1 September 2023

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SYMBIOSES III

FINAL REPORT

Advancing simulation technologies for ecosystem-based assessment of major oil spills in ecologically sensitive and environmentally challenging areas

SYMBIOSES

SYSTEM FOR BIOLOGY-BASED ASSESSMENTS

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Preface

The SYMBIOSES III project (October 2019-December 2022) is a Joint Industry Project supported by seven industry partners; ConocoPhillips Skandinavia, Equinor, Vår energi, Aker BP, Lundin, Wintershall Dea, and OMV. The project developed and tested an advanced, state of the art, simulation system for impact assessment, hypothesis testing, and planning of environmental activities. This document synthesizes and presents key information on the SYMBIOSES III project. The report includes information on the design requirements and approach, development steps, evaluation procedures and final assessment of the system leading up to a new version of a SYMBIOSES software (SYMBIOSES V.2.0).

SYMBIOSES simulates individuals and populations of selected marine species with life cycles connected to the Eastern North Atlantic and the Norwegian and Barents Seas. SYMBIOSES has been developed to improve assessments of environmental impacts linked to oil spill scenarios, and in particular, effects of oil spills on several fish stocks at the population level. It is designed to provide decision-support for the industry, regulators, and the science community, and, to present balanced assessments of risks and benefits from activities in the marine environment.

The SYMBIOSES system links several pre-existing and, subsequently improved, models into a single simulation platform. The system includes a physical model to simulate oceanographic features, an oil transport and behavior model, and two ecological models that simulate the distribution and behavior of different life stages of fish and zooplankton and the effects of petroleum components on fish. The fish species addressed by SYMBIOSES III are Northeast Arctic (NEA) Cod, NEA Haddock, NEA Saithe, Barents Sea (BS) Capelin, Norwegian Spring Spawning (NSS) Herring, Sandeel and Polar cod.

The models are fully 4-dimensional, producing data series in 3 spatial dimensions (x,y,z) and time (t). During a simulation, survival probabilities for Early Life Stages (ELS) of the fish species are computed for two cases (with oil/without oil). The difference in survival probabilities for the two cases is then calculated and transferred to an area-based fish population model. The fish population model describes changes for the entire habitat in fish stock distributions and fishing effort as a function of predation, harvesting and climate conditions over a specified number of years (e.g., 10 years).

SYMBIOSES parameter values are gathered from a variety of resources. Oceanographic and atmospheric data series are retrieved from recognized international organizations. Routine monitoring programs carried out by national authorities provide data on fish stocks and fishing effort. Ecological data on population structure, distribution, life cycles, as well as ecotoxicology parameter values to predict the biological effects of exposure to oil were established using data assimilated during the present and previous SYMBIOSES projects from private and publicly financed research.

The SYMBIOSES III project delivers 1) a new version of the SYMBIOSES software, 2) a portfolio of simulation results expanding from Barents Sea/Lofoten area to a wider grid, 3) sensitivity test results, and 4) peer-reviewed publications. The goals and activities outlined in the dissemination plan (Appendix IV – Section 16) were also accomplished.

1. Executive summary

SYMBIOSES III is a further development of the modular simulation system for assessing impacts of accidental oil spills on Early Life Stages (ELS) of fish and the subsequent impact on the Spawning Stock Biomass (SSB). It is a cooperation of several Norwegian Research institutes, including the Institute of Marine Research, SINTEF, the Arctic University of Norway, the University of Oslo, SINTEF and Akvaplan-niva.

It addresses populations of several fish species, including North East Arctic (NEA) Cod, North East Arctic (NEA) Haddock, North East Arctic (NEA) Saithe, Norwegian Spring Spawning (NSS) Herring and Barents Sea (BS) Capelin. Of these, current status of population models allows SSB reduction to be calculated for NEA Cod, NEA Haddock and BS Capelin. Sandeel and Polar Cod were also reviewed.

The project included developments and improvements of the SYMBIOSES V.1.0 system, including an enlarged model domain, an improved toxicity module and new standards for setup of oil drift and fate modelling. Also, the model for calculating ELS exposure was expanded to provide the option of including oil droplets, on top of dissolved oil, in toxicity assessments.

Comprehensive testing of the model was undertaken with respect to stability of and linkages between its components in order to arrive at a stable model regime with a prediction of impacts based on best available data and assumptions.

Three major sets of simulations were undertaken in the project:

1. A set of simulations from a discharge at the original SYMBIOSES location with starting dates from January to October at 14 days intervals, to document the importance of time of release on impacts of NEA Haddock and NEA Cod ELS. The results of these were published in the November 2022 issue of Marine Pollution Bulletin (Carroll *et al.*, 2022).
2. A set of simulations nominated by the research team from a set of locations in the Northern Norwegian Sea and the Southern Barents Sea, for a set of several years, including years of good and bad recruitment for the individual fish species.
3. A set of simulations nominated by industry partners, for existing and recent activities on the Norwegian Continental Shelf, addressing the impacts of an accidental spill that forms the basis for the oil spill response requirements from the Norwegian Environment Agency.

All simulations reported ELS mortality from oil exposure based on four toxicity parameter sets, from P1 to P4, with increasing sensitivity. While parameter set P1 and

P2 involved a dynamic exposure, parameter sets P3 and P4 assumed an instantaneous mortality when ELS encountered concentrations of Sum PAH exceeding 1 and 0.1 ppb respectively.

The set of simulations with 14 days intervals (Set no. 1) showed that the largest impacts on fish early life stages occurred for spills initiated in February-March, concomitant with the initial rise in marine productivity and the earliest phase of the spawning season. The reproductive health of the adult fish populations was maintained in all scenarios.

For the locations in the Northern Norwegian Sea and the Southern Barents Sea (Set no. 2), applying toxicity parameter set P1, the maximum ELS mortality modelled was less than 0.1 % for all years and locations. For toxicity parameter set P2, the maximum ELS mortality modelled was 2,4 %, for NEA Saithe. Applying toxicity parameter set P3 and P4, the maximum ELS mortality was 34,4 % and 55.6 %, respectively, both for NEA Saithe. The maximum SSB reduction in any year was 12.6 % when applying toxicity parameter set P3 and 18.1 % applying toxicity parameter set P4. Cumulative long-term reduction in harvestable resources can be approximated by the cumulative SSB reduction over a 10 year period.

For the set of simulations based on current and recent activities on the Norwegian Continental Shelf (Set no. 3), applying parameter set P1 and P2 resulted in a maximum modelled ELS mortality of less than 0.1 % for all years and locations. Applying toxicity parameter set P3, the highest modelled ELS mortality from oil was 2,5 %, for NEA Saithe, and for toxicity parameter P4, the highest mortality was 13,7 %, for NSS Herring. The maximum SSB reduction in any year was 1.8 %, for NEA Haddock.

Both sets of simulations showed the importance of including several years to assess the effects of oil spills in years of varying strengths of recruitment.

In addition to the simulation results, key achievements of SYMBIOSES III include:

- a library of 25+ years of simulation data covering the Nordic and Barents seas.
- an improved toxicity module, taking into account contributions from all components of the oil, and thus following EU recommendations
- recommendations for setup of the oil drift model that more correctly derives concentration fields to be applied in assessments
- a biology module developed to include additional species of zooplankton,
- development of a generic ELS module, ready for inclusion of additional fish species, now also including oil droplets
- a model developed to predict the evolution of spawning stocks of NEA Haddock and BS Capelin. The existing NEA cod model has been updated and extended

temporal coverage. In addition, a first version of a NSS Herring model has been developed.

At the end of the SYMBIOSES III project, an updated SYMBIOSES software (V. 2.0) are operational for the entire Norwegian Continental Shelf to model ELS mortalities from oil exposure on NEA Cod,

NEA Haddock, NEA Saithe, NSS Herring and BS Capelin. Impacts on spawning stock from reduced recruitment (i.e., ELS mortality) can further be modelled for NEA Cod, NEA Haddock and BS Capelin.

As the new version of SYMBIOSES (V.2.0) is developed as a modular system, future developments may be improvements or replacements of individual modules, as well as possibilities for of additional ecosystem components of linkages. The research team suggests the following topics for further consideration, which are described further in section 11.3:

- Refine toxicity parameterizations
- Higher resolution and application of autonomous vessels.
- New species and improved linkages
- Improve algorithms for fish larvae to juvenile;
- Additional environmental and ecosystem compartments
- Other impact factors

The research team has completed a comprehensive dissemination plan, has successfully published three papers in peer reviewed scientific journals, and will continue their joint work to prepare four additional manuscripts for submission in Q2 – Q4 2023.

2. Acronyms and abbreviations

Term	Description
ADCP	Acoustic Doppler Current Profiler
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
BB	Body burden
Blim	limit biomass reference point
BS	Barents Sea
CBB	Critical Body Burden
CF	Climate and Forecast
CPU	Central Processing Unit
DEB	Dynamic Energy Budget
ECMWF	European Centre for Medium Range Weather Forecasts
ECOTOX	The Ecotoxicity module of SYMBIOSES
ELS	Early Life Stage
ERA	Environmental Risk Assessment
ERA Acute	Industry standard model for environmental risk assessments
GADGET	Globally applicable Area-Disaggregated General Ecosystem Toolbox
HYPE-R	An R package for working with HYPE hydrological model files
IBCAO	International Bathymetric Chart of the Arctic Ocean
IBM	Individual-Based Model
k_{ow}	Octanol-Water partition coefficient
LARMOD	The ELS drift and exposure module in SYMBIOSES
NEA	North East Arctic
NEC	No Effect Concentration
NRC	Norwegian Research Council
NSS	Norwegian Spring Spawning
OMEGA	Optimal Modelling for Ecotoxicological Applications
OSCAR	The oil fate and drift model applied in SYMBIOSES
PAH	Polycyclic Aromatic Hydrocarbons
R-ArcticNet	A Regional, Electronic, Hydrographic Data Network For the Arctic Region
SINMOD	The oceanographic and zooplankton model applied in SYMBISOSES
SSB	Spawning Stock Biomass
SyEx	Symbioses Extension, part of SYMBIOSES II
TBB	Total Body Burden
THC	Total Hydrocarbon Concentration

3. Introduction

3.1 What is SYMBIOSES

SYMBIOSES (SYsteM for BIOlogy-based asSESsments) was originally developed as an advanced state of the art modeling system that performs simulations of individuals and populations of selected marine species with life cycles connected to the Barents Sea. SYMBIOSES includes a physical model to simulate the oceanographic and atmospheric features of a given region, a model to simulate the transport and behavior of petroleum components, and ecological models that simulate the distribution and behavior of different life stages of important commercial fish species and their prey as well as effects of petroleum components on the early life stages (ELS) of fish and zooplankton (Figure 1).

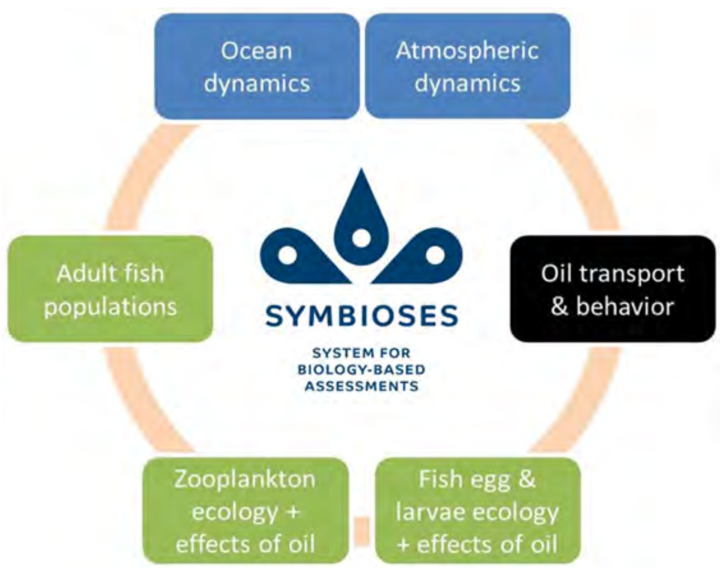


Figure 1 SYMBIOSES simulates key environmental and ecological components and the effects of oil compounds on key species of the Barents Sea ecosystem.

SYMBIOSES links several pre-existing, state of the art environmental models into a single computational framework. By leveraging existing, tested, and validated models, development efforts were drastically reduced. By making information available through one system, SYMBIOSES eliminates the pitfalls of using different datasets, tools, and models that are not intended to work together and as a result, may produce incompatible or conflicting results.

SYMBIOSES is designed for the following applications:

- Comparison of impacts associated with combinations of fisheries and petroleum activities

- Spatial/temporal planning and risk reduction
- Identification of focus areas for further scientific research
- Support for stakeholder communication

3.2 The Need for SYMBIOSES

Norway's oil and gas industry uses environmental risk analysis and models to compare the risk of various events as a basis for making operational decisions that will lead to minimal environmental damage (Smit *et al.*, 2011, Stephansen *et al.*, 2021). However, the use of worst case assumptions in the Environmental risk assessment (ERA) process tends to focus on only worst case events and their impacts. As operations move into potentially sensitive areas, it is equally important to have available accurate quantitative predictions of the most likely long term environmental impacts of oil spill scenarios.

In addition, both Norway and the European Union have ecosystem-based management policies for the marine environment (e.g., European Council, 2008, Management Plan for Norwegian Seas, 2020). These management policies generate the need for more advanced modeling systems that include individual-level organism responses, and population size and structure to represent the complexity of ecological systems. Such models add more value to environmental-based management and industry decision-making by allowing exploration of possible outcomes from a range of risk scenarios.

3.3 System development

3.3.1 The model domain

SYMBIOSES was originally developed for application in the North Atlantic/Barents Sea region (Figure 2). The SYMBIOSES model domain was expanded as part of the SYMBIOSES III project, creating the SYMBIOSES v.2.0 model.

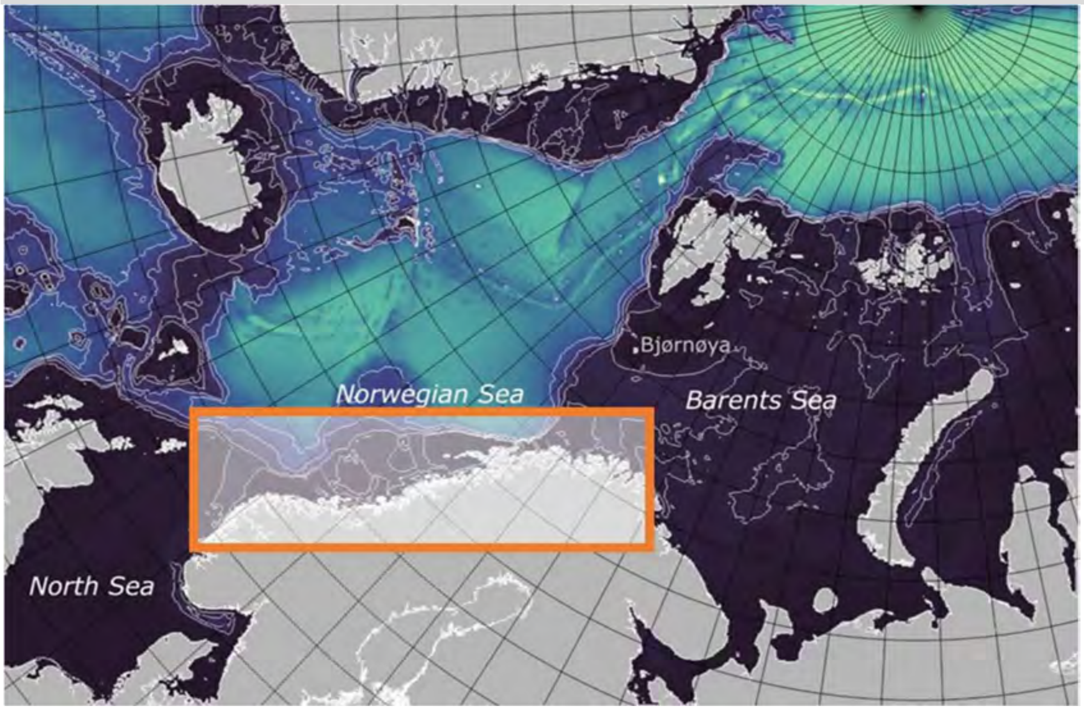


Figure 2. Map of the SYMBIOSES domain. The yellow rectangle is the domain area for SYMBIOSES V1.0, a 1340 km by 460 km region. The entire area on the map is the domain for SYMBIOSES V2.0, covering the North Atlantic, North Sea, and Barents Sea up to the North Pole.

There have been four steps in the development of the SYMBIOSES simulation system (Table 1).

Table 1 Development steps for the SYMBIOSES simulation system

Step	Description
1: System construction (SYMBIOSES I project) (2009-2011)	All modules and system components are assembled on a single server.
2: System performance testing (SYMBIOSES I project) (2011-2014)	Test/debug all modules and the full system and delivery of SYMBIOSES V1.0.
3: Case study (SYMTECH DEMO and SyEx projects – SYMBIOSES II) (2014-2018)	Testing and case study of simulations using the SYMBIOSES V.1.0 model with NEA cod.
4: Extension of domain, addition of fish species, mixture ecotoxicology module and case study (SYMBIOSES III project) (2018-2023)	Development, testing, and case study of additional fish species using the mixture ecotoxicology module and extended domain from Lofoten/Barents Sea area to North Atlantic, North Sea and Barents Sea up to the North Pole. Delivery of SYMBIOSES v.2.0.

Step 1 – System construction

Step 1 created the components of the SYMBIOSES system and assembled them for operation on the Norwegian National Supercomputer at UiT - The Arctic University of Norway. It further involved developing a customized driver program to manage the flow of information and a software library to store and organize information for use during simulations. At the completion of Step 1, all system components were assembled on the supercomputer server.

Step 2 – System performance testing

Step 2 performed initial system tests to check the performance of individual system components and the complete system. System performance testing was carried out in two phases. First, the independent models and system were tested, simulating ecosystem processes without petroleum activities. The second phase included test simulations of petroleum discharge events (a top-side release of 8500 tons/day for 50 days and a subsea release of 4500 tons/day for 14 days). System improvements were implemented in response to the test results. Step 2 completed the process of assessing the functionality of all components of the system. The completion of Step 2 marked the end of the SYMBIOSES I project. See Carroll *et al.*, (2014) for the final report from SYMBIOSES I.

Step 3 – Case study of NEA cod

Step 3 tested the validity of simulation outputs and evaluated system behavior to understand the most important processes controlling simulation results. This step involved multiple simulations of pre-defined scenarios. Based on the results, adjustments were made to the computer code to improve system operations and predictive capacity (SYMBIOSES II project). The case study was performed on Northeast Arctic (NEA) cod and the results published in Carroll *et al.*, (2018): https://doi.org/10.1016/j.marpolbul.2017.10.069.

Step 4 – New fish species and ecotoxicology module

Step 4 extended the SYMBIOSES model domain (Figure 2) to cover the Northern North Atlantic, North Sea, and Barents Sea up to the North Pole (SYMBIOSES v.2.0). Step 4 uses the new domain for simulations on several fish species. Seven species were assessed for inclusion in the new model version coming out from the SYMBIOSES III project. Of these, available data allowed modelling of larval mortalities for five species (NEA cod, NEA haddock, BS Capelin, NSS Herring and NEA Saithe). Sandeel and Polar Cod were also addressed, while for these species, data from ongoing studies are needed for future assessments and their spawning areas are outside of the impact area of most scenarios run. The SYMBIOSES V1.0 ecotoxicology module is replaced with a mixture toxicity module in alignment with recommendation (best practice) from EU.

3.4 Technical products/deliverables

The technical deliverables from SYMBIOSES I and II were:

1. SYMBIOSES software library

The SYMBIOSES software library contains the computer codes for all procedures for the performance of simulations.

2. SYMBIOSES driver program

The SYMBIOSES driver program controls the overall system operation. It accesses procedures in the software library and transfers instructions to and from the independent models that are linked to the system.

3. Ecotoxicology database

A database is available containing ecotoxicology data representing effects of oil on arctic species (http://www.symbioses.no). The database includes information on selected phytoplankton-, zooplankton- and fish- species collected from 123 literature sources spanning 76 different compounds. It includes the complete collection of species-specific toxicity endpoints for both single (oil and chlorinated) compounds and mixed compounds (crude oil and dispersants).

4. SYMBIOSES V1.0

The original SYMBIOSES modeling system (SYMBIOSES V1.0) ran on the Norwegian National Supercomputer (UNINETT Sigma2 - the National Infrastructure for High Performance Computing and Data Storage in Norway). The complete system includes 1) the software library, 2) the customized driver program, and 3) four independent models (Table 2).

The technical deliverables from the SYMBIOSES III project were:

5. Mixture toxicity module

The mixture toxicity module addresses mixture effects in the SYMBIOSES simulation system. In the original SYMBIOSES model (V1.0) the toxicity module treated compounds (oil pseudo-components) as independent of one another, and effects occurred only when the NEC value of an individual compound was exceeded. In SYMBIOSES V2.0, all toxic compounds contribute to the NEC. An effect occurs when the No Effect Concentration (NEC) value of the mixture of compounds is exceeded.

6. SYMBIOSES V2.0

The latest version of the SYMBIOSES modeling system (SYMBIOSES V2.0) runs on the Norwegian National Supercomputer (UNINETT Sigma2 - the National Infrastructure for High Performance Computing and Data Storage in Norway). It includes 1) the software library, 2) the customized driver program, and 3) four independent models (Table 2). New features of the system are the larger model domain, the mixture toxicity module, and the inclusion of the following species of fish - NEA haddock, BSS Capelin, NSS Herring, NEA Saithe, in addition to NEA cod.

4. Design principles and technical specifications

4.1 Design principles

The key design principle for SYMBIOSES was to link together pre-existing, state of the art environmental models. By leveraging existing, tested, and validated models, development efforts were drastically reduced. Another important design principle was that models must be easily replaceable, without affecting any other parts of the system. This allows upgrading parts of the system with relative ease as new models become available. The final major design principle was that the method for linking models should interfere as little as possible with the internal architecture of the individual environmental models. Otherwise, there is a risk that further external development of these models may be a challenge for SYMBIOSES. See Appendix I for additional details on the design principles.

4.2 System architecture

The system consists of four **independent models** with their respective data, a software library, and a driver program (Figure 3). The **software library** houses the procedures needed to interact with the independent models while the **driver program** initiates and directs computations. Thus, the library serves as a storage receptacle for the information needed to direct system operations while the driver program initiates and directs these operations.

All models are fully 4-dimensional, data series are produced in three spatial dimensions (x,y,z) plus time (t), with the exception of the adult fish population model (GADGET). GADGET is an area-based model that describes population changes for the entire habitat. Any of these independent models are in principle replaceable by alternative models with similar capabilities.

SINMOD, covering ocean dynamics, zooplankton ecology and effects of oil, is a Eulerian (grid-based) model where computations are carried out on a regular grid that does not change for the duration of a given simulation. LARMOD, covering fish ELS and effect of oil, is a Lagrangian (particle-based) model, where each particle represents a super individual. OSCAR works internally as a Lagrangian model but exports its data on a grid. Exports from OSCAR are presented on a grid with different spatial resolution than SINMOD. Special procedures are included in the software library to allow models with different computational approaches to interact.

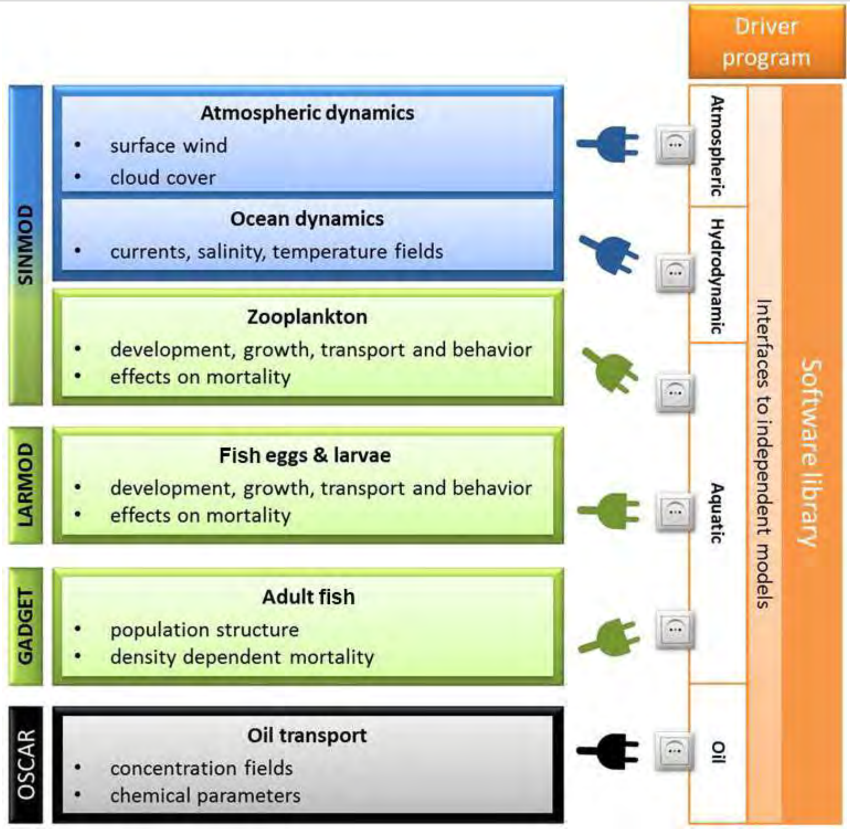


Figure 3.The key components of the system architecture are four independent models (to the left), a software library and the driver program, which initiates and directs computations.

Table 2. Names and descriptions of the four pre-existing, independent models linked within the SYMBIOSES system. Further information on each of the models is presented in section 5.

Acronym	Description	Responsible/Owner
OSCAR©	Oil transport & behavior	SINTEF Ocean
SINMOD	Ocean dynamics Zooplankton ecology & effects of oil	SINTEF Ocean
LARMOD	Fish ELS and effects of oil	Institute of Marine Research
GADGET	Adult fish population	Institute of Marine Research
ECOTOX	Ecotoxicology module	Akvaplan-niva

Different models also exhibit different spatial and temporal resolutions. The linking of models with different resolutions is performed by aggregating model output from the model with fine spatial and temporal resolution to the aggregation level used by the model with the lower resolution. In some cases, statistical methods are used to translate model output from one resolution to a compatible resolution (e.g., Stige *et al.* 2009).

Both ocean dynamics and zooplankton ecology/effects are accessed by the SYMBIOSES system through SINMOD. SINMOD, LARMOD, and GADGET are open-source software, developed over many years at their respective responsible institutes (Table 2). OSCAR© is a proprietary software owned and operated by SINTEF.

The **software library** is partitioned into a set of four programming interfaces and each of the independent models is linked to the system through one or more of these interfaces (Table 3). The independent models are registered as providing specific *features*. The programming interfaces retrieve these features, making them available to other parts of the system, as required for the performance of computations.

Table 3. Relationships among the four programming interfaces, the independent models, and their associated features.

INTERFACE	INDEPENDENT MODEL	FEATURES
Atmospheric	Data from ECMWF ERA-Interim	Surface wind, precipitation, air temperature, cloud cover
Hydrodynamic	Ocean dynamics (SINMOD)	Currents, salinity, temperature
Oil	Oil transport & behavior (OSCAR)	Concentration fields, droplet distribution, state of oil (droplets or dissolved), chemical properties
Aquatic	Zooplankton ecology & effects of oil (SINMOD)	Abundance, biomass, life stage, growth, size, age, survival, mortality, reproduction, lipid content, body burden
	Fish ELS ecology & effects of oil (LARMOD)	
	Adult fish populations (GADGET)	

4.3 System resolution

The spatial domain of the SYMBIOSES system is defined by the SINMOD domain. There are two operational SINMOD domains. The small one is a 1340 km by 460 km region (Figure 2). The larger one covers the whole North Atlantic, North Sea, Barents Sea up to the North Pole. Both domains work with a 4 x 4 km grid resolution. The small model receives boundary conditions from the larger 4 km domain. The larger domain receives boundary conditions from a course, large-scale domain pre-calculated at SINTEF (20 km horizontal grid resolution). The ocean dynamics model uses a vertical structure of the ocean separated into 30-40 layers. The vertical layer thickness ranges from 5 m close to the surface to 500 m at depths > 1000 m. Because GADGET is an area-based model, population changes are described for the entire spatial domain for SYMBIOSES. OSCAR© domains can be easily adapted to the single oil spill scenario in size, resolution, and position.

4.4 User interface

The user interface is based on a standard Unix command line interface. The "symbioses" command has two subcommands to initialize and run the system. The user writes an input file that specifies the simulation parameters. Based on the general input, the "init" command configures and sets up each of the specific models for calculation. The "run" command starts the actual simulation. Both "init" and "run" have several options that can be seen with the "--help" switch.

4.5 System operations

During system operations, the independent models are loaded (plugged in) to the system at runtime. Each model registers itself, informing the system about the features it provides and which features it requires.

During simulations, the independent models are provided with the appropriate features and configurations within their own private compartments of the system. For each individual model, there is little difference between running standalone or running while linked to the system. The SYMBIOSES framework runs the registered models sequentially. The models themselves are responsible for utilizing parallelization.

The computational efficiency for SYMBIOSES depends on the models and features that are included in a simulation. A typical simulation with the large SINMOD area and two fish species needs on the order of 1.5 hours per simulated day. Turning off the very time intensive simulation of copepods in SINMOD reduces the time by ~80% for short to medium simulation durations. Simulating different combinations of fish species has a negligible effect on the run time.

4.6 System output

A range of outputs, from time series of water current fields and plankton distributions to toxicological endpoints and effects, fish stock sizes and population parameters, are generated during a SYMBIOSES simulation (Appendix II). The SYMBIOSES system produces output in the NetCDF-4 format (hereafter identified as NetCDF). The output archives follow the Climate and Forecast (CF) Metadata Conventions (http://cfconventions.org/). Simulation data is saved by default every 12 hours and the save interval can be easily changed. The data is saved in time series of 2D or 3D variables on a reference grid given in the archive.

The saved variables are ocean velocity, temperature, and salinity (3D), surface wind velocity and cloud cover (2D), total and compound-specific dissolved oil concentration (3D), abundance, body burden and mortality for six zooplankton copepod stages , zooplankton nauplii abundance and total zooplankton biomass (2D), fish larval position, age, body weight, stomach fullness and various mortality factors.

4.7 Programming languages

The models are written in various languages (mostly Fortran 90/2008 and C++). They communicate via an interface written in C. The framework itself is written in Python 3 and Fortran 90 and offers C interfaces to all models.

Additional technical details may be found in the SYMBIOSES technical reference manual as a pdf file accompanying this document and on www.symbioses.no/docs.

5. Independent models

As described in the previous section, the system architecture includes four independent models (Table 2). This section provides an overview of the features and capabilities of the individual independent models that are today part of the new version of the model (SYMBIOSES V2.0 system).

Ecological models simulate the distribution/abundance and behavior of zooplankton (SINMOD) and the early life stages of important commercial fish (LARMOD) (Figure 4). A third ecological model (GADGET) simulates population dynamics for juveniles (> 6 months) to adult fish. A fish ecotoxicity module (ECOTOX) is embedded in LARMOD. The oil transport and fate model (OSCAR) is used to track chemicals in the marine environment and the SINMOD model also simulates ocean dynamics (Moore *et al.*, 2004; Shchepetkin and McWilliams, 2003, 2005). Available ecology and ecotoxicology datasets are used in model validation activities and to establish current environmental conditions.

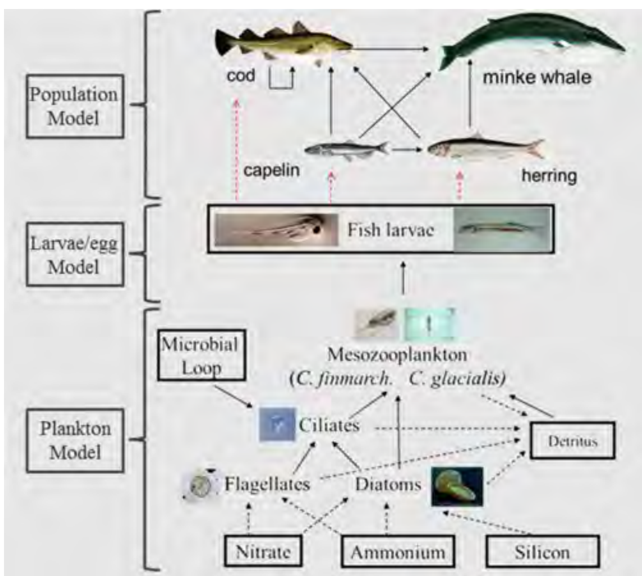


Figure 4 Three ecological models form the SYMBIOSES ecosystem. Individual-based larvae (LARMOD) and plankton (SINMOD) models are linked via recruitment (larval survival) to a multispecies population model (GADGET).

5.1 Ocean and atmospheric dynamics

The ocean dynamics are calculated by the SINMOD system, a 3D free-surface, primitive equations ocean model system used for a diverse range of applications (Slagstad and McClimans 2005). The primitive equations are solved by a finite difference scheme on an Arakawa C-grid. Vertical mixing is handled by a Richardson scheme (Sundfjord *et al.* 2007. Atmospheric forcing was applied using data from ECMWFs ERA Interim.

Freshwater runoff from land was based on data from The Norwegian Water Resources and Energy Directorate, HYPE-R, and R-ArcticNet, while bathymetry data was taken from the Norwegian Mapping Authority and IBCAO. Through SINMOD's hydrodynamic component, SYMBIOSES is provided with ocean currents, temperature, salinity sea ice, and turbulence in 4 dimensions (3 spatial dimensions and time).

5.2 Oil transport & behavior

The fate and transport of oil and chemicals in the marine environment is simulated using the OSCAR model[1] (Version 12.1). OSCAR is a component of Sintef's Marine Environmental Modeling Workbench (MEMW). OSCAR simulates the oil distribution and composition in the marine environment after a discharge event in three spatial dimensions and time (Reed *et al.*, 2004. OSCAR simulates the distribution of chemical groups (pseudo-component groups) rather than individual compounds (up to 25 compounds, see Table 4). The approach assumes that hydrocarbons in each group behave similarly, i.e., have similar distribution and fate in the environment. Each pseudo-component group has a set of parameters that govern the fate processes, such as biodegradation rates (Brakstad *et al.*, 2015). Note that the biodegradation rates are adjusted to the ambient temperature using the Q10 approach (Bagi *et al.*, 2013, Nordam *et al.*, 2020) . The model supplies chemical concentration data for these pseudo-components to the biological models. The model provides distribution maps of oil together with concentrations of petroleum compounds and oil droplets in 4-dimensions.

OSCAR contains an integral plume model that calculates the trajectory and fate of the near-field plume generated at the origin of a sub-sea discharge (Johansen, 2000). Typically, oil plumes contain some gas, and are positively buoyant under typical ocean conditions, but composition, initial temperature, discharge depth and ocean currents will influence the plume behavior and dictate whether it reaches the surface or is trapped at intermediate depths.

For a sub-sea blow-out, oil droplets are typically generated at the source, and the conditions there control the oil droplet sizes that are generated, which is included in the plume model (Johansen *et al.,* 2013). Oil on surface (surface slick) may be broken up and entrained by waves, in which case a different model is used to predict the droplet size spectrum (Johansen *et al.*, 2015). In both cases, OSCAR tracks the droplet

[1] www.sintef.no/OSCAR

sizes of the oil throughout the simulation, and the total concentration of oil (including droplets) are available on a grid which is used by the SYMBIOSES system.

OSCAR receives forcing data “online” from the SYMBIOSES system, such as currents and wind, at a frequency which is only limited by the ocean model time step, in practice much smaller than what is used for the oil spill model. The version of OSCAR now in use (12.1) can use 3D temperature and salinity fields, a new feature compared to the old version (6.5.1), and these data are now passed to OSCAR from SINMOD through the SYMBIOSES interface. This affects biodegradation (via the Q10 adjustment mentioned above), as well as the plume trajectory and potentially trapping depths for sub-sea releases.

5.3 Zooplankton ecology & effects of oil

SINMOD's ecosystem component simulates the distribution and behavior of the lower trophic level ecosystem from nutrients up to mesozooplankton (Slagstad & McClimans, 2005). This is fully coupled with the ocean and atmospheric dynamics component. The model has state variables for nutrients and the lower tropic levels in the marine ecosystem: phytoplankton, the most important components of the microbial loop and two species of meso-zooplankton. The ecosystem model structure is described in Wassmann *et al.* (2006) and shown in the lower part of Figure 4. The model used in SYMBIOSES also simulates the life cycle stages of zooplankton. The model is nitrogen-driven, and conversion to carbon is according to Redfield's ratio. Additional literature on the principles and application of the model is documented through several peer-reviewed scientific papers (e.g., Sakshaug & Slagstad 1992, Wassmann & Slagstad 1993, Slagstad *et al.* 1999, Ellingsen *et al.* 2008, 2009).

A sub-model for the uptake and retention of oil in zooplankton has been incorporated into SINMOD. This sub-model is based on the Optimal Modelling for Ecotoxicological Applications (OMEGA) approach (Hendriks *et al.*, 2001; Hendriks and Heikens, 2001). OMEGA is an allometric bioaccumulation model estimating accumulation of contaminants in biota (body burden) as a function of the external exposure concentration of the substance and the body weight and trophic level of the organism. Bioaccumulation in OMEGA has been calibrated on thousands of uptake/elimination data from laboratory experiments with aquatic species.

Table 4. The classification system for hydrocarbon compounds (pseudo-component groups) used by OSCAR.

Group	Identification	Compound
1	C1-C4-saturates	C1 to C4 gases
2	C5-saturates	n-pentane, iso-pentane, cyclopentane
3	C6-saturates	n-hexane, 2-methylpentane, 3-methylpentane, methylcyclopentane, cyclohexane
4	Benzene	Benzene
5	C7-saturates	n-heptane, 3-methylhexane, 2,3-dimethylpentane, methylcyclohexane
6	C1-benzenes	Toluene
7	C8-saturates	n-octane
8	C2-benzenes	Ethylbenzene; o-, m-, p-xylene
9	C9-saturates	n-nonane
10	C3-benzenes	Propylbenzene, 1-methyl-3-ethylbenzene, 1-methyl-4-ethylbenzene, 1-methyl-2-ethylbenzene, 1,3,5-trimethylbenzene, 1,2,4-trimethylbenzene, 1,2,3- trimethylbenzene
11	C10-saturates	n-decane
12	C4-C5-benzene	n-butylbenzene, 1,2,3,4,5-tetrametylbenzene, n-pentylbenzene
13	C11-C12	C11-C12 total saturates + aromatics
14	C0-C4-Phenols	C0- to C4-phenols
15	Naphthalenes 1	C0- to C1-naphthalenes
16	C13-C14	C13-C14 total saturates + aromatics
17	Naphthalenes 2	C2- to C3-naphthalenes
18	C15-C16	C15-C16 total saturates + aromatics
19	PAH-1	C4-naphthalenes, biphenyl, acenaphthylene, acenaphthene, dibezofurane, C0- to C1-fluorenes, C0- to C1-phenanthrenes/ anthracenes, C0- to C1- dibenzothiophenes
20	C17-C18	C17-C18 total saturates + aromatics
21	C19-C20	C19-C20 total saturates + aromatics
22	UCM	Unresolved chromatographic materials
23	C21-C25	C21-C25 total saturates + aromatics
24	PAH-2	C2- to C3-fluorenes, C2- to C4-phenanthrenes/anthracenes, C2- to C4-dibenzothiophenes, fluoranthrene, pyrene, C1-to C3-fluoranthrenes/pyrenes, benzo(a)anthracene, C0- to C4-crysenes, benzo(b,k)fluoranthene, benzo(e,a)pyrene, perylene, dibenzo(a,h)anthracene, benzo(g,h,i)perylene, indeno(1,2,3-c,d)pyrene
25	C25+	Longer alkanes

OMEGA assumes first order kinetics and uses classical fugacity theory to model bioaccumulation. The model requires physicochemical data like the octanol-water partition ratio (e.g., log Kow) for each compound of interest as well as the body weight, lipid content, and trophic level of an individual. OMEGA then relates exposure to contaminated seawater to internal concentration of oil concentrations, and model compartments have been added for all OSCAR pseudo components for every zooplankton developmental stage, assuming a fixed lipid content for each stage (Broch *et al.*, 2020). The internal oil component concentrations are linked to lethal (acute mortality) and sub lethal (reduced egg production) effects though a near-linear relation between a critical body burden (CBB) and a total body burden (TBB) as described in DeLaender *et al.* (2011).

In SYMBIOSES, the OMEGA ecotoxicology algorithm and associated parameter values (Hendriks *et al.*, 2001; Hendriks and Heikens, 2001) are used to quantify the effects of petroleum concentrations on zooplankton. Three estimates of parameter values are currently available for quantifying the effects of exposure to oil by zooplankton: the best estimate, upper boundary (maximum ecotoxicological effect) and lower boundary (minimum ecotoxicological effect). The values assigned for these three estimates were established using published data from scientific literature on toxicities of oil components for a wide range of species. The best estimate is based on literature values for crustaceans only (most taxonomically related to copepods). The upper and lower boundaries are based on data on crustaceans and other aquatic species.

The parameter values are listed in Broch *et al.* (2020). See also Hendriks *et al.* (2014), Corr and deHoop *et al.* (2016) for additional details on the origin of these values.

When performing iterations during a simulation, the results from the zooplankton ecotoxicology calculations are utilized in communication pathways as shown in Figure 5. First, oil pseudo-component concentrations are transferred from the oil compartment to the Plankton Ecotox compartment to determine responses of the different zooplankton life stages to chemical exposures via direct contact with contaminated seawater. Chemical exposure is related to internal concentration (integrating varying concentrations over time) whereby the accumulation of contaminants in an individual zooplankton is described as a function of the exposure concentration, body weight and lipid content. Oil-induced zooplankton mortality is described as a function of the critical- (CBB) and total (TBB) body burdens of oil components, and the zooplankton abundance is updated based on the sum of the oil and background mortality rates. Egg production rates are likewise affected by CBB and TBB. The abundance of zooplankton is then passed on to the larvae compartment.

5.4 Fish early life stages

5.4.1 Modeling approach

LARMOD simulates fish eggs and larvae (early life stages; ELS) growth, drift, natural mortality and survival and effects of oil. Fish ELS drift modelling is based on the work of Vikebø *et al.* (2005, 2007), Kristiansen *et al.* (2008) and Husebø *et al.* (2009). Fish ELS (up to 18 mm length) are characterized by a standard length, body mass, and probability of survival since hatching is in an individual based model (IBM). Fish ELS are modelled in 3D space and time with uniform mortality and simple rules of vertical migration (for larvae). The IBM predicts larvae growth and natural mortality based on light, temperature, and body size. Vertical migration for larvae is a function of length while growth is a function of body mass, temperature, light, and swimming activity. Predation by fish and invertebrates is included. Predation by invertebrates is expressed as a function of body length while predation by fish is based on a coefficient reflecting the ability of a fish to detect the position of larvae through sight. This sub-model then predicts individual fitness as the total survival probability from the early larval phase (post hatching) up to 18 mm. An algorithm describing how internal oil pseudo-component concentrations are translated into effects (ECOTOX) is embedded in LARMOD. The resulting subroutines simulate responses of fish ELS to chemical exposures via direct contact with contaminated seawater containing dissolved oil. The details of this model are presented in the section of this report entitled - fish ecotoxicology model (section 5.6).

A major update of LARMOD during SYMBIOSES III is the addition of several new fish species that can be run simultaneously for a scenario. Having this infrastructure in place now makes it easy to add additional species at a later stage pending sufficient information for parameterization of the species.

LARMOD has also been prepared for the use of oil droplets in the Ecotox routine for sticky fish eggs in addition to the concentrations of dissolved oil. OSCAR currently reports the total mass concentration of oil (dissolved+droplets) and the total dissolved concentration of oil at any given position, which is used to calculate the total mass concentration of droplets at the individual positions. To get the number concentration of droplets, the mass is distributed among four droplet size bins using a statistical distribution. The size bins cover droplet diameters up to 100 µm, which is assumed to be the relevant size range. In the statistical distribution, the size bins account for 95% of the total number of droplets and 30.2% of the total droplet mass (Table 5):

Table 5. Droplet size bins used to calculate number concentrations of oil droplets.

Bin #	Number contribution	Mass contribution	Start diameter [µm]	End diameter [µm]	Characteristic diameter [µm]
1	25%	0.008%	1.0	6.0	2.45
2	25%	0.2%	6.0	15.0	9.49
3	25%	2%	15.0	35.0	22.91
4	20%	28%	35.0	100.0	59.16

After the mass has been distributed among the size bins, mass concentrations are converted to number concentrations using a characteristic mass per droplet. This is calculated assuming spherical droplets, the characteristic diameter and a fixed oil density of ρ=864 kg/m^3. Note that the calculations only use total concentrations, not pseudo-components. Also, for comparison it is worth noting that the relevant fish eggs have a diameter in the order of 1.4 mm.

5.4.2 NEA cod

LARMOD was originally implemented for NEA cod and no major changes in the model were needed for NEA cod. Spawning is modelled by nine spawning grounds (Figure 5) where pelagic eggs are released from a depth of 30 m from Mar 1st until Apr 30th with a peek spawning intensity on Mar 31st. The nine spawning grounds are weighted in the calculations by observed spawning intensity.

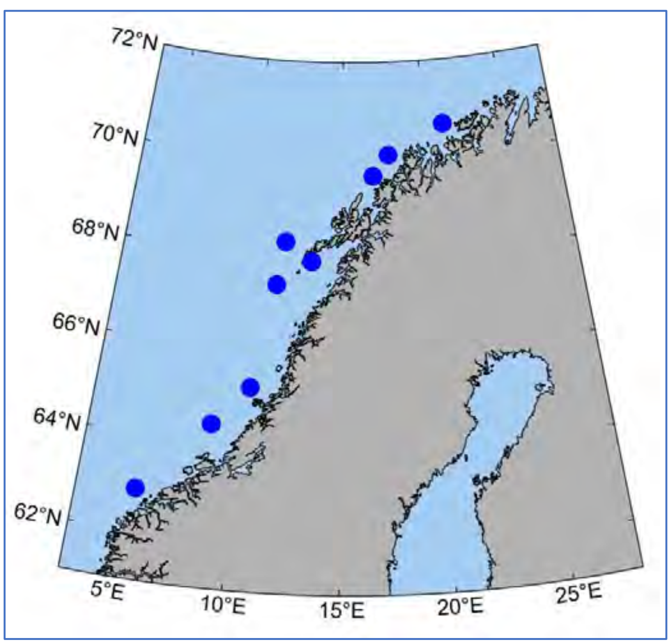


Figure 5 NEA cod spawning grounds in model (center coordinates). See Figure 25 for extension of grounds.

5.4.3 NEA haddock

NEA haddock was the first new species to be added as it is the most similar to NEA cod and also the top priority from the sensitivity analysis performed before selection of species. The implementation uses the module for NEA cod but has specific egg parameter values and spawning information. The spawning is modelled by sampling from larger spawning areas (Figure 6) instead of the more specific spawning grounds used for NEA cod (Figure 5) Pelagic eggs are released from a depth of 30 m from Mar 15th until May 14th with a peak spawning intensity at Apr 14th. Since NEA haddock has sticky eggs, one also has to consider the added exposure effect of oil droplets sticking to the egg surface. Functionality for calculating collision rates between oil droplets and haddock eggs has been implemented, but an effects model is still needed for calculating additional mortality due to droplet exposure.

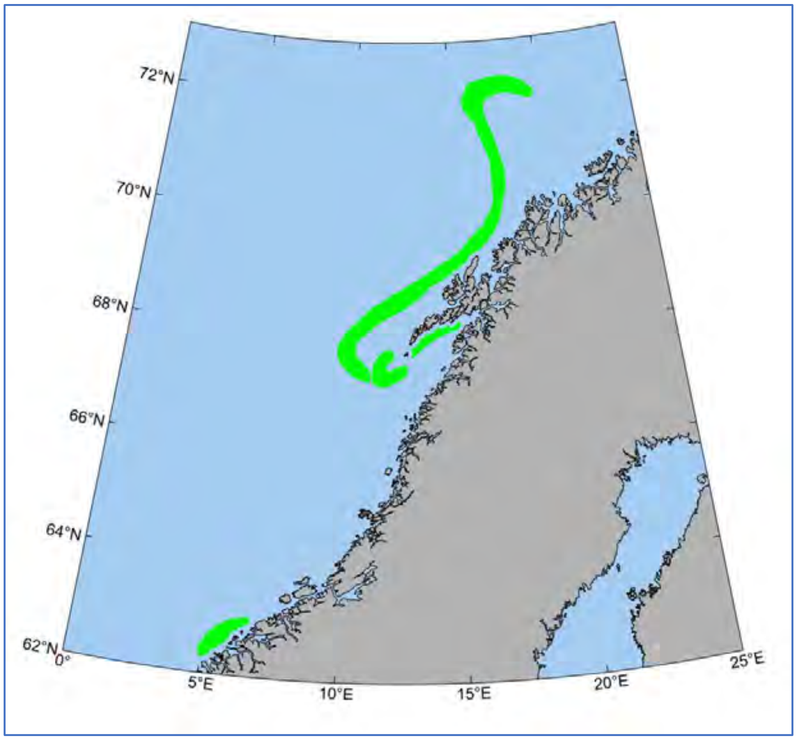


Figure 6. NEA haddock spawning areas in the model.

5.4.4 BS capelin

BS capelin was the second new species added and has several features that deviate significantly from NEA cod. Most importantly, the eggs are demersal and remain at the bottom until they hatch about one month after spawning. This process is modelled by releasing eggs within the spawning area (Figure 7) and keep their position fixed at the bottom until they hatch based on the experienced temperature. Spawning is modelled from Mar 1st until Apr 30th with a peak spawning intensity on Mar 31st. Due to the spawning areas being close to shore, there might be some problems with resembling the full spawning area due to the resolution of the ocean model (Figure 2). After the capelin super-individuals hatch in the model, we use the same larvae model as for NEA cod.

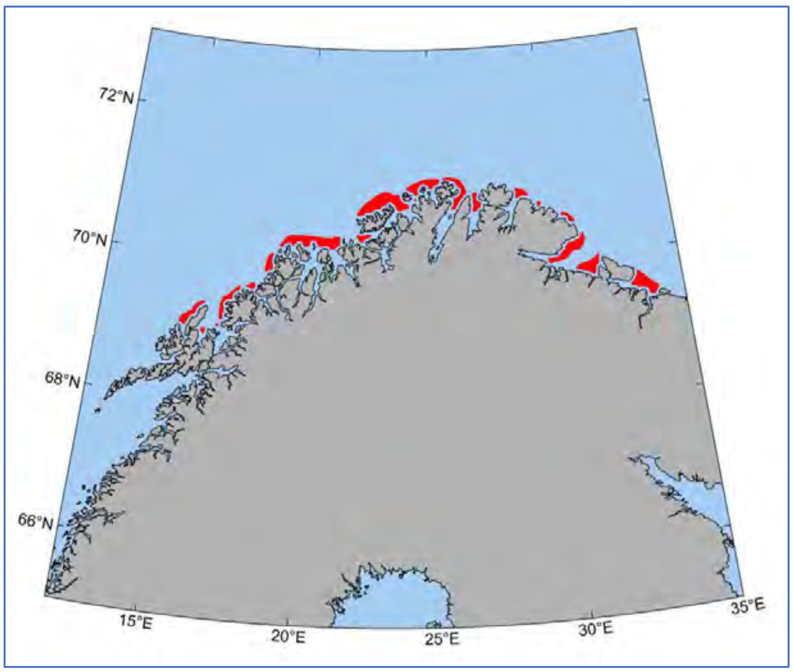


Figure 7. BS capelin spawning areas in model.

5.4.5 NSS herring

NSS herring (Figure 8) is modelled similarly as for capelin, only with a fixed hatching time of three weeks after the egg is spawned due to the lack of a temperature dependent hatching function. Spawning is modelled from Mar 1st until Apr 30th with a peak spawning intensity on Mar 31st.

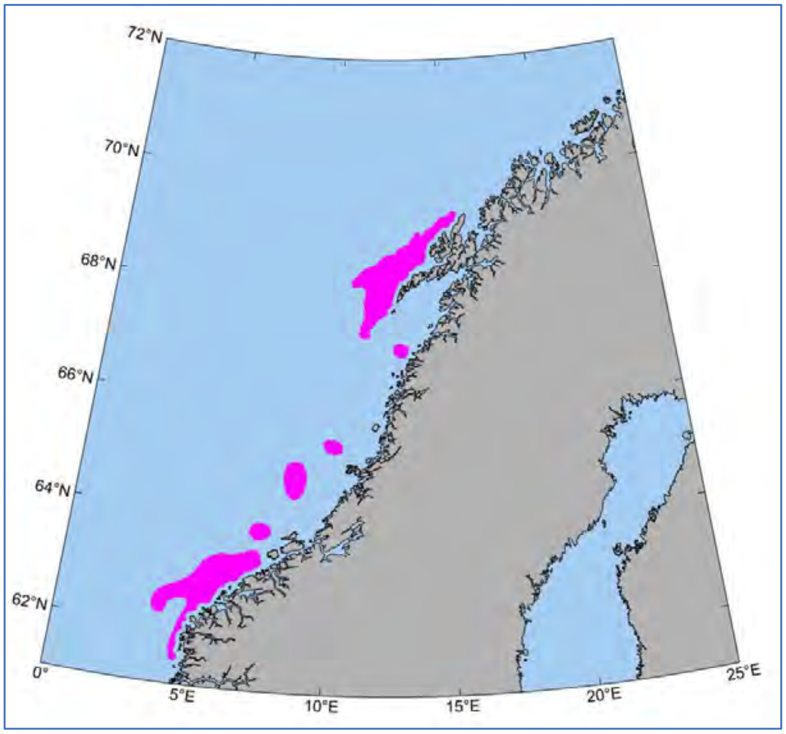


Figure 8. NSS herring spawning areas in model.

5.4.6 NEA saithe

NEA saithe is implemented using the NEA cod model, only with specific egg parameters and spawning areas (Figure 9). The spawning is modelled from Mar 1st until Apr 30th with a peak spawning intensity on Mar 31st.

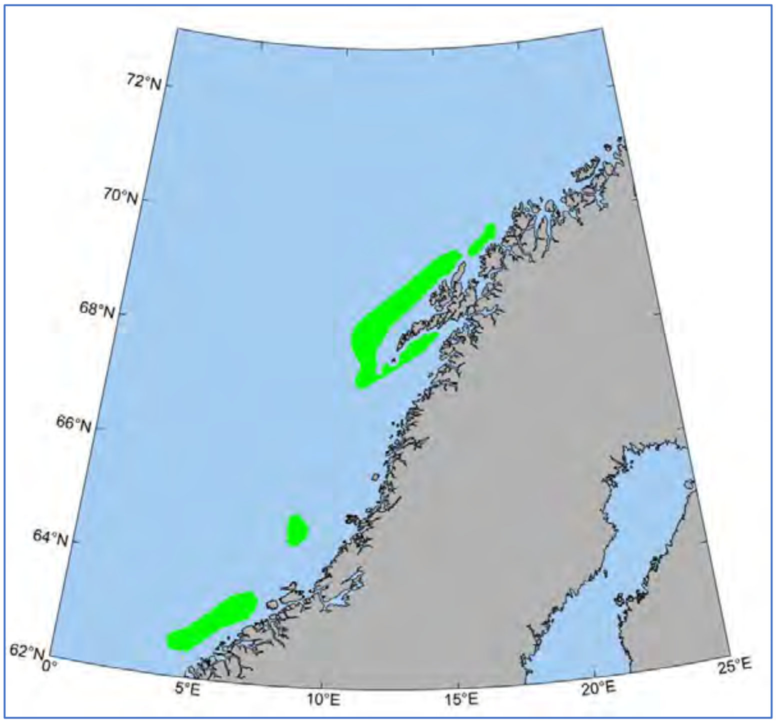


Figure 9. NEA saithe spawning areas in model.

5.4.7 Sandeel

Sandeel habitats in the North Sea (Figure 10) are defined as particularly vulnerable and valuable areas (Faglig Forum, 2019), and require particular considerations under the development of human activities to ensure integrity. Knowledge gaps are described in Johnsen *et al.* (2021) and followed up in a joint IMR and industry funded project at IMR to assess; i) the ability to hold Sandeel in lab for idealized experiments, ii) oil exposure and effects of sandeel early life stages, iii) connectivity between oceanic and coastal Sandeel, iv) populations structure through genetic and stable isotopes studies, v) in situ Sandeel distribution and behavior from multibeam echosounder. The early life stage module is now generic and there are no obstacles to implement new knowledge on Sandeel for risk assessments as it emerges.

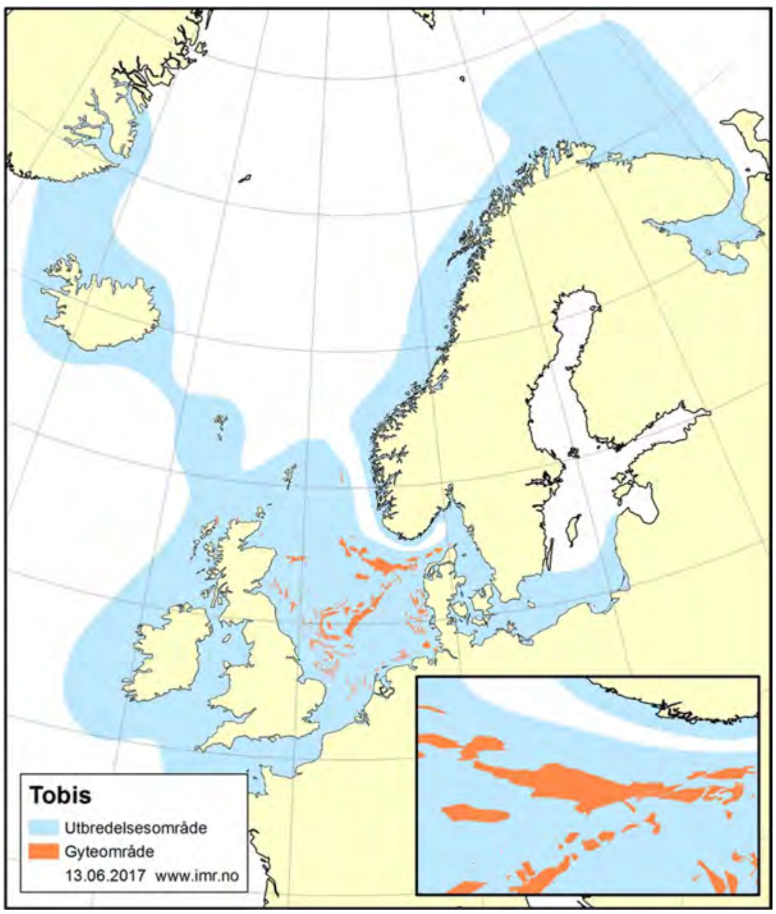


Figure 10. Spawning areas of Sandeel. Map retrieved from IMR webpage (in Norwegian) on Sandeel (https://www.hi.no/hi/temasider/arter/tobis).

5.4.8 Polar cod

The spawning areas of polar cod (Figure 11) are outside the impact region of the current oil release scenarios. For this reason, polar cod has not been prioritized for implementation in the model system at this stage. The ongoing project Arctic ecosystem impact assessment of oil in ice under climate change (ACTION) may provide information for implementation of polar cod in Symbioses at a later stage, see NRC project number 314449.

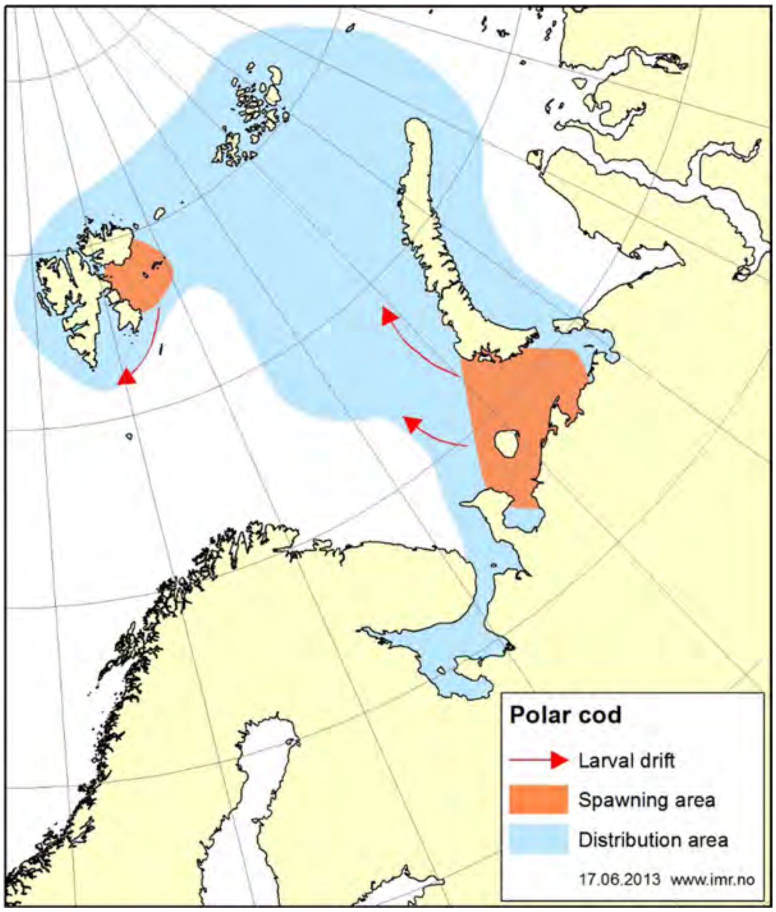


Figure 11. Spawning areas of polar cod. Map retrieved from IMR webpage on polar cod (https://www.hi.no/en/hi/temasider/species/polar-cod).

5.5 Adult fish populations

5.5.1 Modeling approach

GADGET (Globally applicable Area-Disaggregated General Ecosystem Toolbox) is designed to be a biologically realistic forward-simulation model of fish population dynamics (Begley and Howell 2004; Lindstrøm *et al.* 2009). GADGET is used to simulate juvenile (> 6 months) to adult fish populations. The model is highly flexible and is designed to be able to reproduce realistic biological processes (growth, predation, maturation, etc.) of fish populations through their life, and allows for spatio-temporal variations as required. The model is age-length structured, allowing for process to be modelled as a function of length, giving greater realism than is often possible in standard age-structured models. GADGET allows for multi-area, multi-fleet and multi-species models where the populations may be structured by age and/or length groups. The main state variables are the number and mean weight of individuals in each age/length group for a given population and area. The time step is user definable, typically monthly, or quarterly. It is important to recognize that GADGET simulates whole populations of a given species, rather than the movement and distribution of individual organisms. Although the model does allow for multi-area models, these typically consist of up to 2 or 3 large areas (for instance distinguishing between feeding and spawning areas), with no spatial distribution modeled within the designated areas. There is not sufficiently detailed spatial and temporal resolution in the fish population data to match the high-resolution structure of the fish larval and plankton components of SYMBIOSES. GADGET is a freely available open-source computer program, with full manual and source code available to download (http://www.hafro.is/gadget).

The GADGET model is tuned to available fisheries and survey data. As such, it is most reliable once the fish have entered the fishery, less reliable for juvenile (age 1+) fish only covered by the surveys, and not suitable for larval or 0-group modelling. In particular, the model does not realistically account for the year-to-year variability in mortality on the youngest fish. The youngest fish have both the highest annual variation in mortality and the highest difficulty in collecting accurate data. In the current simulations, cod haddock and capelin are modelled from age 1, although they only enter the fishery around age 3 for cod and haddock and age 3 or 4 for capelin.

In SYMBIOSES, LARMOD transfers to GADGET only the change in fish abundance caused by oil-induced mortality at the start of the 0-group stage[2]. The mortalities on these younger fish show year-to-year variability and an underlying density dependent mortality. Density dependence refers to the fact that there is a finite amount of food available, and mortalities are higher for a large population size than for a low population. This interacts with any oil induced mortalities and, to some extent, mitigates early-stage mortality. In SYMBIOSES, the density dependent mortality on the 0-group is estimated from field data on the abundance of the youngest cod individuals.

We focus on the adult biomass (termed Spawning Stock Biomass, or SSB) in presenting results. This is the most reliable output of the model, since the fish have been through multiple years of data collection by the time they mature. The SSB is also the key

[2] The 0-group stage of fish is associated with the start of the transition from freely floating larvae to swimming larvae.

management parameter in both standard fisheries management and in any response to oil-induced mortalities. Above some biomass level (termed Blim, the limit biomass reference point), the fish produce more eggs than can survive, and recruitment success is either not affected or only minimally affected by further changes in SSB. Both cod and haddock are currently above this Blim level, and the key measure of impact in assessing additional mortality is if the SSB remains above the Blim level. If this is the case, then the fish stock should be able to recover rapidly. If the SSB is pushed below Blim then recruitment is impaired, and the stock reduction is likely to take multiple generations to recover. Experience (in for example Norwegian Spring Spawning Herring and Grand Banks cod) is that recovery in these cases can take an unpredictably long time, running into multiple decades. We cannot therefore accurately model recovery from these low biomass levels, but it is clear that they are stock levels we should avoid reaching.

In order to track the impacts of an oil spill on future recruitment we project forward from the oil spill, ideally through the entire life span of the fish, and at least until that yearclass has its maximum contribution to the spawning stock. In the work conducted here, neither cod nor haddock were driven below Blim by any of the scenarios tested. It could therefore be expected that these species will recover rapidly from any of the tested oil spills. Capelin naturally fall below this Blim level in some years, and any oil spill will naturally make this occur more often and to a more severe extent. There is not currently a level of scientific data or understanding to predict the speed of recovery in this case.

5.5.2 NEA cod

The previous cod model was based on a model which has been run as an auxiliary assessment model. However, this model only ran to 2011. The model has now been updated to run to 2020. This allows for simulation of the impacts of oil spills on the whole lifespan (the time at which it remains a significant fraction of the stock) to about 2005, and for the maximum contribution to the SSB from oil spills up to 2012. Cod are cannibalistic, and this effect is included in the modelling.

Density dependence on the 0-group is included but is only tuned to data from the original model (I.e. up to 2011). Given that this covers the recruitment periods where the stock can be tracked through its life, this is not a significant issue.

It should be stresses that we have modelled “North East Arctic cod” - this is the large cod stock in the Barents Sea that migrates to spawn in the Lofoten area. There is a separate stock of coastal cod along the Norwegian coast and in the fjords, some of which also spawn in the Lofoten area. This coastal cod is smaller and believed to be at a lower stock status and spends more time in and around potential oil-spill areas. One could therefore expect coastal cod to be more vulnerable to any oil spill. These are not covered by the current simulations.

5.5.3 NEA haddock

A new GADGET haddock model has been created for the SYMBIOSES project. The model draws upon data and the output of the haddock assessment and runs to 2020. This allows for modelling of oil spills up to around 2010 (full life span) or 2012 (maximum impact on SSB). A key feature of haddock dynamics is that the occasionally (around once every 10 years or so) have much better recruitment events, and these large year classes of fish drive the dynamics of the stock. This gives a much more variable response to oil spills than is typical for cod. The most recent peak recruitment event was unusual in that it consisted of two or three consecutive good recruitment years. We therefore model both the impact of on a single year class ("what would have happened with an oil spill in that year”) and one affecting the entire recruitment peak (“what might happen with an oil spill in a more normal single peak recruitment”) to explore the range of possible oil impacts.

Several key features are still to be developed. Density dependence on 0-group is not currently included. Due to the variable recruitment, there are very few data points on the “good recruitment” events, and it is therefore not obvious how to parameterize density dependent mortality for these. Given the high survival of the recruiting fish, density dependence is expected to be much lower than might be estimated from data from the low recruitment years, but it is not clear how much lower. The juvenile and adult haddock also show density dependent growth, with the abundant yearclasses growing slightly more slowly, this is also currently not included. Finally, it is known that haddock eggs tend to attract oil more than cod eggs, leading to a higher mortality rate even at low oil concentrations (Sørhus *et al.*, 2015). This effect is also not included in the current version. Haddock are subject to significant predation from cod in the first few years of their life. This is also not included, although it could be incorporated in future (GADGET is designed to be a multispecies model, and both cod and haddock are now in the SYMBIOSES framework).

5.5.4 Capelin

A new capelin GADGET model has been developed for the SYMBIOSES project. This model tracks the capelin from age 1 until the spawn and die, typically at age 4 (with smaller numbers at age 3 or 5. The model runs to 2018 and is therefore able to track oil spills up to around 2012 or 2013.

Capelin recruitment is even more variable than haddock, and the SSB largely consists of a single yearclass. This results in high swings in capelin SSB, naturally falling below Blim in some years. The capelin stock is able to recover from these low stock levels, but not in every year. There is no good understanding of what leads to good capelin recruitment (although there is data to suggest that a large stock of young herring can depress recruitment by feeding on capelin larvae). Given this lack of scientific knowledge, the model is not able to capture the recruitment impacts of reduced SSB. The model assumes that recruitment will be unaffected by changes in SSB. As a result the model does track the immediate reduction in biomass but is likely too optimistic in predicting the eventual recovery time from any oil event. This is not something that can be readily remedied. Also, due to the extreme variation in recruitment there is likely variation in density dependence on the 0-group, and this is also not included in the current model.

It should be noted that the capelin assessment model is being updated at the end of 2022, and there should therefore be an improved data set and scientific understanding to be used in any future revisions of the model.

5.5.5 Herring

A GADGET herring model is developed, and a first version was completed by the end of the project.

5.5.6 Saithe

Time did not permit a saithe model to be developed during the project. All data and a stock assessment model exists for the saithe, which is split into one "northern" stock along the coast up to and including Lofoten and Vesterålen, and one "southern" stock in the North Sea. Creating a GADGET model to include in a future version of SYMBIOSES is therefore highly feasible.

5.5.7 Sandeel

No sandeel GADGET model was created. The main sandeel grounds are further south from the current areas, and the dynamics of the fish are very different from those of the other species under consideration. Whereas the other species tend to migrate and spawn together, sandeel have a much patchier distribution and less migratory behavior. It is therefore likely that there is a spatially defined series of substocks, and it may be that spatial modelling techniques would be required to model the response of this species to any oil spill. Given this, and the more limited data available, any modelling here would be a major task.

5.5.8 Polar cod

A polar cod model has also not been developed. This species does not suffer from the problem of substock dynamics that sandeel does and is therefore easier to model. However, the data is limited when compared with cod, capelin, haddock or herring, especially given that the range of the stock extends outside the survey areas. Any model would therefore have longer development time and much higher uncertainties than the other stocks.

5.6 Fish ecotoxicology

5.6.1 Methodology

The algorithm describing how internal oil pseudo-component concentrations are translated into effects (ECOTOX) is embedded in LARMOD. The resulting subroutines simulate responses of fish ELS to chemical exposures via direct contact with contaminated seawater. The technical basis for this algorithm is the Dynamic Energy Budget (DEB) theory (Kooijman 2000). This theory presents simple mechanistic rules that describe the uptake and use of energy and nutrients (substrates, food, light) and the consequences for physiological organization throughout an organism's life cycle, including the relationships of energetics with aging and effects of toxicants. All living organisms are covered in a single quantitative framework, the predictions of which are tested against a wide variety of experimental results at the various levels of biological organization. This mechanistic non-species-specific metabolic theory allows differences between species to reduce to changes in a set of parameter values. DEB describes the energy pathways in individuals, predicting individual level effects based on an assessment of the allocation and use of energy by an organism (http://www.bio.vu.nl/thb/deb/index_main.html).

Based on a given exposure scenario, the algorithm calculates chemical concentrations of an organism (internal concentration) using chemical uptake kinetics and elimination rates for a given species and life stage. This predicts the energy balance associated with changes in an organism's physiological parameters (e.g., food assimilation, excretion, growth, maintenance, reproduction) and how these energy changes affect critical demographic parameters (mortality, growth, reproduction). This approach provides a framework to interpret effects of mixtures of toxicants or multiple stressors in general.

The algorithm predicts mortality for an individual organism as a function of the internal concentration of a chemical compound. This relation can be estimated based on toxicity data generated through laboratory experiments. Point estimates like LC50 values provide limited information on the survival function in time. Therefore, preferably, several observations over time are available from laboratory exposure experiments that can be used to determine the concentration-depended survival function. The algorithm predicts mortality effects using three-time independent toxicity parameters ($\dot{b}$ = killing rate, NEC_m= No effect concentration for mortality and $\dot{k}_e$ = elimination rate constant). When this information is available for one oil compound, extrapolation relations are available to estimate mortality effects for compounds with a similar mode of action (Ashauer and Jager 2018; Galic *et al.* 2017; Teal *et al.* 2018). These extrapolation relations allow for the assessment of impacts of oils with variable composition.

5.6.2 Toxicity parameters fish early life stages

Due to the absence of properly described dose-response results over time from the available literature, we could not develop species-specific DEB parameters. As an alternative, DEB parameters were derived from a study on juvenile Fathead minnow (*Pimephales promelas*) exposed to naphthalene (Jager and Kooijman, 2009; Baas *et al.*, 2009). For this study, data on the number of survivors over time was available allowing for full DEB survival analyses (Klok *et al.*, 2014).

Based on the value of $\dot{k}_e$ for naphthalene and fathead minnow (Jager *et al.*, 2011) and equations for $\dot{k}_e$, NEC_m and $\dot{b}$, the three DEB parameters were extrapolated for 14 of the 26 pseudo-component groups (Klok *et al.,* 2014). Extrapolation for phenols (a polar substance) was not possible since phenols have a different mode of action than naphthalene (polar) and can therefore not be extrapolated from the naphthalene-based values. For some of the pseudo-component groups solubility was lower than the predicted NEC_m. Therefore, these are not evaluated further, except for C8-saturates and PAH-2. The last two groups contain a variety of components of which some have a relatively high solubility that may contribute to toxicity. To be conservative these two groups are also included as relevant groups for the extrapolation. See Klok *et al.,* 2014 for toxicity parameter values used to model the impact of oil components on fish larvae.

A general limitation of toxicity models is the availability of experimental data that supports modeling (De Laender et al, 2011; Olsen et al, 2013; Klok et al, 2014). Due to the limitations of data and current knowledge on the effects of exposure to petroleum compounds, we apply four toxicity parameter sets, producing four survival probabilities for each simulation. This is a recognized procedure to estimate uncertainty by exploring a range of simulated model outcomes associated with different parameters sets (Bassis, 2021). Briefly, parameter set P1 is based on empirically supported linear relationships between log Kow and the NEC for individual compounds, k_e and *b* that were estimated for juvenile fathead minnow (Klok *et al.*, 2014) with the addition of an assessment factor (AF) of 50 to account for higher sensitivity at younger development stages (ELS) than in adults. For parameter set P2, an assessment factor of 500 was applied to polyaromatics (including naphthalenes) to account for uncertainties in the toxicity mechanisms for marine fish eggs and larvae exposed to PAHs. The NECs for naphthalenes 1 and 2 and PAH 1 and 2 for parameter set P1 are 92.1, 18.1, 13.1, 2.26

μg/L; for parameter set P2 the values are 9.21, 1.81, 1.31, 0.226 μg/L (SI Table 2). Uptake kinematics slow down with decreasing threshold for effect (NEC) as reflected in the corresponding k_e for the four polyaromatic groups equal to 3.82, 1.14, 0.87 and 0.23 day^{-1}. Parameter sets P3 and P4 have threshold levels for the four polyaromatic groups at 1.0 and 0.1 μg/L, respectively. Lethality is instantaneous when the internal concentration of the sum of the four polyaromatic groups exceeds these threshold levels.

There are two important distinctions between P1/P2 and P3/P4. First, acute lethality occurs only in response to the outcome of the time varying uptake and elimination (TK) processes for P1 and P2 while for P3 and P4, lethality is instantaneous when the exposure concentrations of the sum of the four polyaromatic groups exceed the selected threshold values. In other words, a NEC value has the same unit as water concentration and is applied to a scaled internal concentration, which is assumed to be proportional to the internal concentration (body burden). For P1 and P2, delay due to uptake and elimination is equivalent to the scaled internal concentrations of the pseudo-components. For P3 and P4, instantaneous uptake is assumed such that the scaled internal concentrations are equal to the water concentrations.

Second, for P1 and P2, the NECs for the four polyaromatic groups are based on the temperate freshwater fish fathead minnow (Klok et al., 2014) while the P3 and P4 NEC values are based on published studies of toxic effects (lethal and sublethal) performed on a variety of marine cold water fish species. These four parameter sets encompass a wide range of uncertainty in both threshold levels and effects for petroleum compounds (Carroll et al, 2018).

When performing an iteration (Figure 3), the results from the ecotoxicology effect calculations are utilized in communication pathways. First, oil pseudo-component concentrations are transferred from the oil compartment to the fish ECOTOX module. Based on a given exposure scenario (exposures via direct contact with contaminated seawater), chemical concentrations for fish ELS (internal concentration) are derived using chemical uptake kinetics and elimination rates for a given life stage. Then the ECOTOX module supplies data on mortality.

5.6.3 Additional parameter sets for fish early life stages.

Both SYMBIOSESV1.0 and V2.0 produces four survival probabilities for each simulation in accordance with the protocol developed at a workshop (Table 6). These four parameter sets encompass a range of uncertainty in both threshold levels and effects for petroleum compounds (Carroll *et al.*, 2018). The workshop (March 5, 2015) was held to discuss data and current knowledge on the effects of exposure to petroleum compounds. The participants concluded that the data limitations and related uncertainties in our understanding of effects to fish early life stages warranted the development and application of three additional toxicity parameter sets (see Appendix II - section 15). This is a recognized procedure to estimate uncertainty by exploring a range of simulated model outcomes associated with different parameters sets (Bassis, 2021).

By applying a wide range of parameter values to quantify survival probability, mortality also serves as a 'proxy' for sublethal effects. The idea is that exposures to oil compounds that do not immediately lead to mortality may result in mortality later. For example, poor swimming that makes an individual easy prey, or poor heart condition that does not allow an individual to capture prey, etc. The instantaneous death of these individuals is how SYMBIOSES accounts for deaths that may occur later because of sublethal effects. It is relevant to address in more detail as a follow-up investigation, how the SYMBIOSES model addresses sub-lethal effects.

Table 6Parameter sets for sensitivity testing in SYMBIOSES established at the March 5, 2015 workshop* and used in SYMBIOSES V1.0 and V2.0

Parameter set	Description
P1	Original parameter set from Klok *et al.* (2014) with an assessment factor of 50 for all groups.
P2	Original parameter set from Klok *et al.* (2014) with an assessment factor of 50 for non-PAH groups and an assessment factor of 500 for PAH and naphthalene groups
P3	Original parameter set from Klok *et al.* (2014) with an assessment factor of 50 for non-PAH groups. The PAH and naphthalene groups all have a NEC of 1 ppb and an infinitive slope (100% effect once NEC has been exceeded)
P4	Original parameter set from Klok *et al.* (2014) with an assessment factor of 50 for non-PAH groups. The PAH and naphthalene groups all have a NEC of 0.1 ppb and an infinitive slope (100% effect once NEC has been exceeded)

*Workshop participants: Frode Vikebø (IMR), Bjørn Grøsvik (IMR), Sonnich Meier (IMR), Trond Nordtug (SINTEF), Mathijs Smit (Shell), Starrlight Augustine (Akvaplan-niva), Tone Frost (Statoil, now Equinor)

5.6.3.1 Parameter sets for new fish species.

The parameter values in SYMBIOSES V1.0 were established using a database containing experimental results on all fish species (Olsen *et al.*, 2013). As previously discussed, a general limitation of toxicity models is the availability of experimental data that supports modelling. As part of the ecotoxicology work package of the SYMBIOSES III project, the database was updated to include the most recent experimental data available in the scientific literature. This information was distributed to the Steering Committee as a note (Appendix IV). After the addition of new data into the database, the toxicity parameter sets (Appendix II) were re-assessed. It was determined that these values remained valid. Therefore, the same parameter sets were applied in SYMBIOSES V2.0. with no adjustments needed to accommodate the expanded list of fish species.

5.6.4 Survival probability calculation

Each simulation produces a survival percentage for the early life stages (to the end of the pelagic stage). We quantify the cumulative difference in survival for identical simulations with and without oil. We then transfer the reduction in larval survival to the fish population model and use this to modify the number of recruits to a fish population model.

In SYMBIOSES V1.0, all the mortality effects for the individual pseudo-component groups are added, assuming effect addition (Carroll *et al.*, 2018). Effects occur only when the NEC value of an individual pseudo-component group is exceeded. This information is used to update the survival probability of individual fish larvae with and without toxicants. The reduction in larval abundance due to chemical stressors is quantified and information is transferred to the adult fish compartment to model fish population dynamics.

In SYMBIOSES V2.0, all toxic compounds contribute to the NEC. An effect occurs when the NEC value of the mixture of pseudo-component groups is exceeded (Baas *et al.* 2015, Baas *et al.*, 2009). This information is used to update the survival probability of individual fish larvae with and without toxicants. The reduction in larval abundance due to chemical stressors is quantified and information is transferred to the adult fish compartment to model fish population dynamics.

The change from an independent to a mixture ecotoxicology algorithm is in accordance with the state-of-the-art scientific literature. Many studies have revealed that mixtures of compounds below their individual effects threshold concentrations (e.g., NOEC, NOEL, LC50) can still show a toxic effect (Drakvik *et al.*, 2020). The mixture approach is in accordance with the latest scientific understanding (Vlaeminck *et al.,* 2019, 2021; EFSA Scientific Committee *et al.* 2019; Bopp *et al.*, 2019; Bopp *et al.* 2018). The method for including the mixture approach in SYMBIOSES V2.0 is described in Carroll et al.,

2022. The mixture approach is now successfully implemented and running in Symbioses V2.0 simulation procedure.

6. Simulation procedure and data resources

6.1 Simulation procedure

When describing the performance of a simulation, we aim to trace the flow of information among the environmental compartments. This contrasts with Section 2 where we introduced terminology to describe the architecture behind the SYMBIOSES operating system. Hence, the ecosystem compartments used in this section do not directly map to the independent models and interfaces defined in Section 2. The information provided by or to the environmental compartments for the constructed ecosystem is stored in the SYMBIOSES architecture as follows:

- Atmosphere -> originates in SINMOD and is stored in the ATMOSPHERE interface of the software library.
- Hydrodynamic -> originates in SINMOD and is stored in the HYDRODYNAMIC interface.
- Oil -> originates in OSCAR and is stored in the OIL interface.
- Adult Fish -> originates in GADGET and is stored in the AQUATIC interface.
- Plankton -> originates in SINMOD and is stored in the AQUATIC interface.
- Fish ELS -> originates in LARMOD and is stored in the AQUATIC interface.
- Plankton Ecotox -> originates in SINMOD and is stored in the AQUATIC interface.
- Fish Ecotox -> originates in LARMOD and is stored in the AQUATIC interface.

As described above, when performing a simulation, information is generated or received by these environmental compartments (Figure 5). This information corresponds directly to *features*; a term introduced in Section 2 in the description of the SYMBIOSES architecture. It is this information, or *features,* which is the common currency for the ecosystem simulations performed by the SYMBIOSES system.

A simulation begins with the definition of initial conditions. These include defining the atmospheric and hydrodynamic conditions (climate), as well as the simulation length (run-time). The petroleum release characteristics are defined, specifying a start time, duration, release rate, release depth and position, and composition of oil. The atmosphere is then initialized, and atmospheric information is transferred to the hydrodynamic and oil compartments. The oceanographic data is in turn transferred to the oil, zooplankton, and fish ELS compartments. Data on oil (pseudo-component concentration fields) is then transferred from the oil interface to the interfaces that contains zooplankton and fish ELS components. The respective ecotox compartments supply body burdens, survival/reproduction rates (plankton ecotox) and mortality/growth rates (fish ecotox) which are then used to update the plankton and fish ELS compartments. At each time-step, the plankton compartment provides data (copepod characteristics and distributions) to the fish ELS compartment to update the prey field. An iteration scheme is used to repeat these calculations for all time steps specified for a given scenario. To achieve statistical power, multiple scenarios, modified systematically, may be run. For example, the simulation start date or petroleum release date may shift forward or backward by a selected number of days or years. Over time, the accumulation of runs will result in an archive of simulation results that will continue to improve our understanding and quantification of the uncertainty associated with individual system runs.

At each stage of a simulation, the fish ELS compartment updates the survival probability of individual fish ELS representatives. At the end of a simulation, the average survival probability of the fish larvae weighted by spawning intensity is computed. By relating the survival probabilities for identical scenarios, with and without toxicants, the reduction in larval abundance due to chemical stressors is quantified. The resulting value for the reduction in larval abundance is then transferred to the adult fish compartment (GADGET).

GADGET determines the fish population structure on a monthly time-step for a selected number of years (typically 10 years). Information on the Harvest Rule (regulated fishing quotas) and predation (loss of fish due to predator/prey interactions) for each year is provided by the user as input to this model. The SYMBIOSES simulation procedure results in the determination of the difference in fish population structure for the two cases (with oil/without oil) as a function of predation, harvesting and climate conditions.

The results from a given simulation (Table 6) are stored in NetCDF files. These files are then distributed to the relevant experts (individual modelers and ecotoxicology specialists) to evaluate the results.

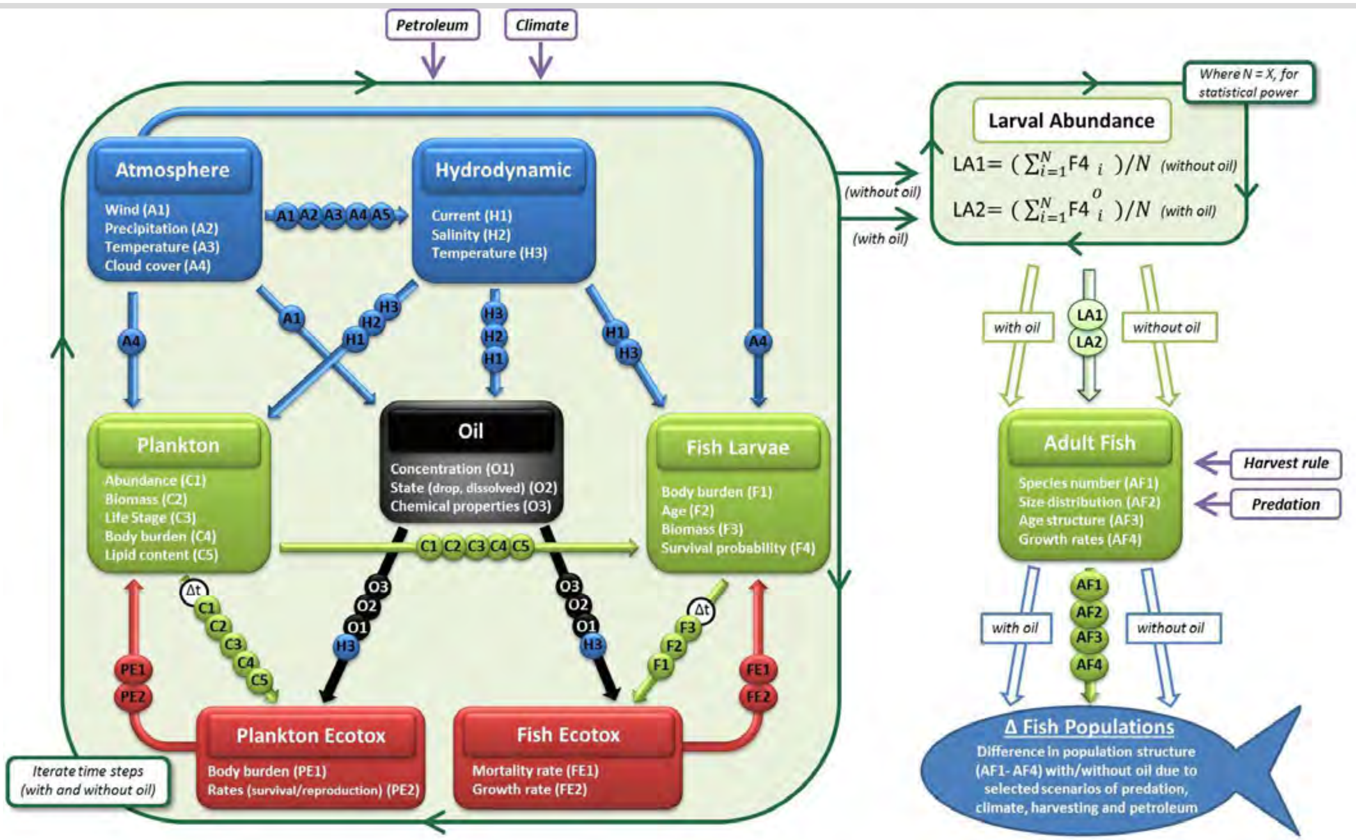


Figure 12 Environmental compartments (colored boxes) with listed features showing the communication pathways (arrows) amongst the compartments. Boxes outlined in purple (Petroleum and Climate - top) represent pressures on the marine ecosystem included in SYMBIOSES. L = number of particles (larvae); N = number of scenarios for which simulations are performed.

Table 7. Summary outputs from SYMBIOSES.

Group	Variables
Population level – not spatially resolved: • Fish populations - time series for individual species at monthly resolution	Biological parameters (population level): • Age structure • Growth rate • Differences in parameter values for base case and simulated petroleum discharge events
Parameter distributions in 4 dimensions: • Biological patterns (multiple species) • Chemical patterns (multiple components) • Physical patterns	Biological parameters (individual level): • Fish larvae & egg distributions (different species) • Zooplankton distributions (different species and stages) • Phytoplankton distributions (different species) • Components of the microbial loop • Nutrient distributions (different components) • Differences in parameter values for base case and simulated petroleum discharge events Chemical parameters: • Surface oil distribution • Concentrations of dissolved oil components (up to 25 components) • Concentrations and composition of oil droplets in seawater Physical parameters: • Water currents • Salinity • Temperature • Waves • Sea ice • Turbulence
Ecotoxicology	Body burden of chemical compounds in species life stages Individual effects on mortality, growth, reproduction Population effects on mortality, growth, reproduction

6.2 Data sources

The various independent models rely on a variety of input data sources to define parameter values for initial model runs. These data requirements and their linkages to other outputs are shown in Figure 12. Oceanographic and atmospheric data series are retrieved from recognized international organizations (ECMWF). Routine monitoring programs carried out by national authorities provide data on fish stocks and fishing effort[3]. Ecological data on population structure, distribution, life cycles, as well as ecotoxicology parameter values to predict the biological effects of exposure to oil were established using data assimilated during the SYMBIOSES project from publicly available literature sources. Table 7 provides an overview of the input data sources used by the independent models.

Table 8 Data sources used by SYMBIOSES. Data supplied by ocean-atmosphere data are supplied by international organizations (green). Input data supplied by monitoring programs is marked in black. Input data assimilated from R&D programs is marked in red.

	Model parameterization:	Source
Ocean/Atmosphere	Wind, Cloud Cover, Air temperature, Humidity, River runoff, Tides, Turbidity.	International Meteorological & Oceanographic organizations
Chemical fate	Oil type characteristics. Chemical/Physical properties of oil.	Compiled data base
Ecotoxicology endpoints: 1. Survival 2. Growth 3. Reproduction	Dose-response curves (i.e. the LC50 and slope). Lethal-sublethal ratios (i.e. LC50-EC50) for crustaceans Bioassays of growth, reproduction, survival under different food conditions for different life stages of target organisms. Lipid contents of different life stages of target organisms.	Laboratory experiments Laboratory experiments Laboratory experiments Field collections
Zooplankton	Spatial/temporal data series of zooplankton species and stages. Natural mortality, growth, reproduction process investigations (phytoplankton & zooplankton).	Field collections and scientific literature Field collections and scientific literature
Fish ELS	Spatial/temporal data series of predator species. Egg distribution and abundance. Egg density and size distribution. Prey body burden. Natural mortality, growth, reproduction process investigations.	Field collections – data is mainly for cod. Field collections
Adult fish populations	Fishing effort. Stock size. Mean body weight in each age/length group. Prey items, Mortality function.	ICES databases Field collections (IMR)

[3] The GADGET model estimates an internal effort parameter, which is tuned during optimization to almost match the reported catch exactly (adjusted for estimated under-reporting in some periods). The effort parameter has no physical meaning and is included partly to prevent difficulties in the optimization (it allows for slight noise in the catch data) and mostly as a technical measure to make running alternate harvest scenarios easier.

7. Sensitivity testing and assessment

Sensitivity testing was conducted to evaluate system performance as part of the development of SYMBIOSES V1.0 (Step 2). Detailed descriptions of the evaluation methods and the analysis of individual test results are available in a separate report (Carroll *et al.*, 2014), 'System testing: results of the implementation of the testing protocol.' The results do not represent actual predictions of petroleum impacts on the marine environment.

Sensitivity testing was also conducted as part of the development of SYMBIOSES V2.0 (Step 4). These activities are described below.

7.1 Model linkages and stability

A systematic review was made of the transfer of information throughout the linkages between the individual models, from oceanography to larval mortality and subsequent reduction in SSB. Issues addressed are given below.

7.1.1 Time steps

The SINMOD Ocean and Biology model have iteration steps of 6 minutes, while OSCAR and LARMOD have iteration steps of 12 minutes, Tests were made on changing to longer iteration steps, and shorter iteration steps, concluding that the original iteration steps were maintained.

7.1.2 Spatial resolution and grids

While the SINMOD modules of SYMBIOSES operates on a 4 by 4 km grid, LARMOD and OSCAR are particle based. OSCAR calculates concentration on a 1.5 km grid according to the principles outlined in Figure 13. The OSCAR concentration grid has the same vertical layers as the SINMOD modules, except for the uppermost layer, which is from the surface to 2 m depth.

In the sensitivity testing, oil concentrations were extracted from the several top layers and compared with the ELS distribution and toxicity. While higher oil concentrations were observed in the uppermost layer for surface releases, ELS was distributed at greater depths.

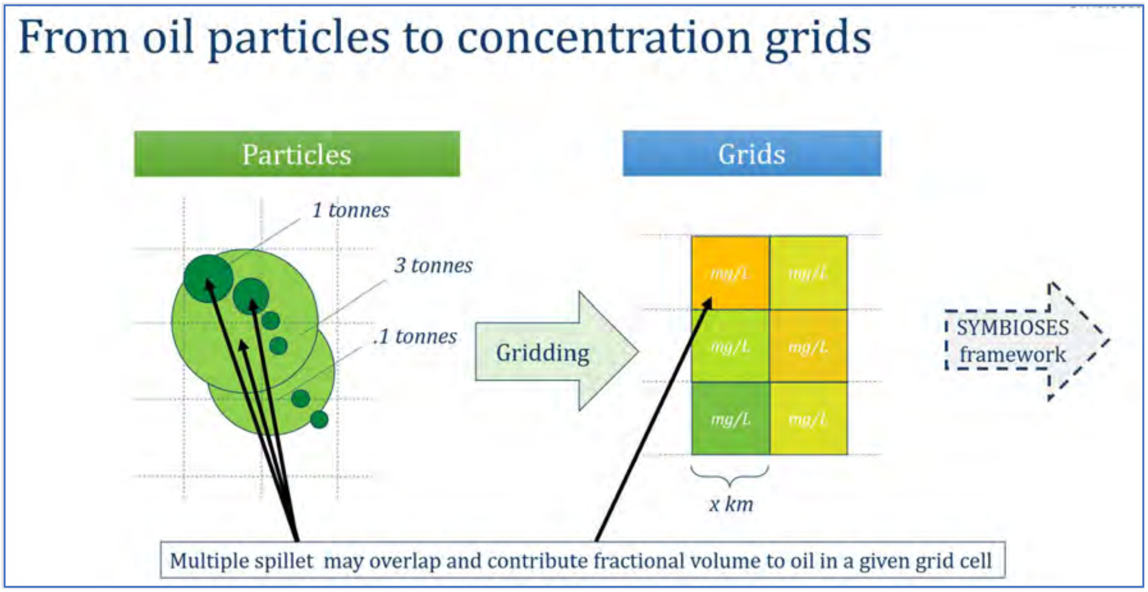


Figure 13. From oil particles to concentration grids.

The parameter values P3 and P4 state immediate mortality of ELS encountering water column concentrations of 1 and 0.1 ppb respectively. To confirm the functioning of these algorithms, geospatial data on point of death of ELS superindividuals were compared with geospatial data on oil concentrations exceeding the two threshold values. By extracting data from a given time step on position of ELS superindividuals encountering water with oil concentrations exceeding parameter set value as well as time of death, it was shown that the values were applied correctly (Figure 14).

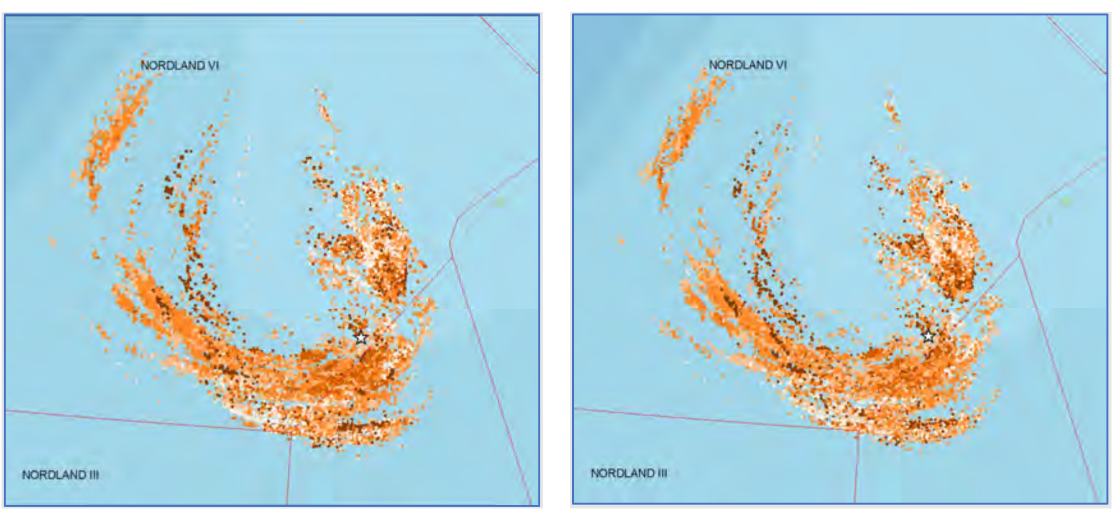


Figure 14 First encounter of PAH exceeding P4 threshold value (left) and point of death of superindividual (right).

7.2 Variation between spawning locations

For NEA Cod there are several distinct spawning locations. For a given year, the fraction of ELS originating from each of these may vary. A set of variations between the individual fields were addressed in Carroll et al, (2018), and the distribution concluded in that paper was also applied in SYMBIOSES III.

7.3 Location

In the SyEx part (see table 1) of the SYMBIOSES II project, simulations were carried out for six different locations in the Northern part of the Norwegian Sea and the Southern part of the Barents Sea, with a range of reservoir parameters provided by the Norwegian Petroleum Directorate. To address the sensitivity in terms of location in relation to oceanographic conditions and fish spawning areas, simulations were carried out for all SyEx locations with identical crude oil types, release rates, release depth and release duration (See Section 10).

7.4 Interannual variation

The different fish species addressed in SYMBIOSES III show a wide variation in characteristics in terms of recruitment. From this, years of good and bad recruitment were reviewed, and a selection was made as described in Section 8.5

7.5 Time of year

The impact from accidental oil releases at different times of year was addressed in a set of simulations with start dates at 14 days intervals from January to October. The results are presented in Carroll *et al.*, 2022, and the results for haddock ELS survival are given in Figure 15.

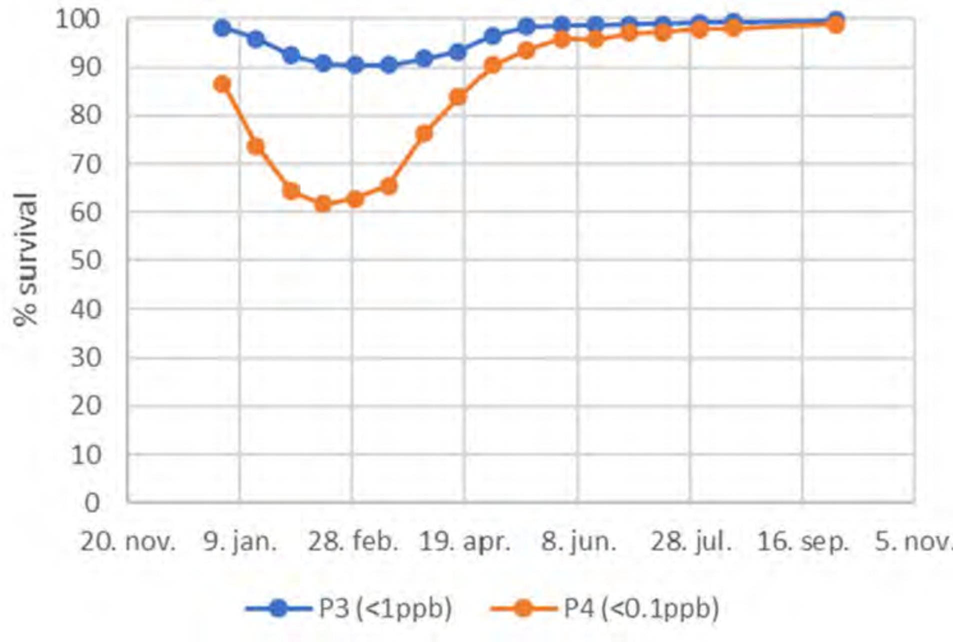


Figure 15. Haddock ELS survival for a release starting at different times of year (Carroll *et al.*, 2022).

7.6 Mixed vs. individual model.

One improvement in SYMBIOSES III was a change in the toxicity module, moving from NEC derivations based on single compounds toxicity to a model where each pseudocomponent of the oil contributes to the NEC (see Section 5.6). This improved model better address the variable composition of crude oil, and also lead to a slightly larger area of impact and ELS mortality, as shown in Figure and Table 9.

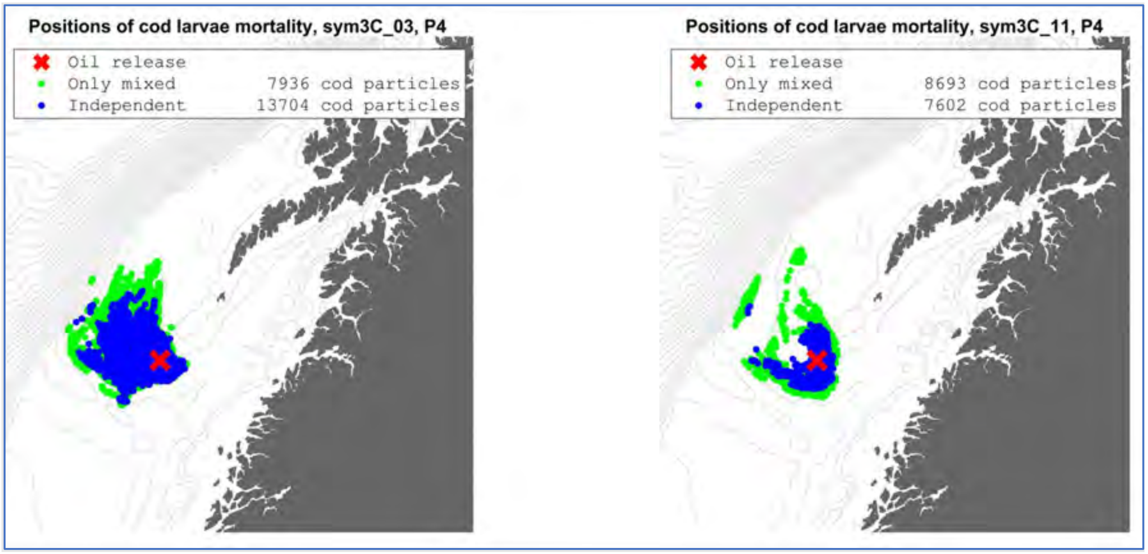


Figure 16. Illustration of region of effect for ELS mortality for two different simulations. The green larvae particles experience mortality only for the mixed (new) model, while the blue particles experience mortality also for the independent (old) model .

Table 9. ELS survival with original (individual) and new (mixed) model.

Oil type	**Release duration (days)**	**ELS Survival – P4 (%)**		**ELS Survival – P3 (%)**	
		Individual model	*Mixed model*	*Individual model*	*Mixed model*
Draugen	14	99	99	99	99
Draugen	45	99	96	100	100
Draugen	90	96	93	99	98
Draugen	45	92	84	100	99
Draugen	90	90	81	100	99
Svale	45	75	70	94	92

7.7 Oil particle size and number

When applying the OSCAR model in ERA Acute environmental risk assessments where THC concentrations are applied to estimate ELS mortality, the Offshore Norway Best Practice group undertook a set of sensitivity tests regarding mass of oil per particle released, concluding that the mortality increased with decreasing particle size, due to increased dissipation in the water column.

However, initial testing in SYMBIOSES showed that although THC concentrations increased with less mass per particle, ELS mortality decreased. Further study showed a different fate of THC as such and TPAH, the latter causing ELS mortality in SYMBIOSES.

As ELS mortality is one of the key results of SYMBIOSES simulations, a systematic study with increasing particle numbers was conducted (each particle representing a smaller mass of oil). The results for P3 and P4 respectively are shown in Figure 16 and Figure 17.

Our conclusion is that in the SYMBIOSES context, a mass of 1 000 kg per oil particle (termed a "spillet" in the model) is considered relevant for large scale releases. It is recommended as a future standard, as a slightly conservative choice, and taking into account simulation time.

It should be noted that an implication of these findings is a lower ELS mortality than reported in earlies studies, where fewer particles were used in simulations.

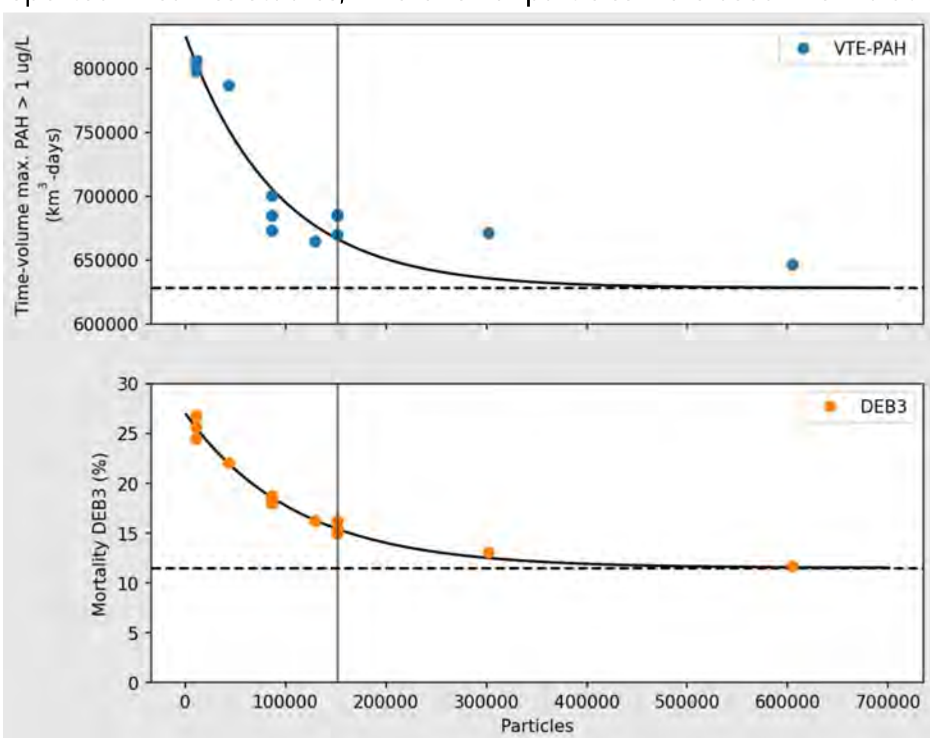


Figure 16. Time-volume PAH > 1ug/l (km^3/days) (top) and DEB3 Mortality (bottom) for different numbers of particles

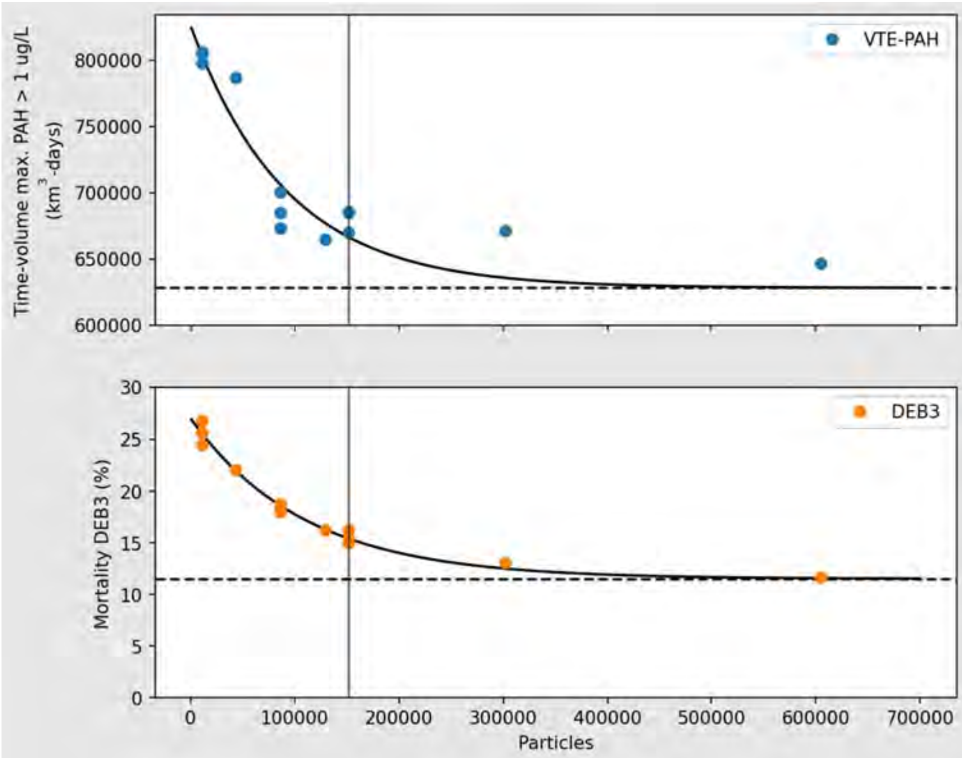


Figure 17. Time-volume PAH > 1ug/l (km^3/days) (top) and DEB4 Mortality (bottom) for different numbers of particles

7.8 Effect of Calanus

The SINMOD Biology module requires a high number of numerical calculations, with implications for the CPU hours required for running simulations.

While inclusion of the SINMOD Biology module providing the food fields for fish ELS are important for natural recruitment, it was assumed that their impact on additional oil induced mortality was minimal. To verify this, a set of simulations were run with and without the SINMOD module. The results (Figure 18) supported this assumption, leading to a decision on running the majority of the subsequent simulations without the SINMOD Biology module.

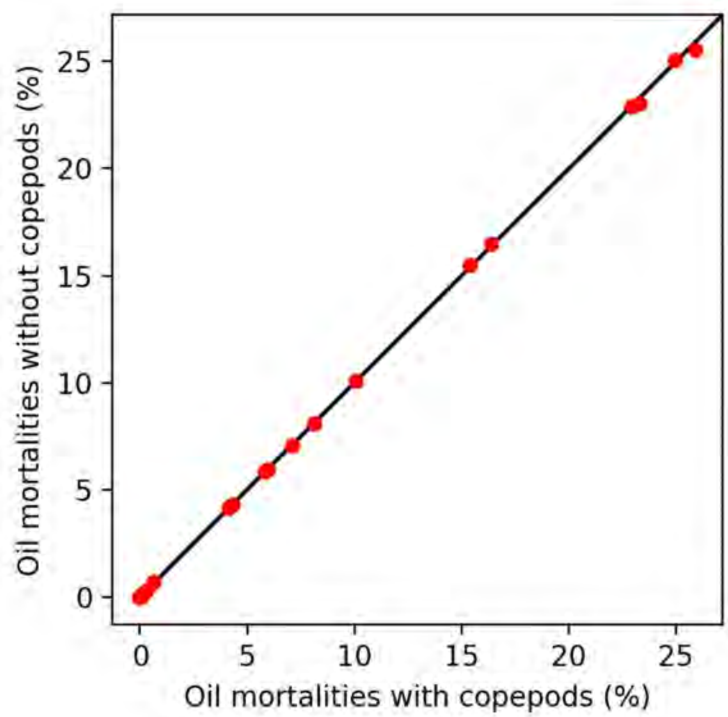


Figure 18. Comparison of oil mortalities with (x-axis) and without (y-axis) Calanus, across all species and parameter sets.

7.9 Effect of dispersants

Using the SYMBIOSES framework, we can investigate the effect of dispersant use on oil fate and consequent impacts on ELS mortality. To approximate the effects of dispersant, we ran simulations with a reduced oil-water interfacial tension parameter in the OSCAR model, reducing it by a factor of 100. The Weber models implemented in OSCAR then predicts a different (typically smaller) oil droplet diameter, which can lead to more (by number) droplets and higher retention of oil droplets in the water column, as well as an increased dissolved fraction. The dispersant simulations were run with 90 day discharge and Balder oil, 4500 m^3/day for both surface and sub-sea releases. An example snapshot of dissolved oil concentration is shown in Figure 19 (no dispersant variant, surface release).

We found that changes in oil fate mass balance when dispersant was applied (through reduced IFT) resulted in increased submerged and biodegraded oil. A reduction in surface, stranded and evaporated oil were also observed, and this is to be expected considering the effect reduced IFT has on the oil, as discussed above; overall smaller median droplet size was observed in the simulations when IFT was reduced. In terms of cod and haddock ELS impacts, there was only a minor difference in the effect levels for P3 and P4. We must stress here that the direct effects of oil droplets on haddock eggs (Section 5.4.3) were *not* considered in these simulations, as that feature was added later in the project, and may lead to changed results for haddock. For P1 and P2, the impact levels were small (<0.02% and < 0.5% respectively), but there was a more substantial increase in the dispersant scenarios compared to the non-dispersant scenarios.

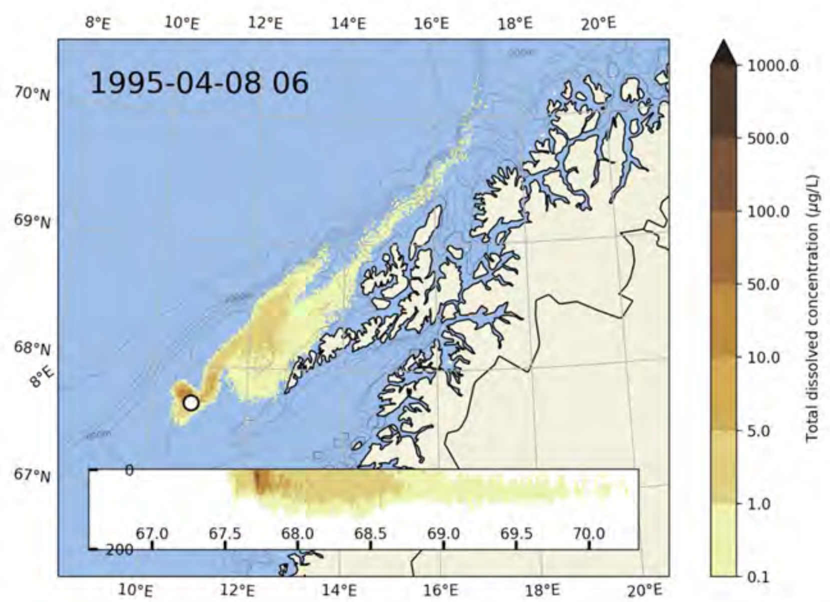


Figure 19 Surface release snapshot of dissolved oil, see text for details.

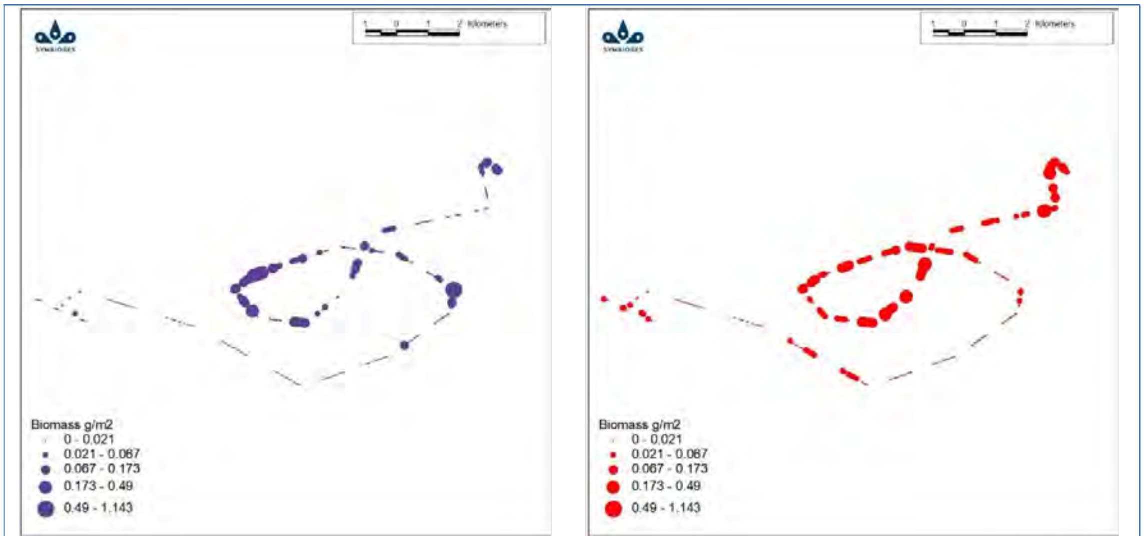
7.10 AUV and ASV versus model data sets

Autonomous Underwater Vehicles (AUV) and Autonomous Surface Vehicles (ASV) is a cost effective and, to a large extent, CO_2 neutral manner in which to collect biological and physicochemical data with a high spatial and temporal resolution. On the NCS, AUVs and ASV are currently applied in a number of R&D projects, e.g. the Glider II and the Polar Fronts projects.

For SYMBIOSES type projects, AUVs and ASVs can collect data that can be applied off-line, e.g. variability in food availability, as exemplified in Figure . Such data can be applied to assumptions of food availability for ELS.

As part of the Glider project, the Norwegian Met Office has developed protocols for real-time assimilation of current measurements from Acoustic Doppler Current Profiler

(ADCP) on ASVs. Such information has significance for improving current models and identification of areas of retention as well as areas of high current speeds.



10 m depth	20 m depth

Figure 21. Spatial variation in Zooplankton distribution as measured by ASV. Data provided by Muriel Dunn.

In a real time context, AUVs and ASVs can monitor a range of parameters and report these data through onboard transmitters. One application will be field studies and as verification of modelled drift paths and ELS distribution in 4D. In such a context, AUVs and ASVs can be directed by onshore operators, and may also be designated an area for a "holding pattern", where e.g. ASVs are located at specific times to avoid conflicts with other activities.

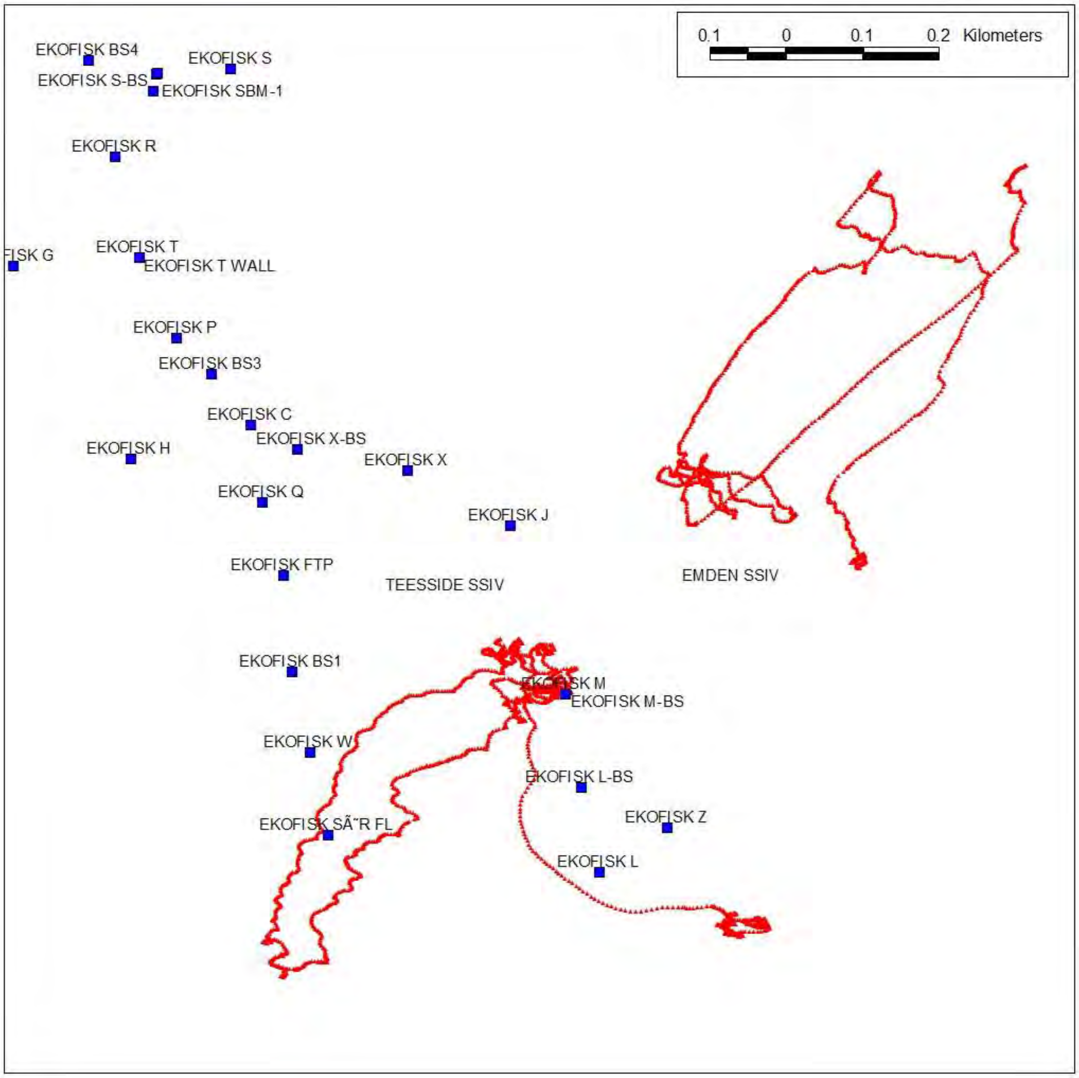


Figure 20 Example of ASV use in field studies, including location of holding pattern (bottom right).

8. Simulation parameters and presentation formats

8.1 System operation

Operational tests for the full SYMBIOSES V2.0 system focused on simulations of NEA cod and haddock using both the original (individual toxicity approach) and new ecotoxicology module (mixture approach). A series of oil spill simulation runs were performed with the oil spill occurring at the original SYMBIOSES test location on the Lofoten-Vesterålen shelf (67.700N 10.841E). These simulation results are presented in full in Carroll *et al.*, 2022, and an example provided in section 6.4.

In addition to simulations run in a sensitivity assessment context, a range of simulations for species, locations and years were carried out, based on nominations from industry partners as well as the Research Team. These are presented in this section.

8.2 Result parameters

8.2.1 Larval mortality

For each simulation, added mortality (or reduced survival) of ELS caused by exposure to oil is calculated, for five of the species.

8.2.2 SSB reduction

For NEA Cod and NEA Haddock, population models are available to the extent that impact of the reduced recruitment on the Spawning Stock Biomass (SSB) over a 10-year period can be modelled.

8.3 Spawning areas

As shown in Section 7 impacts from application of P3 and P4 parameter sets are not too far from the release site, the implication being that distance from release point to spawning products is an important factor. In Figure 21, Figure 22, and Figure 23, locations of spawning areas are presented in relation to SYMBIOSES III release sites, to provide context for the reader when reviewing simulation results.

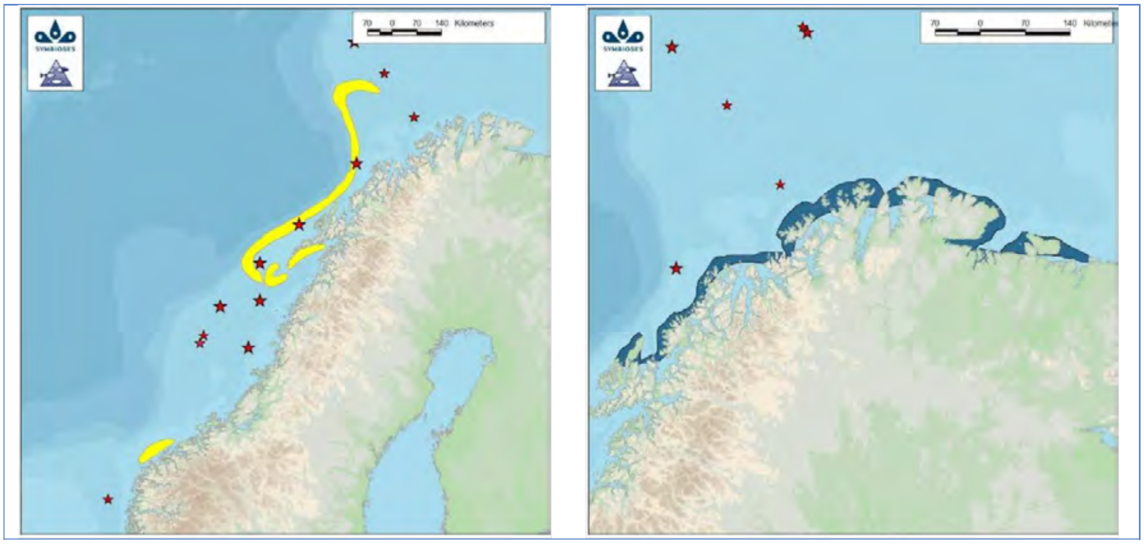


Figure 21. Spawning area of NEA Haddock (Left) and BS Capelin (Right). SYMBIOSES III simulation release scenarios indicated by red stars.

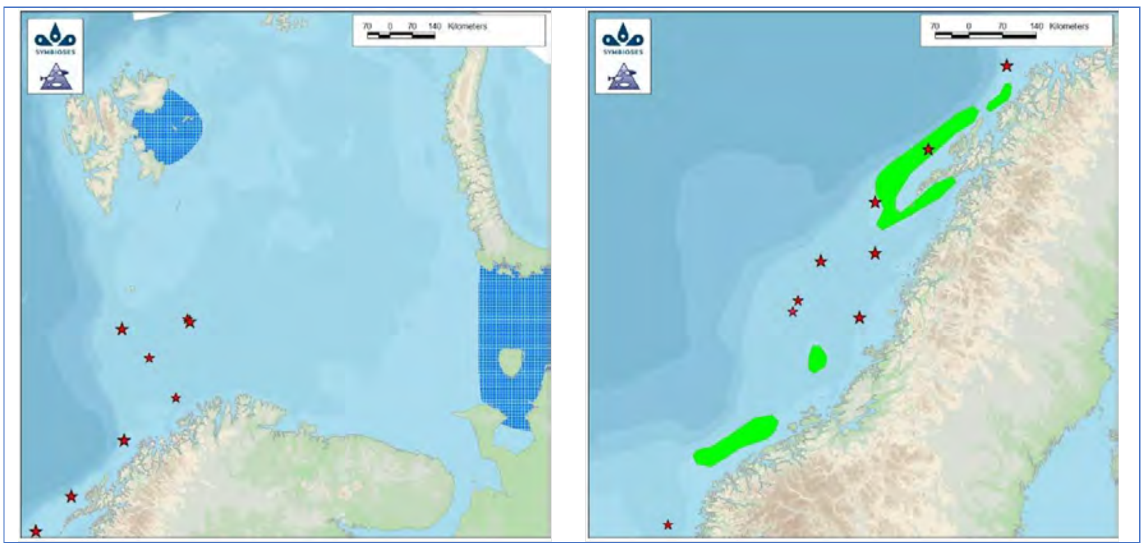


Figure 22. Spawning area of Polar Cod (Left) and NEA Saithe (Right). SYMBIOSES III simulation release locations for simulations set 2 and 3 indicated by red stars.

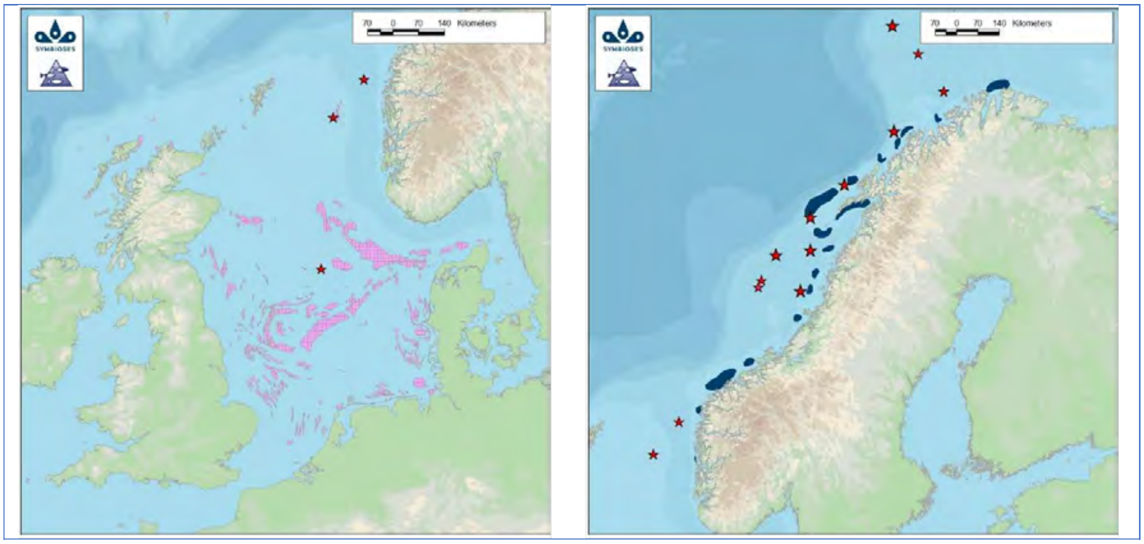


Figure 23. Spawning area of Sandeel (Left) and NEA Cod (Right). SYMBIOSES III simulation release locations for simulations set 2 and 3 indicated by red stars.

8.4 Selection of species

NEA cod was the only species implemented in the model at the beginning of the project period. When considering new species for implementation during the project a list of six candidate species were made. To evaluate the vulnerability of these, nine traits were evaluated and given a score of low, medium, or high for how likely it is that the trait will worsen the impact of an oil spill for the given species (Table 10).

Table 10. Traits of selected species for SYMBIOSES III. 0.1, 0.5 and 0.9 refer to a low, medium, or high probability that the species will experience an added impact from a spill due to the trait. Values marked with * are more uncertain.

	Sticky eggs	Egg stage duration	Sporadic recruitment	Pelagic eggs	Contracted spawning habitat	Retention of eggs and larvae	Contranted spawning period	Filling of swim bladder	Larval stage duration
NEA cod	0.1	0.5	0.1	0.9	0.1	0.1	0.9	0.1	0.5
NEA haddock	0.9	0.5	0.9	0.9	0.5	0.1	0.9		0.5
BS capelin	0.5*	0.9	0.9	0.1	0.1	0.1	0.9		0.9
NSS herring	0.5*	0.5	0.9	0.1	0.5	0.1	0.9	0.9	0.5
NEA saithe	0.1	0.5	0.1	0.9	0.5	0.5	0.9		0.5
Polar cod	0.5	0.9		0.9	0.5	0.5	0.9		0.5
Coastal cod	0.1	0.5	0.5	0.9	0.9	0.9	0.9		0.5

The trait of sticky eggs was determined as a key feature to decide the choice of species. As haddock have been shown to have sticky eggs (Sørhus *et al.*, 2015), NEA haddock was chosen as the first new species to be added in the model. BS capelin and NSS herring, both with demersal eggs, were chosen as the next species implemented after NEA haddock. The final species implemented was NEA saithe. Polar cod and sandeel were considered, but not implemented. See chapter 5 for more information. Coastal cod can be modelled using the module as for NEA cod with an updated spawning file. This is an example that if scenarios move outside the Lofoten region, it will become important to add new stocks of existing species, not only new species.

8.5 Selection of years

The fish species addressed in SYMBIOSES III show a wide variation in Spawning Stock Biomass (SSB) and annual recruitment, as visualized in Figure 24 and Figure 25. The Capelin stock is the most variable of all the stocks examined here, and among the most variable of any stock in the world. Capelin have highly variable recruitment success, and because they spawn and die, the SSB is largely dependent on a single recruitment event. Haddock and herring are reliant on occasional good yearclasses, although not to the same extent as capelin. Although cod have had more even recruitment, two good yearclasses in the early 2000s coincided with good environmental conditions and reduced fishing pressure leading to a large peak in SSB. These patterns mean that all species examined here have individual years where recruitment has the largest impact on the stock development, and we have selected years to examine to reflect this variability by focusing on the years with large recruitments. These yearclasses form the basis for a large part of the stock and fishery in subsequent years. Capelin is the only species examined here where the stock has fallen to levels where recruitment could be impaired in the last 30 years. Since capelin, haddock and herring all depend on occasional good recruitment events, we also wish to address the question of how the stock survives between the good yearclasses. Therefore, there are two years selected to examine if an oil spill in between the good yearclasses could have affected the ability of capelin and haddock to maintain their SSB until the next good recruitment event.

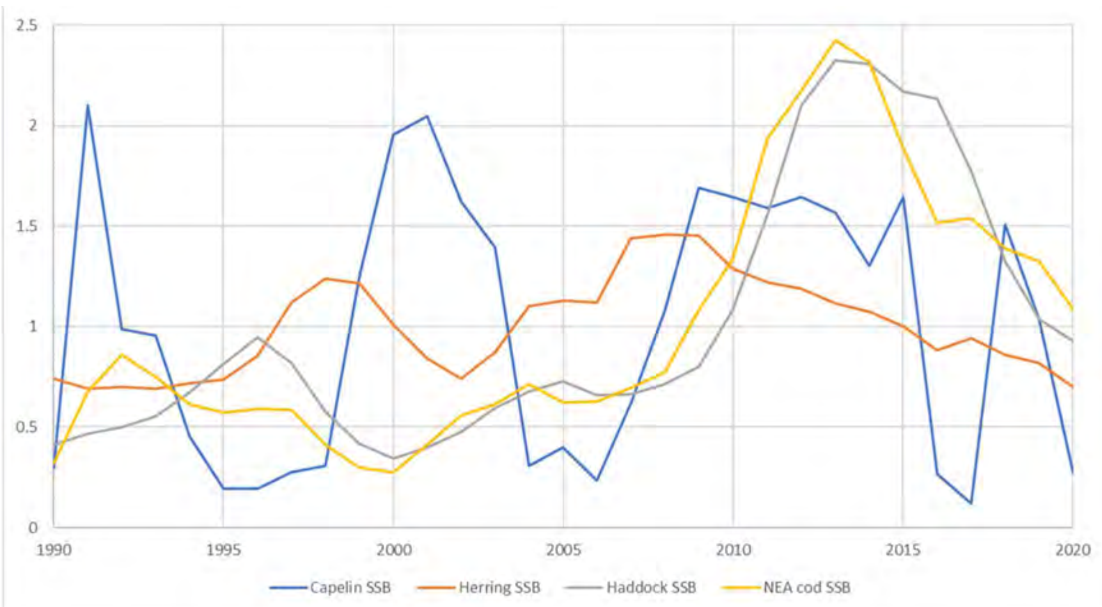


Figure 24. Relative SSB of SYMBIOSES stocks, 1990-2020.

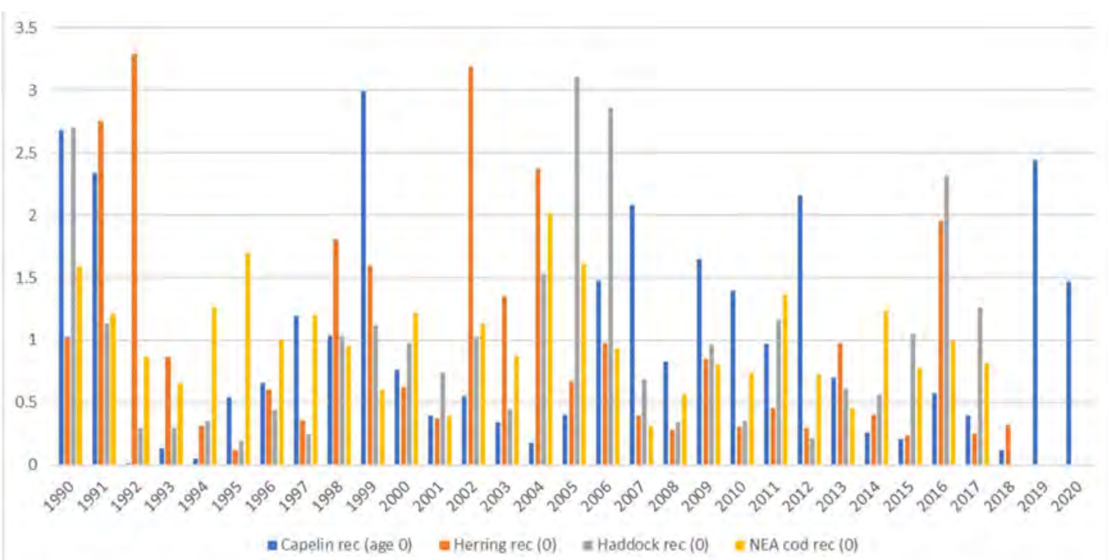


Figure 25. Relative recruitment of SYMBIOSES stocks, 1990-2020, plotted against year of spawning.

To address the impact of oil mortalities on SSB across a range of years, including years with good recruitment and limited recruitment for the individual species, the following years were selected for SYMBIOSES III simulations:

- 1995 – Base case year for SYMBIOSES
- 1999 – Good yearclass for Capelin
- 2002 – Good yearclass for Herring
- 2004 - Good yearclass for most fish except Capelin. might be interesting in terms of cumulative impact over all stocks rather than particularly on one species or another.
- 2005 – Good yearclass for Haddock
- 2011 – Best of a poor run for Haddock
- 2016 – stand out as a year good for haddock and herring, and best of a poor run for capelin

It should be noted that as well as stock variability, there are ecosystem wide patterns. The strongest effect is that a good herring year is generally followed by several years of poor recruitment. Juvenile herring reside in the Barents Sea for 3 to 4 years, and prey heavily on 0-group capelin. A large yearclass of herring can therefore severely reduce capelin recruitment success. Another key impact comes from cod predation, where cod have important impacts on the mortality of spawning capelin and small cod and haddock. At present SYMBIOSES is formulated as a separate single species model, and therefore these effects (apart from cod cannibalism) are not accounted for in the simulations.

8.6 Presentation of results

In SYMBIOSES III, more than 300 full simulations were run, using approximately 30 000 simulation days and around 1,500,000 CPU hours at the Saga supercomputer. There were 15 locations for oil release, a range of oil types, release depth and durations, addressing six different fish species, of which impact on Spawning Stock Biomass (SSB) were modelled for four of these.

These simulations generated a significant set of results from the simulations, and a selection of parameters have been made for the purpose of this report, focusing on ELS mortalities from oil exposure and the subsequent impact on Spawning Stock Biomass (SSB). The full set of results on all parameters resides on a series of 5 Tb disks at Akvaplan-niva.

The presentation format developed is in a form of tables, showing the results with numerical values, as well as a value neutral purple color coding, increasing in intensity with increasing values, as shown below.

<0.1	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.0	24.0	26.0	28.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0

9. Simulations nominated by industry partners (Set # 3)

The project steering committee members were invited to provide input to the process in terms of specific issues that they would like to be included in the testing plan in SYMBIOSES III. Nominees were reviewed by Akvaplan-niva, and a final list was developed, their location presented in Figure 26.

It should be noted that two additional locations in the Barents Sea also were nominated. However, the reservoir characteristics for these indicated very low flow rates, so these locations were discarded from the simulation runs.

Figure 26. Map showing the sites of simulations nominated by industry partners (Set # 3).

Simulations nominated by industry partners (Set # 3)

9.1 Simulation matrix

For all sites, and all years listed in section 8.5, simulations were run according to the simulation matrix presented in Table 11. The base case for all sites were the release characteristics forming the basis for the oil spill response level in the permit from the Norwegian Environment Agency. As may be seen, there is a wide range of oil types, release rates and release durations.

Table 11. Simulation matrix - simulations nominated by industry partners.

Location	Simulation	Release depth	GOR	Oil type	Release rate (m^3/day)	Release duration (days)
Site 1	IS01	Top	-	Ekofisk Blend	2437	9x
Site 2	IS02	Top	-	Oseberg C	6700	13
Site 2	IS03	Subsea	96	Oseberg C	7100	17
Site 3	IS04	Subsea	223	Skarfjell	4675	17
Site 3	IS05	Subsea	223	Skarfjell	4675	62
Site 3	IS12	Subsea	223	Skarfjell	5194	62
Site 3	IS13	Subsea	223	Skarfjell	2789	41
Site 4	IS16	Top	-	Martin Linge	4360	6
Site 5	IS07	Top		Skarv	3733	11
Site 5	IS08	Subsea	137	Skarv	10807	12
Site 6	IS09	Top		Kobbe	4123	10
Site 7	IS10	Top		Skrugard	8300	13
Site 8	IS11	Top		Wisting Central	8000	6
Site 9	IS17	Top		Skrugard	3400	16

9.2 ELS mortalities by release sites

In the following subsections, results from simulations in terms of mortality (%) from exposure to oil are presented.

9.2.1 Site 1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

Figure 27. ELS mortalities (%) from oil exposure - location Site 1 – simulation IS01. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.2 Site 2

9.2.2.1 Simulation IS02

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

Figure 28. ELS mortalities from oil exposure - location Site 2 – simulation IS02. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.2.2 Simulation IS03

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

Figure 29. ELS mortalities from oil exposure - location Site 2 – simulation IS03. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.3 Site 3

9.2.3.1 Simulation IS04

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	0.2	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.7	0.8	5.4	
1999	<0.1	0.7	1.3	6.7	
2002	<0.1	1.2	0.3	5.5	6.4
2004	<0.1	1.4	0.9	6.8	
2005	<0.1	0.1	0.1	2.8	
2011	<0.1	0.1	0.5	3.5	
2016	<0.1	1.4	0.7	3.5	

Figure 30. ELS mortalities from oil exposure - location Site 3 – simulation IS04. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.3.2 Simulation IS05

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	0.3	
1999	<0.1	<0.1	<0.1	0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	0.2	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.5	1.3	10.8	
1999	<0.1	0.3	1.5	13.4	
2002	<0.1	1.2	0.4	12.2	6.8
2004	<0.1	0.4	0.5	12.4	
2005	<0.1	0.1	0.2	5.6	
2011	<0.1	<0.1	0.3	8.7	
2016	<0.1	0.9	0.4	4.6	

Figure 31. ELS mortalities from oil exposure - location Site 3 – simulation IS05. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.3.3 Simulation IS12

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	0.3	
1999	<0.1	<0.1	<0.1	0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	0.2	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.7	1.0	10.4	
1999	<0.1	0.3	1.2	12.2	
2002	<0.1	1.6	0.7	13.7	8.3
2004	<0.1	0.6	0.6	12.5	
2005	<0.1	<0.1	0.2	5.7	
2011	<0.1	0.2	0.3	8.6	
2016	<0.1	0.7	0.3	4.1	

Figure 32. ELS mortalities from oil exposure - location Site 3 – simulation IS12. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.3.4 Simulation IS13

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.4	1.1	9.6	
1999	<0.1	0.5	1.0	10.3	
2002	<0.1	1.1	0.6	10.7	5.3
2004	<0.1	0.9	0.7	10.8	
2005	<0.1	<0.1	0.1	4.6	
2011	<0.1	<0.1	0.3	7.2	
2016	<0.1	0.5	0.2	2.4	

Figure 33. ELS mortalities from oil exposure - location Site 3 – simulation IS13. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.4 Site 4

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	0.7	<0.1	0.4	1.5
2005	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	0.3	<0.1	0.3	0.8

Figure 34. ELS mortalities from oil exposure - location Site 4 – simulation IS16. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.5 Site 5

9.2.5.1 Simulation IS07

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	0.2	<0.1	0.1	

Figure 35. ELS mortalities from oil exposure - location Site 5 – simulation IS07. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.5.2 Simulation IS08

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	0.1	0.1
2004	<0.1	0.8	<0.1	0.3	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	1.1	<0.1	1.0	

Figure 36. ELS mortalities from oil exposure - location Site 5 – simulation IS08. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.6 Site 6

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	1.8	<0.1	<0.1	
1999	<0.1	0.3	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

Figure 37. ELS mortalities from oil exposure - location Site 6 – simulation IS09. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.7 Site 7

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	0.3	2.7	<0.1	<0.1	
1999	<0.1	0.7	0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	0.2	<0.1	<0.1	<0.1	
2016	<0.1	0.3	<0.1	<0.1	

Figure 38. ELS mortalities from oil exposure - location Site 7 – simulation IS10. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.8 Site 8

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

Figure 39. ELS mortalities from oil exposure - location Site 8 – simulation IS11. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.2.9 Site 9

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	0.3	<0.1	0.1
1999	<0.1	<0.1	0.1	<0.1	0.3
2002	<0.1	<0.1	0.3	<0.1	0.6
2004	<0.1	<0.1	0.2	<0.1	0.3
2005	<0.1	0.3	0.5	<0.1	0.5
2011	<0.1	0.6	1.6	<0.1	1.4
2016	<0.1	2.2	1.5	<0.1	2.5

	Capelin	Cod	Haddock	Herring	Saithe
1995	0.5	0.3	3.4	<0.1	1.0
1999	0.8	1.0	0.2	<0.1	0.9
2002	0.2	1.6	1.9	<0.1	3.0
2004	0.3	1.1	0.8	<0.1	1.3
2005	<0.1	1.6	4.9	0.2	4.7
2011	<0.1	1.9	8.8	0.2	5.7
2016	0.3	7.3	8.5	0.2	7.1

Figure 40. ELS mortalities from oil exposure - location Site 9 – simulation IS17. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

9.3 ELS mortalities by species

9.3.1 NEA Cod

P1:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P2:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P3**:**

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.6
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	2.2

P4:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	0.7	0.5	<0.1	<0.1	1.8	2.7	<0.1	0.7	0.4	<0.1	0.3
1999	<0.1	<0.1	<0.1	0.7	0.3	<0.1	<0.1	0.3	0.7	<0.1	0.3	0.5	<0.1	1.0
2002	<0.1	<0.1	<0.1	1.2	1.2	<0.1	<0.1	<0.1	<0.1	<0.1	1.6	1.1	<0.1	1.6
2004	<0.1	<0.1	<0.1	1.4	0.4	<0.1	0.8	<0.1	<0.1	<0.1	0.6	0.9	0.7	1.1
2005	<0.1	<0.1	<0.1	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.6
2011	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	1.9
2016	<0.1	<0.1	<0.1	1.4	0.9	0.2	1.1	<0.1	0.3	<0.1	0.7	0.5	0.3	7.3

Figure 41. ELS mortalities from oil exposure by release location and year for NEA Cod. From top to bottom_ Parameter set P1, P2, P3, and P4.

9.3.2 NEA Haddock

P1:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P2:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P3:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.5
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.6
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.5

P4:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	0.8	1.3	<0.1	<0.1	<0.1	<0.1	<0.1	1.0	1.1	<0.1	3.4
1999	<0.1	<0.1	<0.1	1.3	1.5	<0.1	<0.1	<0.1	0.1	<0.1	1.2	1.0	<0.1	0.2
2002	<0.1	<0.1	<0.1	0.3	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	0.7	0.6	<0.1	1.9
2004	<0.1	<0.1	<0.1	0.9	0.5	<0.1	<0.1	<0.1	<0.1	<0.1	0.6	0.7	<0.1	0.8
2005	<0.1	<0.1	<0.1	0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	0.1	<0.1	4.9
2011	<0.1	<0.1	<0.1	0.5	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	0.3	<0.1	8.8
2016	<0.1	<0.1	<0.1	0.7	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	0.2	<0.1	8.5

Figure 42. ELS mortalities from oil exposure by release location and year for NEA Haddock. From top to bottom_ Parameter set P1, P2, P3, and P4.

9.3.3 NEA Saithe

P1:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995													<0.1	<0.1
1999													<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004													<0.1	<0.1
2005													<0.1	<0.1
2011													<0.1	<0.1
2016													<0.1	<0.1

P2:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995													<0.1	<0.1
1999													<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004													<0.1	<0.1
2005													<0.1	<0.1
2011													<0.1	<0.1
2016													<0.1	<0.1

P3:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995													<0.1	0.1
1999													<0.1	0.3
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.6
2004													<0.1	0.3
2005													<0.1	0.5
2011													<0.1	1.4
2016													<0.1	2.5

P4:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995													<0.1	1.0
1999													<0.1	0.9
2002	<0.1	<0.1	<0.1	6.4	6.8	<0.1	0.1	<0.1	<0.1	<0.1	8.3	5.3	<0.1	3.0
2004													1.5	1.3
2005													<0.1	4.7
2011													<0.1	5.7
2016													0.8	7.1

Figure 43. ELS mortalities from oil exposure by release location and year for NEA Saithe. From top to bottom Parameter set P1, P2, P3, and P4.

9.3.4 BS Capelin

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P1:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P2:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P3:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	<0.1	<0.1	<0.1	<0.1	0.5
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.8
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3

P4:

Figure 44. ELS mortalities from oil exposure by release location and year for BS Capelin. From top to bottom_ Parameter set P1, P2, P3, and P4.

9.3.5 NSS Herring

P1:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P2:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P3:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	0.2	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P4:

	IS01	IS02	IS03	IS04	IS05	IS07	IS08	IS09	IS10	IS11	IS12	IS13	IS16	IS17
1995	<0.1	<0.1	<0.1	5.4	10.8	<0.1	<0.1	<0.1	<0.1	<0.1	10.4	9.6	<0.1	<0.1
1999	<0.1	<0.1	<0.1	6.7	13.4	<0.1	<0.1	<0.1	<0.1	<0.1	12.2	10.3	<0.1	<0.1
2002	<0.1	<0.1	<0.1	5.5	12.2	<0.1	0.1	<0.1	<0.1	<0.1	13.7	10.7	<0.1	<0.1
2004	<0.1	<0.1	<0.1	6.8	12.4	<0.1	0.3	<0.1	<0.1	<0.1	12.5	10.8	0.4	<0.1
2005	<0.1	<0.1	<0.1	2.8	5.6	<0.1	<0.1	<0.1	<0.1	<0.1	5.7	4.6	<0.1	0.2
2011	<0.1	<0.1	<0.1	3.5	8.7	<0.1	<0.1	<0.1	<0.1	<0.1	8.6	7.2	<0.1	0.2
2016	<0.1	<0.1	<0.1	3.5	4.6	0.1	1.0	<0.1	<0.1	<0.1	4.1	2.4	0.3	0.2

Figure 45. ELS mortalities from oil exposure by release location and year for NSS Herring. From top to bottom_ Parameter set P1, P2, P3, and P4.

9.3.6 Polar cod

The distances between the spawning areas of Polar Cod and the release locations were so large that there was no overlap between HC concentrations exceeding P4 parameter sets and spawning areas for any simulation.

9.3.7 Sandeel

As discussed in Section 5, data status on Sandeel does currently not allow for modelling larval mortality. However, results from oil drift simulations for all modelled years resided in the SYMBIOSES archives and may be applied in future assessments. An example of results is provided in Figure 46.

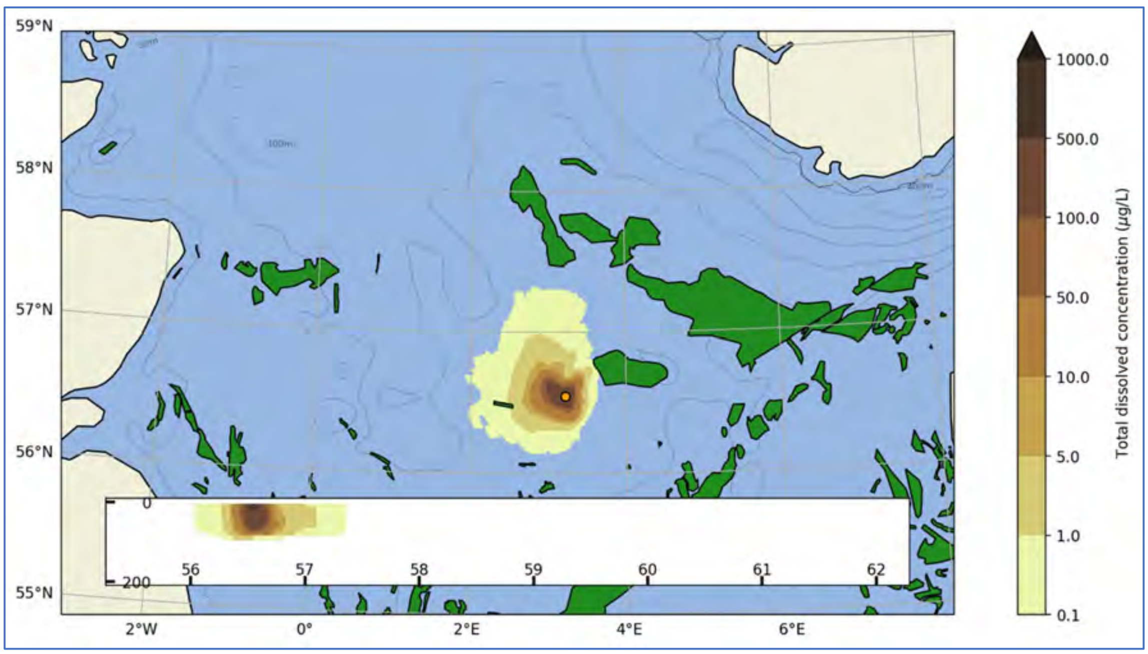


Figure 46. Overlap between oil drift simulations from IS01 and spawning areas of Sandeel.

9.4 Spawning Stock Biomass reduction by year (SSB)

9.4.1 1995

		P1 Cod	P1 Haddock	P2 Cod	P2 Haddock	P3 Cod	P3 Haddock	P4 Cod	P4 Haddock
Site 1	IS01	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 2	IS02	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS03	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 3	IS04	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	<0.1
	IS05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	<0.1
	IS12	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	<0.1
	IS13	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	<0.1
Site 4	IS16	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 5	IS07	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS08	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 6	IS09	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.7	<0.1
Site 7	IS10	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.1	<0.1
Site 8	IS11	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 9	IS17	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.2

Figure 47. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 1995, for each parameter set.

9.4.2 1999

		P1 Cod	P1 Haddock	P2 Cod	P2 Haddock	P3 Cod	P3 Haddock	P4 Cod	P4 Haddock
Site 1	IS01	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 2	IS02	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS03	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 3	IS04	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.2
	IS05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2
	IS12	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2
	IS13	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2
Site 4	IS16	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 5	IS07	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS08	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 6	IS09	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 7	IS10	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1
Site 8	IS11	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 9	IS17	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	<0.1

Figure 48. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 1999 for each parameter set.

9.4.3 2002

P1

		Cod	Haddock
Site 1	IS01	<0.1	<0.1
Site 2	IS02	<0.1	<0.1
	IS03	<0.1	<0.1
Site 3	IS04	<0.1	<0.1
	IS05	<0.1	<0.1
	IS12	<0.1	<0.1
	IS13	<0.1	<0.1
Site 4	IS16	<0.1	<0.1
Site 5	IS07	<0.1	<0.1
	IS08	<0.1	<0.1
Site 6	IS09	<0.1	<0.1
Site 7	IS10	<0.1	<0.1
Site 8	IS11	<0.1	<0.1
Site 9	IS17	<0.1	<0.1

P2

		Cod	Haddock
Site 1	IS01	<0.1	<0.1
Site 2	IS02	<0.1	<0.1
	IS03	<0.1	<0.1
Site 3	IS04	<0.1	<0.1
	IS05	<0.1	<0.1
	IS12	<0.1	<0.1
	IS13	<0.1	<0.1
Site 4	IS16	<0.1	<0.1
Site 5	IS07	<0.1	<0.1
	IS08	<0.1	<0.1
Site 6	IS09	<0.1	<0.1
Site 7	IS10	<0.1	<0.1
Site 8	IS11	<0.1	<0.1
Site 9	IS17	<0.1	<0.1

P3

		Cod	Haddock
Site 1	IS01	<0.1	<0.1
Site 2	IS02	<0.1	<0.1
	IS03	<0.1	<0.1
Site 3	IS04	<0.1	<0.1
	IS05	<0.1	<0.1
	IS12	<0.1	<0.1
	IS13	<0.1	<0.1
Site 4	IS16	<0.1	<0.1
Site 5	IS07	<0.1	<0.1
	IS08	<0.1	<0.1
Site 6	IS09	<0.1	<0.1
Site 7	IS10	<0.1	<0.1
Site 8	IS11	<0.1	<0.1
Site 9	IS17	<0.1	<0.1

P4

		Cod	Haddock
Site 1	IS01	<0.1	<0.1
Site 2	IS02	<0.1	<0.1
	IS03	<0.1	<0.1
Site 3	IS04	0.3	<0.1
	IS05	0.3	<0.1
	IS12	0.4	<0.1
	IS13	0.3	<0.1
Site 4	IS16	<0.1	<0.1
Site 5	IS07	<0.1	<0.1
	IS08	<0.1	<0.1
Site 6	IS09	<0.1	<0.1
Site 7	IS10	<0.1	<0.1
Site 8	IS11	<0.1	<0.1
Site 9	IS17	0.4	0.2

Figure 49. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 2002 for each parameter set.

9.4.4 2004

P1

		Cod	Haddock
Site 1	IS01	<0.1	<0.1
Site 2	IS02	<0.1	<0.1
	IS03	<0.1	<0.1
Site 3	IS04	<0.1	<0.1
	IS05	<0.1	<0.1
	IS12	<0.1	<0.1
	IS13	<0.1	<0.1
Site 4	IS16	<0.1	<0.1
Site 5	IS07	<0.1	<0.1
	IS08	<0.1	<0.1
Site 6	IS09	<0.1	<0.1
Site 7	IS10	<0.1	<0.1
Site 8	IS11	<0.1	<0.1
Site 9	IS17	<0.1	<0.1

P2

		Cod	Haddock
Site 1	IS01	<0.1	<0.1
Site 2	IS02	<0.1	<0.1
	IS03	<0.1	<0.1
Site 3	IS04	<0.1	<0.1
	IS05	<0.1	<0.1
	IS12	<0.1	<0.1
	IS13	<0.1	<0.1
Site 4	IS16	<0.1	<0.1
Site 5	IS07	<0.1	<0.1
	IS08	<0.1	<0.1
Site 6	IS09	<0.1	<0.1
Site 7	IS10	<0.1	<0.1
Site 8	IS11	<0.1	<0.1
Site 9	IS17	<0.1	<0.1

P3

		Cod	Haddock
Site 1	IS01	<0.1	<0.1
Site 2	IS02	<0.1	<0.1
	IS03	<0.1	<0.1
Site 3	IS04	<0.1	<0.1
	IS05	<0.1	<0.1
	IS12	<0.1	<0.1
	IS13	<0.1	<0.1
Site 4	IS16	<0.1	<0.1
Site 5	IS07	<0.1	<0.1
	IS08	<0.1	<0.1
Site 6	IS09	<0.1	<0.1
Site 7	IS10	<0.1	<0.1
Site 8	IS11	<0.1	<0.1
Site 9	IS17	<0.1	<0.1

P4

		Cod	Haddock
Site 1	IS01	<0.1	<0.1
Site 2	IS02	<0.1	<0.1
	IS03	<0.1	<0.1
Site 3	IS04	0.6	0.2
	IS05	0.2	0.1
	IS12	0.2	0.1
	IS13	0.4	0.2
Site 4	IS16	0.3	<0.1
Site 5	IS07	<0.1	<0.1
	IS08	0.3	<0.1
Site 6	IS09	<0.1	<0.1
Site 7	IS10	<0.1	<0.1
Site 8	IS11	<0.1	<0.1
Site 9	IS17	0.4	0.2

Figure 50. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 2004 for each parameter set.

9.4.5 2005

Site	Release	P1 Cod	P1 Haddock	P2 Cod	P2 Haddock	P3 Cod	P3 Haddock	P4 Cod	P4 Haddock
Site 1	IS01	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 2	IS02	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS03	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 3	IS04	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS12	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS13	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 4	IS16	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 5	IS07	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS08	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 6	IS09	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 7	IS10	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 8	IS11	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 9	IS17	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	0.4	1.8

Figure 51. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 2005 for each parameter set.

9.4.6 2011

Site	Release	P1 Cod	P1 Haddock	P2 Cod	P2 Haddock	P3 Cod	P3 Haddock	P4 Cod	P4 Haddock
Site 1	IS01	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 2	IS02	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS03	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 3	IS04	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS12	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS13	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 4	IS16	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 5	IS07	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	IS08	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 6	IS09	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 7	IS10	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 8	IS11	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Site 9	IS17	<0.1	<0.1	<0.1	<0.1	0.1	0.2	0.4	1.1

Figure 52. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 2011 for each parameter set.

9.5 Summary- simulations nominated by industry partners

For parameter set P1 and P2, the maximum ELS mortality modelled was less than 0.1 % for all years and locations.

Results for parameter sets P3 and P4, maximum modelled ELS mortalities are presented in Figure 76.

For parameter set P3, the highest modelled mortalities for NEA Cod were observed in 2016, for NEA Haddock in 2011 and NEA Saithe in 2016. all for simulation IS17. For NSS Herring highest modelled mortality was observed in 1995, in simulations IS05 and IS12. For BS Capelin, all results were less than 0.1 %.

For parameter set P4, the highest modelled mortality for NEA Cod was in 2016, for NEA Haddock in 2011, both for simulation IS17. For NEA Saithe, 2002 exhibited the highest modelled mortality, for simulation IS12. For BS Capelin, highest modelled ELS mortalities were in 1999, for simulation IS17, and for NSS Herring, simulation IS12 in 2002.

Simulation IS12 in 2002 with parameter set P4 modelled ELS mortalities of 1.6 % of NEA Cod, 0.7 % of NEA Haddock, 8.3 % of NEA Saithe, 13.7 % of NSS Herring and <0.1% of BS Capelin.

It should be noted that SYMBIOSES III does not address cumulative effects in terms of interactions between ELS of different species.

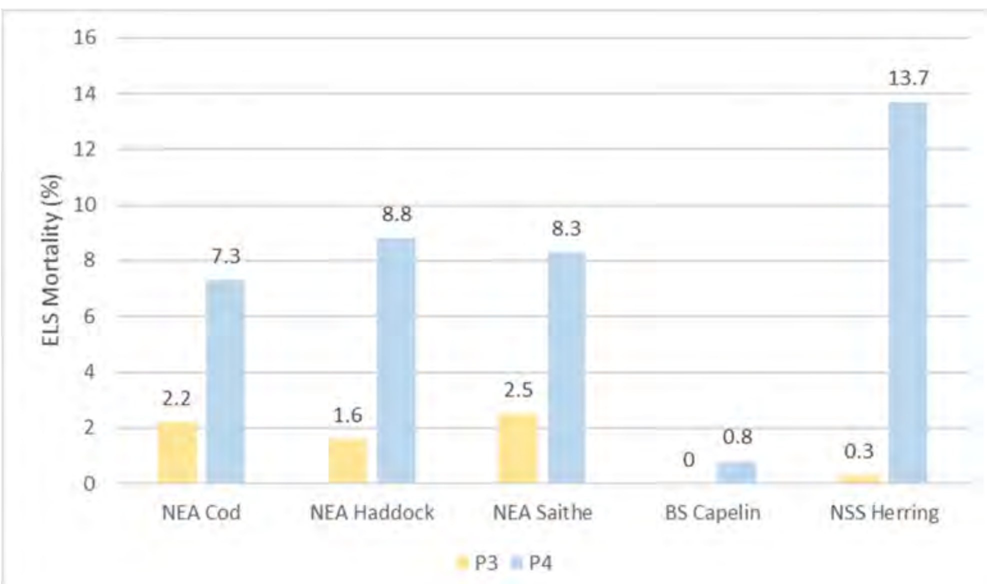


Figure 53. Maximum ELS mortality modelled across all simulations, sites and years for parameter sets 3 and 4.

10. Simulations nominated by research team partners (Set # 2)

In addition to the significant work on sensitivity testing and assessment, the research team focused on the sites used in SYMBIOSES II, SyEx project, with a new set of simulations including the new species. Release characteristics were kept constant, allowing comparisons with previous model runs and publications. Locations of the release sites are shown in Figure 54.

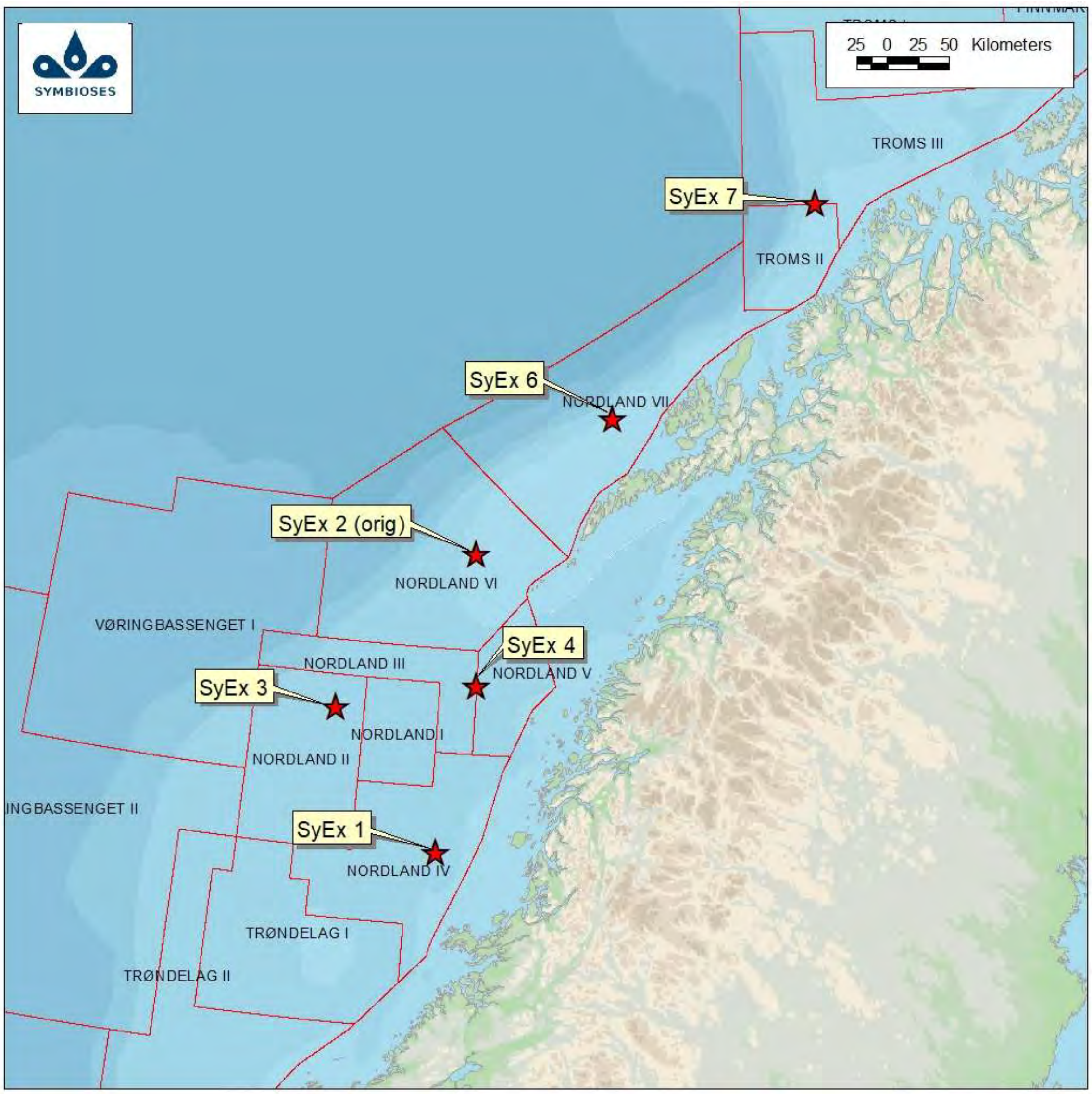


Figure 54. Map showing the sites of simulations nominated by industry partners.

Simulations nominated by research team partners (Set # 2)

10.1 Simulation matrix

For all sites, and all years listed in section 8.5, simulations were run according to the simulation matrix presented in Table 12.-

Table 12. Simulation matrix - simulations nominated by industry partners.

Release site	Simulation	Release depth	GOR	Oil type	Release rate (m3/day)	Release duration (days)
SyEx1	L01	top	-	Balder blend	4500	45
SyEx1	L06	subsea	100	Balder blend	4500	45
SyEx3	L02	top	-	Balder blend	4500	45
SyEx3	L07	subsea	100	Balder blend	4500	45
SyEx4	L03	top	-	Balder blend	4500	45
SyEx4	L08	subsea	100	Balder blend	4500	45
SyEx6	L04	top	-	Balder blend	4500	45
SyEx6	L09	subsea	100	Balder blend	4500	45
SyEx7	L05	top	-	Balder blend	4500	45
SyEx7	L10	subsea	100	Balder blend	4500	45

10.2 ELS mortalities by release sites

In the following subsections, results from simulations in terms of mortality (%) from exposure to oil are presented.

10.2.1 Syex 1

10.2.1.1 Simulation L01

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	0.2	<0.1	0.1	
2002	<0.1	<0.1	<0.1	<0.1	
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	0.3	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	3.1	<0.1	2.9	3.6
1999	<0.1	3.8	<0.1	3.1	
2002	<0.1	2.6	<0.1	3.4	
2004	<0.1	4.9	<0.1	5.2	
2005	<0.1	2.3	<0.1	3.3	
2011	<0.1	3.6	<0.1	2.3	
2016	<0.1	3.3	0.1	4.7	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	7.4	2.4	7.0	8.1
1999	<0.1	9.4	7.6	6.3	
2002	<0.1	7.7	6.3	8.6	
2004	<0.1	9.5	6.4	9.3	
2005	<0.1	7.1	3.2	6.8	
2011	<0.1	9.6	3.8	6.1	
2016	<0.1	7.6	3.0	8.3	

Figure 55. ELS mortalities from oil exposure - location SyEx 1 – simulation L01. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

Simulations nominated by research team partners (Set # 2)

10.2.1.2 Simulation L06

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	0.1	0.2
1999	<0.1	0.3	<0.1	0.2	0.5
2002	<0.1	<0.1	<0.1	<0.1	0.1
2004	<0.1	0.2	<0.1	0.3	0.4
2005	<0.1	<0.1	<0.1	0.1	0.3
2011	<0.1	0.2	<0.1	0.1	0.2
2016	<0.1	0.3	<0.1	0.4	0.7

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	2.9	<0.1	3.1	3.8
1999	<0.1	4.0	<0.1	2.7	5.1
2002	<0.1	2.1	<0.1	1.4	2.7
2004	<0.1	2.4	<0.1	3.5	4.5
2005	<0.1	2.0	<0.1	2.4	3.8
2011	<0.1	2.5	<0.1	1.5	3.1
2016	<0.1	2.8	<0.1	3.5	5.3

	Capelin	Cod	Haddock	Herring	Saithe
1995	0.2	10.7	12.4	9.8	15.1
1999	<0.1	10.9	15.1	9.1	15.0
2002	<0.1	10.1	12.2	11.5	13.2
2004	<0.1	8.7	9.8	10.0	11.3
2005	<0.1	9.9	10.3	8.5	15.1
2011	<0.1	8.8	5.9	6.0	12.6
2016	<0.1	8.7	4.6	8.6	13.2

Figure 56. ELS mortalities from oil exposure - location SyEx 1 – simulation L06. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

10.2.2 SyEx 3

10.2.2.1 Simulation L02

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.2	<0.1	0.1	0.4
1999	<0.1	0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	0.8	<0.1	0.4	
2011	<0.1	0.3	<0.1	<0.1	
2016	<0.1	0.3	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.9	0.3	0.8	1.6
1999	<0.1	0.8	0.2	0.3	
2002	<0.1	0.2	<0.1	0.6	
2004	<0.1	0.3	<0.1	0.6	
2005	<0.1	2.4	0.4	1.7	
2011	<0.1	1.5	<0.1	0.8	
2016	<0.1	1.3	<0.1	0.8	

Figure 57. ELS mortalities from oil exposure - location SyEx 3 – simulation L02. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

10.2.2.2 Simulation L07

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.1	<0.1	<0.1	0.3
1999	<0.1	0.1	<0.1	<0.1	0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	0.5	<0.1	0.3	0.5
2011	<0.1	0.2	<0.1	<0.1	0.6
2016	<0.1	<0.1	<0.1	<0.1	<0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	1.8	2.9	2.0	3.4
1999	<0.1	1.7	1.5	0.6	1.7
2002	<0.1	0.7	0.2	1.0	2.1
2004	<0.1	0.2	<0.1	0.3	0.6
2005	<0.1	2.5	0.6	2.1	3.4
2011	<0.1	1.7	0.7	0.7	2.5
2016	<0.1	1.6	<0.1	0.7	1.8

Figure 58. ELS mortalities from oil exposure - location SyEx 3 – simulation L07. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

10.2.3 SyEx 4

10.2.3.1 Simulation L03

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	0.2	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.6	0.4	1.0	1.2
1999	<0.1	0.3	<0.1	0.2	
2002	<0.1	0.5	0.1	0.6	
2004	<0.1	1.0	0.3	1.2	
2005	<0.1	0.9	0.1	0.2	
2011	<0.1	0.9	0.1	0.4	
2016	<0.1	2.3	<0.1	1.7	

	Capelin	Cod	Haddock	Herring	Saithe
1995	0.6	8.1	21.2	14.4	15.6
1999	<0.1	3.0	7.2	2.2	
2002	<0.1	4.1	10.6	7.7	
2004	<0.1	5.2	15.5	7.0	
2005	<0.1	7.3	11.3	5.4	
2011	<0.1	6.3	13.9	8.0	
2016	<0.1	5.6	6.6	6.2	

Figure 59. ELS mortalities from oil exposure - location SyEx 4 – simulation L03. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

10.2.3.2 Simulation L08

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	0.2	<0.1	<0.1	0.2

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.4	0.2	0.5	0.9
1999	<0.1	0.1	<0.1	0.1	0.2
2002	<0.1	0.3	0.1	<0.1	0.1
2004	<0.1	0.2	<0.1	0.1	0.5
2005	<0.1	0.2	<0.1	<0.1	0.3
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	1.4	0.1	0.9	1.4

	Capelin	Cod	Haddock	Herring	Saithe
1995	0.8	10.6	25.3	17.3	21.7
1999	<0.1	3.2	6.8	2.1	4.1
2002	0.1	6.8	16.1	10.0	13.5
2004	<0.1	5.0	16.2	7.2	11.7
2005	0.2	9.5	15.7	6.6	15.5
2011	0.1	5.1	15.0	4.8	10.0
2016	0.1	8.5	10.4	8.2	14.4

Figure 60. ELS mortalities from oil exposure - location SyEx 4 – simulation L08. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

10.2.4 SyEx 6

10.2.4.1 Simulation L04

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.4	0.3	0.8	0.6
1999	<0.1	0.4	0.3	0.7	
2002	<0.1	0.5	0.4	1.0	
2004	<0.1	0.3	<0.1	0.6	
2005	<0.1	1.0	0.5	1.0	
2011	<0.1	0.5	0.2	0.6	
2016	<0.1	0.9	0.6	1.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	1.1	17.8	16.6	22.6	28.7
1999	0.9	20.8	15.1	23.0	
2002	2.1	18.3	16.4	23.0	
2004	2.8	14.2	11.8	20.1	
2005	1.1	20.7	18.5	22.8	
2011	1.7	15.7	18.3	21.5	
2016	0.9	13.7	16.8	23.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	5.6	45.4	36.3	34.0	48.8
1999	5.5	48.8	42.6	37.7	
2002	6.2	34.0	36.2	28.7	
2004	6.5	33.9	34.2	28.5	
2005	5.9	45.9	45.4	32.6	
2011	6.0	42.8	44.8	36.6	
2016	6.5	38.9	43.5	30.6	

Figure 61. ELS mortalities from oil exposure - location SyEx 6 – simulation L04. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

10.2.4.2 Simulation L09

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	1.0	0.7	1.2	1.2
1999	<0.1	0.9	0.6	1.0	1.2
2002	<0.1	0.8	0.6	1.2	1.5
2004	<0.1	0.8	0.3	0.9	1.6
2005	<0.1	1.5	0.8	1.6	2.2
2011	<0.1	0.6	0.4	0.8	1.1
2016	<0.1	1.4	0.8	1.6	2.4

	Capelin	Cod	Haddock	Herring	Saithe
1995	1.6	14.0	15.4	20.2	26.1
1999	1.4	24.7	16.6	22.3	31.6
2002	2.3	19.0	18.4	22.4	32.2
2004	2.1	17.4	15.1	21.3	29.6
2005	1.4	24.2	19.1	22.9	33.0
2011	1.9	18.5	20.0	22.0	34.4
2016	1.4	16.7	17.4	24.1	30.6

	Capelin	Cod	Haddock	Herring	Saithe
1995	6.2	43.2	36.4	31.9	47.8
1999	5.7	51.7	51.0	37.0	55.6
2002	6.2	34.8	41.5	27.5	47.8
2004	7.3	36.0	42.7	26.8	47.0
2005	5.7	45.5	49.6	31.3	50.5
2011	7.4	45.6	50.7	35.7	52.8
2016	7.0	40.0	47.4	29.5	49.7

Figure 62. ELS mortalities from oil exposure - location SyEx 6 – simulation L09. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

10.2.5 SyEx 7

10.2.5.1 Simulation L05

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	
2002	<0.1	<0.1	<0.1	<0.1	
2004	<0.1	<0.1	<0.1	<0.1	
2005	<0.1	<0.1	<0.1	<0.1	
2011	<0.1	<0.1	<0.1	<0.1	
2016	<0.1	<0.1	<0.1	<0.1	

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.2	0.7	<0.1	0.3
1999	<0.1	0.8	0.8	0.4	
2002	<0.1	0.4	0.9	0.2	
2004	<0.1	2.1	0.9	0.4	
2005	<0.1	1.1	0.8	0.3	
2011	<0.1	0.5	0.7	<0.1	
2016	<0.1	0.5	0.6	0.6	

	Capelin	Cod	Haddock	Herring	Saithe
1995	0.4	9.6	10.8	1.1	7.2
1999	0.1	12.0	13.4	4.4	
2002	1.7	11.4	12.1	2.3	
2004	0.4	17.3	12.4	5.6	
2005	0.4	13.8	13.5	4.2	
2011	0.3	9.3	14.2	2.2	
2016	0.6	13.5	15.8	7.2	

	Capelin	Cod	Haddock	Herring	Saithe
1995	13.6	20.4	28.2	5.8	18.3
1999	5.5	24.7	36.6	10.9	
2002	17.8	21.9	26.1	5.1	
2004	10.4	26.3	30.9	11.1	
2005	8.3	26.7	32.0	10.9	
2011	14.5	20.1	32.8	6.4	
2016	8.6	26.2	40.7	13.0	

Figure 63. ELS mortalities from oil exposure - location SyEx 7– simulation L05. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

10.2.5.2 Simulation L10

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	<0.1	0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	0.2	0.9	<0.1	0.4
1999	<0.1	0.8	1.1	0.7	1.2
2002	<0.1	0.3	1.2	0.1	0.9
2004	<0.1	1.0	1.5	0.6	2.0
2005	<0.1	1.1	1.5	0.6	1.7
2011	<0.1	0.2	1.0	0.2	0.8
2016	<0.1	0.7	1.0	0.9	1.3

	Capelin	Cod	Haddock	Herring	Saithe
1995	<0.1	4.9	7.5	0.6	3.4
1999	0.2	9.0	11.5	3.6	9.9
2002	0.4	9.4	12.4	1.8	11.9
2004	0.2	10.6	14.3	4.7	13.7
2005	0.2	9.6	12.1	3.8	11.6
2011	0.3	7.0	12.9	1.7	10.5
2016	0.5	9.4	12.9	6.0	14.1

	Capelin	Cod	Haddock	Herring	Saithe
1995	11.0	19.5	28.7	5.8	17.2
1999	6.2	24.4	39.7	11.6	28.2
2002	17.3	26.9	31.9	5.4	28.2
2004	10.2	23.3	39.2	9.8	31.3
2005	8.3	27.7	35.7	11.4	31.0
2011	14.3	20.6	36.5	6.6	27.6
2016	10.0	27.5	43.9	13.5	36.2

Figure 64. ELS mortalities from oil exposure - location SyEx 7 – simulation L10. Top left: Parameter set P1, top right: Parameter set P2, Bottom left: Parameter set P3, Bottom right: Parameter set P4.

10.3 ELS mortalities by species

10.3.1 NEA Cod

P1:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P2:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	<0.1	0.4	0.2	<0.1	<0.1	<0.1	1.0	0.2
1999	0.2	<0.1	<0.1	0.4	0.8	0.3	<0.1	<0.1	0.9	0.8
2002	<0.1	<0.1	<0.1	0.5	0.4	<0.1	<0.1	<0.1	0.8	0.3
2004	<0.1	<0.1	<0.1	0.3	2.1	0.2	<0.1	<0.1	0.8	1.0
2005	<0.1	<0.1	<0.1	1.0	1.1	<0.1	<0.1	<0.1	1.5	1.1
2011	<0.1	<0.1	<0.1	0.5	0.5	0.2	<0.1	<0.1	0.6	0.2
2016	<0.1	<0.1	0.2	0.9	0.5	0.3	<0.1	0.2	1.4	0.7

P3:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	3.1	0.2	0.6	17.8	9.6	2.9	0.1	0.4	14.0	4.9
1999	3.8	0.1	0.3	20.8	12.0	4.0	0.1	0.1	24.7	9.0
2002	2.6	<0.1	0.5	18.3	11.4	2.1	<0.1	0.3	19.0	9.4
2004	4.9	<0.1	1.0	14.2	17.3	2.4	<0.1	0.2	17.4	10.6
2005	2.3	0.8	0.9	20.7	13.8	2.0	0.5	0.2	24.2	9.6
2011	3.6	0.3	0.9	15.7	9.3	2.5	0.2	<0.1	18.5	7.0
2016	3.3	0.3	2.3	13.7	13.5	2.8	<0.1	1.4	16.7	9.4

P4:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	7.4	0.9	8.1	45.4	20.4	10.7	1.8	10.6	43.2	19.5
1999	9.4	0.8	3.0	48.8	24.7	10.9	1.7	3.2	51.7	24.4
2002	7.7	0.2	4.1	34.0	21.9	10.1	0.7	6.8	34.8	26.9
2004	9.5	0.3	5.2	33.9	26.3	8.7	0.2	5.0	36.0	23.3
2005	7.1	2.4	7.3	45.9	26.7	9.9	2.5	9.5	45.5	27.7
2011	9.6	1.5	6.3	42.8	20.1	8.8	1.7	5.1	45.6	20.6
2016	7.6	1.3	5.6	38.9	26.2	8.7	1.6	8.5	40.0	27.5

Figure 65. ELS mortalities from oil exposure by release location and year for NEA Cod. From top to bottom_ Parameter set P1, P2, P3, and P4.

Simulations nominated by research team partners (Set # 2)

10.3.2 NEA Haddock

P1:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P2:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	<0.1	0.3	0.7	<0.1	<0.1	<0.1	0.7	0.9
1999	<0.1	<0.1	<0.1	0.3	0.8	<0.1	<0.1	<0.1	0.6	1.1
2002	<0.1	<0.1	<0.1	0.4	0.9	<0.1	<0.1	<0.1	0.6	1.2
2004	<0.1	<0.1	<0.1	<0.1	0.9	<0.1	<0.1	<0.1	0.3	1.5
2005	<0.1	<0.1	<0.1	0.5	0.8	<0.1	<0.1	<0.1	0.8	1.5
2011	<0.1	<0.1	<0.1	0.2	0.7	<0.1	<0.1	<0.1	0.4	1.0
2016	<0.1	<0.1	<0.1	0.6	0.6	<0.1	<0.1	<0.1	0.8	1.0

P3:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	0.4	16.6	10.8	<0.1	<0.1	0.2	15.4	7.5
1999	<0.1	<0.1	<0.1	15.1	13.4	<0.1	<0.1	<0.1	16.6	11.5
2002	<0.1	<0.1	0.1	16.4	12.1	<0.1	<0.1	0.1	18.4	12.4
2004	<0.1	<0.1	0.3	11.8	12.4	<0.1	<0.1	<0.1	15.1	14.3
2005	<0.1	<0.1	0.1	18.5	13.5	<0.1	<0.1	<0.1	19.1	12.1
2011	<0.1	<0.1	0.1	18.3	14.2	<0.1	<0.1	<0.1	20.0	12.9
2016	0.1	<0.1	<0.1	16.8	15.8	<0.1	<0.1	0.1	17.4	12.9

P4:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	2.4	0.3	21.2	36.3	28.2	12.4	2.9	25.3	36.4	28.7
1999	7.6	0.2	7.2	42.6	36.6	15.1	1.5	6.8	51.0	39.7
2002	6.3	<0.1	10.6	36.2	26.1	12.2	0.2	16.1	41.5	31.9
2004	6.4	<0.1	15.5	34.2	30.9	9.8	<0.1	16.2	42.7	39.2
2005	3.2	0.4	11.3	45.4	32.0	10.3	0.6	15.7	49.6	35.7
2011	3.8	<0.1	13.9	44.8	32.8	5.9	0.7	15.0	50.7	36.5
2016	3.0	<0.1	6.6	43.5	40.7	4.6	<0.1	10.4	47.4	43.9

Figure 66. ELS mortalities from oil exposure by release location and year for NEA Haddock. From top to bottom_ Parameter set P1, P2, P3, and P4.

10.3.3 NEA Saithe

P1:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999						<0.1	<0.1	<0.1	<0.1	<0.1
2002						<0.1	<0.1	<0.1	<0.1	<0.1
2004						<0.1	<0.1	<0.1	<0.1	<0.1
2005						<0.1	<0.1	<0.1	0.1	0.1
2011						<0.1	<0.1	<0.1	<0.1	<0.1
2016						<0.1	<0.1	<0.1	0.1	<0.1

P2:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	<0.1	0.6	0.3	0.2	<0.1	<0.1	1.2	0.4
1999						0.5	<0.1	<0.1	1.2	1.2
2002						0.1	<0.1	<0.1	1.5	0.9
2004						0.4	<0.1	<0.1	1.6	2.0
2005						0.3	<0.1	<0.1	2.2	1.7
2011						0.2	<0.1	<0.1	1.1	0.8
2016						0.7	<0.1	0.2	2.4	1.3

P3:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	3.6	0.4	1.2	28.7	7.2	3.8	0.3	0.9	26.1	3.4
1999						5.1	0.1	0.2	31.6	9.9
2002						2.7	<0.1	0.1	32.2	11.9
2004						4.5	<0.1	0.5	29.6	13.7
2005						3.8	0.5	0.3	33.0	11.6
2011						3.1	0.6	<0.1	34.4	10.5
2016						5.3	<0.1	1.4	30.6	14.1

P4:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	8.1	1.6	15.6	48.8	18.3	15.1	3.4	21.7	47.8	17.2
1999						15.0	1.7	4.1	55.6	28.2
2002						13.2	2.1	13.5	47.8	28.2
2004						11.3	0.6	11.7	47.0	31.3
2005						15.1	3.4	15.5	50.5	31.0
2011						12.6	2.5	10.0	52.8	27.6
2016						13.2	1.8	14.4	49.7	36.2

Figure 67. ELS mortalities from oil exposure by release location and year for NEA Saithe. From top to bottom_ Parameter set P1, P2, P3, and P4.

10.3.4 BS Capelin

P1:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P2:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P3:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	<0.1	1.1	0.4	<0.1	<0.1	<0.1	1.6	<0.1
1999	<0.1	<0.1	<0.1	0.9	0.1	<0.1	<0.1	<0.1	1.4	0.2
2002	<0.1	<0.1	<0.1	2.1	1.7	<0.1	<0.1	<0.1	2.3	0.4
2004	<0.1	<0.1	<0.1	2.8	0.4	<0.1	<0.1	<0.1	2.1	0.2
2005	<0.1	<0.1	<0.1	1.1	0.4	<0.1	<0.1	<0.1	1.4	0.2
2011	<0.1	<0.1	<0.1	1.7	0.3	<0.1	<0.1	<0.1	1.9	0.3
2016	<0.1	<0.1	<0.1	0.9	0.6	<0.1	<0.1	<0.1	1.4	0.5

P4:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	0.6	5.6	13.6	0.2	<0.1	0.8	6.2	11.0
1999	<0.1	<0.1	<0.1	5.5	5.5	<0.1	<0.1	<0.1	5.7	6.2
2002	<0.1	<0.1	<0.1	6.2	17.8	<0.1	<0.1	0.1	6.2	17.3
2004	<0.1	<0.1	<0.1	6.5	10.4	<0.1	<0.1	<0.1	7.3	10.2
2005	<0.1	<0.1	<0.1	5.9	8.3	<0.1	<0.1	0.2	5.7	8.3
2011	<0.1	<0.1	<0.1	6.0	14.5	<0.1	<0.1	0.1	7.4	14.3
2016	<0.1	<0.1	<0.1	6.5	8.6	<0.1	<0.1	0.1	7.0	10.0

Figure 68. ELS mortalities from oil exposure by release location and year for BS Capelin. From top to bottom: Parameter set P1, P2, P3, and P4.

10.3.5 NSS Herring

P1:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1999	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2002	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2004	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2011	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2016	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

P2:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	<0.1	<0.1	<0.1	0.8	<0.1	0.1	<0.1	<0.1	1.2	<0.1
1999	0.1	<0.1	<0.1	0.7	0.4	0.2	<0.1	<0.1	1.0	0.7
2002	<0.1	<0.1	<0.1	1.0	0.2	<0.1	<0.1	<0.1	1.2	0.1
2004	<0.1	<0.1	<0.1	0.6	0.4	0.3	<0.1	<0.1	0.9	0.6
2005	<0.1	<0.1	<0.1	1.0	0.3	0.1	<0.1	<0.1	1.6	0.6
2011	<0.1	<0.1	<0.1	0.6	<0.1	0.1	<0.1	<0.1	0.8	0.2
2016	0.3	<0.1	<0.1	1.1	0.6	0.4	<0.1	<0.1	1.6	0.9

P3:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	2.9	0.1	1.0	22.6	1.1	3.1	<0.1	0.5	20.2	0.6
1999	3.1	<0.1	0.2	23.0	4.4	2.7	<0.1	0.1	22.3	3.6
2002	3.4	<0.1	0.6	23.0	2.3	1.4	<0.1	<0.1	22.4	1.8
2004	5.2	<0.1	1.2	20.1	5.6	3.5	<0.1	0.1	21.3	4.7
2005	3.3	0.4	0.2	22.8	4.2	2.4	0.3	<0.1	22.9	3.8
2011	2.3	<0.1	0.4	21.5	2.2	1.5	<0.1	<0.1	22.0	1.7
2016	4.7	<0.1	1.7	23.1	7.2	3.5	<0.1	0.9	24.1	6.0

P4:

	L01	L02	L03	L04	L05	L06	L07	L08	L09	L10
1995	7.0	0.8	14.4	34.0	5.8	9.8	2.0	17.3	31.9	5.8
1999	6.3	0.3	2.2	37.7	10.9	9.1	0.6	2.1	37.0	11.6
2002	8.6	0.6	7.7	28.7	5.1	11.5	1.0	10.0	27.5	5.4
2004	9.3	0.6	7.0	28.5	11.1	10.0	0.3	7.2	26.8	9.8
2005	6.8	1.7	5.4	32.6	10.9	8.5	2.1	6.6	31.3	11.4
2011	6.1	0.8	8.0	36.6	6.4	6.0	0.7	4.8	35.7	6.6
2016	8.3	0.8	6.2	30.6	13.0	8.6	0.7	8.2	29.5	13.5

Figure 69. ELS mortalities from oil exposure by release location and year for NSS Herring. From top to bottom: Parameter set P1, P2, P3, and P4.

10.4 Spawning Stock Biomass reduction by year (SSB)

10.4.1 1995

		P1 Cod	P1 Haddock	P2 Cod	P2 Haddock	P3 Cod	P3 Haddock	P4 Cod	P4 Haddock
SyEx1	L01	<0.1	<0.1	<0.1	<0.1	1.2	<0.1	3.0	0.2
	L06	<0.1	<0.1	<0.1	<0.1	1.1	<0.1	4.2	0.9
SyEx3	L02	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.4	<0.1
	L07	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.7	0.2
SyEx4	L03	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	3.2	1.5
	L08	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	4.2	1.8
SyEx6	L04	<0.1	<0.1	0.2	<0.1	7.1	1.2	18.1	2.6
	L09	<0.1	<0.1	0.4	<0.1	5.6	1.1	17.2	2.6
SyEx7	L05	<0.1	<0.1	<0.1	<0.1	3.8	0.8	8.1	2.0
	L10	<0.1	<0.1	<0.1	<0.1	1.9	0.5	7.7	2.0

Figure 70. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 1995, for each parameter set.

10.4.2 1999

		P1 Cod	P1 Haddock	P2 Cod	P2 Haddock	P3 Cod	P3 Haddock	P4 Cod	P4 Haddock
SyEx1	L01	<0.1	<0.1	<0.1	<0.1	0.7	<0.1	1.8	1.2
	L06	<0.1	<0.1	<0.1	<0.1	0.8	<0.1	2.1	2.4
SyEx3	L02	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	<0.1
	L07	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	0.2
SyEx4	L03	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.6	1.2
	L08	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.6	1.1
SyEx6	L04	<0.1	<0.1	<0.1	<0.1	4.0	2.4	9.5	6.9
	L09	0.2	<0.1	<0.1	<0.1	4.8	2.7	10.0	8.2
SyEx7	L05	0.2	0.1	<0.1	<0.1	2.3	2.2	4.8	5.9
	L10	0.2	0.2	<0.1	<0.1	1.7	1.9	4.7	6.4

Figure 71. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 1999, for each parameter set.

10.4.3 2002

		P1 Cod	P1 Haddock	P2 Cod	P2 Haddock	P3 Cod	P3 Haddock	P4 Cod	P4 Haddock
SyEx1	L01	<0.1	<0.1	<0.1	<0.1	0.6	<0.1	1.8	0.8
	L06	<0.1	<0.1	<0.1	<0.1	0.5	<0.1	2.4	1.5
SyEx3	L02	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	L07	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	<0.1
SyEx4	L03	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	1.0	1.3
	L08	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.6	2.0
SyEx6	L04	0.1	<0.1	<0.1	<0.1	4.4	2.0	8.1	4.4
	L09	0.2	<0.1	<0.1	<0.1	4.5	2.2	8.3	5.1
SyEx7	L05	0.1	0.1	<0.1	<0.1	2.7	1.5	5.2	3.2
	L10	<0.1	0.1	<0.1	<0.1	2.2	1.5	6.4	3.9

Figure 72. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 2002, for each parameter set.

10.4.4 2004

		P1 Cod	P1 Haddock	P2 Cod	P2 Haddock	P3 Cod	P3 Haddock	P4 Cod	P4 Haddock
SyEx1	L01	<0.1	<0.1	<0.1	<0.1	1.9	<0.1	3.8	1.6
	L06	<0.1	<0.1	<0.1	<0.1	1.0	<0.1	3.4	2.5
SyEx3	L02	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1
	L07	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SyEx4	L03	<0.1	<0.1	<0.1	<0.1	0.4	<0.1	2.1	4.0
	L08	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	2.0	4.1
SyEx6	L04	<0.1	<0.1	0.1	<0.1	5.6	3.0	13.5	8.8
	L09	<0.1	<0.1	0.3	<0.1	6.9	3.9	14.3	10.9
SyEx7	L05	<0.1	<0.1	0.8	0.2	6.8	3.2	10.4	7.9
	L10	<0.1	<0.1	0.4	0.4	4.2	3.7	9.3	10.0

Figure 73. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 2004, for each parameter set.

10.4.5 2005

		P1		P2		P3		P4	
		Cod	Haddock	Cod	Haddock	Cod	Haddock	Cod	Haddock
SyEx1	L01	<0.1	<0.1	<0.1	<0.1	0.6	<0.1	2.0	1.2
	L06	<0.1	<0.1	<0.1	<0.1	0.5	<0.1	2.7	3.8
SyEx3	L02	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	0.7	0.1
	L07	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	0.7	0.2
SyEx4	L03	<0.1	<0.1	<0.1	<0.1	0.3	<0.1	2.0	4.1
	L08	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	2.6	5.8
SyEx6	L04	<0.1	<0.1	0.3	0.2	5.7	6.8	12.7	16.6
	L09	<0.1	<0.1	0.4	0.3	6.7	7.0	12.6	18.1
SyEx7	L05	<0.1	<0.1	0.3	0.3	3.8	4.9	7.4	11.7
	L10	<0.1	<0.1	0.3	0.6	2.6	4.4	7.7	15.1

Figure 74. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 2005, for each parameter set.

10.4.6 2011

		P1		P2		P3		P4	
		Cod	Haddock	Cod	Haddock	Cod	Haddock	Cod	Haddock
SyEx1	L01	<0.1	<0.1	<0.1	<0.1	0.9	<0.1	2.3	0.5
	L06	<0.1	<0.1	<0.1	<0.1	0.6	<0.1	2.1	0.7
SyEx3	L02	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.4	<0.1
	L07	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.4	<0.1
SyEx4	L03	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	1.5	1.7
	L08	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.2	1.9
SyEx6	L04	<0.1	<0.1	0.1	<0.1	3.7	2.3	10.2	5.5
	L09	<0.1	<0.1	0.2	<0.1	4.4	2.5	10.9	6.3
SyEx7	L05	<0.1	<0.1	0.1	<0.1	2.2	1.8	4.8	4.0
	L10	<0.1	<0.1	<0.1	0.1	1.7	1.6	4.9	4.5

Figure 75. Spawning Stock Biomass Reduction (%) as a result of ELS mortalities from exposure to oil from releases in year 2011, for each parameter set.

10.5 Summary – simulations nominated by Research Team

For parameter set P1, the maximum ELS mortality modelled was less than 0.1 % for all years and locations for all species. For parameter set P2, the maximum ELS mortality modelled was 2,4 % for NEA Saithe, 1,6 % for NSS Herring, 1.5 % for NEA Haddock and 2.1 % for NEA Cod. For BS Capelin, modelled mortality was less than 0.1 %.

Results for parameter sets P3 and P4, maximum modelled ELS mortalities are presented in Figure 76.

For parameter set P3, the highest mortality for NEA Cod was in 1999, NEA Haddock and NEA Saithe had highest mortalities in 2011, BS Capelin exhibited the highest mortalities in 2002 and NSS herring in 2016. Simulation L09 resulted in the highest mortalities for NEA Cod, NEA Haddock, NEA Saithe and NSS Herring, while L04 gave the highest mortalities for BS Capelin.

For parameter set P4, the highest mortality for NEA Cod, NEA Haddock and NEA Saithe was in 1999. For these three populations, simulation L09 resulted in the highest mortalities. For BS Capelin, the highest modelled ELS mortalities were in 2002, for simulation L05, and for NSS Herring simulation L04 in 1999.

Simulation L09 in 1999 with parameter set P4 modelled ELS mortalities of 51.7 % of NEA Cod, 51 % of NEA Haddock, 55.6 % of NEA Saithe, 37 % of NSS Herring and 5.7 % of BS Capelin.

It should be noted that SYMBIOSES III does not address cumulative effects in terms of interactions between ELS of different species.

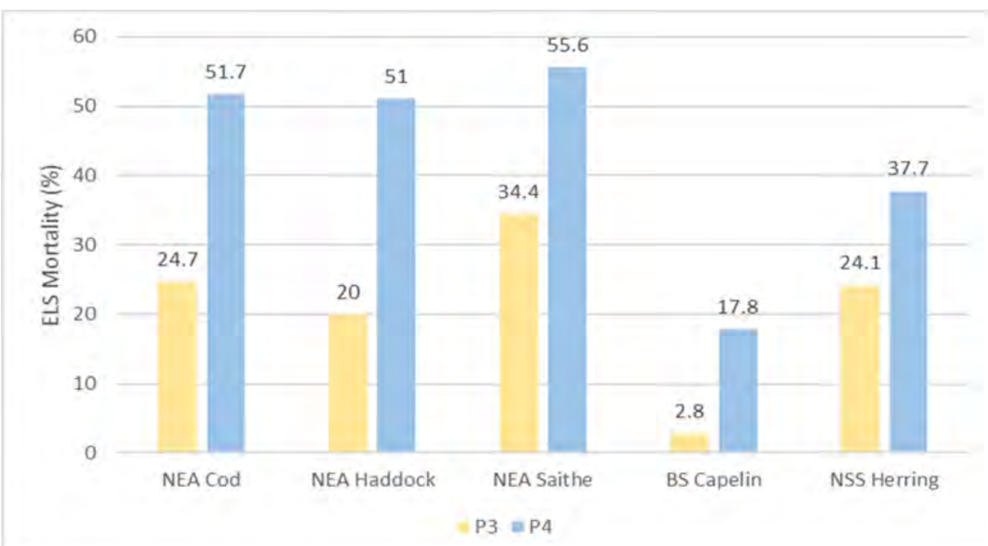


Figure 76. Maximum ELS mortality modelled across all simulations, sites and years for parameter sets 3 and 4.

Subsea releases resulted in higher ELS mortality than surface releases with identical release rate and duration.

In the previous section, the maximum modelled SSB in any year after the oil spill is reported. However, it also relevant to address the cumulative SSB reduction for the years modelled in GADGET since they may be used as an approximation to long term reduction in harvestable resources. An example is provided in Figure 77.

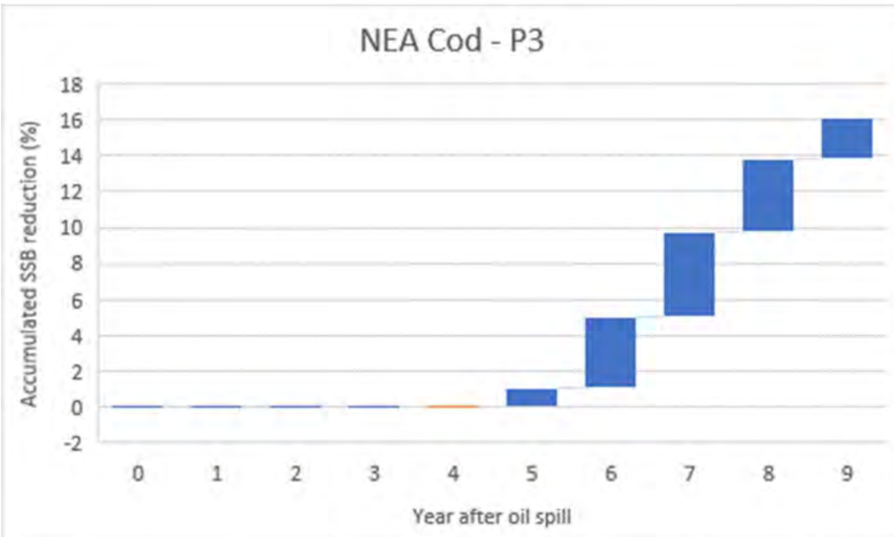


Figure 77 Cumulative SSB reduction in the 10 years after an oil spill from L09 in 1999, using parameter set P3.

To put these results in context, NEA Cod landings these past years have been in the order of 1 billion NOK, so the accumulated loss of harvestable resources (reduced income for fisheries) would be in the order of 160 MNOK. However, as shown in previous phases of SYMBIOSES, reduced fishing intensity in years following an oil spill is a compensatory measure.

11. Final perspectives

11.1 Achievements

SYMBIOSES is an advanced simulation software tool for the marine pelagic environment that delivers holistic impact assessments for fish at a higher level of ecological complexity and realism than has previously been available. The core SYMBIOSES service is simulations coupled to expert support with analysis, interpretation, and reporting of results. SYMBIOSES augments traditional Environmental Risk Assessments for single activities as it provides users with a comprehensive understanding of the potential impacts of multiple activities. Users are given more information to assist in managing their operations in the marine environment. The SYMBIOSES V2.0 simulation tool is designed to evaluate potential impacts from combinations of petroleum and fisheries activities.

SYMBIOSES has contributed to more advanced ecological understanding into environmental management. By successfully creating a population-based approach to impact assessment, this project has moved significantly forward from today's risk analysis models toward the goal of an ecosystem-based model system. Such an approach will further benefit risk analysis tools in use today. However, given the time and resources involved, full SYMBIOSES runs will not replace today's environmental risk assessment analysis performed on regular basis, but will be more relevant related to Impact assessment processes etc. The system is generic but uses available ecosystem and fisheries model components to expedite the development of methodologically similar impact assessment systems for different locations and human activities. The core function of SYMBIOSES is performing single simulations or scenarios, providing clients with analysis, interpretation, and comprehensive reporting of results.

SYMBIOSES also comprises a library of 25+ years of simulation data covering the North, Norwegian and Barents seas. This library contains simulation results on physical (currents, temperature, and salinity), chemical (nutrients) and biological (bacteria, phytoplankton, zooplankton) variables, and provides initial/start conditions for the model system covering the period 1995-2020.

SYMBIOSES v.2.0 includes an improved toxicity module, taking into account contributions from all components of the oil in a mixture approach , and thus follows EU recommendations.

The P1 to P4 parameter values represent a wide range in order to account for uncertainty and the ongoing developments in science on toxic effects of oil. SYMBIOSES is based on the knowledge to date, provides valuable insights, but there is still a lot more science to be done on this topic, including how to distinguish address lethal and sublethal effects. The SYMBIOSES team wishes to examine and explore these issues further in the future and in the manuscripts to be submitted.

Comprehensive sensitivity testing has demonstrated the stability of the model.

Sensitivity testing of the OSCAR module has resulted in recommendations for setup of the oil drift model that more correctly derives concentration fields in the model grid cells. The model has also been expanded to report droplets concentrations and size distributions, available for the LARMOD module.

The SINMOD biology module has been developed to include additional species of zooplankton, to allow improved applications in the northern parts of the Norwegian waters.

The LARMOD module has been developed to a generic format, which are ready for inclusions of additional fish species, it has also been developed to include droplets, and work will continue to further implement this in Q1/Q2 2023.

The GADGET module has been developed for NEA Haddock and BS Capelin, and the existing NEA cod model has been updated and extended. In addition, a prototype NSS Herring model has been developed.

A comprehensive effort has been placed on optimizing the linkages between the individual modules, allowing an improved model speed, and decreased load on CPU resources.

At the end of SYMBIOSES III, SYMBIOSES v. 2.0 are operational for the entire Norwegian Continental Shelf to model ELS mortalities from oil exposure on NEA Cod, NEA Haddock, NEA Saithe, NSS Herring and BS Capelin. Impacts from reduced recruitment (i.e. ELS mortality) can further be modelled for NEA Cod, NEA Haddock, and BS Capelin.

11.2 On-line resources

Information on the SYMBIOSES project is openly available on the links below.

SYMBIOSES website: http://www.symbioses.no/

SYMBIOSES manual: http://symbioses.no/docs/

11.3 Recommendations

Throughout the software development process and testing activities, the consortium identified ways to improve software performance and/or the quality of simulation output. Some items have been identified by members of the consortium and these are synthesized below as a guide for further development of the system.

Refine toxicity parameterizations.

Mortality, and hence forecasted impacts, is determined by the oil toxicity parameters. Hence refinement of these parameter values will lead to improvements in the validity of results. The following actions have been proposed:

- OMEGA-based algorithms, while presently only applied to zooplankton, could also be used to predict the survival and individual growth of fish larvae.
- Validate the predicted effect levels for fish ELS by comparison with available effect data (e.g. LC50, biomarker, etc.) for more chemical compounds, and species (Atlantic cod, Atlantic and Pacific herring).
- Determine the sensitivity to lipid content of zooplankton mortality and hydrocarbon bioaccumulation.
- Refine the DEB-based parameters established for modeling effects of oil to fish life stages by performing dedicated toxicity tests. Today, the SYMBIOSES system includes all 4 parameter values. Designing targeted toxicity tests on SYMBIOSES fish species, considering both ecotoxicological modeling requirement and new ecotoxicological information in exposure set-up will result in a foundation for developing more accurate parameter values for each fish species.
- Perform simulation experiments to determine if there are significant differences between mortality values based on external oil concentrations and those based on body burdens.

Improved resolution and application of autonomous vehicles

Oceanographic conditions in several of the key spawning areas are characterized by current patterns of high spatial and temporal complexity.

As retention times of ELS in water with HC concentrations are key to ELS mortalities, an improved resolution in currents, applying the routines available for integration of ADCP data from ASVs, combined with AUV and ASV measurement of ELS, zooplankton and phytoplankton biomass would provide improved information for these key areas.

AUV can employ intelligent and adaptive sampling strategies, such as following an experimental release (natural or artificial tracers such as fluorescent dyes or hydrocarbons) and mapping both oceanographic and geochemical variables and planktonic life along the way.

New species and improved linkages

SYMBIOSES III currently addresses five populations of fish species. Other populations are also relevant for impact and ecosystem assessments and should be considered on the basis of data status with regards to spawning areas, intensity, population structure and SSB management models. With regards to the SINMOD module, Calanus glacialis is now included, and also further species are relevant in the Arctic areas. As SYMBIOSES is currently designed, the fish species exist independently of each other. In reality there are significant interactions between the species, which would affect how the impact of any oil spill is felt throughout the ecosystem. Adding predation linkages between the fish populations is possible, and is discussed in the ecosystem section, below.

There are also several aspects that may be added to improve the model results, including effects of adsorption of oil by phytoplankton, transfer of BB through Food chain and Adsorption of PAH to particles and sedimentation.

Improve algorithms for fish larvae to juvenile.

Cannibalism influences the density dependent mortality function of fish. Further calibration of this function using field data for young juveniles (< 3 yrs) will improve the predictive capability of the adult fish population model.

Further optimization of the density dependent mortality function for initial recruits will improve the predictive capability of the adult fish population model.

There is potential to examine wider ecosystem effects of an oil spill in a future SYMBIOSES project by taking modelled reductions in 0-group populations as well as subsequent fish stock development and using the NoBar Atlantis ecosystem model developed for the Barents and Norwegian Seas (Hansen *et al.*, 2019). The nature of such ecosystem models is to give less precise information on each component of the ecosystem than models such as the data-tuned GADGET model used in the SYMBIOSES project, but ecosystem model can be used alongside the more precise models to give a wider perception of the overall impacts of any driver (Howell *et al.*, 2021).

Additional environmental and ecosystem compartments

The initial SYMBIOSES system is an open ocean based system. There is a demand for systems that address other environmental compartments, including seafloor sediments, and coastal shoreline areas. The OSCAR module already reports data for other environmental compartments, which may be applied in Net Environmental Benefit Analysis (NEBA).

Additional ecosystem components and ecosystem understanding

Initially, the SYMBIOSES system is designed to assess population impacts to fisheries. Additional ecosystem components of interest that have been identified are seabirds and marine mammals, sensitive seafloor communities as well as shallow water and shoreline communities. There are several ongoing research projects that could easily be integrated in an expanded SYMBIOSES.

Impacts of oil mortalities will have impacts across the whole ecosystem. Reductions in predator biomass (especially cod) will have impacts, but reductions in food supply can be more severe. We do not currently model these inter-species impacts. The two main food sources linking zooplankton and predatory fish in the Barents Sea are capelin and the combined total biomass of all species of 0-group fish (i.e., post larval but not yet juvenile fish, e.g., ICES 2022). An oil impact on capelin will therefore have impacts across the whole ecosystem, especially if the oil spill occurred in a moderate or low capelin year. Large capelin years would need a very large reduction in biomass to have an impact via food supply, since the capelin biomass in these years exceeds the consumption capacity of the predators. However, in low capelin years the predators can eat a significant proportion of the capelin, and in particular in some years almost all mature capelin are consumed during their spawning migration by cod. Any further reduction would therefore have impacts on the food supply for cod, as well as for marine mammals including minke and humpback whales and harp seals (Lindstrøm *et al.*, 2009), and potentially coastal nesting sea birds. 0-group fish are another important food source in the Barents Sea and an oil spill impacting on these would also have an impact on food availability for most fish and mammal species. We do not model the food limitation effect in SYMBIOSES, and it is in any case difficult to parameterize. However, there is clear evidence from the capelin collapse in the 1980s that reductions in food supplies can have severe impacts on the health of the predator fish and marine mammals (Gjøsæter *et al.*, 2009). In future iterations of SYMBIOSES, it would be possible to consider the predation impacts on stock responses by combining the GADGET population models into a full multispecies model (e.g., Lindstrøm *et al.* 2009), and wider ecosystem impacts could potentially be evaluated by taking the results of the SYMBIOSES simulations and importing these into the NoBa Atlantis ecosystem model (Hansen *et al.* 2016)

Other impact factors

In addition to petroleum activities and accidental releases of oil, there is a range of other activities with an environmental footprint that could be addressed in an expanded SYMBIOSES, including, carbon capture and storage (CCS) activities, seafloor mineral extraction, offshore wind farms and aquaculture.

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14. Appendix I - Design concepts

SYMBIOSES was designed based on the following concepts:

1. GENERIC TOOL: The conceptual design of the SYMBIOSES computational Framework may be applied in any open water marine environment. The system requires sub-models and data on the oceanographic features of a particular region.
2. APPLICATIONS & SYSTEM USERS:
    - Performance of integrated impact assessments/ E&P professionals
    - Expert evaluation & testing of environmental scenarios/ E&P environmental advisors/consultants
    - Ecosystem management & planning/ Environmental authorities
    - Marine ecosystem research/ Academic researchers
3. SCENARIOS: The system focuses on predicting the impact of environmental perturbations at the population level for targeted biological components of the marine ecosystem. The system performs analyses of natural system variability and quantifies deviations from the natural system that result from E&P and/or fisheries activities.
4. PREDICTIVE CAPABILITY: The system uses mathematical formulations to describe relevant ecological and ecotoxicological processes. The mathematical formulations implemented in the system were chosen based on the need to achieve a realistic balance between theory and data accessibility. The development team incorporated the latest technical/scientific knowledge into the mathematical algorithms.
5. UNCERTAINTY EVALUATION: Quantitative measures of uncertainty are derived through multiple simulation runs.
6. ACCESSIBILITY & TRANSPARENCY: SYMBIOSES is for scenario testing and evaluation that will support the petroleum industry with documenting and communicating the impact of their development activities on marine ecosystems. Public trust of the results demands that the principles and methods employed in the system are available for evaluation. Furthermore, one of the aims is to make this decision support tool available to a wide variety of system users. Therefore, SYMBIOSES was established based on the principle of accessibility and transparency. This is achieved by documenting the methods and use of SYMBIOSES through publication in the scientific peer-review literature.
7. FLEXIBILITY: The technical field of environmental monitoring is in a period of rapid development with new sensors and data collection systems and routines being developed that will provide new sources of environmental information to support decision-making. SYMBIOSES was developed to allow incorporation of new data streams in the future.

15. Appendix II - System components

15.1 Model interaction and data exchange.

Table presents the explicit data exchanges for the hydrodynamics, zooplankton, fish ELS, oil, and fish models.

From	To	Feature	Unit	Purpose
SINMOD	OSCAR	Water depth	m	Oil movement
		3D ocean velocity	m/s	
		2D wind velocity	m/s	Oil surface movement
		Temperature	°C	Oil chemistry; plume behavior
		Salinity	g/kg	
OSCAR	SINMOD	Oil concentration	ppb	Copepod ecotox
OSCAR	LARMOD	Oil concentration	ppb	Fish ELS ecotox
		Chemical properties of oil	MW, K_{ow}	
SINMOD	LARMOD	Water depth	m	ELS movement
		3D ocean velocity	m/s	
		Mixing coefficients	m^2/s	
		2D Wind Field	m/s	Turbulence used in prey calculations
		Temperature	°C	ELS development and movement
		Salinity	g/kg	ELS position (buoyancy)
		2D Calanus abundance	$\#/m^2$	ELS development (prey for larvae)
		2D Calanus stages	$\#/m^2$	
		Total Calanus biomass	$g[C]/m^2$	
LARMOD	GADGET	Relative reduction of ELS	%	Survival probability

15.2 Toxicity parameter sets (P1, P2, P3, P4)

The four parameter sets (P1-P4) that include assessment factors to lower the concentration for effects on fish early life stages (Table 6). Parameter set P1 was developed by Klok *et al.* (2014). Parameter sets P2, P3, and P4 were developed at the March 5th, 2015 workshop. In parameter sets P3 and P4, the PAH and naphthalene groups were artificially set to induce immediate mortality at concentrations (P3: 1.0 µg/L; P4: 0.1 µg/L).

Identification	$\dot{k}_e$ (/day)				NEC (mmol/L)				$\dot{b}$ (L/mmol/day)			
Naphthalene	5.53				4.40 x10^{-02}				1.00 x10^{+02}			
	P1	**P2**	**P3**	**P4**	**P1**	**P2**	**P3**	**P4**	**P1**	**P2**	**P3**	**P4**
C1-C4 saturates	4.31	4.31	4.31	4.31	8.19x10^{-04}	8.19 x10^{-}	8.19 x10^{-04}	8.19 x10^{-04}	4.11 x10^{+02}	4.11 x10^{+02}	4.11 x10^{+02}	4.11 x10^{+02}
C5-saturates	6.50	6.50	6.50	6.50	1.52x10^{-03}	1.52 x10^{-}	1.52 x10^{-03}	1.52 x10^{-03}	2.53 x10^{+02}	2.53 x10^{+02}	2.53 x10^{+02}	2.53 x10^{+02}
C6-saturates	4.69	4.69	4.69	4.69	9.29 x10^{-04}	9.29 x10^{-}	9.29 x10^{-04}	9.29 x10^{-04}	3.72 x10^{+02}	3.72 x10^{+02}	3.72 x10^{+02}	3.72 x10^{+02}
C7-saturates	1.90	1.90	1.90	1.90	2.39 x10^{-04}	2.39 x10^{-}	2.39 x10^{-04}	2.39 x10^{-04}	1.09 x10^{+03}	1.09 x10^{+03}	1.09 x10^{+03}	1.09 x10^{+03}
C8-saturates	1.70	1.70	1.70	1.70	2.02 x10^{-04}	2.02 x10^{-}	2.02 x10^{-04}	2.02 x10^{-04}	1.24 x10^{+03}	1.24 x10^{+03}	1.24 x10^{+03}	1.24 x10^{+03}
C9-saturates	0.80	0.80	0.80	0.80	6.56 x10^{-05}	6.56 x10^{-}	6.56 x10^{-05}	6.56 x10^{-05}	3.01 x10^{+03}	3.01 x10^{+03}	3.01 x10^{+03}	3.01 x10^{+03}
Benzene	30.3	30.3	30.3	30.3	1.53 x10^{-02}	1.53 x10^{-}	1.53 x10^{-02}	1.53 x10^{-02}	4.09 x10^{+01}	4.09 x10^{+01}	4.09 x10^{+01}	4.09 x10^{+01}
C1-benzenes	13.2	13.2	13.2	13.2	4.41 x10^{-03}	4.41 x10^{-}	4.41 x10^{-03}	4.41 x10^{-03}	1.09 x10^{+02}	1.09 x10^{+02}	1.09 x10^{+02}	1.09 x10^{+02}
C2-benzenes	7.67	7.67	7.67	7.67	1.94 x10^{-03}	1.94 x10^{-}	1.94 x10^{-03}	1.94 x10^{-03}	2.08 x10^{+02}	2.08 x10^{+02}	2.08 x10^{+02}	2.08 x10^{+02}
C3-benzenes	3.88	3.88	3.88	3.88	6.98 x10^{-04}	6.98 x10^{-}	6.98 x10^{-04}	6.98 x10^{-04}	4.66 x10^{+02}	4.66 x10^{+02}	4.66 x10^{+02}	4.66 x10^{+02}
C4/C5-	1.74	1.74	1.74	1.74	2.09 x10^{-04}	2.09 x10^{-}	2.09 x10^{-04}	2.09 x10^{-04}	1.20 x10^{+03}	1.20 x10^{+03}	1.20 x10^{+03}	1.20 x10^{+03}
C10-sat	0.57	0.57	0.57	0.57	3.91 x10^{-05}	3.91 x10^{-}	3.91 x10^{-05}	3.91 x10^{-05}	4.53 x10^{+03}	4.53 x10^{+03}	4.53 x10^{+03}	4.53 x10^{+03}
Naphthalenes	3.82	3.82	∞	∞	6.82 x10^{-04}	6.82 x10^{-}	7.41 x10^{-06}	7.41 x10^{-07}	4.75 x10^{+02}	4.75 x10^{+03}	∞	∞
Naphthalenes	1.14	1.14	∞	∞	1.11 x10^{-04}	1.11 x10^{-}	6.13 x10^{-06}	6.13 x10^{-07}	1.99 x10^{+03}	1.99 x10^{+04}	∞	∞
PAH-1	0.87	0.87	∞	∞	7.42 x10^{-05}	7.42 x10^{-}	5.65 x10^{-06}	5.65 x10^{-07}	2.73 x10^{+03}	2.73 x10^{+04}	∞	∞
PAH-2	0.23	0.23	∞	∞	1.01 x10^{-05}	1.01 x10^{-}	4.49 x10^{-06}	4.49 x10^{-07}	1.32 x10^{+04}	1.32 x10^{+05}	∞	∞

16. Appendix III Sponsors

16.1 SYMBIOSES III:

Role	Name	Representatives
Project Investors	Equinor Energy AS	Hanne Greiff Johnsen Randi Hagemann Jürgen Weissenberger
	ConocoPhillips Skandinavia AS, NOR	Eimund Garpestad Harald Lura
	Wintershall Dea Norge AS	Carl Joerg Petersen David Bjørnsen
	OMV (Norge) AS	Svein Olav Drangeid Sønnøve McIvor
	Lundin Norway AS	Axel Kelley
	Aker BP ASA	Anita Fjellså
	Vår Energi AS	Sveinung Birkeland

16.2 SYMBIOSES II:

Role	Name	Representatives
Project Investors	Equinor Energy AS	Hanne Greiff Johnsen Randi Hagemann Jürgen Weissenberger
	ConocoPhillips Skandinavia AS, NOR	Eimund Garpestad Harald Lura
	Wintershall Dea Norge AS	Carl Joerg Petersen David Bjørnsen
	OMV (Norge) AS	Svein Olav Drangeid Sønnøve McIvor
	Lundin Norway AS	Axel Kelley
	Aker BP ASA	Anita Fjellså Nina Aas
	Vår Energi AS	Sveinung Birkeland

16.3 SYMBIOSES I:

Role	Name	Representatives
Project Investors	Norwegian Research Council (NFR), NOR	Andreas Q. Nielsen
	BP Exploration Operating Company Limited, GBR	Paul Page Andrew Watson Peter Evans
	ConocoPhillips Skandinavia AS, NOR	Eimund Garpestad Harald Lura
	Eni Norge AS, NOR	Nora Hveding Bergseth Erik Bjørnbom
	ExxonMobil Upstream Research Company, USA	Tim J. Nedwed David Palandro Aaron Redman Thomas F. Parkerton
	Shell Technology Norway on behalf of Norske Shell A/S, NOR	Gina Ytteborg Mathijs Smit
	Statoil Petroleum AS, NOR	Tonje Waterloo Rogstad Hanne G. Johnsen Jürgen Weissenberger
	TOTAL E&P Norge AS, NOR	Grethe Kjeilen-Eilertsen Laurence Pinturier Jean-Marie Libre Lucie Le-Doeuff

17. Appendix IV Dissemination

- Q1 2022: Presentation Faglig Forum Management Plan
  - Presented 03.02.22
- Q4 2022: Presentation ON Network Climate and Environment
  - Presented 18.11.22
- Q3: Presentation ON Network Environmental Risk and Oil Spill Response
  - Presented 21.11.22
- Q4: Key findings presentation to Faglig Forum Management Plan
  - Tentative early 2023 – awaiting confirmation

18. Appendix V Ecotoxicology pamphlet

The SYMBIOSES ecotoxicological database developed during SYMBIOSES I, has been updated during the SYMBIOSES III project. The database now include new studies on more species (haddock, herring, capelin, NEA saithe, polar cod) (http://www.akvaplan.niva.no/en/symbioses/). The new studies are summarized in a pamphlet, and a table on ecotoxicological data for each fish species. The pamphlet and table are submitted as a separate deliverable together with the report.

19. Appendix VI Technical reference manual

For a technical documentation of the SYMBIOSES framework and its components, please see http://symbioses.no/docs/.