Toxic Tides in a Melting Arctic: Climate Change, Harmful Algal Blooms and Their Impact on the Food Security of Alaskan Arctic Indigenous Communities

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Abstract

The Alaskan Arctic is undergoing a profound transformation. As climate change reshapes the landscape, the balance of the ecosystem is disrupted. This has far reaching consequences for Indigenous communities who have called this area their home for over a thousand years. This paper examines the impact of climate change on the Arctic marine ecosystem and its consequences for Indigenous communities, with a special focus on the Alaskan Arctic and Alaskan Indigenous communities. Rising temperatures are dramatically altering sea ice dynamics, additionally, increased nutrient influxes are creating increasingly favourable conditions for harmful algal blooms (HABs). This study focuses on two primary toxin producing species, *Alexandrium* and *Pseudo-nitzschia* that produce saxitoxin (STX) and domoic acid (DA) which are very harmful, often lethal to humans and other organisms. These toxins have been detected throughout the Arctic food web, from bottom feeding clams to top predator marine mammals and sea birds. The pervasive presence of these bio-toxins poses significant risks to the health of ecosystem and the Indigenous communities that rely on it for subsistence. This paper highlights the urgent need for comprehensive monitoring programs and adaptation strategies to protect both the Arctic marine environment as well as the cultural practices of Indigenous Alaskans in the face of rapid climate driven changes.

Layman's summary

Climate change is causing the Arctic environment to change fast. These changes have many effects on the lives surrounding it, including the Alaskan Indigenous people that have lived there for thousands of years. With an increase in temperature and subsequent change in the landscape of the Arctic, the new conditions in the Arctic allows for more algae to grow. While algae is the foundation of the food system in the Arctic, its growth in this excess allows for specific algae species that are toxic to grow in excess as well. These toxins can be very harmful to those who ingest it, even cause death. This toxic producing algae will spread through the food chain as they are eaten by smaller organisms in the arctic that in return are eaten themselves until it reaches the top of the food chain or are hunted by the Indigenous people. Within this paper, we look into existing research done in the Alaskan Arctic on the presence of these toxic producing algae and if their toxins can be found in the food chain. We see that these toxins are detected throughout the entire food web, with high amounts of toxins detected in mammals that Indigenous people rely on for food. This paper shows the urgent need to continuously monitoring the development of these algae and their toxins in the Arctic in order to protect these Indigenous groups, their traditions, livelihoods and health.

1 Introduction

When people think of the North Pole, or the Arctic, they imagine a lifeless frozen wasteland. However, despite its extreme low temperatures, the Arctic is still filled with life by organisms small and large. All of whom have adapted to these extreme ecosystems. While the exact definition of the Arctic varies between experts (for example defined by temperature or ecological boundaries, see Figure 1), it generally refers to the northernmost area of the earth, the wide area north of the Arctic Circle (66° 32"N) [41, 46]. It consists of eight Arctic states that together make up the Arctic council; Canada, The kingdom of Denmark (via Greenland and the Faeroe Island), Iceland, Norway, Sweden, Finland, Russia and the United States of America[41, 46] .

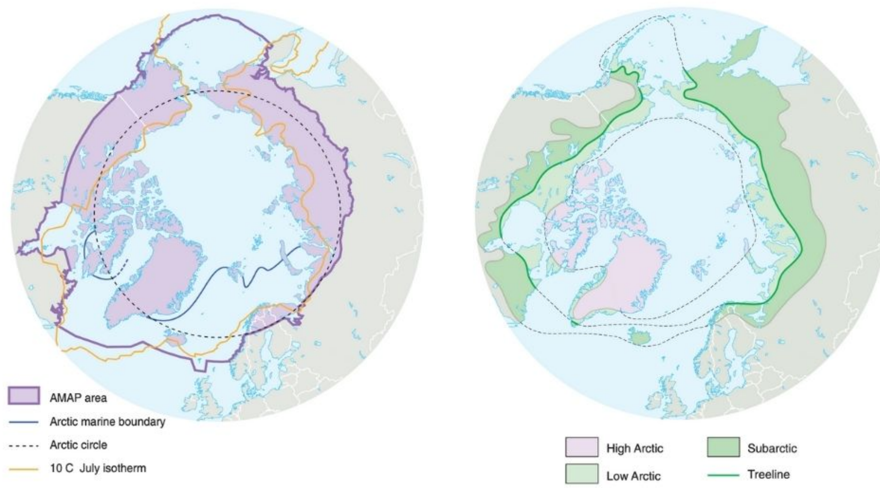

Figure 1: The figure shows acknowledged Arctic boundaries. On the left: The Arctic as defined by temperature, the Arctic marine boundary, and the boundary of the Arctic monitoring and assessment program (AMAP) and the area north of the 10°C July isotherm. On the right: The Arctic is the Arctic defines by floristic boundaries. Divided into the high Arctic, Subarctic and low Arctic, as defined by ecologists. The map additionally shows the Treeline boundary, or the northern limits beyond which trees do not grow. Figure compiled from AMAP[41].

Today, approximately 4 million people inhabit the Arctic, with Indigenous peoples, who have lived there for millennia, comprising 28% (about 1.13 million) of the current population. [45, 25, 60]. There are more than 50 different ethnic Indigenous groups that live across all the Arctic states, with the exception of Iceland. Within Russia alone, around 40 different groups are recognized by the Russian association of Indigenous people of the North, which includes groups such as Yaktus, Komi, the Nenets, Khanty, Evenk, Even, Chukchi and Sami. While in the Nordic countries of Finland, Sweden and Norway, Sami is the only indigenous group (also known as Saami, Sámi or Same). Some of the groups in Canada include the Inuit, Inuvialuit, Dene, and Athapaskans; and in Alaska in the United States reside the Athabaskan, Aleut, Iñupiat, Alutiiq and Yupik. In Greenland, reside the Kalallit and Inughuit communities [60, 48, 49, 46].

Indigenous Arctic peoples have a much closer relationship with nature than most other communities. Living on the land for generations, they've gained deep knowledge of the ecological and biophysical processes of the land. They use this knowledge and the natural resources in the ecosystem as a central part of their livelihood and culture [16, 49]. Despite their surroundings, these communities maintain a subsistence way of life[1], by fishing, hunting, foraging, and preparing their food in a way that has been done for thousands of years, often referred to as "traditional", "wild" or "country" foods [49, 45, 39]. These activities remain important for Indigenous communities as they are based on continuing the relationship between each part of the ecosystem: Themselves, the organisms and the environment itself on which they depend. Furthermore, it helps people connect with and celebrate

[1]Subsistence way of life refers to living life off the land. Using the resources of nature for food, shelter, clothing, transportation and trade

their history. Beyond providing food and cultural importance, subsistence livelihoods are a vital part of their economy [45].

However, climate change is posing significant challenges for these traditional ways of life. The Arctic is warming at a rate two to four times faster than the global average [12, 61], leading to rapid environmental changes. These include widespread melting of glaciers and sea ice as well as rising permafrost temperatures, which in turn affect the migration patterns of animals, altering vegetation growth and causing coastal erosion Notably, it creates favorable conditions for an increase in algal blooming, which as a consequence increase their frequency and intensity. These algal blooms produce excessive amounts of toxins whose effects can be harmful, and sometimes deadly to those who consume them[12, 55]. With these factors combined, it will impact the food security and cultural practices of indigenous communities, who depend on the health of these ecosystems[12].

Within this work we will investigate the current body of research available on the impact of increase of algal blooming events on Arctic Indigenous communities, with a particular focus on the Alaskan Indigenous population. This review will examine the potential toxic effects of these algal blooms and how they move through the Arctic food chain, threatening the health of the ecosystem but additionally impacting the harvest and health of the Alaskan Indigenous communities in the Arctic regions. In order to address this, the review will explore existing literature on the following topics:

1 How the changing Arctic allows for increased Algal blooms

2 The toxic algal species that are present in the Alaskan Arctic

3 The presence of toxins within the Alaskan Arctic food chain

4 The cultural and nutritional significance of traditional marine resources for Alaskan Arctic Indigenous communities and the implications of harmful algal blooms on these resources for these communities.

This literature review aims to shed light to the broader implications for environmental and human sustainability in the Arctic. Although focus will be on the Alaskan Arctic and the Alaskan Indigenous population, this review aims to provide insight on the Arctic as a whole and the potential impact on Indigenous communities across the entire region.

2 Alaskan Arctic Indigenous communities: Their connection to the ecosystem and cultural resilience

Despite the widespread social and technological changes, Indigenous communities in Alaska maintain a strong connection to their ecosystem. Subsistence practices such as hunting, fishing and gathering continues to play a vital role in their daily lives. These practices are not only essential for sustenance but also for reinforcing cultural identity and strengthening community bonds by using practices passed down for generations [41]. Moreover, subsistence practices in these communities are often vital due to challenges in accessing nutritious retail foods, as many Indigenous communities in the Arctic live in extremely remote areas where retail stores are scarce. In addition, for the few stores available, fresh produce is often limited or nonexistent, with the prices of retail food often being at least twice as high as in populated areas [26, 28].

2.1 Nutritional challenges and the significance of traditional diets

With colonization and globalization within these communities, more ”western” diets have become more widespread. In combination with the limited access and high pricing in retail stores, high saturated fats, sugars and processed foods are increasingly being consumed in the Arctic Indigenous community. As a result, a variety of health problems have been observed, where research shows that the Indigenous Arctic community experience lower life expectancy, higher infant mortality rates and have a greater burden of chronic diseases (such as obesity, Type 2 diabetes and cardiovascular diseases) compared to non-Indigenous populations in the same regions, as well as national averages[28, 26]. This further emphasizes the importance of keeping traditional food in the forefront of these communities, which is far superior in its nutritional density, both in micro- and macro-nutrients, with an abundance of minerals, vitamins, proteins and valuable unsaturated fats derived from various sources of sea and land mammals as well as fish, fowl, wild plants and berries [32, 33, 54]. Additionally, nutrients most commonly associated with only plants and fruits (such as Vitamin C) is found in abundance in the meat sources Indigenous communities consume. Furthermore, research on the nutritional density of traditional food diet is shown to be a far better choice for these communities than that of the limited nutritional variety of available retail food[33]. Moreover, it highlights the need to protect not only the generational knowledge of subsistence practices but the ecosystem that supports it.

Figure 2: The Alaskan Arctic community joining efforts in hunting and preparing their harvest according to traditional customs. The community brings these traditions together to life. Top left: Yupik women gather to prepare freshly caught salmon for curing[40]. Bottom left: Alaskan Indigenous men hauling a section of bowhead whale skin and blubber[27]. Top right: Traditional whale hunters harvesting their successful bowhead whale hunt[14]. Bottom right: Alaskan hunters on St. Lawrence Island walrus hunting around 1950-1980[50].

2.2 Marine resources and their cultural significance in the Alaskan Arctic

The Indigenous people of the Alaskan Arctic have practiced subsistence living for over a thousand years. As hunters, gatherers, fishers, and reindeer herders, they have long depended on resources from both land and sea. However, within the scope of this paper, we will focus exclusively on marine mammals, other marine species, and fowl connected to the Arctic marine environment. Marine mammals play a particularity crucial role in their subsistence practices as approximately 61% of Inupiat Inuit Alaskans report that more than half of their food comes from harvesting activities[45, 18]. Marine mammals are considered a crucial and a highly valued resource, making up around 42% of the subsistence diet. On average, each person consumes about 99kg a year of the marine mammal harvest [45].

The primary species that are hunted include whales (beluga-, narwhal-, mink-, fin- and the bowhead whale), walruses, seals (bearded-, ringed-, fur-, hooded-, harp- and harbour seals) as well as sea lions and polar bears [24, 41]. While bowhead whales make up around 70% of the hunted marine mammals consumed. Fishing also makes up a major part of the harvest. Important fish species include salmon, tom cod and smelt along with shellfish such as clams and crabs. Although, not a primary part of their diet, birds like geese, ducks, seabirds, cranes swans, owls and ptarmigan are hunted. This diverse array of marine resources has sustained the Alaskan Arctic communities for generations, reflecting the deep connection between Indigenous communities and their environment[24].

For the Indigenous people in Alaska, hunting, fishing and foraging for food is not only a means of survival but a deeply-rooted source of identity. These activities, often performed in harmony with nature and community, are a ceremonious acts that connect people to their cultural heritage. The harvesting of food, along with its preparation, consumption and distributing, reinforces social bonds and maintains a vital link to ancestral practices[41, 54, 24]. This practice of community is reflected in Figure 2.

A prime example is the preparation of seal oil, a time consuming task done communally. Considered the salt and pepper of Alaskan Indigenous cuisine, seal oil is used for storing many foods and is integral to numerous dishes (see Figure 3)[54]. Traditional methods and recipes, passed down through generations through hands-on teaching and shared experiences, ensure that each meal is not just nutritional sustenance, but a celebration of history and culture. These range from methods of cooking every part of the seal, from the head to the intestines, how to prepare blubber, as well as recipes for walrus liver broth among many more. Enjoying their food raw, boiled, dried, smoked or preserved. These traditional recipes, passed down through generations, are more than just methods of food preparation, they embody the community's history, cultural heritage, and accumulated wisdom of living in the Arctic environment [41, 54, 24].

Given the challenges and risks outlined above, preserving these practices is crucial. The Arctic ecosystem's marine resources provide essential sustenance and maintain a connection to ancestral knowledge and customs. Moreover, their nutritional density makes them vital for the continued health of the community. Therefore, the health of the Arctic ecosystem is paramount as it is not merely a matter of an environmental concern but additionally a matter of a cultural preservation, food security and public health for Indigenous people. With continued manifestation of the effects of climate change a likely disruption to ecosystem will lead to a profound impact to the lives, health and cultural continuity of communities that have thrived in this region for millennia [47].

3 Algal blooms in the Arctic: the primary producers in the ecosystem

3.1 From melting ice to blooming seas

The warming of the Arctic is the most emblematic manifestation of climate change. The Arctic has warmed by 2-3°C since the late 19th century while the Earth's average over the same period is approximately 0,8°C, which is equivalent of the Arctic warming for the last decade alone [1, 51]. There are many consequences that follow the increase in Arctic temperatures such as Arctic sea- and land-ice loss, with sea ice concentrations dropping approximately 9% each decade since 1978 [6]. Additionally, ice loss contributes to global sea level rise, primarily due to thermal expansion of the ocean water as well as melting mountain glaciers and permafrost. Furthermore, the thawing of permafrost poses additional challenges by accelerating the release of greenhouse gases into the atmosphere. These changes will not only disrupt the ecosystem but also threatens native wildlife through habitat loss and traditional human livelihoods as well as causing extreme weathers at lower latitudes [51]. These changes driven by climate change, have significantly altered the ecology of the Arctic[22].

Fundamental components of the Arctic ecosystem are phytoplankton, as they provide a foundation for the ocean's food web. Phytoplankton are photosynthetic organisms that convert carbon dioxide into organic compounds that are conducive to life, making them the oceans primary producers[22]. The link between increasing water temperature and the growth of phytoplankton has long been recognized as temperature influences physiological processes such as nutrient uptake, photosynthesis, motility, and germination [59]. With favorable conditions, phytoplankton thrive under sea ice, as sea ice chlorophyll concentrations rank among the highest for any aquatic environments [35]. As sea ice continues to reduce in thickness, concentration and persist for shorter duration, more light penetrates the surface ocean. This increase in light transmission further heats the water and thus creating a feedback loop. The warmer water further inhibits ice growth in winter and accelerates melting in spring and summer. Consequently, the window of opportunity for phytoplankton growth lengthens [59, 6]. Moreover, increased precipitation, river outflow and ice melting are some of the reasons for an increase in the influx of new nutrient to the Arctic seas, leading to a 57% increase of phytoplankton production from 1998 to 2018 [38, 44].

Although, sea-ice provides a critical habitat for phytoplankton, it has historically been assumed that their blooming events happened at the edge of the sea ice. Since the ice itself is optically thick with a high albedo, the regions underneath the sea-ice are therefore thought to be incapable of supporting the photosynthetic conditions required for phytoplankton growth [56, 22]. However, this paradigm was challenged following a July 2011 expedition in the Arctic Pacific environment. The findings of Arrigo et al.[5] scientific expedition reported a massive phytoplankton bloom beneath a 0.8-1.3m thick first year

Figure 3: Seal oil, the salt and pepper of Indigenous cuisine.The process of harvesting and processing seal fat to render seal oil. The seal oil is later used to dip the seal meat and used to drizzle over traditional foods. Figures combined from [19]

ice[2] in the Chukchi Sea continental shelf [5]. In their paper they report of a significant change in the physical environment of the Arctic, as fractions of first-year ice (0.5-1.8m) is becoming much higher

[2] First year ice, refers to ice that is thicker than 30cm but has not yet gone through summer melt season. While multi year ice is about 2-4m thick and has already survived summer season

than that of the historically dominant multiyear ice pack (2-4m). This observation correlates with findings of Kwok et al [34], whose data shows a 50% decrease in multi year ice coverage with Arctic ice coverage trends shifting towards first year ice [34]. In the warming temperatures, fraction of melt ponds on top of the ice increases as well (from 25 to 50%)[3] [5]. According to Arrigo et al.[5], the optical measurements of these melt ponds transmitted 47-59% incident light while the adjacent snow free ice transmitted 13-18%, making the sub-ice conditions with melt ponds favourable for phytoplankton blooms[5]. Additional sub-ice phytoplankton blooming events have been observed across the Arctic; in the Barents's Sea, the Beaufort Sea, the Canadian Archipelago and the Fram strait [5, 11]. This increase in phytoplankton growth creates an imbalance to the ecosystem and allows for the excessive growth of harmful algae to bloom, which negatively impacts surrounding organisms.

3.2 The shift from a vital to a toxic foundation for the Arctic ecosystem

Seasonal blooming events of phytoplankton are a natural part of the seasonal cycle in the marine ecosystem and vital to the Arctic food web[7]. The ice-algae and the phytoplankton form the foundation of the Arctic food web as the primary producers. They then provide nutrition for zooplankton which are key Arctic grazers, such as copepods. Zooplankton additionally serve as a crucial link between primary producers and higher trophic levels, as they transfer the energy to pelagic predators such as the amphipods *Themisto libellula*.[53, 30]. With the energy concentrated in zooplankton, they can be transferred up to fish and other larger predators, eventually reaching top predators such as seals, whales and polar bears [29, 31], thus, completing the food chain. This is evidenced in [10] where biomarkers were used to trace the carbon from phytoplankton and ice-algae. Some algal biomass supports the benthic communities as it sinks to the seafloor, creating an additional energy transfer pathway for the Arctic ecosystem, see Figure 4 for a schematic view of the Arctic marine food web.

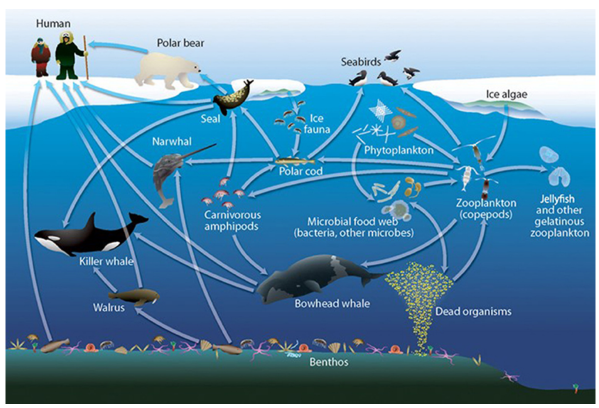

Figure 4: A schematic view of the Arctic marine food web. From primary producers to top predators, including the humans that hunt. Figure from Darnis et al. [15]

However, their increased blooming events pose as a threat to the same system due to the bio-toxins some species produce[7]. These toxins are harmful, even lethal, to both humans and other organisms in the ecosystem. Therefore, this proliferation is commonly referred to as harmful algal blooms (HAB) [7]. In the Arctic there are two main HAB species, *Alexandrium spp.* that produces saxitoxin (STXs) and *Pseudo-nitzschia* species that produces domoic acids (DA) [3]. Both saxitoxins and domoic acids are powerful neurotoxins that have the ability to cause severe illness in both humans and animals when ingested[17].

3.2.1 *Alexandrium spp.* and saxitoxin

Saxitoxin (STXs) is associated with paralytic shellfish poisoning. It binds with high affinity to voltage-gated sodium channels on cell membranes. As a result, it inhibits the influx of sodium ions into cells, thus suppressing action potential which leads to muscle paralysis [17]. The toxin is rapidly absorbed

[3] Melt ponds form as liquid water collects in depressions on the surface of the ice as it melts and deepens them. An increase in Carbon dioxide and other greenhouse gasses driving an increase in melting ponds as the temperature rises.

and easily distributed throughout the entire body, including the brain. The effects of the toxin therefore manifest just as rapidly (within an hour). Symptoms of the toxins include tingling, numbness, reduced motor activity, incoherent speech and even respiratory paralysis and death. Currently, there are no specific anecdotal treatment options available for STXs and treatment for the poisoning is usually symptomatic [8]. *Alexandrium* species pose as a particularly concerning threat as the species forms dormant cyst that can survive in the seafloor sediments, waiting for favorable conditions that are suitable for germination and bloom formation[2].

The Alaskan Arctic has seen an increasing presence of both STXs and DA in recent years [3]. While *Alexandrium* was only sporadically identified in the last 65+ years, recent studies have shown a significant increase in its occurrence [4]. The presence of *Alexandrium* cysts and blooming events have been identified in multiple locations throughout the Alaskan Arctic. Research done by Gu et al. show the presence of *Alexandrium catenella* cysts in the Chukchi sea [20]. Further testing in the Chukchi sea and the east Bering sea done by Natsuike et al[42] show the abundance of *Alexandrium tamarense* cysts distributed on the shallow continental shelf in locations that correlate to high blooming events. The abundance of cysts identified in the east Chukchi sea during Natsuike et al. highlights the real threat that these cysts and the toxins they produce, can pose to the ecosystem as the germinate. Furthermore, a more recent study by Natsuike et al. [43], show an abundance of *Alexandrium fundyense* cysts in the sediments of the eastern Bering Sea and the Chukchi Sea. Their tests on the strain show it grows at temperature as low as 5°C however, the strain shows increasing potential to germinate and grow when water temperatures increases. Their results concluded that as a consequence of these cysts the risk of paralytic shellfish poisoning was high . Moreover, a recent multi-year research conducted in the Alaskan Arctic by Anderson et al.[4] show a massive accumulation of resting *Alexandrium* cysts across a large area in the, see Figure 5. These cysts closely correlate with dense blooms of vegetative cells in the surface waters. With these blooming events happening frequently already, the presence the large quantity of cysts in the Chukchi sea suggest that these self-initiating blooming events will occur annually, as they already do, but will continue to increase.

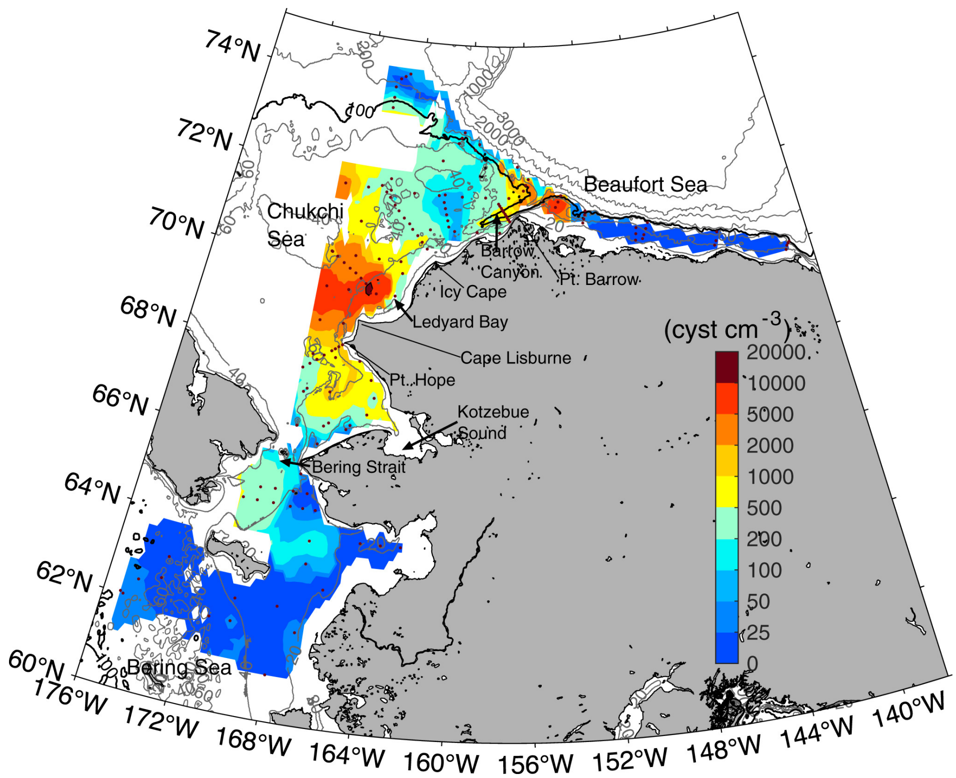

Figure 5: Results from Anderson et al. study shows the distribution and the abundance of cysts in surface sediments (0-3cm) during 2018 and 2019 in the Alaskan Arctic. [4]

Figure5 shows the dense cyst accumulation in the Chukchi sea. With large cyst beds in the Ledyard Bay with maximum 17.600 cyst/cm3 and another dense accumulation of cysts in the Barrow

Canyon with a maximum of 14.800 cysts/cm3[4]. Anderson et al. [4] replicated experiments similar to those conducted by Natsuike et al.[43], focusing on the relationship between increasing temperature and germination time. Their findings demonstrate a strong inverse correlation, as temperature rises, germination time decreases significantly, Given that the Arctic is warming at an accelerated rate compared to global averages, this relationship suggests a growing concern for the regions ecosystem.

3.2.2 *Pseudo-Nitzschia* and domoic acid

In comparison the STXs, domoic acid (DA) is not as easily absorbed from the gut, with only about 5-10% of the ingested dose typically entering the bodies circulation. However, DA has the ability to cross the blood brain barrier. Combined with its prolonged half-life in mammals, it contributes to potent neurotoxic effects. The toxin is an analog of an important neurotransmitter, and is therefore able to interact with a type of glutamate receptors located in the central nervous system. An interaction that leads to several toxic effects that lead to symptoms such as seizures, memory formation and memory loss [13]. The toxic effects of DA typically manifest in two different stages, the acute stage (usually within 24-48 hours) that has typical gastrointestinal symptoms along with headaches, dizziness, confusion and motor weakness; the chronic phase (can persist for months or years) that presents in seizures, cognitive impairment and anterograde memory deficits. DA has additionally been shown to have a significantly more effects on developing nervous systems at lower concentrations, causing permanent and long lasting neurological impacts [13].

The presence of *Pseudo-Nitzschia* in Arctic waters is not uncommon. However, in comparison to *Alexandrium* species, less is known about their history, diversity and toxicity in the region [2]. Increased testing and long term observation for *Pseudo-Nitzschia* species in the Alaskan Arctic is needed as there is still a lot unknown about its blooming events, presence and behaviour in the area[3]. A sampling cruise conducted by Hubbard et al.[23] in the fall and summer of 2018 in the Chukchi, Bering and Beaufort seas show that over *Pseudo-Nitzschia* species that produce DA are widespread throughout the Alaskan Arctic. The research provided some much needed understanding of the *Pseudo-Nitzschia* species present in the area as well as giving a much needed foundation to understand their spatiotemporal dynamics, highlighting the significant risk of Amnesic Shellfish Poisoning (ASP) and domoic Acid Poisoning (DAP) in the Alaskan Arctic[23].

While more research seems to be available on the presence of *Alexandrium spp.* in the Alaskan Arctic seas compare to published research of *Pseudo-Nitzschia* species, there is still a critical need to increase monitoring and understanding of both genera in this region. Existing research on the presence of these genera in the area highlight the potential for consistent and possibly increasing harmful algal blooming events. Therefore, understanding how these species act in a changing Arctic environment is vital. These changes have far reaching consequences for the Arctic ecosystem as it shifts the basis of the food chain, to a possible toxic foundation which highlights the need for increased monitoring of its effects up the food chain.

3.3 Tracing the path of algal toxins in the Alaskan Arctic ecosystem

Harmful algal blooms have been sporadically observed in the Alaskan Arctic. Historical records show scattered observations of *Alexandrium spp.* with studies from the last 70 years not detecting the species in any significance. More recent studies, particularly in the early 2000s, have confirmed the presence and toxicity of *Alexandrium spp.* in the Chukchi Sea, including a high concentration of resting cysts in sediments[4, 2]. It is becoming increasingly important to develop comprehensive monitoring programs and early warning systems. These efforts will be crucial to protect the humans who depend on that ecosystem for subsistence as well as the overall health of the ecosystem itself. Understanding how these blooming events and the increased presence of toxic species on the Alaskan Arctic food chain serves two main purposes. It provides a foundation for enhancing our broader understanding of how climate change is altering marine ecosystems. Additionally it helps predict shifts in resource availability, allowing subsistence hunters and fishers to better prepare for changes in their food sources. Moreover, it aids in protecting Indigenous communities from detrimental effects of these toxins [2] .

A recent paper by Lefebvre et al. detailing results from their excursion in the Beaufort, Chukchi, and Bering seas highlight the alarming levels of STXs across the Arctic marine ecosystem, during an unusual warm summer[36]. Sampling took place during the unusually warm summer of 2019 and spanned multiple trophic levels, sampling phytoplankton, zooplankton, benthic clams and worms, as well as pelagic fish. Of a particular concern were the toxic concentration found in the benthic clams that were harvested from the continental shelf across the three seas. Many of whom exceeded the regulatory safety limit form human consumption (80µg/100g tissue). Additionally, the study highlighted a potential threat to Pacific walruses, known to feed on these benthic species north of Saint Lawrence Island. Analysis of fecal samples from 13 walruses that had been harvested for subsistence near the island in spring 2019, revealed detectable STXs levels in all specimens. Of which, two were approaching the seafood safety threshold. In comparison, toxin levels were lower but still present in bowhead whales, which primarily feed on zooplankton. Fecal samples from 64% of the nine harvested bowhead whales between March and September 2019 in coastal Beaufort Sea waters tested positive for STXs. However, the concentrations were significantly lower than those found in the tested walruses (8.5µg/g versus 78µg/g), aligning with the lower toxin levels observed in their zooplankton prey.

Another paper by Lefebvre et al.[37] analyses the samples from 905 mammals across 13 species that were collected during the Northern Alaska Pinniped Unusual Mortality Event. Samples were collected from four cetaceans (humpback whales, bowhead whales, beluga whales and harbor porpoises), two otariids (norther fur seals and Stellar sea lions), five phocids (harbor, ringed, bearded, spotted and ribbon seals), Pacific walruses and northern sea otters. Variety of samples were taken from different sources of the mammals that had been stranded, harvested for subsistence purposes or captured for research. All samples were analysed for presence of STX or DA. STX was detected in 10 out of the 13 species studied. The highest prevalence was observed in the humpback whale (50%) and bowhead whales (32%). Pacific walruses contained the highest concentrations of STX among the species examined. In all 13 species sampled, DA was detected with bowhead whales and harbour seals showing the greatest prevalence (68% and 67% respectively). Notably, the Pacific walruses exhibited the highest concentration of both STXs and DA, with the levels of DA comparable to those found previously in California sea lions that exhibited clinical signs of toxicosis seizures. Moreover, the research highlighted the risk of combined exposure as samples from 46 of the individual mammals had detectable concentration of both DA and STX. This dual presence of toxins could have compounding effects on marine mammal health. The result of this study on marine mammals also revealed concerning impacts of DA exposure. Detectable DA concentrations in fetuses of beluga whales, harbor porpoises and sea lions demonstrate maternal toxin transfer, which raises concerns about long-term species viability[37]. Additionally, a 2019 study on sea otters in Kachemak Bay, found the animals had altered gene expression due a chronic low level exposure to DA. This gene expression indicated neurological, cardiac, immune and detoxification effects[9]. These findings collectively emphasize the diverse risk associated with algal toxin exposure in marine mammals, underscoring the urgent need for further research on potential threats to species maintenance and overall ecosystem health.

Another extensive study done on 998 seals (bearded, ringed, spotted and ribbon seals) harvested for subsistence purposes in the western and northern Alaska between 2005 and 2019 further proved that ice seals in the Bering, Chukchi and Beaufort seas are regularly exposed to HAB toxins, such as STX as well as DA[21]. Furthermore, this study showed that the stomach content of bearded seals sampled from the Bering sea had a significant increase in DA over time. Since bearded seals rely heavily on the filter feeding benthic organisms as a food source, they serve as an excellent indicator for monitoring the presence of HAB species and their associated toxins for the area. Moreover, as information on the presence of *Pseudo-Nitzschia* species in the Alaskan Arctic is limited, these findings are crucial. They highlight the notable increase in toxic producing *Pseudo-Nitzschia* species, not just in seals but in the area in the last 14 years of the study[21]. This provides insight into the evolution of these species in the region. These studies, extensively tested marine mammals in the Alaskan Arctic, many of whom were being hunted for subsistence purposes. The findings provide compelling evidence that harmful algal blooms and their toxins are present throughout the Alaskan waters at levels high enough to be detected in marine mammals [21, 37, 36, 9].

The effects of these toxins extend beyond these marine mammal to other components of the Arctic ecosystem, including seabirds. A 2019 study focusing on the alarming increase in seabird mortality events in Alaska since 2015, shows the connection to STXs (and other paralytic shellfish toxin (PST) equivalents) [58]. Starvation was initially thought to be the cause of these excessive mortality events. However, the research done by Van Hemert et al.[58] on Arctic Terns nesting colonies near Juneau, Alaska sheds new light on the probable cause of death. Researchers found elevated concentrations of STXs in the samples that were collected from the birds, their foraged fish, and nearby mussels. Analysis of the Arctic Tern tissue revealed STXs levels ranging from 2.5 to 51.2µg/100g, comparable to concentrations reported in other PTS-induced bird die-offs. These findings strongly indicate that PST contributed to the mortality events. Results of the study also showed an alarmingly high PST levels in the local food web. Blue mussels collected from nearby beaches contained over 11.000µg/100g of PSTs, while the foraged fish that was retrieved from Arctic Tern nests had concentrations up to 494µg/100g. Moreover, in a related study, Van Hemert et al. [57]further expanded their investigation to seabird mortality events in the Bering and Chukchi seas between 2014 and 2017. This research focused on a multi-species die-off that primarily effected Norther Fulmars and Short-tailed Shearwaters. STXs was found in 60% of all tested bird, with STX detected in 88% of Northern Fulmars species, the species most frequently recorded in carcass counts.

The extensive research on saxitoxin (and similar paralytic shellfish toxins) in the Alaskan Arctic demonstrates the pervasive nature of these toxins throughout the entire marine food web, affecting species from zooplankton and up to top predators like whales and seabirds, many of whom are already part of a subsistence harvest which could lead to potential health impacts in humans. This threat underscores the urgent need to monitor and manage the threats that follow harmful algal blooms. As was outlined before, some studies have detected a co-occurrence in of both STX and DA in marine mammals, highlighting the potential for compounding effects on the health of the marine ecosystem. However, Indigenous Alaskans have already started taking matters into their own hands in cases for harvested shellfish. As testing for shellfish toxins (such as STX and DA) are often only done for commercial harvests, tribes across the Southeast of Alaska have felt the need to address this lack of state or federal toxin testing for their subsistence and/or recreational harvesting and have formed their own toxin testing and ocean monitoring program[52]. This highlights the need for increased testing in the Alaskan Arctic, not only for commercial batches but for the protection of the Indigenous communities.

4 Discussions

The Arctic ecosystem is undergoing a rapid transformation that is driven by climate change. With the Arctic warming at a rate around 4x faster than the global average. These changes are profoundly impacting both the marine environment and as a result, the Indigenous communities that depend on it.

Recent expeditions have documented a significant shift in Arctic sea ice composition, with first-year ice becoming dominant as multi-year ice diminishes. The melt ponds present on this ice create more favorable conditions for ice-algae growth, resulting in a massive increase in algal biomass as was first observed by Arrigo et al.[5] 2011 expedition. This shift not only alters the physical structure of the Arctic environment but also sets the stage for potential ecological disruptions.

Of particular concern is the increasing prevalence of harmful algal blooms (HABs) in the Alaskan Arctic, especially those producing saxitoxin (STX) and domoic acid (DA). Research has shown a significant increase in the presence of *Alexandrium* and *Pseudo-nitzschia* species, which are producers of these bio-toxins. *Alexandrium* species are of particular concern due to their ability to form dormant cysts. Studies in the Alaskan Arctic have identified massive cyst beds in multiple areas that are associated with seasonal *Alexandrium* blooms. While specific testing for the presence of *Pseudo-nitzschia* is not as extensive for the area, the detection of DA throughout the food web indicates that an urgent need is for more testing and better understanding of the species in the area. Moreover, as the link between increasing water temperature and phytoplankton growth has long been recognized, the accelerated warming of the Arctic is a cause for great concern. Furthermore, Lefebvre et al. [36] observed during their research expedition an alarming amount of STXs levels across the Arctic marine ecosystem during an unusual warm summer, we can expect that unusually warm summers will become the norm. this trend is likely to exacerbate the frequency and intensity of HABs in the region. Further temperature correlation studies on the HAB strains highlighted by Natsuike et al. and Anderson et al. [43, 4] demonstrate that the cyst beds found in the Alaskan Arctic are highly sensitive to temperature changes. These studies provide evidence of the dramatic expansion of these large cyst beds in response to shifting Arctic condition and underscores the urgent need for continued monitoring of temperature trends, ice composition, and HAB occurrences.

This shift in the foundation of the food chain has cascading effects through higher trophic levels, potentially disrupting the delicate balance of the Arctic ecosystem that Indigenous communities have relied upon for millennia. Research has demonstrated the pervasive presence of these bio-toxins throughout the Arctic marine ecosystem. Multiple studies on marine mammals and other organisms connected to the Arctic ecosystem have shown the widespread nature of STX and DA in the system. These toxins have been detected in species ranging from bottom feeding clams to whales and seals. Notably, research has found varying levels of toxins across different marine mammals, where mammals that rely on filter feeding benthic species and zooplankton as primary nutrient sources showing high amounts of toxins. These findings suggest that the concentration of toxins may be influenced by an animals position on the food chain and its feeding habits. Additionally, it highlights how connected the ecosystem is, showcasing the extent of bio-accumulation and bio-magnification occurring in the Alaskan Arctic marine ecosystem.

Furthermore, the presence of these toxins could potentially explain the significant increase in seabird mortality events, an aspect that had not been previously studied. Many of the effected species are crucial parts of the Indigenous subsistence harvests which raises serious concerns about potential human health impacts. The co-occurrence of STX and DA in marine mammals adds an additional complexity and suggests a possible compounding effects on ecosystem health. Both of these toxins can be dangerous and even lethal to humans, animals and overall the health of the entire ecosystem. Highlighting the urgency of addressing this issue.

Although not within the scope of this work, the Indigenous communities of the Alaskan Arctic have endured a long history of cultural suppression. This makes their continued use of traditional practices all the more crucial. Additionally, the introduction of "western foods" has already posed significant health threats to these communities, further underscoring the vital importance of maintaining a healthy Arctic ecosystem for a continued subsistence living. As the Arctic undergoes these rapid changes, protecting the ecosystem and educating Indigenous communities about emerging risks, especially from harmful algal blooms and their toxins, becomes increasingly crucial. Adapting traditional practices might become necessary, such as excluding recipes that use highly contaminated animal parts like the intestines. Increased testing and monitoring will shed light on these concerns. While community led initiatives for toxin testing are commendable, Indigenous communities should not bear this burden alone. As the literature shows, the algal blooms in the area are increasing rapidly and their toxins have already made their way far into the food chain, with alarmingly high amounts of toxins detectable across most, if not all species. This highlights the pressing need for a comprehensive federal monitoring program that extends beyond commercial harvests to encompass the entire Arctic marine ecosystem. Such programs would not only serve as a necessary monitor for the changing Arctic ecosystem but also protect Indigenous communities and their century old ways of life.

The research findings emphasize how interconnectedness of the Alaskan Arctic ecosystem and highlight how climate-driven changes cab have far-reaching consequences for both marine life and human communities. As temperatures in the Alaskan Arctic continue to rise, we are likely only beginning to witness the initial effects on Harmful Algal Bloom production and their subsequent impacts on the food chain. The full extent of these changes and their long-term implications are yet to be fully understood, emphasizing the urgency of establishing comprehensive monitoring systems immediately. By implementing robust monitoring systems now, we can better anticipate and mitigate the effects of increasing HAB on the food chain, thereby helping protect Indigenous communities from potential health risks and food insecurity.

It is crucial to recognize that climate change manifests in numerous ways but one of its impacts is the threat it poses to the cultural and traditional heritage of Alaskan Indigenous peoples by jeopardizing their subsistence practices. By potentially altering the availability and safety of traditional food sources with the increase in HAB toxins, climate change strikes at the heart of Indigenous ways of life that have sustained communities for generations. Therefore, in addressing the challenges posed by climate change and increasing HABs is not just an environmental or health issue, but a crucial step in safeguarding the cultural continuity and traditional heritage of Alaskan Indigenous communities for future generations.

References

[1] Jimena Alvarez, Dmitry Yumashev, and Gail Whiteman. A framework for assessing the economic impacts of arctic change. *Ambio*, 49:407–418, 2020.

[2] DM Anderson, ML Richlen, and KA Lefebvre. Harmful algal blooms in the arctic. *Arctic report card*, 2018:81, 2018.

[3] Donald M Anderson, Evangeline Fachon, Katherine Hubbard, Kathi A Lefebvre, Peigen Lin, Robert Pickart, Mindy Richlen, Gay Sheffield, and Caroline Van Hemert. Harmful algal blooms in the alaskan arctic. *Oceanography*, 35(3/4):130–139, 2022.

[4] Donald M Anderson, Evangeline Fachon, Robert S Pickart, Peigen Lin, Alexis D Fischer, Mindy L Richlen, Victoria Uva, Michael L Brosnahan, Leah McRaven, Frank Bahr, et al. Evidence for massive and recurrent toxic blooms of alexandrium catenella in the alaskan arctic. *Proceedings of the National Academy of Sciences*, 118(41):e2107387118, 2021.

[5] Kevin R Arrigo, Donald K Perovich, Robert S Pickart, Zachary W Brown, Gert L Van Dijken, Kate E Lowry, Matthew M Mills, Molly A Palmer, William M Balch, Frank Bahr, et al. Massive phytoplankton blooms under arctic sea ice. *Science*, 336(6087):1408–1408, 2012.

[6] Kevin R Arrigo and Gert L van Dijken. Continued increases in arctic ocean primary production. *Progress in oceanography*, 136:60–70, 2015.

[7] Elisa Berdalet, Lora E Fleming, Richard Gowen, Keith Davidson, Philipp Hess, Lorraine C Backer, Stephanie K Moore, Porter Hoagland, and Henrik Enevoldsen. Marine harmful algal blooms, human health and wellbeing: challenges and opportunities in the 21st century. *Journal of the Marine Biological Association of the United Kingdom*, 96(1):61–91, 2016.

[8] OPCW Scientific Advisory Board. Saxitoxin fact sheet. *Twenty-First Session*, pages 23–27, 2014.

[9] Lizabeth Bowen, Susan Knowles, Kathi Lefebvre, Michelle St. Martin, Michael Murray, Kim Kloecker, Daniel Monson, Benjamin Weitzman, Brenda Ballachey, Heather Coletti, et al. Divergent gene expression profiles in alaskan sea otters: An indicator of chronic domoic acid exposure? In *Oceans*, volume 3, pages 401–418. MDPI, 2022.

[10] Thomas A Brown, Melissa P Galicia, Gregory W Thiemann, Simon T Belt, David J Yurkowski, and Markus G Dyck. High contributions of sea ice derived carbon in polar bear (ursus maritimus) tissue. *PloS one*, 13(1):e0191631, 2018.

[11] Andrew P Castagno, Till JW Wagner, Mattias R Cape, Conner W Lester, Elizabeth Bailey, Catharina Alves-de Souza, Robert A York, and Alyson H Fleming. Increased sea ice melt as a driver of enhanced arctic phytoplankton blooming. *Global Change Biology*, 29(17):5087–5098, 2023.

[12] Robert W Corell. Challenges of climate change: an arctic perspective. *AMBIO: A Journal of the Human Environment*, 35(4):148–152, 2006.

[13] Lucio G Costa, Gennaro Giordano, and Elaine M Faustman. Domoic acid as a developmental neurotoxin. *Neurotoxicology*, 31(5):409–423, 2010.

[14] Sean Cunningham. What happens on a traditional whale hunt in alaska, 2016.

[15] Gérald Darnis, Dominique Robert, Corinne Pomerleau, Heike Link, Philippe Archambault, R John Nelson, Maxime Geoffroy, Jean-Éric Tremblay, Connie Lovejoy, Steve H Ferguson, et al. Current state and trends in canadian arctic marine ecosystems: Ii. heterotrophic food web, pelagic-benthic coupling, and biodiversity. *Climatic Change*, 115:179–205, 2012.

[16] Birgitta Evengard and Anthony McMichael. Vulnerable populations in the arctic. *Global Health Action*, 4, 2011.

[17] Samantha Faber. Saxitoxin and the induction of paralytic shellfish poisoning. *Journal of Young Investigators*, 23(1):1–7, 2012.

[18] Georgina A Gibson, Hajo Eicken, Henry P Huntington, Clara J Deal, Olivia Lee, Katherine M Smith, Nicole Jeffery, and Josephine-Mary Sam. How earth system models can inform key dimensions of marine food security in the alaskan arctic. *Earth Science, Systems and Society*, 3:10082, 2024.

[19] Bethany Sonsini Goodrich. A taste of home: Joni elisoffs seals grease, 2022.

[20] Haifeng Gu, Ni Zeng, Zhangxian Xie, Dazhi Wang, Weiguo Wang, and Weidong Yang. Morphology, phylogeny, and toxicity of atama complex (dinophyceae) from the chukchi sea. *Polar Biology*, 36:427–436, 2013.

[21] Alicia M Hendrix, Kathi A Lefebvre, Lori Quakenbush, Anna Bryan, Raphaela Stimmelmayr, Gay Sheffield, Gabriel Wisswaesser, Maryjean L Willis, Emily K Bowers, Preston Kendrick, et al. Ice seals as sentinels for algal toxin presence in the pacific arctic and subarctic marine ecosystems. *Marine Mammal Science*, 37(4):1292–1308, 2021.

[22] Christopher Horvat, David Rees Jones, Sarah Iams, David Schroeder, Daniela Flocco, and Daniel Feltham. The frequency and extent of sub-ice phytoplankton blooms in the arctic ocean. *Science advances*, 3(3):e1601191, 2017.

[23] Katherine A Hubbard, Maria Célia Villac, Christina Chadwick, Alexandra A DeSmidt, Leanne Flewelling, April Granholm, Molly Joseph, Taylor Wood, Evangeline Fachon, Michael L Brosnahan, et al. Spatiotemporal transitions in pseudo-nitzschia species assemblages and domoic acid along the alaska coast. *Plos one*, 18(3):e0282794, 2023.

[24] Henry P Huntington, Jens H Mosli, and Valeri B Shustov. Peoples of the arctic: Characteristics of human populations relevant to pollution issues. *AMAP Assessment Report: Arctic Pollution Issues*, pages 141–182, 1998.

[25] Henry P Huntington, Andrey Zagorsky, Bjørn P Kaltenborn, Hyoung Chul Shin, Jackie Dawson, Maija Lukin, Parnuna Egede Dahl, Peiqing Guo, and David N Thomas. Societal implications of a changing arctic ocean. *Ambio*, 51(2):298–306, 2022.

[26] JenniferS Johnson, Elizabeth D Nobmann, and Elvin Asay. Factors related to fruit, vegetable and traditional food consumption which may affect health among alaska native people in western alaska. *International journal of circumpolar health*, 71(1):17345, 2012.

[27] Dan Joling. Alaskas inuit link steady food supply environment, 2015.

[28] Tiff-Annie Kenny, Matthew Little, Tad Lemieux, P Joshua Griffin, Sonia D Wesche, Yoshitaka Ota, Malek Batal, Hing Man Chan, and Melanie Lemire. The retail food sector and indigenous peoples in high-income countries: a systematic scoping review. *International Journal of Environmental Research and Public Health*, 17(23):8818, 2020.

[29] Doreen Kohlbach, Martin Graeve, Carmen David, Benjamin Lange, and Hauke Flores. Transfer of ice algae-based energy in a summerly arctic ocean: Food web insights revealed by state-of-the-art biomarker approaches. 2015.

[30] Doreen Kohlbach, Martin Graeve, Benjamin Allen Lange, Carmen L. David, Ilka Peeken, and Hauke Flores. The engine of life in the central arctic ocean: Ice algae. 2016.

[31] Doreen Kohlbach, Martin Graeve, Benjamin Allen Lange, Fokje L. Schaafsma, Benoit Lebreton, Carmen L. David, and Hauke Flores. Sea ice algae as food source- high trophic dependency of important energy transmitters in the central arctic ocean. 2017.

[32] Harriet V Kuhnlein. Benefits and risks of traditional food for indigenous peoples: focus on dietary intakes of arctic men. *Canadian Journal of Physiology and Pharmacology*, 73(6):765–771, 1995.

[33] Harriet V Kuhnlein, Olivier Receveur, Rula Soueida, and Grace M Egeland. Arctic indigenous peoples experience the nutrition transition with changing dietary patterns and obesity. *The Journal of nutrition*, 134(6):1447–1453, 2004.

[34] Ron Kwok. Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018). *Environmental Research Letters*, 13(10):105005, 2018.

[35] Delphine Lannuzel, Letizia Tedesco, Maria Van Leeuwe, Karley Campbell, Hauke Flores, Bruno Delille, Lisa Miller, Jacqueline Stefels, Philipp Assmy, Jeff Bowman, et al. The future of arctic sea-ice biogeochemistry and ice-associated ecosystems. *Nature Climate Change*, 10(11):983–992, 2020.

[36] Kathi A Lefebvre, Evangeline Fachon, Emily K Bowers, David G Kimmel, Jonathan A Snyder, Raphaela Stimmelmayr, Jacqueline M Grebmeier, Steve Kibler, D Ransom Hardison, Donald M Anderson, et al. Paralytic shellfish toxins in alaskan arctic food webs during the anomalously warm ocean conditions of 2019 and estimated toxin doses to pacific walruses and bowhead whales. *Harmful Algae*, 114:102205, 2022.

[37] Kathi A Lefebvre, Lori Quakenbush, Elizabeth Frame, Kathy Burek Huntington, Gay Sheffield, Raphaela Stimmelmayr, Anna Bryan, Preston Kendrick, Heather Ziel, Tracey Goldstein, et al. Prevalence of algal toxins in alaskan marine mammals foraging in a changing arctic and subarctic environment. *Harmful algae*, 55:13–24, 2016.

[38] KM Lewis, GL Van Dijken, and Kevin R Arrigo. Changes in phytoplankton concentration now drive increased arctic ocean primary production. *Science*, 369(6500):198–202, 2020.

[39] Tim Lougheed. The changing landscape of arctic traditional food, 2010.

[40] Oliver Milman. Alaska indigenous people see culture slipping away as sea ice vanishes. *The Guardian*, 2015.

[41] Hacquebord L. Gregor D.J. Murray, J.L. and H. Loeng. *AMAP assessment report: Arctic pollution issues*. Arctic Monitoring and Assessment Programme (AMAP),, 1998.

[42] Masafumi Natsuike, Satoshi Nagai, Kohei Matsuno, Rui Saito, Chiko Tsukazaki, Atsushi Yamaguchi, and Ichiro Imai. Abundance and distribution of toxic alexandrium tamarense resting cysts in the sediments of the chukchi sea and the eastern bering sea. *Harmful Algae*, 27:52–59, 2013.

[43] Masafumi Natsuike, Hiroshi Oikawa, Kohei Matsuno, Atsushi Yamaguchi, and Ichiro Imai. The physiological adaptations and toxin profiles of the toxic alexandrium fundyense on the eastern bering sea and chukchi sea shelves. *Harmful Algae*, 63:13–22, 2017.

[44] Aleksi Nummelin, Mehmet Ilicak, Camille Li, and Lars H Smedsrud. Consequences of future increased arctic runoff on arctic ocean stratification, circulation, and sea ice cover. *Journal of Geophysical Research: Oceans*, 121(1):617–637, 2016.

[45] M Nuttall, F Berkes, F Forbes, G Kofinas, T Vlassova, and G Wenzel. 2005. hunting, herding, fishing and gathering: Indigenous peoples and renewable resource use in the arctic. Technical report, Arctic Climate Impact Assessment, 2005.

[46] Mark Nuttall. *Encyclopedia of the Arctic*. Routledge, 2005.

[47] Mark Nuttall. An environment at risk: Arctic indigenous peoples, local livelihoods and climate change. In *Arctic alpine ecosystems and people in a changing environment*, pages 19–35. Springer, 2007.

[48] University of Lapland. Arctic indigenous peoples. https://www.arcticcentre.org/EN/arcticregion/Arctic-Indigenous-Peoples#:~:text=Arctic%20indigenous%20peoples%20include%20for,Inuit%20(Kalaallit)%20in%20Greenland. Accessed: 2024-05-15.

[49] PAME. Indigenous food security in the arctic: Implications of a changing ocean. Technical report, The Arctic Council, 2021.

[50] Thayer Family Papers. Walrus hunting.

[51] Eric Post, Richard B Alley, Torben R Christensen, Marc Macias-Fauria, Bruce C Forbes, Michael N Gooseff, Amy Iler, Jeffrey T Kerby, Kristin L Laidre, Michael E Mann, et al. The polar regions in a 2 c warmer world. *Science advances*, 5(12):eaaw9883, 2019.

[52] Hugh B Roland, Jacob Kohlhoff, Kari Lanphier, Sneha Hoysala, Esther G Kennedy, John Harley, Christopher Whitehead, and Matthew O Gribble. Perceived challenges to tribally led shellfish toxin testing in southeast alaska: Findings from key informant interviews. *GeoHealth*, 8(3):e2023GH000988, 2024.

[53] Janne E Søreide, Eva VA Leu, Jørgen Berge, Martin Graeve, and STIG Falk-Petersen. Timing of blooms, algal food quality and calanus glacialis reproduction and growth in a changing arctic. *Global change biology*, 16(11):3154–3163, 2010.

[54] Zona Spray. Memories of a vanishing eskimo cuisine. In *Food and the Memory: Proceedings of the Oxford Symposium on Food and Cookery*, 2000.

[55] JC Stroeve, G Veyssiere, C Nab, B Light, D Perovich, J Laliberté, K Campbell, J Landy, R Mallett, A Barrett, et al. Mapping potential timing of ice algal blooms from satellite. *Geophysical Research Letters*, 51(8):e2023GL106486, 2024.

[56] Letizia Tedesco, Marcello Vichi, and Enrico Scoccimarro. Sea-ice algal phenology in a warmer arctic. *Science Advances*, 5(5):eaav4830, 2019.

[57] Caroline Van Hemert, Robert J Dusek, Matthew M Smith, Robert Kaler, Gay Sheffield, Lauren M Divine, Kathy J Kuletz, Susan Knowles, Julia S Lankton, D Ransom Hardison, et al. Investigation of algal toxins in a multispecies seabird die-off in the bering and chukchi seas. *The Journal of Wildlife Diseases*, 57(2):399–407, 2021.

[58] Caroline Van Hemert, John R Harley, Gwen Baluss, Matthew M Smith, Robert J Dusek, Julia S Lankton, D Ransom Hardison, Sarah K Schoen, and Robert SA Kaler. Paralytic shellfish toxins associated with arctic tern mortalities in alaska. *Harmful algae*, 117:102270, 2022.

[59] Mark L Wells, Vera L Trainer, Theodore J Smayda, Bengt SO Karlson, Charles G Trick, Raphael M Kudela, Akira Ishikawa, Stewart Bernard, Angela Wulff, Donald M Anderson, et al. Harmful algal blooms and climate change: Learning from the past and present to forecast the future. *Harmful algae*, 49:68–93, 2015.

[60] T Kue Young and Peter Bjerregaard. Towards estimating the indigenous population in circumpolar regions. *International journal of circumpolar health*, 78(1):1653749, 2019.

[61] Wenyu Zhou, L Ruby Leung, and Jian Lu. Steady threefold arctic amplification of externally forced warming masked by natural variability. *Nature Geoscience*, pages 1–8, 2024.