Potential Impacts to Snow Crab (*Chionoecetes opilio*) in Warming Waters of the Bering Sea and Possible Management Solutions

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Abstract

The climate of the Bering Sea is both extremely variable, and altering as result of climate change. Water temperatures are increasing and the ice sheets are melting causing great alterations to the ecosystem and the species living in the Bering Sea. One such species dependent on this volatile environment is the snow crab (*Chionoecetes opilio*), which represents one of the most valuable fisheries in Alaska. Management of this species has been extremely difficult due to complex migration patterns and often unstable populations. These have resulted in frequent crashes of the fishery that have proved detrimental to communities reliant on the species. The niche of the snow crab within the larger Bering Sea ecosystem, and its reliance on the volatile environmental conditions in the region will be explored as well as possible effects of warming temperatures on their movements and populations examined. In this paper, we consider the importance of the snow crab both to the Bering Sea and to the larger worldwide economy as well as explore different management plans that have been utilized worldwide and their comparative effectiveness. In this way we attempt to isolate areas in which more research is needed and examine the most successful management techniques for the future success of snow crab in changing waters.
I. Introduction

In this paper, we describe the biology of the snow crab (*Chionoecetes opilio*), as well as the ecosystem of the Bering Sea and potential impacts the ecosystem faces from climate variability and temperature increases. We compare current trends of warming to historical warming with climate variability. Both the ecological and socioeconomic implications are explored through the severity of the impact on the Bering Sea environment, as well as the effects on the communities and higher trophic level species reliant on the snow crab fishery. Finally, we look at various management policies worldwide and discuss options for the snow crab in the Bering Sea given current warming conditions.

II. The Bering Sea Ecosystem

The Bering Sea lies between Russia and Alaska and is considered the “only direct ocean link between the Arctic and Pacific oceans” (Stabeno et al., 1999). The Bering Sea often sees extreme temperature variation, both seasonally and annually (Stabeno et al., 1999). Even with the extreme climate variation, the Bering Sea maintains a massive amount of nutrient rich upwelling and circulation via the Alaskan Coastal Current that leads to one of the most productive and diverse ecosystems in the world (Stabeno et al., 1999; Orensanz et al., 2004; NOAA, 2016).

The Bering Sea is often split into several regions due to oceanographic differences among the regions. In this paper, we focus primarily on the Eastern Bering Sea which is divided into two main sections: the shelf and the slope (NOAA, 2016). The area is greatly affected by the interaction of air, ice, and ocean, the relationship between climate temperature and storms, ice, and currents (Stabeno et al., 1999). During the late fall to early spring, as much as 75% of the Eastern Bering Sea shelf water can be covered in ice; the ice advances and retreats nearly 1,700 kilometers each year (Orensanz et al., 2004). As
the ice melts, it causes stratification within the water column, leading to large “cool pools” that cover a large area of the Eastern Bering Sea’s seafloor, with an average temperature 2 °C lower than the water surrounding it (Orensanz et al., 2004). It has been noted that the cool pool expands and contracts as the Bering Sea experiences climate variability; the cool pool has moved 230 kilometers to the North compared to its location in the 1980s (Orensanz et al., 2004).

III. Snow Crab

Snow crab can be found from the Japan Coast across the Bering Sea, and northward as far as the Beaufort Sea, but they are not found in the Gulf of Alaska (Figure 1) (Urban and Hart, 1999). They are mainly harvested in the Eastern Bering Sea as a single stock (one group) when within U.S. waters and, although snow crab are not as valuable as other crab species on a per poundage basis, they often represent a larger harvest in Alaskan waters compared to other species (Urban and Hart, 1999; Ernst et al., 2005). Bering Sea snow crab support one of the largest crab fisheries world-wide, making them of great economic importance to Alaska and small coastal communities (Urban and Hart, 1999).

Young larval snow crab (Chionoecetes opilio) undergo several molting phases and distinct stages before growing and settling to the ocean floor (ADF&G, 2016). Female crabs reach a final molt at approximately 5 years of age, and are then considered “mature”; males reach this maturity molt at age 6.
(ADF&G, 2016). After mating, females incubate eggs for a year, and hatching occurs from April to June, in correspondence with a spring bloom of plankton, allowing larvae access to high food (ADF&G, 2016). Many female snow crabs in the Bering Sea often only produce 1-3 clutches of eggs in a lifetime due to 2-year reproductive cycles. The number of eggs produced by a female varies greatly with the size of her carapace, generally fluctuating between 1000 and 3000 eggs per clutch. (Webb et al., 2007).

Like many organisms, snow crabs are affected by the environment surrounding them. Particularly, the growth period for larval snow crab is temperature dependent, and migration is also dependent on ice retreat patterns and water temperature stratification (ADF&G, 2016; Ernst et al., 2005). The stratification of the Bering Sea’s water column after ice melt affects where cool pools are found, and thus could dictate migration patterns. There appears to be a temperature based cue for snow crab mating and egg release: it is thought that male snow crabs travel to females based on water temperatures, and females release their egg clutch according to temperature cues such that hatching will coincide with spring phytoplankton blooms (Long, personal interview, 2016). As waters warm, it would be expected that snow crab are affected both developmentally and spatially due to this temperature dependence.

IV. Food Web

The place of a snow crab in its associated food web is dependent on the snow crab’s life stage. Larval crab eat phytoplankton while juvenile crab eat young gastropods and bivalves (phylum Mollusca) with thin shells (Kolts et al., 2013). Older crabs, that are stronger, are able to eat fully developed bivalves, gastropods, polychaetes (phylum Annelida), ophiuroid (phylum Echinodermata), and crustaceans (phylum Arthropoda), but are noted to have a wide and variable diet that depends on local prey abundance (Kolts et al., 2013). Juvenile and larval crab are eaten by commercially important species such as pollock, salmon, pacific cod,
and herring (phylum Chordate); older crab are consumed by marine mammals and other larger organisms, including humans (Kolts et al., 2013).

V. Harvest Fishery History

Snow crab were first commercially harvested by the U.S. in the Bering Sea in 1977. However, the Japanese were harvesting snow crab in the Bering Sea as early as 1960, before the Law of the Sea was imposed in 1982, and the U.S. took control of the 200 mile radius surrounding its coast (NOAA, 2010).

Since then, commercial harvest has varied both in start time and in total allowable catch (TAC). The fishery’s harvest peaked in the 1990s, crashed in the 2000s and has slowly been recovering (NOAA, 2010). Table 1 gives each season’s TAC in the Eastern Bering Sea beginning with the 2005 season. It has been noted that in the Northern Atlantic, snow crab stock is a cyclical resource, meaning the stock shows relatively consistent fluctuation across a period of 12 years (Pinfold, 2006). This is thought to be a result of male-female and prey-predator ratios, but increased fishing pressure could also increase the extremity of this cycle (Pinfold, 2006). It is reasonable to assume that a similar cyclic nature might exist in Bering Sea, though no research has been done on the subject.

<table>
<thead>
<tr>
<th>Season</th>
<th>Total Allowable Catch (pounds)</th>
</tr>
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<tbody>
<tr>
<td>2014/2015</td>
<td>67,950,000</td>
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<tr>
<td>2013/2014</td>
<td>67,950,000</td>
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<td>2012/2013</td>
<td>66,350,000</td>
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<tr>
<td>2011/2012*</td>
<td>66,350,000</td>
</tr>
<tr>
<td>2010/2011</td>
<td>64,281,000</td>
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<tr>
<td>2009/2010</td>
<td>48,017,000</td>
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<tr>
<td>2008/2009</td>
<td>58,550,000</td>
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<tr>
<td>2007/2008</td>
<td>63,004,000</td>
</tr>
<tr>
<td>2006/2007</td>
<td>36,566,000</td>
</tr>
<tr>
<td>2005/2006</td>
<td>37,184,000</td>
</tr>
</tbody>
</table>

* In 2012, the season's end was extended from May 31 to June 15 due to slow melting of ice in the spring.
Source: NOAA, 2016
https://alaskafisheries.noaa.gov/fisheries-data-reports?id=2898&=
Snow crab are not largely targeted for subsistence, nor are they widely considered culturally important. Several small communities along the Aleutian chain are dependent on snow crab harvest for economic stability (Swetzof and Merculief, 2002). Thus, their historical and current value is mainly socioeconomic.

VI. Current Management of Snow Crab

Snow Crab are wide ranging and found in both the Atlantic and Pacific Oceans. Depending on location, management varies, though few countries have found successful methods for managing stocks as a sustainable resource. According to Bishop et al., “The base harvest strategy [in the U.S.] for Chionoecetes fisheries includes a closure during the male molt period, a male-only fishery, and a minimum size limit” (2011). In the Bering Sea, crab are managed under the Federal Fishery Management Plan, which works to prevent overfishing and to rebuild fisheries, but allows the state to set guidelines on the harvest of crabs (Bishop et al., 2011). The main duty of the federal government is to determine if the stock is being overfished, and respond accordingly (Bishop et al., 2011). ADFG can set and control gear requirements, sex and size requirements, licenses and permits if their requirements follow national guides set in the Magnuson-Stevens Act (NOAA, 2010).

Guidelines are set such that the fishery is male only, and minimum size limits are used (Ernst et al., 2005; ADFG, 1992). Initially these size limits were to be used to give the Alaskan fishery a higher, more competitive value as larger crabs allowed for greater socioeconomic success, but eventually, as stocks fell, size limits became a way to ensure proper growth, recruitment and reproduction (ADFG, 1992).

Snow crabs are caught in pots using herring or other similar bait along the Bering Sea Shelf and Aleutian chain (ADFG, 2016). The main fishery bycatch is Tanner Crab (C. bairdi). The start of the spring
Ice melt is a factor in management; as recently as 2012, late and slow ice melt resulted in an extended season (NOAA, 2016). Generally, only a few, larger companies are involved in the harvesting and processing of snow crab (Higashimura and Kato, 2006). Crabs are also harvested by smaller vessels for non-commercial purposes (personal uses, sport, etc.) (ADFG, 2016). Qualified participants are given individual quotas based on a Crab Rationalization program (CRP), which requires vessel owners to give 90% of crab to designated processors. This is meant to protect processor’s investments, and keep regional shares of the TAC constant, preventing undue pressure on certain regions (North Pacific Fishery Management Council, 2016).

Data used to determine distribution of snow crab comes from an annual Eastern Bering Sea Trawl survey, occurring in the summer months. Management bodies take into account surveys of crab suggesting populations for recruitment purposes (NOAA, 2016). These bodies do not always consider north shifts in stock due to climate variability and migration.

Other countries use various management techniques. For example, in the Japanese Snow Crab Fishery, soft shelled females are targeted, fishing season is shortened and fishing areas are protected (Higashimura and Kato, 2006). In addition, the Japanese Snow Crab Fishery uses special equipment to prevent bycatch of non-targeted snow crab and limiting the number of total crabs harvested (Higashimura and Kato, 2006). Another example of a management plan is that of the Canadian snow crab fishery. In Canada, larger companies are not allowed to play a role in the fishery. Even with these different methods in place, there are many crashes in stocks around the world which cause issues in local communities (Swetzof and Merculief, 2002). As a result, many of the programs in place for management focus on stock recovery, and fishery rehabilitation, though often see little success (Higashimura and Kato, 2006)
VII. Socioeconomic Significance

Snow crab fisheries are one of the world’s most economically significant species of crab. (Pinfold, 2006). The vast majority of snow crabs (Chionoecetes opilio) harvested internationally originate from only six countries. As of 2013, Alaska contributed about 15% of global supply exclusively from the Bering Sea (Pinfold, 2006).

Economically, snow crab are lumped with tanner crab (Chionoecetes bairdi), and both are commonly sold under the label of snow crab. (NOAA, 2010). The U.S. and Japan represent the two largest global markets for snow crab (Pinfold, 2006). The U.S. markets are primarily supplied by Canadian and Alaskan fisheries. Historically, the Japanese have been supplied primarily by Russia and their own domestic harvest. Due, however, to declines in the Eastern Russia fishery, they have recently begun to court additional markets, including Canada and Alaska. On average, the price of Japanese snow crab are between five and ten times higher than those imported from Alaska or Canada, due to the fact that the domestic harvest is sold whole (Higashimura and Kato, 2006). Additionally, the market for fresh crab in China, including snow crab, has increased in the past few years. Much of the import of seafood to Northern China has traditionally been processed in the country before being exported once again to Japan, Europe, and the U.S.. This has, however, been slowing since 2011 due to rising costs of processing in China and the appreciation of the yuan (Xian, 2012). Due to the growth in demand for snow crab throughout each of these major markets, there is likely to continue to be a large demand for the harvest from the Alaskan fishery. NOAA states, “Global prices vary drastically from year to year with a market so dependent on limited and highly volatile fisheries… The average market price between 1992 and 2005 was $4.25 per pound, adjusted for inflation.” (2010). The peak price for snow crab came in 1996, at $6.90 per pound (NOAA, 2010).
Due to the location of snow crab in deep waters and often far from shore, the Bering Sea fishery was only established in the 1960s and has not played a large role in traditional subsistence fishing along the coast of Alaska. The importance of this fishery to the economic stability of the region greatly influences the fishing communities along the Bering Sea. The dependence of these communities on the fishery leaves them open to economic hardship should this resource be disrupted, or should a moratorium be placed on their harvest. These communities are additionally subject to economic downturns due to the cyclical busts that the fishery experiences and a lack of economic diversity in many communities (Swetzof and Merculief, 2002). The severe impact on these communities during the 2000 crash prompted the Department of Commerce to propose appropriations providing these Aleutian fishing villages with between 10% and 85% of the community’s income attributable to the snow crab fishery (Swetzof and Merculief, 2002). The significance of the species to the coastal communities must be accommodated for in future management plans.

VIII. Possible Impacts of Warming Waters on Snow Crab

Research has begun to show that movement and distribution of snow crabs is determined in part by water temperature and sea ice melt. Studies suggest that as colder water moves north, snow crab distribution moves with it (Orensanz et al., 2004). The ice-created cold pool has moved nearly 230 km north since the 1980s (Mueter and Litzow, 2008; Ernst et al., 2005). With moving populations comes changes in snow crab catch areas, according to Mueter and Litzow, “57% of variability in commercial snow crab… catch is explained by winter sea ice extent” (2008). However, current management ignores sea ice extent and population dynamics caused by warming waters in favor of more simplified stock analyses (Ernst et al., 2004). Orensanz et al. implies that snow crab will likely not redistribute to the south due to depleted stocks.
and high cod predation; the physical oceanography of the northern area is also favorable for larval snow crab due to weaker currents (2004). As waters warm, it is important to monitor this “climate forced distribution” for research and fishery purposes (Mueter and Litzow, 2008).

The spatial dynamics of the snow crab population is only one way snow crab will be affected by warming waters and changes in the sea ice extent. The energetics of male snow crab are limited by temperature, they cannot function in waters above 7°C, and show peak activity at 0°C; thus, their distribution and population could be affected by greater warming (Webb et al., 2007). Warming temperatures can also cause changes in embryonic development in snow crab. Webb et al. found that increased water temperature corresponds to an increase in speed of embryonic development (2007). This suggests that embryos in warmer waters could hatch earlier, when there are fewer nutrients due to a lack of overlapping phytoplankton bloom, which would decrease recruitment.

IX. Possible Impacts of Warming Waters on Bering Sea Food Web in Relation to Snow Crab

Warming waters causes changes in phytoplankton bloom timing. Specifically, early ice melt may cause an earlier bloom which might not correspond with the embryonic development of the snow crab (Webb et al., 2007). If the hatching of snow crab embryos occurs asynchronously with phytoplankton bloom, the young snow crab may show lower recruitment due to insufficient nutrients. Furthermore, greenhouse conditions will likely cause a shift to nanoplankton, rather than diatom, dominance, which would affect the diatom dominated Bering Sea’s food web dynamics (Hare et al., 2007).

Changes in phytoplankton bloom could have drastic effects on organisms other than crab as well. As such changes occur, groundfish that prey on juvenile snow crab will likely show lowered recruitment numbers. However, if groundfish populations became depleted in response to changes in phytoplankton
bloom and composition, snow crab could benefit since predation on larva would be reduced. The ice melt also seems to play a role in groundfish distribution: Pacific cod, like snow crab, appear to follow the cold pool created by the spring ice retreat (Hunt et al., 2002). Hunt et al. suggests that warm regimes may allow for increases in Pacific cod populations; and predators will determine prey populations as waters warm (2002). Increased pressure from such predators could further exacerbate snow crabs northern move to compensate for moving predators and predator controlled food webs.

Past research suggests that snow crab would fare poorly as predator numbers increase and the ecosystem becomes controlled by top-down processes (Hunt et al., 2002). Overall, snow crab are likely to show lowered recruitment with northern moving groundfish, changes in phytoplankton blooms and composition, and fishing pressures.

X. Current Research

According to research scientist Chris Long of NOAA, there are two main studies being conducted in relation to snow crab (personal communication, November 17, 2016). One study examines the growth of crab each time they molt, and their maximum size, which could provide information relating to minimum size limits for management. Male migration of snow crabs is being studied so management can improve under the current male-only fishery; determining where crabs are and which crabs travel to mate is key to managing an effective fishery (Chris Long, personal communication, November 17, 2016).

XI. Our Proposed Management and Research Plans

To better protect the snow crab under a new management plan, we propose that more research be done into the possible impacts of warming water temperatures, changes in spring ice coverage area and melting
in the Bering Sea; this could help us better understand how the cold pool created by melting ice is changing. This will help to correct the historic pattern of mismanagement in the species that has occurred in all countries since the fisheries were established. We feel that research should be focused on ways in which the migration patterns of both male and female snow crab will be affected, and effects on their interactions throughout the year, as these patterns are largely unresearched. This could have major implications for the future species populations, as well as sampling to determine the TAC for a year. Additionally, given the cyclical nature of the crab populations that has been observed in Eastern Canada, there needs to be research into whether such a consistent cycle is present in the Bering Sea, which could give insight into climatic pressures on the fishery and help to prevent future crashes. The concrete discovery of a pattern would allow for the adjustment of the TAC to respect the changes in population and would allow communities to reserve funds in years of high catch, for those years in which there is a below average harvest. The impacts of sea ice extent on the migration of the crabs, as well as the ability of the fishery to operate, must be given further study with the future hope of including the change in ice extent and melting date in the management plan and stock analysis.

For the protection of fisherman, and the communities abutting the Bearing Sea, we propose to continue and expand on current safety nets for the fishery’s dependents. The state of Alaska should continue to utilize the CRP implemented in 2005 to provide a safety net for years with low TACs. This program has provided a safety net for communities with economies heavily dependent on the snow crab as a source of employment and income, ensuring greater safety for these fishermen. In addition, the state of Alaska should retain the Individual Transferable Quotas (ITQ), with the condition that they not be moved from the region in which they were granted to prevent overfishing of an area. Overall, it is important that the
resource be managed conservatively and that management be able to quickly respond to the changing ecosystem's needs.

**XII. Conclusion**

In conclusion, a great deal more research must be done on the fishery and the impacts climate change might have on the region. It is not yet clear what specific changes the warming water temperatures in the Bering Sea will bring to the species within it, though there is reason to believe that the snow crab will continue their current Northward migration and attempt to seek out cold pools of ice melt. Their success in these regions will depend largely on the success of lower trophic level species on which they are dependent; and upon predators, and their new ranges. Regardless of these changes, research will need to be done with regard to male and female migration, cycles in populations, and the effects of ice sheet melting.

In addition to any future ecological situations of these crab, the overarching importance of those individuals and communities depend on the fishery remain present. This is a fishery of international importance, and its health plays a large role in the global crabbing industry. In Alaska, it represents a significant fishery with huge implications for communities along the Bering Sea, for whom the protection of this resource is paramount. Additionally, snow crab support a number of highly profitable and ecologically important higher trophic level fisheries in the Bering Sea.

It is due to this complexity that we feel more research on the subject must be the first priority in improving the current management of the species in a changing climate. The environmental factors are fluctuating so quickly, the migration patterns so critical, and the species so thoroughly woven into the ecosystem as to make the management of the species for greatest health of the Bering Sea extremely
intricate. It is for these reasons that our team proposes that additional research be carried out to be used in adapting the current management plan to protect this valuable asset for Alaska, and protect our communities from its loss.

XIII. References


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