Climate Change and Anthropogenic Impacts on Greenland Sharks (*Somniosus microcephalus*)

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Introduction

Climate change has been causing accelerated change in the Arctic in comparison to the rest of the world (Cai et al. 2021). Annual minimum sea ice extent has been decreasing steadily since the 80s (Wang and Wu 2021), and the top 15 record low sea ice extent years have all taken place in the last 15 years. As sea ice continues to retreat each year, Arctic animals are forced to adapt to an ever changing environment. Marine Arctic species who rely so heavily on sea ice for their survival are left struggling to find enough food as their typical prey moves to new locations in search of adequate habitat (Cai et al. 2021). As sea surface temperatures rise, both multiyear and annual ice have had a severe decrease in overall extent and thickness (Cai et al. 2021; Wang and Wu 2021). These changes have not arrived without consequence, however. Entire ecosystem shifts have already occurred within the Arctic (Grebmeier 2012), and the inconsistency of annual ice leaves those who rely on the ice to birth and rear young, such as ice seals and polar bears (*Ursus maritimus*), to do so.

The Greenland shark (*Somniosus microcephalus*) is a species of sleeper shark (*Somniosus* sp.) that inhabits the frigid polar waters surrounding Greenland, Scandinavia, eastern Canada, and occasionally the northeastern United States. They are well known for their unusually long lifespan of an estimated 270-500 years and abnormally slow swim speed (Watanabe et al. 2012). Rivaling the white shark (*Carcharodon carcharias*) in size, the Greenland shark can reach lengths of up to 6.4 meters (21 feet) (MacNeil et al. 2012). Almost all Greenland sharks are blind due to a parasite, *Ommatokoita elongata*, that attaches to the eyeball (MacNeil et al. 2012). These sharks spend most of their time living in the depths of the ocean and are rarely seen by humans, often utilizing deep water channels for safe transportation between coastal waters and off-shore waters (Edwards et al. 2022). However, these sharks are not bound to only deep water. Studies have shown that Greenland sharks utilize the entire water column, sometimes moving through mid-water zones and occasionally coming to the surface (Fisk et al. 2012). This type of behavior is likely driven by their near-constant search for food.

Despite their extremely slow movement, Greenland sharks are avid hunters and actively hunt fish and seals (Leclerc et al. 2012). Although diet may vary between locations, stomach

content analysis of Greenland sharks revealed they primarily predate on a variety of fish, namely Atlantic cod (*Gadus morhua*), wolffish, haddock, halibut, and herring (MacNeil et al. 2012; Leclerc et al. 2012). Secondary food sources include squid, seals, and benthic organisms such as crustaceans and rays. In addition to active hunting, Greenland sharks will scavenge for food in the form of dead whales or seals (Leclerc et al. 2012). Climate change will inevitably affect the food sources available to the sharks as their prey migrates to adapt to the changing environment. This will likely contribute to a shift in the habitat of Greenland sharks, either northward or southward, in an attempt to follow food sources.

Anthropogenic, or human sourced, threats such as noise pollution, fishery bycatch, and other forms of marine pollutants such as contaminants and garbage pose risks to the safety and health of Greenland sharks. Noise pollution causes stress and physical harm to whales and sharks, often displacing them from their natural environments as they attempt to avoid disruptive frequencies (McWhinnie et al. 2018). Bycatch has been a longstanding problem for Greenland sharks as they occupy regions of the water column that are heavily fished by commercial fisheries, and often become entangled in fishing nets and longlines (Hendrickson et al. 2013). Other sources of pollution such as garbage and debris may pose a threat to Greenland sharks if ingested (Yano et al. 2007; Lu et al. 2014). However, there are gaps in the research on this specific topic due to these elusive deepwater sharks being notoriously difficult to study.

Cultural Significance and History

S. microcephalus has historically been fished for liver oil and skins (MacNeil et al. 2012; Hedeholm et al. 2018), although this is no longer a regular occurrence. In the early to mid 1900s, there was a high demand for shark liver oil. Liver oil was used for machines and oil lamps until synthetic oil was developed in the 1940s, ceasing the demand for natural oils (Nielsen et al. 2014). However, Greenland sharks were the primary source of liver oil during this time, and were heavily fished for it. Experts estimate that Greenland and Norway combined were harvesting as many as 150,000 sharks annually (McMeans et al. 2013; Devine et al. 2018) throughout the early 1900s. Due to the low fecundity of Greenland sharks, the population has been slow to recover. Today, the most common occurrence of Greenland sharks being caught by humans is through accidental bycatch, often from benthic trawling.

Additionally, a small amount of fishing for Greenland sharks occurs in select high Arctic communities. These typically are communities that rely on dog sleds for transportation, where dog teams are commonly fed the meat of Greenland sharks as their main source of nutrition (MacNeil et al. 2012; Devine et al. 2018; Hedeholm et al. 2018). There is mention of shark meat being consumed by humans as well (Devine et al. 2018), although there is no specificity on the popularity or frequency of eating shark meat. The number of sharks taken for these purposes each year is estimated to be less than 100, and is not enough to have any significant impact on the overall shark population. Greenland sharks are widely regarded as unwanted bycatch by both Indigenous and commercial fishers (Idrobo and Berkes 2012), which is one of the reasons why there is so little known about them.

Habitat and Behavior

S. microcephalus mainly inhabits north Atlantic waters above 40°N along the coasts of Greenland, Canada, northern Europe, and occasionally extending along the eastern coast of the United States (Figure 1). Due to the limited knowledge available on Greenland sharks, there is little data on the full extent of their range. These sharks tend to prefer cold water, and so are primarily observed in Arctic and sub-Arctic regions (MacNeil et al. 2012) where sea temperatures are often 5° Celsius or less. Greenland sharks typically move between deep open water and relatively shallow bays, presumably to follow food sources. Greenland and the Canadian archipelago provide ideal habitat in this sense, with seemingly unending numbers of inlets, channels, and fjords. Baffin Bay, situated in between Greenland and Canada, spans nearly 700,000 square kilometers of open water and reaches depths of over 2,000 meters in some areas. The majority of Baffin Bay gets covered in sea ice in the winter, providing the icy waters in which these sharks thrive. Hedeholm et al. (2018) found evidence of “hot spots”, more specifically certain points throughout Greenland waters, where the density of individuals is higher than other locations, indicating some degree of habitat preference.

Greenland sharks typically occupy depths greater than 20 meters, occasionally diving to extreme depths (>1000 meters) or approaching the surface (Watanabe et al. 2012; Fisk et al. 2012). The precise movements of the sharks has been difficult to track as certain tracking devices, such as archival pop-off tags (Fisk et al. 2012), can only travel to limited depths. Their incredibly slow movement can be partially explained by their need to conserve energy in frigid

water temperatures, a common trait in ectothermic, or cold blooded, animals. In a study of the tail beat frequency of Greenland sharks, Watanabe et al. (2012) found that these sharks travel at an average speed of 0.2 meters per second. This use of the water column, along with their slow swim speed, aligns with the behavior of other sleeper sharks, such as the closely related Pacific sleeper shark (*Somniosus pacificus*).

As climate change continues to cause rapid changes throughout the Arctic Ocean, the outcome of Greenland sharks is largely unknown. Increasing sea temperatures may drive the sharks further north to satiate their need for cold water, a global trend scientists are already observing in countless marine and terrestrial species alike (Chen et al. 2011). This could mean that, in the future, Greenland sharks may only be observed in the northernmost fringes of Canada, Greenland, and Scandinavia. It is possible to infer that the distribution may extend along the northern coast of Russia, but that is not currently an area in which sightings commonly occur. It is very unlikely that the distribution of the sharks will extend beyond the Arctic shelf into the Arctic basin. This is due to the low productivity, food availability, and relatively low biodiversity in the basin (Popova et al. 2010; Grebmeier 2012; Carscallen and Romanuk 2012).

Diet

Considered to be benthic predators (MacNeil et al. 2012), *S. microcephalus* tends to forage for food along the seafloor. Their diet consists of a wide variety of fish, although this is highly dependent on location. For example, Svalbard populations tend to consume a higher proportion of Atlantic cod while Greenland populations consume more Greenland halibut (*Reinhardtius Hippoglossoides*) (Yano et al. 2007; Leclerc et al. 2012; Reeves et al. 2014). Greenland sharks typically swallow their prey whole, only occasionally biting prey that is too large to be swallowed, such as adult seals, other sharks, or whale carcasses. Greenland shark gastrointestinal tract (GIT) analysis conducted by Leclerc et al. (2012) revealed an array of prey items that had been swallowed whole, including cod, wolffish, halibut, and even seal pups.

Seals comprise the second most important food source for Greenland sharks, fish being the first (Yano et al. 2007; Leclerc et al. 2012; Nielsen et al. 2014). Ringed seals (*Pusa hispida*) are reportedly the most commonly consumed seal species amongst Greenland sharks (Leclerc et al. 2012). However, infrequent findings of bearded seal (*Erignathus barbatus*) and hooded seal

(*Cystophora cristata*) remains in the GITs of sharks studied in Svalbard, Norway confirm that ringed seals are not the only species that are being consumed (MacNeil et al. 2012). Additionally it is theorized, but not confirmed, that Greenland sharks actively hunt harbor seals (*Phoca vitalina*) in Svalbard (Leclerc et al. 2012).

How Greenland sharks hunt so efficiently despite their blindness remains widely unknown, since the species is so elusive and active hunting is rarely seen. It is theorized that their extremely slow speed and dark, mottled coloration allow them to slowly stalk their prey (Leclerc et al. 2012). Similar to other shark species, Greenland sharks are equipped with an extraordinary sense of smell (Schluessel et al. 2009; Yopak et al. 2019) and electroreceptors (Hopkins 2010) which allow them to accurately locate prey from large distances. Their sense of smell is so acute, in fact, that their olfactory bulbs make up over 30% of their brain (Yopak et al. 2019). Using these tools, it is likely that the sharks are very efficient at sneaking up on unsuspecting prey, such as seals and flatfish.

In addition to hunting, Greenland sharks are widely regarded as scavengers. A small, although not insignificant, proportion of their diet consists of benthic species. Cephalopods, skates, and rays have all been documented in the GIT of Greenland sharks (Yano et al. 2007; Leclerc et al. 2012), and are considered secondary food sources. Extraneous prey types observed include echinoderms, crustaceans, and gastropods, which are believed to be from the stomachs of main prey items such as fish (Leclerc et al. 2012). Whale carcasses, or whale falls, are another commonly scavenged food source. Chunks of whale meat, blubber, and other tissues were observed in approximately 18.2% of Greenland shark GITs studied by Leclerc et al. (2012)

Taking all these aspects of the *S. microcephalus* diet into consideration, it is extremely likely that there will be changes in the available food sources due to climate change. Polar food webs are very sensitive due to the relatively short food chains present in the Arctic Ocean (Carscallen and Romanuk 2012). The recession of sea ice disrupts the primary production from both phytoplankton and ice algae, subsequently creating further disruption throughout the entire food web (Grebmeier 2012). Current patterns consist of phytoplankton blooms coinciding with the annual sea ice melt. As sea ice degradation continually occurs earlier each year (Cai et al. 2021), so do the phytoplankton blooms. Declining ice coverage due to higher sea surface

temperatures may produce larger scale blooms, which can have both positive and negative effects on the marine ecosystem (Huntington 2009; Dong et al. 2020).

Researchers are already observing new trends of polar fish populations migrating away from areas they have historically inhabited due to the new lack of sea ice. The Arctic cod (*Boreogadus saida*), for example, is a keystone species in the Arctic ecosystem that relies heavily on sea ice as breeding grounds (Huserbråten et al. 2019). *B. saida* is a crucial link between upper and lower trophic levels as it feeds on phytoplankton while serving as prey for seals, whales, sharks, and birds (Huserbråten et al. 2019). The decline or complete loss of this species will have dramatic impacts on nearly every high trophic level species in the Arctic. As an example, the reduced abundance of Arctic cod in the Beaufort Sea has led to a shift in diet for Mandt's black guillemot (*Cepphus grylle mandtii*), which predates heavily on Arctic cod (Divoky et al. 2015). This seabird has since resorted to feeding sculpin, a less nutritious and more bony fish, to its chicks. The chicks often are unable to swallow sculpin due to its hard body and sharp spines, and consequently die of starvation.

Other impacts of declining ice coverage include reduced habitat availability for polar seal species such as the ringed seal, one of the common prey of Greenland sharks. Ringed seals are ice-obligated animals, meaning they rely entirely on sea ice instead of land as their habitat. Shorefast ice and snow provide dens for these seals for birthing, nursing, and overall shelter (Goertz et al. 2019), and the severe decline of sea ice extent will very likely lead to reduced birth rates and pup survival, and an overall decline in population over time (Reimer et al. 2019; Cai et al. 2021). As one of the main food sources for Greenland sharks, a stark decline in ringed seal availability could either lead to a decline in shark population due to starvation or create a new pressure on other prey species, such as fish, to fill in the nutritional gap left behind. With either outcome, the Arctic ecosystem will shift dramatically with the loss of an apex predator or reduced fish populations due to increased feeding needs.

As a primary food source, shifts in fish populations will likely have negative dietary impacts for Greenland sharks. Arctic fish populations are already experiencing a shift in spatial distribution due to climbing sea surface temperatures. Sub-Arctic species are migrating northwards to escape warming waters, while polar fish populations are suffering from increased competition and have limited options in terms of spaces to migrate to (Fossheim et al. 2015; Fauchald et al. 2021). As climate change continues to open up the Arctic, fisheries are starting to

take advantage of the newly available fishing grounds. Fishery activity must be closely monitored and regulated coinciding with climate change to avoid overfishing (Davis et al. 2013), which can decimate fish populations to the point where chances of successful recovery are slim.

Increased Arctic fishery activity is cause for concern regarding the impact of upper trophic levels in the marine ecosystem. If fisheries are not properly managed and fish populations decrease, the lack of fish availability may drive Greenland sharks to increase hunting efforts on other species, such as ringed seals. The outcome of increased seal predation by sharks is not known, but it is likely that reduced seal populations will impact upper trophic levels throughout the Arctic. Polar bears also predate heavily on ringed seals, and are already undergoing a climate-induced struggle to find adequate food (Tseng 2021). Countless other high trophic level species in the Arctic rely on fish as a primary food source, meaning decreased fish populations will see disruptions throughout the entire Arctic food web.

A wide variety of whales inhabit Arctic and sub-Arctic regions, but ice-reliant species such as the bowhead whale (*Balaena mysticetus*), beluga whale (*Delphinapterus leucas*), and narwhal (*Monodon monoceros*) face unique threats as Arctic acceleration wreaks havoc on the delicate ecosystem. Aside from the clear loss of habitat, anthropogenic threats such as noise pollution and chemical contaminants are causing a decline in the overall health of whales (Huntington 2009). The stress-inducing sounds emitted by large vessels is driving whales from their breeding and nursery grounds. Increasing levels of pollutants in the water caused by human expansion into the Arctic have had noticeable impacts on the neural, reproductive, and overall physical health of whales (Huntington 2009). These factors are contributing to an overall decline in whale populations. Increased Arctic whale mortality leads to an increase in the frequency of whale carcasses that both wash up on beaches and sink to the sea floor. The presence of whale carcasses, regardless of location, can have numerous effects on the surrounding environment.

Whale carcasses that sink to the bottom of the ocean provide a large burst of productivity in events known as whale falls. Once a whale carcass reaches the sea floor, benthic scavengers from all over arrive to partake in the massive feast that ensues. These events are a crucial part of the deep sea ecosystem as they provide mass amounts of food for nearly every occupant, including Greenland sharks (Li et al. 2022). While increased whale mortality would lead to a higher frequency of whale falls over a short period, the long term frequency would see a sharp decline. This removes a critical source of food for the majority of the deep sea in the long term.

Anthropogenic Threats

The Arctic has historically been protected from marine noise pollution due to the impenetrable ice cover, but that is changing rapidly (McWhinnie et al. 2018). While many corporations may be eager to finally utilize the northwest passages that are opening up due to the retreat of the sea ice, Arctic marine inhabitants are facing the new threats that come along with the presence of humans. Noise pollution from passing ships in areas where ships historically could not access has negative impacts on many marine vertebrates such as whales, seals, and sharks (Chapuis 2015; McWhinnie et al. 2018). The noise emitted from ships, especially large cargo ships, interferes with these groups due to their sensitivity to sound (Reeves et al. 2014; McWhinnie et al. 2018). Arctic species such as the bowhead whale, beluga whale, narwhal, and Greenland shark have not been exposed to these disruptive frequencies up until recently.

Loud and disruptive noises are known to cause stress in these species. While it is widely accepted that whales have high sensitivity to sound, sharks are easily affected as well. Sharks have delicate inner ears that are sensitive to lower frequencies, such as the sounds emitted from large ships (Chapuis 2015). Not only does noise pollution cause physical stress in sharks, it can drown out sounds that are important for sharks such as prey, predators, or potential mates. If the noise pollution is loud enough, it can cause damage to the inner ear or even to the shark's lateral line, the organ used to detect prey by sensing subtle changes in pressure. Whales and sharks alike will often choose to abandon the area in response to the intense noise (Chapuis 2015; McWhinnie et al. 2018).

The increasing frequency of commercial ships in the Arctic presents a cause for concern in regards to the safety and distribution of Greenland sharks. As commercial shipping routes and industrial exploration expand further into the Arctic, conservation and protection of sharks and cetaceans must be taken into careful consideration (Reeves et al. 2014; McWhinnie et al. 2018). Intense noise may drive the sharks out of their habitat, either further north into the Arctic basin or further south into warmer waters. In the Arctic basin, the sharks risk mass starvation due to food scarcity. Moving further south into the Atlantic Ocean, it is unlikely that the sharks would be able to escape noise pollution as the frequency of vessel traffic is higher than in the Arctic. While there may be no shortage of food, a new apex predator moving in may severely disrupt the balance of ecosystems throughout the mid-Atlantic.

As the diminishing sea ice offers new opportunities for fisheries to expand to areas that have been previously inaccessible, extra caution must be exercised to ensure the protection of vulnerable marine species, such as the Greenland shark. Although no fishery exists today for the dedicated catch of Greenland sharks, they have historically been a primary bycatch species in high latitude fisheries (MacNeil et al. 2012; Hendrickson et al. 2013). Since these sharks occupy mostly benthic and mid-water levels of the water column, they are commonly subject to entanglement from trawls (Davis et al. 2013). This is a common occurrence still to this day in Canada (Hendrickson et al. 2013), where large scale fisheries trawl for Greenland halibut and shrimp (MacNeil et al. 2012; Devine et al. 2018). Bycatch of Greenland sharks was historically an issue in Greenland as well (Hedeholm et al. 2018), however, preventative measures have been taken to protect this species.

Plastics and microplastics in the ocean have been a source of pollution for decades due to inadequate waste management and disposal. Sources of plastic debris include both maritime vessels and terrestrial communities (Bergmann et al. 2022). These plastics leak toxins into the water, having various negative impacts on sealife. Furthermore, macroplastics can smother, asphyxiate, and entangle marine animals, most often resulting in death. Instances of human waste, such as fishing gear and other unspecified plastics, have been documented in the GITs of Greenland sharks (Yano et al. 2007). It is possible that this waste was first consumed by fish which were subsequently swallowed by Greenland sharks. Regardless, the waste ended up in the stomachs of the sharks. It is currently unknown what the full scale of effect of plastic debris in the ocean has on Greenland sharks as a species.

Polychlorinated biphenyl (PCB) contamination has been a concern for both human and environmental health for years. PCBs accumulate in the body, negatively impacting the health of those contaminated (Ubl et al. 2012) by affecting multiple body processes, such as the nervous or reproductive systems, and even causing cancer (Yu 2014). This toxin has been distributed throughout the land, oceans, and atmosphere. Tissue analysis of both Greenland sharks and their prey confirmed the presence of PCBs, with differing concentrations depending on geographical location (Lu et al. 2014). Due to the high trophic level of the Greenland shark, the consumption of other contaminated individuals leads to a higher bioaccumulation of PCBs.

Conservation

The prolonged lifespan of *S. microcephalus* makes population recovery difficult. In addition to their slow movement, they also have extremely slow growth rates. Studies have revealed that female Greenland sharks do not reach sexual maturity until they are approximately 134 years old (Nielsen et al. 2020) at the earliest, while others estimate the average age to be closer to 150 years (Hedeholm et al. 2018). The loss of sexually mature adults from Greenland shark populations could mean that the total number of sharks may not begin to increase significantly for many decades. To ensure recovery, it is crucial to enforce conservation measures to mitigate as much loss as possible.

The International Union for Conservation of Nature (IUCN) currently has the extinction status of Greenland sharks listed as “vulnerable”, with population numbers decreasing (IUCN 2019). Continual decrease is supplemented by the estimated 3,500 sharks (IUCN 2019) annually removed through bycatch. However, this estimate comes from catch reports from fisheries, and is likely much higher due to the inconsistency in catch reports (MacNeil et al. 2012; Hendrickson et al. 2013). Despite the fact that population numbers have been on a steady decline for years, the future is starting to look a little brighter for these sharks.

Currently standing policies require all fishers to make efforts to mitigate the accidental catch of Greenland sharks. This includes using gear modifications, such as grids or circle hooks, to reduce the risk of entangling a shark (Madigan et al. 2022). Additional limitations on fishing mesh sizes based on the targeted species being fished are enforced in north Atlantic countries (NAFO 2022). In the event of entanglement of a shark, fishers are required to return the shark to the ocean while doing as little harm to the individual as possible. Any bycatch of sharks must be documented, along with records of the length, estimated weight, sex, and whether the shark is alive or dead (NAFO 2022). Policies such as these have helped reduce the loss of Greenland sharks through bycatch while also monitoring the amount of bycatch that is still occurring. However, the expansion of deep water fisheries into the Arctic Ocean as sea ice cover recedes boasts the risk of increased bycatch amounts (MacNeil et al. 2012).

In September of 2022, the Northwest Atlantic Fisheries Organization (NAFO) granted new international protection policies for Greenland sharks. These policies state that any retention of Greenland sharks is strictly prohibited (NAFO 2022). This includes fishing, bycatch, or landing of any kind of these sharks. Some small exceptions are made for countries that have

local bans on discarding dead fish, such as Norway and Iceland. However, the retention or transportation of any Greenland shark for profit is prohibited. Although it is too early to see the benefits from these new policies, they hold great promise in aiding the recovery of this truly remarkable animal.

Looking towards the future, there is much work to be done in regards to mitigating climate change and restoring the health of the environment. For the Arctic, conserving and restoring sea ice coverage can help rehabilitate the delicate ecosystem. However, new policies are necessary to ensure the protection of polar species by reducing vessel traffic through the Arctic and carefully managing commercial fishing to avoid risks of overfishing. Beyond these, ceasing the reliance on fossil fuels and instead turning to green energy is one of, if not the, biggest steps towards a healthier planet. While our society is starting to take steps towards change, there is still much progress to be made.

Figures

Legend
EXTANT (RESIDENT)

Compiled by:
IUCN SSC Shark Specialist Group 2020

Figure 1: A map showing the global distribution of *S. microcephalus*, obtained from the IUCN Greenland shark assessment (IUCN 2019).

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