya-Schmidt et al. 2023). Additionally, efforts to mitigate whale entanglement have included measuring tension in down ropes (Peck et al. 2024) and developing "smart" buoy lines that, when under tension for a set period, automatically cut the rope (Peck 2024). Finally, sound-emitting devices designed to mimic eating sounds are under development.

In addition to his presentation, Paul Winger led a tour of the CSAR, including the flume tank, which provides the physical environment for researchers and fishers to carry out evaluations of newly developed or existing fishing gear. Winger discussed ongoing research at the CSAR as workshop participants explored other CSAR areas including the net loft.

Incorporating Indicators into Fishery Management: Health Indicator Identification (Alaska)

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Crab health indicators may include size at maturity, clutch fullness, energetic condition, and disease prevalence. These may combine to influence natural morality, recruitment, and reproductive potential. Regarding energetic condition, a metric based on weight at size is not useful for crabs as weight is a function of the molting process. A number of other metrics (e.g., Brix index or percent dry weight of hepatopancreas) require species-specific validation and calibration. At present, lipids and fatty acid concentrations are the best methods to assess crab health. Lipids are major sources of metabolic energy, and fatty acids serve as trophic biomarkers as they are transferable from prey to predator with limited modification.

A hepatopancreas sampling program for EBS snow crab started in 2019 and continued following the collapse of the population in 2021. The hepatopancreas is the primary organ for nutrient and energy storage in crab. During the start of the population collapse in 2019, juvenile crab were in very poor energetic condition in the EBS, but there was no evidence of energetic limitation in northern Bering Sea snow crab in 2019. However, there has been a weakly positive temperature effect on energetic condition in the northern Bering Sea. In the EBS, there was a negative effect of temperature during the decline but a positive effect after the collapse, and the same pattern was observed with population density.

A common theme among presentations at this workshop has been the beneficial effects of cold ocean temperatures and sea ice on snow crab productivity. One potential mechanism for these relationships has emerged in the EBS: whether the spring phytoplankton bloom is ice-associated or open-water. Ice-associated blooms tend to predominate in cold years and open-water blooms are dominant in warm years (Nielsen et al. 2024). DNA metabarcoding of snow crab stomachs showed that diatoms are their most prevalent dietary item. There was an increase in diatom-sourced fatty acids in snow crabs in cold years, pointing to the potential importance of diatoms to energetic condition (Copeman et al. 2021). Apparently, diatoms are directly ingested by juvenile snow crab, likely owing to a "benthic fluff" layer of carbon deposition to the benthos that snow crab consume. Under warm conditions, open-water blooms tend to favor small, energy-poor planktonic species, most of which remain in the water column rather than sinking to the seafloor.

Laboratory starvation studies under different temperatures (2, 5, and 8° C) are underway. Among other objectives, the utility of the non-lethal Brix index to indicate snow crab starvation will be validated.

In addition to studies on energetic condition, research is also being conducted on other types of health indicators, including bitter crab disease (BCD). Formerly, visual methods, which tend to underestimate prevalence, have been largely used to detect BCD. Now, hemolymph samples are taken to detect BCD with greater accuracy. Some samples from the northern Bering Sea show prevalence approaching 70%, which is historically high. There was a dramatic increase in BCD over 2015–2017, potentially contributing to recent population declines in snow crab. Size at 50% maturity continues to be monitored in the EBS, and there has been a long-term decline in male size at maturity since 1989. Females showed a decline from 1987 to 1995, increase from 1996 to 2008, and a subsequent decline through 2023.

Finally, preliminary egg clutch fullness analysis indicates that periods of decline in mature male biomass may be associated with declines in female clutch fullness.

Incorporating Indicators into Fishery Management: Health Indicator Identification (Newfoundland)

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Fishery management typically relies on a harvest control rule in which exploitation rates vary as a function of stock biomass. However, it may be important to consider other factors when setting target harvest rates, such as stock composition and reproductive health. Snow crab have a complex reproductive biology including sexual dimorphism and structures (spermatheca) to store sperm from previous mates. There are differences between primiparous (first-time spawners) and multiparous (multi-spawners) females, whereby the latter can use stored sperm to fertilize their egg clutches. Their flexible mating strategy involves sperm economy, wherein the quantity of sperm released varies based on the level of competition among males. Males divert much energy to mating by exhibiting courting and holding behavior to protect females during molting. Large males generally hold a female longer and provide more sperm. Smaller males demonstrate an abbreviated holding period and provide brief inseminations.

High rates of removal of males can skew the sex ratios toward females and preferential removal of large males can change stock age structure (reduction in male size distribution), resulting in fewer large male mates and reduced fecundity. The probability of mortality for females increases as a function of the number of males with whom they mate. With the removal of large males, immature males in the population will mature earlier (i.e., undergo terminal molt) and at smaller sizes to participate in reproduction. Sperm limitation has the potential to occur in populations depleted of large-male snow crab by fishing, thus diminishing the reproductive capacity of the stock (Baker et al. 2022). Size at maturity may provide a useful indicator for these processes. However, it is important to also consider that size at maturity is also influenced by factors such as temperature.

Another useful indicator of stock health may be egg clutch fullness. Females with incomplete egg clutches are more likely to lose the entire clutch of eggs with potential decline in reproductive potential at the population level. Fortune Bay, Newfoundland, is an interesting case with large females and small males, where this stock is not recovering compared to other Newfoundland regions. A new study is planned to look at histology, genomics, and proteomics between Fortune and St. Mary's Bays. Indicators of stock composition and reproductive health have the potential to provide early indicators of conservation issues.

Considerations of Legal Size in Fishery Management (Alaska)

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In the EBS, legal size for snow crab is ≥79 mm CW (3.1 in), mean size at maturity is ~95 mm CW (3.7 in), and industry preferred size is ≥101 mm CW (4.0 in). Economic considerations factor into the industry's preferred size, including market competition for snow crab, marketing of "Alaskan snow crab" that includes snow crab and the larger Tanner crab, and crab rationalization, which links harvesters and processors. Industry-preferred size also factors into the State of Alaska's harvest control rule that includes a threshold level of biomass needed to open the fishery, a harvest rate applied to the estimated mature male biomass, and a maximum harvest rate on exploitable legal males based on industry preferred size. The exploitation rate on preferred size males steadily increased from 2000 until the stock collapsed in 2019. Also, since 2011 there has been a sharp increase in discard rates of undersized males, associated with increases in the ratio of relatively smaller-sized (95–100 mm) to larger-sized crab (≥101 mm). With the EBS experiencing warming trends, a more-northerly distribution of snow crab, and a decline in size at 50% morphometric maturity for males, concerns arise regarding yield potential and the responsiveness of preferred size to climate change. Concerns include the potential for a genetic basis for the decline in mean size at maturity associated with high rates of removal of large crab and associated *de facto* conservation of smaller-maturing individuals within the breeding population. The impacts of the current use of industry preferred size remain unresolved. ADF&G is looking for science-based rationale for changes in fishery management. The scientific basis should include analyses of exploitation rates, changes in mating dynamics and/or genetic impacts caused by selective removal of large males, and other considerations. Owing to these uncertainties, precaution is needed.

Precautionary Approaches in Fishery Management (Alaska & Newfoundland)

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The Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) provides the legal framework for management of fisheries in the US EEZ. The North Pacific Fishery Management Council has implemented a Fishery Management Plan (FMP) for BSAI king (*Lithodidae*) and Tanner crabs, covering 10 crab stocks, including EBS snow crab. The crab FMP provides for cooperative federal-state fisheries management. Stock assessment utilizes annual NMFS trawl survey data, as well as fishery-dependent data. Assessments involve the determination of Overfishing Levels (OFLs), and Acceptable Biological Catches (ABCs) that account for scientific uncertainty. The State of Alaska determines Total Allowable Catches (TACs), consistent with the MSFCMA and the Alaska Board of Fisheries Policy on King and Tanner Crab Resource Management. Snow crab TACs are set annually based on a biomass threshold for opening the fishery, mature male exploitation rate that increases with relative biomass, maximum harvest caps on legal males, and other considerations (Zheng et al. 2002).

The processes associated with stock assessment and catch specifications are not without challenges. These include difficulties in estimating mature male biomass. Often, there are significant discrepancies between observed trawl area-swept estimates and assessment model estimates, particularly in the terminal (most recent) year. A PA in Alaska is built into the State's TAC-setting process based on the perceived level of uncertainty in the assessment, with additional flexibility to consider concerns related to the health of the stock or ecosystem. For example, if uncertainty is low, then the TAC is computed using assessment model estimates. If uncertainty is moderate to high, greater weighting is given to the area-swept estimates of abundance; and if uncertainty is very high, then harvest control rules are abandoned and other TAC-setting approaches are considered, including fishery closure. The Bristol Bay red king crab fishery was a recent example where several factors influenced management decisions: unfavorable environmental conditions (pH, temperature, chlorophyll-a [i.e., a proxy for primary productivity], and predator density), low recruitment, uncertainty in population abundance estimates, and population projections under varying exploitation rates all led to a lower harvest rate being applied than the harvest strategy would have otherwise indicated. An earlier workshop presentation on ecosystem approaches in Alaska (i.e., E. Fedewa) described the development of Ecosystem and Socioeconomic Profiles (ESPs) and Ecosystem Status Reports (ESRs) that can contribute to Risk Tables used for establishing and evaluating buffers between OFLs and ABCs on the federal side of the catch-specification process. A PA includes a diverse variety of other actions, as well, including monitoring (e.g., size structure, reproductive condition), bycatch controls on groundfish fisheries, pot escape rings and biodegradable mesh, and modified bottom trawls to raise trawl sweeps off the seafloor. For a broad overview of EBFM applied to BSAI crab fisheries, see Kruse et al. (2025).

In NL, a multi-indicator PA was implemented by DFO in 2018 (Mullowney et al. 2024) to meet eco-certification requirements and mandates of the Canadian Fisheries Act. The approach relies most heavily on survey biomass in the setting of catch quotas, but also considers other information, including predicted CPUE, predicted discards, and clutch fullness in assessing stock and fishery health status. These metrics are used to establish stock health scores that are categorized as healthy, cautious, and critical zones (Mullowney and Baker 2023). The primary harvest control rules in the PA allow for up to 42%, 35%, and 20% exploitation rates, with no lower bounds, when the stock is in the healthy, cautious, and critical zones, respectively. In this framework, there is limited potential for fishing even in critical zones, allowing flexibility in management decisions. Zone determination is based on stock health metrics including predicted CPUE (at different levels of exploitation rates to provide insight into population trends under varying fishing pressures), predicted discards (at different exploitation rates, helping to assess the impact of fishing activities on discarded individuals), and clutch fullness (signals of insufficient density of large males). Prior to the PA system, harvest rates were quite variable across NL assessment districts, but now they have become much more consistent. The PA was put into place when the stock units were at low biomass levels. All stock units have responded very favorably with overall improvements in size at maturity, clutch fullness, and CPUE.

Appropriate metrics for the inclusion of reproductive potential in fishery management remain a matter of ongoing debate in both Alaska and Canada. Unlike females, whose maturity status is easily determined by the size of the abdominal flap and presence of an egg clutch, determination of male maturity status is more complex. Male maturity may be considered as physiological (ability to produce sperm), morphological (large claw indicating terminal molt), and functional (competitively dominant and able to mate with any female). The current metric used by US management is morphometric maturity, which is measured for a subsample of males caught during the EBS trawl survey and which may not accurately reflect the portion of the male population that actually participates in reproduction. The use of size limits may lead to high exploitation rates on large (legal) males and protection of small mature males, resulting in potential genetic effects (e.g., higher survival of males with genetic predisposition for small size). Moreover, removal of large males reduces competition for mates, resulting in a decline in size at maturity as crabs attain terminal molt at smaller sizes. In a recent genetics study of EBS snow crabs, Slater et al. (2024) found that embryo clutches of most females were fertilized typically (82%) by 1 sire and rarely (18%) by 2 sires, despite the fact that females are capable of storing sperm from multiple mates for up to three years. In general, females must remate each year to produce fully-fertilized egg clutches. Scientists in both Canada and Alaska scrutinize female clutch fullness for indications of reproductive failure. Clutch fullness is formally included in the PA for snow crab in NL. In general, female clutch fullness is higher in NL than EBS snow crab; in 2022, just 37% of mature females had clutch fullness of 75% full or greater, the lowest on record dating back to 1980. Also, a decline in size at 50% maturity in EBS snow crab since 2006 could be a sign that exploitation rate is too high. A similar decline in size at 50% maturity was reversed after implementation of the PA system in NL (Mullowney et al. 2024). In the future, Alaska fishery managers may consider a multi-indicator approach, similar to the PA system in NL, which includes various measures of stock health.

Lessons from Fishery Management: Comparison of Harvest Rates vs. Stock Outcomes (Alaska and Canada)

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Harvest (exploitation) rates are determined via harvest control rules, a set of agreed-upon calculations that scale harvest levels to stock status. Harvest control rules are generally tuned to the concept of MSY. A generic sloping control rule was described that consists of: (1) a maximum harvest rate at high stock abundance levels; (2) the "ramp" over which harvest rates decline at abundances that are below a predetermined stock level; and (3) a low stock abundance level where harvest rate is 0. The BSAI federal-state co-management regime includes federal OFL, ABC, and TAC. For EBS snow crab, both federal and state harvest control rules include fishery closure thresholds of 25% of estimated MSY. It was noted that while management discussions are often centered on the upper harvest rates when stock abundance is high, the fishery closure threshold gets comparatively little attention. Although a 25% stock status may be arbitrary as a fishery closure threshold, it serves as a good starting point for continued refinement in future analyses.

A comparison of the EBS, NL, and southern GSL harvest levels and harvest control rules illustrates similarities and differences across regions. The EBS and southern GSL have similar harvest control rules where exploitation rate increases based on relative stock biomass; however, EBS stock biomass is determined via total mature biomass whereas the southern GSL considers commercial biomass (i.e., males ≥95 mm CW). Relative to the EBS, the southern GSL harvest control rule employs exploitation rates that are higher for a given stock biomass but includes a more conservative threshold for closing the fishery (i.e., 50% of BMSY compared to 25% for the EBS) and defines critical, cautious, and healthy zones. The Newfoundland region utilizes a harvest control rule based on stock health scores, incorporating predicted CPUE, predicted discards, and female clutch fullness scores. The NL harvest control rule stock health critical zone allows for exploitation rates that range from 0% up to 20%.

Despite differences in target sizes and management strategies, comparisons between EBS, NL, and southern GSL indicate that historical fisheries have been managed with reasonably similar exploitation rates. However, NL management areas 2HJ and 3K experienced substantially higher exploitation rates in recent years, and these areas have also experienced reductions in size at maturity, which have generally been attributed to overfishing. More recent reductions in exploitation rates in these areas coincided with subsequent improvements in size at maturity. Accordingly, it is generally thought that exploitation rates were too high and demonstrated potential for biological corrections through reduced fishing rates. Concerns about declining size at maturity in certain regions underscore the need for corrective measures to reduce fishing pressure. Canadian management considers commercial biomass (male crab ≥95 mm CW) as the currency of management, whereas EBS management considers morphologically mature males as the currency of management. Three definitions of male maturity include physiological maturity (individuals with small claws, but capable of sperm production), morphological maturity (individuals with large claws that have undergone terminal molting), and functional maturity (individuals that actively participate in population mating dynamics). Functionally mature males are typically large-clawed, vigorous, and competitively dominant. The use of ≥95 mm CW as a proxy for functional maturity suggests that individuals meeting this size requirement are likely to exhibit the characteristics associated with functional maturity, such as possessing large claws and actively engaging in mating dynamics within the population.

Overall, both EBS and Canadian management employ similar harvest strategies wherein both regions have harvest control rules that adjust exploitation rates to stock health and establish fishery closure thresholds. The NL harvest control rule is unique in that it considers CPUE, discards, and clutch fullness, in addition to biomass, for management decisions. The EBS fishery targets ≥101 mm CW crab, whereas the Canadian fisheries target ≥95 mm CW crab. Despite differences, both regions maintain similar exploitation rates. Yet, Canadian biomass and landings are at their highest in two decades, while the EBS stock experienced a significant collapse during 2018–2021. Looking ahead, there are signs of hope for the EBS crab population, with recent increases in the abundance of immature components of the stock. However, it may take several years for individuals to reach legal size, indicating the need for continued monitoring and management strategies. Key questions for future consideration include how to manage fisheries at low population abundance levels and whether pre-crash productivity levels are attainable, particularly in light of predicted environmental changes.

DISCUSSION

From the side of the participants from the USA, the main catalyst for this workshop was the crisis currently facing the Bering Sea crab fisheries. Many crab stocks are depressed, and the additional recent declines of Bristol Bay red king crab and EBS snow crab have created an economic disaster for fishery stakeholders, including affected communities. Disaster relief funding is available to support fishers, and a portion of those funds have been made available to support research. It is important to identify critical issues that, once resolved, can quickly inform effective management decisions. Although there is a sense of urgency to undertake research that can have immediate impact, there is also the realization that climate-driven changes in the marine ecosystem are heavily involved in the crab declines. In the short term, there is strong interest among the Bering Sea crab industry in finding ways to safely reopen fisheries, even with small quotas, without exacerbating conservation concerns that may threaten the likelihood of recovery. Workshop participants were reminded of the collapses of king crab fisheries throughout the Gulf of Alaska that have failed to recover even after more than 4 decades of fishery closures. A case was made not to lose track of the medium and long-term. Along these lines, there is strong support for climate and ecosystem-level research involving crabs, while recognizing the challenges in communicating impacts of climate change to stakeholders.

During this workshop, comparisons of snow crab in the North Pacific and North Atlantic revealed several important observations about the roles of climate, ecology, and fishing in snow crab stock dynamics. Brief summaries are provided below.

Climate Effects on Snow Crab Productivity

- Snow crab are an Arctic species thriving in cold water; thus, the connection between modes of climate variability and snow crab involves sea ice and temperature. In Newfoundland, the CIL is most important to snow crab, whereas in the EBS it is the cold pool. Specifically, in Newfoundland, cold bottom water is a primary component of the Habitat Index, which reflects factors that regulate juvenile snow crab abundance. Sea ice extent data correlates positively with abundance of age-1 snow crab. Most of the Newfoundland shelf is dominated by cold water in summer. In the EBS, the bottom cold pool in summer is a function of sea ice extent the previous winter.

- The NAO and AO are modes of climate variability affecting temperature in the mid-latitudes. The two modes are highly correlated (Hamouda et al. 2021). Sea level pressure associated with these modes drive ocean circulation. The AO operates through wind and the jet stream. The phase of the NAO/AO shunts the relative flow of the cold LC either west toward southern Newfoundland and the GSL or east back toward the mid-Atlantic.
- Bottom temperatures and sea ice covary with NAO/AO oscillations. Fishable snow crab biomass has a 5–9 year lag from changes in the NAO. Generally, the EBS and NL snow crab stocks have covaried together but also out of phase with the southern GSL stock. However, the correlation between EBS and Newfoundland snow crabs has broken down since 2020, owing to the collapse of EBS snow crab and sustained strong performance of Newfoundland snow crab. The out-of-phase correlation between NL and southern GSL stocks of snow crab are attributed to the alternating orientation of the cold LC and its effect on the CIL of the two regions.
- At least 2 mechanisms may be responsible for the relationship between cold temperatures and snow crab productivity: (1) cold temperatures serve as a refuge for small snow crab from groundfish predation (Mullowney et al. 2023); and (2) cold temperatures along with extensive sea ice promotes ice-related phytoplankton blooms composed of nutritious diatoms (Nielsen et al. 2024) that settle to the seafloor during senescence where they can be consumed by snow crabs (Copeman et al. 2021). Interestingly, whereas colder temperatures benefit juvenile snow crab, warmer temperatures promote the molting, growth, and mating of adult snow crab.
- Historically, sea ice conditions have been driven by greenhouse gas emissions and atmospheric teleconnections. Now, greenhouse gas emissions are the primary driver, and teleconnections generate more “noise” than signal (Mullowney et al. 2023).

OTHER ECOLOGICAL FACTORS AFFECTING SNOW CRAB

- Snow crab are often found in the stomachs of cod in both the North Pacific and North Atlantic. However, predation studies have yielded, at best, mixed results about the role of cod predation on snow crab population dynamics. Although some studies have implicated cod in snow crab declines, most have failed to detect such an effect in the EBS, NL, and southern GSL regions. One NL study suggested that predation could be deemed more as a recruitment index than a mortality indicator in stock assessment, particularly given that cod regularly consume a size range of crab that are not well sampled by survey trawls.
- Bitter crab disease (BCD) is a parasitic infection that gives crab a bitter taste and renders infected crab as unmarketable. It has been detected in both North Pacific and North Atlantic snow crab. Current methods that involve sampling of hemolymph (fluid that functions as both blood and lymph in crustaceans) detect BCD with much greater accuracy than former visual detection methods that generally underestimate the prevalence of infection. In the EBS, there was a dramatic increase in BCD from 2015–2017, raising the question whether it contributed to recent population declines in snow crab. Some samples from the northern Bering Sea show prevalence approaching 70% in some size ranges, which is historically high. Because of the imprecision of historical visual methods, it is not possible to infer long-term trends in BCD prevalence. Visual detection of BCD is particularly challenging

in EBS surveys due to summer seasonality whereby the disease is not advanced enough to be reliably macroscopically detected.

FISHING EFFECTS ON STOCK REPRODUCTIVE HEALTH AND SIZE AT MATURITY

- Harvest rates are quite similar among EBS and Canadian snow crab fisheries. Although there are differences in their specification, when harvest control rules are expressed using the same "apples-to-apples" metrics (i.e., biomass of males >95 mm CW), exploitation rates applied in the EBS are quite similar to those used in the southern GSL and NAFO Divisions 3Ps and 3LNO, but slightly lower than those used in Divisions 3K and 2HJ.
- In NL, a Precautionary Approach was put into place when the stocks were at low biomass levels and thought to be overexploited. Since implementation of the Precautionary Approach, the stocks have responded very favorably. Discards became low, clutch fullness became high, and CPUE became high. Also, importantly, size at maturity, which had previously declined, turned around and increased.
- In the NL Precautionary Approach, harvest control rules are based on estimated biomass but they also consider stock health scores based on predicted fishery CPUE, predicted discards, and female egg clutch size (Mullowney and Baker 2023). The primary harvest control rules in the PA allow for up to 42%, 35%, and 20% exploitation rates, with no lower bounds, when the stock is categorized to be in healthy, cautious, and critical zones, respectively.
- EBS male snow crab have been experiencing a concerning long-term decline in size at maturity, but the causes have not yet been examined. However, similar downward shifts in size of maturity in the Newfoundland and Labrador region were attributed to cold conditions and low crab densities. Low densities were caused by elevated fishery exploitation rates.
- The mechanism behind the relationship between higher harvest rates and declines in size of maturity relates to competition by males for mates (Mullowney and Baker 2021). Large males outcompete smaller males for mating opportunities. Large males can deliver large sperm loads to females for fertilization of large egg clutches. Although population densities of large males are high, small immature males tend to continue growing so as to ultimately reach large sizes that allow them to be reproductively successful. With the removal of large males by high fishery exploitation rates, small males undergo terminal molt to maturity sooner because they no longer need to compete with large males for mates. However, they are less competent in mating and multiple small mates may be required for the female to acquire sufficient sperm to fertilize full clutches. Also, mating with multiple smaller males cause females to suffer more injuries during mating, due to increased male aggression, and is sometimes fatal.
- In general, female egg clutch fullness is higher in NL than EBS snow crab: in 2022 just 37% of mature females in the EBS had clutch fullness of 75% full or greater, the lowest on record dating back to 1980.
- Mullowney and Baker (2021) also investigated skip-molting in snow crab in Newfoundland and Labrador. Skip-molting is the process by which a crab does not molt in the current year but retains the ability to molt again in subsequent years before attaining terminal molt. They found that skip-molting occurs most frequently under extreme cold and high population density conditions. This phenomenon has not been fully evaluated in

EBS snow crab and may also be critical in determining the evolution of size structure and reproductive dynamics in arctic systems (e.g., Barents, Kara, northern Bering, Chukchi, and Beaufort Seas) into which snow crab are expected to expand their populations as climate change progresses.

The workshop included time for questions and answers after each presentation, discussion sessions on each day, and a concluding discussion session that attempted to summarize the workshop with a future outlook and research directions. Here, we summarize some important discussions raised during this workshop.

A number of research priorities for snow crab were identified. They are presented below in no particular order.

- Strengthening collaborative efforts is important, particularly in refining stock health metrics and establishing red flag indicators for assessing stock health. There are excellent opportunities for additional comparative analyses of snow crabs in response to sea ice dynamics over multiple stocks. Continuing such collaborative workshops and fostering ongoing dialogue were seen as important for addressing the challenges facing Bering Sea crab populations effectively.
- More work is needed on the apparent effects of exploitation rate on size at maturity. It is not clear that reductions in size at maturity are always associated with elevated exploitation rates. There is a need to look at EBS snow crab, as well as other time periods for Newfoundland snow crab.
- Skip-molting deserves further study. Tracking cohorts over time and controlled laboratory studies were suggested.
- Conduct a "post-mortem" (i.e., retrospective analysis of its dynamics) on the effects of the 2018–2019 EBS marine heat wave. How far in advance did we have indications of impending stock collapse? The 2019 EBS trawl survey provided a warning. We also missed the decline in maturity. What could have been done? What are the appropriate response actions?
- Pursue studies on snow crab physiology with respect to temperature and reconciling apparently different responses in the field versus in the laboratory. A question is whether laboratory studies may underestimate the true caloric requirements of snow crab.
- If omnivorous snow crabs starve in the ocean, is the benthic community depleted? Can we detect this with respect to current alterations in epifaunal and infaunal community structure; and can we establish a monitoring program that could detect such shifts in real time should a similar event occur?
- Use telemetry to study movement patterns of adult snow crab throughout the year and in relation to the continental slope and the USA/Russia border.
- Further study predation and other sources of mortality on juveniles. What are the recruitment bottlenecks for snow crab?
- Conduct habitat identification, particularly mating grounds and areas that may experience high mortality rates (e.g., nursery areas) to establish protection zones that promote population recovery.
- Study the effects of trawling on juveniles. There is a need for research on impacts of "pelagic" trawling on crabs.
- Enhance our understanding of fisheries as coupled socio-ecological systems, with adaptation strategies becoming increasingly important.

- Incorporate long-term considerations involving the northern Bering Sea and climate shifts into management frameworks.
- Develop adaptive responses to stock declines and the need to forecast heatwave effects on mortality. Approaches may include incorporating climate and fishing effects into Management Strategy Evaluations (MSEs).
- Recognize the importance of communicating the role of climate change on crab stock productivity and associated research to stakeholders and the public.
- Although much of climate research addresses the long term, it may be possible to identify some short-term actionable items. For example, establishment of robust cause-and-effect relationships between temperature and trawl survey catchability could be incorporated directly into stock assessments. Likewise, relationships identified between temperature or sea ice and crab productivity could be incorporated into stock rebuilding plans. Other environment-crab relationships, after being vetted through the ESP process, could lend themselves for incorporation into stock assessments and catch specification processes.
- Examine how to move away from 4″ (101 mm) CW as the target size for marketing in EBS. The necessity of maintaining "preferred size" was questioned. High rates of discards of undersized crab is an issue and the maintenance of a preferred size may reduce the rate at which the fishery is able to respond to changes in abundance and population structure.
- Ghost fishing should be examined. What is the ability of lost pots to continue fishing? How effective are current biodegradable escape mechanisms? What fraction of the snow crab stock is killed by ghost fishing?
- There is a need for gear research to reduce bycatch. For example, use of lights to increase CPUE or glow-in-the-dark netting to reduce whale entanglement; use of smart buoy lines that break away if a whale becomes entangled.

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APPENDIX A. LIST OF WORKSHOP ATTENDEES

Fisheries and Oceans Canada (NL)

Krista Baker	Katie Morrissey
William Coffey	Darrel Mullowney (co-Chair)
Frédéric Cyr[9]	Hannah Munro
Martin Henri	Julia Pantin
Mariano Koen-Alonso	Erika Parrill

Fisheries and Oceans Canada (Gulf)

Stephanie Boudreau	Tobie Surette

Bering Sea Fisheries Research Foundation

Scott Goodman (co-Chair)	Madison Heller-Shipley
Gordon Kruse (Chair)	Gary Stauffer
Timothy Loher	Doug Wells
Edward Poulsen	

Alaska Department of Fish and Game

Benjamin Daly	Mark Stichert
Katie Palof	

NOAA Fisheries, Alaska Fisheries Science Center

Kerim Aydin	Elizabeth (Ebett) Siddon
Erin Fedewa	Cody Szuwalski
Mike Litzow	

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Terrance Wang

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Maxime Olmos

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Fisheries & Marine Institute, Memorial University of Newfoundland

Tomas Araya-Schmidt
Shannon Bayse
Kristine Cerbule
Meghan Donovan
Tyler Eddy
Colin Frank
Genevieve Park
Raquel Ruiz-Diaz (Rapporteur)[10]
Paul Winger

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APPENDIX B: LIST OF ACRONYMS

ABC – Acceptable Biological Catch

ADF&G – Alaska Department of Fish and Game

AL – Aleutian Low Pressure System

AMOC – Atlantic Meridional Overturning Circulation

AO – Arctic Oscillation

BCD – Bitter Crab Disease

BSAI – Bering Sea and Aleutian Islands

CIL – Cold Intermediate Layer

CMA – Crab Management Area

COG – Center of Gravity

CSAR – Centre for Sustainable Aquatic Resources (Memorial University of Newfoundland)

CW – Carapace Width

DFO – Fisheries and Oceans Canada

EAFM – Ecosystem Approach to Fisheries Management

EBFM – Ecosystem-based Fisheries Management

EBS – Eastern Bering Sea

EEZ – Exclusive Economic Zone

ENSO – El Niño Southern Oscillation

EPU – Ecosystem Production Unit

ESP – Ecosystem and Socioeconomic Profile

ESR – Ecosystem Status Report

FMP – Fishery Management Plan

GAM and GAMM – Generalized Additive Modelling and Generalized Additive Mixed Models

GLMM – Generalized Linear Mixed Models

GSL – Gulf of St. Lawrence

INLA – Integrated Nested Laplace Approximation

IPM – spatiotemporal Integrated Population Modelling

LC – Labrador Current

LCC – Labrador Coastal Current

MSE – Management Strategy Evaluation

MSFCMA – Magnuson-Stevens Fishery Conservation and Management Act

-continued-

MSY – Maximum Sustainable Yield

NAFO – North Atlantic Fisheries Organization

NAO – North Atlantic Oscillation

NMFS – National Marine Fisheries Service

NL – Newfoundland and Labrador

OFL – Overfishing Limit

PA – Precautionary Approach

PDO – Pacific Decadal Oscillation

SDM – Species Distribution Models

sdmTMB – Spatial and Spatiotemporal SPDE-Based Generalized Mixed Models with Template Model Builder

SSFM – Single-species Fisheries Management

TAC – Total Allowable Catch

US(A) – United States of America

VAST – Vector-Autoregressive Spatio-Temporal model