A food chain-based ecological risk assessment model for oil spills in the Arctic environment

Fahd, Faisal; Yang, Ming; Khan, Faisal; Veitch, Brian

DOI
10.1016/j.marpolbul.2021.112164

Publication date
2021

Document Version
Final published version

Published in
Marine Pollution Bulletin

Citation (APA)
Fahd, F., Yang, M., Khan, F., & Veitch, B. (2021). A food chain-based ecological risk assessment model for oil spills in the Arctic environment. *Marine Pollution Bulletin*, *166*, Article 112164. https://doi.org/10.1016/j.marpolbul.2021.112164

Marine Pollution Bulletin 166 (2021) 112164

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

A food chain-based ecological risk assessment model for oil spills in the Arctic environment

Faisal Fahd [a], Ming Yang [b], Faisal Khan [a,*], Brian Veitch [a]

[a] Centre for Risk, Integrity and Safety Engineering (C-RISE), Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's A1B 3X5, NL, Canada
[b] Safety and Security Sciences Section, Faculty of Technology, Policy and Management, TU Delft, the Netherlands

ARTICLE INFO

Keywords:
Arctic
Food web
Oil spill
Ecological risk assessment
Arctic risk
Environmental risk

ABSTRACT

This paper investigates the linkage between the acute impacts on apex marine mammals with polar cod responses to an oil spill. It proposes a Bayesian network-based model to link these direct and indirect effects on the apex marine mammals. The model predicts a recruitment collapse (for the scenarios considered), causing a higher risk of mortality of polar bears, beluga whales, and Narwhals in the Arctic region. Whales (adult and calves) were predicted to be at higher risk when the spill was under thick ice, while adult polar bears were at higher risk when the spill occurred on thin ice. A spill over the thick ice caused the least risk to whale and adult polar bears. The spill's timing and location have a significant impact on the animals in the Arctic region due to its unique sea ice dynamics, simple food web, and short periods of food abundance.

1. Introduction

The Arctic is melting and becoming more attractive and accessible to human activities. The relatively pristine Arctic region is open to shipping and oil and gas exploration activities (Hoop et al., 2011; Chapman and Riddle, 2003; Gardiner et al., 2013). Accidental oil spills may occur during these activities and impose severe impacts on the Arctic aquatic ecosystem (Lee et al., 2015; Helle et al., 2020; Nevalainen et al., 2017). There is an urgent need to assess the potential impacts these activities will have on the Arctic apex aquatic mammals and the food web of those animals. The challenges and knowledge gaps in oil spill ecological impact assessment in the Arctic region can be categorized broadly as the following:

- Lack of knowledge in oil spill fate and transport modeling in ice-infested waters: The presence of sea ice and its uncertainties hampers the clean-up in ice infested waters (Afenyo et al., 2017). Studies such as Sorstrom et al. (2010), Dickins et al. (2011), and Singsaas et al. (2020) have conducted field and laboratory-scale experiments to study the oil spill fate and transport in ice infested waters. Afenyo et al. (2015) has described the oil spill transport process in ice-infested water in terms of spreading, dispersion, advection, sedimentation, and encapsulation. The presence of ice cover significantly impacts the weathering and transport processes in the Arctic region. Sea ice either could impede or facilitate the oil exposure to marine animals, based on the location of an oil spill and other environmental conditions (Fahd et al., 2019).
- Lack of aquatic toxicity data on Arctic species: Toxicity data for Arctic marine species is limited (Fahd et al., 2019). Toxicity data, such as the No Observed Effects Concentration (NOEC) of crude oil to various species, is based on experimental studies or modeling based on a surrogate species. The knowledge gap in the toxicity data of Arctic species is also filled by using temperate fish data. Fahd et al., 2017, 2019, 2020 proposed that Arctic marine species toxicity data could be estimated based on the probability of cellular damage and metabolite interactions in the organism. The metabolite interactions, quantified by ecotoxicological biomarkers, are represented in causal relationships using a Bayesian Network (BN). Fahd et al. (2019, 2020) demonstrated the BN model by estimating mortality for *Boreogadus saida* (Arctic cod) populations for various assumed oil spill scenarios.
- Unique features of the food chain and the feeding behaviors of the marine species: The Arctic food web is comparatively simple. Therefore, the impact on one trophic level develops cascading effects on other trophic levels (Nevalainen et al., 2017). Apart from the animals' susceptibility to oil exposure, the non-availability of prey

* Corresponding author.
E-mail address: fikhan@mun.ca (F. Khan).

https://doi.org/10.1016/j.marpolbul.2021.112164
Received 26 November 2020; Received in revised form 29 January 2021; Accepted 5 February 2021
Available online 26 February 2021
0025-326X/

further compounds the population dynamics of the animals in the region. The availability of prey also impacts the ability to reproduce offspring; thus meeting energy requirements for the apex predators plays a significant role in their thriving. Arctic animals are over-dependent on one animal as a major source of energy. For example, a major part of the whale diet comprises of small fish, such as polar cod and capelin, while the seals are pivotal to the survival and reproduction energy requirement of polar bears. Studies such as Amstrup et al. (2008) have reported reduced body condition, reproduction, and survival for polar bears in ranges where sea ice reduction was observed. Sea-ice by itself may not be directly related to the population density. However, sea ice is an indicator of seals' presence, which forms a main source of nutrition for the polar bear. Across the range of the polar bears, the relationship between ringed seals and polar bears is such that an abundance of ringed seals appears to regulate the density of the polar bears in the region.

This study has attempted to tackle the above challenges and fill the knowledge gap by developing a Bayesian network (BN)-based approach for ecological risk assessment of oil spills' impact on Arctic animals. The objective of this research is to develop a novel and comprehensive marine risk model for apex species combining the effects from exposure to oil spill and ripple effects through the food chain from decreased prey availability. This research develops on the previous work from the authors estimating the dose response and risk to polar cod from similar oil spill scenarios considered in this study.

The BN is based on the current understanding of the Arctic food chain and also takes into account foraging and other behavioural aspects of the marine species in consideration. The rest of the paper is organized as follows. Section 2 presents the Arctic food chain first, based on which the BN-based ecological risk assessment approach is proposed. In Section 3, this method is applied to a hypothetical oil spill near Svalbard. This is followed by results and discussions in Section 4. Finally, Section 5 concludes the study.

2. The proposed methodology

The Arctic food web was developed based on Steiner et al. (2019), Amstrup et al. (2008), and Bluhm and Gradinger (2008), as shown in Fig. 1. Understanding the idiosyncratic responses of the lower trophic level Arctic marine animals is crucial to predicting risks to the polar bear and beluga whale populations and essential for efficient conservation strategies (Chevalier et al., 2018). Identifying susceptible concentrations of PAH to individual Arctic mammals and the probability of exposure of the distribution of animals provides little insight unless they are combined with cascading effects in the marine food web. Overall impacts on the ecosystem are evaluated. Modeling studies, such as Carroll et al. (2018) and Gallaway et al. (2017), simulated impacts on polar cod and northeast Arctic cod fisheries. Studies such as Nevalainen et al. (2017) and Helle et al. (2020) have linked the susceptibility and vulnerability of polar bears (individual and population) to the exposure of oil spills. No study has considered synergistic effects of prey availability changes in the food web with oil spill impact on apex marine mammals. Polar cod, an endemic Arctic keystone species (Cusa, 2016; Huserbraten et al., 2019), is selected. Its responses to oil spills are used to predict the mortality in polar cod populations. The cascading impacts of the changing polar cod populations in the Arctic apex marine mammals' food web is then studied.

Fig. 2 presents the framework of the model developed in this study. Oil spill conditions and environmental conditions are used as model input to check for the immediate risk of an oil spill to the Arctic animal species. To measure the indirect risk (i.e., from changing prey availability), prey requirement and availability are estimated for each trophic level in the food web based on their annual energy requirements. The species in the higher trophic level are assessed for immediate risk and impact on their food abundance.

The cascading effects in food chain as shown in Fig. 2 are estimated based on the following step-by-step methodology:

1. Estimate the population of polar cod
2. Determine the population of seals and the quantity of fish (as food) required for such seal population (see Section 3.3.2)
3. Determine the ratio of step 1 and step 2.
4. Based on the step 3 and the information of any alternate seal food source availability, a quantitative assessment of seal prey abundance is made.
5. Estimate the population of polar bears and calculate the number of seals required for survival of such polar bear population (see Section 3.3.2).

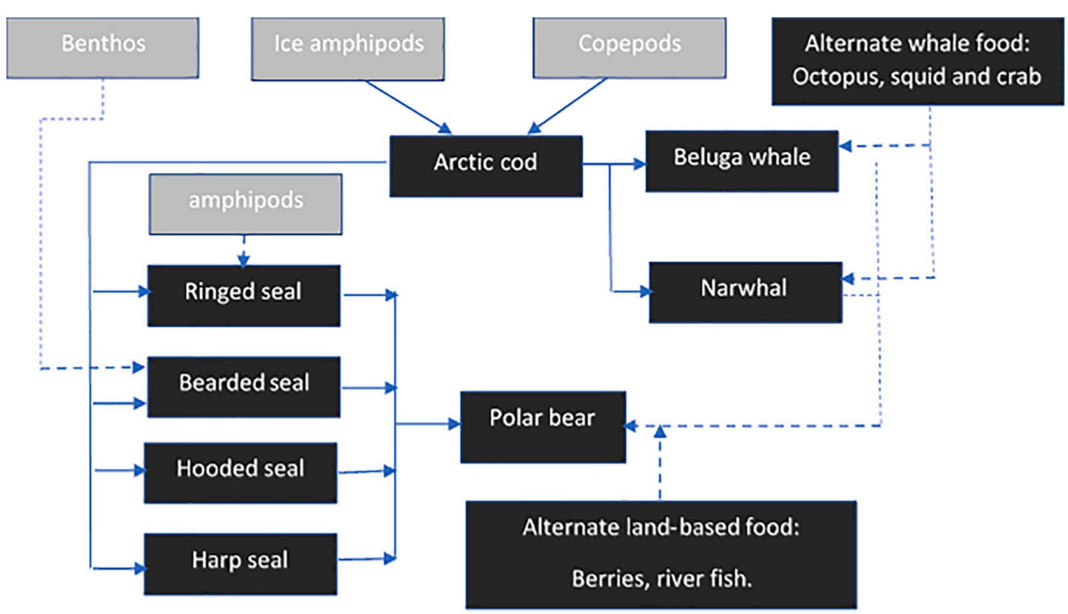


Fig. 1. Food chain of apex marine mammals.
Note: Dashed line represents alternate food options. Grey colored boxes are out of the scope of the study but used to present the completeness of the food web.

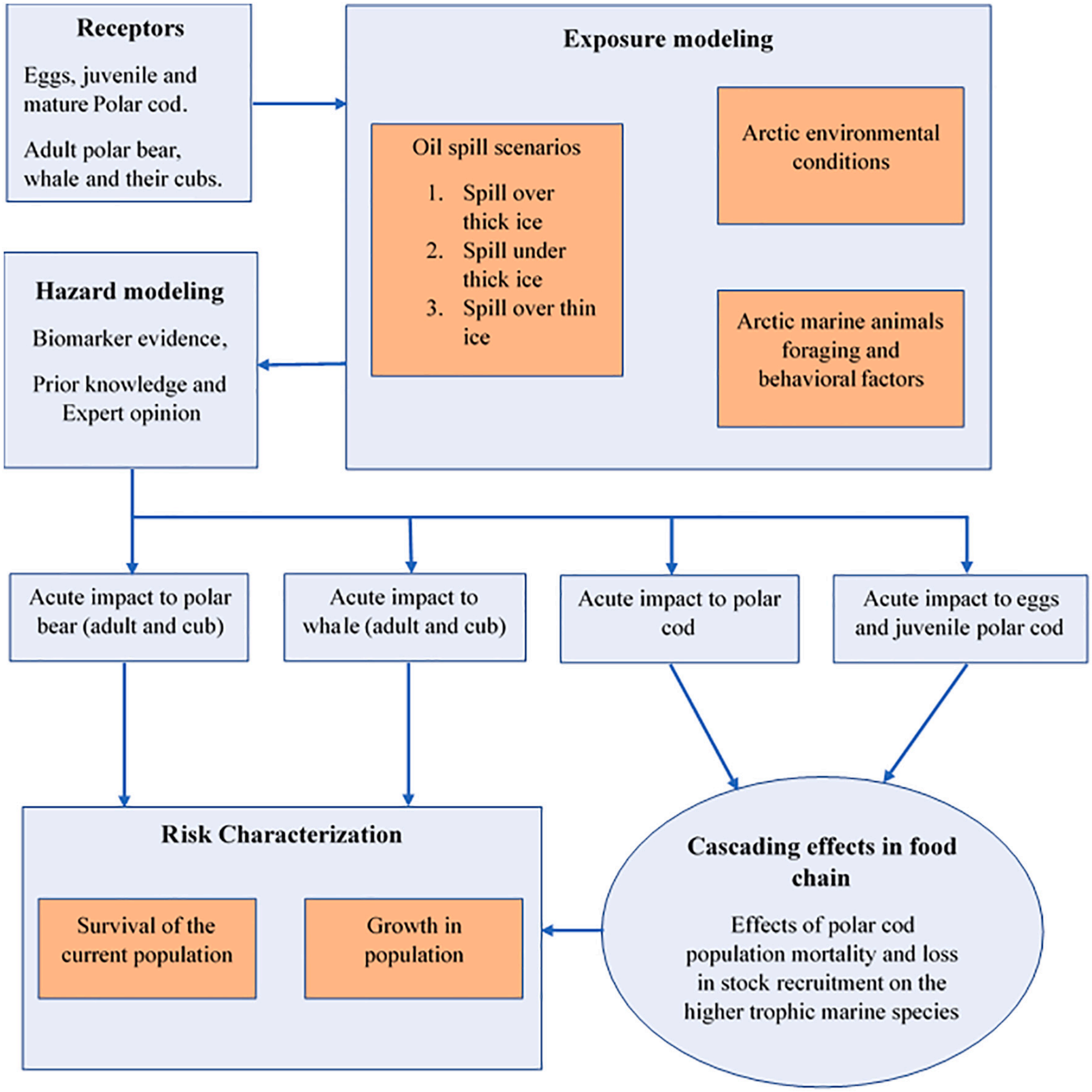


Fig. 2. Framework for the BN model of Arctic marine mammals' survival and population growth.

6. Based on step 4 and step 5, a quantitative assessment of risk is made using the BN model. See Supplementary document for more information on probabilistic modeling and BN.

The direct and indirect risk from oil spill exposure is defined as:

Risk (Direct oil spill exposure) = f (exposure, susceptibility)

Risk (Direct and indirect) = f (exposure, susceptibility, change in food abundance)

The changes in the food availability along with the acute impact of oil spills for apex Arctic mammals are modeled using a Bayesian network (BN). A BN represents the causal dependence between the nodes connected by arrows. The parent nodes are the nodes with no incoming dependence from other nodes. The probabilities of these parent nodes are the prior probabilities. The prior probabilities are calculated based on expert elicitation or based on the frequency of occurrence of the evidence. The intermediate nodes are nodes that have a parent node and further influence other nodes (child nodes). Intermediate nodes are described by conditional probability tables (CPTs). An advantage of the BN in such modeling is that with new knowledge/data, conditional probabilities can be updated for updated results from the model. The three main components of a BN are the structure of the network, data discretization, and data parametrization (Pitchforth and Mengersen, 2013).

Many studies, such as Hoyle and Maunder (2004) and Marcot et al. (2001), used BN to model population dynamics in protected species. BN is especially used in studies where data can be used in conjunction with reliable field observations and beliefs. BN is ideal for developing frameworks of models with complexities in the data availability and uncertainty in the causal process in models.

Two separate BNs were developed for the two tiers of the study. The first tier assesses the impact of oil spill using the current stock of polar cod in the assumed area. The second tier of the study assesses the predicted recruitment in the fish stock due to oil spill exposure and evaluates the impact on the apex predators. The adult polar cod mortality to oil spill scenarios was estimated using the results of the BN model of Fahd et al. (2019, 2020). The probability of acute impact to polar bears and whales, i.e., the direct risk from oil spill exposure, was estimated and modified for current scenarios based on expert opinions from Nevalainen et al. (2017) and Helle et al. (2020). Assumptions were used by the researchers to approximate for scenarios considered; with new information on animal behaviour, the probability tables can be updated in the BN model.

3. Case study

3.1. Geographical context of the study

A hypothetical spill is assumed near Svalbard. As shown in Fig. 1, polar cod is a keystone Arctic species of fish and serves as the primary energy source to many of the top predators in the region (Gallaway et al., 2017). Previous studies have investigated the impact of sea ice and recruitment in the polar cod stock (Huserbraten et al., 2019). The Arctic cod eggs and larvae in the Barents Sea region drift with the ocean currents to the spawning assemblages around the Svalbard Island as modeled by Huserbraten et al. (2019). A spill around the spawning assemblages can prove detrimental to the recruitment of polar cod stock. The hypothetical spill area is shown in Fig. 3. The line in Fig. 3 represents the spill along the coast, while '+' in the figure represents the spawning assemblages around Svalbard. The area of a hypothetical spill is selected around the spawning assemblages near Svalbard Island to model the worst-case scenario.

3.2. Hypothetical spill conditions

The spill area is selected as the coastline of Svalbard Island, as shown in Fig. 3. The length of the coastline along the spill was calculated to be about 780 km using QGIS software. The hypothetical spill conditions, such as spill volume of 42,000 m^3 of crude oil, in the current research were like those assumed by Helle et al. (2020). A uniform spread of 1 km along the coastline was assumed. Based on this, the spill area was calculated to be 780 km^2. It is also assumed that a uniform dissolution of PAH occurs for 50 m in the water column. The spill size was determined based on the experiments conducted by Nahrgang et al. (2009, 2010, 2016, 2019) wherein filtered seawater was passed through crude oil laced rock columns into the tanks holding polar cod. The crude oil spill simulation used in the experiments was 3, 6, and 12 g crude oil kg^{-1} gravel corresponding to low, medium, and high treatments. The corresponding total PAH concentrations calculated for each treatment were 15 μg/L, 18 μg/L, and 40 μg/L PAH concentration in water, respectively. Establishing a context in terms of the field oil spill for the considered exposure concentrations in this paper, the spill conditions leading to such a PAH concentration in the ocean are 15,000 t, 18,000 t, and 40,000 t for low, medium, and high PAH concentrations. Assuming 3.9% weight of PAH in crude oil (Huesemann et al., 2002) and considering a hypothetical spill area (780 km^2) and 50 m dissolution in the water column, the spill in tonnes was calculated. This case study estimates the probabilities of acute impact or mortality to the polar bears and whales for spills in different seasons based on the probabilities reported by Helle et al. (2020).

Apart from the spill size (spill volume and PAH concentration), the initial spill scenarios considered in the study relate to sea ice and season. These factors also play an essential role in the life cycles of marine species such as polar cod, seals, polar bears, and whales.

The sea ice scenarios considered were as follows:

- Spill over thick ice
- Spill under thick ice
- Spill over thin ice

3.3. Developing the Bayesian network (BN) model

3.3.1. The model

The BN is developed for the spill scenarios based on Figs. 1 and 2 for the current stock of fish (Tier 1) and shown in Fig. 4A. The Bayesian Network for recruitment fish stock (Tier 2) is presented in Fig. 4B.

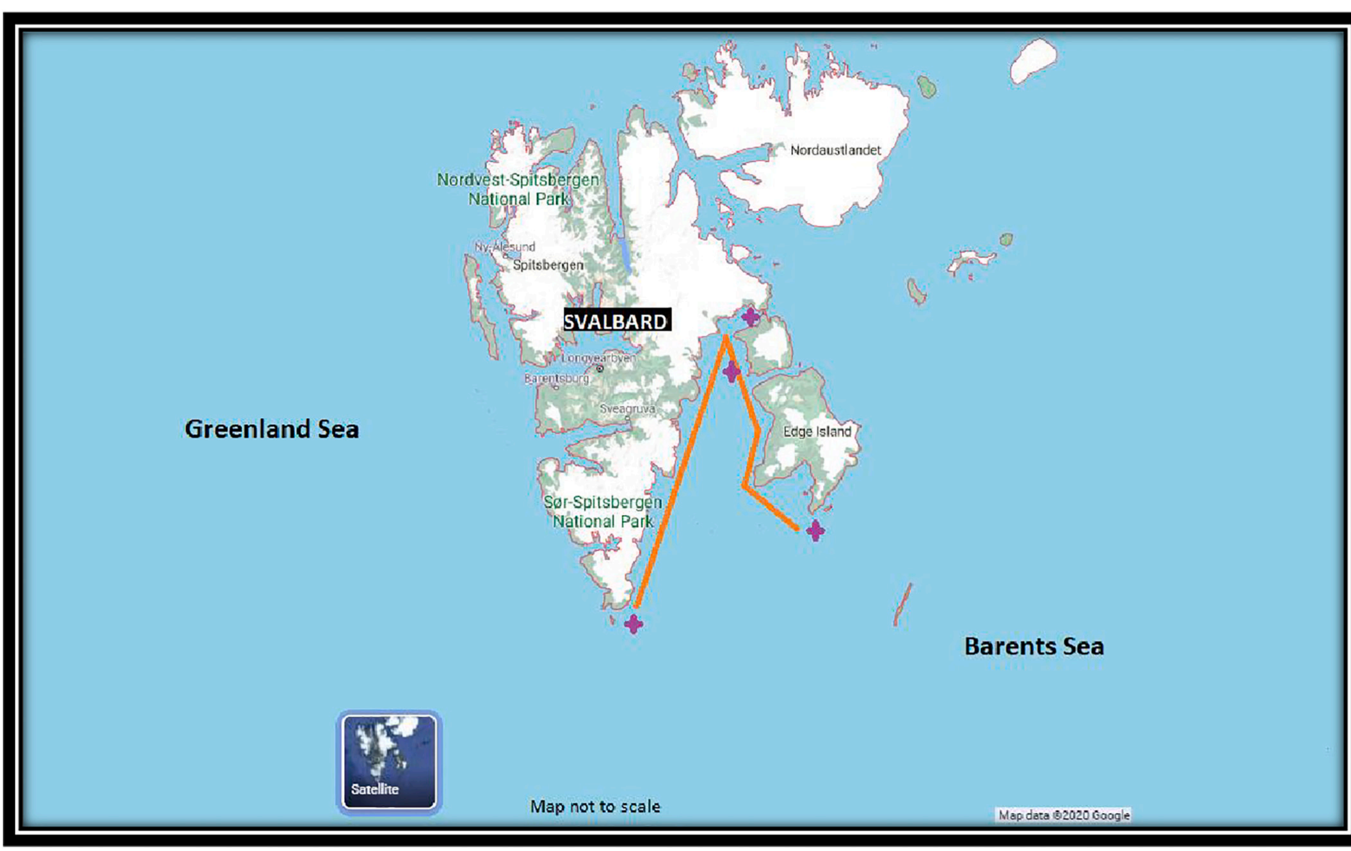


Fig. 3. Hypothetical spill area assumed for the study (source: Google Map). The orange color line represents the extent of the hypothetical spill spread. Purple color '+' sign represents the polar cod spawning areas around Svalbard Is. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

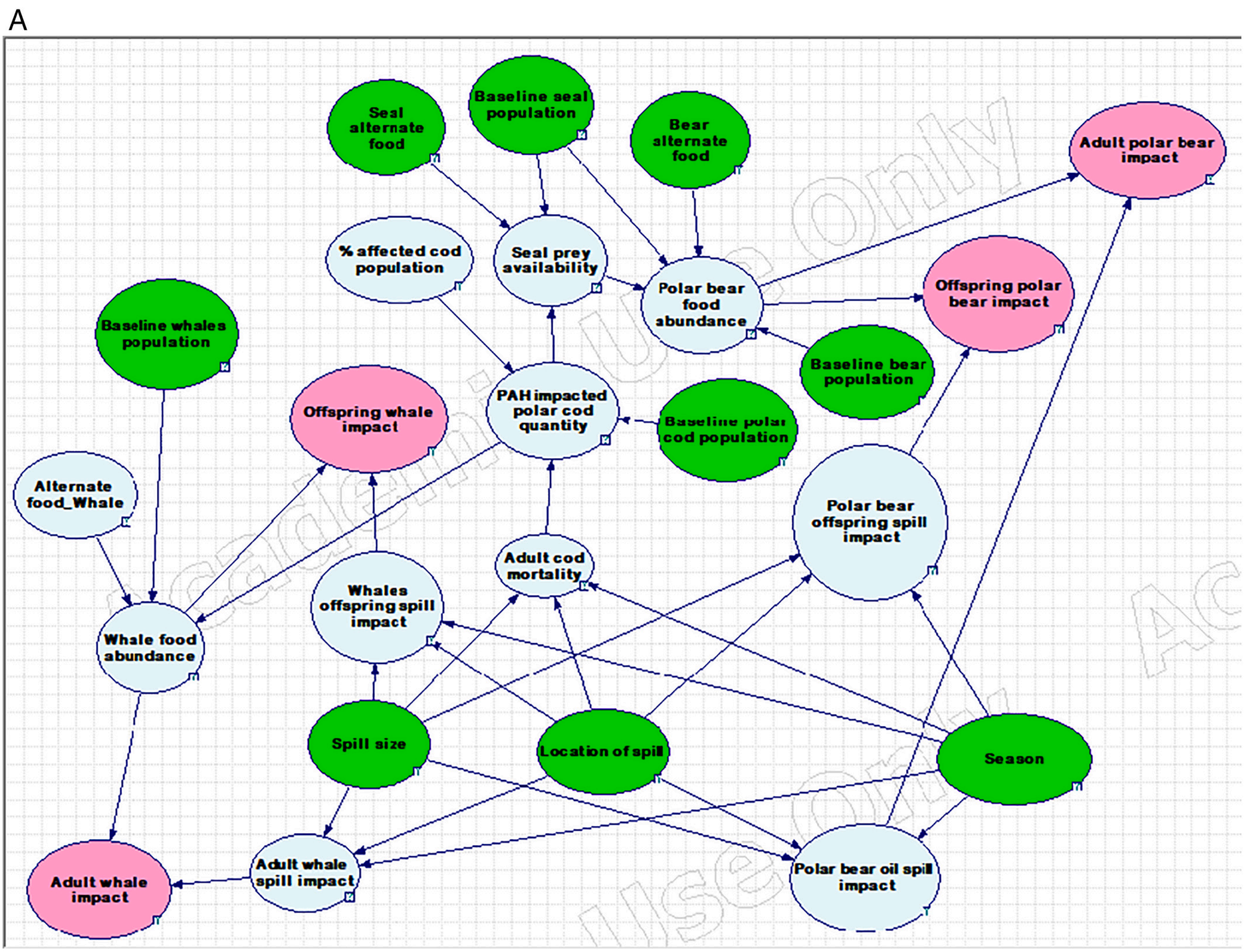


Fig. 4. A: BN for the apex marine mammals oil spill impact using current fish stock
B: BN for the apex marine mammals oil spill impact using recruitment fish stock.
Note:The teal colored nodes are the parent nodes or nodes representing initial spill conditions, environmental conditions and animal behavioural conditions. Blue colored nodes are intermediate nodes and pink colored nodes present the outcome of the model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3.2. Data discretization and parametrization for the model

Data for the BN risk model for the apex marine species is based on expert opinion, available literature studies, and some assumptions.

The nodes in the network shown in Fig. 4A and B could have two or more states. The discretization of the data refers to converting the continuous data sorted into different intervals or ordinal groups defining the states of a node in the network. The states of the BN nodes are based on information on the lifecycle, habitat, and feeding behaviors of the species considered. Parameterisation refers to adding values to each state of the nodes in the network. The animal lifecycle, behavioural, and fecundity data is discussed below. Discretization and parametrization for each node in the network are accomplished based on these data. The CPTs for each of the nodes are detailed in the Supplementary data document.

3.3.2.1. Polar cod. Polar cod is a fish associated with cold sub-zero Arctic waters. Arctic cod is a small fish with lengths up to 300 mm and in some cases, up to 460 mm have been recorded. Arctic cod is the most abundant and circumpolar distributed fish in the region. The polar cod plays a major role in the energy transfer in the Arctic food web by transferring the energy from the planktons to the apex marine mammals (Steiner et al., 2019; Parker-Stetter et al., 2011). The Arctic cod act as a high-energy prey, due to their high lipid content, for the upper trophic levels in the Arctic food web. The polar cod is a major food source of marine mammals such as the ringed seals, narwhals and beluga whales (Hop and Gjosaeter, 2013). The standing biomass of the Arctic cod in the Barents Sea varies between 0.5 and 1.5 million tonnes (Hop and Gjosaeter, 2013). From 1986 to 2016, the yearly variations in the polar cod stock in the Barents Sea region is provided by MOSJ (2019). The Arctic cod has a life span of 7 years, with maturity at about 3 years. The Arctic cod spawns only once during its lifetime (FAO, 2015). While there are fish stocks in the Barents Sea area, the Svalbard region is identified as one of the spawning assemblages for the Arctic cod. The spawning usually occurs in January and February, with an incubation period varying between 30 and 60 days (FAO, 2015). The relationship of the Arctic cod with sea ice is significant. Polar cod mainly feeds on the amphipods. Ice algal bloom causes an increase in amphipods, which feed on them. Although the Arctic cod are present in the ice-covered areas of the ocean, only the larval and juvenile stages of the fish are directly associated with the ice for food and protection.

The node 'Baseline Arctic cod' has an interval of 0.3 million tonnes of

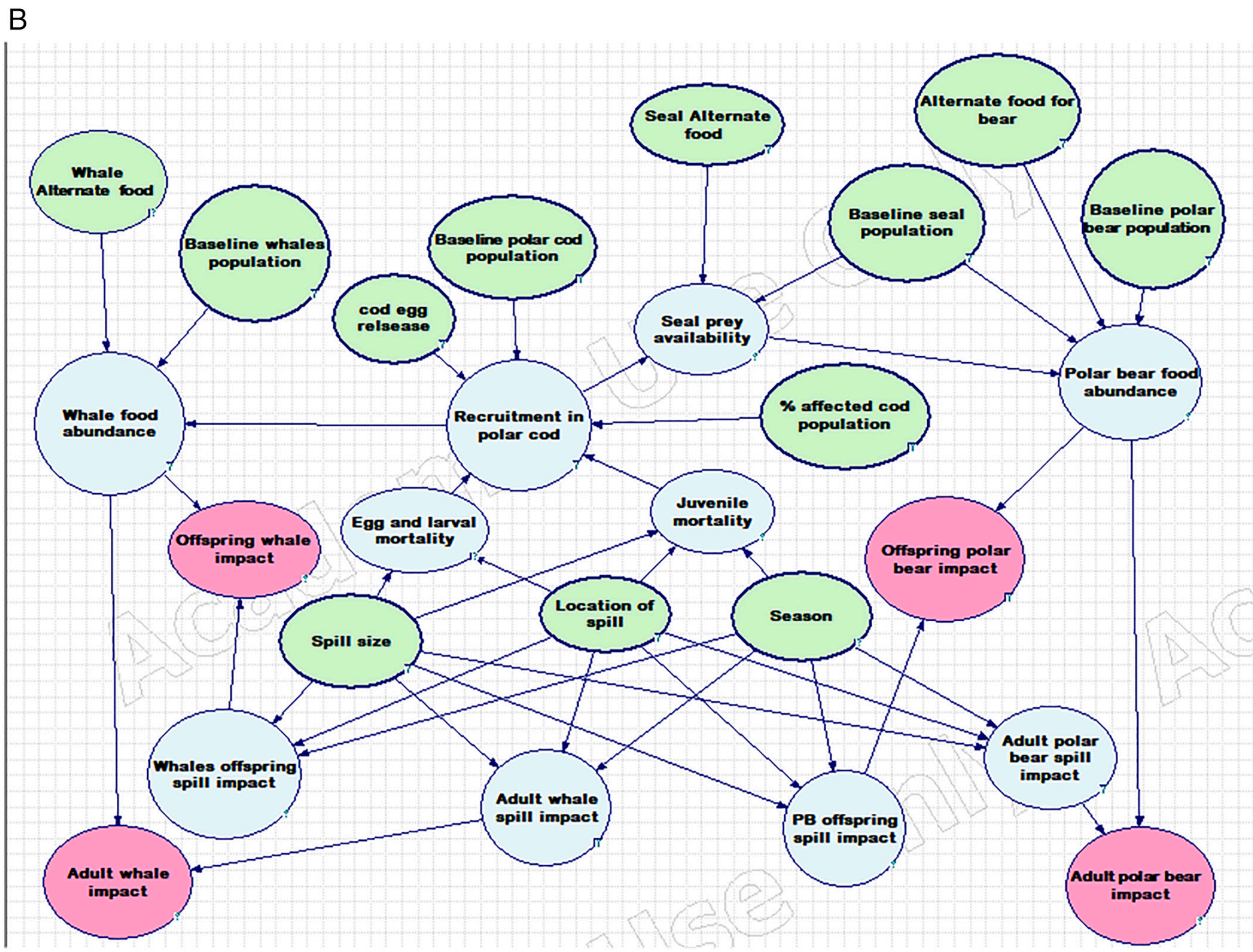


Fig. 4. (*continued*).

fish stock between its states, which vary from 0.5 to 1.5 million tonnes. The relative frequency of occurrence, i.e., probability, for each of the states of the node 'Baseline Arctic cod' is calculated based on MOSJ (2019). The first tier of apex mammals risk assessment is accomplished using the oil spill induced mortality in the current stock of Arctic cod, as shown in node 'Adult cod mortality'. The prior probabilities for the node are influenced by the season, size, and location of the spill. These probabilities are obtained from the results of Arctic cod toxicity modeling by Fahd et al. (2020). The second tier of apex marine mammals' assessment combines the probabilities of 'Egg and larval mortality' and 'Juvenile cod mortality' to determine the recruitment in the Arctic cod population and subsequent risk to apex mammals. The 'Egg and larval mortality' and 'Juvenile cod mortality' nodes are assigned the following states: baseline, low, medium, and high mortalities.

The baseline mean of instantaneous mortality rates in eggs and larval stages of northeast Arctic cod (*Gadus morhua*) were estimated to 0.17 d^{-1}, with a 95% confidence interval between 0.15 and 0.19 d^{-1} (Langangen et al., 2014). An instantaneous mortality rate of 0.19 d^{-1} was used for Arctic cod (*Boreogadus saida*) in this study. Nahrgang et al. (2016) conducted experiments on the eggs and larvae hatching and survival for 3 g/kg gravel (low spill concentration) was 39% and for 6 g/kg gravel (Medium spill concentration) was 24%. The experiment by Nahrgang et al. (2016) did not investigate the effects of what could be considered as high spill concentration, which is 12 g/kg gravel crude oil. An assumption of 10% survival for 12 g/kg gravel of crude oil was made for this study. Based on the experimental data (Nahrgang et al., 2016), instantaneous mortality rates in Arctic cod eggs and larvae for low, medium, and high spill concentration were established as 0.204, 0.217, and 0.230 d^{-1}. The baseline mortality rate for juvenile cod is reported as 0.009 d^{-1} (Gallaway et al., 2017). Based on the experimental data from Nahrgang et al. (2016), the mortality rates for juvenile Arctic cod are estimated to be 0.015, 0.03, and 0.04 d^{-1} for low, med, and high states of the node 'Juvenile mortality'.

3.3.2.2. Seals. Six species of seals live in the Arctic, namely, ringed, bearded, spotted, hooded, harp, and ribbon seals. As denoted by the node 'Baseline seal quantity', the seal population considered in this study varied between 0.5 million, 0.75 million, and 0.9 million for low, medium, and high states of the node (Laidre et al., 2015). The seal population was estimated based on the population studies from the Barents Sea. In the absence of such data, the populations of seal species in the Greenland Sea were used (Laidre et al., 2015). The birthing season for the seals is in spring, ranging from February to April (NSIDC, 2020). Some seal species depend entirely on the sea ice for survival. Many seals birth their offspring on ice and nurse them on ice around the breathing holes; the seals forage for food along the ice edge and under the ice for fish such as polar cod and shrimp (NSIDC, 2020). Therefore, changing ice conditions, especially in spring could impact the presence of the seals in the region and subsequently also impact the food availability of polar bears in the region. The conditional probabilities of 'seal prey availability' and 'polar bear food abundance' is detailed in the Supplementary data document. Understanding the role of the predator in the ecosystem depends on identifying and quantifying its diet (Ryg and Øritsland, 1991). The annual energy budget of the ringed seals was calculated by Ryg and Øritsland (1991) and it was observed that the food consumption rates varied seasonally. The energy requirements calculated by Ryg and Øritsland (1991) considered the maintenance, growth, and feeding of the offspring. The annual gross energy consumption of the females exceeds the energy consumption of the male seals in the experiments. It was also observed that average energy consumption was three times the energy required to basal metabolic rate (BMR). The average consumption per individual in the seal population was calculated to be 4.6×10^9 joules gross energy per year (Ryg and Øritsland, 1991). Assuming the 1 kg of fish to produce 810 kJoules gross energy (Dyck and Kebreab, 2009), the quantity of fish consumption for the seal population is estimated. This data is further used to obtain the probabilities of the node 'Seal prey availability'.

3.3.2.3. Polar bear. Polar bear is an apex predator in the Arctic marine food web. Polar bears birth their cubs in winter, mostly in December–January. Polar bears primarily prey on ringed seals and bearded seals resting on the sea ice. Polar bears turn hyperphagic in spring when there is plenty of young seal pups (Dyck and Kebreab, 2009). In the regions where little to no sea ice is present in the summer, polar bears prefer to spend the time onshore foraging for land-based food sources. These include berries and fruits, some nesting birds and eggs, small land animals, and river fishes in some cases (Dyck and Kebreab, 2009). The energy requirements and budget of the polar bear with different body masses were studied using three diets: berries, Arctic charr, and seal. The energy budget calculations assumed that the polar bears were restricted to land. The gross energy content from ringed seal raw blubber was calculated to be 34,430 kJ per 1 kg. The diet (kg) required to cover the daily energy loss was calculated for polar bears with masses varying from 100 kg to 650 kg. The data was used to predict the probabilities in the nodes 'Polar bear food abundance'. A 500 kg polar bear would need to consume 1 kg of seal blubber or 4 kg of fish to maintain its body mass (Dyck and Kebreab, 2009). Hilderband et al. (1999) reported that captive brown bears consumed an average of 10.8 kg of fish per day and estimated that a polar bear of up to 650 kg would have energy surplus and gain mass in such a scenario. The polar bear population in the Barents Sea is estimated to be about 2644, with a 95% confidence interval between 1899 and 3592 (Laidre et al., 2015). The states of the node 'Baseline polar bear quantity' are defined based on the population data from the Barents Sea.

3.3.2.4. Whales. Three whale species, *Delphinapterus leucas* (Beluga whale), *Monodon monoceros* (Narwhal), and *Balaena mysticetus* (bowhead whale), are endemic to the Arctic region all year. Beluga whales are the most abundant whales in the Arctic waters and only they were considered in this study (Kastelein et al., 1994). The lifespans of the belugas range from 15 to 30 years; they attain sexual maturity at the age of 5–7. Belugas give birth every three years on average. The habitat of beluga whales varies seasonally. As sea ice breaks up, beluga whales swim along the ice edges and also penetrate the leads. When the sea ice becomes sparse or disappears during summer, belugas are found along the coastline and in shallow waters and river estuaries. In autumn months, they move to locations of feed in deep waters. In winter, they prefer the sea ice areas. From mid-August, the belugas move back to the deep waters. The belugas were observed to be in polynyas and loose pack ice. The aerial survey also observed that the belugas preferred ice cover of 4/10 to 8/10 concentration. Barber et al. (2001) observed that the belugas avoided ice cover of 10/10 concentration. Belugas have the lowest body fat content in summer. In late summer, intensive feeding increases their blubber content. Arctic cod is the main diet of belugas along with other fishes such as capelin and saffron cod. The amount of food consumption depends on the sex, sexual activeness and age group of the belugas. Kastelein et al. (1994) found belugas of about 200 kg ate around 4.5% of their body weight. While the belugas around 1400 kg ate 1.2% of the body weight. Calving time for belugas could occur in late spring or early summer. The peak of the calving season is observed to be mid-June to early July. The information on the relationship between the whale species and sea ice was used to develop the CPTs for the nodes 'Adult whale spill impact' and 'Whale offspring spill impact' nodes.

4. Results and discussion

4.1. Oil spill initial conditions

Sea ice is a ubiquitous geophysical feature in the Arctic region with a crucial role in the foraging, resting, and breeding behaviors of marine mammals. The spill scenarios were selected to reflect several possibilities of spill in ice infested waters, such as spill over and under thick sea ice and spill over thin ice. The oil spill release quantities considered in this study are 15,000, 18,000, and 40,000 t of crude oil in the polar cod spawning areas around Svalbard Island. The results from all scenarios are presented in the Supplementary data document. The best- and worst-case scenarios of each of the species of food web are discussed in this section.

4.2. Impact on the current polar cod stock

It is reasonable to assume that a percentage of the fish stock in the region was exposed to the spill instead of all the fish stock in the region. The node 'fish stock affected' in the model has probabilities assigned showing 99% of the probability the spill causes less than 20% of the stock to be affected. The mortality in exposed adult cod was lowest when the spill occurred over thick ice and for the low spill volume and was highest when the spill occurred under the ice. However, for the given best and worst scenarios for polar cod, the change in its population and subsequently the increased risk was not drastic.

4.3. Recruitment stock impact

The significant factors affecting the recruitment are average fecundity in each female cod, mortality in egg and larval stages, and juvenile cod mortality. The spill scenario causing the least mortality in juveniles and eggs/larvae occurs for the spill over thick ice, and the scenario with the highest risk is when the spill is under the ice. A variation in the average fecundity from low (9000 eggs per female) to high (25,000 eggs per female) causes a significant increase in the recruitment stock. Low eggs per female resulted in lower fish stock (in million kg) than the baseline stock, while medium fecundity resulted in increased fish stock compared to the baseline fish stock. An average of 25,000 eggs per female increases the stock from 500 million kg to 2100 million kg. Such drastic changes in the fish have previously been reported in the region of study. Refer to the Supplementary data document for the baseline stock variation in the last two decades.

4.4. Risk to apex predators

The species in the higher trophic level are assessed for direct risk and impact on their food abundance. The conditional probabilities for the direct risk, given spill size, location, and season, were based on expert opinions and assumptions. The risk from only the oil spill is termed as the baseline risk. This case study also aims to investigate the additional risk due to changes in the prey availability in the food web.

4.4.1. Direct risk/baseline from oil spill

4.4.1.1. Impact on whales. The baseline risk from the oil spill for whales is presented in Table 1. The worst-case scenario for both the adult whale species and their offspring is a high-volume spill under thick ice. The

Table 1
Baseline risk from oil spill for whales.

Spill size	Spill location	Risk to adult whales	Risk to whale offspring	Risk to polar bear	Risk to polar bear offspring
High	Under ice	Adult whale spill im... Impact_10 18% Impact_20 45% Impact_40 25% Impact_60 9% Impact_80 3% Impact_100 0%	Whales offspring s... Impact_10 50% Impact_20 35% Impact_40 9% Impact_60 5% Impact_80 2% Impact_100 0%	Adult polar bear spil... Impact_10 45% Impact_20 50% Impact_40 4% Impact_60 1% Impact_80 1% Impact_100 0%	PB offspring spill im... Impact_10 87% Impact_20 10% Impact_40 3% Impact_60 0% Impact_80 0% Impact_100 0%
Low	Under ice	Adult whale spill im... Impact_10 48% Impact_20 28% Impact_40 12% Impact_60 10% Impact_80 2% Impact_100 0%	Whales offspring s... Impact_10 77% Impact_20 17% Impact_40 5% Impact_60 2% Impact_80 0% Impact_100 0%	Adult polar bear spil... Impact_10 84% Impact_20 14% Impact_40 2% Impact_60 0% Impact_80 0% Impact_100 0%	PB offspring spill im... Impact_10 98% Impact_20 2% Impact_40 0% Impact_60 0% Impact_80 0% Impact_100 0%
High	Over thick ice	Adult whale spill im... Impact_10 49% Impact_20 43% Impact_40 6% Impact_60 2% Impact_80 0% Impact_100 0%	Whales offspring s... Impact_10 75% Impact_20 14% Impact_40 7% Impact_60 3% Impact_80 2% Impact_100 0%	Adult polar bear spil... Impact_10 82% Impact_20 17% Impact_40 1% Impact_60 0% Impact_80 0% Impact_100 0%	PB offspring spill im... Impact_10 41% Impact_20 19% Impact_40 26% Impact_60 12% Impact_80 2% Impact_100 0%
Low	Over thick ice	Adult whale spill im... Impact_10 63% Impact_20 27% Impact_40 10% Impact_60 0% Impact_80 0% Impact_100 0%	Whales offspring s... Impact_10 91% Impact_20 7% Impact_40 2% Impact_60 0% Impact_80 0% Impact_100 0%	Adult polar bear spil... Impact_10 91% Impact_20 9% Impact_40 0% Impact_60 0% Impact_80 0% Impact_100 0%	PB offspring spill im... Impact_10 61% Impact_20 36% Impact_40 2% Impact_60 0% Impact_80 0% Impact_100 0%
High	Over thin ice	Adult whale spill im... Impact_10 29% Impact_20 38% Impact_40 22% Impact_60 9% Impact_80 2% Impact_100 0%	Whales offspring s... Impact_10 62% Impact_20 23% Impact_40 8% Impact_60 5% Impact_80 2% Impact_100 0%	Adult polar bear spil... Impact_10 26% Impact_20 54% Impact_40 16% Impact_60 2% Impact_80 2% Impact_100 1%	PB offspring spill im... Impact_10 60% Impact_20 26% Impact_40 12% Impact_60 2% Impact_80 0% Impact_100 0%
Low	Over thin ice	Adult whale spill im... Impact_10 60% Impact_20 37% Impact_40 3% Impact_60 0% Impact_80 0% Impact_100 0%	Whales offspring s... Impact_10 76% Impact_20 12% Impact_40 12% Impact_60 0% Impact_80 0% Impact_100 0%	Adult polar bear spil... Impact_10 84% Impact_20 15% Impact_40 2% Impact_60 0% Impact_80 0% Impact_100 0%	PB offspring spill im... Impact_10 81% Impact_20 16% Impact_40 2% Impact_60 1% Impact_80 0% Impact_100 0%

next worse case is a spill over thin ice. The scenario of spill over thick ice showed the least baseline risk in the whale species. Comparing the baseline risks in the adults and offspring shows that the predicted risk for adult whale species for all the spill scenarios was higher. Beluga whales are known to inhabit the areas of thin and thick ice as well. The risk from spill over thick ice, although less compared to other scenarios, could be due to the frequent visits to the breathing holes by whale species. As the whale forage for food under the ice, the spill under thick ice causes the highest exposure and, subsequently, higher risk to both the adults and offspring.

4.4.1.2. Impact on polar bear. Direct risk assessed for adult polar bears indicated the worst-case scenario is a high volume of spill over thin ice, followed by a spill under thick ice, and lastly, the scenario of a spill over thick ice. The scenarios posing a higher direct risk to polar bear offspring are spill over thick ice, followed by a spill over thin ice, and finally a spill under thick ice. It is estimated that adult polar bears would avoid the spill over the thick ice; however, they can be exposed to a spill under the ice due to their hunting habitat around the ice edge. It is also observed that the polar bears prefer thick ice as habitation and hunt the seals on thin ice floes. Based on such observations, the risk from a spill on thin ice is predicted to be higher than a spill under the ice. The polar bear cubs are housed in the ice caves on thick sea ice. Polar bear cubs' behaviour in their habitat could potentially expose them to a spill over thick sea ice. Since the cubs do not hunt seals along the ice edge, the scenario of spill under the ice is predicted to be of least risk.

4.4.2. Indirect risk from cascading effects of oil spill

The indirect risk from the synergistic effects of decreasing food availability with the risk from oil spill exposure follows similar trends as the direct risk discussed previously, albeit with higher risk probability.

Table 2
Additional risk from cascading effects of the oil spill in food web.

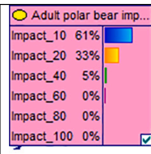
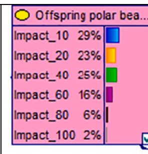
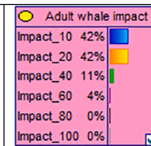
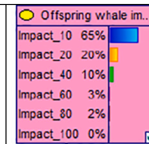
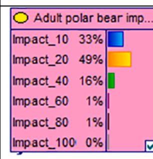
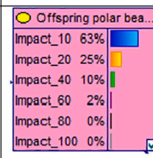
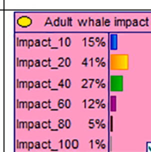
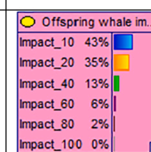
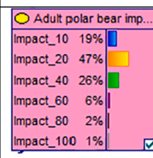
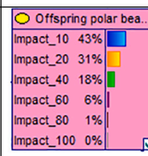
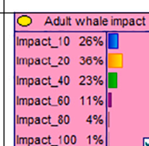
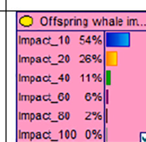
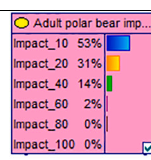
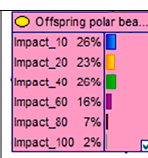
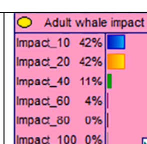
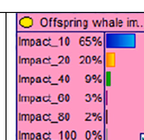
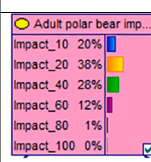
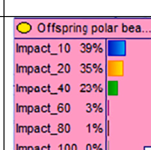
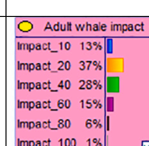
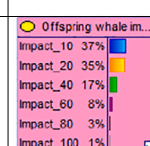
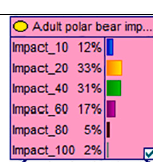
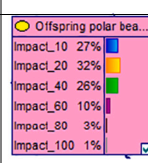
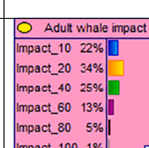
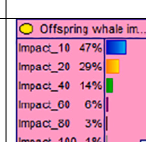
Spill location	Spill size	Risk to adult polar bear	Risk to polar bear offspring	Risk to adult whales	Risk to whale offspring
Tier 1					
Over thick ice	High				
Under ice	High				
Over thin ice	High				
Tier 2					
Over thick ice	High				
Under ice	High				
Over thin ice	High				

Table 2 presents the risk for the high-volume crude oil spill with varying spill locations on the sea ice. The CPTs for these outcome nodes (adult polar bear impact, polar bear offspring impact, adult whale impact, and whale offspring impact) are presented in the Supplementary data document.

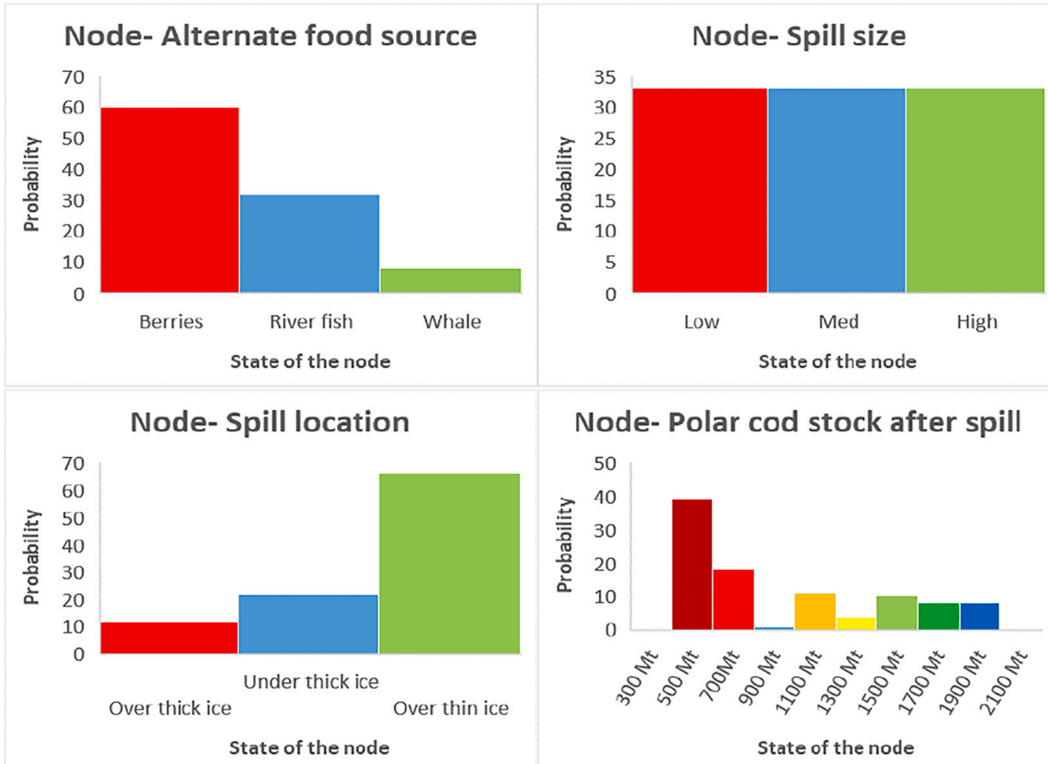
Using the Tier 1 of the BN toxicity model, the risk to adult and offspring polar bear and whales was estimated to be higher than the risk from the baseline oil spill scenario. In Tier 2 of the toxicity model, the risk to adult and offspring apex marine species was even higher than the risk estimated from the Tier 1 model (Table 2).

The probability of the polar bear food availability to be lower than or up to minimum maintenance was estimated to be 54% for current stock. The same probability was 75% for recruitment stock. Subsequent mortality risks to polar bear cubs were predicted to be higher in the Tier 2 recruitment model. However, the risk for the adult polar bear showed a marginal increase in risk for the recruitment model.

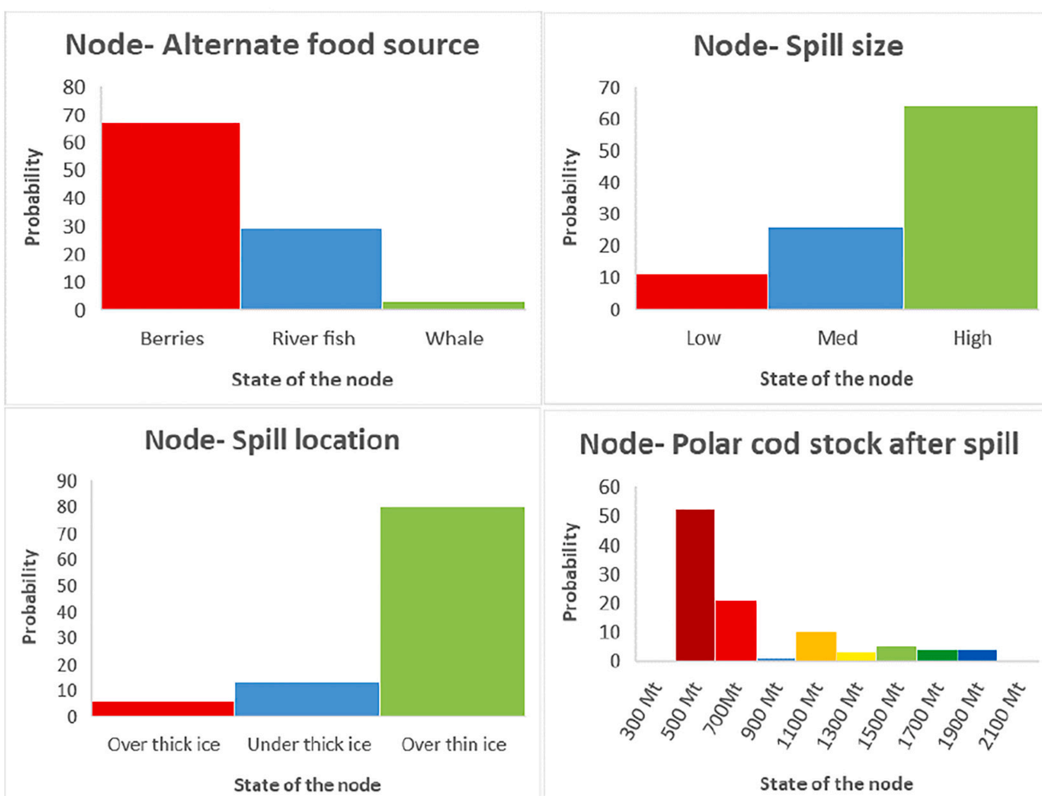
4.4.3. Sensitivity analysis

The sensitivity analysis is performed using the software developed by Bayesfusion (Bayesfusion, n.d.). The factors affecting the probability of risk to apex predators are the presence of sea ice, season, quantity of Arctic cod, alternate food availability, and location of the spill with respect to sea ice. The sensitivity of the outcome nodes ‘adult whale impact’ and ‘whale offspring impact’ shows that the nodes that have maximum effect on the outcome are ‘whale food abundance’, ‘spill size’, and ‘location of spill’. To further study the relationship between these sensitive factors and risk, the BN model was set with 50% risk to target species as evidence. The resulting changes in probabilities, i.e., posterior probability of the sensitive nodes was back calculated by the BN model as shown in Figs. 5 and 6.

Sensitivity analysis of the risk to the polar bears and their offspring shows that the kind of prey availability and quantity of food availability plays a significant role in determining risk. The location of the spill is



(A)



(B)

Fig. 5. (A) The prior probabilities of sensitive nodes for polar bear; (B) posterior probabilities of sensitive nodes when the 50% of polar bear population at risk is set as evidence.

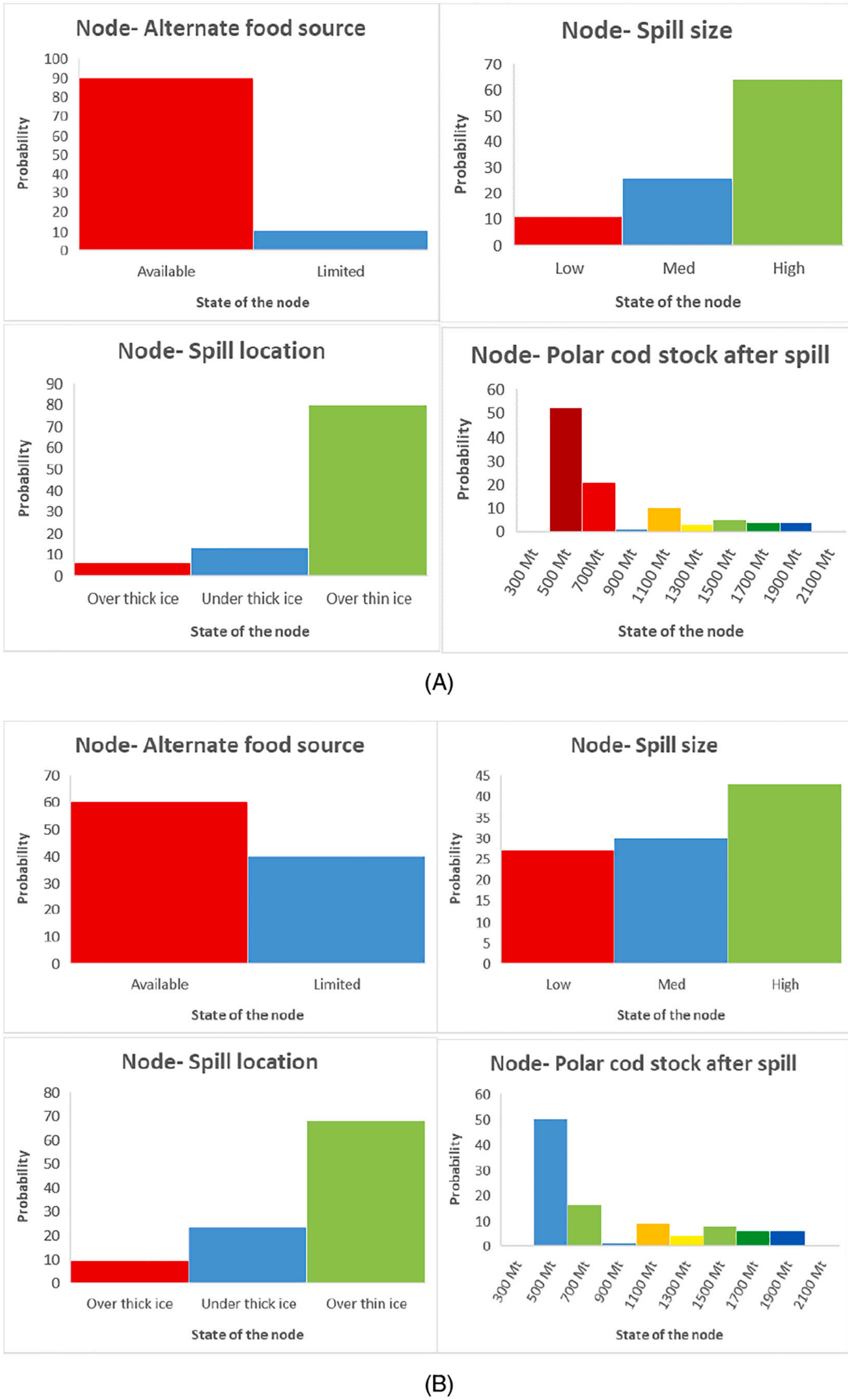


Fig. 6. (A) The prior probabilities of sensitive nodes for whales; (B) posterior probabilities of sensitive nodes when the 50% of whale population at risk is set as evidence.

also a factor in determining the total risk to polar bears. Comparing the risk sensitivity of the apex predators shows that the food availability node has a greater influence on the risk of polar bears than whales. This observation further emphasizes the importance of seals availability to polar bear survival.

To observe the sensitivity of the fish stock's presence to the apex predators, the node 'stock after recruitment' was set to 300 million tonnes and 1900 million tonnes, and the results were compared. Lower fish stock elicited a higher risk of mortality to polar bears. The risk increased significantly for polar bear offspring, as presented in Table 3.

5. Conclusions

This study develops an approach to quantitatively assess the combined effects of oil spill impacts to apex marine species and its cascading effects on the food web. Such a comprehensive insight into the impacts in the region could facilitate the identification of significant lower trophic species, and enhanced conservation methods for apex marine predators. Arctic Council, an intergovernmental forum, addresses the common concerns and challenges and enhances cooperation in the eight Arctic-rim states. The strategy adopted by the Arctic Council is published as the 'Arctic Environmental Protection Strategy' (AEPS), a multilateral and non-binding agreement among the eight Arctic states. This model could contribute to the Arctic environmental protection and serve as a comprehensive marine risk model from an oil spill. In future, more factors such as Arctic peoples hunting behaviors and yearly fish catch quantities could also be included in the BN model to get a more realistic impact on the apex marine species populations. Such studies could help in creating measured and regulated anthropogenic activities in this sensitive region.

Notable findings from this study are:

1. A spill at an Arctic cod spawning assemblage could lead to recruitment collapse in fish stock and subsequent increased risk to polar bears and whale species.
2. The non-availability of food to apex predators or imbalance in the food web could lead to drastic changes in the survival of polar bears and whale species. Among the apex predators, the effect on polar bear could be more devastating than whale species.
3. The risk to survival for whale and polar bear offspring is lower than their adults when cascading effects in the food web are taken to account.

Limitations of the study:

The probabilities considered for the nodes did not take gender of the polar bears into account. The sex of polar bears determines different exposure probabilities based on hunting cub rearing activities. The probabilities used for various nodes were based on literature or expert

Table 3
Affect of varying fish stock on the risk to apex predators.

Fish stock (million tonnes)	Risk to adult polar bear	Risk to polar bear offspring	Risk to whales	Risk to whale offspring
300	Adult polar bear imp... Impact_10 25% Impact_20 36% Impact_40 28% Impact_60 9% Impact_80 2% Impact_100 1%	Offspring polar bea... Impact_10 31% Impact_20 35% Impact_40 26% Impact_60 6% Impact_80 2% Impact_100 0%	Adult whale impact Impact_10 29% Impact_20 37% Impact_40 20% Impact_60 9% Impact_80 3% Impact_100 1%	Offspring whale im... Impact_10 50% Impact_20 30% Impact_40 13% Impact_60 5% Impact_80 2% Impact_100 0%
700	Adult polar bear imp... Impact_10 41% Impact_20 35% Impact_40 19% Impact_60 4% Impact_80 1% Impact_100 0%	Offspring polar bea... Impact_10 43% Impact_20 32% Impact_40 19% Impact_60 5% Impact_80 1% Impact_100 0%	Adult whale impact Impact_10 39% Impact_20 38% Impact_40 15% Impact_60 6% Impact_80 2% Impact_100 0%	Offspring whale im... Impact_10 62% Impact_20 25% Impact_40 9% Impact_60 3% Impact_80 1% Impact_100 0%
1100	Adult polar bear imp... Impact_10 53% Impact_20 31% Impact_40 13% Impact_60 2% Impact_80 0% Impact_100 0%	Offspring polar bea... Impact_10 43% Impact_20 31% Impact_40 18% Impact_60 6% Impact_80 2% Impact_100 0%	Adult whale impact Impact_10 48% Impact_20 36% Impact_40 11% Impact_60 5% Impact_80 1% Impact_100 0%	Offspring whale im... Impact_10 73% Impact_20 17% Impact_40 7% Impact_60 2% Impact_80 1% Impact_100 0%
1500	Adult polar bear imp... Impact_10 69% Impact_20 25% Impact_40 6% Impact_60 1% Impact_80 0% Impact_100 0%	Offspring polar bea... Impact_10 51% Impact_20 29% Impact_40 14% Impact_60 5% Impact_80 1% Impact_100 0%	Adult whale impact Impact_10 50% Impact_20 35% Impact_40 10% Impact_60 4% Impact_80 1% Impact_100 0%	Offspring whale im... Impact_10 74% Impact_20 16% Impact_40 7% Impact_60 1% Impact_80 1% Impact_100 0%
1900	Adult polar bear imp... Impact_10 70% Impact_20 25% Impact_40 4% Impact_60 1% Impact_80 0% Impact_100 0%	Offspring polar bea... Impact_10 65% Impact_20 23% Impact_40 9% Impact_60 3% Impact_80 0% Impact_100 0%	Adult whale impact Impact_10 44% Impact_20 37% Impact_40 13% Impact_60 5% Impact_80 1% Impact_100 0%	Offspring whale im... Impact_10 68% Impact_20 20% Impact_40 8% Impact_60 2% Impact_80 1% Impact_100 0%

opinions, however, some assumptions were also made of the conditional probabilities in this study. The advantage of using a BN model is that with the availability of new information, these probabilities could be easily adjusted in the model to generate new risk probabilities in apex predators.

CRediT authorship contribution statement

Faisal Fahd: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing. **Ming Yang:** Formal analysis, Writing – review & editing, Supervision. **Faisal Khan:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Brian Veitch:** Methodology, Validation, Formal analysis, Project administration, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The financial support of the Lloyd's Register Foundation is acknowledged with gratitude. Lloyd's Register Foundation helps to protect life and property by supporting engineering-related education, public engagement, and the application of research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.112164.

References

Afenyo, M., Veitch, B., Khan, F., 2015. A sate-of-the-art review of fate and transport of oil spills in open and ice covered water. Ocean Eng. 119.
Afenyo, M., Khan, F., Veitch, B., Yang, M., 2017. Arctic shipping accident scenario analysis using Bayesian Network approach. Ocean Eng. 133, 224–230.
Amstrup, S.C., Marcot, B.G., Douglas, D.C., 2008. A Bayesian Network modeling approach to forecasting the 21st century worldwide status of polar bears. In: De Weaver, E.T., Bitz, C.M., Tremblay, L.B. (Eds.), Arctic Sea Ice Decline: Observations, Projections, Mechanisms, and Implications. Geophysical Monograph, 180. American Geophysical Union, Washington DC, pp. 213–268.
Barber, D.G., Saczuk, E., Richard, P., 2001. Examination of beluga-habitat relationships through the use of telemetry and a geographic information system. Arctic 54, 305–316.
Bayesfusion (n.d.) https://support.bayesfusion.com/docs/QGeNIe.pdf (Last accessed: November, 25th 2020).
Bluhm, B.A., Gradinger, R., 2008. Regional variability in food availability for Arctic marine mammals. Ecol. Appl. 18 (2), 77–96.
Carroll, J., Vikebo, F., Howell, D., Broch, O.J., Nepstad, R., Augustine, S., Skeie, G.M., Bast, R., Juselius, J., 2018. Assessing impacts of simulated oil spills on the Northeast Arctic cod fishery. Mar. Pollut. Bull. 126, 63–73.
Chapman, P.M., Riddle, M.J., 2003. Missing and needed: polar marine ecotoxicology. Mar. Pollut. Bull. 46 (8), 927–928.
Chevalier, M., Comte, L., Laffaille, P., Grenouillet, G., 2018. Interactions between species attributes explain population dynamics in stream fishes under changing climate. Ecosphere 9, 1.
Cusa, M.L.J., 2016. The Effect of Seasonality on Polar Cod (Boreogadus saida) Dietary Habits and Temporal Feeding Strategies in Svalbard Waters. Thesis. Faculty of Biosciences, Fisheries and Economics, Department of Arctic and Marine Biology, The Arctic University of Norway.
Dickins, D., et al., 2011. Behavior of oil spills in ice and implications for Arctic spill response. In: OTC Arctic Technology Conference. Offshore Technology Conference.
Dyck, M.G., Kebreab, E., 2009. Estimating the energetic contribution of polar bear (Ursus Maritimus) summer diets to the total energy budget. J. Mammal. 90 (3), 585–593.
Fahd, F., Khan, F., Veitch, B., Yang, M., 2017. Aquatic ecotoxicological models and their applicability in Arctic regions. Mar. Pollut. Bull. 120 (1-2).
Fahd, F., Khan, F., Veitch, B., 2019. Arctic marine fish 'biotransformation toxicity' model for ecological risk assessment. Mar. Pollut. Bull. 142, 408–418.
Fahd, F., Veitch, B., Khan, F., 2020. Risk assessment of Arctic aquatic species using ecotoxicological biomarkers and Bayesian network. Mar. Pollut. Bull. 156, 111212.
FAO, Food and Agriculture Organization of the United Nations, 2015. http://www.fao.org/fishery/species/2233/en.
Gallaway, B.J., Konkel, W.J., Norcross, B.L., 2017. Some thoughts on estimating change to Arctic cod populations from hypothetical oil spills in the eastern Alaska Beaufort Sea. Arctic Science 3, 716–729.
Gardiner, W.W., Word, J.Q., Word, J.D., Perkins, R.A., McFarlin, K.M., Hester, B.W., Word, L.S., Ray, C.M., 2013. The acute toxicity of chemically and physically dispersed crude oil to key Arctic species under Arctic conditions during the open water season. Environ. Toxicol. Chem. 32 (10), 2284–2300.
Helle, I., Makinen, J., Nevalainen, M., Afenyo, M., Vanhatalo, J., 2020. Impacts of oil spills on Arctic marine ecosystems: a quantitative and probabilistic risk assessment perspective. Environ. Sci. Technol. 54 (4), 2112–2121.
Hilderband, G.V., Hanley, T.A., Robbins, C.T., Schwartz, C.C., 1999. Role of brown bears (Ursus arctos) in the flow of marine nitrogen into a terrestrial ecosystem. Oecologia 121, 546–550.
Hoop, L.D., Schipper, A.M., Leuven, R.S.E.W., Huijbregts, M.A.J., Olsen, G.H., Smit, M.G.D., Hendriks, A.J., 2011. Sensitivity of polar and temperate marine organisms to oil components. Environ. Sci. Technol. 45, 9017–9023.
Hop, H., Gjosaeter, H., 2013. Polar cod (Boreagadus saida) and capelin (Mallatus villosus) as key species in marine food webs of the Arctic and the Barents Sea. Mar. Biol. Res. 9, 878–894.
Hoyle, S.D., Maunder, M.N., 2004. A Bayesian integrated population dynamics model to analyze data for protected species. Anim. Biodivers. Conserv. 27, 1.
Huesemann, M.H., Hausmann, T.S., Fortman, T.J., 2002. Microbial factors rather than bioavailability limit the rate and extent of PAH biodegradation in aged crude oil contaminated model soils. Bioremediation Journal 6 (4), 321–336.
Huserbraten, M.B.O., Eriksen, E., Gjosaeter, H., Vikebo, F., 2019. Polar cod in jeopardy under the retreating Arctic sea ice. Communication Biology 2, 407.
Kastelein, R.A., Ford, J., Berghout, E., Wiepkema, P.R., Van Boxsel, M., 1994. Food consumption, growth and reproduction of Belugas (Delphinapterus leucas) in human care. Aquat. Mamm. 20 (2), 87–97.
Laidre, K.L., Stern, H., Kovacs, K.M., Lowry, L., Moore, S.E., Regehr, E.V., Ferguson, S.H., Wiig, O., Boveng, P., Angliss, R.P., Born, E.W., Litovka, D., Quakenbush, L., Lydersen, C., Vongraven, D., Ugarte, F., 2015. Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. Conserv. Biol. 29 (3), 724–737.
Langangen, O., Stige, L.C., Yaragina, N.A., Vikebo, F.B., Bogstad, B., Gusdal, Y., 2014. Egg mortality of northeast Arctic cod (Gadus morhua) and haddock (Melanogrannus aeglefinus). ICES J. Mar. Sci. 71 (5), 1129–1136.
Lee, K., Boufadel, M., Chen, B., Foght, J., Hodson, P., Swanson, S., Venosa, A., 2015. Expert Panel Report on the Behavior and Ecological Impacts of Crude Oil Released Into Adqueous Environments. Royal Society of Canada, Ottawa, ON (ISBN: 978-1-928140-0203).
Marcot, B.G., Holthausen, R.S., Raphael, M.G., Rowland, M.M., Wisdom, M.J., 2001. Using Bayesian belief networks to evaluate fish and wildlife population viability under land management alternatives from an environmental impact statement. For. Ecol. Manag. 153, 29–42.
MOSJ, 2019. Environmental Monitoring of Svalbard and Jan Mayen. http://www.mosj.no/en/fauna/marine/polar-cod.html.
Nahrgang, J., Camus, L., Gonzalez, P., Christiansen, J.S., Hop, H., 2009. PAH biomarker responses in polar cod (Boreogadus saida) exposed to benzo(a)pyrene. Aquat. Toxicol. 94 (4), 309–319.
Nahrgang, J., Camus, L., Broms, F., Christiansen, J.S., Hop, H., 2010. Seasonal baseline levels of physiological and biochemical parameters in polar cod (Boreogadus saida): implications for environmental monitoring. Mar. Pollut. Bull. 60, 1336–1345.
Nahrgang, J., Dubourg, P., Frantzen, M., Storch, D., Dahlke, F., Meador, J.P., 2016. Early life stages of an arctic keystone species (Boreogadus saida) show high sensitivity to a water-soluble fraction of crude oil. Environ. Pollut. 218, 605–614.
Nahrgang, J., Bender, M.L., Meier, S., Nechev, J., Berge, J., Frantzen, M., 2019. Growth and metabolism of adult polar cod (Boreogadus saida) in response to dietary crude oil. Ecotoxicol. Environ. Saf. 180, 53–62.
Nevalainen, M., Helle, I., Vanhatalo, J., 2017. Preparing for the unprecedented - towards quantitative oil risk assessment in the Arctic marine areas. Mar. Pollut. Bull. 114, 90–101.
NSIDC, 2020. National Snow Ice Data Centre. https://nsidc.org/cryosphere/seaice/environment/mammals_seals.html.
Parker-Stetter, S.L., Horne, J.K., Weingartner, T.J., 2011. Distribution of polar cod and age-0 fish in the U.S. Beaufort Sea. Polar Biol. 34, 1543–1557.
Pitchforth, J., Mengersen, K., 2013. A proposed validation framework for expert elicited Bayesian networks. Expert Syst. Appl. 40 (1), 162–167.
Ryg, M., Øritsland, N.A., 1991. Estimates of energy expenditure and energy consumption of ringed seals (Phoca hispida) throughout the year. Polar Res. 10 (2), 595–602.
Singsaas, I., Leirvik, F., Daling, P.S., Guénette, C., Sørheim, K.R., 2020. Fate and behaviour of weathered oil drifting in sea ice, using a novel wave and current flume. Mar. Pollut. Bull. 159, 111485.
Sorstrom, S.E., Brandvik, P.J., Buist, I., Daling, P., Dickins, D., Faksness, L.-G., Potter, S., Fritt-Rasmussen, J., Singsaas, I., 2010. Joint industry program on oil spill contingency for Arctic and ice-covered waters: summary report. In: Tech. Rep. SINTEF.
Steiner, N.S., Cheung, W.W.L., Cisneros-Montemayor, A.M., Drost, H., Hayashida, H., Hoover, C., Lam, J., Sou, T., Rashid, Sumaila U., Suprenand, P., Tai, T., C., and VanderZwaag D. L., 2019. Impacts of the changing ocean-sea ice system on the key forage fish Arctic cod (Boreogadus Saida) and subsistence fisheries in the western Canadian Arctic – evaluating linked climate, ecosystem and economic (CEE) models. Front. Mar. Sci. 6, 179.