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Toxicity data for modeling impacts of oil components in an Arctic ecosystem☆

G.H. Olsen[a], C. Klok[b], A.J. Hendriks[c], P. Geraudie[a], L. De Hoop[c], F. De Laender[d], E. Farmen[e], B.E. Grøsvik[f], B.H. Hansen[g], M. Hjorth[h], C.R. Jansen[d], T. Nordtug[g], E. Ravagnan[i], K. Viaene[d], J. Carroll[a,*]

[a] Akvaplan-niva, FRAM – High North Research Centre for Climate and the Environment, 9296 Tromsø, Norway
[b] Institute for Marine Resources and Ecosystem Studies, IMARES, P.O. Box 57, 1780 Den Helder, The Netherlands
[c] Radboud University Nijmegen, Institute for Water and Wetland Research, Department of Environmental Science, P.O. Box 9010, NL-6500 GL Nijmegen, The Netherlands
[d] Ghent University, Laboratory of Environmental Toxicology and Aquatic Ecology, Plateaustraat 22, 9000 Ghent, Belgium
[e] Norwegian Institute for Water Research, Gaustadallèen 21, 0349 Oslo, Norway
[f] Institute of Marine Research, P.O. Box 1870, Nordnes, 5817 Bergen, Norway
[g] SINTEF Materials and Chemistry, Marine Environmental Technology, P.O. Box 4760 Sluppen, 7465 Trondheim, Norway
[h] Consultancy within Engineering, COWI, Nature and Environment, Parallelvej, 22800 Kgs Lyngby, Denmark
[i] International Research Institute of Stavanger (IRIS), Environment, Mekjarvik 12, 4070 Randaberg, Norway

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ABSTRACT

Ecological impact assessment modeling systems are valuable support tools for managing impacts from commercial activities on marine habitats and species. The inclusion of toxic effects modeling in these systems is predicated on the availability and quality of ecotoxicology data. Here we report on a data gathering exercise to obtain toxic effects data on oil compounds for a selection of cold-water marine species of fish and plankton associated with the Barents Sea ecosystem. Effects data were collated from historical and contemporary literature resources for the endpoints mortality, development, growth, bioaccumulation and reproduction. Evaluating the utility and applicability of these data for modeling, we find that data coverage is limited to a sub-set of the required endpoints. There is a need for new experimental studies for zooplankton focused on the endpoints development and bioaccumulation and for larvae and juvenile fish focused on growth and development.

1. Introduction

The Barents Sea supports a productive and diverse marine ecosystem of major significance for the wider Arctic. It includes a rich benthic fauna including cold-water coral reefs and sponge communities coupled closely with a productive pelagic marine ecosystem of diverse fisheries and marine mammals (Wassmann et al., 2006a). The region supports major fish harvesting activities, particularly for cod, haddock and capelin, and these activities are the mainstay of coastal communities from Norway to Russia (Olsen et al., 2010). The region is also of major commercial importance for industries that include tourism, shipping, and the extraction of energy resources (Anon, 2003, 2004a,b). The ecosystem approach to management underpins the response to resource extraction in the Arctic with the objective of minimizing impacts, acting within the constraints of the ecosystem and ensuring that environmental quality is maintained. The Barents Sea in particular is managed by the Plan for the Integrated Management of the Marine Environment of the Barents Sea and the Sea Areas off the Lofoten (hereafter IMP) (Anon, 2006, 2011). The IMP was designed as an approach to maintain ecosystem integrity and to achieve sustainable use of ecosystem goods and services. The IMP is to be used to identify and take action on influences which are critical to the health of the marine ecosystem (Anon, 2006).

* Corresponding author. Tel.: +47 77750314.
E-mail address: jc@akvaplan.niva.no (J. Carroll).

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While the IMP acknowledges the generally good scientific knowledge for the Barents Sea, it also identifies the need for more knowledge of the ecosystem response to the combined impacts of multiple pressures from different sectors (e.g., oil exploration, fishing and shipping). Further effort is needed to quantify both the realized and potential impacts of commercial activities on habitats and species distributions. To help identify and quantify some of these potential impacts, a new modeling system, based on the ecosystem approach, is being developed for the Barents Sea. This system consists of a suite of existing ecological and toxicological models linked into a single modeling framework (Carroll and Smit, 2011). The system is designed to perform simulations of fish harvesting dynamics and the combined impacts on the populations of key commercial fish species of oil discharges and fisheries biomass extraction.

Briefly, the system includes three ecological models, one to simulate ecological processes up through zooplankton (Wassmann et al., 2006b), a second to simulate the behavior and distribution of fish from larval to juvenile stages (Vikebø et al., 2007) and a third to simulate the behavior and distribution of adult fish (Begley and Howell, 2004). These ecological models are further linked to a fate and transport model that predicts biological exposure levels for individual organisms (Reed et al., 2001). Toxic effects to individual organisms are evaluated for chemical uptake from sea water (water soluble fraction of chemical compounds) and/or food ingestion (De Laender et al., 2010a). At present, the model does not address chemical exposure via oil droplets. Oil droplets form when oil disperses, either naturally by wave action or after application of chemical dispersants. Species are exposed to oil droplets by adhesion to body surfaces or by dietary uptake. Although research has begun producing insight into the effect of oil droplets on marine organisms, at the present time, this area is not sufficiently mature to incorporate into ecological impact assessments (Hansen et al., 2009, 2012; Nordtug et al., 2011).

A key challenge for modeling is to identify and obtain data of sufficient quality that is appropriate for quantifying the potential toxic effects of petroleum discharges (De Laender et al., 2010b). In recent years, there have been a number of efforts to gather and assess existing ecotoxicology data for Arctic species mainly to compare the relative sensitivity of temperate and Arctic organisms to toxic exposures (Olsen et al., 2011; De Hoop et al., 2011). The present paper takes a further step by collecting and extracting data from historical and contemporary literature sources and assembling these into a common database. The present study gathers toxicity studies on a selection of species with habitats extending into the northern areas. These studies include toxicity data on oil substances from several oil groups: benzenes (toluene, xylene, ethyl benzenes), naphthalenes (bicyclic aromatic hydrocarbons), polycyclic aromatic hydrocarbons (PAHs), phenols and C6, C7 saturates. Our specific aim is to identify studies of sufficient quality to meet the needs of ecotoxicology modeling. To achieve this aim, we have organized the obtained toxicity data for implementation into the integrated ecosystem based modeling system described herein. This modeling system provides a valuable test of the utility and applicability of existing data resources for ecotoxicology modeling.

We briefly review the ecotoxicology data requirements for the selected ecotoxicology algorithms and fate/effects model in the ecosystem based modeling system. We then present the process and results of our literature search and data gathering and assessment exercise. We further evaluate the value and limitations of data gathered from existing literature sources and finally, we identify the most critical areas where additional data are likely to lead to improved effects modeling. We believe this new database is of general value for the ecotoxicology community, and that our experiences in organizing these data for use in integrated ecosystem based modeling provides useful insights for others engaged in similar or related modeling activities.

2. Materials and methods

2.1. Ecotoxicology algorithms

Ecotoxicology algorithms relate an exposure concentration to an effect concentration or alternatively, a biological threshold above which effects are to be expected (De Laender et al., 2010b). Two complimentary ecotoxicology models are incorporated into the Barents Sea ecosystem model. These models quantify changes in rates of survival, growth, reproduction etc., linked to chemical exposures. The data needs connected to the application of these algorithms were used to set priorities for the literature search.

The first algorithm uses a mechanistic bioaccumulation approach to predict toxicant effects on survival, and reproduction (Hendriks et al., 2001, 2005a,b). Internal concentrations (body burden) in biota are estimated based on uptake and elimination rate constants and the exposure concentration of the chemical. Based on classical fugacity theory, the uptake and elimination kinetics are a function of species characteristics (body mass, lipid content and trophic level of the species) and the chemical property octanol-water partition coefficient (K_{ow}) (Hendriks et al., 2001; Hendriks and Heikens, 2001). The estimated body burden and experimental single species toxicity data are used to predict impacts of oil components on the population level. For example, survival and reproduction rates are given as functions of internal concentrations exceeding critical body burdens (CBB) (Hendriks et al., 2005a,b). The algorithm has been calibrated using thousands of accumulation and toxicity values from laboratory experiments with aquatic species. Similar approaches have been used in dynamic ecosystem models to assess variations in bioaccumulation patterns as a result of varying food web relations (De Laender et al., 2010a) and effects on population sizes in ecosystems (De Laender et al., 2008). In the present context, the prediction of effects using this algorithm requires toxicity and bioaccumulation data together with the physicochemical properties of the selected substances.

The second algorithm uses a mechanistic approach to predict toxicant induced changes in individual growth, development, and survival. Mechanistic rules describe the uptake and use of energy by the organism and the consequences for physiological organization throughout the life cycle of the organism (Kooijman, 2000). Uptake and elimination kinetics of a toxicant are a function of the chemical characteristics of a toxicant and body size and lipid content of an organism. When the internal toxicant concentration is above a no effect concentration (NEC) effects evolve as a consequence of disruptions in the energy balance. In the present context, the prediction of effects requires toxicity data for oil components on body size, development and/or survival for the selected species and substances (Jager and Zimmer, 2012; Klok et al., 2012; Kooijman, 2010; Klok, 2007) and the physicochemical properties of these oil components.

Both algorithms have been included in the Barents Sea ecosystem modeling system as they provide complimentary approaches to the assessment of effects of petroleum hydrocarbons on marine organisms. The fugacity based approach (algorithm 1), which is based on the intrinsic properties of chemicals and species characteristics, is useful when the availability of ecotoxicology data is limited. The energy balance approach (algorithm 2) links the toxicity of individual oil components to measured effects derived through experimentation. Both algorithms can be used to determine effect concentrations for all organisms in the core food web complex: phytoplankton-zooplankton-fish, however, at present we only apply algorithm 1 on plankton and algorithm 2 on fish larvae.