Preparing for the unprecedented – Moving towards quantitative understanding of oil spill impacts on Arctic marine biota

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DOCTORAL DISSERTATION

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The thesis consists of the summary and the following papers, which are referred to in the summary by their Roman numerals:

I Nevalainen, M., Helle, I., Vanhatalo, J., 2017. Preparing for the unprecedented — Towards quantitative oil risk assessment in the Arctic marine areas. Marine Pollution Bulletin 114, 90–101.

II Nevalainen, M., Helle, I., Vanhatalo, J., 2018. Estimating the acute impacts of Arctic marine oil spills using expert elicitation. Marine Pollution Bulletin 131, 782–792.

III Nevalainen, M., Vanhatalo, J., Helle, I. *Accepted for publication*. Index-based approach for estimating vulnerability of Arctic biota to oil spills. Ecosphere.

IV Helle, I., Mäkinen, J., Nevalainen, M., Afenyo, M., Vanhatalo, J. Impacts of oil spills on Arctic marine ecosystems: A quantitative and probabilistic risk assessment perspective. Submitted manuscript.

Author's contribution to the papers:

I The original research idea was developed jointly by all the authors. Nevalainen carried out the literature review and had the main responsibility in constructing the framework and the conceptual models. The paper was jointly written by the authors.

II The original research idea was developed jointly by all the authors. The elicitation tool was built by Nevalainen and Vanhatalo. Nevalainen had the main responsibility in designing and implementing the expert elicitation. Nevalainen processed and analyzed the data and had the main responsibility in interpreting the results and writing the paper.

III Nevalainen was responsible for the original research idea and all parts of the work including literature review, constructing the conceptual model, designing and implementing the indexing method, processing the data, interpreting the results and writing the manuscript. Vanhatalo and Helle assisted by evaluating and discussing the work plan and results and by commenting the manuscript.

IV Vanhatalo was responsible for the original idea, which was then further developed by Helle, Nevalainen, Mäkinen and Vanhatalo. Helle had the main responsibility in compiling and interpreting the results, structuring the manuscript and leading the writing process. Afenyo provided the oil spreading estimates. Mäkinen and Vanhatalo provided the species distributions and environmental covariate estimates, and calculated the expected proportions of populations within the potentially oiled areas along the studied shipping routes. Nevalainen provided the estimates of the impacts of oil on biota and visualized the results jointly with Helle. All authors contributed to the interpretation of the results and writing the manuscript.

Abstract

The risk of a major oil spill in the Arctic has become a matter of global concern, since climate change is extending the ice-free period and bringing more shipping to the area. The Arctic is already under great pressure from climate change, and an oil spill in this unique and sensitive environment could be a catastrophe for its biota. Fortunately, no major oil spill has happened in the true Arctic yet, but as the probability of one is increasing, we need to prepare for the potential consequences. Understanding the likely impacts of Arctic oil spills could greatly benefit conservation of the area as, for example, spatially and temporally varying risk could be taken into account when selecting shipping routes. Hence, comprehensive knowledge about the impacts of oil spills on Arctic ecosystems is needed. So far, however, knowledge about the likely impacts of oil on Arctic biota is scarce and insufficient for comprehensive risk assessment.

The thesis constructs and applies a probabilistic framework for assessing the environmental risk oil spills pose for marine biota in the data-poor Arctic. The work consists of the summary and four research papers. Paper **I** brings together the current understanding about Arctic oil spills and their environmental impacts, and conceptualizes that knowledge as a probability-based framework that can guide further risk assessment. It further identifies the key Arctic marine functional groups that environmental risk assessment should focus on. Paper **II** carries out an expert elicitation to quantify the acute oil spill -induced mortality of adult and offspring individuals belonging to each functional group. Paper **III** develops a vulnerability index describing the acute mortality and the longer-term recovery potential of the functional groups based on scientific and grey literature. Paper **IV** uses the information collected in papers **I**–**III** and combines it with estimates of oil spreading and species distributions to compare the spatiotemporally varying mortality risk for polar bears, ringed seals and walrus in a case study area, the Kara Sea.

The results of the thesis suggest that, in general, polar bears and marine birds are most at risk from spilled oil in the Arctic, but there is great variation in the risk depending on the timing of the spill and the type of oil spilled. Moreover, the distribution of biota in relation to shipping routes can have a major impact on the risk the spilled oil poses to them. Furthermore, the amount of ice present at the spill site can alter the risk to biota, as ice cover affects both the spreading of oil and the abundance of species in the vicinity of the oil spill. On an acute scale, medium density oil spilled when ice concentration are relatively low seems to be the worst-case accident scenario when considering the joint impact on all biota, but determining the safest shipping route may prove to be challenging.

This thesis offers new insights into the risk that oil spills pose to Arctic biota, and is a step on the way towards a comprehensive understanding of the impact of Arctic oil spills. However, there are still great knowledge gaps, which this thesis both identifies and aims to minimize by suggesting different methods for efficient data collection to benefit risk management related to Arctic shipping. Additional research is needed to evaluate the longer-term impacts of spilled oil and the persistence of oil in cold environments in particular. Furthermore, the need for a valuing method to guide both risk assessment and management is recognized.

Contents

1 Introduction

The world is changing rapidly. Since the beginning of the industrial revolution circa 250 years ago, the human population has increased by a vast six billion people (Roser and Ortiz-Ospina, 2018). The revolution has brought unprecedented economic and industrial developments as well as improved quality of life. However, it has also resulted in numerous negative consequences. The population growth has been, and still is, closely tied to the increased use of natural resources, energy and land, and consequently, to the production of waste. This has caused many problems for the environment including loss of biodiversity, pollution of the air, water and soil, and degradation of the land (Goudie, 2018). Perhaps the most severe environmental problem of our time is global warming, also resulting from the growing human population and increased consumption of natural resources (IPCC, 2014).

This thesis focuses on one particular problem caused by climate change and the humankind's growing need for natural resources: Arctic marine oil spills. As the warming climate causes the sea ice to retreat, new opportunities for human activities in the far north open up. In particular, maritime shipping in the Arctic is increasing, which increases the probability of an oil spill. The thesis studies the potential impacts that such accidents can have on Arctic biota, and seeks to provide information to assist further risk assessment and management related to Arctic shipping.

1.1 The Arctic

The Arctic is characterized by a cold environment, unpredictable weather, long winters, and relatively cool, short summers with long periods of sunlight (CAFF, 2017). The number of species in the Arctic is low compared to temperate regions, and the ecosystems consist of relatively short food webs, making trophic interactions comparatively simple (Grebmeier et al., 2006; Kaiser et al., 2011). In summer, the number of species multiply, as the area serves as a summertime breeding ground for many species and may host major proportions of the global populations of several species at once (see e.g. Miquel, 2001; van Hemert et al., 2015; CAFF, 2017). Overall, the Arctic is unique among Earth's ecosystems, and all life in the Arctic has adapted to a short growing season and harsh winter (AMAP, 2010; Kaiser et al., 2011). The physical boundaries of the Arctic can be drawn based on many criteria, such as tree line or the Arctic Circle (AMAP, 2010). In this thesis, the focus is on the marine Arctic covering the Arctic Ocean and its marginal seas together with the adjacent coastline.

The cold Arctic seawater is rich in nutrients due to strong ocean currents and major rivers with large catchment areas, which results in high concentrations of organisms, like plankton and algae, which serve as the base of the food web (Sakshaug, 2003). The long dark season prevents plankton from utilizing nutrients until the early spring, when an algae bloom occurs under the sea ice and along the ice edges. The uneven seasonal and spatial variability in plankton and algae distribution affects the distribution of all other species too.

On an Arctic scale, this creates species diversity hotspots that are important for the biodiversity of the whole Arctic (CAFF, 2017).

The strong seasonality and the resulting dynamism of its ecosystems are some of the best-known characteristics of the Arctic, but the area is also known for its exceptional biota. Polar bears (*Ursus maritimus*) are probably the most renowned Arctic animal, but the high north also receives massive migrations of birds, such as murres and eiders, and mammals, such as whales, that travel great distances to enjoy the short, but highly productive Arctic summer. Many of the migrating animals arrive to the area during spring, have offspring during late spring or early summer, and move to winter in warmer areas in autumn when offspring have grown strong enough for the journey (see e.g., Belikov et al., 1996; Egevang et al., 2010; Hauser et al., 2014). Some animals, such as ringed seals (*Pusa hispida*), walruses (*Odobenus rosmarus*) and belugas (*Delphinapterus leucas*), have adapted to survive the Arctic conditions year round, but also they typically migrate within the area following their preferred prey and optimal ice conditions and may winter in subarctic areas as well. Similarly, the Arctic is home to many fish and crustaceans, not to mention the smaller animals, and we are just beginning to understand the rich life within and under the ice (Eamer et al., 2013; CAFF, 2017).

The Arctic is in trouble nowadays: it is warming two to three times faster than the rest of the world (ACIA, 2004; Overland et al., 2017), resulting in icebergs and sea ice melting at an unprecedented pace. The summertime sea ice is now declining at an overwhelming rate of over ten percent per decade (Perovich et al., 2017) and the Arctic Ocean is projected to become nearly ice-free in summer within the next 30 to 40 years (Overland and Wang, 2013). As a result of climate change and sea ice decline, ice dependent species suffer from habitat degradation, boreal species spread northward competing for living space with native species (Hellmann et al., 2008; Rahel et al., 2008; Miller and Ruiz, 2014), and increasing primary production alters marine ecosystem structures (Arrigo et al., 2008). Furthermore, humans induce disturbances through natural resources exploitation (Richter-Menge et al., 2017), tourism (Arctic Council, 2016), air pollutants (Law and Stohl, 2007; Sharma et al., 2013) and fisheries (Peterson and Rocha, 2016).

As the ice-free period is extending, the northern shipping routes may offer an economically and temporally competitive alternative to the more southern shipping routes (Liu and Kronbak, 2010; Schøyen and Bråthen, 2011; Zhang et al., 2016). For example, shipping through the Northern Sea Route (NSR) along the Russian Arctic coast can reduce navigation time by one-third compared to the Suez Canal Route, which is currently the main shipping route between Europe and Asia (Khon et al., 2010; Schøyen and Bråthen, 2011). The cargo volume on NSR increased by 25% in 2017 to total of about 10 million tons, and it has been predicted that the total cargo could be 40 million by 2020 and 67 million by 2025 (AGCS, 2018). The amount of future maritime traffic in the Arctic remains uncertain (see e.g. Beveridge et al., 2016), but the intensifying traffic raises several concerns for biota including, but not limited to, the introduction of alien species, noise pollution and emissions from shipping, and disruption of migrating marine biota (Arctic Council, 2009). Yet, the single most significant threat from the increasing shipping is predicted to be the accidental release of oil into the marine environment (Arctic Council, 2009). Even though the altered ice conditions have eased shipping, it continues to be challenging due to hard winds, severe storms, heavy fog and ice, especially during winter (Heininen, 2012; Khan et al., 2018). Hence, the increasing shipping will also increase the risk of an oil spill. Oil can also be released into marine environments as the result of oil drilling. So far, oil drilling in the Arctic has been relatively small-scale and largely exploratory (Shapovalova and Stephen, 2019), but as the oil prices are recovering from the 2010s oil glut and the ice cover continues to shrink, the offshore oil resources in the Arctic have once again piqued the interest of oil companies (Hunter, 2018).

There have been major efforts to enhance the safety of shipping and to minimize the risk of oil spills worldwide. For example, better navigation systems, ship design and crew training lower the likelihood of an accident (Hetherington et al., 2006; Kristiansen, 2013; Khan et al., 2018). In the Arctic, the safety of shipping is most importantly guided by the 'International Code for Ships Operating in Polar Waters' (Polar Code) that entered into force in 2017. It decrees that, for example, discharges of oil or oily mixtures into the sea are prohibited, and oil tankers operating in the Arctic must be equipped with a double hull and double bottom (IMO, 2014; Hildebrand et al., 2018). Moreover, Arctic oil spill response is an increasingly studied topic (see Wenning et al., 2018) and improving preparedness may decrease the risk spilled oil poses to environment in the future. Furthermore, there is a strong political will to protect the Arctic environment by banning the carriage and use of heavy fuel oil (HFO) in the Arctic, since HFO includes a lot of impurities and can be nearly impossible to clean up after it has been spilled (Prior and Walsh, 2018). Whatever steps are taken to minimize the risks from spilled oil, a comprehensive, science-based understanding of the environmental impacts of Arctic oil spills and the related uncertainties is needed.

1.2 The environmental impacts of marine oil spills

Although shipping is an efficient way to move large quantities of oil, it poses a great threat to marine environments, since large oil spills have the potential to significantly injure not only individual animals, but also ecosystem function (see e.g. Peterson et al., 2003; Transportation Research Board, National Research Council, 2003). Spilled oil can have various negative effects on biota through physical smothering, the toxicity of aromatic hydrocarbons, and habitat alteration. The consequences of these aspects of oil spills vary from direct mortality to a variety of sublethal effects. Oiled birds and mammals are particularly prone to suffer from physical smothering as oil sticks to their feathers or fur, which impairs their ability to insulate themselves, making the oiled animals less buoyant and more prone to suffer from hypothermia (Transportation Research Board, National Research Council, 2003; AMAP, 2010). Mammals that have blubber and tough skin instead of fur may suffer less from spilled oil, although they and especially their offspring can exhaust if oiled, which may lead to drowning (AMAP, 2010). Small organisms, especially invertebrates, can be smothered by a thick layer of oil, which can hinder both their movement and breathing. Moreover, most biota are likely to experience at least some toxicological effects after an oil spill through either the direct toxicity of oil or the ingestion of contaminated prey leading to, for example, impaired reproduction, depressed growth or death (see e.g. Engelhardt, 1983; Albers, 1998; Carls et al., 1999). Avian embryos and fish eggs have been shown to have particularly low tolerance to toxins (Leighton, 1993; Briggs et al., 1997), and offspring in general are believed to suffer from spilled oil particularly much (Malins, 1977; AMAP, 2010).

The impacts of oil on marine biota in temperate regions are relatively well understood, due to field observations and laboratory studies (see e.g. Heintz et al., 2000; Kingston, 2002; Albers, 2003; Hemmer et al., 2011). In the Arctic, however, the effects of oil are generally only understood for a few species for which laboratory experiments can be conducted, including the Arctic scallop (*Chlamys islandica*), polar cod (*Boreogadus saida*) and Greenland cockle (*Serripes groenlandicus*) (e.g. Mageau et al., 1987; Rice et al., 1979; Albers, 1998; Hannam et al., 2010; Jonsson et al., 2010). Moreover, only general syntheses of the likely effects of Arctic oil spills have been reported (AMAP, 2010). Hence, the current understanding is scattered and limited, making it difficult to predict the impacts of an oil spill on an Arctic ecosystem. Consequently, estimating which parts of Arctic ecosystems are most at risk from oil spills and whether it varies between accident scenarios is not possible, even though such information could be important for the conservation of the Arctic.

Moreover, predicting the impacts of unprecedented accidents is challenging. Every accident is unique, and the overall impact of the spill depends on, for example, the amount and properties of the spilled oil, the location and timing of the spill, the weather conditions during and after the spill, and the characteristics of biota and the habitats affected by the spilled oil (see e.g. Kingston, 2002; Le Hir and Hily, 2002; Peterson et al., 2003; Transportation Research Board, National Research Council, 2003; Payne et al., 2008, Young et al., 2011). The issue is complicated further by numerous interactions between these factors. For instance, the extent of the oiled area depends on the spreading of oil along with spatiotemporally varying weathering processes, which, in turn, are dependent on the oil type as well as prevailing weather and oceanographic conditions (Transportation Research Board, National Research Council, 2003). However, data on these are generally lacking in the Arctic.

Previous oil spills can provide some guidance for estimating the likely impacts of future oil spills. From most oil spills we know or can estimate, with some accuracy, at least the type and amount of oil spilled, the duration and size of the spill, and (some of) the impacts on biota. One of the most famous oil spills in history is the Exxon Valdez oil spill (EVOS), which took place in Prince William Sound in sub-Arctic Alaska in 1989. Approximately 42 000 m^3 of crude oil were spilled into a biologically rich and poorly-understood marine ecosystem. Hundreds of thousands of seabirds were estimated to have been killed along with other animals such as otters, harbor seals (*Phoca vitulina*), and salmonids. Fisheries of many species including salmon, herring and shrimp were closed for years following the accident (Picou et al., 1992) and tourism suffered greatly, as the recreational use of the area was prevented (Paine et al., 1996). Oil originating from EVOS can still be found on the shores of the sound nearly 30 years after the accident (Nixon and Michel, 2015; Lindeberg et al., 2018) and some species, such as pigeon guillemots (*Cepphus columba*) and orcas (*Orcinus orca*), continue to show very little or no recovery from the population-level harm caused by the spill. Since EVOS is the largest marine oil spill that has occurred in the vicinity of the Arctic, it is a relevant source of information when assessing the potential impacts of oil spills in the Arctic. Plenty of literature has been published documenting the environmental impacts of EVOS (see e.g. Piatt et al., 1990; Carls et al., 2001; Bodkin et al., 2002; Peterson et al., 2003; Rice and Peterson, 2018), but the data are far from comprehensive (see Paine et al. (1996) for lessons learnt in the aftermath of EVOS) and should therefore be extrapolated with caution.

Although field data contain only limited amount of information, there are some oil spill models that can be used to assess the fate and impacts of spilled oil. Some oil fate models are relatively detailed (Spaulding, 2017), but they often have a limited ability to model oil spreading in ice-filled waters (however, see e.g. Arneborg et al. (2017) and Beegle-Krause et al. (2017)) and cannot assess the environmental consequences of spilled oil. There are also some models that can assess both the fate of oil and (some of) the environmental consequences of the spill. Perhaps the most widely used are the Oil Spill Contingency and Response (OSCAR) model (Reed et al., 1995), the General NOAA Operational Modeling Environment (GNOME) together with Environmental Sensitivity Index (ESI) (Beegle-Krause, 2001; Petersen et al., 2002), and the Integrated Oil Spill Impact Model System (SIMAP) (French-McCay, 2004). Currently, SIMAP is the most advanced of the existing oil fate and impact models in terms of assessing the impacts of spilled oil on biota in addition to modeling the fate of oil in detail. This model's elements and assumptions are discussed in more detail throughout the thesis.

The use of oil spill models in the Arctic is often either impossible or challenging. They usually require detailed data about, for example, weather, currents and shoreline types, which are not typically available for the true Arctic, which is characterized by demanding climatic conditions and consequently, limited field data. For instance, SIMAP can be used in the Arctic (see French-McCay et al., 2014; French-McCay et al., 2018; Wilson et al., 2018), but enough data exists only for a few areas and a few species. Moreover, although SIMAP assesses the impact on biota quantitatively, the impact is estimated as a point estimate instead of a probability distribution, thus impairing its viability for use in quantitative risk assessment. This is a relevant shortcoming of the model particularly in the Arctic, where underlying uncertainties are typically large (Emmerson and Lahn, 2012). Moreover, SIMAP does not fully account for the significance of seasonality when assessing an oil spill's impact, as it uses the same point estimate to describe the impact on biota year-round.

In general, the above-mentioned much-utilized models have a limited capacity to document uncertainty related to both the fate and the environmental impacts of spilled oil. Yet there are a few oil spill models that use probability distributions to allow for the incorporation of uncertainty. For example, Aps et al. (2009), Carriger and Barron (2011), Helle et al. (2011), Goerlandt and Montewka (2014) and Lehikoinen et al. (2015) have built Bayesian networks to describe the various elements related to oil spills in temperate regions. In these models, probability distributions for the variables related to the accident scenarios (such as weather conditions) are usually calculated based on existing statistics, which are typically not available for the Arctic. The approach by Lecklin et al. (2011) for assessing both acute and longer-term impacts of spilled oil in the Gulf of Finland by relying on expert knowledge is rather detailed and could be utilized in the Arctic as well, but their expert elicitation process is imprecisely documented and thus, difficult to reproduce. Moreover, the estimates are tied to the unique environment of the northern Baltic Sea and provide very limited information when assessing the impacts of Arctic oil spills.

Additionally, some methodologies for oil spill response planning in the Arctic include estimates about the expected harm spilled oil causes to habitats or biota (see Wenning et al., 2018 for a review). For example, Methodology for Environmental Risk Analysis (MIRA) and Environmental Risk Assessment-Acute (ERA-Acute) estimate the potential effects and recovery of Arctic biota in relation to spill impact mitigation (DNV-GL, 2014; Stephansen et al., 2017). Such methods have mainly been developed for the most thoroughly studied and therefore data-rich parts of the Arctic, such as the Norwegian Arctic continental shelf and the US Alaskan region (see e.g. Aurand and Essex, 2012; DNV-GL, 2014; Robinson et al., 2017). For the majority of the Arctic, such methods are not available. Moreover, the methodologies do not generally account for the uncertainty related to the topic (however, see Lu et al. (2019) for a probability-based model for assessing oil spill recovery effectiveness in the ice-covered Northern Baltic Sea), and the estimates on the harm to biota or habitats are most often formed by a few experts and the reasoning behind the estimates is not typically well-documented.

1.3 Environmental risk assessment

Environmental risk assessment (ERA) provides a practical tool for studying risks to the environment posed by human action, such as shipping. So far, Arctic ERA's have been mostly qualitative (see e.g. EPPR, 1996; Ford and Smit, 2004; Bolsunovskaya and Bolsunovskaya, 2015), and the few quantitative ones have focused on, for example, persistent organic chemicals (Skaare et al., 2002) and polychlorinated biphenyls (Brunström and Halldin, 2000) in marine mammals and birds, and ballast-mediated invasions of nonindigenous species (Bailey et al., 2013). Recent ERA's have also studied the (toxicological) risks related to subsea oil spills in the Arctic (Arzaghi et al., 2018). Presently, the risks related to oil shipping in the Arctic have been assessed from the accident probability point of view (see e.g. Khan et al., 2018 and references therein) and the risk spilled oil poses to the Arctic ecosystem has been discussed only in qualitative terms (AMAP, 2010).

There are many definitions of 'risk' depending on the context (Fowle and Dearfield, 2000; Burgman, 2005). In everyday language, it is often a synonym for 'probability' for an unwanted event. Moreover, terms 'hazard' and 'risk' are sometimes used interchangeably, but in risk assessment 'hazard' refers to an agent that can cause harm or damage, and 'risk' to the potential consequences of the hazard combined with the probability they realize (Gormley et al., 2011). The definition of 'risk assessment' varies, too. In general, it refers to the process of formally evaluating a risk, but there are dissenting opinions about whether risk management should be considered a part of the risk assessment cycle, or a distinct process (HM Treasury, 2004; Fig. 1).

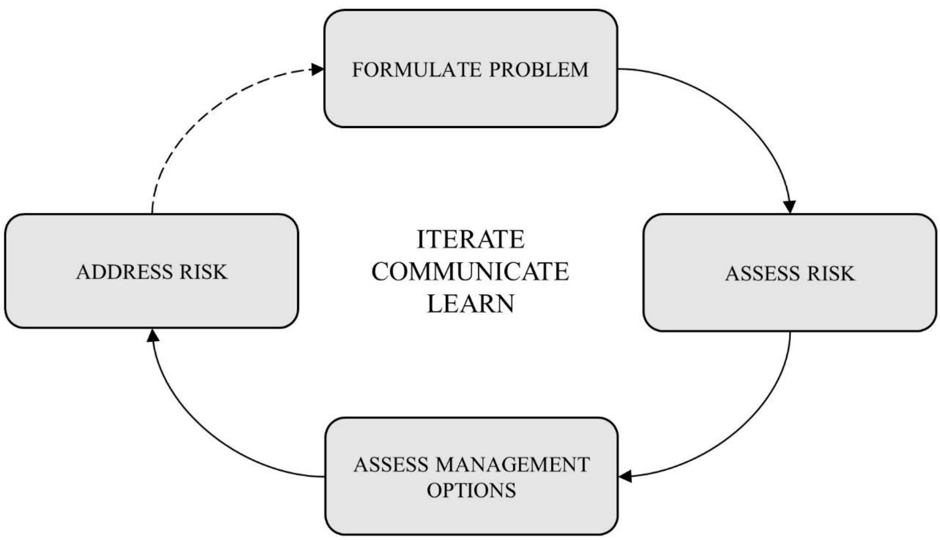

Fig. 1. ERA framework (based on Gormley et al., 2011). The ERA process starts from formulating the problem (Step 1) which is followed by assessing the risk(s) (Step 2) and management options (Step 3), after which the risk is addressed (Step 4). The problem can be formulated again if necessary based on the proceeding of the ERA process. The thesis focuses on the first two steps of ERA: formulating the problem (papers **I**, **III**, **IV**) and assessing the risk (papers **II–IV**).

ERA, similar to risk assessment in general, consists of four steps: 1. Formulating the problem, 2. Carrying out an assessment of the risk, 3. Identifying and appraising the management options available, and 4. Addressing the risk with the chosen risk management strategy (Fig. 1). The first two steps can be described as the first part of ERA (namely risk assessment) and the two latter steps as the second part of ERA (namely risk management). After the best possible (and available) management option identified has been implemented (Step 4), the risk assessment cycle may be started again from Step 1 if, for example, new information collected during ERA allows for a more accurate framing of the problem (Gormley et al., 2011). Ideally, ERA includes iteration and learning, and communication between different parties (generally the risk analyst and the risk manager, but potentially also other stakeholders).

A critical early step in ERA is to determine 'what' is at risk, i.e. which aspects of the environment to focus on in the risk assessment – and, in essence, which aspects of the environment to protect (Gormley et al., 2011). This process is known as selecting the assessment endpoints. They can be chosen based on different criteria – such as ecological importance or relevance to management goals. In the Arctic, an ecologically relevant assessment endpoint for oil spill ERA could be, for example, the survival of polar cod, since it is a key species in Arctic food webs (Hop and Gjøsæter, 2013). An assessment endpoint relevant for management goals could be, for example, retaining water quality at a level that does not impede commercial fishing. The assessment endpoints can be identified at different levels, such as the individual (e.g. survival of an individual), population (e.g. abundance of individuals) or community (e.g. taxa richness) (US EPA, 2003) level. The risk can also be assessed for a habitat in which case the selected assessment endpoints aim to determine whether a habitat will be adversely modified by human activity (US EPA, 2003). To improve the usability of ERA results for decision-making, the assessment endpoints can be chosen in collaboration with the decision-maker to ensure their relevancy.

Appropriate methods for measuring the assessment endpoints depend on the availability of data and resources. Risk assessment can be either qualitative or quantitative, depending on the amount and quality of data and the purpose of the risk assessment. Quantitative risk assessment often requires past data, which can be accumulated from different sources, such as laboratory experiments or field studies, whereas qualitative risk assessment often relies on expert opinion, particularly when assessing risks related to unforeseen events (Suter II et al., 2007; Gormley et al., 2011; see also paper **II** for using expert knowledge in quantitative risk assessment). In qualitative studies, risk can be assessed in terms of, for example, 'high', 'medium' and 'low' or 'very likely', 'likely', 'not likely' and 'very unlikely.' Quantitative risk assessment is typically more informative and the results obtained can be more easily used in further models, but such an approach is not always feasible due to, for example, limited data (Suter II et al., 2007).

The detailed steps and methods of ERA can differ depending on which risks and assessment endpoints are considered (US EPA, 2003; Suter II et al., 2007). ERA can provide anything from very holistic, coarse-level estimates of multiple stressors (see e.g. EPPR, 1996; Hayes and Landis, 2004; Fock, 2011; Kaikkonen et al., 2018), to a very detailed assessment of an impact a certain chemical has on a certain study species (see e.g. Aas et al., 2000; van der Oost et al., 2003; Pekey et al., 2004; Li et al., 2014). In toxicology, a dose descriptor (relationship between an effect of a chemical and the dose at which it takes place) is used to describe the risk to biota and can be expressed as, for example, LC_{50} (lethal concentration 50%: a concentration that kills half the tested population) or NOAEL (no-observed-adverse-effect level). Such assessments have been conducted for some Arctic species such as amphipods, copepods and fish (e.g., Buhl and Hamilton, 1991; Chapman and McPherson, 1993; Hansen et al., 2014). Moreover, the toxicological approach has recently been used in a few Arctic ERA's related to oil spills (see e.g. Afenyo et al., 2017; Arzaghi et al., 2018). However, most toxicological studies are performed for temperate species in relatively warm water, and it is unclear how easily these results can be applied in the Arctic (Lee et al., 2015). Moreover, the approach may work for smaller animals, like fish and invertebrates, but could be highly problematic for mammals and birds. Furthermore, toxicology-based risk assessment overlooks the physical impacts stressors may have and generally produces knowledge only on an individual-, not a population-level (however, see de Vries et al. (2018) for extrapolating population level consequences of oil from toxicity data on Arctic copepods). Therefore, Arctic oil spill ERA should not be (solely) based on available toxicological data.

In an ideal world, risk assessment would be based on strong evidence, but in reality, information is often limited. The uncertainty is particularly high when incomplete knowledge is used to make predictions about an unobserved event. Therefore, risk estimates, both quantitative and qualitative, should always include a transparent presentation of the related uncertainties. Since the main goal of ERA is to synthesize information for environmental management and policy, it is important that decision-makers are explicitly and transparently informed about the uncertainties and their sources (Burgman, 2005). It can also be beneficial to classify uncertainty to guide further research. A typical strategy for doing this is to classify uncertainties as either epistemic or aleatory. Epistemic uncertainty refers to uncertainty due to lack of knowledge, which can be reduced or even fully eliminated through research. Aleatory uncertainty in turn, relates to natural variation that cannot be measured (at least with the currently available methods) and therefore, rendering this type of uncertainty irreducible (O'Hagan, 2004). Both types of uncertainty are likely to be present in Arctic oil spill ERA. For example, the toxicity of oil to Arctic biota can be (and to some extent has been) studied in laboratories therefore reducing the epistemic uncertainty in the estimates of the lethality of spilled oil. Contrarily, habitat use of Arctic biota includes natural variation and therefore, the uncertainty cannot be fully removed (however, see paper **IV** for using species distribution modeling in reducing such uncertainty).

2 Outline of the thesis

2.1 Structure and objectives

This thesis consists of two main themes: (i) Building a probabilistic framework for conducing quantitative ERA of Arctic oil spills and (ii) quantitatively assessing some of the risks spilled oil poses for Arctic marine biota. Within the first theme, presented in Section 3.1, the problem is framed and the important variables contributing to the environmental impacts of Arctic oil spills are identified based on an extensive literature review. A conceptual model for risk assessment is developed and the relevant biota at risk are identified. Moreover, appropriate accident scenarios are defined. In other words, the first theme conceptualizes the existing knowledge about Arctic oil spills gathered from scientific and grey literature and builds guidelines for subsequent, quantitative risk assessment. Within the second theme, presented in Section 3.2, the risk spilled oil poses to Arctic biota is quantified. Both the acute and longer-term impacts of spilled oil are studied, the first one in quantitative terms and the latter in semi-quantitative terms. Moreover, a spatiotemporal risk assessment is performed to study how the risk spilled oil poses can be altered depending on the type of oil that is shipped, and when and where it is shipped. Thereafter, Section 4 discusses the most important results of the thesis with special emphasis on the related uncertainties and the applicability of the results to risk management and conservation. Both the new knowledge acquired about the impacts of Arctic oil spill and the strengths and weaknesses of the methods used are examined. Moreover, the lessons learned are described and the most important directions for future research regarding Arctic oil spills are underlined. Lastly, Section 5 summarizes the thesis with concluding remarks.

The thesis develops a general approach for Arctic oil spill ERA applicable throughout the Arctic to improve the understanding of this data-poor topic and ultimately to support decision-making related to Arctic shipping.

The main objectives of the thesis are:

1. To build a probability-based, general framework for studying the impacts of spilled oil on Arctic biota in the data-poor Arctic (papers **I**, **III**, **IV**), and
2. To use that framework to quantify the risk posed by spilled oil to Arctic biota (papers **II**–**IV**).

2.2 Description of the papers

Paper **I** collects and summarizes the existing knowledge about Arctic biota from an oil spill perspective, and sets boundaries for Arctic oil spill ERA based on a literature review. The main aim of the paper is to bring together the current understanding about the impacts of oil on Arctic biota in to an easily understood format, and to describe the major knowledge gaps related to the environmental impacts of Arctic oil spills. The paper suggests that Arctic oil spill ERA should focus on food webs at the functional group -level to estimate the impacts of oil spills on entire ecosystems. To achieve this, the paper identifies the Arctic biota most likely to be affected by spilled oil and places them into 20 functional groups based on both their ecological role and the expected impact of oil spills on them. The classification takes into account, for example, species' habitat use, physical characteristics, and behavior. The paper also presents a novel network for assessing both the acute and longer-term impacts of oil on the functional groups. Moreover, the paper discusses various ways to move from qualitative descriptions of the risk towards quantitative estimates, and gives recommendations for how data can be collected. The paper can also be used as a basis for more detailed risk assessment.

Paper **II** seeks to fill some knowledge gaps identified in paper **I** by performing expert elicitation. The paper has two main aims: to collect quantitative data on acute, oil spill - induced mortality of Arctic biota, and to test the use of expert knowledge in acquiring such data. The paper develops an elicitation tool suitable for remotely implemented expert elicitation. Eight experts participated in the study, and data on the exposure potential and sensitivity of seals, anatids and seabirds to spilled oil are collected. The experts used probability distributions to describe their understanding of the exposure potential and sensitivity (see Section 3.1.2 for definition of the terms) and the uncertainty related to their assessments. The paper discusses the quantity and quality of the data obtained, and pays special attention to the credibility of the obtained results.

Paper **III** continues to fill the knowledge gaps identified in paper **I** by building an index-based approach for assessing the acute and longer-term risks posed by spilled oil on Arctic biota. The paper aims to bring a vast amount of published literature on the impacts of oil from both Arctic and temperate environments together, and turns that knowledge into an index that can be used to compare the relative harm spilled oil causes to different functional groups under the different accident scenarios identified in paper **I**. The index takes into account both the acute and longer-term impacts of oil and functional groups' ability to recover from a potential oil-induced population decline. The paper begins by building a conceptual model identifying the most important variables contributing to exposure potential and the sensitivity of biota (see Section 3.1.2 for definition of the terms), and then applies the conceptual model to assign a probability distribution to describe how each of the identified variables contributes to the overall exposure potential and sensitivity of the functional groups. Moreover, the paper performs sensitivity analysis to better understand the sources of uncertainty in the results. For many of the functional groups, the paper provides the first estimates of their exposure potential and sensitivity. This method allows for easy updating when new data become available.

Paper **IV** is based on the framework from paper **I** and uses data collected in papers **II** and **III,** as well as from related works by Mäkinen and Vanhatalo (2016; 2018) and Afenyo et al. (2016B). The paper presents a case study located in the Kara Sea along the Russian Arctic coast where the acute risk associated with different shipping routes is assessed. The paper combines estimates of the vulnerability of biota in spill areas (paper **II**) to estimates of spatiotemporally varying species densities and oil spreading, thus producing a more detailed than before assessment of the acute risks posed by spilled oil in the Arctic. The assessment is based on three Arctic marine mammal species: polar bears, ringed seals and walruses. The main aim of the paper is to enhance the understanding of the spatiotemporal variation in the acute risk posed by spilled oil in the Arctic. The results allow for both the comparison of the acute risk associated with different shipping routes and the relevance of different data (such as the environmental impact of oil vs. oil spreading) to the total risk. The results of the paper can inform both risk management and future risk assessment.

3 Materials and methods

The thesis utilizes various methodologies and sources of information in its attempt to conceptualize and quantify Arctic oil spill risk (Table 1). In Section 3.1, a probability-based, general framework for studying the impacts of spilled oil on Arctic biota in the data-poor Arctic environment, built based on a literature review, is presented. In Section 3.2, the methods utilized for quantifying the oil spill impacts in papers **II–IV** are presented.

3.1 Framing the Arctic oil spill ERA

3.1.1 Identifying biota at risk

As the knowledge about the potential impacts of oil on Arctic biota is still very limited, environmental risk assessment should start with a general description of the ecosystem to identify which parts of the ecosystem are at the highest risk (paper **I**). The risk assessment could focus on, for example, endangered species or keystone species, but the ecosystem approach provides a more comprehensive overview of the total risk (see e.g. Burgman, 2005; Suter II et al., 2007; Lecklin et al., 2011). It can also guide future research by identifying the parts of an ecosystem that should be studied in more detail (paper **III**). Moreover, the ecosystem approach can effectively identify the biggest knowledge gaps related to the risk to biota.

The thesis proposes that for Arctic oil spill ERA to cover the whole marine ecosystem, the risk should be assessed for functional

Table 1. Main methodologies utilized in papers **I–IV**.

Methodology	**Paper I**	**Paper II**	**Paper III**	**Paper IV**
Literature review	x		x	
Conceptualization	x		x	
Expert elicitation		x		
Semi-quantitative analysis			x	
Quantitative analysis		x		x
Spatiotemporal analysis				x

groups instead of individual species (similar to King and Sanger, 1979; Lecklin et al., 2011; French-McCay, 2004). The reason is twofold. Firstly, the range of functional groups present in an ecosystem is likely to be more closely related to the stability of an ecosystem than the number of species within it (Allaby, 2010). Secondly, data in the Arctic are often limited, and the functional group -approach allows for more efficient utilization of the little data available (paper **III**).

Moreover, the relationships (mainly prey–predator) between the groups should be considered in ERA, as the loss of a prey or a predator is likely to affect a functional group in addition to the direct impacts of oil. Therefore, a food web approach enables a holistic analysis of the risks to whole ecosystem and it offers a practical way to extend the analysis from acute to longer-term effects (papers **I**, **III**). In more detailed ERAs, competition between species could also be taken into account, but because majority of competition is likely to occur within and not between functional groups, such relationships are not considered in this thesis.

It should be noted that in this thesis the term 'functional group' refers to a group that is formed not only based on the ecological characteristics of the species within it (see e.g. Allaby (2010)), but also considering the expected impacts of oil spills on them: how and on what time-scale spilled oil is likely to affect them (paper **I**). For example, groups'

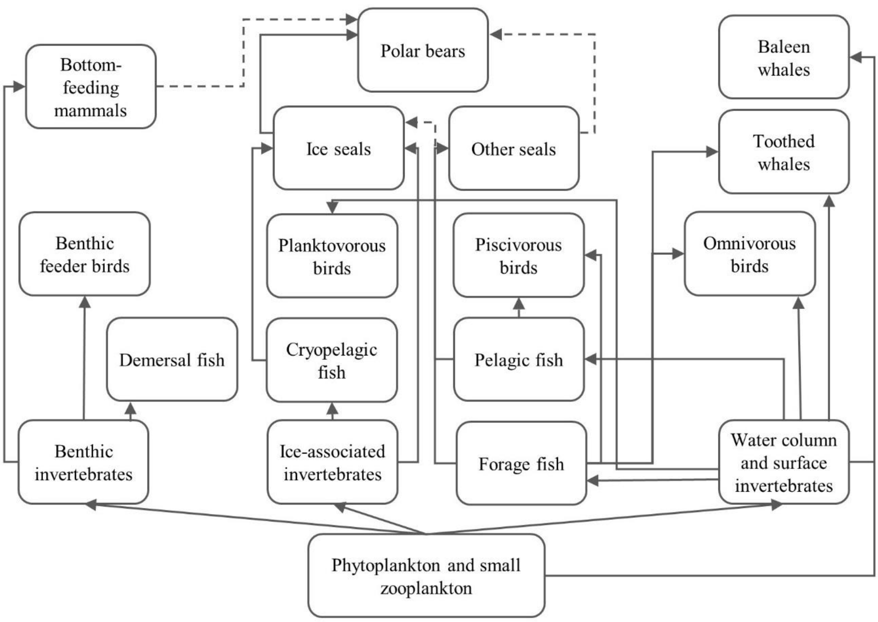

Fig. 2. Food web suitable for Arctic oil spill ERA (modified from papers **I** and **III**). Solid lines describe the main prey(s) of each functional group and dashed lines the secondary prey(s).

habitat use and feeding behavior, among other things, affect whether they are likely to suffer from spilled oil on an acute timescale or are likely to experience longer-term, chronic impacts through food web.

Papers **I** and **III** form 20 functional groups to be used in Arctic oil spill ERA (Fig. 2). The groups include invertebrates, fish, birds and mammals, and include species that are assumed to be those most likely to be affected by oil based on knowledge gleaned from temperate and sub-Arctic regions (see e.g. Paine et al., 1996; AMAP, 2010; Lecklin et al., 2011; Chang et al., 2014). This classification of the functional groups should be thought of in terms of convenience and it loosely resembles the grouping used e.g. by SIMAP (French-McCay, 2004). The functional groups identified are exposed to oil in different ways, have different tolerance levels and varying ability to avoid oil. For example, fish are divided into pelagic, cryopelagic, foraging and demersal fish. All fish groups are likely to have similar tolerance to oiling, but are exposed to oil in different ways due to their differing use of habitat. As another example, whales are divided into two groups: toothed and baleen whales. Their use of habitat resembles each other's, but they may be exposed to oil in different ways due to their differing feeding behavior.

The groups do not cover all Arctic biota, but the classification is convenient for practical ecosystem-level ERA. For example, six groups of marine birds are considered (according to recommendation of Arctic Council's Circumpolar Seabird Monitoring Plan (Irons et al., 2015)). In comparison, SIMAP divides marine birds into 13 groups (French-McCay, 2004). The number of the groups is kept moderate to allow for efficient quantification of the risk (similar to Lecklin et al., 2011). For example, in paper **III** the authors assign 7,360 probability distributions altogether to describe the vulnerability of the 20 functional groups. Each additional functional group would increase the number of required probability distributions by hundreds. However, the methods presented in this thesis can be applied to other functional groups or individual species as well. Moreover, the food web does not provide a perfect description of an Arctic ecosystem, but does display the most relevant dependencies in it (Fig. 2). Again, a relatively simple approach like this is adequate for the purposes of this thesis. The impacts of oil spills on primary producers are not quantified in this thesis as studies in temperate waters have shown that the damage to them caused by oil spills is likely to be relatively modest and short in duration (see AMAP (1998) and references therein), nevertheless their role in the food web is still considered (paper **III**).

3.1.2 Defining the risk

Spilled oil can affect individuals and habitat in many ways. From an ecosystem perspective, the most relevant question is how an oil spill may affect populations. In this thesis, the risk is assessed through the probability that biota dies due to an oil spill, which is assessed separately for the different seasons, oil types and life stages of the 20 key functional groups (papers **II**, **III**). Other possible assessment endpoints relevant for ecosystem-level ERA could be, for example, the effect of oil on the reproductive efficiency of biota or on significant breeding grounds.

Most oil spill models assess the risk posed by spilled oil, which is based on the expected intersection between the species and the spilled oil, determined by comparing species distribution to the trajectory of oil without considering, for example, the behavior of individuals (e.g. Reed et al., 2000; Petersen et al., 2002; see also paper **IV**). In reality, it is unlikely that all the individuals within an oiled area come into contact with oil. For example, some species may be able to avoid oil (Rice, 1973; Lipcius et al., 1980; Bohle, 1986; Ryder et al., 2004) and some individuals, such as ringed seal cubs, stay on pack ice, where oil is not likely to reach them (AMAP, 2010; Kelly et al., 2010). Therefore, the 'probability that an individual comes into contact with oil if oil is spilled in its habitat' (from now on called *exposure potential*[1]) needs to be assessed (paper **I**; Lee et al., 2015). Based on that, the proportion of a population that comes into contact with oil can be estimated for any given spill scenario (papers **I**–**IV**). Secondly, not all oiled individuals die. For example, whales' skin may repel oil (Geraci, 1990) and some mollusks can survive oiling for a short duration by closing their shells (Conan et al., 1982; Mosbech, 2002). Thus, the 'probability that an individual dies due to contact with oil' (from now on called *sensitivity*) must also be assessed (paper **I**; Lee et al., 2015). Based on that, the proportion of the oiled population that dies due to oiling can be estimated for any given spill scenario (papers **I**–**IV**). Such logic is not usually applied in oil spill models, with the exception of SIMAP. It uses an estimate of species' probability of encountering spilled oil (corresponding to exposure potential) and mortality once oiled (corresponding to sensitivity), but assesses them as a joint single point estimate (for example, 75% for furbearing marine mammals and 1% for pinnipeds). Furthermore, it uses the same point estimate for every accident scenario (French-McCay, 2004).

In this thesis, exposure potential and sensitivity are assessed in the form of probability distributions to account for the uncertainty related to them (papers **II**, **III**). They are also assessed separately because assessing conditional probabilities typically becomes easier the more explicitly they are defined (see e.g. O'Hagan et al., 2006). Moreover, such separation improves our understanding of the topic. Furthermore, it could potentially contribute to protection of biota. For example, an oil spill response could be targeted to safeguard the most vulnerable species, as the highly sensitive groups do not automatically suffer most from spilled oil if they are unlikely to come into contact with it (papers **II**–**IV**). As both exposure potential and sensitivity can vary between seasons and based on the type of oil spilled, Arctic oil spill ERA should consider a range of potential accident scenarios to provide a comprehensive overview of the potential risk posed by oil spills (papers **II**–**IV**). In the Arctic, it is particularly important to account for the seasonal variation in the ecosystem, as it can significantly affect the risk spilled oil

[1] Note that in paper **II** the probability that an individual comes into contact with oil if oil is spilled in its habitat is referred to as *vulnerability*

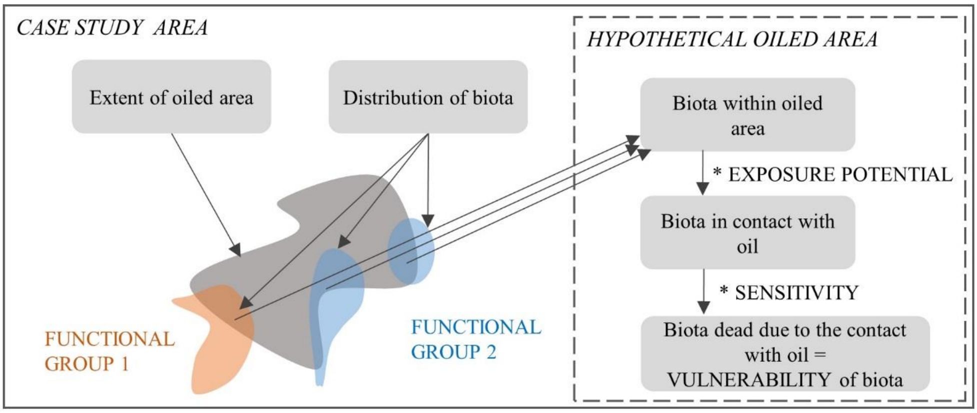

Fig. 3. Definition of the (acute) risk posed by spilled oil. Exposure potential (probability of contact with spilled oil), sensitivity (probability of death given the contact) and vulnerability (probability of death) are sufficient for studying the impact of an oil spill on a hypothetical area (papers **II** and **III**). For a case study, species distribution and oil spreading need to be additionally assessed (paper **IV**).

poses (paper **IV**). For example, species richness is generally higher during summer compared to other seasons (CAFF, 2017), which can alter the overall impact of spilled oil considerably. Season also has an effect on the extent of the ice cover, which in turn, affects both the oil spreading and the distribution of biota (paper **IV**).

Vulnerability is the product of exposure potential and sensitivity, equaling the probability of death due to an oil spill[2]. It can be assessed for individuals (paper **II**) or a hypothetical population (paper **III**) in a hypothetical Arctic marine area (Fig. 3: 'biota within oiled area'). Here, a population should be understood as a quantity at the functional group -level summarizing the amount and distribution of the individuals in that functional group. It would be possible to study the overall population in the Arctic, but considering a (sub)population in a smaller study region where an oil spill is assumed to occur is more convenient (paper **IV**). Vulnerability can be assessed without any location-specific knowledge about, for example, species distributions and oil spill trajectory, which are not typically available for the Arctic (papers **II**, **III**). Species distributions and areal densities can be left out of the analysis by assuming that individuals are randomly distributed throughout the area (similar to Lecklin et al., 2011). If data on species distributions and oil spill trajectory are available, they can be easily combined with the before-mentioned probabilities, and so the risk assessment can be further detailed as a location-specific case study (paper **IV**).

3.1.3 Structuring the conceptual model

The exposure potential and sensitivity of Arctic biota depend on the characteristics of accidental oil spills, the extent of oil

[2] Note that in paper **II** the probability of death due to an oil spill is referred to as *acute impact*

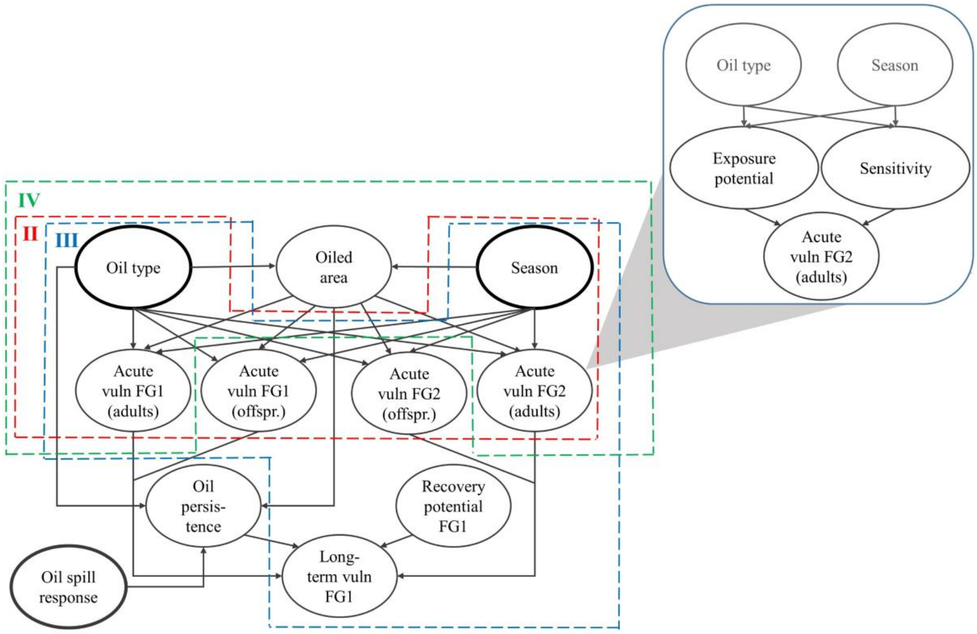

Fig. 4. Conceptual model of the vulnerability of two functional groups (FG1 and FG2) right after an accident ('Acute vuln') and over the longer-term ('Long-term vuln', only demonstrated for FG1) (modified from paper **I**). FG1 and FG2 present functional groups that have a prey-predator relationship. The colored dashed lines indicate to which parts of the conceptual model papers **II**–**IV** focus. The variables in bold circles present where risk management decisions can be applied.

contamination, and a set of ecological parameters (Fig. 4). The structure of the model and the framework in general are based on a literature review (paper **I**), and the variables and their relationships are modified from the related model by Lecklin et al. (2011) for assessing the acute and long-term impacts of spilled oil in the Gulf of Finland. The nodes in the model correspond to random variables and the arrows describe the conditional dependency structure between them: an arrow from one node to another indicates that the latter is conditionally dependent on the first. For example, the acute vulnerability (Fig. 4: 'Acute vuln') depends on the extent of the area polluted by oil ('Oiled area'), the type of oil spilled ('Oil type') and the timing of the accident ('Season'). All the variables are described in Sections 3.1.3.1 and 3.1.3.2.

The conceptual model presents the variables that directly affect the risk to biota with the intention to keep the model as simple as is reasonable. For example, a variable describing the size of the spill (e.g. in tons or barrels), usually included in oil spill models (see e.g. Reed et al., 2000; Lecklin et al., 2011; Spaulding, 2017), is left out, since from an ecological perspective, the relevant information is included in the variable 'oiled area'. This is due to the fact that spill size correlates poorly with the damage caused by the spill (Teal and Howart, 1984). Excluding variables from the network means that they are not included within the scope of the thesis. For example, accident related variables, such as accident probability and variables affecting it, are excluded from the model, although their impact is unquestionably relevant. Moreover, every missing arrow between any two nodes corresponds to an assumption that either there is no direct dependence between the nodes or the dependency is not included within the scope of this thesis.

Besides identifying the variables relevant for Arctic oil spill ERA, the conceptual model allows the estimation of where proactive management decisions can be made to lower the risks related to oil spills in the Arctic. For example, the timing of the shipping and the type of oil shipped, both of which affect the overall vulnerability (paper **IV**), can be guided by legislation. The extent of the oiled area can be controlled by, for example, the size of the tankers allowed to ship in the Arctic. Moreover, an efficient oil spill response can affect especially the longer-term impacts of spilled oil, and the oil spill response capacity can, at least in theory, be guided by risk management. In paper **IV**, an option for decreasing the negative consequences of potential Arctic oil spills through managing 'when', 'where' and 'what kind of' oil to ship is studied. Next, a short description of the variables in the conceptual model is given, paying special attention to the unique characteristics of the Arctic that must be taken into account when conducting Arctic oil spill ERA.

3.1.3.1 Variables related to the acute impacts of spilled oil

'Season' describes the timing of an accident, and it can potentially have a great impact on the overall harm caused by spilled oil: it determines which biota are present in the Arctic and how abundantly, and how much ice is present, contributing to both the distribution of biota and the behavior of spilled oil. Moreover, season is likely to affect the amount of operating ships, as the prime time for shipping in the Arctic is during the ice-free summer (AGCS, 2018). Season can also affect the accident probability through weather conditions (Khan et al., 2018). The effect of season on the environmental impacts of spilled oil is discussed hereinafter in connection with the definition of exposure potential and sensitivity.

'Oil type' describes the type of spilled oil. Different oil types are being transported in the Arctic (Holmes et al., 2018) and it is likely that they have different impacts on the environment when spilled. For example, the density and viscosity of oil, which varies between oil types, affect the weathering processes it undergoes, as well as its likely fate (Fingas, 2000; Transportation Research Board, National Research Council, 2003). However, knowledge about the weathering processes and the fate of oil in cold regions is somewhat limited in comparison with temperate regions (Afenyo et al., 2016A) and we can only guess what types of oil will be shipped in the Arctic in the future (AGCS, 2018). Therefore, to form an overall understanding of the potential impacts of different kinds of accidents, Arctic oil spill ERA should focus on oil type categories instead of specific oils.

'Oiled area' describes the extent of the area affected by a harmful amount of oil. The definition of harmful amount is likely to depend on the functional group, but for the sake of simplicity, it can be assumed that oiled area refers to an area where oil amount (e.g. thickness of the slick or the underwater concentration) exceeds a certain threshold value (similar to SIMAP (French-McCay, 2004)). 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 depending on the type and the amount of spilled oil. Moreover, the size of the area depends on the season-dependent ice-coverage (paper **IV**) and the prevailing weather conditions, wind will facilitate and ice-cover will hinder the oil's spread, while waves mix the oil with water (Afenyo et al., 2016A). In ice-covered waters, oil may become trapped in or under the ice, potentially having a major impact on the likelihood of oil reaching the shore (paper **IV**; Brandvik et al., 2006; Afenyo et al., 2016A, 2016B). The size of the oiled area will, in turn, affect the proportion of a population exposed to oil (similar to SIMAP (French-McCay, 2004); see Fig. 3 and paper **IV**).

'Exposure potential' varies between functional groups and depends on, among other things, their habitat use and ability to escape from an oiled area. It also varies between accident scenarios, depending on the type of oil spilled and the timing of the accident (papers **II**, **III**). In short, the fate of oil, which depends on the oil type, determines whether the oil and biota occupy the same habitat (such as seafloor or water surface). For example, during spring, seabirds primarily spend their time at their nesting sites, during summer, on the other hand, they are in the open water with their offspring King and Sanger, 1979) and their exposure potential changes accordingly. The changing seasonal distribution of ice cover affects not only the fate of oil, but also the habitat preferences of many species (papers **III**, **IV**) and therefore, also their exposure potential.

Similar to exposure potential, the 'sensitivity' of biota varies between functional groups and depends on, among other things, their thermoregulation system and tolerance to toxins. The sensitivity of biota is also affected by the oil type, which affects both the physical and biochemical lethality of oil; light oils tend to be more toxic and less adherent than the heavier ones (Transportation Research Board, National Research Council, 2003; Lee et al., 2015). Moreover, sensitivity is affected by the timing of the accident, most importantly by determining the proportion of offspring within a population (for sensitivity of offspring, see for example Malins, 1977; Leighton, 1993; Carls et al., 1999; AMAP, 2010). Season can also affect the sensitivity of adults as, for example, many birds and mammals molt once or twice per year, during which time they can be particularly sensitive to oiling.

'Acute vulnerability' is a product of exposure potential and sensitivity, and it describes the probability of the death of individuals (and therefore, the proportion of a population that dies) caused by the spilled oil, during and immediately following an accident. The definition of acute may differ between functional groups, seasons and types of oil spilled. In the absence of case-specific knowledge, a two-week period, classified as a 'spill in progress' phase by Boehm and Page (2007), can be considered (papers **II**, **IV**). According to Boehm and Page (2007), during this period, oil at the water's surface is likely to have its maximum exposure potential and the concentrations within the water column can be expected to be at a maximum.

3.1.3.2 Variables related to the longer-term impacts of spilled oil

'Oil persistence' describes both the extent and duration of the oil load in the environment, and it depends on the amount and type of oil spilled. In general, the lighter the oil, the faster it evaporates, whereas heavy oils may sink to the seafloor and cause prolonged harm to biota (Mackay and McAuliffe, 1989). In addition to direct physical or chemical harm, oil can also spoil habitats including breeding grounds. This may be particularly harmful to philopatric biota and biota unable to recognize and avoid oil (AMAP, 2010). Moreover, the remaining oil can cause chronic lethal or sublethal impacts, such as cancer and impaired reproduction (Ainley et al., 1981; Albers, 1998; Carls et al., 1999; Andersen et al., 2015).

'Oil spill response' describes how efficiently the spilled oil can be collected, and it can impact the persistence of oil in nature. Potential oil spill countermeasures in both open and ice-covered waters include mechanical containment and recovery, the use of dispersants, in-situ burning and natural degradation. Some characteristics of the Arctic can have both positive and negative impacts on the success of an oil spill response. For example, ice cover can serve as a natural barrier to oil spreading, thus limiting the operational area of oil spill respondents (EPPR, 2015). However, accessing oil trapped in ice can be challenging and the lack of ports and general infrastructure can complicate oil spill response actions in the Arctic.

'Recovery potential' consists of functional group -specific recolonization and reproduction rates, which affect when and if a population can return to their pre-spill level (similar to Lecklin et al., 2011). Generally, different species have varying recolonization abilities, depending on, for example, their mobility and distributional patterns (Kaiser et al., 2011), and the recolonization by even efficient colonizers can be delayed or fully prevented by oil left in the environment (Nelson, 1981; Day et al., 1997; Fukuyama et al., 2014), especially when the oiled area is isolated (Kubach et al., 2011). The rate of reproduction is affected by group-specific characteristics, including age at maturity and number of offspring (Hill et al., 2012). Reproduction efficiency can also be affected by oil left in the environment, for example, through the chronic impacts of oil or damaged breeding grounds (e.g. Davis and Anderson, 1976; Ainley et al., 1981; Rice et al., 1987).

'Long-term vulnerability' describes the effect of spilled oil on a population after a given period of time. Similar to acute vulnerability, the definition of 'long' may differ between functional groups, seasons and types of oil spilled – and the specific research question (i.e. the assessment endpoint). In addition to 'acute impact', 'oil persistence' and 'recovery potential', longer-term vulnerability may also be affected by the state of other population(s) in a food web, since, for example, the loss of a food source may have an adverse impact on a group and the loss of a predator, a positive one (Palumbi et al., 2008). Simple food webs and strong dependencies between groups can strengthen these impacts and a population decline of a single species can have serious structural and functional consequences for Arctic ecosystems (Chapman and Riddle, 2005), suggesting that such links are particularly important to consider when conducting ERA in the Arctic. The fate of offspring after an accident may also affect longer-term vulnerability, particularly for functional groups with low reproductive rates.

3.2 Quantifying the risk

Moving from the conceptual description of Arctic oil spill ERA towards a quantitative understanding of the risks is challenging due to limited data. Hence, Arctic oil spill ERA must rely heavily on knowledge gathered from subarctic or temperate regions and from experts on the topic (Table 2). The most adequate methods for quantifying the variables within the conceptual model (Fig. 4) are presented in Sections 3.2.1 and 3.2.2. Moreover, major knowledge gaps inhibiting quantification are underlined.

Regardless of the data sources and the methods for obtaining them, the values of all the variables related to Arctic oil spill ERA should be assessed as probability distributions rather than point estimates, if possible, to explicitly and transparently account for the uncertainty within them (papers **I**–**IV**). Especially if data from temperate regions are used to assess the impacts of oil spills in the

Table 2. Potential source(s) of data for the variables in the conceptual model for Arctic oil spill ERA.

Variable	Potential source(s) of data	Data source(s) used in this thesis
'Oil type' 'Season'	Marine transportation statistics, previous studies, expert knowledge	Assigned uniform distributions (papers **II**–**IV**)
'Oiled area'	Previous studies, oil spill models (such as SIMAP and OSCAR), expert knowledge	Simulated by a simple oil spill model for ice covered waters (Afenyo et al., 2016B) in paper **IV**. Data on ice coverage collected from National Snow and Ice Data Center (Cavalieri et al., 1996).
'Oil persistence'	Previous studies, expert knowledge	Not assessed
'Oil spill response'	Marine transportation statistics, expert knowledge	Not assessed
'Recovery potential'	Previous studies, ecosystem models, observational data, expert knowledge	Assessed based on previous studies from temperate regions (paper **III**)
'Exposure potential' 'Sensitivity' 'Vulnerability'	Previous studies, observational data, expert knowledge	Assessed quantitatively by expert elicitation (paper **II**) and semi-quantitatively based on previous studies (paper **III**).
'Biota within oiled area'	Species distribution models, previous studies, observational data, expert knowledge	Assessed based on Mäkinen and Vanhatalo (2018) in paper **IV**.

Arctic, it can potentially necessitate the inclusion of high amounts of uncertainty in the assumptions (paper **III**).

The variables can be discretized into a varying number of classes. For example, 'season' can be classified into four classes: 'spring', 'summer', 'autumn' and 'winter' which can either be assigned a uniform distribution (papers **II**–**IV**) or a distribution reflecting an assumed accident probability (see Khan et al., 2018). Oil type can be discretized into oil type categories, such as light, medium, heavy and extra heavy oils (resembling Helle et al., 2011; Lecklin et al., 2011; Helle et al., 2015), which differ from each other both in physical fate and environmental impacts (papers **I**–**IV**). As another example, 'acute impact' can be classified, depending on the amount and quality of data, into numerical classes (as in paper **II**: 0–10%, 10–20%, etc.) or into semi-quantitative or qualitative (but still well-defined) classes (as in paper **III**: 'none', 'low', 'medium', 'high'). The appropriate scale of discretization depends not only on the variable, but also on the chosen method of obtaining data. For example, a computer-based oil spill trajectory model can handle close to an endless number of scenarios compared to the significantly more limited capacity of a human brain (O'Hagan et al., 2006).

3.2.1 Quantifying the variables describing the accident scenarios

The probability distributions for the variables concerning the accident scenarios ('season', 'oil type', 'oiled area', 'oil spill response' and 'oil persistence') could potentially be calculated from maritime transportation statistics or accident reports (see e.g. Jin et al., 2002; Helle et al., 2011; Kim et al., 2011; Lecklin et al., 2011; Jolma et al., 2014). However, the number of realized accidents in the Arctic or in ice-filled waters in general, are low and no major oil spill has yet occurred in the true Arctic, suggesting that statistics and reports may not provide reliable estimates. There have been a few attempts to estimate the accident probability in the Arctic based on, for example, navigational and operational features, weather, ice conditions and human error (see e.g. Marchenko et al., 2015; Sahin and Kum, 2015; Khan et al., 2018). These models can offer insight into some of the variables related to accident scenarios. For example, they generally include estimates of how accident probability varies between seasons. Before more detailed data are obtained from the Arctic, some rough estimates for some of the accident scenario related variables (such as persistence of oil) can be formed based on statistics from temperate regions, particularly for the ice-free period, but it should be noted that the characteristics of accidents in the Arctic can differ from those of other regions.

The probability distribution for the location-specific extent of the oiled area may be estimated by running oil spill trajectory models (such as OSCAR (Reed et al., 2000) and SIMAP (French-McCay, 2004)) with different parameterizations. However, as previously discussed, these models generally require detailed spatial data that are seldom available for the Arctic and hence, a simpler approach is often needed. Moreover, many of the oil spill models have limited ability to model the behavior of oil in ice (Afenyo et al., 2016A). Oil spreading in ice-filled waters can, however, be calculated with simplified methods that do not require as detailed data as the previously mentioned models (see e.g. Afenyo et al., 2016A; 2016B and references therein). For example, the fate of oil can be calculated based solely on oil spreading determined by the oil type and the extent of the ice coverage (paper **IV**). The oiled area can also be estimated by experts. Lastly, the oiled area can be roughly estimated based on earlier accidents with known properties and fate of oil. However, this could result in an overestimation of the area covered by oil, since ice cover reduces oil spreading (paper **IV**) and observational data of oil spreading in ice-filled waters are limited (Afenyo et al., 2016A; 2016B). Moreover, even if oil spreading can be assessed with some accuracy based on the known properties of oil, drifting of oil depends on location-specific variables, such as winds and surface flows.

Oil persistence is difficult to estimate and is often left out of oil spill models, even when the longer-term effects of spilled oil are of interest (see e.g. Lecklin et al., 2011). However, generally the persistence of oil can be assumed to be high (see e.g. Nixon and Michel, 2015 and Lindeberg et al., 2018 for persistence of oil after EVOS), and the heavier the oil is, the longer it is likely to remain in the environment (Branvik et al., 2006). Moreover, weathering processes are slowed down in cold environments (Fingas and Hollebone, 2003; Brandvik et al., 2006), suggesting that oil may persist in the Arctic for particularly long periods of time. Even if the persistence of oil cannot be quantitatively estimated, it is important not to overlook its significance, since it has potential to greatly affect the longer-term impacts of an oil spill. Moreover, efficiency of an oil spill response in the Arctic can be relatively low compared to those mounted in temperate regions due to, for example, harsh climatic conditions, the remoteness of the area and poor infrastructure (see Transportation Research Board, National Research Council, 2014; EPPR, 2015; Wenning et al., 2018). There may be some local variation in the efficiency of oil spill responses that can be roughly estimated based on, for example, the distance to the nearest port with available response vessels (see e.g. Helle et al., 2011; Lehikoinen et al., 2013). However, it is worth noting that even relatively quickly launched, long-duration oil spill responses executed with a massive amount of resources may not result in a high percentage of the oil being cleaned up. This was proven by the unprecedentedly large cleanup efforts following EVOS, which resulted in total cleanup of only about 25% of the initial amount of spilled oil (Ventikos et al., 2004).

It is possible to conduct Arctic oil spill ERA without data on all the before-mentioned variables. Papers **II** and **III** assess the exposure potential and sensitivity of Arctic biota without informative probability distributions describing the timing of an accident, the type of oil or the extent of the oiled area. The results can be used to compare the relative risk posed by spilled oil on different parts of an ecosystem and to assess variations in risk between seasons and oil types. The results can afterwards be included in a more detailed ERA that contains the chain from accident scenarios to the environmental consequences of oil spills (see e.g. Lecklin et al., 2011; Ehlers et al., 2014, Helle et al., 2015).

When moving from general, non-spatial estimates of risk to more detailed, site-specific risk assessment, additional knowledge is required about oil spreading and the distribution of species. Paper **IV** combines predictions of polar bear, walrus, and ringed seal areal densities (Mäkinen and Vanhatalo, 2018) within a case study area with approximations of oil spreading under different ice conditions (Afenyo, 2016B) and estimates of the exposure potential and sensitivity of the studied groups (see Section 3.2.2). The approach allows for the comparison of the risk related to different shipping routes and the potential variation in the overall risk between seasons and oil types. The paper assumes that an accident can happen with equal probability anywhere within a shipping route (equaling to 'oiled area'), but an estimate of accident probability associated with each shipping route can be added to the analysis later (see e.g. Khan et al., 2018).

3.2.2 Quantifying the variables describing the environmental impacts of spilled oil

Quantifying the environmental impacts of oil is equally, if not more challenging than assessing the fate and persistence of oil. For some of the functional groups (mainly fish and invertebrates) it would be possible to conduct (more) laboratory or even mesocosm studies to assess their exposure potential and sensitivity. For mammals and birds, such experiments would be difficult or impossible to implement, and could lead to a number of ethical questions. Some variables contributing to the overall vulnerability, such as 'recovery potential' or the impact that lost prey (or predation) may have on a functional group, could potentially be estimated using ecosystem models. For example, Atlantis, an ecosystem model that has been used to evaluate the population-level impacts of the Deepwater Horizon oil spill (Ainsworth et al., 2018). However, no such model has yet been calibrated for the true Arctic, as they require vast amount of data. Moreover, ecosystem models are mainly deterministic (Allen et al., 2007; Fulton, 2010; Link et al., 2012; Spence et al., 2018) and are therefore ill-suited for risk assessment, especially in the Arctic. Therefore, at least for the time being, assessing the exposure potential and sensitivity of Arctic biota must rely on information gathered from experts (paper **II**) complemented with knowledge from published literature where applicable (paper **III**).

3.2.2.1 Estimating oil spill impacts using expert elicitation

Expert knowledge is a potential source of information for many of the variables in the conceptual model (Table 2). Expert elicitation refers to a scientific method of formally obtaining expert knowledge about a subject of study, and it is often applied when other types of data are limited or lacking. It has been widely utilized in environmental risk assessment, especially for events for which there are no prior data (Burgman, 2005). Expert elicitation has also been used in some studies related to oil spills (see e.g. Lecklin et al., 2011; Montewka et al., 2013; Valdez

Banda et al., 2015; Fingas, 2017). The greatest benefit from using expert elicitation is that it allows for the examination of topics that would be challenging or impossible to study otherwise. This method has been used in data-poor contexts, such as assessing the risk of nuclear power plant failure (Keeney and Von Winterfeldt, 1991), planning efficient wildlife conservation (MacMillan and Marshall, 2005), and predicting impacts of land use on biota (Martin et al., 2005). It has also been identified as an effective technique for forming accurate judgements under conditions of high uncertainty (Lyon et al., 2015). Expert knowledge can be used at every step of ERA: experts can build a conceptual description of the problem, they can provide qualitative or quantitative estimates on a study topic based on their own expertise (paper **II**), or they can identify and value different management options (see e.g. Kuhnert et al., 2010; McBride and Burgman, 2012).

Besides often being the only reasonable and available option for studying data-poor topics, expert elicitation has a number of other advantages. It is a flexible method that can be implemented remotely or face-to-face, used with individuals or groups, and data can be collected in a variety of forms (see e.g. Kuhnert et al., 2010). The interviewer can be a passive facilitator, guide the discussion or even form quantitative descriptions (such as probability distributions) of the topic based on discussion with or among experts. Expert elicitation is also a relatively low-cost method, a feature that makes it a particularly attractive approach in the Arctic where field research can be highly expensive due to poor working conditions. Moreover, as pointed out by Kuhnert et al. (2010), when it comes to risk management, it is best to use models founded on expert knowledge if the alternative is to delay decision-making until empirical data become available.

However, the method also includes some biases that must be considered when utilizing expert knowledge. For example, experts may be overconfident, underestimating the uncertainty in their own knowledge (see e.g. Haran et al., 2010), which may produce biased results. Estimating the amount of uncertainty may be particularly difficult for the experts when it comes to an unprecedented or extreme events (Barker and Haimes, 2009; Morgan, 2014). Another potential bias is called the anchoring effect, which refers to experts' tendency to start the estimation process with an initial estimate and then to produce the subsequent estimates by adjusting the first, which may lead to too little variation between the estimates (Tversky and Kahnemann, 1974). Moreover, personal values may influence the judgements of even well-trained and -educated experts (Heeren et al., 2017). There are several methods for reducing bias in expert elicitation, but eliminating it completely is very challenging (see e.g. O'Hagan et al., 2006). Moreover, finding skilled and motivated experts can prove to be difficult especially if the topic is relatively unstudied (paper **II**).

In this thesis, expert elicitation is used for collecting data on the acute impacts of spilled oil on Arctic biota. Paper **II** carries out the elicitation process remotely using an elicitation tool built for that purpose. Potential experts were first identified based on their research and publication profile, and the identified experts were asked to recommend other potential experts regardless of their own choice to participate to the study (approach known as the ‘snowball method’, see Biernacki and Waldorf (1981)). Altogether, eight experts participated in the study, and data on the acute impacts of spilled oil on seabirds, anatids and seals were obtained. The data on seals provided by the experts are utilized in paper **IV** and the elicitation tool (described in paper **II**) is also used in paper **IV** along with literature collected in paper **III** (see Section 3.2.2.2) to quantitatively assess the acute exposure potential and sensitivity of polar bears and walruses. Moreover, in paper **III,** the method of assigning probability distributions for the variables resembles expert elicitation, as the estimates are formed based on the expertise of the first author (the author of this thesis) and reviewed and revised together with the other authors.

3.2.2.2 Estimating oil spill impacts based on published literature

Expert knowledge in Arctic oil spill ERA may be supplemented by information from published literature (paper III). For example, if experts cannot be found (paper II), some of the variables within the conceptual model can be quantified based on a systematic literature review. For instance, in paper II data were only obtained for three functional groups, since no experts on the other functional were willing to participate in the study (which may indicate knowledge gaps related to the non-elicited functional groups). Moreover, in paper II, the experts were asked to assess only the acute impacts of spilled oil because the evaluation of the longer-term impacts could be too challenging due to the complexity of the matter. Moreover, it would have increased the already extensive workload of the experts. Therefore, systematic and justified exploitation of the existing knowledge from sub-Arctic and temperate regions is an important additional source of information.

One concrete solution to assist in the construction of probability distributions for the variables within the conceptual model is to develop an index based on published knowledge describing the risk the spilled oil poses to marine biota (paper III). An index is a convenient way of compiling a score from different variables from a variety of data sources with varying levels of precision. Moreover, it can offer a convenient way to move towards quantitative estimates and to efficiently and systematically exploit existing knowledge. Such an approach has been used in oil impact studies by, for example, King and Sanger (1979) for marine birds of North America, Williams et al. (1994) for seabirds of North Sea, and Helle et al. (2016) for threatened species and habitat types of the northern Baltic Sea. A few region-specific indices have been developed for some Arctic or sub-Arctic areas (e.g., Stjernholm et al. 2011; Environment Canada, 2015; Clausen et al., 2016). Extrapolating such indices to the whole Arctic would, however, be challenging, as accurate data on habitats and their physical characteristics in the Arctic are mostly lacking. In paper **III**, existing knowledge about oil spill impacts from Arctic, subarctic and temperate regions was turned into indices describing exposure potential, sensitivity and vulnerability of Arctic biota. First, the relevant variables that contribute to exposure

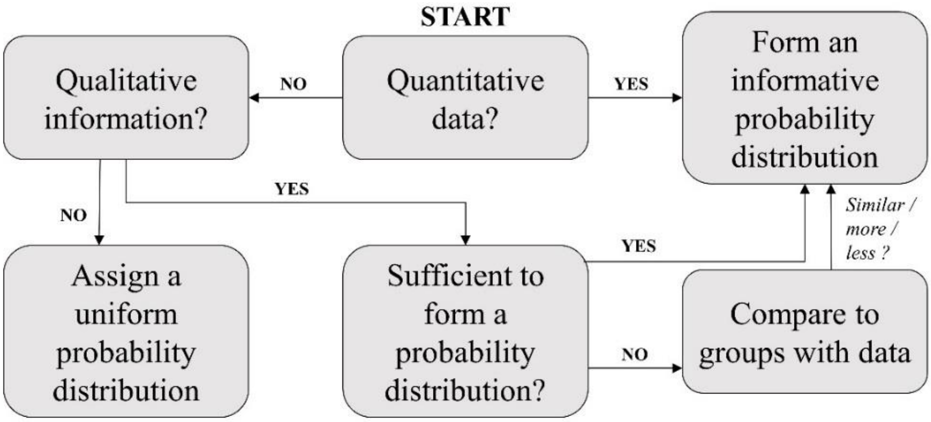

Fig. 5. The steps followed in assigning the probability distributions for variables contributing to index describing exposure potential and sensitivity of Arctic biota (paper **III**).

potential and sensitivity of Arctic biota were identified. To mention a few, functional groups' flocking tendency and use of ice were identified as variables contributing to their exposure potential, and their body size and grooming tendency as variables contributing to their sensitivity. Next, a probability distribution was assigned for each variable based on literature to describe how much the variables contribute to functional groups' overall exposure potential and sensitivity. First, probability distributions of the most data-rich variables were assessed (see Fig. 5). For some such variables, like tolerance to toxins, the distributions could be calculated from quantitative data (see paper **III** Appendix S1). Next, probability distributions were formed for variables with less, but still some (qualitative) information. For some such variables, qualitative data could be used to calculate the probability distribution. For instance, the 'flocking tendency' of some groups have been documented well enough to infer a suitable probability distribution even without quantitative data. Next, uniform distributions were assigned for variables for which there were no data. Lastly, for many variables there was some, but not comprehensive (qualitative) information available. The probability distributions for those variables were formed by comparing them to other, more data-rich functional groups. As an example, data on the escape capability of any invertebrate group could be used with reasonably certainty to deduce the escape capability of other invertebrate groups. Once all the probability distributions had been assigned, the variables were combined into indices representing the overall exposure potential, sensitivity and vulnerability of the functional groups.

It should be noted that the index is not quantitative to the same extent as the probability distributions provided by the experts. Even though some quantitative data were included in the probability distributions of some of the variables, the index itself is a semi-quantitative description of the risk. However, the uncertainty related to the estimates is described quantitatively, and the developed index is a clear step towards a quantitative understanding of the risks when compared to previous qualitative estimates (most importantly by AMAP (2010), which contain no estimates of the uncertainty and very limited descriptions of the logic behind the risk estimates).

4 Results and discussion

4.1 Summary of the main results

The first aim of this thesis was to build a probability-based, general framework for studying the impacts of spilled oil on Arctic biota in the data-poor Arctic. An extensive literature review was conducted and several important variables that contribute to the risk the spilled oil poses to biota were identified (papers **I**, **III**). Moreover, the key marine functional groups at risk and relevant accident scenarios were identified. The second aim of the thesis was to use that framework to quantify the risk posed by spilled oil to Arctic biota. The results suggest that exposure potential, sensitivity and therefore, vulnerability, vary greatly between functional groups, life stages, oil types and seasons (papers **II**–**IV**), proposing that attention should be paid to such variation when assessing and managing the risks related to Arctic oil spills. Moreover, accounting for spatiotemporally varying components of the oil spill risk, such as oil spreading, emphasizes the importance of oil type and the extent of ice cover in determining the risk to biota (paper **IV**). Spatiotemporal components also increase the uncertainty related to the risk. All in all, the uncertainties related to Arctic oil spill impacts are great and must be acknowledged in decision-making.

4.1.1 Season and oil type affect the exposure potential and sensitivity of Arctic biota

Birds and polar bears seem to be the Arctic biota most at risk from oil spills (papers **II**–**IV**). In that regard, the results are in line with previous studies from temperate regions, which suggest that birds and fur-bearing mammals are particularly prone to suffer from spilled oil (see e.g. French-McCay, 2004; AMAP, 2010; Lecklin et al., 2011). The results also bring new knowledge by suggesting that seasonality, which has seldom been comprehensively considered in oil impact studies, may have significant effects on the harm caused by oil (papers **II**–**IV**). Season affects both the exposure potential and sensitivity of most functional groups (papers **II**, **III**) and oil spreading and therefore, also the proportion of a population within an oiled area (paper **IV**; see Section 4.1.2). Season is particularly important for polar bears' exposure potential and vulnerability. These metrics seem to be considerably lower during summer (paper **III**), since the bears may be forced to stay on land due to loss of ice (Molnár et al., 2010) and are therefore less likely to encounter spilled oil.

Furthermore, season has a particularly strong impact on most functional groups' offspring's exposure potential, sensitivity and vulnerability. However, in contradiction to what is often assumed (see e.g. AMAP (2010) and references therein), offspring may not be at higher risk compared to adults, at least when it comes to acute risk (paper **II**). For example, although bird offspring seem to be more sensitive during spring, they also have significantly lower exposure potential making their vulnerability lower than that of adults. This is explained by offspring's tendency to stay in the nest where they will not come into contact with oil, while adults search for food. Regardless, an oil spill during breeding season could cause a variety of indirect harm to biota. For example, offspring may die due to the death of their parent(s), the probability of which was not assessed in this thesis.

Arctic biota have varying exposure potential and sensitivity to different oil types (papers **II**, **III**). For most of the functional groups, oil type is particularly impactful for their exposure potential. For example, functional groups that stay on seafloor (such as demersal fish and benthic invertebrates) are significantly more vulnerable to heavier oils that sink to the seafloor than to light oils that may evaporate straight from the sea surface (paper **III**). Contrariwise, the groups inhabiting the water column (such as pelagic fish and seals) are less vulnerable to heavier oils that occupy the water column only shortly and in relatively solid form before sinking to the seafloor or drifting ashore, compared to lighter oils, which may dissolve into the water column in greater amounts. Furthermore, oil type has an effect on the sensitivity of many of the groups (papers **II**, **III**). In general, Arctic biota is less sensitive to light oils than to medium, heavy and extra heavy oils, but there is some variation between the groups.

Invertebrates and fish seem to be the most vulnerable functional groups due to, for example, their aggregation behavior and limited or absent ability to escape from an oiled area (paper **III**). The sensitivities of all the invertebrate and fish groups are similar, but their exposure potentials differ greatly depending on the type of oil spilled (paper **III**). Similar to invertebrates, the four fish groups – pelagic, cryopelagic, foraging and demersal – have similar sensitivities, but their exposure potential differs greatly depending on the oil type (paper **III**). Ice seals are the least affected group, with their almost certain 'medium' vulnerability with very little variation between accident scenarios. Their relatively low vulnerability is explained by, for example, their blubber-based thermoregulation system and relatively high tolerance to toxins (paper **III**).

4.1.2 The risk posed by spilled oil varies spatiotemporally

When the risk assessment is expanded by adding spatiotemporally varying components describing the areal densities of biota and oil spreading under different ice-conditions to the exposure potential and sensitivity information described above, certain accident scenarios appear to pose significantly higher risks to biota than others (paper **IV**). In short, the more ice there is, the less the oil will spread, and the lighter the oil, the more it will spread (paper **IV**). Hence, an accident scenario where light oil is spilled in low ice conditions results in the largest oiled area. However, such a scenario does not automatically expose larger proportions of populations compared to other accident scenarios. This is due to the fact that the areal distributions of many Arctic species are dependent on ice cover (paper **IV**; Mäkinen and Vanhatalo, 2018) and hence, an accident in ice-covered waters may be less dangerous to species not dependent on ice cover compared to an accident in open water (paper **IV**).

As discussed throughout the thesis, the risk to biota cannot be comprehensively deduced from solely comparing oil spill trajectory to species' areal distributions. Without information about vulnerability, light oils seem to pose the highest acute risk to biota, but since most biota are more sensitive to medium or heavy oils than to light oils (papers **II**, **III**), accounting for vulnerability suggests that medium oil poses a higher acute risk than light oil (paper **IV**). Overall, accounting for vulnerability decreases the risk compared to estimates based solely on oil spill trajectory and species distributions.

However, accounting for vulnerability does not automatically contribute to decision-making. Even though it affects the risk order of accident scenarios, it does not necessarily change the risk order of the shipping routes. In other words, the risk order of the shipping routes may be the same whether it is based solely on oil spill trajectory and species distributions or if vulnerability is accounted for (paper **IV**). The case study described in paper **IV** presents a spatiotemporal risk assessment focusing on adult marine mammals whose exposure potential and sensitivity hardly vary between seasons and oil types (papers **II**, **III**) therefore, accounting for their vulnerability has a relatively small impact on the total risk (paper **IV**). Nonetheless, even if vulnerability does not affect the risk order of shipping routes and thus, the selection of the optimal shipping route, it improves both our understanding of the risk and the amount and sources of the related uncertainties (paper **IV**).

It is worth noting that the case study assumes a constant accident probability along the shipping routes. In reality, if a shipping route is located, for example, near a range of rocks and there are highly vulnerable biota in the vicinity, such a route may very well pose the greatest risk. Moreover, the ice coverage that affects the oil spreading and species distributions is likely to affect the accident probability too (Khan et al., 2018). Therefore, the risk associated with oil spills in low ice concentrations may be lower than the results currently suggest. Accident probabilities have already been assessed for some Arctic areas (see Khan et al., 2018 and references therein) and the methodology of the spatiotemporal risk assessment of this thesis can be extended to account for the (spatiotemporally varying) accident probability, if such data become available for the case study area.

Our understanding of the spatiotemporal variation of the risk may change in the future if new species or functional groups can be included in the analysis. Adding, for example, birds, especially their offspring, could increase the temporal variation in the results, since their exposure potential and sensitivity differ between seasons (papers **II**, **III**). Currently, the limiting factor is the amount of data on the distributions of most biota in many data-poor areas in the Arctic. Some data on bird distributions, or at least on the locations of their breeding colonies, exist (see e.g. Bakken, 2000; AMAP/CAFF/SDWG, 2013), but the data are far from comprehensive. In the future, more data may become available as the easing weather conditions in the Arctic make field studies more feasible. The quantitative data on the exposure potential and sensitivity of birds collected from the experts in paper **II** are readily suitable for such an analysis if detailed enough data on their distribution are obtained.

It should be noted that additional data does not automatically change our understanding about the safest or riskiest shipping routes. If the estimated species range covers a large area and knowledge about the spatiotemporal variation in the abundances is lacking, the additional data may not contribute to decision-making related to the selection of shipping routes. It is also worth noting that climate change may affect the distribution of biota, especially for species that are heavily dependent on ice and may move poleward (ACIA, 2004; Rahel et al., 2008; Brommer et al., 2012). If they do, they would be further away from the areas where maritime traffic volume is expected to grow the most, thus lowering the risk they face.

4.1.3 Uncertainty in oil spill risk needs to be understood and managed

As discussed throughout the thesis, comprehensive processing and transparent presentation of uncertainty is of key importance in Arctic oil spill ERA, especially if the results are to be used in decision-making. Even though the thesis produces new information about the risk posed by spilled oil, it also makes it evident that the uncertainties related to the topic are still large. The greatest uncertainties lie within the longer-term impacts of oil along with the persistence of oil in the environment. Since very little data on the longer-term fate of oil in the Arctic exist, no attempt to quantify the persistence of oil in the environment was made in the thesis (similar to Lecklin et al., 2011). It may be possible to use a simple population model to study how permanent the population-level changes caused by spilled oil would be, especially for species for which such models have already been built (see e.g. Ohlberger and Langangen, 2015; Rahikainen et al., 2017; de Vries et al., 2018). Unfortunately, however, population models have not been built for the majority of Arctic species. Therefore, at least for the time being, the decisions regarding oil spill risk management in the Arctic must primarily rely on estimates of the acute impacts of spilled oil.

There are also varying amounts of uncertainty concerning the acute impacts of oil spills, even though the thesis removes some of it. Most importantly, new knowledge about the exposure potential and sensitivity of Arctic biota was produced (papers **I**–**IV**) and major sources of uncertainty within them were identified (paper **III**, **IV**). However, the probability distributions assigned by the experts are relatively wide for both the exposure potential (with the exception of offspring during spring) and sensitivity of seals and birds (paper **II**). Varying amounts of uncertainty are also included in the vulnerability index and can greatly influence the interpretation of the results. For example, although the index suggests that polar bears are less at risk from spilled oil during summer than during other seasons, there is significantly more uncertainty in their exposure potential and vulnerability during summer (paper **III**). This is because their use of habitat may vary greatly during summer (Amstrup, 2003). Furthermore, when spatiotemporal variables are accounted for, the results suggest that the risk to polar bears generally contains most uncertainty during summer (paper **IV**).

When considering all the functional groups, exposure potential estimates include more uncertainty than sensitivity estimates (papers **II**, **III**). This is at least partially explained by the fact that exposure potential depends on biota's use of habitat (including use of ice), which may vary greatly not only between, but also within seasons (paper **III**). When the biological response (i.e. exposure potential and sensitivity of biota) is complemented with data on species areal densities and oil spreading, uncertainties in the risk estimates are even larger and the variation between seasons increases further (paper **IV**).

The thesis aimed at providing a quantitative description of the uncertainty, but it is worth noting that there are also different approaches for handling uncertainty. Recent literature has suggested that risk assessment should move from purely a quantitative, probability-based approach, to a semi-quantitative approach, which systematically treats the assumptions in the evidence (see e.g. Aven, 2013; Berner and Flage, 2016). These new perspectives argue that probability (used as a measure of uncertainty) cannot reflect the strength of knowledge that the probability is based on. Such a risk assessment approach has been used in developing frameworks for marine oil spill risk assessment (Goerlandt and Montewka, 2015) and in Arctic risk assessment focusing on ice management options (Haimelin et al., 2017). The strength of evidence is undoubtedly of interest to decision-makers and should be accounted for in future studies. The results of this thesis and the description of uncertainties in particular, can be further studied in terms of assumptions in the evidence.

It should be noted that in this thesis, uncertainty originating from a lack of knowledge is not distinguished from uncertainty originating from natural variation. This would have complicated the analysis and further increased the workload of the experts (and the authors). However, the main sources of uncertainty in different variables are assessed (papers **I**, **III**). Moreover, the thesis offers recommendations for reducing uncertainty in future risk assessments. Contrary to what could be assumed, future research should not necessarily target the most uncertain variables, but the benefits of new data should be assessed in relation to the difficulty of collecting them (paper **III**). Moreover, the significance of the uncertainty to decision-making should be assessed: if the decision is the same regardless of the amount of uncertainty, it may not be sensible to use resources for collecting more data (Morgan and Henrion, 1990; Reckhow, 1994).

One concrete way to plan data collection is to perform value of information analysis, so that the expected utility from obtaining new data is maximized (Raiffa and Schlaifer, 1961; Mäntyniemi et al., 2009; Eidsvik et al., 2015). In Arctic areas, such analysis would likely provide tremendous benefits, since the costs of exploration and data collection are high and the current information about the environment is low. Another alternative is to perform sensitivity analysis (note that here *sensitivity* does not refer to functional groups' sensitivity to oil) to study how uncertainty in the model output is apportioned to different sources (paper **III**; Saltelli et al., 2004). The model output is not automatically most sensitive to the most uncertain variables, and sensitivity analysis allows for the analyst to compare variables that cause the most change in the model outputs to the main source(s) of uncertainty and to assess how easily new data can be obtained. In general, data collection should focus on variables in which the greatest uncertainties are due to limited knowledge, not due to natural variation (paper **III**). For example, in Arctic oil spill ERA, changes in habitat use-related variables cause relatively large changes in the model outputs (paper **III**). Collecting data on them would be relatively easy by exploiting, for example, expert elicitation or field surveys. However, the main source of uncertainty for such variables is natural variation, suggesting that the uncertainty may remain high despite additional research (paper **III**). This problem can, however, be addressed by species distribution models (SDM) designed for the data-poor Arctic (paper **IV**). The better the observations, the more accurate the predictions of the distributions and densities of biota. Currently, SDM can only be applied to a few Arctic species with observational data. Most species are still poorly monitored in majority of the Arctic and existing data are limited to those species with economic value (CAFF, 2017). Lastly, the cost of data collection in the Arctic can be expected to be high, and therefore, its cost-efficient implementation will require economic analysis, which is outside the scope of this thesis.

4.2 The significance of the work

The ultimate aim of any ERA is to support decision-making (Burgman, 2005). This thesis aimed to produce new data and methodologies that can be of use in further risk assessment and in management related to Arctic shipping. The developed framework is easy to use and does not require vast computational capacity. The conceptual model is easy to understand and includes a relatively small number of variables, representing only the most relevant factors contributing to Arctic oil spill ERA. The framework developed in paper **I** has been mentioned as a key risk assessment method to be applied in planning the oil spill response in the Arctic by Wenning et al. (2018) and has received wide interest in the literature (17 citations by 4/2019). Moreover, the thesis presents a novel way to assess oil spill impacts when the existing oil spill models, like SIMAP (French-McCay, 2004) and OSCAR (Reed et al., 2000), cannot be used due to their comparatively high data-demands. The thesis further responds to the limitations of the existing oil spill models by considering the behavior of biota and quantifying the role of seasonality on that behavior, both of which have often been overlooked. Furthermore, the thesis accounts for the uncertainties related to oil spill impacts in more detail than most other oil spill models. The results obtained suggest that the approach is feasible, but requires further development (Section 4.3).

For most of the functional groups, this thesis offers the first data on their exposure potential and sensitivity and therefore, improves the understanding of the data-poor topic of Arctic oil spills. Providing estimates of exposure potential and sensitivity separately from other ERA variables (such as oil spreading) enables risk assessment at different levels (see e.g. paper **II** vs. paper **IV**), improves the exchange of knowledge between different areas, and offers easy updatability of the assessments when new evidence become available.

The methods developed are suitable for all key functional groups (in contrast to e.g. toxicological studies). The estimates of the vulnerability of the functional groups were produced following the same procedure (paper **III**), leading to an unprecedented opportunity to transparently compare the relative harm caused by spilled oil on biota under different accident scenarios, while taking into account the uncertainties related to the topic. The results suggest that the exposure potential and sensitivity of biota can affect the overall impact of an oil spill significantly (paper **IV**) and therefore, considering them in future Arctic oil spill ERA is recommended over the frequently used method of simply comparing species distribution to expected oil spill trajectory.

The thesis presents novel methods for studying oil spill impacts in a data-poor environment, and with minor modification, the methodology could be applied in other data-poor regions as well. The results inform us not only of impacts of oil on biota, but also of suitability of different methods for studying them. The index-approach, built in paper **III,** is especially adequate for comparing the functional groups to each other, since the data obtained for each group followed the same, transparent logic. Moreover, the index can be easily updated when new data come available. The elicitation process, in turn, is more time consuming and may not work at all if suitable experts are not found (paper **II**). However, the results of the expert elicitation can more easily be used in further risk assessments since they are in the form of probability distributions. Therefore, the elicitation method can be considered to be a more preferable method of obtaining data for Arctic oil spill ERA, assuming that enough skilled and motivated experts can be found. The thesis encourages the further use of expert knowledge in Arctic oil spill ERA and other data-poor topics, and for methodological development for both acquiring more data and for testing the credibility of the data obtained (paper **II**).

Ideally, the results of this thesis could concretely benefit Arctic conservation. Shipping routes could be designed based on the spatially and temporally varying risk, and if an accident were to occur, possible oil combating resources could be allocated to areas where the ecological risks are the highest. It may be relevant for decision-makers and other stakeholders to know which parts of an ecosystem will face the most harm if an oil spill happens, and whether the risk varies depending on the type of oil spilled and the timing of the accident. For example, the thesis identifies birds and polar bears as the biota most at risk from spilled oil. From a conservational perspective, avoiding shipping near areas that are known to host large aggregations of birds could be relatively easy. However, highly mobile polar bears are likely to be more difficult to protect, but, since they are classified vulnerable by IUCN (Wiig et al., 2015), protecting them is particularly important. Moreover, their regional densities can be assessed relatively precisely (see e.g. Wilson et al., 2016; Wilson et al., 2018), which can aid conservation efforts. The results of the spatiotemporal risk assessment in particular can help risk management related to shipping by demonstrating which routes are the safest for biota and whether the risk varies between seasons.

It should be noted that the hypothetical risk management options studied in this thesis (where, when, and what kind of oil to ship) can be considered to be somewhat speculative. The aim of the thesis was not to suggest the best management options for Arctic stakeholders, but rather to facilitate an understanding of this large and complex entity and hopefully, to serve as a basis for future, more detailed, risk assessment, which ideally, would also include the identification and comparison of management options. The results of this thesis can also be used in decision analysis to justifiably and transparently weigh the costs and benefits of various decisions regarding Arctic shipping.

4.3 Limitations of the study and guidance for future research

The work presented in this thesis is merely a step towards a quantitative understanding of the impacts of oil spills in the Arctic. Plenty of additional research must be conducted to fully understand this complicated environmental problem. First and foremost, limited knowledge complicated every step of the risk assessment process. Many assumptions had to be made based on published literature from temperate regions, since knowledge about oil spill induced risks in the Arctic is primarily qualitative (see e.g. AMAP (2010) and references therein). The framework for Arctic oil spill ERA includes a number of simplifications, while neglecting some components related to oil spills altogether, however the purpose of the framework is to improve the understanding of the main variables contributing to oil spill impacts on Arctic biota. Although the framework represents the current understanding, it is still an educated guess due to scarce data, and there might be 'unknown unknowns' that will not be discovered until an accident occurs. It should be noted that this uncertainty in the model structure (i.e. model uncertainty) was not studied in the thesis. However, it should be considered to better understand the amount and sources of uncertainty in the final results (see e.g. Draper, 1995). Hence, a need for future research is recognized.

The limited knowledge was also reflected in the difficulty of finding experts to participate in the elicitation research (paper **II**). Many people identified as potential experts declined to participate in the study because they did not feel that their expertise was sufficient. Consequently, the difficulty involved in finding any experts on most of the functional groups may point out some particularly wide knowledge gaps. Moreover, the small number of experts that participated in the study limited not only the amount of data at our disposal, but also the credibility of the results. Contrarily, however, the relatively unanimous answers given by the experts independently increased the credibility of the results.

Furthermore, the index-approach included a number of judgement calls that impacted the results remarkably (paper **III**). Overall, it is difficult to validate the results, as prior data are very limited. In the papers, the results were compared to knowledge about oil spill impacts from temperate regions and laboratory experiments (papers **I–IV**), but, as the thesis produces first estimates on exposure potential and sensitivity of most of the functional groups, the difficulty of validation is accepted as a challenge for future studies.

Secondly, although the low response rate among the potential experts might be partly explained by limited knowledge, at its core, the study failed to motivate them to participate (paper **II**). There are many possible reasons. Remote elicitations tend to have lower response rates than those conducted in person (Kuhnert et al., 2010) and the large number of questions included in the elicitation may have lowered the response rate (see e.g. Hemming et al., 2017). There are a number of means by which the number of participating experts could be increased. For example, elicitation carried out by a research institute, like the Arctic Council, which has already developed a good reputation and strong networks could lead to higher response rates (Cook et al., 2000). Moreover, a group discussion among the experts could lead to a higher number of answers (although it could also lead to additional problems, such as peer pressure, resulting in falsely unilateral answers (see e.g. Martin et al., 2012; Heeren et al., 2017)). The thesis encourages future research on data-poor topics, such as the exposure potential and sensitivity of Arctic biota, and to the design the elicitation process to ensure the experts' interest. For example, a pre-elicitation analysis can be carried out in order to enhance the probability of an elicitation's success (Martin et al., 2012). It is also worth considering whether a compromise should be made between the quality and the quantity of data, as smaller number of questions could incite more experts to participate in the study. For example, experts can give their answers in the form of minimum and maximum values instead of probability distributions, thus reducing their workload.

Third, a limited amount of attention was payed to the longer-term impacts of oil spills (also discussed in Section 4.1.3) and this is recognized as a potential shortcoming of the thesis. For instance, accounting for longer-term impacts could suggest that heavy oils pose a greater risk than medium oils, since heavier oils are expected to persist in environment for longer, thus prolonging the harm to biota (Mackay and McAuliffe, 1989). The vulnerability index includes estimates of the recovery rates of the functional groups, but without estimates of oil fate and persistence, the results are somewhat speculative. Oil spreading in ice-filled water can be estimated with some accuracy (paper **IV**), but oil can also get trapped under ice, travel great distances and be released far from the original accident site when the ice melts (Brandvik et al., 2006). Such oil migration is far from the scope of the current oil spill trajectory models. Moreover, the composition of oil may change drastically over time, and the impacts of weathered oil may differ greatly from those of freshly spilled oil. In theory, the elicitation tool built in paper **II** could be used for assessing the longer-term impacts of oil spills as well, but that would further complicate the questionnaire and could decrease the number of participating experts further. It should be noted, however, that with the current knowledge, it cannot be known for sure whether the longer-term impacts differ from the acute impacts from the perspective of decision-making. If a decision would be the same, regardless of whether acute impacts, longer-term impacts or both were considered, assessing the latter may not be necessary from a risk management perspective. If information about longer-term impacts is not available, decisions need to be made based on the acute impacts.

Fourth, the thesis presents the population and ecosystem dynamics in a very simplified manner. Although Arctic food webs are relatively simple, they may have been oversimplified by the decision to focus on the primary predator-prey relationships (paper **III**). All ecosystems are intrinsically variable, and the Arctic in particular is characterized by change and highly adaptable biota (CAFF, 2017). Therefore, gaining a better understanding of the population and ecosystem dynamics within this system could be useful when conducting more detailed Arctic oil spill ERA. The results of this thesis can offer some guidance about where a more detailed understanding of population dynamics would be most beneficial. Furthermore, the risk to the ecosystem was studied through the death of individuals. It is recognized that this is merely one alternative and different assessment endpoints could lead to different understandings of the risk. If the results of a risk assessment are to be used as such for decision-making purposes, the assessment endpoints should be chosen with the decision-maker to ensure the usability of the information produced.

Lastly, a need for a valuing method is identified. The spatiotemporal risk assessment suggests that it might not be possible to find a shipping route that is the safest for all biota (paper **IV**), and therefore, decisions may be required about which species should be preferentially protected over others. In this thesis, no values are assigned for biota, as there are no justifiable scoring criteria available (however, see Noring et al. (2016) for valuation of oil spill risk reductions in the Arctic from an ecosystem services -point of view), and developing one was outside the scope of this thesis. However, there are different ways to value biota. Scoring can be based on, for example, economic or ecological importance, or conservation status (see e.g. Laurila-Pant et al., 2015). From an ecological perspective, scoring can be based on, for example, species' resilience or role in a food web. Such values could also contribute to the weights of variables used in this study, and benefit the exploitation of the current results for the conservation of the marine Arctic. Similar to selecting the assessment endpoints, the valuation method should be designed with the decision-maker.

5 Concluding remarks

In near future, the Arctic is expected to face a dramatic increase in maritime traffic and natural resources exploitation. This thesis sheds light on what may result. From a risk management perspective, it is important to understand the environmental impacts of Arctic oil spills in order to prepare for them, but also to recognize the sources and magnitude of the uncertainty in the impacts estimated. The results suggest that polar bears and birds are most affected by spilled oil, and that the risk to biota may be altered by controlling the type of oil shipped, which shipping routes are used and when. However, there is still a great amount of uncertainty in the estimates, since there are many complex processes involved, and this thesis has simply been a step towards understanding them better.

The future of the Arctic is open, and it remains to be seen how strongly different interests, especially those related to economics and conservation, will collide. As I write these concluding remarks, the U.S. is contemplating oil drilling in Alaska (Nong et al., 2018) and Russia is looking to invest in offshore oil and gas drilling along its Arctic coast (Keil, 2017). This will not only increase the risk of an oil spill in the area, but the further consumption of fossil fuels, which will intensify climate change, which may, in turn, make shipping and drilling for oil in the Arctic all the more compelling. This is a persuasive reason for the further development of the risk assessment framework: the simultaneous risks posed by different human actions can equate to more than the sum of their parts. The more activity there will be in the Arctic, the greater the need to understand the associated risks.

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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.

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., 2016A. A state-of-the-art review of fate and transport of oil spills in open and ice-covered water. Ocean Engineering 119(1), 233–248.

Afenyo, M., Khan, F., Veitch, B., Yang, M., 2016B. Modeling oil weathering and transport in sea ice. Marine Pollution Bulletin 107(1), 206–215.

Afenyo, M., Khan, F., Veitch, B., Yang, M., 2017. A probabilistic ecological risk model for Arctic marine oil spills. Journal of Environmental Chemical Engineering 5 (2), 1494–1503.

AGCS, 2018. Safety and shipping review 2018.

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.

Ainsworth, C.H., Paris, C.B., Perlin, N., Dornberger, L.N., Patterson III, W.F., Chancellor, E., Murawski, S., Hollander, D., Daly, K., Romero, I.C., Coleman, F., Perryman, H., 2018. Impacts of the Deepwater Horizon oil spill evaluated using an end-to-end ecosystem model. PLoS ONE 13(1): e0190840.

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.

Allen, J.I., Somerfield, P.J., Gilbert, F.J., 2007. Quantifying uncertainty in high-resolution coupled hydrodynamic-ecosystem models. Journal of Marine Systems 64(1–4), 3–14.

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.

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

Arctic Council, 2016. Arctic Resilience Report. M. Carson and G. Peterson (Eds.). Stockholm

Environment Institute and Stockholm Resilience Centre, Stockholm.

Arneborg, L., Höglund, A., Axell, L., Lensu, M., Liungman, O., Mattson, J., 2017. Oil drift modeling in pack ice – Sensitivity to oil-in-ice parameters. Ocean Engineering 144, 340–350.

Arrigo, K.R., van Dijken, G., Pabi, S., 2008. Impact of a shrinking Arctic ice cover on marine primary production. Geophysical research letters 35, L19603.

Arzaghi, E., Abbasi, R., Garaniya, V., Binns, J., Khan, F., 2018. An ecological risk assessment model for Arctic oil spills from a subsea pipeline. Marine Pollution Bulletin 135, 1117–1127.

Aurand, D., Essex, L., 2012. Ecological Risk Assessment: Consensus Workshop. Environmental Tradeoffs Associated With Oil Spill Response Technologies. Northwest Arctic Alaska. A report to the US Coast Guard, Sector Anchorage. Ecosystem Management & Associates, Inc., Lusby, MD. 20657. Technical Report 12–01, 54 pages.

Aven, T., 2013. Practical implications of the new risk perspectives. Reliability Engineering and System Safety 115, 136–145.

Bailey, S.A., Wiley, C.J., MacIsaac, H.J., 2013. Relative risk assessment for ballast-mediated invasions at Canadian Arctic ports. Biological Invasions 15(2), 295–308.

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

Barker, K., Haimes, Y.Y., 2009. Assessing uncertainty in extreme events: Applications to risk-based decision making in interdependent infrastructure sectors. Reliability Engineering & System Safety 94(4), 819–829.

Beegle-Krause, J., 2001. General NOAA oil modeling environment (GNOME): A new spill trajectory model. International Oil Spill Conference Proceedings 2001(2), 865–871.

Beegle-Krause, C.J., Nordam, T., Reed, M., Daae, R.L., 2017. State-of-the-art oil spill trajectory prediction in ice infested waters: A journey from high resolution Arctic wide satellite data to advanced oil spill trajectory modeling - What you need to know. Internat. Oil Spill Conf. Proc. 2017 (1), 1507–1522.

Belikov, S., Boltunov, A., Gorbunov, Y., 1996. Distribution and migration of polar bears, pacific walruses and gray whales depending on ice conditions in the Russian Arctic. Proc. NIPR Symp. Polar Biol. 9, 263–274.

Berner, C., Flage, R., 2016. Strengthening quantitative risk assessments by systematic treatment of uncertain assumptions. Reliability Engineering and System Safety 151, 46–59.

Beveridge, L., Fournier, M., Lasserre, F., Huang, L., Têtu, P.-L., 2016. Interest of Asian shipping companies in navigating the Arctic. Polar Science 10(3), 404–414.

Biernacki, P., Waldorf, D., 1981. Snowball sampling: problems and techniques of chain referral sampling. Sociological Methods & Research 10(2), 141–163.

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.

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.

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.

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.

Brommer, J.E., Lehikoinen, A., Valkama, J., 2012. The breeding ranges of central European and Arctic bird species move poleward. PLoS ONE 7(9): e43648.

Brunström, B., Halldin, K., 2000. Ecotoxicological risk assessment of environmental pollutants in the Arctic. Toxicology Letters 112–113, 111-118.

Buhl, K.J., Hamilton, S.J., 1991. Relative sensitivity of early life stages of arctic grayling, coho salmon, and rainbow trout to nine inorganics. Ecotoxicology and Environmental Safety 22(2), 184–197.

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

CAFF, 2017. State of the Arctic Marine Biodiversity Report. Conservation of Arctic Flora and Fauna. International Secretariat, Akureyri, Iceland. 978-9935-431-63-9.

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.

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.

Cavalieri, D.J., Parkinson, C.L., Gloersen, P., Zwally, H.J., 1996. Sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS passive microwave data, version 1 (Sea Ice Concentration), NASA Natl. Snow and Ice Data Cent. Distrib. Active Arch. Cent., Boulder, Colo.

Chang, S.E., Stone, J., Demes, K., Piscitelli, M., 2014. Consequences of oil spills: a review and framework for informing planning. Ecology and Society 19(2), 26.

Chapman, P.M., McPherson, C., 1993. Comparative zinc and lead toxicity tests with Arctic marine invertebrates and implications for toxicant discharges. Polar Record 29(168), 45–54.

Chapman, P.M., Riddle, M.J., 2005. Toxic effects of contaminants in polar marine environments. Environmental Science & Technology 39(9), 200A–206A.

Clausen, D., Mosbech, A., Boertmann, D., Lambert, J.K., Nymand, J., Potter, S., Myrup, M., 2016. Environmental oil spill sensitivity atlas for the Northwest Greenland (75°-77° N) coastal zone. Tehnical report. Report number: SR196, Affiliation: Aarhus University, Danish Centre for Environment and Energy. 10.13140/RG.2.2.15036.85125.

Conan, G., Dunnet, G.M., Crisp, D.J., 1982. The long-term effects of the Amoco Cadiz oil spill [and discussion]. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 297(1087), 323–333.

Cook, C., Heath, F., Thompson, R.L., 2000. A meta-analysis of response rates in web- or internet-based surveys. Educ. Psychol. Meas. 60 (6), 821–836.

Davis, J.E., Anderson, S.S., 1976. Effects of oil pollution on breeding grey seals. Marine Pollution Bulletin 7, 115–118.

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.

de Vries, P., Tamis, J., Hjort, M., Jak, R., Falk-Petersen, S., van den Heuvel-Greve, M., Klok, C., Hemerik, L., 2018. How including ecological realism impacts the assessment of the environmental effect of oil spills at the population level: The application of matrix models for Arctic Calanus species. Marine Environmental Research 141, 264–274.

DNV-GL, 2014. Development of a Methodology for Calculations of Environmental Risk for the Marginal Ice Zone. Report No. 2014-0545, Rev. 01. DNVGL, Høvik, Norway.

Draper, D., 1995. Assessment and Propagation of Model Uncertainty. Journal of the Royal Statistical Society: Series B (Statistical Methodology) 57(1), 45–70.

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.

Egevang, C., Stenhouse, I.J., Philips, R.A., Petersen, A., Fox, J.W., Silk, J.R.D., 2010. Tracking of Arctic terns Sterna paradisaea reveals longest animal migration. PNAS 107(5), 2078–2081.

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.

Emmerson, C., Lahn, G., 2012. Arctic Opening: Opportunity and Risk in the High North. Project Report. Chatham House.

Engelhardt, F.R., 1983. Petroleum effects on marine mammals. Aquat. Toxicol. 4 (3), 199–217.

Environment Canada, 2015. Beaufort Regional Coastal Sensitivity Atlas. ISBN: 978-1-100-25319-0.

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

EPPR, 2015. Guide to Oil Spill Response in Snow and Ice Conditions. Emergency Prevention, Preparedness and Response. Arctic Council, Oslo, Norway. ISBN: 978-82-999755-7-5.

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

Fingas, M.V., 2017. Oil Spill Science and Technology, Second edition. Elsevier Inc.

Fingas, M.V., Hollebone, B.P., 2003. Review of behaviour of oil in freezing environments. Mar. Pollut. Bull. 47 (9–12), 333–340.

Fock, H., 2011. Integrating multiple pressures at different spatial and temporal scales: A concept for relative ecological risk assessment in the European marine environment. Human and Ecological Risk Assessment: An International Journal 17(1), 187–211.

Ford, J.D., Smit, B., 2004. A Framework for assessing the vulnerability of communities in the Canadian Arctic to risks associated with climate change. Arctic 57(4), 389–400.

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.P., 2004. Oil spill impact modeling: development and validation. Environ. Toxicol. Chem. 23, 2441–2456.

French-McCay, D., Gearon, M., Kim, Y., Jayko, K., Isaji, T., 2014. Modeling oil transport and fate in the Beaufort Sea. In: Proceedings of the 37th AMOP Technical Seminar on Environmental Contamination and Response. Environment Canada, Ottawa, ON, Canada, pp. 40e64.

French-McCay, D., Tajalli-Bakhsh, T., Jayko, K., Spaulding, M.L., Li, Z., 2018. Validation of oil spill transport and fate modeling in Arctic ice. Arctic Science 4, 71–97.

Fukuyama, A.K., Shigenaka, G., Coats, D.A., 2014. Status of intertidal infaunal communities following the Exxon Valdez oil spill in PrinceWilliam Sound, Alaska. Mar. Pollut. Bull. 84 (1–2), 56–69.

Fulton, E.A., 2010. Approaches to end-to-end ecosystem models. Journal of Marine Systems 81(1–2), 171–183.

Geraci, J.R., 1990. Physiologic and Toxic Effects on Cetaceans. In: Geraci, J.R., St. Aubin, D.J. (Eds.), Sea mammals and oil: confronting the risk. Academic Press. Pp: 235–239.

Goerlandt, F., Montewka, J., 2014. A probabilistic model for accidental cargo oil outflow from product tankers in a ship–ship collision. Marine Pollution Bulletin 79, 130–144.

Goerlandt, F., Montewka, J., 2015. A framework for risk analysis of maritime transportation systems: A case study for oil spill from tankers in a ship–ship collision. Safety Science 76, 42–66.

Gormley, A., Pollard, S., Rocks, S., Black, E., 2011. Guidelines for Environmental Risk Assessment and Management: Green Leaves III. Canfield University, Department for environmental food and rural affairs.

Goudie, A., 2018. Human impact on the natural environment. 8th edition. John Wiley & Sons Ltd.

Grebmeier, J.M., Cooper, L.W., Feder, H.W., Sirenko, B.I., 2006. Ecosystem dynamics of the Pacific-influenced Northern Bering and Chukchi Seas in the Amerasian Arctic. Prog. Oceanogr. 71(2–4), 331–361.

Haimelin, R., Goerlandt, F., Kujala, P., Veitch, B., 2017. Implications of novel risk perspectives for ice management operations. Cold Regions Science and Technology 133, 82–93.

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–

Hansen, B.H., Altin, D., Bonaunet, K., Øverjordet, I.B., 2014. Acute toxicity of eight oil spill response chemicals to temperate, boreal, and arctic species. Journal of Toxicology and Environmental Health, Part A 77(9–11), 495–505.

Haran, U., Moore, D.A., Morewedge, C.K., 2010. A simple remedy for overprecision in judgment. Judgement Decis. Making 5 (7), 467–476.

Hauser, D.D.W., Laidre, K.L., Suydam, R.S., Richard, P.R., 2014. Population-specific home ranges and migration timing of Pacific Arctic beluga whales (Delphinapterus leucas). Polar Biology 37(8), 1171–1183.

Hayes, E.H., Landis, W.G., 2004. Regional ecological risk assessment of a near shore marine environment: Cherry Point, WA. Human and Ecological Risk Assessment: An International Journal 10(2), 299–325.

Heeren, A., Karns, G., Bruskotter, J., Toman, E., Wilson, R., Szarek, H., 2017. Expert judgment and uncertainty regarding the protection of imperiled species. Conserv. Biol. 31(3), 657–665.

Heininen, L. (Ed.), 2012. Arctic Yearbook 2012. Akureyri, Iceland: Northern Research Forum.

Heintz, R.A., Rice, S.D., Wertheimer, A.C., Bradshaw, R.F., Thrower, F.P., Joyce, J.E., Short, J.W., 2000. Delayed effects on growth and marine survival of pink salmon Oncorhynchus gorbuscha after exposure to crude oil during embryonic development. Marine Ecology Progress Series 208, 205–216.

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.

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.

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.

Hellmann, J.J., Byers, J.E., Bierwagen, B.G., Dukes, J.S., 2008. Five potential consequences of climate change for invasive species. Conservation Biology 22(3), 534–543.

Hemmer, M.J., Barron, M.G., Greene, R.M., 2011. Comparative toxicity of eight oil dispersants, Louisiana sweet crude oil (LSC), and chemically dispersed LSC to two aquatic test species. Environmental Toxicology and Chemistry 30(10), 2244–52.

Hemming, V., Burgman, M.A., Hanea, A.M., McBride, M.F., Wintle, B.C., 2017. A practical guide to structured expert elicitation using the IDEA protocol. Methods Ecol. Evol. 9(1), 169–180.

Hetherington, C., Flin, R., Mearns, K., 2006. Safety in shipping: The human element. Journal of Safety Research 37(4), 401–411.

Hildebrand, L.P., Brigham, L.W., Johansson, T.M., 2018. Sustainable shipping in a changing Arctic. Springer.

Hill, R.W., Wyse, G.A., Anderson, M., 2012. Animal Physiology. 3rd edition. Sinauer Associates Inc., U.S.

HM Treasury, 2004. The Orange Book Management of Risk – Principles and Concepts. London, UK: The Stationary Office.

Holmes, R., McCauley, D., Hanley, N., 2018. Reshaping energy governance in the Arctic? Assessing the implications of LNG for European shipping companies. In: Vestergaard, N., Kaiser, B., Fernandez, L., Nymand, L.J. (Eds.) Arctic Marine Resource Governance and Development. Springer Polar Sciences. Springer, Cham.

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.

Hunter, T., 2018. Redefining energy security: the new prize in a time of arctic petroleum resources and technological development. In: Raszewski, S. (Ed.) The international political economy of oil and gas. International political economy series. Palgrave MacMillan, Cham.

IMO, 2014. International Code for Ships Operating in Polar Waters (Polar Code). MEPC 68/21/Add 1. Annex 10. International Maritime Organization (IMO), London, UK.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Irons, D., Petersen, A., Anker-Nilssen, T., Artukhin, Y., Barrett, R., Boertmann, D., Gavrilo, M.V., Gilchrist, G., Hansen, E.S., Hario, M., Kuletz, K., Mallory, M., Merkel, F., Mosbech, A., Labansen, A.L., Olsen, B., Österblom, H., Reid, J., Robertson, G., Rönkä, M., Strøm, H., 2015.

Circumpolar Seabird Monitoring Plan. CAFF Monitoring Report No.17. CAFF International Secretariat, Akureyri, Iceland. ISBN: 978-9935-431-47-9

Jin, D., Kite-Powell, H.L., Thunberg, E., Solow, A.R., Talley, W.K., 2002. A model of fishing vessel accident probability. Journal of Safety Research 33(4), 497–510.

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.

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.

Kaikkonen, L., Venesjärvi, R., Nygård, H., Kuikka, S., 2018. Assessing the impacts of seabed mineral extraction in the deep sea and coastal marine environments: Current methods and recommendations for environmental risk assessment. Marine Pollution Bulletin 135, 1183–1197.

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.

Keeney, R.L., Von Winterfeldt, D., 1991. Eliciting probabilities from experts in complex technical problems. IEEE Transactions on Engineering Management 38(3), 191–201.

Keil, K., 2017. The Arctic in a global energy picture: international determinants of Arctic oil and gas development. In: Keil K., Knecht S. (Eds.) Governing Arctic Change. Palgrave Macmillan, London.

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. NMFSAFSC-212 250 p.

Khan, B., Khan, F., Veitch, B., Yang, M., 2018. An operational risk analysis tool to analyze marine transportation in Arctic waters. Reliability Engineering and System Safety 169, 485–502.

Khon, V.C., Mokhov, I.I., Latif, M., Semenov, V.A., Park, W., 2010. Perspectives of Northern Sea Route and Northwest Passage in the twenty-first century. Climatic Change 100(3–4), 757–768.

Kim, K., Park, G-K., Jeong, J.S., 2011. Analysis of marine accident probability in Mokpo waterways. Journal of Navigation and Port Research International Edition 35(9), 729–733.

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.

Kingston, P.F., 2002. Long-term environmental impact of oil spills. Spill Science & Technology Bulletin, 7(1–2), 53–61.

Kristiansen, S., 2013. Maritime transportation: safety management and risk analysis. Routledge.

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.

Kuhnert, P.M., Martin, T.G., Griffiths, S.P., 2010. A guide to eliciting and using expert knowledge in Bayesian ecological models. Ecol. Lett. 13, 900–914.

Laurila-Pant, M., Lehikoinen, A., Uusitalo, L., Venesjärvi, R., 2015. How to value biodiversity in environmental management? Ecological Indicators 55, 1–11.

Law, K.S., Stohl, A., 2007. Arctic air pollution: origins and impacts. Science, 315(5818), 1537–1540.

Le Hir, M., Hily, C., 2002. First observations in a high rocky-shore community after the Erika oil spill (December 1999, Brittany, France). Marine Pollution Bulletin 44(11), 1243–1252.

Lee, K., Boufadel, M., Chen, B., Foght, J., Hodson, P., Swanson, S., Venosa, A., 2015. Expert Panel Report on the Behaviour and Environmental Impacts of Crude Oil Released into Aqueous Environments. Royal Society of Canada, Ottawa, ON. ISBN: 978-1-928140-02-3.

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.

Lehikoinen, A., Luoma, E., Mäntyniemi, S., Kuikka, S., 2013. Optimizing the recovery efficiency of Finnish oil combating vessels in the Gulf of Finland using Bayesian networks.

Environmental Science & Technology 47, 1792–1799.

Leighton, F.A., 1993. The toxicity of petroleum oils to birds. Environ. Rev. 1, 92–103.

Li, Z., Ma, Z., van der Kujio, T.J., Yuan, Z., Huang, L., 2014. A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment. Science of The Total Environment 468–469, 843–853.

Lindeberg, M.R., Maselko, J., Heintz, R.A., Fugate, C.J., Holland, L., 2018. Conditions of persistent oil on beaches in Prince William Sound 26 years after the Exxon Valdez spill. Deep Sea Research Part II: Topical Studies in Oceanography 147, 9–19.

Link, J.S., Ihde, T.F., Harvey, C.J., Gaichas, S.K., Field, J.C., Brodziak, J.K.T., Townsend, H.M., Peterman, R.M., 2012. Dealing with uncertainty in ecosystem models: The paradox of use for living marine resource management. Progress in Oceanography 102, 102–114.

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.

Liu, M., Kronbak, J., 2010. The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. Journal of Transport Geography 18(3), 434–444.

Lyon, A., Wintle, B.C., Burgman, M., 2015. Collective wisdom: methods of confidence interval aggregation. J. Bus. Res. 68, 1759–1767.

Mackay, D., McAuliffe, C.D., 1989. Fate of hydrocarbons discharged at sea. Oil and Chemical Pollution 5(1), 1–20.

MacMillan, D.C., Marshall, K., 2005. The Delphi process – an expert-based approach to ecological modelling in data-poor environments. Animal Conservation 9(1), 11–19.

Mageau, C., Engelhardt, F.R., Gilfillan, E.S., Boehm, P.D., 1987. Effects of short-term exposure to dispersed oil in Arctic invertebrates. Arctic 40(1), 162–171.

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.

Marchenko, N.A., Borch, O.J., Markov, S.V., Andreassen, N., 2015. Maritime activity in high North-the range of unwanted incidents and risk patterns. 23rd international conference on port and ocean engineering under Arctic conditions, POAC'15. Trondheim, Norway. Port and Ocean Engineering under Arctic Conditions (POAC); 2015.

Martin, T.G., Burgman, M.A., Fidler, F., Kuhnert, P.M., Low-Choy, S., McBride, M., Mengersen, K., 2012. Eliciting expert knowledge in conservation science. Conserv. Biol. 26 (1), 29–38.

Martin, T.G., Kuhnert, P.M., Mengersen, K., Possingham, H.P., 2005. The power of expert opinion in ecological models using Bayesian methods: impact of grazing on birds. Ecological applications 15(1), 266–280.

McBride, M.F., Burgman, M.A., 2012. What is expert knowledge, how is such knowledge gathered, and how do we use it to address questions in landscape ecology? In: Perera, A.H., Drew, C.A., Johnson, C.J. (Eds.), Expert Knowledge and its Application in Landscape Ecology. Springer Science+Business Media, LLC, pp. 11–38.

Miller, A.W., Ruiz, G.M., 2014. Arctic shipping and marine invaders. Nature Climate Change 4, 413–416.

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.

Molnár, P.K., Derocher, A.E., Thiemann, G.W., Lewis, M.A., 2010. Predicting survival, reproduction and abundance of polar bears under climate change. Biological Conservation 143(7), 1612–1622.

Montewka, J., Weckström, M., Kujala, P., 2013. A probabilistic model estimating oil spill clean-up costs – a case study for the Gulf of Finland. Mar. Pollut. Bull. 76 (1–2), 61–71.

Morgan, M.G., 2014. Use (and abuse) of expert elicitation in support of decision making for public policy. Proc Natl Acad Sci USA 111(20), 7176–7184.

Morgan, M.G., Henrion, M., 1990. Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge University Press.

Mosbech, A., 2002. Potential environmental impacts of oil spills in Greenland. An assessment of information status and research needs. NERI Technical Report, No. 415.

Mäkinen, J., Vanhatalo, J., 2016. Hydrographic responses to regional covariates across the Kara Sea. Journal of Geophysical Research: Oceans 121(12), 8872–8887.

Mäkinen, J., Vanhatalo, J., 2018. Hierarchical Bayesian model reveals the distributional shifts of Arctic marine mammals. Diversity and Distributions 24(10), 1381–1394.

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.

Nelson, W.G., 1981. Inhibition of barnacle settlement by Ekofisk crude oil. Marine Ecology Progress Series 5(1), 41–43.

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.

Nong, D., Countryman, A.M., Warziniack, T., 2018. Potential impacts of expanded Arctic Alaska energy resource extraction on US energy sectors. Energy Policy 119, 574–584.

Noring, M., Hasselström, L., Håkansson, C., Soutukorva, Å., Gren, Å., 2016. Valuation of oil spill risk reductions in the Arctic. Journal of Environmental Economics and Policy 5(3), 298–317.

O'Hagan, A., 2004. Dicing with the unknown. Significance 1(3), 132–133.

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.

Ohlberger, J., Langangen, Ø., 2015. Population resilience to catastrophic mortality events during early life stages. Ecological Applications 25(5), 1348–1356.

Overland, J.E., Hanna, E., Hanssen-Bauer, I., Kim, S.-J., Walsh, J.E., Wang, M., Bhatt, U.S., Thoman, R.L., 2017. Surface air temperature [in Arctic Report Card 2017], http://www.arctic.noaa.gov/Report-Card

Overland, J. E. and Wang, M. 2013. When will the summer Arctic be nearly sea ice free? Geophysical Research Letters 40(10): 2097–2101.

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 spill. Annu. Rev. Ecol. Syst. 27, 197–235.

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.

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.

Pekey, H., Karakas, D., Ayberk, S., Tolun, L., Bakoğlu, M., 2004. Ecological risk assessment using trace elements from surface sediments of İzmit Bay (Northeastern Marmara Sea) Turkey. Marine Pollution Bulletin 48(9–10), 946–953.

Perovich, D., Meier, W., Tschudi, M., Farrell, S., Hendricks, S., Gerland, S., Haas, C., Krumpen, T., Polashenski, C., Ricker, R., Webster, M., 2017. Sea ice [in Arctic Report Card 2017], http://www.arctic.noaa.gov/Report-Card

Petersen, J., Michel, J., Zengel, S., White, C., Lord, C., Plank, C., 2002. Environmental sensitivity index guidelines, version 3.0. National Oceanic and Atmospheric Administration, Seattle, Washington, 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.

Peterson, G., Rocha, J.C., 2016. Arctic regime shifts and resilience. In: Arctic Resilience Report. M. Carson and G. Peterson (Eds.). Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm.

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.

Picou, J.S., Gill, D.A., Dyers, C.L., Curry, E.W., 1992. Disruption and stress in an Alaskan fishing community: initial and continuing impacts of the Exxon Valdez oil spill. Industrial Crises 6(3), 235–257.

Prior, S., Walsh, D., 2018. A vision for a heavy fuel oil-free Arctic, Environment: Science and Policy for Sustainable Development, 60(6), 4–11.

Rahel, F.J., Bierwagen, B., Taniguchi, Y., 2008. Managing aquatic species of conservation concern in the face of climate change and invasive species. Conservation Biology 22(3), 551–561.

Rahikainen, M., Hoviniemi, K.-M., Mäntyniemi, S., Vanhatalo, J., Helle, I., Lehtiniemi, M., Pönni, J., Kuikka, S., 2017. Impacts of eutrophication and oil spills on the Gulf of Finland herring stock. Can. J. Fish. Aquat. Sci. 74: 1218–1232.

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

Reckhow, K.H., 1994. Importance of scientific uncertainty in decision making. Environmental Management 18(2), 161–166.

Reed, M., Daling, P.S., Brakstad, O.G., Singsaas, I., Faksness, L.-G., Hetland, B., Ekrol, N., 2000. OSCAR2000: A multi-component 3-dimensional oil spill contingency and response model. In: Proceedings of the 23rd Arctic and Marine Oil Spill Program (AMOP) Technical Seminar. Vancouver, BC, Environment Canada, pp. 663–680.

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.

Rice, S.D., Babcock, M.M., Brodersen, C.C., Carls, M.G., Gharrett, J.A., 1987. Lethal and sublethal effects of the water-soluble fraction of Cook Inlet crude oil on Pacific herring (Clupea harengus pallasi) reproduction. Technical memo.

Rice, S.D., Moles, A., Taylor, T.L., Karinen, J.F., 1979. Sensitivity of 39 Alaskan marine species to Cook Inlet crude oil and no. 2 fuel oil. International Oil Spill Conference Proceedings: March 1979, Vol. 1979, No. 1, pp. 549–554.

Rice, S., Peterson, C., 2018. Foreword: The evolution from species-specific damage assessment to ecosystem centric studies over the multi-decade period following the Exxon Valdez oil spill. Deep Sea Research Part II: Topical Studies in Oceanography 147, 1–2.

Richter-Menge, J., Overland, J.E., Mathis, J.T., Osborne, E. 2017. Eds. Arctic Report Card 2017.

Robinson, H., Wenning, R.J., Gardiner, W., Rempel-Hester, M., 2017. Spill impact mitigation assessment framework for oil spill response planning in the arctic environment. Internat. Oil Spill Conf. Proc. 1325–1344.

Roser, M., Ortiz-Ospina, E., 2018. World Population Growth. Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/world-population-growth' August 2, 2018.

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.

Sahin, B, Kum, S., 2015. Risk assessment of Arctic navigation by using improved fuzzy-AHP approach. Int J Maritime Eng 157(Part A4).

Sakshaug, E., 2003. Primary and secondary production in the Arctic seas. In: R. Stein and R.W. Macdonald (Eds.). The Organic Carbon Cycle in the Arctic Ocean. Springer.

Saltelli, A., Tarantola, S., Campolongo, F., Ratto, M., 2004. Sensitivity analysis in practice: A guide to assessing scientific models. Wiley, Chichester.

Schøyen, H., Bråthen, S., 2011. The Northern Sea Route versus the Suez Canal: cases from bulk shipping. Journal of Transport Geography 19(4), 977–983.

Shapovalova, D., Stephen, K., 2019. No race for the Arctic? Examination of interconnections between legal regimes for offshore petroleum licensing and level of industry activity. Energy Policy 129, 907–917.

Sharma, S., Ishiziwa, M., Chan, D:, Lavoué, D., Andrews, E., Eleftheriadis, K., Maksyutov, S., 2013. 16-year simulation of Arctic black carbon: Transport, source contribution, and sensitivity analysis on deposition. Journal of Geophysical Research 118(2), 943–964.

Skaare, J.U., Larsen, H.J., Lie, E., Bernhoft, A., Derocher, A.E., Norstrom, R., Ropstad, E., Lunn, N.F., Wiig, Ø., 2002. Ecological risk assessment of persistent organic pollutants in the arctic. Toxicology 181–182, 193–197.

Spaulding, M.L., 2017. State of the art review and future directions in oil spill modeling. Marine Pollution Bulletin 115(1–2), 7–19.

Spence, M.A., Blanchard, J.L., Rossberg, A.G., Heath, M.R., Heymans, J.J., Mackinson, S., Serpetti, N., Speirs, D.C., Thorpe, R.B., Blackwell, P.G., 2018. A general framework for combining ecosystem models. Fish and fisheries 19(6), 1031–0142.

St. Aubin, D.J., 1990. Physiologic and Toxic Effects on Pinnipeds. In: Geraci, J.R., St. Aubin, D.J. (Eds.), Sea mammals and oil: confronting the risk. Academic Press. Pp: 103–127.

Stephansen, C., Bjørgesæter, A., Brude, O.W., Brönner, U., Kjeilen-Ellertsen, G., Libre, Rogstad, T.W., Nygard, C.F., Sørnes, T., Skeje, G.M., Jonsson, H., May 2017. ERA Acute: a multi-compartment quantitative risk assessment for oil spills. Internat. Oil Spill Conf. Proc 2017 (1), 2017432.

Stjernholm, M., Boertmann, D., Mosbech, A., Nymand, J., Merkel, F., Myrup, M., Siegstad, H., Potter, S., 2011. Environmental Oil Spill Sensitivity Atlas for the Northern West Greenland (72°-75° N) Coastal Zone. National Environmental Research Institute, Aarhus University, Denmark. 210 pp. – NERI Technical Report no. 828.

Suter II, G., Mackay, D., Barnthouse, L., Norton, S., MacKay, N., Bartell, S., 2007. Ecological risk assessment. CRC Press, Boca Raton.

Teal, J.M., Howart, R.W., 1984. Oil spill studies: A review of ecological effects. Environmental Management 8(1), 27-43.

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.

Tversky, A., Kahnemann, D., 1974. Judgement under uncertainty: heuristics and biases. Science 185 (4157), 1124–1131.

US EPA, 2003. US Environmental Protection Agency. Generic ecological assessment endpoints (GEAEs). Washington (DC): USEPA Risk Assessment Forum. EPA/630/P-02/004F.

Valdez Banda, O.A., Goerlandt, F., Kujala, P., Montewka, J., 2015. Expert elicitation of risk control options to reduce human error in winter navigations. In: Podofillini (Ed.), Safety and Reliability of Complex Engineering Systems. Taylor & Francis Group, London. ISBN 978-1-138-02879-1.

van der Oost, R., Beyer, J., Vermeulen, N.P.E., 2003. Fish bioaccumulation and biomarkers in environmental risk assessment: a review. Environmental Toxicology and Pharmacology 13(2), 57–149.

van Hemert, C., Flint, P.L., Udevitz, M.S., Koch, J.C., Atwood, T.C., Oakley, K.L., Pearce, J.M., 2015. Forecasting wildlife response to rapid warming in the Alaskan Arctic. Bioscience biv069.

Ventikos, N.P., Vergetis, E., Psaraftis, H.N., Triantafyllou, G., 2004. A high-level synthesis of oil spill response equipment and countermeasures. Journal of Hazardous Materials 107, 51–58.

Wenning, R.J., Robinson, H., Bock, M., Rempel-Hester, M.A., Gardiner, W., 2018. Current practices and knowledge supporting oil spill risk assessment in the Arctic. Marine Environmental Research 141, 289–304.

Wiig, Ø., Amstrup, S., Atwood, T., Laidre, K., Lunn, N., Obbard, M., Regehr, E., Thiemann, G., 2015. Ursus maritimus. The IUCN Red List of Threatened Species 2015: e.T22823A14871490.

Williams, J.M., Tasker, M.L., Carter, I.C., Webb, A., 1994. A method for assessing seabird vulnerability to surface pollutants. Ibis 137: 147–152.

Wilson, R. R., Perham, C., French-McCay, D. P., Balouskus, R., 2018. Potential impacts of offshore oil spills on polar bears in the Chukchi Sea. Environmental Pollution, 235, 652–659.

Wilson, R. R., Regehr, E. V., Rode, K. D., St Martin, M., 2016. Invariant polar bear habitat selection during a period of sea ice loss. Proc. R. Soc. B, 283(1836), 20160380.

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.

Zhang, Y., Meng, Q., Ng, S.H., 2016. Shipping efficiency comparison between Northern Sea Route and the conventional Asia-Europe shipping route via Suez Canal. Journal of Transport Geography 57, 241–249.