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Preparing for the unprecedented — Towards quantitative oil risk assessment in the Arctic marine areas

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ABSTRACT

The probability of major oil accidents in Arctic seas is increasing alongside with increasing maritime traffic. Hence, there is a growing need to understand the risks posed by oil spills to these unique and sensitive areas. So far these risks have mainly been acknowledged in terms of qualitative descriptions. We introduce a probabilistic framework, based on a general food web approach, to analyze ecological impacts of oil spills. We argue that the food web approach based on key functional groups is more appropriate for providing holistic view of the involved risks than assessments based on single species. We discuss the issues characteristic to the Arctic that need a special attention in risk assessment, and provide examples how to proceed towards quantitative risk estimates. The conceptual model presented in the paper helps to identify the most important risk factors and can be used as a template for more detailed risk assessments.

1. Introduction

The risk of an Arctic oil spill has become a global matter of concern during recent decades, and the release of oil into Arctic marine environment is considered the most significant threat from Arctic shipping activities (Arctic Council, 2009). As climate change is extending the ice-free period and opening new sea routes, maritime traffic in the Arctic is increasing (AMAP, 2010; Ho, 2010; Sulistiyono et al., 2015). Moreover, the relatively unexploited Arctic petroleum reserves appear to be the next frontier for oil and gas exploration (AMAP, 2010). The opening of shipping routes means that not only will tankers be moving oil out, but there will be active transport of freight along the entire length of the Arctic sea routes. Increased traffic together with harsh climate and unfavorable navigability increases the likelihood of an oil spill. Hence, there is an obvious need to develop analysis tools that offer a systematic way to quantitatively assess the consequences of possible oil spills so that the oil induced risks can be taken into account when new sea routes or previously unexploited oil reserves are utilized.

As the Arctic environment is globally unique, sensitive, and mainly pristine (Jörundsdóttir et al., 2014) – although not completely untouched by human activities (see e.g. Muir et al., 1992; Miquel, 2001; Weber et al., 2010) – and the warming climate is already putting pressure on the environment (ACIA, 2004; Moore and Huntington, 2008; Kelmelis, 2011; Bolsunovskaya and Bolsunovskaya, 2015), a major oil spill in ice-filled waters could be disastrous to marine mammals, birds, and other biota. Physical geography of the Arctic affects behavior, fate, and ecological effects of oil. The spreading and weathering of oil can be substantially reduced in the cold and icy conditions, oil decomposes slowly in the cold latitudes, and the rate of recovery of the Arctic environment is slow (Fingas and Hollebone, 2003; Brandvik et al., 2006; AMAP, 2010). Moreover, the presence of ice increases the uncertainty related to the fate of oil and the communication and response capabilities in the Arctic are typically far below of what they are in other regions in the world (Arctic Council, 2009). If an oil spill happens in the Arctic, oil is likely to remain in the environment for a long time and subsequent harm will be prolonged, as at this point there are no effective means of containing and cleaning up spilled oil in broken sea ice (Arctic Council, 2009; Transportation Research Board and National Research Council, 2014).

One problem in oil spill risk analysis in the Arctic marine areas is the lack of ecological background data. For example, the information about species' distributions and abundancies can be scarce or totally lacking, and even general biological knowledge, related to, e.g., species level predator-prey dependencies, reproduction and migration patterns, is often limited or non-existent. As a rule of thumb, the more demanding the climatic conditions, the fewer field studies have been conducted (Kaiser et al., 2011). Moreover, there are no data from earlier accidents since luckily no major oil spills have occurred in truly Arctic areas. Follow-up studies on previous oil spills in sub-Arctic regions, such as

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the Exxon Valdez oil spill (EVOS) in Alaska in 1989, are also often deficient and even contradictory (Paine et al., 1996). Monitoring the effects of EVOS has been moderately successful with some species (e.g. Day et al., 1997; Bodkin et al., 2002; Esler et al., 2002; Boehm et al., 2004; Carls et al., 2004), but documenting the effects of the spill on the whole ecosystem and its internal interactions has generally failed. Despite the lack of accurate knowledge in broad scale, effects of oil on some Arctic species are relatively well understood due to several laboratory experiments (e.g. Albers, 1998; Faksness and Brandvik, 2008; Hannam et al., 2010; Jonsson et al., 2010), and some very general syntheses of the likely effects of an Arctic oil spill have been reported (AMAP, 2010). Most empirical and theoretical studies, however, have concentrated only on few specific species or very simplified food chains.

Arctic ecosystems consist of relatively short food webs making trophic interactions comparatively simple (Kaiser et al., 2011). This implies that population changes in just one key species may have strong cascading effects in the entire ecosystem (Palumbi et al., 2008; Hop and Gjøsæter, 2013). Hence, when assessing the risks to the environment, we should assess both the vulnerability of species together with their importance in a food web. Moreover, in order for ecological risk analysis to cover the whole ecosystem, it should be based on functional groups. Functional groups are formed based upon the role species play in an ecosystem rather than their taxonomic status (Calow, 2009), and the range of functional types present in an ecosystem are likely to be more closely related to the stability of an ecosystem than the number of species within it (Allaby, 2010). Hence, focusing on functional groups instead of individual species implies more holistic approach to risk assessment. However, so far risk assessments of oil in the Arctic have concentrated only on few key or otherwise relevant species (e.g. Aas et al., 2000; Gerber et al., 2004; Hannam et al., 2010, Hansen et al., 2011; Nørregaard et al., 2015) and they have rarely aimed for more extensive ecosystem based risk assessment, where the role of species in the ecosystem and in food webs would be taken into account.

In this work, we present a general probability-based approach to assess ecosystem level risks related to oil spills in the Arctic. We concentrate on assessing the acute impacts of spills, and discuss the difficulty of predicting the longer term impacts. We introduce a food web model that displays the most relevant dependencies among oil and the ecosystem response in a functional group level, and discuss an approach to turn this qualitative description of the Arctic marine ecosystem into quantitative risk assessment tool. We pay a special attention to differences in the relevant factors between Arctic and temperate regions that need to be taken into account in this kind of analysis. By constructing such a holistic model, we aim to produce the best possible description of the Arctic ecosystems for oil risk assessment studies and provide a basis for analyzing oil spill impacts in the Arctic ecosystem as holistically as possible.

The paper is structured as follows. First we give a short introduction to probabilistic (Bayesian) risk analysis. Then we introduce a functional groups based Arctic marine food web, which can be used to describe an Arctic marine ecosystem in oil spill risk analysis. The food web is used as a basis for a qualitative description of the ecological oil risk assessment process. For last, we present how this qualitative description can be transformed into a quantitative probabilistic scenario specific oil risk assessment.

2. Probabilistic risk assessment and Bayesian networks

The aim of an ecological risk assessment (ERA) is to systematically enhance our understanding of the probability and intensity of a harmful ecological response to a human activity, so that the decision affecting the outcome can be made based on the best available scientific knowledge (Gentile and Harwell, 1998). ERA typically contains problem formulation, analysis of exposure and ecological effects, and risk characterization, which describes the risks and estimates their magnitude (Fowle and Dearfield, 2000). So far Arctic ERA's are at best qualitative (see e.g. EPPR, 1996; Bolsunovskaya and Bolsunovskaya, 2015). As we aim to move towards quantitative risk analysis, we make use of Bayesian theory which provides a machinery for logical reasoning and decision making under uncertainty (Raiffa and Schlaifer, 1961; Gelman et al., 2013).

Fig. 1 shows our conceptual model (the qualitative description) for ERA related to acute impacts of possible oil spills in Arctic marine ecosystems and we discuss its elements in more detail throughout the paper. After building the qualitative formulation of the problem, we can use Bayesian networks (BNs: Pearl, 1988; Jensen, 1996; Jensen and Nielsen, 2007) to conduct the quantitative risk characterization. BNs, and Bayesian modeling in general, force the analyst to be explicit and transparent about his assumptions, which is particularly important in analyses with broad policy relevance. Hence, BNs are increasingly popular in environmental and ecological research (e.g. McCann et al., 2006; Aguilera et al., 2011; Landuyt et al., 2013), and they have been employed to oil spill related ERAs in sea areas, such as the Baltic Sea (Aps et al., 2009; Helle et al., 2011; Lecklin et al., 2011; Jolma et al., 2014; Helle et al., 2016) and the Gulf of Mexico (Carriger and Barron, 2011).

A BN is a probabilistic graphical model that represents a set of random variables and their dependencies. A typical example of a BN is a directed acyclic graph containing nodes and arrows. Nodes correspond to random variables and arrows describe the conditional independence structure between these variables. An arrow from one node to another indicates that the state of the receiving node (child) is conditionally dependent on the state of the originating node (parent).

Fig. 2 shows a BN that represents the variables and their dependencies relevant for the oil spill risk assessment in the Arctic ecosystem. For example, acute impact of an oil spill on a functional group A (*Acute impact: Group A*) depends on the spatial area polluted by oil (*Oiled area*),

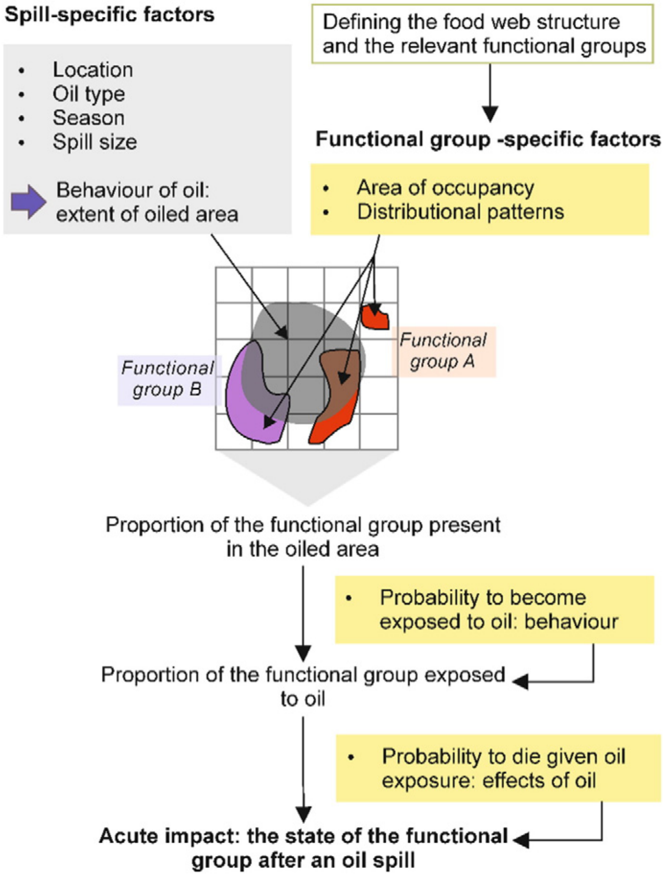

Fig. 1. The conceptual model for estimating the acute impacts of oil spills on the Arctic marine ecosystems.

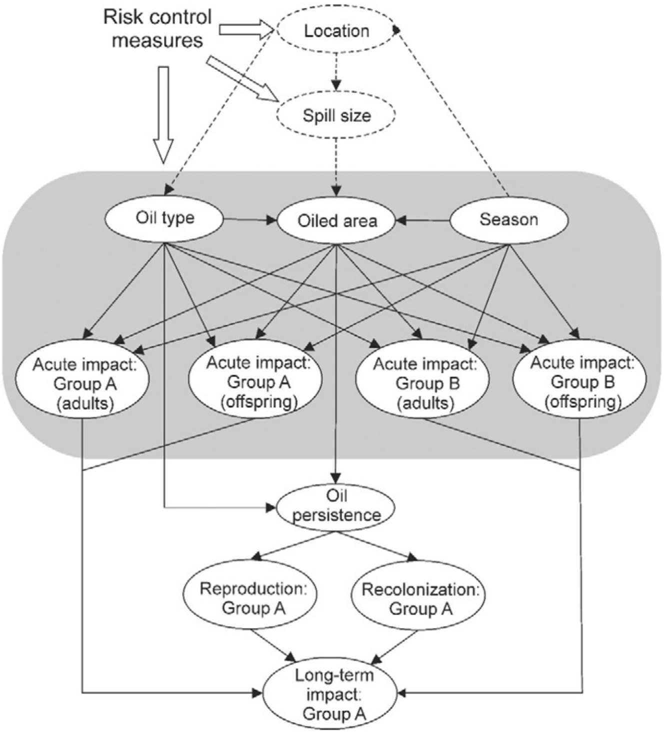

Fig. 2. Bayesian network for analyzing effects of oil spill in the presence of interaction between two functional groups during and right after an accident (acute impact) and over a long-term (long-term impact, illustrated only for Group A). See Section 3.2 and Table 1 for the description of the variables.

type of oil (*Oil type*) and time of an accident (*Season*). Arrows show also conditional independence assumptions – given the states of the parents the probability distribution of the child does not depend on the nodes preceding its parents. When building BNs, each node corresponds to an assumption which we want to make explicit in our reasoning. Excluding variables from a BN means that we are not interested to analyze and make their effect visible in the risk assessment and, technically, we have marginalized over the uncertainty related to them. On the other hand, each missing arrow between any two nodes corresponds to an assumption that there is no direct influence between these nodes.

Variables in a BN are typically discretized to a number of mutually exclusive states. After defining the structure of a BN, one needs to specify the conditional probability distributions for all variables in that network. If a variable does not have any parents, it has one (marginal) probability distribution, whereas a variable with parents has a set of distributions (a conditional probability table, CPT); one distribution for each possible combination of the states of the parents. Several sources of information can be used to specify the distributions, including e.g. experimental and observational data, results from earlier studies, and expert knowledge (Uusitalo, 2007). Since conditional distributions depend only on the states of the parents of a variable, these distributions can also be updated independently (Castelletti and Soncini-Sessa, 2007). Hence, a BN can easily be updated according to the best and the most current information available for each variable.

A BN can also be extended to an influence diagram (ID) by adding decision and utility nodes to it (Howard and Matheson, 2005). IDs can be used to assess the influence of decisions on variables and outcomes in the network, and they can help e.g. in finding the optimal combinations of management measures. However, in the following sections we concentrate only on how BNs can be used to assess the consequences of possible oil accidents in the Arctic seas and discuss how the needed probability distributions can be formed to enable a quantitative risk assessment.

3. Predicting the impacts of an oil spill to the Arctic marine ecosystems

3.1. Step 1: identification of the relevant ecological components at risk in the Arctic marine areas

Instead of traditional species-specific risk assessment, ecological risk assessment should focus on food webs on functional groups level when we aim to assess the effects on ecosystems rather than single species. The range of functional groups affect the stability of an ecosystem more than the number of species within it (Allaby, 2010) and, in the case of an accident, biota is likely to experience indirect effects via food web in addition to direct oil-induced effects (e.g. Peterson et al., 2003; Hjermann et al., 2007). Hence, a food web representation enables a holistic analysis of risks to the whole ecosystem and provides a natural way to extend the analysis from acute to long term effects. Moreover, functional group approach increases the amount of information available for risk analysis which is important in areas with limited data. For example, when we have little data on few species, we can use it to make generalizations to these species' functional group, and at the best case we can even obtain information about their prey and predators.

Commonly functional groups are formed based upon the role species play in an ecosystem rather than their taxonomic status (Allaby, 2010). Using this reasoning, many Arctic species could fit into several functional groups. However, we take additionally into account the main features that contribute to how and on what time-scale oil affects the species, such as mobility, feeding and breeding behavior, and different tolerance levels. Species may also belong to different functional groups during different stages of their life. Therefore the functional groups in our approach should be thought in terms of convenience for practical risk assessment similarly to, for example, Miquel's (2001) general view for contamination studies in the Kara Sea. We do not aim at perfect description of an Arctic ecosystem but at displaying the most relevant dependencies in it. We summarize the food web with the key functional groups above the lowest trophic levels (Fig. 3; Appendix A). Primary producers (here mainly phytoplankton) are left out since studies in temperate waters have shown that the damage to them by oil spills is likely to be rather modest and short in duration (see AMAP (1998) and references therein).

Despite the small existing knowledge, some general assumptions can be made of how an oil spill would affect different parts of an Arctic ecosystem. Most biota are likely to experience at least some toxicological effects after an oil spill through either direct toxicity of oil or ingestion of contaminated prey. In addition to toxicological effects, physical contact with oil can also lead to, for example, smothering. However, species are exposed to oil in different ways, have different tolerance levels, and varying ability to avoid oil (AMAP/CAFF/SDWG, 2013).

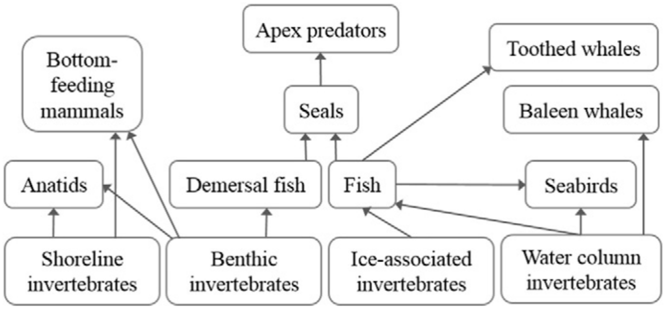

Fig. 3. A food-web of upper trophic levels in the Arctic marine areas. The functional groups should be thought in terms of practical risk assessment taking into account the main features that contribute to how and on what time-scale oil affects the species (see Section 3.1).

Acute impacts, including mortality, caused by physical contact with oil might be particularly significant for species living or feeding at surface waters and shorelines. A major difference between non-Arctic and Arctic environments is that the risk of acute hypothermia is greater in the latter due to colder conditions year-round. Recovery potential varies among species and functional groups, and is affected by e.g. species-specific reproduction and recolonization rates (Kaiser et al., 2011), and the harm caused by an oil spill may be prolonged for species with long life cycles. Generally populations are most vulnerable to oil spills when they form aggregations, commonly when they are migrating, staging, breeding, feeding, or resting. Next we discuss the main characteristics of each functional group with emphasis on oil spill point of view (see also Appendix A for a summary).

Apex predators, also known as top predators, refer to animals that, as adults, have no natural predators in their ecosystem (excluding humans). Generally apex predators have low reproduction capacity, and the young are dependent on their parent(s) for a relatively long time (Storer et al., 1979). They play an important role in an ecosystem, and removal of them can have dramatic and cascading impacts on an ecosystem (Myers et al., 2007; Heithaus et al., 2008; Ordiz et al., 2013). The only species of this functional group in our food web is polar bear (*Ursus maritimus*). Other Arctic apex predators are either non-marine and therefore unlikely to be exposed to spilled oil, like arctic fox (*Vulpes lagopus*), or differ greatly from polar bears based on e.g. their feeding or breeding habits and are therefore placed into different groups in our classification (some seabirds or toothed whales). Polar bears are likely to experience both physical and toxicological harm if oiled. They rely on fur for insulation and buoyancy, and oil contamination may therefore be particularly damaging to them (AMAP, 2010). Some studies suggest that they might avoid oil on the water surface, but once oiled, they will groom their fur leading to ingestion of oil (Engelhardt, 1983; Hurst et al., 1991).

Seals include seals that mainly eat pelagic fish and crustaceans, and have a dense but short fur, for example, ringed seal (*Pusa hispida*) and harp seal (*Pagophilus groenlandicus*). They form an important link between top predators and fish, and are the most important prey item for polar bears. Adult seals are not considered to be highly sensitive to oiling due to their scattered distribution and diminished risk of hypothermia as they rely on blubber, not fur, for insulation (AMAP, 2010). Nonetheless, possible acute effects of oil include, for example, skin irritation, lethargy, and corneal ulcers, but most effects are thought to be largely reversible (Kelly et al., 2010). Pups, however, can be very sensitive to oiling due to lanugo fur to which oil adheres easily causing hypothermia and drowning (AMAP/CAFF/SDWG, 2013).

Bottom-feeding mammals contain mammals that dive food from seabed. For example, walruses (*Odobenus rosmarus*) and bearded seals (*Erignathus barbatus*) belong to the group. Adult individuals are not considered to be highly sensitive to oiling (AMAP/CAFF/SDWG, 2013). Although pups have similar fur as adults and are able to swim soon after their birth, the oil may be a disadvantage for them and exhaustion may lead to death (AMAP/CAFF/SDWG, 2013). The most significant difference between this and the previous group is in the way they obtain food, and thus the fate of oil plays a key role in how the functional groups experience an oil spill.

Toothed whales of the Arctic include, for example, beluga whale (*Delphinapterus leucas*) and narwhal (*Monodon monoceros*) whereas **Baleen whales** of the Arctic include, for example, bowhead whale (*Balaena mysticetus*) and common minke whale (*Balaenoptera acutorostrata*). Feeding habits of the two groups differ greatly, toothed whales are opportunistic feeders mostly feeding on schooling fish whilst baleen whales use their baleen plates for filtering food from water, but otherwise they are assumed to be fairly alike from oil spill perspective. Although information is limited, the general assumption is that whales are relatively unharmed by oil although prolonged exposure may increase their sensitivity (AMAP, 2010). Physical oiling is not likely to be harmful to whales, as all whales rely on blubber for insulation, and their skin prevents adhesion of oil (Ziccardi et al., 2015). The effects of ingested oil are unknown. Moreover, whales may tend to avoid densely trafficked shipping lines altogether (Finley et al., 1990).

Fish are divided into two groups in our food web, **pelagic** and **demersal fish**, based upon their primary habitat. The division reflects also the possible fate of spilled oil. Pelagic fish and fish eggs may come into direct contact with oil more easily while demersal fish are likely to come into contact with oil only if oil sinks and pollutes the seabed. However, in the latter case the living habitat might become destroyed for a long period of time making recolonization hard or impossible. Pinto et al. (1984) suggests that demersal fish are able to avoid sediment contaminated with oil. In general, adult fish and fry might be able to escape contaminated waters whereas larvae and eggs typically have at best limited possibilities to avoid oil by active swimming (Bohle, 1986; Rice, 1973; Hossain et al., 2014). Besides the higher probability of exposure, fish eggs and juveniles seem to also be more sensitive to toxicants (Norcross et al., 1996; Marty et al., 1997; Young et al., 2011). This makes fish spawning sites particularly sensitive to oil spills. Laboratory experiments dealing with the lethal and sublethal effects of oil on fish are numerous (e.g. Carls et al., 1999; Aas et al., 2000; Andersen et al., 2015; Edmunds et al., 2015) but field studies have generally failed to document any widespread effects on fish stocks. Possible explanations are due to combination of several factors including avoidance reactions and highly dynamic nature of fish stocks that reduces the possibilities of identifying changes caused by oil. Moreover, large proportions of larvae would have to be destroyed to affect recruitment. Nonetheless, negative impacts on the key fish species could have large ecological implications as fish form an important link between zooplankton and the upper trophic levels.

Birds are divided into two groups, **anatids** (family of birds that includes ducks, geese, and swans) and (true) **seabirds**, based upon their behavioral characteristics. Both groups share some similarities: most species live on the open sea and only go ashore for breeding. Most species are also migratory, arriving in the spring when melting of ice increases the primary production. Adult birds often molt between breeding and migration, which makes them flightless for one or two months. An accident occurring during molting, and when offspring are still completely dependent on their parent(s) could be particularly devastating. Although few studies have focused on Arctic species specifically, the effects of oil in general are relatively well understood (e.g. Briggs et al., 1997; Wiese and Robertson, 2004; Henkel et al., 2012). Birds rely on feathers for insulation and buoyancy, so the contamination of the plumage can lead to hypothermia, starvation, and drowning, and ingested oil can lead to death or impaired reproduction (AMAP, 2010). Further, avian embryos can be highly sensitive to oil that contaminates eggs shells, and depressed growth in young birds has been reported due to oiling (Leighton, 1993). The impact of a spill will differ from one species to another, as a function of behavioral patterns and sensitivity. In this work, we only consider birds that we expect to be most affected by oil (see e.g. King and Sanger, 1979 for a comprehensive oil vulnerability index listing). From oil spill perspective the main differences between anatids and (true) seabirds are their habitat use outside of breeding season and their way of acquiring food. Anatids dive for benthic invertebrates or eat them by upending in shallow waters, whereas seabirds mainly eat pelagic fish and crustaceans they forage by diving for schooling fish. After breeding they usually occur in pelagic zone. Seabird populations are particularly at risk from oil spill because of the social behavior of the individuals; in large aggregations majority of birds may be oiled at once.

Aquatic invertebrates are divided into four groups, **benthic**, **shoreline**, **ice-associated** and **water column invertebrates**, based upon their primary habitat. Benthic invertebrates live in a close contact with the seabed, while shoreline invertebrates live in shallow waters. Ice-associated invertebrates live under the ice. Water column invertebrates are practically all the remaining marine invertebrates and they can be found from water's surface to great depths. The justification for the categorization is based on the location of individuals as we assume that they have a very limited ability to avoid oil. Harmfulness of an accident to different functional groups is assumed to depend on key species (genera/families) of a functional group as for example crustaceans are more acutely vulnerable to oil than for example mollusks. Oil impacts to aquatic invertebrates have been studied to some extent. In general, zooplankton seems to recover relatively fast after a spill, as they have high reproduction rates and wide distributions (Wells and Percy, 1985). Mobile invertebrates, for example crustaceans, may be able to escape the oil but can also get stuck in it (Bonsdorff and Nelson, 1981) whereas sessile benthic invertebrates such as mussels may survive short-term oil smothering by closing up their shell (Mosbech, 2002). Then again, sessile species may also suffocate under thick layers of oil.

3.2. Step 2: structuring the Bayesian network for the risk assessment

The magnitude of the impacts of an oil spill on the biota depends on, among others, the properties and the amount of the spilled oil, the location and timing of the spill, the weather conditions during and after the spill, and the biological traits of individuals, and habitats affected by the spilled oil (Transportation Research Board and National Research Council, 2003). The issue is complicated further by the numerous interactions between these factors. For instance, the extent of the area affected by oil is dependent, in addition to the volume of the spill, on the spreading and weathering processes of oil, which, in turn, are dependent on the oil type, as well as prevailing weather and oceanographic conditions.

The general BN for assessing ecological effects of oil spills in the Arctic seas (Fig. 2; Table 1) includes variables that describe characteristics of accidental oil spills (e.g. *Season* and *Oil type*) and the extent of oil contamination (*Oiled area*, *Oil persistence*), as well as relevant ecological parameters (*Acute impact*, *Long-term impact*, *Recolonization*, *Reproduction*). Our focus is on the variables that are sufficient for the analysis of acute effects of an oil spill in a specific location (highlighted with gray in Fig. 2). These variables enable a scenario-based assessment at that location; that is an assessment of the effect of, e.g., season or type of spilled oil on the functional groups in that area.

The variables that precede the location-specific variables (indicated with dotted line in Fig. 2) would widen the approach from the location- and spill-specific assessment to a more general risk assessment in the Arctic marine areas. Although the latter is not in the scope of this paper, we want to point out that it is evident that there is a large number of other relevant variables that could be included in the analysis depending on the scope (see e.g. Lehikoinen et al., 2015 and Helle et al., 2015). A comprehensive analysis could also include management measures that affect the variables in the BN, such as regulations related to the opening and closing of shipping routes, and to the structure of vessels. Further, variables with solid line and white background in Fig. 2 would be relevant when describing the long-term effects of oil spills. In the following we give a short description of the variables in the BN, with a special focus on the matters that are important to take into account when conducting ERA in the Arctic. Table 1 describes the proposed technical definition and discretization of the variables.

Table 1
Summary of the variables in the Bayesian network in Fig. 2 and a proposed discretization of the variables.

Variable	Definition and discretization of the variable
Variables relevant for acute impacts	
Season	Time of accident. Discretized into spring, summer and autumn (and possibly winter).
Oil type	Type of spilled oil. Discretized into extra light, light, medium, heavy and extra heavy.
Oiled area	Extent of the area affected by the spilled oil. Depends strongly on the assumed accident location and spill size. Hence, the discretization has to be decided for each ERA separately after the accident location and spill size have been determined and oil spreading estimated.
Acute impact	A percentage of remaining population after the spill compared to the pre-spill population. Combines the likelihood of encounter and response (escape or death) once oiled. Discretized to subintervals between 0 and 100.
Variables relevant for long-term impacts	
Oil persistence	Describes the extent and duration of oil in the environment, and varies spatially depending on oiled area and type of oil. Discretized into high, moderate and low.
Recolonization	Rate at which a functional group recolonizes the area after an accident. Discretized into high, moderate and low.
Reproduction	Average reproduction rate of a functional group. Discretized into high, moderate and low.
Long-term impact	A percentage of remaining population after the spill compared to estimated population without the oil spill. Discretized to subintervals between 0 and 100.

3.2.1. Variables relevant to the assessment of acute impacts

Season describes the time of an accident. This is likely to have a great effect on oil spill impacts, as season affects the population sizes (i.e. which functional groups are present at the area and how abundantly), the likelihood of an exposure (e.g. are the individuals at sea or at land), and relative sensitiveness of functional group (e.g. life stage can have a major impact on sensitivity). In the Arctic, special attention should be addressed to the migration patterns, as they determine e.g. the populated areas and the proportion of offspring in a population. Ice cover, that varies annually but follows the seasons, contributes to both spreading of oil and distribution of functional groups.

Oil type describes the type of spilled oil. Different oil types are being transported in the Arctic, the ecological impacts of which vary. For example, density and viscosity of oil affect weathering processes oil undergoes as well as floating or sinking of oil (Transportation Research Board and National Research Council, 2003; Fingas, 2000). Weathering processes and the fate of oil can be very different in the Arctic compared to more temperate regions, and especially the influence of ice cover is inadequately understood. For example, presence of ice slows down the spreading, evaporation and natural dispersion of oil, and release of oil under ice may lead to encapsulation of oil (Fingas and Hollebone, 2003; Brandvik et al., 2006; Afenyo et al., 2016).

Oiled area describes the extent of the area affected by a harmful amount of oil. Depending on the accident type and the amount of spilled oil, the size of the area affected by oil (e.g. length of oiled coastline or ice edge, proportion of oiled seabed, or volume of water body contaminated) varies, which, in turn, will affect how big proportion of a population is exposed to oil. The definition of harmful amount of oil may depend on the functional group but for simplicity we assume here that the area refers to area where oil amount (e.g. thickness of the slick or the underwater concentration) exceeds a fixed cut-off value. The main factor in the Arctic affecting the fate of oil, including the area oiled, is the presence of ice. For example, in ice covered waters oil will mainly drift with the ice which can have a major impact on the likelihood of oil reaching the shore. In addition, spreading in ice depends on ice type and cover (Brandvik et al., 2006).

Acute impact describes the effect of an oil spill on a functional group during and right after an accident. Here the acute impact is defined as a percentage decrease in the population sizes, and it takes into account the likelihood of encountering the spilled oil and the response once oiled. Response can be either death or escape. For many functional groups like mammals, birds and fish, acute impacts are assessed separately for offspring and adults, as both the exposure likelihood and the responses to oiling can be expected to be different between the life stages. For example, adult fish may be able to avoid oil effectively whereas the fate of fish eggs depends solely on drifting of oil.

3.2.2. Variables relevant to the assessment of long-term impacts

Oil persistence describes both the extent and duration of oil load in the environment, and depends on the amount and type of spilled oil. It varies spatially and could be summarized by an index that has high rank when both the amount and duration of oil load are high, moderate when the amount of oil is moderate or duration of oiling is relatively short, and low when both the amount and duration are low. In reality, the weather conditions have great significance to the long-term intensity of oiling but considering them complicates analysis considerably, and is outside the scope of this paper. While in the Arctic, we can, however, assume that the spilled oil is going to stay in the environment for a long period of time. For example, if large amount of heavy oil has sunk to the seabed, oil may stay there unpredictably long. Crude oil originating from EVOS is still left at the shores of Prince William Sound 30 years after the accident (Nixon and Michel, 2015). Contaminated habitats can impede or fully prevent recolonization from close-by areas and return of individuals who fled after an accident.

Recolonization describes recolonization ability of the functional group. Generally different species have varying recolonization abilities (Kaiser et al., 2011). Further, recolonization rates can be affected by the amount of oil left in the environment (Day et al., 1997; Fukuyama et al., 2014) especially if the spill site is isolated (Kubach et al., 2011). Even if organisms are generally efficient colonizers, remaining oil may prevent or seriously delay recolonization (Pinto et al., 1984).

Reproduction describes the average reproduction efficiency of a functional group, which is affected by a group-specific characteristics, e.g. age at maturity, number of offspring, and average lifespan (Storer et al., 1979). Reproduction efficiency is also affected by the amount of oil left in the environment, and oil can weaken it through both sublethal effects on fertility (Ainley et al., 1981; Peterson et al., 2003) and by destroying breeding grounds (Dunnet et al., 1982; Pinto et al., 1984).

Long-term impact describes the status of the functional group after a chosen period of time. In addition to the acute impacts, long-term impacts are dependent on the status of other functional groups in the food web (i.e. predators and prey). The loss of food sources is likely to have adverse impact on the recovery of the functional groups whereas the disappearance of a predator or a competitor may benefit the prey. Simple food webs and strong dependencies between groups can strengthen these impacts disproportionately compared with temperate regions. The fate of offspring after an accident may also have long-term effects especially to functional groups with low reproductive rates. In general, long-term impacts may be significantly prolonged in the Arctic as the cold environment slows down the weathering processes. As Arctic animals often rely on lipid rich blubber for insulation, chronic exposure accumulates especially in large marine mammals.

3.3. Step 3: quantifying the risk assessment by estimating the probability distributions of the Bayesian network

Before the BN can be used for risk assessment we need to define the probability distributions in it. Probability distributions for variables summarizing the accident scenarios (*Location*, *Spill size* and *Oil type* in Fig. 2) can typically be derived e.g. by using available accident or maritime transportation statistics (see e.g. Helle et al., 2011; Lecklin et al., 2011; Jolma et al., 2014). However, as the volume of traffic in the Arctic has, until recently, been limited, the number of realized accidents is low and the statistics may thus not provide reliable estimates for the variables. Moreover, typical accident patterns in the past may not reflect the situation in the future. Hence, there may be a need to complement the statistics with expert elicitation or modeling. This may especially apply to the *Spill size*, as the characteristics of accidents in ice conditions typically differ from those in open water (Verny and Grigentin, 2009; Ho, 2010; DNV GL, 2014). The probability distribution for the extent of a spill (*Oiled area*) can, in principle, be produced by running an oil spill fate model with alternative parameterizations (e.g. OSCAR: Reed et al., 1995 and SIMAP: French-McCay, 2004, French McCay et al., 2004), but these models typically require e.g. a detailed weather, current and shoreline data that may not be available for all places in the Arctic. Furthermore, the models may have limited ability to model oil in ice conditions (Afenyo et al., 2016). Another option is to calculate a coarse estimate by applying e.g. Fay-based equations that describe the spreading of oil (see e.g. Fingas and Hollebone (2003) and Afenyo et al. (2016), for a review of oil in freezing conditions), or, if this is not feasible, to rely on, as a first step, estimates on the oiled area obtained from earlier accidents, or from expert assessment.

Our main focus in this paper is on the acute effects of oil to biota that depend on the spatial extent of the oil spill (*Oiled area*), the time of the accident (*Season*) and the type of oil (*Oil type*). These three variables summarize where, when, and what kind of oil is found after alternative accident scenarios. Even if we do not have justified probability distributions for these variables, we are able to conduct scenario-based analysis of the ecological effects of potential oil spills. The results can then later be included into more detailed risk assessment analysis that contains the chain from accident scenarios to ecological consequences (Lecklin et al., 2011; Ehlers et al., 2014; Helle et al., 2015).

In principle, the probability distributions for the acute effects given the combinations of different states of the parent variables can be elicitated from experts for each area and accident scenario separately (e.g. Lecklin et al., 2011). However, this approach means that all probability tables would need to be updated for each new assessment. For this reason, we aim at procedure that minimizes the extra work load per new assessment. Moreover, our aim is to break the risk assessment process into pieces for which expert assessment or data analysis (if feasible) is easier to conduct.

When assessing the acute effects, we start by estimating the proportion of individuals in a functional group that is within the oiled area during the period of time when the oil is spreading (Fig. 1). Hence, a sensible time frame included into the acute period may, in principle, differ between season and type of the spill. In the absence of case-specific knowledge, a good rule of thumb can be to consider a two-week period, classified as a 'spill in progress' phase by Boehm and Page (2007). According to them, during this period the oil at water surface is likely to have its maximum exposure potential, and the water column concentrations can be expected to be at maximum.

Here, a population should be understood as a quantity at the functional group level summarizing the quantity and distribution of individuals in that functional group. We could consider the total population in the Arctic region but in practice it is convenient to consider a (sub)population in a smaller study region containing the oiled area. The proportion of population present in the oiled area during the acute period of oil spill is the total population density over that area divided by the total population density over the whole study region. In technical terms, if $L(s,t)$ denotes an abundance or density of a population at location s at time t, the potentially exposed proportion of population is $\phi(t) = \int_{s \in \text{Oiled area}} L(s,t)ds / \int_{s \in \text{Distribution area}} L(s,t)ds$.

Not all individuals come into contact with oil even though they were in the oiled area, and not all individuals die even if they had contact with oil. Some species may be able to avoid oil actively (see e.g. Rice, 1973; Lipcius et al., 1980; Engelhardt, 1983; Bohle, 1986; Ryder et al., 2004) or they are not prone to exposure due to their behavior; e.g. some seabirds that spend most of their time flying and roost on land. Hence, next we estimate the probability of an individual to come into contact with oil given there is oil in the area, and after that, the probability of an individual to die given it is exposed to oil. The expected proportion of individuals in the study area that dies due to an oil spill (*Acute effect*, Fig. 2) at time t is then

$$\text{Acute effect} = \phi(t)\,\Pr(\text{death}|\text{contact})\,\Pr(\text{contact}).$$

One approach to estimate the spatial distribution of a functional group is to use species distribution models (SDM) which link the species occurrence or abundance to spatial location through environmental variables at that location to produce predictions (extrapolate) for population occurrence/density at other locations (Guisan et al., 2002; Gelfand et al., 2006; Elith and Leathwick, 2009). It should be noted that if we can model the relative density of a population we do not need to know the exact size of the population in order to calculate the proportion of a population within the oiled area. With some functional groups and in some areas of Arctic SDMs are potentially very feasible approach. For example, there are studies on distribution of apex predators, seals, bottom-feeding mammals, whales, birds and even some fish species from many Arctic sea areas (Cohen et al., 1990; Bakken, 2000; Boltunov and Belikov, 2002; Bengtson et al., 2005; Boltunov et al., 2010; Matishov et al., 2014). Broad scale low resolution information about many essential environmental variables (such as ice cover, depth and salinity) are also available (e.g., Cavalieri et al., 1996; Jakobsson et al., 2012; Boyer et al., 2013). However, the low resolution of available environmental data restricts also the resolution of predictions of SDMs and in some areas the reliability of environmental data is also questionable (Cavalieri et al., 1996; Jakobsson et al., 2012). Moreover, there are currently no species distribution studies that would cover exhaustively the whole Arctic and in some areas the traditional SDMs alone are hard to apply since available useful data are patchy, sparse, or totally missing. In such situations, novel methods to fuse complementary sources of information may be needed. In some cases expert elicitation may be the only way to get an estimate of the distribution of the population. Moreover, traditional SDMs often only focus on occurrence but in our application, information on species abundance is essential – as it is for management and also for conservation purposes in general (Johnston et al., 2015).

It seems that estimating the probability that an individual comes into contact with oil and the probability of death given there is a contact must rely heavily on expert assessments. For some functional groups, such as benthic invertebrates, fish and birds there are ecotoxicological studies (Aas et al., 2001; Esler et al., 2002; Boehm et al., 2004) that can be used in a meta-analysis to infer the probability of an individual to die given it is exposed to oil. However, also these studies consider only very limited number of species mostly in warm or temperate climates. The same issue applies for the publicly available databases (such as ECOTOX[1] by United States Environmental Protection Agency) of chemical toxicity data; the majority of data concerns temperate species, and most of the tests have been carried out using a single specific chemical, not crude oil as such. A method for interspecies toxicity extrapolation in birds and mammals has been suggested (Luttik et al., 2005) but it has only been found to work for birds and in this case also the limited data of mostly temperate species causes constraints. Furthermore, for obvious ethical and legal reasons, implementing ecotoxicological tests on animals such as polar bears would be impossible for which reason for most of the functional groups, such as apex predators and seals, applicable ecotoxicological studies do not exist. Studies on species behavior in oiled areas are also scarce (Engelhardt, 1983; Scott and Sloman, 2004; Matkin et al., 2008). Thereby, expert elicitation may be the only feasible approach to comprehensively assess the required probabilities for most of the functional groups. However, once these probabilities are assessed they are transferrable to any area in the Arctic region. Hence, for each new oil risk assessment we need to estimate only the species distributions and oil spread in that specific area.

Currently, there is only a limited understanding of the long-term effects of oil spills in Arctic waters. Some long-term studies have been conducted after the sub-Arctic EVOS (Thomas et al., 1999; Golet et al., 2002; Peterson et al., 2003; Payne et al., 2008) but the problem seems to be the poor knowledge of the ecosystem prior to the accident. Nevertheless, long-term effects appear to exist even though they are not fully understood, and ignoring them underestimates the risks related to Arctic oil accidents. Again, one way to assess the long-term impacts is the use of expert knowledge, although the complexity of the matter may pose a challenge even for experts familiar with Arctic ecology. Thus modeling, even if it produces only rough estimates, may be a more reliable way of estimating long-term impacts. In the framework proposed in this paper, long-term impacts depend on the acute effects on adults and offspring, and also on the functional group-specific recolonization and reproduction capacities.

4. Discussion and conclusions

The main objective of the study was to suggest an approach to move towards quantitative oil risk assessment in the Arctic ecosystem. Accurately implemented risk assessment would help us to prepare for the growing risk of an Arctic oil spill, and to guide management of oil spill related factors. We suggest to use Bayesian theory when moving from qualitative to quantitative risk assessment since it allows the integration of information from different sources and with different accuracy. We built a conceptual BN that describes the most important variables and dependencies among them that need to be taken into account when assessing the overall ecological risks of potential spills. Although quantitative knowledge was not yet formally incorporated, the BN reveals the key compartments in the ecosystem and the variables in the chain from accident to ecological consequences that should be taken into account in an ERA concerning oil transportation in the Arctic.

We propose that Arctic oil spill risk analysis should be based on Arctic food web on functional groups level. The main theoretical justification comes from the fact that this representation enables a holistic analysis of risks to the whole ecosystem and provides a natural way to extend the analysis from acute to long term effects. Moreover, using functional groups increases the amount of information available for risk analysis. Alike approach has been used e.g. by Spill Impact Model Application (SIMAP: French-McCay, 2004; French McCay et al., 2004) which does not fit the Arctic but supports the group based approach when modeling the impacts of an oil spill.

There are still major restrictions for conducting an extensive quantitative Arctic oil spill risk analysis. Acute impacts of an oil spill can be analyzed with some precision already. Approach may vary depending on a functional group, e.g. for top predators the only feasible approach to estimate oil spill effects seems to be expert elicitation which may be supplemented with some estimates from literature. Then again, for certain invertebrates toxicological experiments may be available allowing for meta-analysis approach. Available toxicological data are aplenty, and even if data for Arctic species are lacking, good estimates can likely be extrapolated. Estimating the long-term impacts reliably, however, is a real challenge. They depend on so many variables that assessing them may be impossible for experts and we currently lack models that would describe Arctic ecosystems with large enough realism. Even if we are currently forced to leave the long-term impacts out of the analysis, their likely existence must not be overlooked.

Key information sources for conducting a comprehensive analysis on oil spill impacts in the Arctic are the behavior of oil and the distributions of species. The importance of distribution data and accurate oil fate and spreading models grows when we aim to move from general description to location specific analysis. Nonetheless, even without complete knowledge of these subjects our approach can be exploited to compare relative harmfulness of different accident scenarios, and to identify the most sensitive parts of an ecosystem.

One of the central conclusions from our work is that Arctic oil spill risk analysis must at the moment, and likely also in the future, rest heavily on expert knowledge. Hence, similar to many other risk assessment and management problems (Burgman, 2005; O'Hagan et al., 2006) efficient elicitation of that information is a key to a successful analysis. Models for oil spill risk analysis will likely improve in the future but some variables are hopefully always estimated by experts, as we hope not to obtain any data about e.g. effects of oiling to polar bear cubs. That is to say that sources of information such as expert elicitation are needed when direct measurements are infeasible.

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[1] https://cfpub.epa.gov/ecotox/.

Furthermore, we need also cost-efficient means to collect data on Arctic ecosystems. There are development needs not only for data collection methods but also for methods to plan and design cost-efficient data collection. The Bayesian approach allows for value of information analysis (VoI) where one plans the data collection so that the expected utility/loss (e.g., information/ecological risk after management decision) is maximized/minimized after obtaining the new data (Raiffa and Schlaifer, 1961; Mäntyniemi et al., 2009; Eidsvik et al., 2015). In Arctic areas VoI analysis is likely to provide tremendous benefits since the costs of exploration and data collection are high and the current information about the environment is low.

The conceptual description we have built in this paper is neither a perfect representation of the ecological interactions in the Arctic nor an exhaustive list of aspects that should be taken into account when analyzing potential risks related to Arctic activities. However, we provide a holistic picture of the ecological entities that should be taken into account when analyzing the risks to the Arctic environment posed by oil transportation. In a situation where the information is inadequate, the BNs can be used to analyze where extra information is most valuable with the VoI approach. The number and complexity of processes involved in the oil spill problem are clearly great. The BN built here introduces simplifications and neglects some processes but is rather meant to allow support to understand and recognize the risks associated with increased maritime oil transport in the Arctic and guide the future research.

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Appendix A. General information about oil spill relevant characteristics of key functional groups in Arctic marine areas

Functional group	Role in a food web	Reproduction efficiency	Other relevant characteristics	Acute impacts of oil	Long-term impacts of oil	Sensitivity to oiling (according to AMAP/CAFF/SDWG, 2013)	Example species/genera	Key references
Apex predators (polar bear)	At the top of a food web: consumes mainly species from one or two trophic levels lower.	Low. offspring dependent on their mother for more than two years.	Travels great distances when necessary. May favor the same area from year to year, especially when denning.	Smearing: skin reactions, hypothermia, death. Ingestion: damage to organs, death.	Buildup of pollutants. Impaired fertility.	High.	Polar bear.	Hurst et al. (1991), Amstrup (2003), Mauritzen et al. (2003), Boltunov et al. (2010), Molnár et al. (2010)
Seals	Preferred prey is generally small and forms dense aggregations (fish and crustaceans). The most important prey item of polar bears.	Low. Typically single pup/female/year.	Solitary animals that are distributed in large areas at low densities. Adults may be sedentary.	Reduced health and possibly survival. Inhalation may cause serious health effects or death. Pups may drown or freeze.	Most effects believed to be reversible. Prolonged exposure may lead to e.g. dermatitis and eye lesions. Buildup of pollutants.	Moderate or low when migrating, resting or wintering. High when breeding, or when food resources are negatively affected.	Ringed seal, harp seal, harbor seal.	Malins (1977), Stirling (2005), Kelly et al. (2010),Savinov et al. (2011), HELCOM (2013)
Bottom-feeding mammals	Dive food from sea floor, most importantly bivalves. Not important prey item for other species.	Low. E.g. walrus has 5–6-year-long inter-birth intervals.	Limited diving ability and patchy food sources determine suitable habitats. May form massive aggregations. Migratory.	Poorly understood, but at least the tough skin makes the physical oiling less acutely harmful.	The main prey items accumulate toxins, may lead to chronic exposure.	Moderate or low when feeding or resting. High when migrating, breeding or wintering.	Walrus, bearded seal.	Malins (1977), Boltunov et al. (2010), Glazov et al. (2013), Ziccardi et al. (2015)
Toothed whales	Forage small prey, mainly schooling fish. Not important prey item for other species.	Low. Late maturity. Two-to-three-year calving period. Calves can swim at birth but are nursed for up to two years.	Sociable and gregarious, forms great aggregations during summer. Migratory.	Poorly understood. Might avoid heavy shipping altogether.	Poorly understood. Possible (sub)population decline. Contamination of seabed may force to migrate.	High when migrating, breeding or wintering, moderate or low when feeding or resting.	Beluga whale, narwhal.	Finley et al. (1990), Matkin et al. (2008), Luque and Ferguson (2009), Ziccardi et al. (2015)
Baleen whales	Eat zooplankton by filtering. Not important prey item for other species.	Low. Late maturity. Two-to-three-year calving period. Calves can swim at birth but are nursed for up to a year.	Spend their life in water, only come to the surface to breath. Relatively solitary animals, travel alone or in small pods.	Poorly understood. Might avoid heavy shipping altogether.	Poorly understood.	Low.	Bowhead whale, fin whale, humpback whale.	Malins (1977), Reeves and Kenney (2003), Ziccardi et al. (2015)

(continued on next page)

Appendix A (*continued*)

Functional group	Role in a food web	Reproduction efficiency	Other relevant characteristics	Acute impacts of oil	Long-term impacts of oil	Sensitivity to oiling (according to AMAP/CAFF/SDWG, 2013)	Example species/genera	Key references
Anatids	Dive food from sea floor, most importantly bivalves. Not important prey item for other species.	Relatively high with annual breeding. Clutch size differs among species but generally more than one egg/couple/year.	Limited diving ability and patchy food sources determine suitable habitats. Migratory.	Smothering may result e.g. in drowning, hypothermia and starvation. Avian embryos are highly sensitive.	May impair reproduction, and depress growth in young. If oil sinks to the seabed, feeding grounds may get contaminated.	Differs from one species to another. Highly sensitive when aggregating and breeding.	Eiders, loons, scoters.	Hartung (1967), Piatt et al. (1990), Esler et al. (2002), Henkel et al. (2012)
Seabirds	Usually feed on schooling fish and crustaceans near surface waters. Not important prey item for other species.	Lower compared to anatids. Often only one egg/couple/year.	Generally vast breeding colonies. Migratory.	Smothering may result e.g. in drowning, hypothermia and starvation. Avian embryos are highly sensitive. May also suffer if large fish schools disappear due to oil.	May impair reproduction, and depress growth in young. If oil sinks to the seabed, feeding grounds may get contaminated.	Differs from one species to another. Highly sensitive when aggregating and breeding.	Guillemots, gulls, cormorants.	Dunnet et al. (1982), Piatt et al. (1990), Irons et al. (2000), Gaston et al. (2005)
Pelagic fish	Main prey zooplankton. Often a key group in Arctic food webs between zooplankton and mammals and birds.	High.	Highly mobile as adults. May occupy different habitat during different life stages.	Likely death of eggs and juveniles. May limit adults' prey catching, mating and predator avoidance behavior.	E.g. negative impacts on liver development and morphological parameters have been reported.	Varies between species, generally high when spawning (especially eggs but also adults).	Polar cod, white fishes, navaga.	Malins and Hodgins (1981), Lonne and Gulliksen (1988), Carls et al. (1999), Young et al. (2011), Dussauze et al. (2014)
Demersal fish	Feed on benthic invertebrates, are preyed by seals.	High.	Mobile but stay on or near the seabed.	Not known. Not necessarily any, depends on the fate of oil.	E.g. neoplasms and liver lesions.	Varies between species, generally high when spawning (especially eggs but also adults).	Plaice, flounders, sculpins.	Malins and Hodgins (1981), Krahn et al., 1986, Jewett et al. (2002), Young et al. (2011)
Benthic invertebrates	Feed on phytoplankton, are preyed by bottom-feeding animals on upper trophic levels.	High.	Adults highly sessile, juveniles' mobility varies. May occupy different habitat during different life stages.	Only when oil sinks to the seabed. Adults might tolerate acute oiling by closing their shells.	Suffocation. Chronic exposure.	Not assessed.	Bivalves	Carls et al. (2001), Forde (2002), Fetzer and Arntz (2008)
Shoreline invertebrates	Feed on phytoplankton or smaller zooplankton, are preyed by bottom-feeding animals on upper trophic levels.	High.	Mobility varies greatly (e.g. highly sessile mollusks vs. mobile crustaceans). May occupy different habitat during different life stages.	Although generally sensitive, impacts appear to be short-lived. Stranded oil may lead to suffocation.	Suffocation. Chronic exposure.	Not assessed.	Bivalves, amphipods, copepods.	Carls et al. (2001), Forde (2002), Fetzer and Arntz (2008)
Ice-associated invertebrates	Feed plankton under the ice, are preyed by ice-associated fish.	High.	Remains under or in the ice till it melts.	Although generally sensitive, impacts appear to be short-lived.	Oil trapped under ice may prolong the harm.	Not assessed.	Notably amphipods.	Neff and Durell (2012), Eamer et al. (2013).
Water column invertebrates	Feed on phytoplankton or smaller zooplankton. Important prey item of pelagic fish and seabirds.	High.	Primarily found in surface waters where food resources are abundant.	Although generally sensitive, impacts appear to be short-lived.	Seldom changes in biomass due to rapid recruitment and reproduction.	Not assessed.	Amphipods, copepods, rotifers.	Forde (2002), Hansen et al. (2011), Neff and Durell (2012), Nørregaard et al. (2015)

References

Aas, E., Baussant, T., Balk, L., Liewenborg, B., Andersen, O.K., 2000. PAH metabolites in bile, cytochrome P4501A and DNA adducts as environmental risk parameters for chronic oil exposure: a laboratory experiment with Atlantic cod. Aquat. Toxicol. 51, 241–258. http://dx.doi.org/10.1016/S0166-445X(00)00108-9.

Aas, E., Beyer, J., Jonsson, G., Reichert, W.L., Andersen, O.K., 2001. Evidence of uptake, biotransformation and DNA binding of polyaromatic hydrocarbons in Atlantic cod and corkwing wrasse. Mar. Environ. Res. 52, 213–229.

ACIA, 2004. Impacts of a Warming Arctic: Arctic Climate Impact Assessment. ACIA Overview Report. Cambridge University Press, Cambridge, UK.

Afenyo, M., Veitch, B., Khan, F., 2016. A state-of-the-art review of fate and transport of oil spills in open and ice-covered water. Ocean Eng. 119, 233–248.

Aguilera, P.A., Fernández, A., Fernández, R., Rumí, R., Salmerón, A., 2011. Bayesian networks in environmental modelling. Environ. Model Softw. 26 (12), 1376–1388.

Ainley, D.G., Grau, C.R., Roydybush, T.E., Morrell, S.H., 1981. Petroleum ingestion reduces reproduction in Cassin's Auklets. Mar. Pollut. Bull. 12 (9), 314–317. http://dx.doi.org/10.1016/0025-326X(81)90083-7.

Albers, P.H., 1998. An Annotated Bibliography on Petroleum Pollution. Version 2007. USGS Patuxent Wildlife Research Center, Laurel, MD.

Allaby, M., 2010. A Dictionary of Ecology. Oxford University Press, Oxford, UK.

AMAP, 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway (xii + 859 pp).

AMAP, 2010. Assessment 2007: Oil and Gas Activities in the Arctic - Effects and Potential Effects. Volume I. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway (vii + 423 pp).

AMAP/CAFF/SDWG, 2013. Identification of Arctic Marine Areas of Heightened Ecological and Cultural Significance: Arctic Marine Shipping Assessment (AMSA) IIc. Arctic Monitoring and Assessment Programme (AMAP), Oslo (114 pp).

Amstrup, S.C., 2003. The Polar Bear – *Ursus maritimus*. In: Feldhamer, G.A., Thompson, B.C., Chapman, J.A., Second edition (Eds.), Wild Mammals of North America: Biology, Management, and Conservation. Johns Hopkins University Press, pp. 587–610.

Andersen, O., Frantzen, M., Rosland, M., Timmerhaus, G., Skugor, A., Krasnov, A., 2015. Effects of crude oil exposure and elevated temperature on the liver transcriptome of polar cod (*Boreogadus saida*). Aquat. Toxicol. 165, 9–18. http://dx.doi.org/10.1016/j.aquatox.2015.04.023.

Aps, R., Fetissov, M., Herkül, K., Kotta, J., Leiger, R., Mander, U., Suursaar, U., 2009. Bayesian inference for predicting potential oil spill related ecological risk. Safety and Security Engineering III. 108, pp. 149–159. http://dx.doi.org/10.2495/SAFE090151.

Arctic Council, 2009. Arctic Marine Shipping Assessment 2009 Report, April 2009, Second Printing.

Bakken, V. (Ed.), 2000. Seabird colony databases of the Barents Sea region and the Kara SeaNorsk Polarinstitutt Rapportserie. Tromso: Norsk Polarinstitutt. N115, 11–34.

Bengtson, J.L., Hiruki-Raring, L.M., Simpkins, M.A., Boveng, P.L., 2005. Ringed and bearded seal densities in the eastern Chukchi Sea, 1999–2000. Polar Biol. 28, 833–845. http://dx.doi.org/10.1007/s00300-005-0009-1.

Bodkin, J.L., Ballachey, B.E., Dean, T.A., Fukuyama, A.K., Jewett, S.C., McDonald, L., Monson, D.H., O'Clair, C.E., VanBlaricom, G.R., 2002. Sea otter population status and the process of recovery from the 1989 'Exxon Valdez' oil spill. Mar. Ecol. Prog. Ser. 241, 237–253.

Boehm, P.D., Page, D.S., 2007. Exposure elements in oil spill risk and natural resource damage assessments: a review. Hum. Ecol. Risk. Assess. 13 (2), 418–448.

Boehm, P.D., Page, D.S., Brown, J.S., Neff, J.M., Burns, W.A., 2004. Polycyclic aromatic hydrocarbon levels in mussels from Prince William Sound, Alaska, USA, document the return to baseline conditions. Environ. Toxicol. Chem. 23, 2916–2929. http://dx.doi.org/10.1897/03-514.1.

Bohle, B., 1986. Avoidance of petroleum hydrocarbons by the cod (*Gadus morhua*). Fiskeridirektoratets Skrifer, Serie Ernaering 18, 97–112.

Bolsunovskaya, Y.A., Bolsunovskaya, L.M., 2015. Ecological risk analysis as a key factor in environmental safety system development in the Arctic region of the Russian Federation. IOP Conference Series. Earth Environ. Sci. 24 (1), 012003.

Boltunov, A.N., Belikov, S.E., 2002. Belugas (*Delphinapterus leucas*) of the Barents, Kara and Laptev Seas. 4. NAMMCO Scientific Publications, pp. 149–168.

Boltunov, A.N., Belikov, S.E., Gorbunov, Y.A., Menis, D.T., Semenova, V.S., 2010. The Atlantic Walrus of the Southeastern Barents Sea and Adjacent Regions: Review of the Present-Day Status. Marine Mammal Council, WWF-Russia.

Bonsdorff, E., Nelson, W.G., 1981. Fata and effects of Ekofisk crude oil in the littoral of a Norwegian Fjord. Sarsia 66, 231–240.

Boyer, T.P., Antonov, J.I., Baranova, O.K., Coleman, C., Garcia, H.E., Grodsky, A., Johnson, D.R., Locarnini, R.A., Mishonov, A.V., O'Brien, T.D., Paver, C.R., Reagan, J.R., Seidov, D., Smolyar, I.V., Zweng, M.M., 2013. In: Levitus, S. (Ed.), World Ocean Database 2013, NOAA Atlas NESDIS 72. A. Mishonov, Technical Ed.; Silver Spring, MD (209 pp.). http://doi.org/10.7289/V5NZ85MT.

Brandvik, P.J., Sorheim, K.R., Singsaas, I., Reed, M., 2006. Short state-of-the-art report on oil spills in ice-infested waters. Oil behaviour and response options. SINTEF Materials and Chemistry. Report No. STF80MKA06148.

Briggs, K.T., Gershwin, M.E., Anderson, D.W., 1997. Consequences of petrochemical ingestion and stress on the immune system of seabirds. ICES J. Mar. Sci. 54, 718–725.

Burgman, M., 2005. Risks and Decisions for Conservation and Environmental Management. Cambridge University Press, Cambridge, UK.

Calow, P.P., 2009. The Blackwell's Concise Encyclopedia of Ecology. John Wiley & Sons, Malden.

Carls, M.G., Babcock, M.M., Harris, P.M., Irvine, G.V., Cusick, J.A., Rice, S.D., 2001. Persistence of oiling in mussel beds after the Exxon Valdez oil spill. Mar. Environ. Res. 5, 167–190. http://dx.doi.org/10.1016/S0141-1136(00)00103-3.

Carls, M.G., Harris, P.M., Rice, S.D., 2004. Restoration of oiled mussel beds in Prince William Sound, Alaska. Mar. Environ. Res. 57 (5), 359–376. http://dx.doi.org/10.1016/j.marenvres.2003.11.002.

Carls, M.G., Rice, S.D., Hose, J.E., 1999. Sensitivity of fish embryos to weathered crude oil: part I. Low-level exposure during incubation causes malformations, genetic damage, and mortality in larval pacific herring (*Clupea pallasi*). Environ. Toxicol. Chem. 18 (3), 481–493. http://dx.doi.org/10.1002/etc.5620180317.

Carriger, J.F., Barron, M.G., 2011. Minimizing risks from spilled oil to ecosystem services using influence diagrams: the Deepwater Horizon spill response. Environ. Sci. Technol. 45 (18), 7631–7639. http://dx.doi.org/10.1021/es201037u.

Castelletti, A., Soncini-Sessa, R., 2007. Bayesian Networks and participatory modelling in water resource management. Environ. Model Softw. 22, 1075–1088. http://dx.doi.org/10.1016/j.envsoft.2006.06.003.

Cavalieri, D.J., Parkinson, C.L., Gloersen, P., Zwally, H.J., 1996. Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/ISSMIS Passive Microwave Data. 1978–2007. National Snow and Ice Data Center, Boulder, Colorado, USA. http://dx.doi.org/10.5067/8GQ8LZQVL0VL ([27.3.2015]). updated yearly.

Cohen, D.M., Inada, T., Iwamoto, T., Scialabba, N., 1990. FAO species catalogue. Vol. 10. Gadiform fishes of the world (Order Gadiformes). An annotated and illustrated catalogue of cods, hakes, grenadiers and other gadiform fishes known to date. FAO Fisheries Synopsis. No. 125 10. FAO, Rome.

Day, R.H., Murphy, S.M., Wiens, J.A., Hayward, G.D., Harner, E.J., Smith, L.N., 1997. Effects of the Exxon Valdez oil spill on habitat use by birds in Prince William Sound, Alaska. Ecol. Appl. 7 (2), 593–613. http://dx.doi.org/10.2307/2269524.

DNV GL, 2014. The Arctic - The Next Risk Frontier. https://issuu.com/dnvgl/docs/dnv_gl_-_the_arctic_report/1.

Dunnet, G.M., Crisp, D.J., Conan, G., Bourne, R.P., 1982. Oil pollution and seabird populations [and discussion]. Philos. Trans. R. Soc., B 297 (1087), 413–427. http://dx.doi.org/10.1098/rstb.1982.0051.

Dussauze, M., Camus, L., Le Floch, S., Pichavant-Rafini, K., Geraudie, P., Coquille, N., Amerand, A., Lemaire, P., Theron, M., 2014. Impact of dispersed fuel oil on cardiac mitochondrial function in polar cod *Boreogadus saida*. Environ. Sci. Pollut. Res. Int. 21, 13779–13788. http://dx.doi.org/10.1007/s11356-014-2618-0.

Eamer, J., Donaldson, G.M., Gaston, A.J., Kosobokova, K.N., Lárusson, K.F., Melnikov, I.A., Reist, J.D., Richardson, E., Staples, L., von Quillfeldt, C.H., 2013. Life Linked to Ice: a guide to sea-ice-associated biodiversity in this time of rapid change. Conservation of Arctic Flora and Fauna, Iceland. CAFF Assessment Series No. 10.

Edmunds, R.C., Gill, J.A., Baldwin, D.H., Linbo, T.L., French, B.L., Brown, T.L., Esbaugh, A.J., Mager, E.M., Stieglitz, J., Hoenig, R., Benetti, D., Grosell, M., Scholz, N.L., Incardona, J.P., 2015. Corresponding morphological and molecular indicators of crude oil toxicity to the developing hearts of mahi mahi. Sci. Rep. 5, 17326. http://dx.doi.org/10.1038/srep17326.

Ehlers, S., Kujala, P., Veitch, B., Khan, F., Vanhatalo, J., 2014. Scenario based risk management for arctic shipping and operations. ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering: Polar and Arctic Science and Technology. 10(33).

Eidsvik, J., Mukerji, T., Bhattacharjya, D., 2015. Value of Information in the Earth Sciences. Cambridge University Press, Cambridge, UK.

Elith, J., Leathwick, J.R., 2009. Species distribution models: ecological explanation and prediction across space and time. Annu. Rev. Ecol. Evol. Syst. 40, 677–697. http://dx.doi.org/10.1146/annurev.ecolsys.110308.120159.

Engelhardt, F.R., 1983. Petroleum effects on marine mammals. Aquat. Toxicol. 4 (3), 199–217. http://dx.doi.org/10.1016/0166-445X(83)90018-8.

EPPR, 1996. Environmental risk analysis of Arctic activities. Emergency Prevention, Preparedness and Response (EPPR) Risk Analysis Report No. 2, September 1, 1998.

Esler, D., Bowman, T.D., Trust, K.A., Ballachey, B.E., Dean, T.A., Jewett, S.C., O'Clair, C.E., 2002. Harlequin duck population recovery following the 'Exxon Valdez' oil spill: progress, process and constraints. Mar. Ecol. Prog. Ser. 241, 271–286. http://dx.doi.org/10.3354/meps241271.

Faksness, L.G., Brandvik, P.J., 2008. Distribution of water soluble components from Arctic marine oil spills – a combined laboratory and field study. Cold Reg. Sci. Technol. 54 (2), 97–105. http://dx.doi.org/10.1016/j.coldregions.2008.03.005.

Fetzer, I., Arntz, W.E., 2008. Reproductive strategies of benthic invertebrates in the Kara Sea (Russian Arctic): adaptation of reproduction modes to cold water. Mar. Ecol. Prog. Ser. 356, 189–202. http://dx.doi.org/10.3354/meps07271.

Fingas, M., 2000. The Basics of Oil Spill Cleanup. Lewis Publishers, Boca Raton.

Fingas, M.V., Hollebone, B.P., 2003. Review of behaviour of oil in freezing environments. Mar. Pollut. Bull. 47 (9–12), 333–340. http://dx.doi.org/10.1016/S0025-326X(03)00210-8.

Finley, K.J., Miller, G.W., Davis, R.A., Greene, C.R., 1990. Reactions of belugas, *Delphinapterus leucas*, and narwhals, *Monodon monoceros*, to ice-breaking ships in the Canadian High Arctic. Can. Bull. Fish. Aquat. Sci. 224, 97–117.

Forde, S.E., 2002. Modelling the effects of an oil spill on open populations of intertidal invertebrates. J. Appl. Ecol. 39, 595–604. http://dx.doi.org/10.1046/j.1365-2664.2002.00737.x.

Fowle, J.R., Dearfield, K.L., 2000. Risk Characterization Handbook. Prepared for the U.S. Environmental Protection Agency. EPA 100-B-00-002.

French McCay, D., Rowe, J.J., Whittier, N., Sankaranarayanan, S., Etkin, D.S., 2004. Estimation of potential impacts and natural resource damages of oil. J. Hazard. Mater. 107, 11–25.

French-McCay, D.P., 2004. Oil spill impact modeling: development and validation. Environ. Toxicol. Chem. 23, 2441–2456. http://dx.doi.org/10.1897/03-382.

Fukuyama, A.K., Shigenaka, G., Coats, D.A., 2014. Status of intertidal infaunal communities following the Exxon Valdez oil spill in Prince William Sound, Alaska. Mar. Pollut. Bull. 84 (1–2), 56–69. http://dx.doi.org/10.1016/j.marpolbul.2014.05.043.

Gaston, A.J., Gilchrist, H.G., Hipfner, J.M., 2005. Climate change, ice conditions and reproduction in an Arctic nesting marine bird: Brunnich's guillemot (*Uria lomvia* L.). J. Anim. Ecol. 74, 832–841. http://dx.doi.org/10.1111/j.1365-2656.2005.00982.x.

Gelfand, A.E., Holder, M., Latimer, A., Lewis, P.A., Rebelo, A., Silander, J.A., Wu, S., 2006. Explaining species distribution patterns through hierarchical modeling. Bayesian Anal. 1, 41–92. http://dx.doi.org/10.1214/06-BA102.

Gelman, A., Carlin, J.B., Stern, H.S., Dunson, D.B., Vehtari, A., Rubin, D.B., 2013. Bayesian Data Analysis. Third Edition. Chapman and Hall/CRC, Boca Raton, Florida.

Gentile, J.H., Harwell, M.A., 1998. The issue of significance in ecological risk assessments. Hum. Ecol. Risk. Assess. 4, 815–828. http://dx.doi.org/10.1080/10807039891284811.

Gerber, L.R., Buenau, K.E., VanBlaricom, G.R., 2004. Density dependence and risk of extinction in a small population of sea otters. Biodivers. Conserv. 13, 2741–2757. http://dx.doi.org/10.1007/s10531-004-2146-1.

Glazov, D.M., Shpak, O.V., Kuznetsova, D.M., Solovyev, B.A., Udovik, D.A., Platonov, N.G., Mordvintsev, I.N., Ivanov, D.I., Rozhnov, V.V., 2013. Observations of the walrus (*Odobenus rosmarus*) in the Barents, Kara, and Laptev seas in 2010–2012. Biol. Bull. 40 (9), 783–789. http://dx.doi.org/10.1134/S1062359013090057.

Golet, G.H., Seiser, P.E., McGuire, A.D., Roby, D.D., Fischer, J.B., Kuletz, K.J., Irons, D.B., Dean, T.A., Jewett, S.C., Newman, S.H., 2002. Long-term direct and indirect effects of the 'Exxon Valdez' oil spill on pigeon guillemots in Prince William sound. Mar. Ecol. Prog. Ser. 241, 287–304. http://dx.doi.org/10.3354/meps241287.

Guisan, A., Edwards Jr., T.C., Hastie, T., 2002. Generalized linear and generalized additive models in studies of species distributions: setting the scene. Ecol. Model. 157, 89–100. http://dx.doi.org/10.1016/S0304-3800(02)00204-1.

Hannam, M.L., Bamber, S.D., Moody, J.A., Galloway, T.S., Jones, M.B., 2010. Immunotoxicity and oxidative stress in the Arctic scallop *Chlamys islandica*: effects of acute oil exposure. Ecotoxicol. Environ. Saf. 73, 1440–1448. http://dx.doi.org/10.1016/j.ecoenv.2010.06.012.

Hansen, B.H., Altin, D., Rørvik, S.F., Øverjordet, I.B., Olsen, A.J., Nordtug, T., 2011. Comparative study on acute effects of water accommodated fractions of an artificially weathered crude oil on *Calanus finmarchicus* and *Calanus glacialis* (Crustacea: Copepoda). Sci. Total Environ. 409 (4), 704–709. http://dx.doi.org/10.1016/j.scitotenv.2010.10.035.

Hartung, R., 1967. Energy metabolism in oil-covered ducks. J. Wildl. Manag. 31 (4), 798–804. http://dx.doi.org/10.2307/3797987.

Heithaus, M.R., Frid, A., Wirsing, A.J., Worm, B., 2008. Predicting ecological consequences of marine top predator declines. Trends Ecol. Evol. 23 (4), 202–210. http://dx.doi.org/10.1016/j.tree.2008.01.003.

HELCOM, 2013. HELCOM core indicators: final report of the HELCOM CORESET project. Balt. Sea Environ. Proc. No. 136.

Helle, I., Ahtiainen, H., Luoma, E., Hänninen, M., Kuikka, S., 2015. A probabilistic approach for a cost-benefit analysis of oil spill management under uncertainty: a Bayesian network model for the Gulf of Finland. J. Environ. Manag. 158, 122–132. http://dx.doi.org/10.1016/j.jenvman.2015.04.042.

Helle, I., Jolma, A., Venesjärvi, R., 2016. Species and habitats in danger: estimating the relative risk posed by oil spills in the northern Baltic Sea. Ecosphere 7 (5), e01344. http://dx.doi.org/10.1002/ecs2.1344.

Helle, I., Lecklin, T., Jolma, A., Kuikka, S., 2011. Modeling the effectiveness of oil combating from an ecological perspective - a Bayesian network for the Gulf of Finland; the Baltic Sea. J. Hazard. Mater. 185 (1), 182–192. http://dx.doi.org/10.1016/j.jhazmat.2010.09.017.

Henkel, J.R., Sigel, B.J., Taylor, C.M., 2012. Large-scale impacts of the Deepwater Horizon oil spill: can local disturbance affect distant ecosystems through migratory shorebirds? Bioscience 62 (7), 676–685. http://dx.doi.org/10.1525/bio.2012.62.7.10.

Hjermann, D.Ø., Melsom, A., Dingsør, G.E., Durant, J.M., Eikeset, A.M., Roed, L.P., Ottersen, G., Storvik, G., Stenseth, N.C., 2007. Fish and oil in the Lofoten–Barents Sea system: synoptic review of the effect of oil spills on fish populations. Mar. Ecol. Prog. Ser. 339, 283–299. http://dx.doi.org/10.3354/meps339283.

Ho, J., 2010. The implications of Arctic sea ice decline on shipping. Mar. Policy 34 (3), 713–715. http://dx.doi.org/10.1016/j.marpol.2009.10.009.

Hop, H., Gjøsæter, H., 2013. Polar cod (*Boreogadus saida*) and capelin (*Mallotus villosus*) as key species in marine food webs of the Arctic and the Barents Sea. Mar. Biol. Res. 9 (9), 878–894. http://dx.doi.org/10.1080/17451000.2013.775458.

Hossain, K., Koivurova, T., Zojer, G., 2014. Understanding risks associated with offshore hydrocarbon development. In: Tedsen, E., Cavalieri, S., Kraemer, R.A. (Eds.), Arctic Marine Governance Opportunities for Transatlantic Cooperation. Springer, Heidelberg, pp. 159–178.

Howard, R.A., Matheson, J.E., 2005. Influence diagrams. Decis. Anal. 2 (3), 127–143. http://dx.doi.org/10.1287/deca.1050.0020.

Hurst, R.J., Watts, P.D., Oritsland, N.A., 1991. Metabolic compensation in oil-exposed polar bears. J. Therm. Biol. 16, 53–56. http://dx.doi.org/10.1016/0306-4565(91)90052-4.

Irons, D.B., Kendall, S.T., Erickson, W.P., McDonald, L.L., Lance, B.K., 2000. Nine years after the Exxon Valdez oil spill: effects on marine bird populations in Prince William Sound, Alaska. Condor 102 (4), 723–737. http://dx.doi.org/10.2307/1370300.

Jakobsson, M., et al., 2012. The International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3.0. Geophys. Res. Lett. 39, L12609. http://dx.doi.org/10.1029/2012GL052219.

Jensen, F.V., 1996. An Introduction to Bayesian Networks. UCL Press, London, UK.

Jensen, F.V., Nielsen, T.H., 2007. Bayesian Networks and Decision Graphs. Springer, New York.

Jewett, S.C., Dean, T.A., Woodin, B.R., Hoberg, M.K., Stegeman, J.J., 2002. Exposure to hydrocarbons 10 years after the Exxon Valdez oil spill evidence from cytochrome P4501A expression and biliary FACs in nearshore demersal fishes. Mar. Environ. Res. 54, 21–48. http://dx.doi.org/10.1016/S0141-1136(02)00093-4.

Johnston, A., Fink, D., Reynolds, M.D., Hochachka, W.M., Sullivan, B.L., Bruns, N.E., Hallstein, E., Merrifield, M.S., Matsumoto, S., Kelling, S., 2015. Abundance models improve spatial and temporal prioritization of conservation resources. Ecol. Appl. 25, 1749–1756. http://dx.doi.org/10.1890/14-1826.1.

Jolma, A., Lehikoinen, A., Helle, I., Venesjärvi, R., 2014. A software system for assessing the spatially distributed ecological risk posed by oil shipping. Environ. Model Softw. 61, 1–11. http://dx.doi.org/10.1016/j.envsoft.2014.06.023.

Jonsson, H., Sundt, R.C., Aas, E., Sanni, S., 2010. The Arctic is no longer put on ice: evaluation of Polar cod (*Boreogadus saida*) as a monitoring species of oil pollution in cold waters. Mar. Pollut. Bull. 60 (3), 390–395. http://dx.doi.org/10.1016/j.marpolbul.2009.10.014.

Jörundsdóttir, H.Ó., Jensen, S., Hylland, K., Holth, T.F., Gunnlaugsdóttir, H., Svavarsson, J., Ólafsdóttir, Á., El-Taliawy, H., Rigét, F., Strand, J., Nyberg, E., Bignerf, A., Hoydal, K.S., Halldórsson, H.P., 2014. Pristine Arctic: background mapping of PAHs, PAH metabolites and inorganic trace elements in the North-Atlantic Arctic and sub-Arctic coastal environment. Sci. Total Environ. 493, 719–728. http://dx.doi.org/10.1016/j.scitotenv.2014.06.030.

Kaiser, M.J., Attrill, M.J., Jennings, S., Thomas, D.N., Barnes, D.K.A., Brierley, A.S., Hiddink, J.G., Kaartokallio, H., Polunin, N.V.C., Raffaelli, D.G., 2011. Marine Ecology: Processes, Systems, and Impacts. Oxford University Press, Oxford.

Kelly, B.P., Bengtson, J.L., Boveng, P.L., Cameron, M.F., Dahle, S.P., Jansen, J.K., Logerwell, E.A., Overland, J.E., Sabine, C.L., Waring, G.T., Wilder, J.M., 2010. Status Review of the Ringed Seal (*Phoca hispida*). U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-212 250 p.

Kelmelis, J.A., 2011. Arctic warming ripples through eurasia. Eurasian Geogr. Econ. 52 (1), 56–78. http://dx.doi.org/10.2747/1539-7216.52.1.56.

King, J.G., Sanger, G.A., 1979. Oil vulnerability index for marine oriented birds, Conservation of marine birds of Northern North America. In: Bartonek, J.C., Nettleship, D.N. (Eds.), Wildlife Research Report 11. U.S. Fish and Wildlife Service, Washington DC, pp. 228–239.

Krahn, M.M., Rhodes, L.D., Myers, M.S., Moore, L.K., MacLeod Jr., W.D., Malins, D.C., 1986. Associations between metabolites of aromatic compounds in bile and the occurrence of hepatic lesions in English sole (*Parophrys vetulus*) from Puget Sound, Washington. Arch. Environ. Contam. Toxicol. 15, 61–67. http://dx.doi.org/10.1007/BF01055249.

Kubach, K.M., Scott, M.C., Bulak, J.S., 2011. Recovery of a temperate riverine fish assemblage from a major diesel oil spill. Freshw. Biol. 56 (3), 503–518. http://dx.doi.org/10.1111/j.1365-2427.2010.02517.x.

Landuyt, D., Broekx, S., D'hondt, R., Engelen, G., Aertsens, J., Goethals, P.L.M., 2013. A review of Bayesian belief networks in ecosystem service modelling. Environ. Model Softw. 46, 1–11. http://dx.doi.org/10.1016/j.envsoft.2013.03.011.

Lecklin, T., Ryömä, R., Kuikka, S., 2011. A Bayesian network for analyzing biological acute and long-term impacts of an oil spill in the Gulf of Finland. Mar. Pollut. Bull. 62, 2822–2835. http://dx.doi.org/10.1016/j.marpolbul.2011.08.045.

Lehikoinen, A., Hänninen, M., Storgård, J., Luoma, E., Mäntyniemi, S., Kuikka, S., 2015. A Bayesian network for assessing the collision induced risk of an oil accident in the Gulf of Finland. Environ. Sci. Technol. 49 (9), 5301–5309. http://dx.doi.org/10.1021/es501777g.

Leighton, F.A., 1993. The toxicity of petroleum oils to birds. Environ. Rev. 1, 92–103. http://dx.doi.org/10.1139/a93-008.

Lipcius, R.N., Coyne, C.A., Fairbanks, B.A., Hammond, D.H., Mohan, P.J., Nixon, D.T., Staskiewicz, J.J., Heppner, F.H., 1980. Avoidance response of mallards to colored and black water. J. Wildl. Manag. 44 (2), 511–518. http://dx.doi.org/10.2307/3807991.

Lonne, O.J., Gulliksen, B., 1988. Size, age and diet of polar cod, *Boreogadus saida* (Lepechin 1773), in ice covered waters. Polar Biol. 9, 187–191. http://dx.doi.org/10.1007/BF00297174.

Luque, S.P., Ferguson, S.H., 2009. Age structure, growth, mortality, and density of belugas (*Delphinapterus leucas*) in the Canadian Arctic: responses to environment? Polar Biol. 33, 163–178. http://dx.doi.org/10.1007/s00300-009-0694-2.

Luttik, R., Mineau, P., Roelofs, W., 2005. A review of interspecies toxicity extrapolation in birds and mammals and a proposal for long-term toxicity data. Ecotoxicology 14, 817–832. http://dx.doi.org/10.1007/s10646-005-0030-8.

Malins, D.J., 1977. Effects of Petroleum on Arctic and Subarctic Marine Environments and Organisms. V.2: Biological Effects. Academic Press, New York, San Francisco and London.

Malins, D.C., Hodgins, H.O., 1981. Petroleum and marine fishes a review of uptake, disposition, and effects. Environ. Sci. Technol. 15 (11), 1272–1280. http://dx.doi.org/10.1021/es00093a001.

Mäntyniemi, S., Kuikka, S., Rahikainen, M., Kell, L.T., Kaitala, V., 2009. The value of information in fisheries management: north sea herring as an example. ICES J. Mar. Sci. 66 (10), 2278–2283. http://dx.doi.org/10.1093/icesjms/fsp206.

Marty, G.D., Short, J.W., Dambach, D.M., Willits, N.H., Heintz, R.A., Rice, S.D., Stegeman, J.J., Hinton, D.E., 1997. Ascites, premature emergence, increased gonadal cell apoptosis, and cytochrome P4501A induction in pink salmon larvae continuously exposed to oil-contaminated gravel during development. Can. J. Zool. 75, 989–1007. http://dx.doi.org/10.1139/z97-120.

Matishov, G.G., Chelintsev, N.G., Goryaev, Y.I., Makarevich, P.R., Ishkulov, D.G., 2014. Assessment of the amount of polar bears (*Ursus maritimus*) on the basis of perennial vessel counts. Dokl. Earth Sci. 458 (2), 1312–1316. http://dx.doi.org/10.1134/S1028334X14100298.

Matkin, C.O., Saulitis, E.L., Ellis, G.M., Olesiuk, P., Rice, S.D., 2008. Ongoing population-level impacts on killer whales *Orcinus orca* following the 'Exxon Valdez' oil spill in Prince William Sound, Alaska. Mar. Ecol. Prog. Ser. 356, 269–281. http://dx.doi.org/10.3354/meps07273.

Mauritzen, M., Belikov, S.E., Boltunov, A.N., Derocher, A.E., Hansen, E., Ims, R.A., Wiig, Ø., Yoccoz, N., 2003. Functional responses in polar bear habitat selection. Oikos 100, 112–124. http://dx.doi.org/10.1034/j.1600-0706.2003.12056.x.

McCann, R.K., Marcot, B.G., Ellis, R., 2006. Bayesian belief networks: applications in ecology and natural resource management. Can. J. For. Res. 36, 3053–3062. http://dx.doi.org/10.1139/x06-238.

Miquel, J.C., 2001. Environment and biology of the Kara Sea: a general view for contamination studies. Mar. Pollut. Bull. 43 (1–6), 19–27. http://dx.doi.org/10.1016/S0025-326X(00)00235-6.

Molnár, P.K., Derocher, A.E., Thiemann, G.W., Lewis, M.A., 2010. Predicting survival, reproduction and abundance of polar bears under climate change. Biol. Conserv. 143 (7), 1612–1622. http://dx.doi.org/10.1016/j.biocon.2010.04.004.

Moore, S.E., Huntington, H.P., 2008. Arctic marine mammals and climate change: impacts and resilience. Ecol. Appl. 18 (2), S157–S165. http://dx.doi.org/10.1890/06-0571.1.

Potential Environmental impacts of oil spills in Greenland. An assessment of information status and research needs. In: Mosbech, A. (Ed.), NERI Technical Report No. 415. National Environmental Research Institute, Denmark (118 pp).

Muir, D.C.G., Wagemann, R., Hargrave, B.T., Thomas, D.J., Peakall, D.B., Norstrom, R.J., 1992. Arctic marine ecosystem contamination. Sci. Total Environ. 122 (1–2), 75–134. http://dx.doi.org/10.1016/0048-9697(92)90246-O.

Myers, R.A., Baum, J.K., Shepherd, T.D., Powers, S.P., Peterson, C.H., 2007. Cascading effects of the loss of apex predatory sharks from a coastal ocean. Science 315 (5821), 1846–1850. http://dx.doi.org/10.1126/science.1138657.

Neff, J.M., Durell, G.S., 2012. Bioaccumulation of petroleum hydrocarbons in arctic amphipods in the oil development area of the Alaskan Beaufort Sea. Integr. Environ. Assess. Manag. 8 (2), 301–319. http://dx.doi.org/10.1002/ieam.1247.

Nixon, Z., Michel, J., 2015. Predictive modeling of subsurface shoreline oil encounter probability from the Exxon Valdez oil spill in Prince William Sound, Alaska. Environ. Sci. Technol. 49 (7), 4354–4361. http://dx.doi.org/10.1021/es502579u.

Norcross, B.L., Hose, J.E., Frandsen, M., Brown, E.D., 1996. Distribution, abundance, morphological condition, and cytogenetic abnormalities of larval herring in Prince William Sound, Alaska, following the Exxon Valdez oil spill. Can. J. Fish. Aquat. Sci. 53, 2376–2387. http://dx.doi.org/10.1139/f96-212.

Nørregaard, R.D., Gustavson, K., Moller, E.F., Strand, J., Tairova, Z., Mosbech, A., 2015. Ecotoxicological investigation of the effect of accumulation of PAH and possible impact of dispersant in resting high arctic copepod *Calanus hyperboreus*. Aquat. Toxicol. 167, 1–11. http://dx.doi.org/10.1016/j.aquatox.2015.07.006.

O'Hagan, A., Buck, C.E., Daneshkhah, A., Eiser, J.R., Garthwaite, P.H., Jenkinson, D.J., Oakley, J.E., Rakow, T., 2006. Uncertain Judgements. Eliciting Experts' Probabilities. Wiley.

Ordiz, A., Bischof, R., Swenson, J.E., 2013. Saving large carnivores, but losing the apex predator? Biol. Conserv. 168, 128–133. http://dx.doi.org/10.1016/j.biocon.2013.09.024.

Paine, R.T., Ruesink, J.L., Sun, A., Soulanille, E.L., Wonhan, M.J., Harley, C.D.G., Brumbaugh, D.R., Secord, D.L., 1996. Trouble on oiled waters: lessons from the Exxon Valdez oil ppill. Annu. Rev. Ecol. Syst. 27, 197–235. http://dx.doi.org/10.1146/annurev.ecolsys.27.1.197.

Palumbi, S.R., McLeod, K.L., Grunbaum, D., 2008. Ecosystems in action: lessons from marine ecology about recovery, resistance, and reversibility. Bioscience 58 (1), 33–42. http://dx.doi.org/10.1641/B580108.

Payne, J.R., Driskell, W.B., Short, J.W., Larsen, M.L., 2008. Long term monitoring for oil in the Exxon Valdez spill region. Mar. Pollut. Bull. 56 (12), 2067–2081. http://dx.doi.org/10.1016/j.marpolbul.2008.07.014.

Pearl, J., 1988. Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA.

Peterson, C.H., Rice, S.D., Short, J.W., Esler, D., Bodkin, J.L., Ballachey, B.E., Irons, D.B., 2003. Long-term ecosystem response to the Exxon Valdez oil spill. Science 302, 2082–2086. http://dx.doi.org/10.1126/science.1084282.

Piatt, J.F., Lensink, C.J., Butler, W., Kendziorek, M., Nysewander, D.R., 1990. Immediate impact of the 'Exxon Valdez' oil spill on marine birds. Auk 107, 387–397.

Pinto, J.M., Pearson, W.H., Anderson, J.W., 1984. Sediment preferences and oil contamination in the Pacific sand lance *Ammodytes hexapterus*. Mar. Biol. 83 (2), 193–204. http://dx.doi.org/10.1007/BF00394728.

Raiffa, H., Schlaifer, R., 1961. Applied Statistical Decision Theory. MIT Press, Cambridge, MA.

Reed, M., Aamo, O.M., Daling, P.S., 1995. Quantitative analysis of alternate oil spill response strategies using OSCAR. Spill Sci. Technol. Bull. 2, 67–74. http://dx.doi.org/10.1016/1353-2561(95)00020-5.

Reeves, R.R., Kenney, R.D., 2003. Baleen Whales: Right whales and allies (*Eubalaena* spp.). In: Feldhamer, G.A., Thompson, B.C., Chapman, J.A. (Eds.), Wild Mammals of North America: Biology, Management, and Conservation, Second edition Johns Hopkins University Press, pp. 425–466.

Rice, S.D., 1973. Toxicity and avoidance tests with Prudhoe Bay oil and pink salmon fry. Proceedings of the Joint Conference on Prevention and Control of Oil Spills. American Petroleum Institute, pp. 667–670.

Ryder, K., Temara, A., Holdway, D.A., 2004. Avoidance of crude-oil contaminated sediment by the Australian seastar, Patiriella exigua (Echinodermata: Asteroidea). Mar. Pollut. Bull. 49 (11 − 12), 900–909. http://dx.doi.org/10.1016/j.marpolbul.2004.06.013.

Savinov, V., Muir, D.C.G., Svetochev, V., Svetocheva, O., Belikov, S., Boltunov, A., Alekseeva, L., Reiersen, L.-O., Savinova, T., 2011. Persistent organic pollutants in ringed seals from the Russian Arctic. Sci. Total Environ. 409 (14), 2734–2745. http://dx.doi.org/10.1016/j.scitotenv.2011.02.039.

Scott, G.R., Sloman, K.A., 2004. The effects of environmental pollutants on complex fish behaviour: integrating behavioural and physiological indicators of toxicity. Aquat. Toxicol. 68, 369–392. http://dx.doi.org/10.1016/j.aquatox.2004.03.016.

Stirling, I., 2005. Reproductive rates of ringed seals and survival of pups in Northwestern Hudson Bay, Canada, 1991–2000. Polar Biol. 28, 381–387. http://dx.doi.org/10.1007/s00300-004-0700-7.

Storer, T.I., Usinger, R.L., Stebbins, R.C., Nybakken, J.W., 1979. General Zoology. Sixth Edition. McGraw-Hill Book Company, New York.

Sulistiyono, H., Khan, F., Lye, L., Yang, M., 2015. A risk-based approach to developing design temperatures for vessels operating in low temperature environments. Ocean Eng. 108, 813–819. http://dx.doi.org/10.1016/j.oceaneng.2015.08.040.

Thomas, R.E., Harris, P.M., Rice, S.D., 1999. Survival in air of *Mytilus trossulus* following long-term exposure to spilled Exxon Valdez crude oil in Prince William Sound. Comp. Biochem. Physiol. 122, 147–152. http://dx.doi.org/10.1016/S0742-8413(98)10098-1.

Transportation Research Board, National Research Council, 2003,. Oil in the Sea III: Inputs, Fates, and Effects. The National Academies Press, Washington, DC.

Transportation Research Board, National Research Council, 2014,. Responding to Oil Spills in the U.S. Arctic Marine Environment. The National Academies Press, Washington, DC.

Uusitalo, L., 2007. Advantages and challenges of Bayesian networks in environmental modelling. Ecol. Model. 203 (3–4), 312–318. http://dx.doi.org/10.1016/j.ecolmodel.2006.11.033.

Verny, J., Grigentin, C., 2009. Container shipping on the Northern Sea Route. Int. J. Prod. Econ. 122 (1), 107–117. http://dx.doi.org/10.1016/j.ijpe.2009.03.018.

Weber, J., Halsall, C.J., Muir, D., Teixeira, C., Small, J., Solomon, K., Hermanson, M., Hung, H., Bidleman, T., 2010. Endosulfan, a global pesticide: a review of its fate in the environment and occurrence in the Arctic. Sci. Total Environ. 408 (15), 2966–2984.

Wells, P.G., Percy, J.A., 1985. Effects of oil on Arctic invertebrates. In: Engelhardt, F.R. (Ed.), Petroleum Effects in the Arctic Environment. Elsevier Appl. Sci. Publ, London, pp. 101–156.

Wiese, F.K., Robertson, G.J., 2004. Assessing seabird mortality from chronic oil discharges at sea. J. Wildl. Manag. 68 (3), 627–638. http://dx.doi.org/10.2193/0022-541X(2004)068[0627:ASMFCO]2.0.CO;2.

Young, J.W., Skewes, T.D., Lyne, V.D., Hook, S.E., Revill, A.T., Condie, S.A., Newman, S.J., Wakefield, C.B., Lloyd, J., Martin, J., Molony, B.W., 2011. A Review of the Fisheries Potentially Affected by the Montara Oil Spill off Northwest Australia and Potential Toxicological Effects. Report to PTTEP Australasia and SEWPAC.

Ziccardi, M.H., Wilkin, S.M., Rowles, T.K., Johnson, S., 2015. Pinniped and Cetacean Oil Spill Response Guidelines. NOAA Technical Memorandum NMFS-OPR-52.