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

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ABSTRACT

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

1. Introduction

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

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

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

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

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

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

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

2. Probabilistic risk assessment and Bayesian networks

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

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

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

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

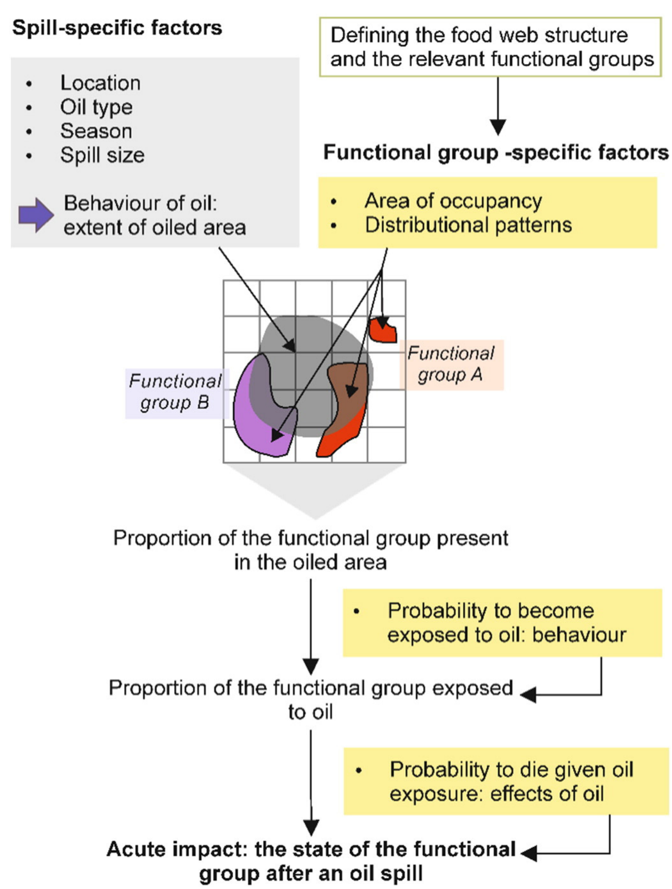

Fig. 1. The conceptual model for estimating the acute impacts of oil spills on the Arctic marine ecosystems.