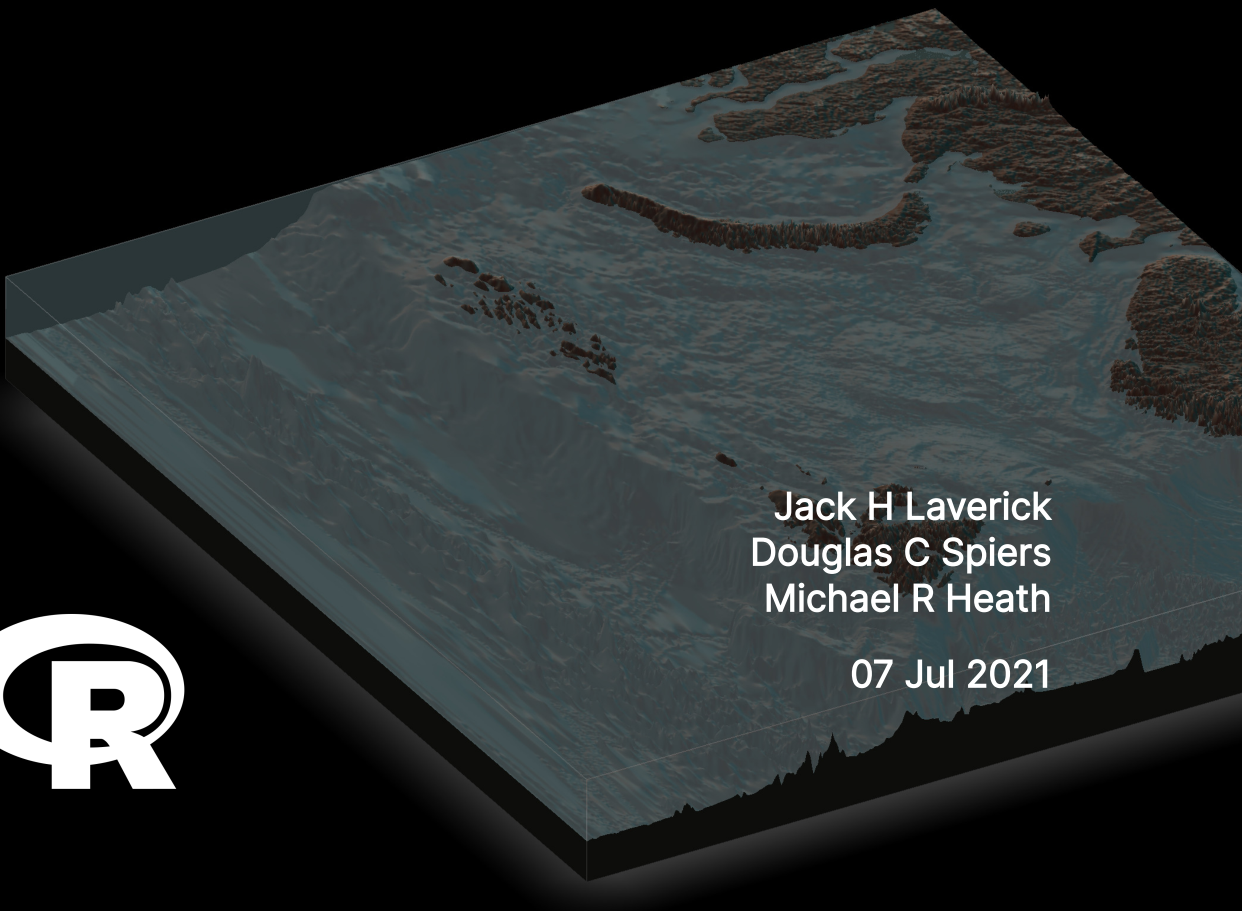
STRATHE2EPOLAR

Barents Sea Implementation



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Introduction

This document describes the configuration of StrathE2E*polar* for the Barents Sea and its parameterisation to enable stationary state fitting for two time periods; 2011-2019 and 2040-2049. These represent contrasting periods of environmental conditions, principally sea-ice concentration and ocean temperatures.

Volumetric and seabed habitat data define the physical configuration of the system. We regard these as being fixed in time. Similarly, we regard the physiological parameters of the ecology model as being fixed in time. Some of these are set from external data. The remainder are fitted, as detailed here. Changes in the model performance between the different time periods therefore stem from the hydrodynamic, hydro-chemical and fishery driving data. This are detailed in the ecological drivers and fishing fleet sections.

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> The code written to support this parameterisation is documented on github.

> **WARNING**: This is a working document, subject to update and revision.

Model Domain

The model splits the domain into three zones, inshore/shallow, offshore/shallow, and offshore/deep (Figure 1). The inshore/shallow zone covers waters shallower than 60 m or 20 km from shore. The offshore zone covers the remaining area of the model domain (Figure 2). The offshore zone is divided further into a shallow and deep layer. The shallow layer represents water from the surface to 60 m depth, and shares a boundary with the inshore shallow zone. The offshore/deep zone covers the same area as the offshore/shallow zone, but represents water between 60 m and 400 m deep. There is a second internal boundary between the two offshore zones.

The seafloor of the model domain is represented by 8 habitat types. There are three sediment classes – fine (muddy, 1), medium (sandy, 2) and coarse (gravel, 3). The fourth class (rock, 0) represents an absence of soft sediment. These sediment classes are defined in both the inshore/shallow and offshore/deep zones, yielding 8 habitats (Figure 2). The rock class has different geochemical properties and in the inshore zone supports the kelp forests in the model food web.

The perimeter of the Barents Sea model is defined by a 400 m depth contour. The model domain is bounded by Norwegian and Russian coastlines, with open ocean boundaries to the North Atlantic, the Arctic, the Norwegian sea, and the Kara sea. We impose boundaries to limit the model area at constrictions between the coastline and the 400 m countour.Our eastern limits to model domain are to the North of Severny Island (16.23E, 70N to 20.25E, 68.5N) and to the south of Yuzhny Island (64E, 68N to 57.5E, 70.74N). Our south-western limit is along 16.23E, 70N to 20.25E, 68.5N off the Norwegian coast.

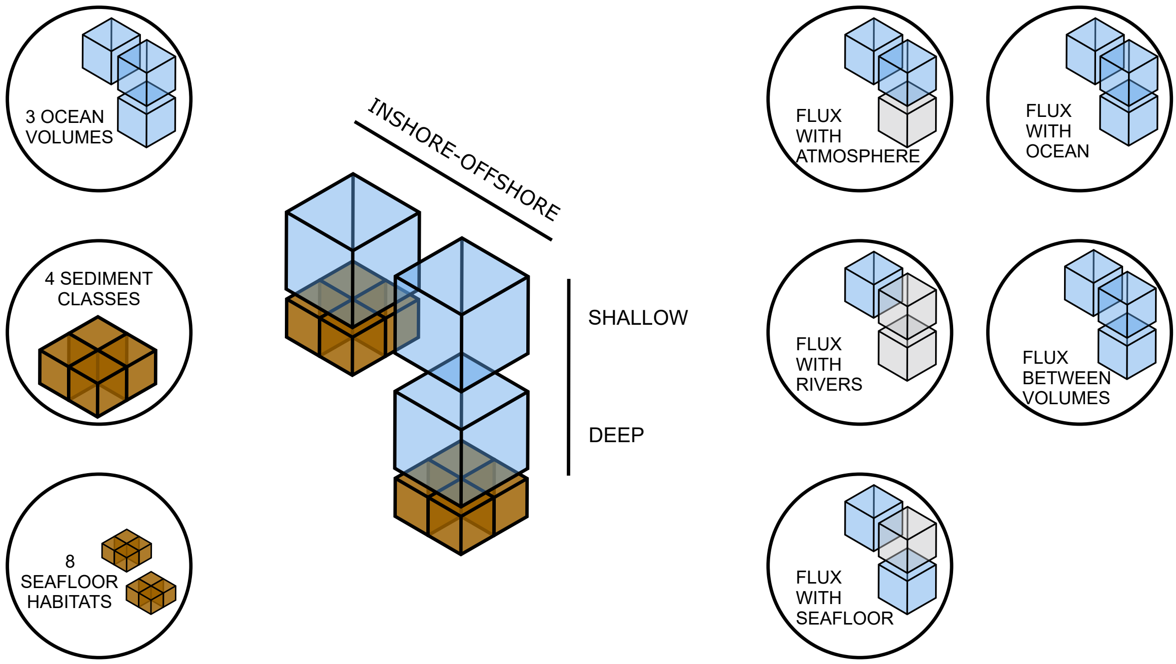

Figure 1: The spatial structure of StrathE2E; Ocean volumes and seafloor habitats. StrathE2E is built around a simplified spatial structure which represents shelf seas. These spatial units are connected to each other and to boundaries as shown to the right. The volumes connected to each spatial component are highlighted in blue.

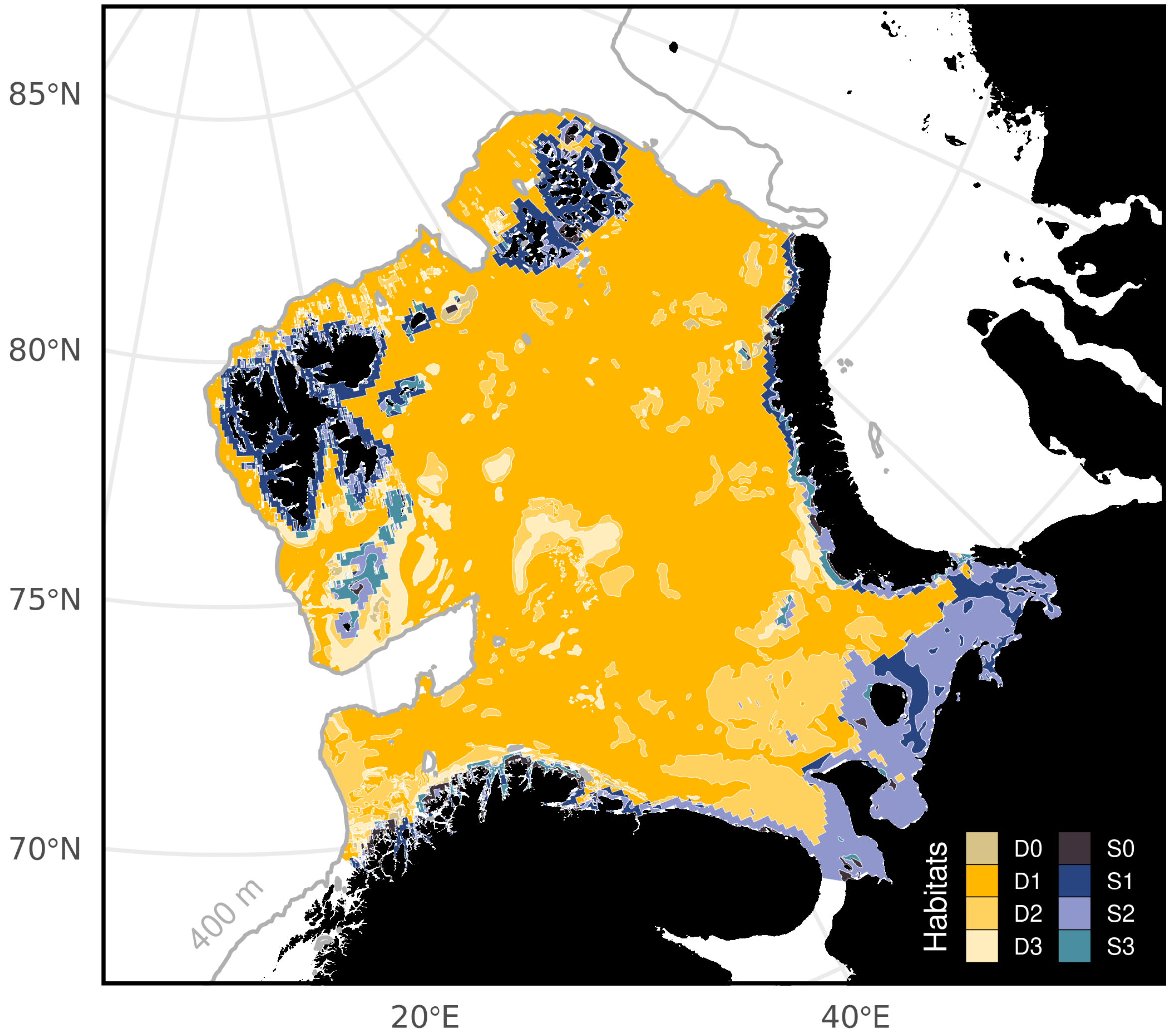

Figure 2: Map of the model domain. StrathE2Epolar defines seabed sediment habitats as inshore (blues) or offshore (yellows). Within each zone, three sediment classes are represented – fine (muddy, 1), medium (sandy, 2) and coarse (gravel, 3). A fourth class (rock, 0) represents an absence of soft sediment. Sedimentary data are from Laverick et al. (Under review).

Fixed Physical

Background

Water column inshore/shallow and offshore/deep zone area proportions and layer thicknesses; seabed habitat area proportions and sediment properties:

Area proportions of depth zones and seabed habitats derived from 1/100th degree resolution atlas of seabed sediment properties (Laverick, Speirs, and Heath Under review). The atlas provides gridded data sets of bathymetry, mean grain size, mud, sand and gravel content, porosity, permeability, organic nitrogen and carbon content, and natural disturbance by waves and bed shear stress.

Parameters for relationship between median grain size, sediment porosity and permeability. Permeability is used as the basis for estimating hydraulic conductivity which is a parameter in the representation of sediment processes in the model:

Porosity (proportion by volume of interstitial water) and permeability of each sediment habitat were derived from median grain sizes using empirically-based relationships.

$$log_{10}(porosity) = p_3 + p_4 \left(\frac{1}{1 + e^{\left(\frac{-log_{10}(D_{50}) - p_1}{p_2}\right)}} \right)$$

D_{50} = median grain size (mm); parameters p_1 = -1.227, p_2 = -0.270, p_3 = -0.436, p_4 = 0.366 (Heath et al. 2015)

$$permeability = 10^{p_5} \bullet D_{50}^{*p_6}$$

where D_{50}^* = 0.11 ≤ D_{50} ≤ 0.50 p_5 = -9.213, p_6 = 4.615 (Heath, Wilson, and Speirs 2015).

These relationships are coded into the StrathE2E2 R-package with the parameters in the csv setup file for the North Sea model. The parameters are probably a reasonable starting point for any future model of a new region. Derivation of the parameters is described in the following text sub-sections.

Parameters for in-built relationship between sediment mud content, and slowly degrading (refractory) organic nitrogen content of seabed sediments (see description in this document):

Values for each sediment type derived from parameterised relationships between total organic nitrogen content of sediments (TON%, percent by weight), mud content (mud%, percent by weight) and median grain size (D_{50}, mm).

$$mud\% = 10^{p_7} \bullet D_{50}^{p_8}$$

p_7 = 0.657, p_8 = -0.800

$$TON\% = 10^{p_9} \bullet mud\%^{p_{10}}$$

p_9 = -1.965, p_{10} = 0.590

Proportion of TON estimated to be refractory = 0.9

These relationships are coded into the StrathE2E2 R-package with the parameters in the csv setup file for the North Sea model. The relationships and parameters are probably a reasonable starting point for any future model of a new region, though there are clear regional variations. Derivation of the parameters is described in the following sub-sections.

Model area proportions

Table 1: Area-proportions of the inshore and offshore zones and the thicknesses of the water column layers. The sea surface area of the model domain is an estimated 1608975.7 km^2.

Property	Inshore/shallow	Offshore/deep
Sea-surface area proportion	0.1672	0.8328
Upper layer thickness (m)	97.1359	60.0000
Lower layer thickness (m)	NA	168.2374

We derived the area-proportions of seabed habitat in the inshore and offshore zones from the atlas of seabed sediment properties from Laverick et al. (Under review). The atlas provides a range of seabed data for 1/100th degree cells over the Barents and Greenland Seas, including the presence of rock, the percentage of mud, sand and gravel fractions in the sediments, the whole–sediment mean grain size, and the natural disturbance rate by currents and waves. These values are derived from habitat classes used by the Norwegian Geological survey in partnership with the Russian Federal State Unitarian Research and Production Company for Geological Sea Survey (NGU-SEVMORGEO). We assigned the NGU-SEVMORGEO sediment classes as fine, medium, coarse, or absence of sediment habitats within each zone (Figure 2). The actual area of each habitat was then the sum of the areas of each set of assigned cells (Table 2, Figure 2).

Table 2: Area proportions and other characteristics of the 8 seabed habitat classes defined in the model by depth, rock or sediment type. The sea surface area of the model domain is an estimated 1608975.7 km^2. Grain size is the median in mm, Permeability in units of m^2, nitrogen content in %dw.

Habitat	Sediment	Area Proportion	Grain size	Porosity	Permeability	Nitrogen content
Inshore - Shallow						
S0	None (Rock)	0.0097	NA	NA	NA	NA
S1	Fine	0.0638	0.0316	0.6712	0.0000	0.1243
S2	Medium	0.0770	0.2740	0.4347	0.0000	0.0340
S3	Coarse	0.0167	4.3814	0.3726	0.0000	0.0258
Offshore - Deep						
D0	None (Rock)	0.0068	NA	NA	NA	NA
D1	Fine	0.6497	0.0230	0.6792	0.0000	0.1372
D2	Medium	0.1314	0.2551	0.4395	0.0000	0.0360

Sediment porosity

Log-transformed porosity has been shown to have a sigmoidal relationship with log_{10}(median grain size) (D_{50}, mm) (Wilson et al. 2018):

$$log_{10}(porosity) = p_3 + p_4 \left(\frac{1}{1 + e^{\left(\frac{-log_{10}(D_{50}) - p_1}{p_2}\right)}} \right)$$

We use this relationship to calculate porosity for sea bed sediments in the Barents Sea (Table 2), using an alternative parameterisation to Wilson (Pace et al. 2021). This alternative set of parameters extends the relationship to fine, muddy sediments (Table 3).

Table 3: The four parameters for the function relating sediment porosity to median grain size. From Pace et al. (in review)

P1	P2	P3	P4
-1.035	-0.314	-0.435	0.302

Hydraulic conductivity

Hydraulic conductivity (H, $m.s^{-1}$) represents the ease with which fluids flow through the particle grain matrix. The related term ‘permeability’ (m^{-2}) is a measure of the connectedness of the fluid filled void spaces between the particle grains. Permeability is a function only of the sediment matrix, whilst conductivity is a function of both the sediment and the permeating fluid, in particular the fluid viscosity and density. Hydraulic conductivity is related to permeability by:

$$H = Permeability \bullet fluid\ density \bullet \frac{g}{dynamic\ viscosity}$$

where: seawater density = 1027 $kg.m^{-3}$ at salinity 35 and temperature 10°C; seawater dynamic viscosity = 1.48×10^{-3} $kg.m^{-1}.s^{-1}$ at salinity 35 and temperature 10°C; g = acceleration due to gravity = 9.8 $m.s^{-1}$

Hence, $H = Permeability \cdot 6.8004 \cdot 10^6$ ($m.s^{-1}$ at salinity 35 and temperature 10°C)

Whole sediment permeability can be related to the proportion of sediment classed as mud (D_{50} < 62 μm) (Pace et al. 2021). This relationship was used in the production of the Barents Sea sediment atlas (Laverick, Speirs, and Heath Under review), which provides the values used in this model implementation (Table 2).

Sediment organic nitrogen content

The magnitude of the static (refactory) organic nitrogen detritus pool in each sediment type is a required input to the model. The code includes an option to impute values from empirical relationships between total organic nitrogen (TON) and mud content, and between mud content and median grain size. This relationship has been documented in the North Sea implementation of the temperate StrathE2E2 package (Heath et al. 2021), and is based on sediment data off northeast Scotland.

To supplement the relationship within the package, predictions of sediment organic nitrogen content for the Barents Sea have been sourced from the sediment atlas (Laverick, Speirs, and Heath Under review) to parameterise StrathE2E directly (Table 2).

Fixed biological

Configuration parameters

Assimilation efficiencies for each living guild in the model.

Fixed parameters defining the proportion of ingested mass of food that contributes to new body tissue, after subtracting defecation and the metabolic costs of digestion and synthesis (Heath 2012).

Biomass loss rates due to temperature-dependent metabolism for each living resource guild.

Proportion of biomass lost to ammonia per day due to non-feeding related metabolism at a given reference temperature. Rates for individual guilds broadly related to typical body mass of representative species. Temperature dependency following a Q_{10} function.

Q_{10} values for temperature dependent processes, and the Q_{10} reference temperature.

Separate Q10 values for autotrophic uptake of nutrient, heterotrophic feeding, and heterotrophic metabolism based on literature data.

Light intensity required to saturate autotrophic nutrient uptake.

Light saturation intensity for nutrient uptake cannot be treated as a fitted value since it is confounded with other uptake parameters. Value estimated from survey of laboratory experiments.

Annual weight specific fecundities of planktivorous and demersal fish guilds and the two benthos guilds in the model (suspension/deposit feeders and carnivore/scavenge feeders).

Guild-level values derived by surveying the literature.

Harvestable biomass density threshold for each resource guild.

The living resource guilds in the model represent a mixture of harvestable and non-harvestable species, especially the invertebrate guilds. The density threshold parameter sets a limit for the guild biomass below which the harvestable species are assumed to be exhausted. Values set from analysis of trawl, plankton and benthos survey species biomass compositions.

Minimum inedible biomass of carnivorous zooplankton.

The carnivorous zooplankton guild is a key component of the food web, predated on by all the fish and top-predators. However it represents an extremely diverse range of fauna many of which are not edible in significant quantities by the guild predators, e.g. scyphomedusae. A minimum edible threshold is set to ensure that the guild as a whole cannot be extirpated by predation. The value is a rough estimate of scyphomedusae biomass.

Event timing parameters (not fitted)

Spawning start and end dates for fish and benthos

For the fish guilds the dates were obtained from literature survey (Heath 2012), while others came from ecological surveys in Hornsund fjord on southern Spitsbergen (WĘsławski et al. 1988). The annual weight-specific fecundity is assumed to be shed uniformly between the start and end dates of spawning.

Recruitment start and end dates for fish and benthos

Obtained from literature survey (Heath 2012). The annual cohort of larvae/juveniles of each fish and benthos guild is assumed to recruit to the settled stage at a uniform daily rate between the start and end dates.

Extra-domain stock biomass of migratory, and the proportion invading the domain each year. Start and end dates for the annual invasion, and start and end dates for the emigration. (see description below).

The main migratory fish species undertaking a seasonal transit of the North Sea is the Atlantic mackerel. Data on the North East Atlantic stock biomass, the proportion entering the Barents Sea and the timing of the migration, were derived from stock assessment literature (ICES 2013).

Event timing parameters (fitted)

Migratory fish in the Barents Sea model are assumed to be Atlantic mackerel. The fishery for Atlantic mackerel is one of the most valuable in the northeast Atlantic. Spawning takes place off southwest Ireland in April. After spawning, fish rapidly migrate to summer feeding zones thousands of kilometres northwards along the continental shelf edge to the Norwegian and Barents Seas. More recently some fish feed off Iceland (Holst, Jansen, and Slotte 2016).

For the purposes of the model, we assume that there is no feedback between fishing and environmental conditions in the Barents Sea and the biomass and migration patterns of the whole northeast Atlantic mackerel stock. In this version of StrathE2E*polar* the timing of immigration and emigration, and the mass influx across the ocean boundary during the annual immigration phase are treated as period-specific external driving data.

Data on the ‘global’ stock of northeast Atlantic mackerel (wet biomass) are available from stock assessments (ICES 2013), and converted to molar nitrogen mass using appropriate conversion ratios (Greenstreet 1996). The proportion of the migrating stock entering the Barents Sea, and the timing of the inward and outward migrations are estimated from monthly resolved data on the spatial distribution of fishery catches. A residual proportion of the peak abundance in the North Sea remaining as residents (if any) is estimated from summer trawl survey data. The model setup code calculates the parameters which are needed in the ecology model.These are the only fixed (i.e. non-fitted) ecology model parameters which are period-specific.

In addition to migratory fish, birds and cetaceans also migrate to the Barents Sea to feed during the summer, and leave during the winter. Polar bears similarly leave the model area during winter to hibernate. A constant rate of loss is applied to the hibernating guild while outside the model, in contrast to migratory guilds which continue to feed elsewhere. The values used for the timings of these events represent a synthesis of anecdotal reports.

Table 4: Biological event timing parameters, constant acorss the 2011-2019 and 2040-2049 time periods. The data are processed in the model setup to calculate the immigration flux parameters needed in the ecology model.

Parameter	Value
Planktivorous fish spawning start day	60
Planktivorous fish spawning duration (days)	90
Planktivorous fish recruitment start day	200
Planktivorous fish recruitment duration (days)	150
Demersal fish spawning start day	60
Demersal fish spawning duration (days)	90
Demersal fish recruitment start day	200
Demersal fish recruitment duration (days)	150
Susp/dep benthos spawning start day	60
Susp/dep benthos spawning duration (days)	150
Susp/dep benthos recruitment start day	180
Susp/dep benthos recruitment duration (days)	120
Carn/scav benthos spawning start day	60

Table 4 Continued.

Parameter	Value
Carn/scav benthos spawning duration (days)	150.000
Carn/scav benthos recruitment start day	180.000
Carn/scav benthos recruitment duration (days)	120.000
Migratory fish switch (0=off 1=on)	1.000
Migratory fish ocean biomass (Tonnes wet weight)	3800000.000
Migratory fish carbon to wet weight (g/g)	0.184
Model domain sea surface area (km2)	1608975.700
Propn of ocean population entering model domain each year	0.050
Migratory fish immigration start day	150.000
Migratory fish immigration end day (must be later than start day even if migration disabled)	195.000
Migratory fish propn of peak popn in model domain which remains and does not emigrate	0.010
Migratory fish emigration start day	240.000
Migratory fish emigration end day (must be later than start day even if migration disabled)	285.000
Bird winter migration switch (0=off 1=on)	1.000
Bird spring immigration start day	90.000
Bird spring immigration end day (must be later than start day even if migration disabled)	150.000
Bird propn of peak popn in model domain which remains and does not emigrate (must be>0)	0.050

Table 4 Continued.

Parameter	Value
Bird autumn emigration start day	270.00
Bird autumn emigration end day (must be later than start day even if migration disabled)	315.00
Pinniped winter migration switch (0=off 1=on)	0.00
Pinniped spring immigration start day	90.00
Pinniped spring immigration end day (must be later than start day even if migration disabled)	150.00
Pinniped propn of peak popn in model domain which remains and does not emigrate (must be>0)	0.85
Pinniped autumn emigration start day	270.00
Pinniped autumn emigration end day (must be later than start day even if migration disabled)	315.00
Cetacean winter migration switch (0=off 1=on)	1.00
Cetacean spring immigration start day	90.00
Cetacean spring immigration end day (must be later than start day even if migration disabled)	150.00
Cetacean propn of peak popn in model domain which remains and does not emigrate (must be>0)	0.25
Cetacean autumn emigration start day	270.00
Cetacean autumn emigration end day (must be later than start day even if migration disabled)	315.00
Maritime mammal winter migration switch (0=off 1=on)	1.00
Maritime mammal spring immigration start day	75.00

Table 4 Continued.

Parameter	Value
Maritime mammal spring immigration start day	75.00
Maritime mammal spring immigration end day (must be later than start day even if migration disabled)	150.00
Maritime mammal propn of peak popn in model domain which remains and does not emigrate (must be>0)	0.85
Maritime mammal autumn emigration start day	270.00
Maritime mammal autumn emigration end day (must be later than start day even if migration disabled)	315.00

Ecological drivers

Monthly resolution time-varying physical and chemical driving parameters for the model were derived from a variety of sources:

- Temperature, cryosphere variables, vertical mixing coefficients, volume fluxes, and boundary nutrient, detritus and phytoplankton concentrations from outputs of a NEMO-MEDUSA coupled hydro-geochemical model run at RCP85 with a 2005/2006 historical/future split (Yool, Popova, and Anderson 2013).
- Surface shortwave radiation, surface air temperature, and freshwater volume outflows from HadGEM2-ES model output (Jones et al. 2011) used to force the NEMO-MEDUSA coupled hydro-geochemical model mentioned above (Yool, Popova, and Anderson 2013).
- River nitrate and ammonia concentrations taken from river Ob' field samples by the Arctic Great Rivers Observatory (Holmes et al. 2020).
- Atmospheric deposition of nitrate and ammonia from EMEP MSC-W (European Monitoring and Evaluation Programme; (Simpson et al. 2003))
- Oceanic Nitrate and ammonia data from Changing Arctic Ocean programme (CAO) cruises in the Barents Sea, published by BODC (Brand, Norman, Mahaffey, et al. 2020; Brand, Henley, Mahaffey, et al. 2020a, 2020b; Brand, Norman, Henley, et al. 2020).
- Remote sensing data products on Suspended Particulate Matter (Globcolour L3b; ftp://ftp.hermes.acri.fr/GLOB/merged/month/).
- Habitat disturbance due to tidal currents and waves from the Barents Sea sediment atlas (Laverick, Speirs, and Heath Under review).
- Wave height, period, and direction from the CERA-20C 'Ocean Wave Synoptic Monthly Means' product accessed through ECMWF for 2000-2010.

Details of how these data were processed are given below, supported by the nemomedusR and MiMeMo.tools packages.

Vertical mixing coefficients between the upper and lower layers of the deep zone:

Vertical diffusivity from the NEMO-MEDUSA coupled hydro-geochemical model output (Yool, Popova, and Anderson 2013) was interpolated for each grid cell at the 60 m boundary depth between the shallow and deep layers of the offshore zone. These values were summarised as monthly averages into period-specific climatological annual cycles of data for the 2011-2019 and 2040-2049 simulation periods.

Monthly averaged temperatures and cryosphere variables for each water column layer:

Derived by monthly averaging values at grid points within the inshore and vertical layers of the offshore zones from the NEMO-MEDUSA coupled hydro-geochemical model output (Yool, Popova, and Anderson 2013), weighted by grid point volumes. Values were summarised into period-specific climatological annual cycles of data for the 2011-2019 and 2040-2049 periods.

Monthly averaged suspended particulate matter (SPM) concentrations (mg.m^{-3}) in the shallow zone and the deep zone upper layer:

Monthly averaged values of inorganic suspended particulate matter in sea water are available from the Globcolour project, starting from September 1997. These data are derived from satellite observations using the algorithm of Gohin (2011). Data were downloaded from the ftp server (ftp://ftp.hermes.acri.fr/GLOB/merged/month/). We summarised these values as zonal statistics for the model domain to acquire a climatological annual cycle of data for the 2011-2019 simulation period only.

Monthly average light attenuation coefficients for the inshore and offshore surface layers:

Light attenuation in open water was parameterised from a linear relationship between the light attenuation coefficient and suspended particulate matter concentration (SPM) (Devlin et al., 2008). Light attenuation and albedo for snow and ice were sourced from (Castellani et al. 2017).

Monthly averaged daily integrated irradiance at the sea surface ($E.m^{-2}.d^{-1}$):

Derived from HadGEM2-ES model output (Jones et al. 2011) which forces the NEMO-MEDUSA model run used throughout our implementation. Monthly mean values were summarised into a climatological annual cycle of data for both the 2011-2019 and 2040-2049 periods.

Monthly averaged daily atmospheric deposition rates of wet and dry, oxidised and reduced nitrogen onto the sea surface in the shallow and deep zones ($mMN.m^{-2}.d^{-1}$):

Sourced from 50 x 50 km^2 gridded data for 2000 - 2017 as monthly averages (Simpson et al. 2003), available from EMEP (https://thredds.met.no/thredds/fileServer/data/EMEP/2018_Reporting/). Monthly values were summarised into climatological annual cycles of monthly oxidised and reduced nitrogen deposition rates extracted for 2011-2017.

Monthly averaged, freshwater river inflow rates (expressed as a daily proportion of the receiving layer volume), and concentrations of oxidised and reduced dissolved inorganic nitrogen in the inflowing river waters ($mMN.m^{-3}$):

Freshwater inflow derived from HadGEM2-ES model output (Jones et al. 2011) which forces the NEMO-MEDUSA model run used throughout our implementation. Monthly values were summaries into a climatological annual cycle of data for both the 2011-2019 and 2040-2049 periods.

The closest estimates of the concentrations of oxidised and reduced dissolved inorganic nitrogen in river water to the Barents Sea were from the river Ob', provided by the Arctic Great Rivers Observatory (Holmes et al. 2020). We derived a climatological annual cycle of data for the 2011-2019 simulation period only.

Volume fluxes into the model domain across open sea boundaries, and from the upper layer of the offshore/deep zone into the inshore/shallow zone, expressed as proportions of the receiving layer volume per day:

Monthly averaged daily inflow and outflow volume fluxes derived by integrating daily mean velocities directed perpendicular to transects along the model domain boundary at grid points in each depth layer along transects through outputs from the NEMO-MEDUSA coupled hydro-geochemical model output (Yool, Popova, and Anderson 2013). Monthly averaged daily inflow volume fluxes then divided by the volume of the receiving layer in the model domain to estimate a daily flushing rate. Period-specific climatological annual cycles of data used for 2011-2019 and 2040-2049 simulation periods.

Mean concentrations of nitrate, ammonia, phytoplankton and suspended detritus (mMN.m^{-3}), in adjacent ocean waters inflowing to the offshore/deep zone upper layer, adjacent ocean waters inflowing to the offshore/deep zone lower layer, and adjacent shelf waters inflowing to the inshore/shallow zone:

NEMO-MEDUSA outputs included phytoplankton and suspended detritus, as well as Dissolved Inorganic Nitrogen (DIN). We calculated the depth-averaged concentrations for pixels within the shallow and deep layers of StrathE2E. We then sampled the pixels using the same transects around the model domain as for sampling volume fluxes. Only transects where water flowed into the model domain were sampled, and the average concentration of inflowing waters for target variables was calculated weighting by the flow rate across a transect and the cross-sectional area represented by a transect (average depth and length). Concentrations were then averaged into climatological annual cycles for both the 2011-2019 and 2040-2049 periods.

DIN was decomposed into nitrate and ammonia concentrations using a ratio of ammonia:DIN derived from field observations collected during NERC Changing Arctic Ocean Cruises (Brand, Norman, Mahaffey, et al. 2020; Brand, Henley, Mahaffey, et al. 2020a, 2020b; Brand, Norman, Henley, et al. 2020). Concentrations were averaged by depth layer into two correction factors across all samples located in the model domain and across all time steps.

Fishing fleet

Background

The key configuration data for the fishing fleet model are the definitions of the gears in terms of their power with respect to each of the harvestable resource guilds, discarding rates, processing-at-sea rates, and their seabed abrasion rates. These can be regarded as static parameters for each gear.

An additional class of static parameters is the scaling coefficients between effort (activity x power) and the harvest ratio generated on each model resource guild. These parameters have to be derived by fitting.

Finally, there are parameters which we can consider as driving data since they would be expected to vary with time. These are the activity rates of each gear, and their spatial distributions across the habitat types.

For the Barents Sea implementations we started with the implementation for the North Sea (Heath et al. 2021). Any parameters which could be updated using data specific to the Barents Sea are described below. Our principal data sources were ICES https://www.ices.dk/data/dataset-collections/Pages/Fish-catch-and-stock-assessment.aspx, IMR, STECF, and Global Fishing Watch (Kroodsma et al. 2018). These were supplemented with additional data sources to improve the representation of bycatch, discard, and small recreational and artisanal fisheries.

Static gear-definition parameters in the fishing fleet model

Static parameters for the fishing fleet model were taken from the North Sea implementation (Heath et al. 2021), with the new set of gears operating in the Barents Sea reconciled with StrathE2E gear types as detailed below (Table 5). These parameters would be expected to remain constant over time, so any changes invoked would imply a change in the design or operation of a gear type.

Table 5: The gear labelling systems of STECF, IMR, and Global Fishing Watch were reconciled with StrathE2E gear types. Gears were condensed considering their target species and their likely impact on the sea-bed.

StrathE2E Gear	Sourced Gear	Gear Type	Gear Code	Source
Trawls	Undefined trawl	Mobile	50	IMR
Trawls	Double trawl	Mobile	58	IMR
Trawls	Triple trawl	Mobile	59	IMR
Trawls	Beam trawl	Mobile	56	IMR
Trawls	Bottom trawl	Mobile	51	IMR
Trawls	Bottom otter trawl	Mobile	OTB	STECF
Trawls	Bottom pair trawl	Mobile	PTB	STECF
Trawls	Mid-water pair trawl	Mobile	PTM	STECF
Trawls	Otter twin trawls	Mobile	OTT	STECF
Pelagic	Mid-water otter trawl	Mobile	OTM	STECF
Pelagic	Pelagic trawl	Mobile	53	IMR
Pelagic	Purse seine	Mobile	11	IMR
Pelagic	Pelagic trawl (pair)	Mobile	54	IMR
Longlines_and_Jigging	Undefined hook gear	Static	30	IMR
Longlines_and_Jigging	Other hook and line	Static	32	IMR
Longlines_and_Jigging	Floating hooks	Static	31	IMR
Longlines_and_Jigging	Jigging	Static	33	IMR
Gillnets	Undefined net	Static	20	IMR

Table 5 Continued.

StrathE2E Gear	Sourced Gear	Gear Type	Gear Code	Source
Gillnets	Gillnet (static)	Static	22	IMR
Gillnets	Gillnet (drifting)	Static	21	IMR
Seines	Undefined seine net	Mobile	10	IMR
Seines	Danish seine	Mobile	61	IMR
Pots	Pot	Static	42	IMR
Pots	Pots	Static	FPO	STECF
Dropped	Other	NA	80	IMR
Dropped	Unknown	NA	NK	IMR
Harpoons	Harpoon and similar unspecified types	Mobile	70	STECF
Rifles	Rifle	Mobile	73	STECF
Kelp harvesting	Kelp harvesting	Mobile	NA	NA
Dredging	Dredge	Mobile	DRB	IMR
Shrimp trawl	Shrimp trawl	Mobile	55	STECF
Recreational	Recreational	Mobile	NA	NA

Potentially time-varying parameters of the fishing fleet model

The following briefly describes the potentially time-varying driving data for the fishing fleet model.

Catching power and discard rates of each resource guild by each gear.

An annual average was calculated for the 2011-2019 period using the data available within this time period for the Norwegain fishing fleet (IMR) and the EU fleet (STECF). Values were summed and inflated for estimates of total international activity using ICES data to infer the missing Russian catch in the Barents Sea. This assumes the Russian fishing fleet operates a similar gear distribution to the EU and Norwegian fleets when combined.

Regional activity rates, of each gear type.

An annual average was calculated for the 2011-2019 period using the data available within this time period for the Norwegian fishing fleet (IMR) and the EU fleet (STECF). Values were summed and inflated for estimates of total international activity using Global fishing watch data to infer the missing Russian activity in the Barents Sea for static and mobile gears. This assumes the Russian fishing fleet operates a similar gear distribution (within static and mobile gear types) to the EU and Norwegian fleets when combined.

Spatial proportional distribution of activity by each gear.

Proportion of domain-wide annual average activity rate over each seabed habitat type, derived by overlaying spatial distributions of activity from IMR (Norwegian), STECF (EU), and Global FIshing Watch (Russian), onto spatial distributions of seabed sediment types derived from the atlas of sediment properties (Laverick, Speirs, and Heath Under review).

Data processing to derive time-varying parameters of the fishing fleet model

Norwegian fishing catch and activity in the Barents Sea

IMR provided us with daily catch and activity data for the Norwegian fishing fleet on request. This data was broken down by species caught and gear used in fishing areas. We limited the data to 2011-2019, from the first year of the electronic reporting system to the last complete year of data. Cetacean records appeared to start from 2013, so averages were calculated for cetaceans from 2013-2019.

1. We aggregated gears and species to StrathE2E gear types and guilds. Data was totaled within years, then averaged across the target time period. Effort and landings were summed by gear and guild within years and IMR area codes.

2. IMR areas do not perfectly align with the StrathE2E model domain, we therefore applied a correction factor to landings and effort to account for IMR data falling outside the model domain. We summarised the data available from global fishing watch from 2012-2016 into average annual 0.01° grids of total yearly fishing activity for mobile and static gears. We intersected the polygons representing IMR area codes, and the StathE2E model domain, and calculated the total mobile and static gear activity within each polygon according to GFW. We then calculated the proportion of mobile and static gear activity for each IMR area code which fell within the StrathE2E model domain.

3. We used the same approach to calculate the proportion of fishing effort across the 8 strathE2E habitat types. Instead of the intersection between the StrathE2E model domain and the IMR area codes, we intersected the Barents Sea habitats with IMR area codes (Figure 2). We then calculated the proportion of mobile and static gear activity for each IMR area code which fell within the StrathE2E habitats.

4. Corrected landings were totaled across area codes and saved as a matrix by gear and guild. Corrected effort was totaled across area codes and saved by StrathE2E gear types. Corrected effort was also totaled across area codes and saved as a matrix by gears and habitats.

Norwegian seal hunting in the Barents Sea

Norges Råfisklaget track catches and sales by fishermen in Norway. We downloaded annual catch reports for the years 2011 - 2019. We downloaded the reports for the whole of Norway, as well as the regions with coastline in the Barents Sea (Troms, East and West Finnmark). We compared the data between IMR and Råfisklaget and found additional landings of Pinnipeds by Rifles. We added these to the IMR data for an estimate of total Norwegian catch and activity in the Barents Sea. Råfisklaget data also revealed that Norwegian macrophyte harvesting does not occur in the Barents Sea, so the landings and activity were set to 0.

Hunters target seal pups of the Barents Sea population, effort is therefore located in the seal whelping area. Seal reproduction occurs in the White Sea, which is not part of the Barents Sea model domain. We distribute the activity of sealers across habitats by calculating the proportion of different StrathE2E habitats at the entrance to the White see at the edge of our model domain (An area centred on 42.3 W, 66.9 N, with a radius of 120 km).

Demersal and migratory catch by tourist and recreational fishing activity

Introduction

Arctic Fisheries Working Group (AFWG) reports since 2010 include catches of cod by non-commercial fishing activity in assessments for the coastal cod stock which inhabits the inshore waters of western and northern Norway. Coastal cod are considered to be distinct from the more abundant Northeast Arctic cod which are mostly found offshore but migrate inshore to breed in the spring. The non-commercial activity includes both fishing-tourism (businesses offering fishing trips to visitors), and recreational fishing by Norwegian residents. The former is a rapidly growing sector in Norway, but still smaller in terms of catch than the recreational sector. In some years the combined tourist and recreational catch was estimated to account for up to one-third of the total catch of coastal cod. According to ICES (2020), since 2010 seven thousand tonnes of the Norwegian cod quota has been set aside annually to cover the catches taken in the recreational and tourist fisheries and to motivate young people to become fishers.

The fishing methods for non-commercial activity are primarily hooks for the tourist sector, and hooks and gillnets for the recreational sector. Many tourist businesses operate a catch and release system. Fish which are released are assumed to survive and are not included in assessments of tourist catch (Vølstad et al. 2011). Likewise, some recreational fishers offer a proportion their catches for sale. ICES assessments assume that these sales are already included in the catch statistics compiled by the Norwegian Directorate for Fisheries, and hence not classified as part of the recreational catch.

Estimation of Norwegian tourism and recreation catches

Subject to the above limitations, the 2010 AFWG prepared a record of both recreational and tourist catches of coastal cod between 1984 and 2009, based on studies by Anon (2005; Hallenstvedt and Wulff

2004), and annual surveys on the number of Norwegian residents who said they had been fishing in the sea. These strands of evidence indicated the total recreational and tourist catch of cod to be 13,400 tonnes in 2004 and the tourist catch 1,100 tonnes. It was estimated that participation in sea fishing tourism increased by 19% per year between 1995 and 2000, by 16% per year until 2004, and then by 10% per year up to 2009 (ICES 2010). No new data have become available since 2009 and subsequent AFWGs up to 2020 have simply projected the 2009 estimated total catch of 12,700 tonnes forwards year on year, without distinguishing between the tourist and recreation sectors (ICES 2020). Here, we have conservatively assumed that tourism catches have increased by 5% year-on-year since 2009, and derived the recreational catch as the difference between the stated total (ICES 2020) and our estimated tourist catch (Table 6).

Table 6 provides the total annual recreational and tourist catches of coastal cod, which occurs in western and northern Norway, northward of around 62N. However, we required the catch not just of cod but also of the other species taken by these fisheries, and the subset of these that originate from our Barents Sea model area. Data from Vølstad et al. (2011) provide some information to attempt this extrapolation.

Vølstad et al. (2011) surveyed Norwegian sea fishing tourism businesses in 2009 (Figure 3) to gather data on the level of activity (boat days), participants and catch composition. Catch quantities by species were integrated for regions north and south of 62N (Table 7). There was a clear different in composition, with cod forming over 50% of the catch north of 62N, and less than 10% to the south. By way of corroboration, ICES (2010) also estimated that cod formed around 50% of the recreational and tourism catch north of 62N during the early 2000's. South of 62N, saithe was the main species caught, followed by mackerel in 2009 (Vølstad et al. 2011). Apart from mackerel, all the species were members of the demersal fish guild in our model.

Figure 3: From (Vølstad et al. 2011) (Figure 2). Map of tourist-fishing businesses from which catch and effort data were gathered in 2009.

In the absence of any other catch composition data we estimated the total demersal catch, and the mackerel catch for the area north of 62N in each year from the 2009 data, assuming a constant ratio of all demersal species : cod of 1.857, and mackerel : cod of 0.0086 (Table 7).

Tourism and recreation catches along the Norwegian coast bordering our Barents Sea model would clearly be less than the total north of 62N. However, the breakdown of catches in 2009 at finer resolution than that reported by Vølstad et al. (2011) was not available. Hence we crudely estimated the proportion of annual catches from north of 62N that might have been taken in our model area based on the proportion of sea fishing tourism businesses participating in the 2009 study which were located in the Troms and Finmark areas (Figure 3; 11 out of 52 businesses north of 62N; 21.57%). The results are estimates, albeit obviously crude, of the catch of demersal fish and migratory fish (mackerel) guilds in our Barents Sea model domain (Table 8).

Estimation of Norwegian fishing activity

Data on the level of fishing activity by recreation and tourism sectors is even more hard to locate than catch quantities and composition. We could only find one estimate – 1.43 x 105 boat days by the entire Norwegian tourism sector in 2009 (Vølstad et al. 2011). Across the 4000 boat-days sampled in 2009, the mean number of fishing tourists per boat was typically 2–3, and the mean catch per boat-day ranged from 7 to 27 kg.

Lacking any other data, we crudely apportioned the total annual activity in 2009 to the Troms and Finmark regions in proportion to the numbers of businesses participating in the 2009 study (Figure 3; 11 in Finmark and Troms out a Norway total of 79; 13.92%) – Troms and Finmark activity = 1.99 x 104 boat days. We further assumed that each boat day involved a notional 4h of hooks-in-the-water time, so that the effective activity was 79,646 hours. Finally, the most challenging assumptions – firstly that the 2009 total catch per unit activity by the tourist sector (7.86 kg/h) was constant over the years covered by the ICES 2020 time series, and secondly that this was identical for both the tourist and recreational sectors. The latter is extremely problematic since there is evidence that some recreational fishers operate more powerful gears than the predominantly rod and line tourist sector, such as gill nets and longlines. So our assumption will certainly lead to a biased estimate of total activity depending on the proportion of total catch due to tourism (Table 9).

Estimates of Russian tourism and recreational catches and activity

Recreational sea fishing in Russia is extremely popular, and subsistence fishing provided an important source of nutrition during the decades immediately following World War II. Artisanal fishing has also been an important source of food with the landings not being recorded in official records. Sea fishing tourism at the Barents Sea and White Sea coastal areas has expanded rapidly since 1990, with an emphasis on salmon fishing especially in the Kola Peninsula. However, assembling quantitative data on the catches from these fisheries is extremely difficult. Popov & Zeller (2018) provide the only accessible estimates, based on analyses of salmon catches, coastal population data and dietary records, and assumed fractions of the total reported Russian landings from the region (Table 10).

Species composition data for the artisanal, subsistence and recreational fisheries are not accessible, but discussion in Popov & Zeller (2018) indicates that a significant fraction of the recreational catch is represented by salmon, while demersal fish make up the bulk of everything else. Hence we assumed that 50% of recreational landings were salmon, and everything else was demersal. Since the salmon catch is presumably taken from rivers and not coastal waters, and since the Norwegian recreational and tourist data did not include salmon fishing (which is a substantial activity in Norway), we excluded the salmon catch from our assembly of inputs to our Barents Sea model (Table 10).

No effort or activity data were reported by Popov & Zeller (2018). We therefore crudely assumed that the catch per unit activity in the Norwegian tourist fishery was also applicable to the Russian recreational, artisanal and subsistence catches (excluding salmon), in order to estimate activity rates.

Total catches and activity for recreational and tourist fisheries in the Barents Sea region

The combined Russian and Norwegian estimates of annual fish guild catches and overall activity are shown in Table 11. Clearly these should be treated as highly uncertain given the heroic assumptions which have been applied.

Table 6: Coastal cod catch from ICES areas 1 and 2 by tourist businesses recreational fishers. Between 1984 and 2009 the tourist-only catch is from ICES ((2010); Table 2.1c), while the combined tourist + recreation catch (1984-2019) is from ICES ((2020); Table 2.1e). Between 2010 and 2019 the tourist catch (grey shaded) is assumed to increase at 5% per year (ICES 2020). The recreation-only catch is the difference between the total and tourism.

Year	Combined tourism & recreation catch (tonnes)	Tourist catch (tonnes)	Implied recreation catch (tonnes) = total- tourist
1984	13300	0	13300
1985	13400	0	13400
1986	13500	0	13500
1987	13500	0	13500
1988	13600	0	13600
1989	13700	100	13600
1990	14500	100	14400
1991	15300	100	15200
1992	16100	100	16000
1993	14800	100	14700
1994	14700	100	14600
1995	14700	200	14500
1996	14500	200	14300
1997	14500	300	14200
1998	14600	300	14300
1999	13900	400	13500
2000	13600	500	13100

Table 6 Continued.

Year	Combined tourism & recreation catch (tonnes)	Tourist catch (tonnes)	Implied recreation catch (tonnes) = total- tourist
2001	13400	700	12700
2002	13600	800	12800
2003	13900	900	13000
2004	13400	1100	12300
2005	13200	1200	12000
2006	13000	1300	11700
2007	13000	1500	11500
2008	12800	1600	11200
2009	12700	1800	10900
2010	12700	1890	10810
2011	12700	1985	10716
2012	12700	2084	10616
2013	12700	2188	10512
2014	12700	2297	10403
2015	12700	2412	10288
2016	12700	2533	10167
2017	12700	2659	10041
2018	12700	2792	9908
2019	12700	2932	9768
Mean 2011-2019	12700	2431	10269

Table 7: Data for the 2009 national survey of tourist recreational fishing in Norway from (Vølstad et al. 2011), Table 2. The data were presented for two regions, North and South of 62N. The additional column shown here for the Finmark and Troms area is a 21.57% subset of the data for "North of 62N" based the proportion (11 out of 52) of the tourist businesses in "North of 62N" which were located in these administrative areas. Values are the annual catch weight in tonnes.

	North of 62N	South of 62N	Estimated Finmark and Troms regions (21.57% of "North of 62N")
Cod	1586.00000	27.000	335.50000
Haddock	115.10000	9.400	24.30000
Saithe	825.20000	208.000	174.60000
Pollack	81.10000	21.400	17.20000
Hallibut	79.70000	0.200	16.90000
Mackerel	13.60000	54.400	2.90000
Ling	68.50000	40.400	14.50000
Tusk	173.70000	15.900	36.70000
Wolffish	15.30000	0.300	3.20000
Total weight	2958.20000	377.000	625.80000
Total weight excl. mackerel	2944.60000	322.600	622.90000
Ratio of total demersal guild : cod	1.85700	11.948	1.85700
Ratio of mackerel : cod	0.00858	2.015	0.00858

Table 8: Finmark and Troms area tourism and recreation catch quantity (tonnes) and composition derived from the data in Table 6 and Table 7.

	Tourist			Recreation			Combined	
Year	Cod	Total Demersal	Mackerel	Cod	Total Demersal	Mackerel	Total Demersal	Mackerel
1984	0	0	0	2479	4603	21	4603	21
1985	0	0	0	2498	4638	21	4638	21
1986	0	0	0	2516	4673	22	4673	22
1987	0	0	0	2516	4673	22	4673	22
1988	0	0	0	2535	4707	22	4707	22
1989	19	35	0	2535	4707	22	4742	22
1990	19	35	0	2684	4984	23	5019	23
1991	19	35	0	2833	5261	24	5296	24
1992	19	35	0	2982	5538	26	5573	26
1993	19	35	0	2740	5088	23	5123	24
1994	19	35	0	2721	5053	23	5088	23
1995	37	69	0	2703	5019	23	5088	23
1996	37	69	0	2665	4950	23	5019	23
1997	56	104	0	2647	4915	23	5019	23
1998	56	104	0	2665	4950	23	5053	23
1999	75	138	1	2516	4673	22	4811	22
2000	93	173	1	2442	4534	21	4707	22
2001	130	242	1	2367	4396	20	4638	21
2002	149	277	1	2386	4430	20	4707	22

Table 8 Continued.

	Tourist			Recreation			Combined	
Year	Cod	Total Demersal	Mackerel	Cod	Total Demersal	Mackerel	Total Demersal	Mackerel
2003	168	312	1	2423	4500	21	4811	22
2004	205	381	2	2293	4257	20	4638	21
2005	224	415	2	2237	4153	19	4569	21
2006	242	450	2	2181	4050	19	4500	21
2007	280	519	2	2143	3980	18	4500	21
2008	298	554	3	2088	3877	18	4430	20
2009	336	623	3	2032	3773	17	4396	20
2010	352	654	3	2015	3742	17	4396	20
2011	370	687	3	1997	3709	17	4396	20
2012	388	721	3	1979	3675	17	4396	20
2013	408	757	3	1959	3638	17	4396	20
2014	428	795	4	1939	3601	17	4396	20
2015	450	835	4	1918	3561	16	4396	20
2016	472	877	4	1895	3519	16	4396	20
2017	496	920	4	1871	3475	16	4396	20
2018	520	967	4	1847	3429	16	4396	20
2019	546	1015	5	1821	3381	16	4396	20
Mean 2011-2019	453	842	4	1914	3554	16	**4396**	**20**

Table 9: Derivation of annual activity for the combined tourism and recreation sectors in the Troms and Finmark regions (hours of gear-in-the-water time). Total catch weight per unit activity (CPUA) for the tourist sector in 2009 was estimated to be 7.86 kg/h (626 tonnes (highlighted in red) as a result of 79,646 hours gear-in-the-water time (see text). This rate was then used to derive the total activity for the combined tourism and recreation sectors (total catch/CPUA). Tourist sector catch and total catch are from Table 8

Year	Tourist sector catch (tonnes)	Total catch (tourist + recreation; tonnes)	Total annual activity (hours of wet gear time)
1984	0	4625	588492
1985	0	4659	592917
1986	0	4694	597342
1987	0	4694	597342
1988	0	4729	601767
1989	35	4764	606191
1990	35	5042	641589
1991	35	5320	676987
1992	35	5598	712385
1993	35	5146	654864
1994	35	5112	650439
1995	70	5112	650439
1996	70	5042	641589
1997	104	5042	641589
1998	104	5077	646014
1999	139	4833	615041
2000	174	4729	601767

Table 9 Continued.

Year	Tourist sector catch (tonnes)	Total catch (tourist + recreation; tonnes)	Total annual activity (hours of wet gear time)
2001	243	4659	592917
2002	278	4729	601767
2003	313	4833	615041
2004	382	4659	592917
2005	417	4590	584068
2006	452	4520	575218
2007	522	4520	575218
2008	556	4451	566368
2009	**626**	4416	561944
2010	657	4416	561944
2011	690	4416	561944
2012	725	4416	561944
2013	761	4416	561944
2014	799	4416	561944
2015	839	4416	561944
2016	881	4416	561944
2017	925	4416	561944
2018	971	4416	561944
2019	1020	4416	561944
Mean 2011-2019	845	4416	561944

Table 10: Annual catches (tonnes) of fish by the artisanal, subsistence and recreational fisheries in Russia, digitised from Figure 2 of Popov & Zeller (2018). Catches have been combined and distributed between planktivorous fish and demersal fish assuming that 50% of recreational catches are salmon and all others are demersal. Annual activity (hours of wet gear time) was estimated by assuming the same catch per unit activity as for the Norwegian tourist fishery (7.86 kg/h).

Year	Artisinal catch	Subsistence catch	Recreational catch	Salmon catch	Demersal fish catch	Total catch incl.salmon	Total annual activity
1984	736	613	123	61	1411	1472	179522
1985	859	736	123	61	1656	1718	210743
1986	613	491	61	31	1135	1166	144398
1987	368	675	61	31	1074	1104	136593
1988	307	552	61	31	890	920	113177
1989	245	491	982	491	1227	1718	156106
1990	123	491	859	429	1043	1472	132690
1991	491	429	3988	1994	2914	4908	370752
1992	1104	368	11166	5583	7055	12638	897610
1993	982	613	8098	4049	5644	9693	718088
1994	613	1104	6258	3129	4847	7975	616619
1995	491	1350	4785	2393	4233	6626	538566
1996	491	1350	5399	2699	4540	7239	577593
1997	491	1227	4908	2454	4172	6626	530761
1998	429	1166	4785	2393	3988	6380	507345
1999	429	1104	4479	2239	3773	6012	480026

Table 10 Continued.

Year	Artisinal catch	Subsistence catch	Recreational catch	Salmon catch	Demersal fish catch	Total catch incl.salmon	Total annual activity
2000	491	1104	5031	2515	4110	6626	522955
2001	736	1104	6135	3067	4908	7975	624424
2002	859	1104	9448	4724	6687	11411	850778
2003	491	1104	6258	3129	4724	7853	601008
2004	307	1104	3497	1748	3160	4908	401973
2005	307	1080	3583	1791	3178	4969	404315
2006	307	1166	3681	1840	3313	5153	421486
2007	368	1288	3926	1963	3620	5583	460513
2008	368	1472	3558	1779	3620	5399	460513
2009	491	1718	4540	2270	4479	6748	569787
2010	491	2025	5828	2914	5429	8344	690769
2011	491	2086	5644	2822	5399	8221	686867
2012	491	2086	5399	2699	5276	7975	671256
2013	613	2086	6503	3252	5951	9202	757115
2014	552	2025	5276	2638	5215	7853	663451
Mean 2011-2014	537	2071	5706	2853	5460	8313	694672

Table 11: Combined data on catches of fish guilds and overall activity for Norwegian and Russian artisanal, subsistence, tourist and recreational fisheries in the Barents Sea, excluding salmon. 'NA' indicates no data for Russia and hence no combined total.

Year	Demersal fish catch (tonnes)	Migratory fish catch (mackerel; tonnes)	Total fish catch (tonnes) excluding salmon	Activity (hours of wet gear time)
1984	6014	21	6036	768014
1985	6295	21	6316	803660
1986	5808	22	5829	741740
1987	5746	22	5768	733935
1988	5597	22	5619	714943
1989	5969	22	5991	762297
1990	6062	23	6085	774279
1991	8210	24	8234	1047739
1992	12628	26	12654	1609995
1993	10767	24	10790	1372952
1994	9935	23	9958	1267058
1995	9321	23	9345	1189005
1996	9559	23	9582	1219182
1997	9191	23	9214	1172350
1998	9041	23	9064	1153359
1999	8584	22	8606	1095067
2000	8818	22	8839	1124722
2001	9546	21	9567	1217341

Table 11 Continued.

Year	Demersal fish catch (tonnes)	Migratory fish catch (mackerel; tonnes)	Total fish catch (tonnes) excluding salmon	Activity (hours of wet gear time)
2002	11394	22	11416	1452545
2003	9535	22	9557	1216049
2004	7798	21	7819	994890
2005	7747	21	7768	988382
2006	7812	21	7833	996704
2007	8119	21	8140	1035731
2008	8050	20	8070	1026881
2009	8874	20	8895	1131731
2010	9825	20	9846	1252713
2011	9795	20	9815	1248811
2012	9672	20	9692	1233200
2013	10347	20	10367	1319058
2014	9611	20	9631	1225395
2015	NA	NA	NA	NA
2016	NA	NA	NA	NA
2017	NA	NA	NA	NA
2018	NA	NA	NA	NA
2019	NA	NA	NA	NA
Mean 2011-2014	9856	20	9876	1256616

EU (including UK) fishing catch and activity in the Barents Sea

The European commission's Scientific, Technical, and Economic Committee for Fisheries (STECF) provide spatially explicit datasets on annual fish catch (https://stecf.jrc.ec.europa.eu/dd/fdi/spatial-land-map) and fishing effort (https://stecf.jrc.ec.europa.eu/dd/fdi/spatial-eff-map) by the fishing fleets of member states around the world. Data is available for the years 2015-2018 by fishing gear. The landings dataset is further resolved by species caught.

The data processing steps were similar to those described above for the Norwegian fishing fleet.

1. Once again we corrected landings and fishing effort according to the overlap between STECF reporting areas and our model domain. We summarised the data available from global fishing watch from 2012-2016 into average annual 0.01° grids of total yearly fishing activity for mobile and static gears. We intersected the polygons representing STECF reporting areaa, and the StathE2E model domain, and calculated the total mobile and static gear activity within each polygon according to GFW. We then calculated the proportion of mobile and static gear activity for each STECF area code which fell within the StrathE2E model domain and scaled the values reported by STECF.

2. We aggregated gears and species to StrathE2E gear types and guilds. Data was totaled within years, then averaged across the target time period. Effort and landings were summed by gear and guild within years.

3. We used the same approach to calculate the proportion of fishing effort across the 8 strathE2E habitat types. Instead of the intersection between the StrathE2E model domain and the STECF reporting regions, we intersected the Barents Sea habitats with STECF reporting regions (Figure 2). We then calculated the proportion of mobile and static gear activity for each reporting region which fell within the StrathE2E habitats.

4. Corrected landings were summed spatially and saved as a matrix by gear and guild. Corrected effort was totaled across area codes and saved by StrathE2E gear types. Corrected effort was also totaled across area codes and saved as a matrix by gears and habitats.

International fishing catch and activity in the Barents Sea

Though we have spatially explicit data of fisheries landings and effort for the Norwegian and EU fishing fleet in the Barents Sea a sizeable portion of activity is missing. The Russian fishing fleet has a notable presence in the Barents Sea according to ICES and GFW. Unfortunately the ICES data does not resolve landings by gear used, and the spatial resolution of landings is coarse. GFW provides only a coarse description of gear types.

International Catch by gear and guild

To approximate international catch we use the ICES data on fisheries landings from our internal database to calculate an inflation factor.

1. We divide the total weight landed per guild in areas 27.1, 27.2.a.2, 27.2.b.2 by the total international catch represented by flags other than Russia.
2. We sum the Norwegian and EU matrices described above, and multiply by the ICES correction factor per guild. This assumes the Russian fishing fleet has a distribution of fishing gears similar to the combined EU and Norwegian fishing fleet.
3. Norwegian seal hunting, and the tourist and recreational catch was added to the international matrix after the application of the inflation factor.

International effort by gear

To approximate international catch we use the GFW data (Kroodsma et al. 2018) to calculate an inflation factor.

1. We divide the total effort by mobile and static gears by the total international effort represented by flags other than Russia. The appropriate correction factors were matched to StrathE2E gear types based on whether they were mobile or static gears (Table 5). The following gears were not inflated as they are unique to the Norwegian fleet: Harpoons, Rifles, Kelp harvesting, Recreational.
2. We sum the Norwegian and EU effort vectors described above, and multiply by the GFW correction factor per gear.
3. The tourist and recreational effort (described above) was added to the international effort after the application of the inflation

factor.

4. Annual hours of fishing effort were then converted into to daily effort in s/m^2.

Proportion of international effort by gear and habitat

To get to the distribution of international fishing effort across habitat types we had to estimate Russian fishing effort before adding to the Norwegian and EU fishing effort by habitat.

1. We calculated the proportion of fishing effort in habitat types by static and mobile Russian gear according to GFW.

2. We estimated the total Russian fishing effort by gear by subtracting the Norwegian and EU fishing effort by gear from the international estimate of fishing effort by gear described above.

3. We distributed the Russian fishing effort across habitats in step 2 according to step 1.

4. We summed the Norwegian, EU, and estimated Russian activity per gear and habitat, and converted to proportions of all effort.

5. We added the spatial distribution of seal hunting (described above), set all kelp harvesting to occur over inshore rock (habitat S0), and distributed recreational and tourist effort across the inshore zone in proportion to the areal extent of the four inshore habitats.

Discard rates

We used the discard data available from STECF as a start point for estimating discard rates in the Barents Sea. We then supplemented this initial set of estimates with data on specific cases of guilds discarded by particular gears. Data on discarding by the Russian and Norwegian fleet were unavailable, so we apply the discard rates derived below to all fishing activity in the Barents Sea.

EU fishing fleet

STECF provides a record of fisheries discards "FDI-catches-by-country" for the years 2015-2019. These records are at a coarser resolution than the data used above for landings and fishing effort. We limited the dataset to records from FAO fisheries areas 27.1.A, 27.1.B, 27.2.A, and 27.2.B, to represent the Barents Sea. Some entries are marked as confidential when there is a risk of identifying specific vessels. This aspect of the dataset is particularly dominant in the Barents Sea, as few EU vessels appear to be active in the area.

For entries with known discard quantities, we calculated the discard rates as $discard/(landings + discard)$ and summarised to mean discard rates for StrathE2E gear classes and guilds over the whole time period. Unrepresented combinations of gear and guild were automatically assigned a discard rate of 0. We manually set the discard rates for a number of guilds which are only targetted by a single specialist gear to 1. These were cetaceans, pinnipeds, birds, and macrophytes. Harpoons for cetaceans, Rifles for pinnipeds, and kelp harvesting for macrophytes were then all assigned a discard rate of 0.

Fish discarded in the Barents Sea shrimp trawl fishery

There are various interpretations of the quantities of fish discarded by the Barents Sea shrimp trawl fishery. First, ICES ((2019b); Figure 0.1) presents graphs of the discard quantity (millions of individuals) of cod, haddock, Greenland Halibut and redfish in the international shrimp trawl fishery in the Barents Sea during 1994-2018. These graphs, which originate from (Breivik, Storvik, and Nedreaas 2017), represent analysis of sampling aboard Norwegian vessels, assuming that these were representative of the international shrimp trawl effort, and an exploration of various statistical methods for extrapolating to the international discard quantities.

However ICES ((2018); Figure 0.1 and Table 3.26) also show interpretations of the quantities of fish discarded in the shrimp trawl fishery, based on unpublished Working Documents by Ajiad et al. (2008). The former shows discards (numbers) of cod, haddock and redfish, while the latter shows numbers at age of cod. Inexplicably, the estimated total numbers of cod discarded in Figure 0.1 and Table 3.26 are highly inconsistent. However, the data in Table 3.26 are consistent with the data from Breivik et al. (2017) in ICES (2019b).

We accepted the data from ICES (2019b) as the best estimate of numbers discarded by the shrimp fishery (Figure 4, Table 12). In order to convert to weight discarded we required estimates of the mean weight per individual of each species. For cod, we calculated mean weight per individual from the numbers at age discarded ((ICES 2018); Table 3.26) and mean weight at age in the wider catch of North East Arctic cod ((ICES 2018); Table 3.8 – with some extrapolation to ages 0, 1 and 2). In the absence of any data on the length or age distribution of discarded haddock or halibut, we were forced to assumed the same mean weight per individual as cod (Table 13).

For redfish discards we first assumed that these were mainly *Sebastes mentella*. Again, in the absence of data on age or length distributions of discarded redfish in the shrimp fishery, we estimated the mean weight at age of *S. mentella* in research vessel trawl hauls during the annual Barents Sea Ecosystem Survey. Numbers at age in the survey of *S. mentella* were obtained from ICES ((2018); Table 6.16b). Mean weight at age from a combination of fishery and survey data was obtained from ICES ((2018); Table 6.7).

The product of annual number per species discarded and mean weight by individual provides an estimate of total weight discarded (Table 14). The results indicate that averaged over 2011-2018 the fishery discarded **3867.89 tonnes** of the planktivorous fish guild, and **1822.57 tonnes** of the demersal fish guild. Clearly these are minimum estimates of guild discards since it is likely that other undocumented bycatch species are also discarded.

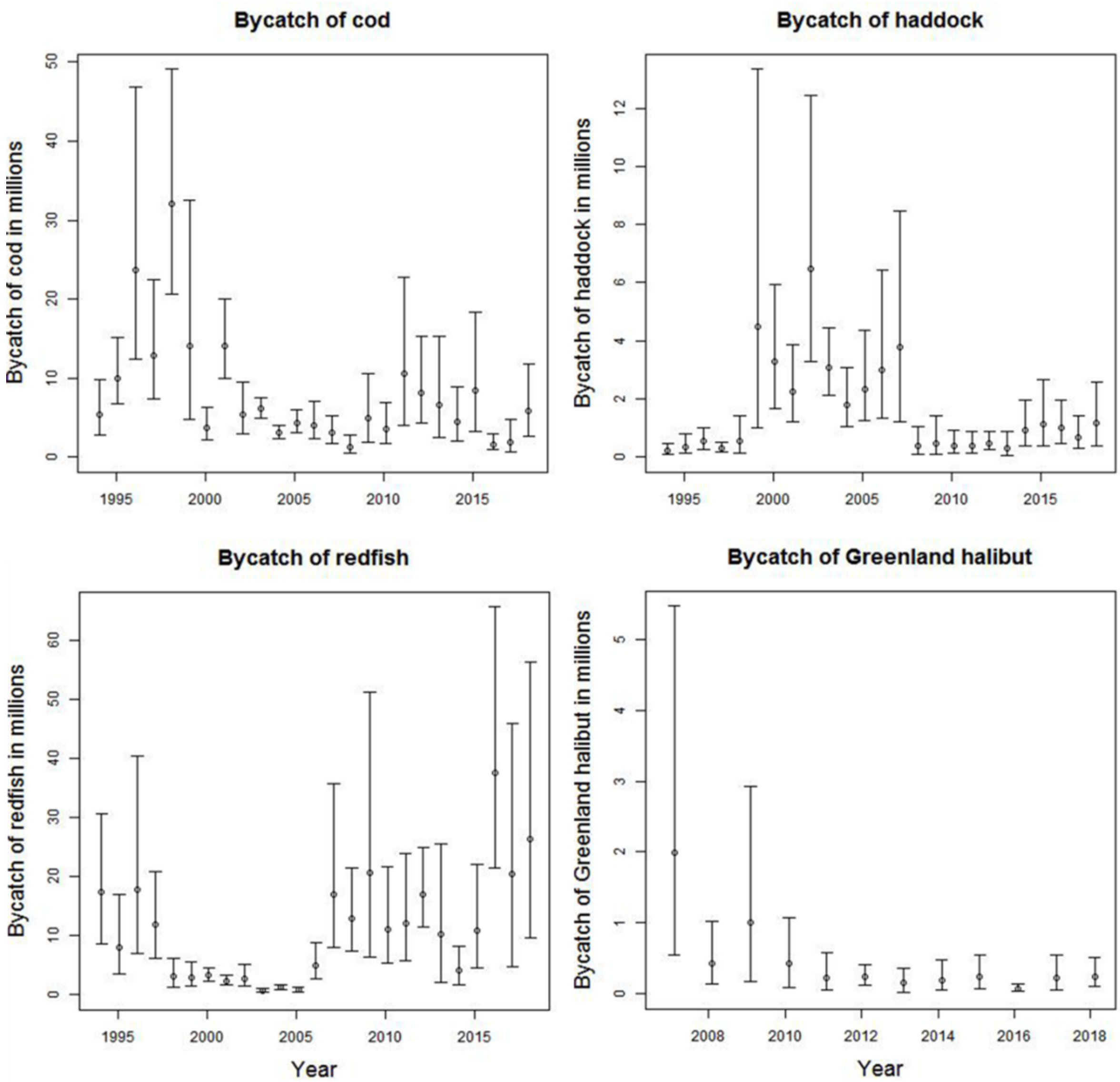

Figure 4: Annual bycatch (discards; millions) from the Barents Sea shrimp trawl fishery. Images from ICES (2019b); Figure 0.1 – "Estimated bycatch of cod, redfish, haddock, and Greenland Halibut in the Barents Sea shrimp fishery. Intervals are 90% confidence intervals." Original data from (Breivik, Storvik, and Nedreaas 2017).

Table 12: Annual mean numbers of cod, haddock, halibut and redfish discarded by the Barents Sea shrimp trawl fishery. “NA” indicates no data. Values are the number discard in millions, digitised from Figure 4.

Year	Cod	Haddock	Redfish	Halibut
1994	5.4487	0.3057	17.5439	NA
1995	9.6154	0.4586	8.0702	NA
1996	23.3974	0.6115	17.8947	NA
1997	12.5000	0.3822	11.5789	NA
1998	31.7308	0.6115	3.1579	NA
1999	13.7821	5.1975	3.1579	NA
2000	3.5256	3.7452	3.5088	NA
2001	13.7821	2.5223	2.4561	NA
2002	5.1282	7.3376	2.8070	NA
2003	5.7692	3.5159	1.0526	NA
2004	2.8846	2.0637	1.4035	NA
2005	4.1667	2.5987	1.0526	NA
2006	3.8462	3.3631	5.2632	NA
2007	2.8846	4.2803	17.1930	2.0055
2008	1.6026	0.4586	12.9825	0.4670
2009	4.8077	0.5350	20.7018	1.0714
2010	3.5256	0.4586	11.2281	0.4670
2011	10.2564	0.4586	12.2807	0.2198
2012	8.0128	0.5350	17.1930	0.2747
2013	6.4103	0.4586	10.5263	0.1923

Table 12 Continued.

Year	Cod	Haddock	Redfish	Halibut
2014	4.1667	1.1465	4.2105	0.2198
2015	8.3333	1.3758	10.8772	0.2473
2016	1.2821	1.2229	37.5439	0.0824
2017	1.6026	0.8408	20.7018	0.2473
2018	5.4487	1.4522	26.6667	0.2747
Mean 2011-2018	5.6891	0.9363	17.5000	0.2198

Table 13: Estimates of annual mean weight per individual for species discarded by the Barents Sea shrimp trawl fishery. Data for cod derived from numbers at age discarded ((ICES 2018); Table 3.26) and mean weight at age in the wider catch of North East Arctic cod ((ICES 2018); Table 3). Redfish discards assumed to be *Sebastes mentella*, with mean weight derived from numbers at age in the annual Barents Sea Ecosystem Survey trawl catches (2018; Table 6.16b) and mean weight at age from ICES ((2018); Table 6.7). Mean weight per individual in discards for haddock and halibut assumed equal to cod.

Year	Cod	Haddock	Redfish	Halibut
1994	0.284	0.284	0.175	0.284
1995	0.245	0.245	0.148	0.245
1996	0.287	0.287	0.165	0.287
1997	0.253	0.253	0.239	0.253
1998	0.264	0.264	0.191	0.264
1999	0.226	0.226	0.246	0.226
2000	0.307	0.307	0.252	0.307
2001	0.250	0.250	0.265	0.250
2002	0.364	0.364	0.283	0.364
2003	0.213	0.213	0.370	0.213
2004	0.252	0.252	0.322	0.252
2005	0.280	0.280	0.390	0.280
2006	0.236	0.236	0.372	0.236
2007	0.266	0.266	0.128	0.266
2008	0.266	0.266	0.107	0.266
2009	0.266	0.266	0.142	0.266
2010	0.266	0.266	0.131	0.266

Table 13 Continued.

Year	Cod	Haddock	Redfish	Halibut
2011	0.266	0.266	0.100	0.266
2012	0.266	0.266	0.224	0.266
2013	0.266	0.266	0.226	0.266
2014	0.266	0.266	0.231	0.266
2015	0.266	0.266	0.234	0.266
2016	0.266	0.266	0.234	0.266
2017	0.266	0.266	0.236	0.266
2018	0.266	0.266	0.236	0.266
Mean 2011-2018	0.266	0.266	0.215	0.266

Table 14: Total annual weight (tonnes) of species and guilds discarded by the Barents Sea shrimp trawl fishery. Species weights derived by the product of Table 12 and Table 13. "NA" indicates no data. Guild discarded weights: planktivorous fish = redfish; demersal fish = cod + haddock + halibut. Demersal fish weights in brackets – partial estimates lacking data on halibut.

					Guild totals	
Year	Cod	Haddock	Redfish	Halibut	Planktivorous	Demersal
1994	1544.90	86.69	3068.61	NA	3068.61	−1631.59
1995	2353.39	112.24	1192.03	NA	1192.03	−2465.64
1996	6724.64	175.74	2952.90	NA	2952.90	−6900.38
1997	3165.39	96.78	2770.10	NA	2770.10	−3262.17
1998	8380.41	161.49	604.71	NA	604.71	−8541.90
1999	3111.16	1173.27	775.94	NA	775.94	−4284.43
2000	1083.79	1151.29	884.43	NA	884.43	−2235.08
2001	3440.86	629.72	650.05	NA	650.05	−4070.58
2002	1869.01	2674.23	793.92	NA	793.92	−4543.25
2003	1228.41	748.62	389.32	NA	389.32	−1977.03
2004	727.46	520.44	452.07	NA	452.07	−1247.90
2005	1164.61	726.36	410.76	NA	410.76	−1890.97
2006	909.24	795.04	1955.84	NA	1955.84	−1704.28
2007	768.04	1139.64	2199.80	533.97	2199.80	2441.66
2008	426.69	122.10	1384.59	124.35	1384.59	673.15
2009	1280.07	142.46	2931.86	285.27	2931.86	1707.80
2010	938.72	122.10	1470.98	124.35	1470.98	1185.18
2011	2730.82	122.10	1227.08	58.52	1227.08	2911.45

Table 14 Continued.

					Guild totals	
Year	Cod	Haddock	Redfish	Halibut	Planktivorous	Demersal
2012	2133.46	142.46	3844.13	73.15	3844.13	2349.06
2013	1706.77	122.10	2382.02	51.20	2382.02	1880.07
2014	1109.40	305.26	971.19	58.52	971.19	1473.18
2015	2218.80	366.31	2548.57	65.83	2548.57	2650.94
2016	341.35	325.61	8786.39	21.94	8786.39	688.91
2017	426.69	223.86	4893.76	65.83	4893.76	716.38
2018	1450.75	386.66	6290.01	73.15	6290.01	1910.56
Mean 2011-2018	1514.75	249.30	3867.89	58.52	**3867.89**	**1822.57**

Additional bycatch in the Barents Sea

Harbour porpoise bycatch in gillnets

The ICES Fisheries Overview of the Barents Sea Ecoregion (ICES 2019a) (page 20) states that “The harbour porpoise is subject to bycatch in the gillnet fishery (targeting cod, monkfish, and saithe), and bycatch is estimated to be around 7000 individuals across the whole area; the impact on population is, however, not known.”

However, the source for this statement (Bjørge, Skern-Mauritzen, and Rossman 2013) reports that “… about 6900 harbour porpoises are taken annually in the **coastal** monkfish and cod gillnet fisheries.” - referring to the whole of Norway not just the Barents Sea (Figure 5).

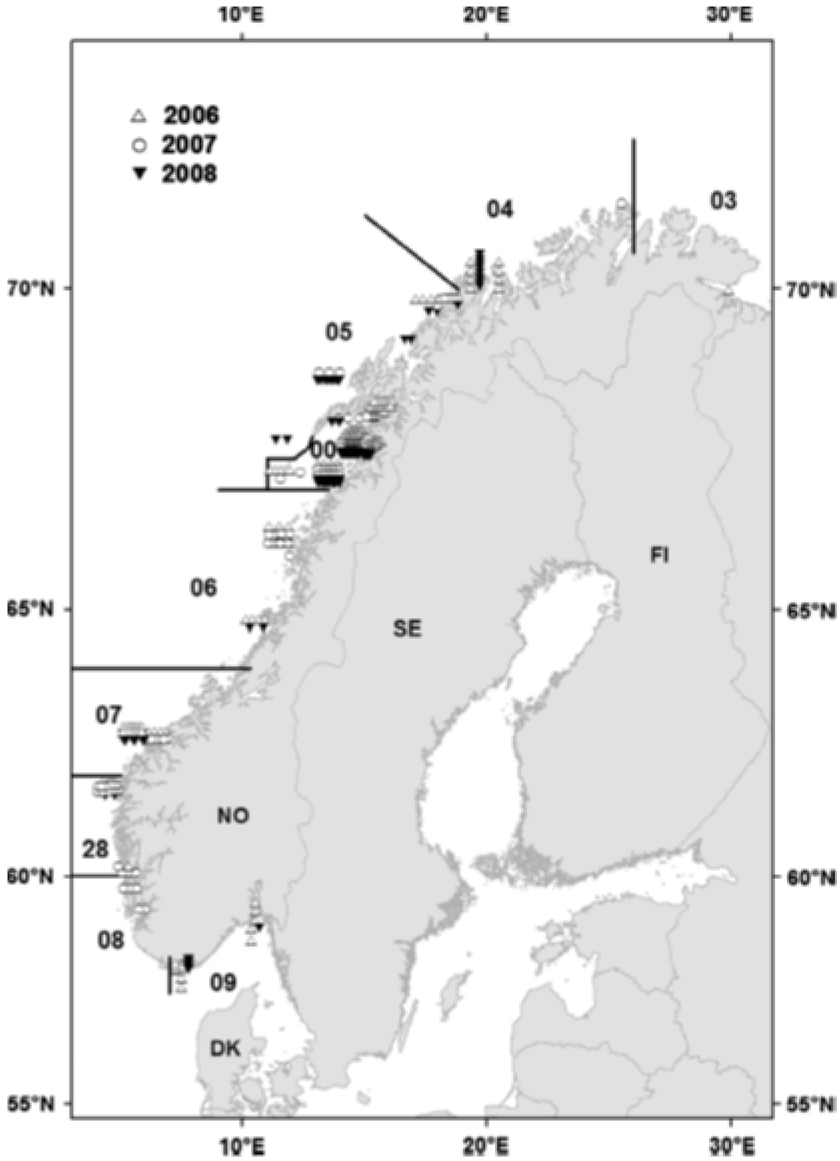

Figure 5: Bjørge et al (2013) Fig.1. Nine domestic Norwegian coastal fishery statistics areas and the distribution of porpoises caught on gillnets set for monkfish or cod by the monitored segment of the fleet (CRF) in 2006, 2007and 2008.

Subsequently, Moan et al (2020) reported that the estimate by Bjørge,et al. (2013) was an overestimate due to an error in fishery landings data. Instead, Moan et al. estimated an annual bycatch of 2871 animals during 2006-2018 for the entire Norwegian costal gillnet fishery.

Moan et al. (2020) provided gillnet bycatch estimates disaggregated by region, which show that the mean annual bycatch in combined areas 3, 4 and 5 during 2006-2018 was 893 animals (95% CI 552–1260). The data indicated that the bycatch rate may have declined over time (2014-2018 bycatch 578 animals, 95% CI 385–889)

We extrapolated the 2006-2018 area 3,4,5 bycatch quantities to the Barents Sea model domain based on the total international gillnet activity in the Barents Sea domain relative to the Norwegian activity in areas 3, 4 and 5, and assuming a uniform catch rate per unit time spent fishing (Table 15).

Table 15: Extrapolation of 2006-2018 inshore porpoise annual bycatch (individuals) to offshore bycatch and total Barents Sea. Conversion to annual bycatch tonnes assuming typical weight of a porpoise = 50 kg. Note that only part of statistical area 5 is within the Barents Sea model domain, which accounts for the fact that Barents Sea gillnet activity is less than that in areas 3, 4, 5.

	Gillnets
2011-2019 annual average Norwegian activity in areas 3, 4 and 5 (hours fishing)	94641.0
2006-2018 annual average porpoise bycatch in areas 3, 4 and 5 (individuals)	893.0
2011-2019 annual average international activity in the Barents Sea model domain (hours fishing)	33489.0
Barents Sea fleet total annual bycatch (ind.)	316.0
Barents Sea fleet total annual bycatch (tonnes)	**15.8**

Pinniped bycatch

The ICES Fisheries Overview of the Barents Sea Ecoregion (ICES 2019a) provides no information on pinniped bycatch rates in the region. However, several publications report sampling and studies of bycatch in the Norwegian coastal gillnet fisheries (Bjørge et al. 2002, 2017; A. G. Moan 2016). The coastal catches are entirely of harbour and grey seals. There are no quantitative data on by bycatches of other pinniped species in offshore waters.

Bjørge et al. (2017) report on three separate threads of evidence for the extent of pinniped bycatch in the Norwegian coastal gillnet fishery for cod and monkfish. First was a mark-recapture study involving tags attached to pups in coastal breeding sites between 1997 and 2014 and returned by gillnet fishers. The data indicated a mean annual bycatch of 555 harbour and 466 grey seals for the Norwegian coast north of 62°N. This study built on earlier tagging work (Bjørge et al. 2002) between 1975 and 1998.

The second thread of evidence was the database of fully documented catches taken by the 'Coastal Reference Fleet' – a subset of the Norwegian coastal fishing fleet recruited to provide complete information on all species and quantities caught (Figure 6). The reference fleet data were extrapolated to the entire fleet using a variety of co-variate models. The analysis indicated a mean annual bycatch of 479 harbour and 84 grey seals in the period 2006-2014.

The third thread was evidence from modelling studies of mortality in populations of harbour and grey seals that could nit be explained by any other cause. This analysis indicated a mean annual bycatch of 150 harbour and 80 grey seals.

Bjørge et al. (2017) considered the mark-recapture data to be the most reliable in terms of total numbers, but lacked spatial granularity. On the other hand the results derived from the reference fleet database provided both spatial and temporal resolution.

We used the data from the reference fleet analysis of Bjørge et al. (2017) (Figure 7) to estimate the proportions of "all-Norway" harbour and grey seals caught in statistical areas 03, 04 and 05 (Table 16). All or part of these areas fall within our Barents Sea model domain. We then applied these proportions to the "all-Norway" estimates of bycatch derived from the mark-recapture data (Table 17). Assuming a mean weight per individual in the bycatch of 60kg for harbour seal and 100kg for grey seal (the captured individuals were mainly young-of-the-year), yields a bycatch weight of both species combined in areas 03, 04 and 05 of 17.5 tonnes.

The annual average Norwegian gillnet effort in areas 03, 04 and 05 derived from data provided by the Norwegian Directorate of Fisheries was 94,641 hours. The estimated international gillnet effort within our Barents Sea model domain was 33,489 hours. Hence the estimated bycatch within the model domain was **6.2 tonnes** (Table 18).

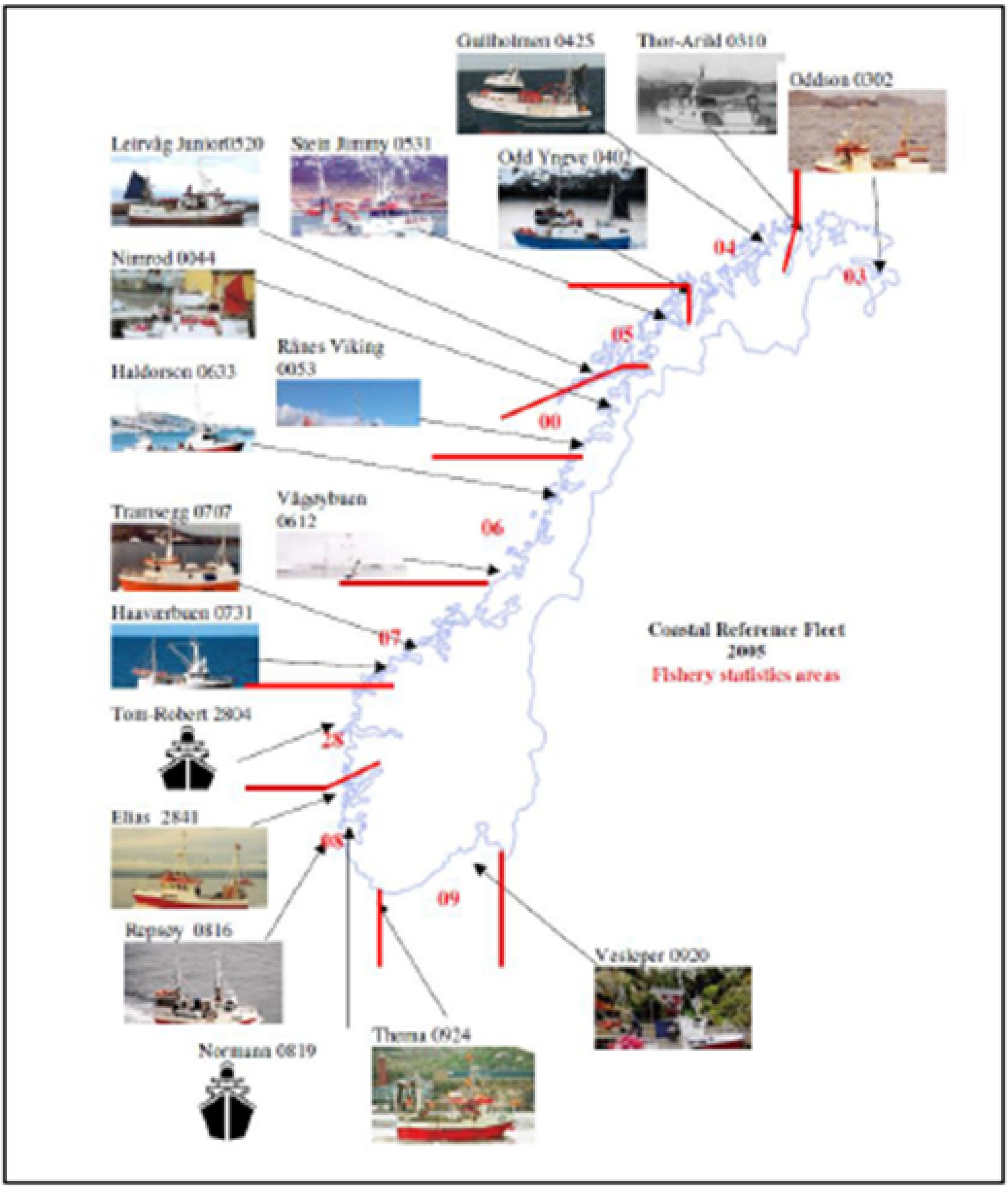

Figure 6: Bjørge et al. (2017) Figure 1. The nine coastal fishery statistics areas (red) and the 18 vessels constituting the Coastal Reference Fleet in 2005-2006.

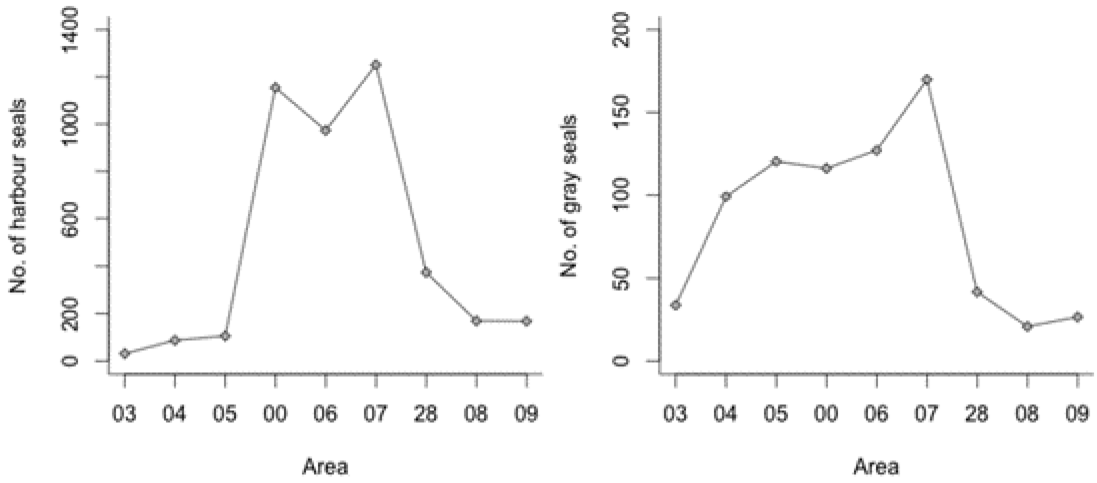

Figure 7: Bjørge et al. (2017) Figure 3. Harbour seal (left) and gray seal (right) bycatch over the 9 year period 2006 – 2014 from GAM models of catch rates in the Norwegian coastal gillnet fleet, aggregated by statistical area.

Table 16: Mean annual seal bycatches by region during the 9 year period 2006-2014. Digitised from Figure 7.

Statistical area	Harbour seals	Grey seals
3	38.000	34.0000
4	88.000	102.0000
5	113.000	121.0000
0	1163.000	116.0000
6	988.000	129.0000
7	1263.000	171.0000
28	388.000	43.0000
8	188.000	20.0000
9	175.000	27.0000
Total 2006-2014	4400.000	763.0000
Mean annual bycatch	489.000	85.0000
Proportion from areas 03, 04 and 05	0.054	0.3372

Table 17: Estimation of the mean annual bycatch weight of harbour seals in areas 03, 04 and 05. The combined bycatch weight of both species is 17.5 tonnes.

	Harbour seal	Grey seal
“All-Norway” mean annual bycatch from mark-recapture	555.000	466.0000
Proportion from areas 03, 04, 05 from reference fleet analysis (Table 1)	0.054	0.3372
Mark-recapture mean annual bycatch from areas 03, 04 , 05	30.000	157.0000
Mean body weight (kg)	60.000	100.0000
Bycatch weight in areas 03, 04, 05 (tonnes)	1.800	15.7000

Table 18: Extrapolation of areas 03, 04, 05 pinniped annual bycatch (tonnes) to total Barents Sea. Note that only part of statistical area 5 is within the Barents Sea model domain, which accounts for the fact that Barents Sea gillnet activity is less than that in areas 3, 4, 5.

	Gillnets
2011-2019 annual average Norwegian activity in areas 03, 04, 05 (hours fishing)	94641.0
1997-2014 annual average pinniped bycatch in areas 03, 04, 05 (tonnes)	17.5
2011-2019 annual average international activity in the Barents Sea model domain (hours fishing)	33489.0
Barents Sea fleet total annual bycatch (tonnes)	**6.2**

Seabird bycatch

The ICES Fisheries Overview of the Barents Sea Ecoregion (ICES 2019a) provides little advice on seabird bycatch rates in the region. The report states that although “gillnet fishing primarily affects coastal and pelagic diving seabirds, while the surface-feeding species will be most affected by longline fishing,” documentation of the scale of bycatch is incomplete”. The overview cites one publication on the issue (Fangel et al. 2011). However, there are some more recent publications which have advanced knowledge of seabird bycatch.

Fangel et al. (2011) was a preliminary report on numbers of birds captured in coastal gillnet fisheries for cod and lumpsucker off northern Norway (northern Nordland, Troms and Finnmark regions), and in the Greenland halibut longline fishery in the same area. The results were presented in terms of bycatch per unit catch weight of the target species in these fisheries (Table 19).

Subsequent work and more extensive sampling by the same and additional authors (Fangel et al. 2015, 2017; Bærum et al. 2019) have greatly extended the observational database and understanding. Primarily, there is no evidence for a correlation between seabird bycatch and the catch rate of target fishery species. Hence, all subsequent data are presented in terms of bycatch per trip, or per net for gillnet fisheries, or per 1000 hooks in longline fisheries (Table 20).

In all studies, the primary species caught in the gillnet and longline fisheries have been Northern fulmar and Common guillemot, but other species include cormorants, black guillemots, Atlantic puffins and razorbills.

Not all studies have provided fleet annual bycatch estimates, based on extrapolating from the sampled subset of vessels to the whole fleet, or at least not at a spatial granularity which allows us to extract values for the Barents Sea coast. Data identifiers 6, 7, 8 and 9 in Table 19 provide robust estimate of fleet annual bycatch in the Nordland/Troms/Finmark region (statistical areas 2, 4 and 5) or 4 distinct fisheries (Table 20).

Raw data provided by Bærum et al. (2019) show that the majority of sampling by the available studies has been from vessels operating within 35km of the coast, i.e. within the inshore zone of the StrathE2E model. We have been unable to find any significant sampling for offshore areas. Hence we extrapolated the bycatch quantities by Norwegian vessels in statistical areas 3, 4 and 5 to the international fleets of equivalent gears operating in our Barents Sea model domain, assuming a uniform catch rate per unit time spent fishing (Table 21).

Table 19: Assembled data on seabird bycatch in coastal Norwegian fisheries. Articles: 1, (Fangel et al. 2011); 2, (Bærum et al. 2019); 3. (Fangel et al. 2015); 4, (Fangel et al. 2017). Sampling area 3, Finmark; 4, Troms; 5, Vesterålen. Values from article 2 were extracted from raw data. Fleet annual bycatch: NA = no estimate provided. The main bird species caught in all studies were fulmar and guillemot.

Id	Gear	Target	Bycatch per unit effort	Units	Fleet annual bycatch	Comments
Article 1 - 2009:2010 - Fishery areas: 3, 4, 5						
1	Gillnet	Cod	0.070	birds/tonne cod	NA	Preliminary study
2	Gillnet	Lumpsucker	0.693	birds/tonne lumpsucker	NA	Preliminary study
3	Longline	Greenland halibut	0.759	birds/tonne halibut	NA	Preliminary study
Article 2 - 2006:2015 - Fishery areas: 2, 3, 4						
4	Gillnet	Cod? not specified	0.139	birds/trip	NA	Annual bycatch estimate only provided for the whole Norwegian coast
Article 3 - 2009 - Fishery areas: 3, 4, 5						
5	Longline	Halibut	1.900	birds/trip	1500	Small sample size
6	Longline	Cod/haddock	0.220	birds/trip	3300	Robust annual estimate
7	Gillnet	Lumpfish	1.600	birds/trip	3200	Robust annual estimate
8	Gillnet	Cod	0.100	birds/trip	3300	Robust annual estimate
Article 4 - 2012:2014 - Fishery areas: 3, 4, 5						
9	Longline	Greenland halibut	0.240	birds/trip	153	Robust annual estimate

Table 20: Fleet annual bycatch (numbers of individuals) for coastal fisheries in northern Norway (areas 3, 4 and 5), extracted from Table 22.

Fishery	Annual seabird bycatch
Gillnet fishery for cod	3300
Gillnet fishery for lumpsucker	3200
Longline fishery for cod and haddock	3300
Longline fishery for Greenland halibut	153
Total gillnets	**6500**
Total longlines	**3453**

Table 21: Extrapolation of areas 3, 4 and 5 seabird annual bycatch (individuals) by gear, to total Barents Sea bycatch. Conversion annual bycatch tonnes assuming typical weight of fulmar = 0.805 kg; guillemot = 0.947 kg, and equal numbers of each species. Note that only part of statistical area 5 is within the Barents Sea model domain, which accounts for the fact that Barents Sea gillnet activity is less than that in areas 3, 4, 5.

	Gillnets	Longlines
2011-2019 annual average Norwegian activity in areas 3, 4 and 5 (hours fishing)	94641.000	169675.000
Annual average seabird bycatch in areas 3, 4 and 5 (individuals)	6500.000	3453.000
2011-2019 annual average international activity in the Barents Sea model domain (hours fishing)	33489.000	382537.000
Barents Sea fleet total annual bycatch (individuals)	2300.000	7784.000
Barents Sea fleet total annual bycatch (tonnes)	**2.015**	**6.819**

Final processing

1. Total catch by gear and guild was calculated by inflating landings according to EU discard rates before adding additional known discarded weight (described above for cetaceans, birds, planktivores and demersal fish).

2. Discarded weight was calculated as catch - landings.

3. Demersal non quota and quota limited were combined into a single Demersal guild for catch, landings and discards.

4. New discard rates reflecting all data sources were calculated as discarded weight / caught weight. When catch was 0 discard rates were set to 1 except for kelp harvesters which were assigned a discard rate of 0 for macrophytes.

5. Fishing power was calculated as catch / activity per gear.

End

Acknowledgements

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