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Research

Radiocarbon Releases to the Kattegat

2026:15

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SSM's perspective

Background

Carbon-14 (^{14}C) is an important radionuclide from a radiation protection point of view as it often dominates the dose to the public from activities such as operation of nuclear power plants, reprocessing of spent nuclear fuel and storage of radioactive waste. Unlike most other radionuclides (metals), redistribution and accumulation in the marine ecosystems of ^{14}C cannot be described as easily with a distribution coefficient (Kd). Carbon (C), and thus the radionuclide ^{14}C, is highly bioavailable and taken up during photosynthesis by primary producers (phytoplankton and macro algae). From the primary producers, the ^{14}C is transferred to other parts of the marine ecosystem. In addition to being biologically active, ^{14}C is also part of the seasonal carbonate cycle in the sea and is controlled by the seawater's seasonal variations in temperature, pH, etc., and thus a varying exchange of carbon (^{14}C) between sea surface and air. These properties of ^{14}C involve specific modelling methods compared to other radionuclides when estimating doses to humans and the environment. Due to a general lack of data regarding ^{14}C in the environment around nuclear facilities, the possibilities to validate dose models for ^{14}C in general are limited.

The Radiation Safety Authority (SSM) in 2021 announced funds for research within the field of radioecology linked to models for calculating concentrations of ^{14}C in the marine environment. The overall purpose of the project was to develop the national and international ability to calculate the dose to humans and the environment from ^{14}C by development of models and to assess the ability of the models to predict levels of ^{14}C in the marine ecosystem.

Results

In the research project an ecosystem model, developed within the Ecopath with Ecosim software suite, was applied to predict the levels of ^{14}C in the marine ecosystem in Kattegat on the Swedish west coast were Ringhals nuclear power plant (NPP) discharges. Using an ecosystem model to predict radionuclide uptake and transfer in the environment is still very novel. To the authors knowledge this is the first study to model discharges of a radionuclide in a spatially resolved dynamic ecosystem model with multiple environmental drivers forcing ecosystem changes. Although further work is required to assess the modelled ecosystem dynamics, it is apparent that the model captures the trends observed during the calibration period up to 2008. Tracing ^{14}C discharged by Ringhals Nuclear Power Plant in the time dynamic module Ecosim shows consistent output up to the end of the model simulations in 2025 indicating minimal model uncertainty.

Results are provided for predicted ^{14}C activities in the marine biota of the Kattegat as a result of discharges from Ringhals nuclear power plant using the dynamic ecosystem model developed within the Ecopath with Ecosim software suite. The ecosystem model was calibrated for the period 1982-2009 and is shown to predict the key ecosystem changes that have been observed in the Kattegat. Using the time dynamic ecosystem model Ecosim with the contaminant tracing Ecotracer plug-in, the mean ^{14}C activity for biota in the entire Kattegat was predicted to increase by up to 7 Bq $kg^{-1}C$ due to atmospheric and marine discharges from Ringhals up to the year 2025. To predict ^{14}C activities in specific areas of the Kattegat, the ecosystem model was spatially resolved using the Ecospace module with multiple environmental drivers forcing biomass changes and movement through the model space. Two Intergovernmental Panel on Climate Change (IPCC) scenarios were also introduced in addition to changes in nutrient loading to create best-case and worst-case scenarios and model simulations were projected to 2050. Predicted ^{14}C activities were highest at the discharge point and in areas directly north of the discharge point where accumulations occurred against the coastline and at mouths of fjords, particularly the Kungsbacka Fjord.

The highest predicted contribution to biota of ^{14}C activity from Ringhals was approximately 200 Bq $kg^{-1}C$, however more typical increases of 10 – 25 Bq $kg^{-1}C$ were predicted. Model resolution meant that the fjords themselves were not included in the model and these appear to be the most likely regions for increased activities due to accumulations of discharged ^{14}C.

The predicted ^{14}C activities up to 2025 in both Ecosim and Ecospace appear to be reliable within the constraints of the quality of the data that were input to the model and the model limitations themselves. The small increase in ^{14}C predicted in Ecosim for the entire Kattegat ecosystem as a result of discharges from Ringhals is reasonable. Larger increases have been observed and modelled in, for example, the Irish Sea, however discharges from the Sellafield nuclear fuel reprocessing facility have historically been orders of magnitude higher. Increased activities closer to the source of discharges would be expected and are shown in the Kattegat Ecospace model and the range in values also appear to be reasonable.

Relevance

In addition to ^{14}C being the dominating radionuclide contributing to dose, it accumulates and is transferred in a different way in ecosystems than the typical radionuclide (a metal). Calculation models for ^{14}C need to describe this correctly and these models need to be validated against measured data for ^{14}C, in order to estimate and assess risk for the public and environment. This project has demonstrated a way to model ^{14}C discharges in a spatially resolved dynamic ecosystem with multiple environmental drivers forcing ecosystem changes. The results will contribute to better risk assessments for public and environment in marine ecosystems and the results will be useful within permit review and supervision and disseminate the information to authorities that regulate similar activities.

Need for further research

Need for further research with regard to this specific project would be to test the model output, to a larger reliable dataset of ^{14}C activities in a range of biota from the region, ideally obtained from the vicinity of Ringhals and of the coastal region north of Ringhals, including Kungsbacka Fjord. Further research in order to untangle the source terms and contributions of ^{14}C to the area from other sources, particularly Sellafield and the La Hague reprocessing facilities would also be needed.

Further modelling studies should initially focus on reducing model uncertainty. For modelling the very recent past and future this would involve increasing the ecosystem calibration period towards the present day. There is also additional software development required for EwE so that Ecotracer can handle extreme events in the ecosystem predictions. The use of dynamic ecosystem models will enable possibilities to predict ^{14}C levels in changing ecosystems. Ecosystems do change (not least caused by climate change), biota presence in an area will vary and changes to the flow of a contaminant or tracer will occur as a result and to capture this requires the use of dynamic ecosystem models in order to make reliable predictions.

Present national and international regulation means that operators of nuclear facilities not only need to demonstrate that humans are protected, but also the environment, and so-called ecosystem services. Further research of how dynamic ecosystem models could be applied in this context will contribute to this area where methodology is under development.

Project information

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Summary

Results are provided for predicted ^{14}C activities in the marine biota of the Kattegat as a result of discharges from Ringhals nuclear power plant using a dynamic ecosystem model developed within the Ecopath with Ecosim software suite. The ecosystem model was calibrated for the period 1982-2009 and is shown to predict the key ecosystem changes that have been observed in the Kattegat. Using the time dynamic ecosystem model Ecosim with the contaminant tracing Ecotracer plug-in, the mean ^{14}C activity for biota in the entire Kattegat was predicted to increase by up to 7 Bq $kg^{-1}C$ due to atmospheric and marine discharges from Ringhals up to the year 2025. To predict ^{14}C activities in specific areas of the Kattegat, the ecosystem model was spatially resolved using the Ecospace module with multiple environmental drivers forcing biomass changes and movement through the model space. Two IPCC scenarios were introduced in addition to changes in nutrient loading to create best-case and worst-case scenarios and model simulations were projected to 2050. Predicted ^{14}C activities were highest at the discharge point and in areas directly north of the discharge point where accumulations occurred against the coastline and at mouths of fjords, particularly the Kungsbacka Fjord. The highest predicted contribution to biota ^{14}C activity from Ringhals was approximately 200 Bq $kg^{-1}C$, however more typical increases of 10 – 25 Bq $kg^{-1}C$ were predicted. Model resolution meant that the fjords themselves were not included in the model and these appear to be the most likely regions for increased activities due to accumulations of discharged ^{14}C. Although there were some differences between the modelled IPCC scenarios, it was difficult to draw any conclusions from the effect of these scenarios due to increased model uncertainty causing unrealistic predictions for ^{14}C activities towards the end of the model runs. Despite this, model output up to 2025 was reasonable. Further work should try to address the software issues that were encountered. In addition, it is recommended that a body of analytical work is conducted to measure ^{14}C activities in a range of biota from the region to test the model predictions. The model together with data to validate the predictions has the potential to be a valuable tool to aid management and monitoring of discharges of ^{14}C to the Kattegat marine environment.

Sammanfattning

Resultat i form av ^{14}C-aktivitet i Kattegatts marina biota som ett resultat av utsläpp från Ringhals kärnkraftverk beräknas med hjälp av en dynamisk ekosystemmodell utvecklad inom mjukvarupaketet Ecopath med Ecosim. Ekosystemmodellen kalibrerades för perioden 1982-2009 och förutsäger de viktigaste ekosystemförändringarna som har observerats i Kattegatt. Med hjälp av den tidsdynamiska ekosystemmodellen Ecosim och insticksprogrammet Ecotracer för spårning av föroreningar, förutspåddes den genomsnittliga ^{14}C-aktiviteten för biota i hela Kattegatt öka med upp till 7 Bq $kg^{-1}C$ på grund av atmosfäriska och marina utsläpp från Ringhals fram till år 2025. För att förutsäga ^{14}C-aktiviteter i specifika områden i Kattegatt användes Ecospace-modulen för att representera området rumsligt. Ecospace drivs av flera miljöparametrar som genererar rumsliga biomassaförändringar och rörelser i aktuellt område. Utöver förändringar i näringsämnesbelastningen tillämpades också två IPCC-scenarier för att skapa bästa- och värsta-fall-scenarier. IPCC-scenarierna projicerades i modellsimuleringar till 2050. Resultaten från simuleringarna visade att ^{14}C-aktiviteter var högst vid utsläppspunkten och i områden direkt norr om utsläppspunkten där ansamlingar förekom mot kusten och vid mynningar av fjordar, särskilt Kungsbackafjorden. Den högsta ^{14}C-aktivitet, orsakat av utsläpp från Ringhals, som simulerades i biota var cirka 200 Bq $kg^{-1}C$. Men mer typiskt låg ökningar på 10 – 25 Bq $kg^{-1}C$. Modellupplösningen innebar att själva fjordarna inte ingick i modellen och dessa verkar vara de mest sannolika regionerna för ökade aktiviteter på grund av ansamlingar av utsläppt ^{14}C. Även om det fanns vissa skillnader mellan de modellerade IPCC-scenarierna, var det svårt att dra några slutsatser från effekten av dessa scenarier på grund av ökad modellosäkerhet som orsakade orealistiska förutsägelser för ^{14}C-aktiviteter mot slutet av modellkörningarna. Trots detta var modellproduktionen fram till 2025 rimlig. Ytterligare arbete bör försöka lösa de programvaruproblem som uppstod. Dessutom rekommenderas det att ett analysarbete utförs för att mäta ^{14}C-aktiviteter i en rad biota från regionen för att testa modellförutsägelserna. Modellen tillsammans med data för att validera förutsägelserna har potential att vara ett värdefullt verktyg för att hjälpa till att hantera och övervaka utsläpp av ^{14}C till Kattegatts marina miljö.

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1. Background

The Ringhals nuclear power plant is located on the Kattegat (Fig. 1) and is authorised to release ^{14}C, produced during routine operations, to the atmosphere and to the marine environment. The radionuclide ^{14}C is a weak beta emitter and releases of it are not considered to pose any radiological risk. However, ^{14}C has a long half-life, is highly bioavailable and is, therefore, a large contributor to collective dose from civil nuclear activities (UNSCEAR 2008). A body of work has shown that discharges of ^{14}C in the UK resulted in increased ^{14}C activities through the marine ecosystem (e.g., Muir et al., 2017; Tierney et al., 2017a, 2017b) and was modelled using the Ecopath with Ecosim (EwE) software suite (Tierney et al., 2018). Work by Mattsson et al. (2022) has shown that ^{14}C activities in seaweeds are consistently higher than the expected background at sites south of Ringhals and this is likely to be due to discharges from Ringhals as well as the Sellafield and La Hague nuclear fuel reprocessing facilities. The authors were assigned by the Swedish Radiation Safety Authority to develop a model to predict marine biota uptake of ^{14}C released from the Ringhals nuclear power plant.

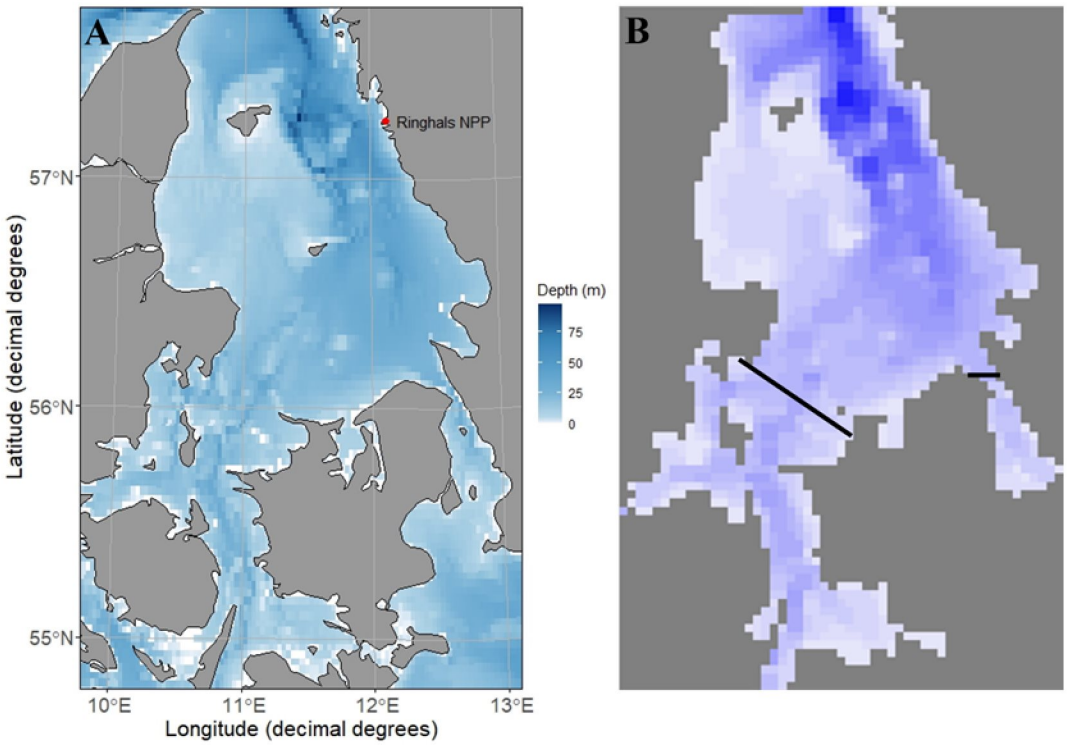


Figure 1. A) Bathymetric map of the Kattegat area showing the location of the Ringhals nuclear power plant and B) the Kattegat as defined in the model domain. The areas below the black lines, Great Belt in the southwest and Øresund in the southeast, were removed from model calculations.

1.1. The Kattegat marine environment

The Kattegat is situated between the North and Baltic Seas (Fig. 1) and forms an ecological transition zone between the two areas (Andersson, 1996; ICES, 1998). Apart

from a deeper central trench along the Swedish coast (>90 m), the area is relatively shallow (mean depth of 23 m) with an extensive shelf area (depths of ~10 m) covering most of the western region bordering Denmark. Although the northern boundary with Skagerrak is broad, the narrow southern straits of the Sound and Belt Sea restrict water exchange, causing highly variable hydrographic conditions, largely dependent on wind patterns, river run-off, sea-level variations, and atmospheric pressure (Danielsson et al., 2004). The hydrodynamic regime is dominated by the northward flow of the brackish Baltic surface current and an opposite southern flow of high saline bottom water from the North Sea (Pedersen, 1993), resulting in a strong northwest-southeast salinity gradient and a permanent halocline at approximately 15 m (Gustafsson, 2000).

The Kattegat ecosystem experienced a regime-shift phenomena between the late 1980s and early 1990s, from a pelagic-dominated state to a benthic-dominated state (Lindegren 2012). This was caused by climate and anthropogenic effects, especially fishing and management intervention to reduce nutrient enrichment. These changes in food-web structure resulted in changes to energy transfer pathways from primary producers to the higher trophic levels.

2. Methods

Models were developed using the Ecopath with Ecosim (EwE) ecosystem modelling suite (Christensen et al., 2005). EwE was previously used to model a hypothetical release of ^{14}C in the Baltic Sea (Sandberg et al., 2007) and releases from the Sellafield nuclear fuel reprocessing plant to the Irish Sea (Tierney et al., 2018). It has shown strong capability to model the dynamic flow of ^{14}C through a food-web including the effect of time-integrated ^{14}C activity and that the ^{14}C activity in an organism is strongly affected by the trophic level from which it feeds (Tierney et al., 2018). The software comprises of the predator-prey food-web model (Ecopath), the temporal dynamic extension (Ecosim), a spatial and temporal dynamic module (Ecospace), and the Ecotracer plug-in to model the uptake and transfer of contaminants in the food-web. Two different types of simulations were conducted for this work, 1) temporal dynamic simulations using Ecotracer and Ecosim where the Kattegat was considered as a single box to provide average values for the entire region; and 2) Ecotracer and Ecospace where the Kattegat region was spatially resolved. Model development followed the approach in Tierney et al. (2018), however, there are a number of significant differences including the addition of multiple environmental drivers that force dynamic changes to the modelled biota in Ecosim and Ecospace. A summary of how the model was parameterised is provided below.

2.1. Ecopath

The mass-balance food-web model was parameterised to describe the Kattegat ecosystem in 1982. Primary producers are represented by phytoplankton (spring and other), macroalgae, and seagrass. The planktonic groups are also represented by mesozooplankton (copepods and cladocerans) and gelatinous zooplankton. The benthic community was split into seven groups: meiofauna, molluscs (blue mussel, clam etc), shrimps and mysids, crustaceans (mainly crabs), nephrops (Norway lobster), polychaeta, and echinodermata. There are fourteen functional groups of fish: sprat, herring, sandeel, Norway pout, blue whiting, whiting, flounder, dab, sole, plaice and cod. To represent the ontogenetic diet composition changes of three fish species (cod,

plaice and whiting), younger and older age stanzas (aggregated age groups) were used according to the procedure in Walters et al. (2008). Top predators are represented by grey seals, harbour porpoise and fish-eating birds. The human impact was indicated by using fishing effort for the following fishing activities: gillnets, trammel nets, bottom otter trawls, pelagic otter trawls, bottom pair trawl and anchored seine.

The biomass (B), production rate (P/B), consumption rate (Q/B) and diet composition were provided for all functional groups, except for fish that were split into younger and older age stanzas where B and Q/B were given for the oldest stanza only and the total mortality (Z) for all stanzas. Moreover, for each fish species ecological parameters were introduced: growth rate (k) from the von Bertalanffy growth function, the ratio of the weight at maturity to the weight at infinity (W_{mat}/W_{inf}) and the relative biomass accumulation (BA/B). The age of stanza was structured separately for the different fish species related to their specific spawning time and life history. The PreBal approach (Link, 2010), a set of diagnostic tools ensuring that the modelled trophic flows are realistic in relation to ecological theory, was applied to the multiple trophic levels. Model development was guided by the best practices set out in Heymans et al. (2016). Further information on Ecopath equations, capabilities and limitations can be found in Christensen (2005); Christensen and Walters (2004); and Pauly et al. (2000).

2.2. Ecosim

The Ecosim module (Walters et al., 1997) was used to analyse the temporal dynamics of the Kattegat food-web and calibrated for the period 1982 to 2009. Calibration data includes biomass (surveys and models) on almost all trophic levels, fisheries catches and landings, and concentrations of chlorophyll-a for primary productivity. Model dynamics are driven by predator-prey relationships between functional groups, fishing effort, functional group responses to environmental forcing (primary productivity, sea surface temperature, salinity, oxygen concentration) and forcing seal biomass as a proxy of top-predator predation. Using a Monte Carlo routine, 2000 model simulations were conducted to check model uncertainty.

2.3. Ecospace

Ecospace is represented by a set of water and land grid cells. Functional groups and fisheries interact within the water cells according to modified versions of the Ecosim equations. Habitat capacity for a functional group within a cell depends on the values of environmental drivers in a cell and the group's response function to these. Upon initialisation in Ecospace, functional group biomasses are distributed based on their respective habitat capacity values. These biomass distributions change in the following time-steps due to the interplay of food-web interactions, fishing, and species dispersal until Ecospace reaches spatial equilibrium. By including a model "spin-up" period, spatial equilibrium was reached before the actual model simulation ran. Spatial migration among cells is represented by redistributing the functional groups' biomasses among cells with a speed depending on their basal migration rate. Relative habitat capacity is inversely proportional to the rate of migration out of grid cells, as organisms are assumed to be less likely to leave habitats with higher capacity and more likely to migrate out of habitats with lower capacity. Fishing fleet efforts are distributed among cells based on the attractiveness of each cell for the fleet. Fishing mortality caused by each fleet on its target species in each cell is proportional to its fishing effort in that cell. Further information on the Ecospace module can be found in Christensen et al. (2014).

The Kattegat marine environment was spatially resolved in a 4x4 km grid (Fig. 1). A series of spatially and temporally resolved environment drivers were developed and are listed in Table 1. Maps were generated for each environmental driver in Ecospace and were derived from either the outputs of the RCO-SCOBI model (Eilola et al., 2009) or published by the HELCOM Map and Data Service (www.helcom.fi). These environmental drivers were loaded into Ecospace on a monthly time-step using the EwE spatial-temporal framework (Steenbeek et al., 2021). Information on the responses of species to abiotic factors were collected from prior studies to parametrise environmental response functions for functional groups (Clemmesen et al., 2016 and references therein).

Table 1. Ecospace environmental drivers

Ecospace Environmental Driver	Description
Bathymetry	In metres
Sea Surface Salinity	Annual mean salinity at sea surface in psu
Sea Bottom Salinity	Annual mean salinity at sea bottom in psu
Sea Surface Temperature	Annual mean sea surface temperature in °C
Summer Sea Surface Temperature	Mean sea surface temperature in summer in °C
Sea Bottom Temperature	Annual mean sea bottom temperature in °C
Midwater Spring Temperature	Mean temperature at 50 m depth in spring in °C
Bottom Oxygen Concentration	Annual mean in ml/l
Bottom Oxygen Saturation	Annual mean %
Low Oxic Area	Areas of oxygen concentration between 0.5 – 2 ml/l
Hypoxia	Areas of oxygen concentration below 0.5 ml/l
Mud	Areas of benthic substrate dominated by mud
Sand	Areas of benthic substrate dominated by sand
Primary Productivity	Ratio of productivity (measured in chlorophyll-a concentration) to phytoplankton biomass

2.4. Ecotracer

The uptake and transfer of ^{14}C within the Kattegat ecosystem was modelled using the Ecotracer module whilst the biomass dynamic equations of Ecosim and Ecospace were solved in parallel (Walters and Christensen, 2018). The only input of ^{14}C into the model were the discharges from Ringhals nuclear power plant and the output should therefore be considered as excess ^{14}C in addition to other sources including background. Background ^{14}C for the Kattegat is assumed to be approximately 249 Bq $kg^{-1}C$, a value reported for the non-Sellafield influenced east Atlantic (Tierney et al. 2016). However, background ^{14}C does vary in time and space, largely due to the effect of decreasing concentrations since a peak that occurred as a result of atmospheric nuclear weapons testing in the 1960s. Discharges from Ringhals to the atmosphere were assumed to enter the CO_2 pool and marine discharges were assumed to enter the marine dissolved inorganic carbon (DIC) pool.

Modelled ecosystem uptake of ^{14}C was parameterised as being by primary producers only (phytoplankton, macroalgae and seagrass) with photosynthesis as the only route that inorganic ^{14}C can be incorporated into organic tissues. Initially an equilibrium model was established as biota ^{14}C activity (Bq kg^{-1} C) will be in equilibrium with the ambient ^{14}C activity and this allows uptake and loss parameters for each functional group to be calculated. For the purposes of this model, environmental activity was calculated for DIC and based on the background value of 249 Bq kg^{-1} C (Tierney et al., 2016) and an average DIC mass for the Kattegat of 13,318 kilotons (Gustafsson et al., 2017). Direct uptake of ^{14}C was calculated for primary producers from their

productivity rates, assuming that ^{14}C uptake is identical to uptake of stable carbon and calculated using the following equation:

$$Direct\ uptake = u_i/B_i/C_0$$

Where ui is the mass of carbon intake by primary producer i, Bi is the biomass and C_0 is the DIC ^{14}C activity. The metabolic decay rate is the rate at which assimilated ^{14}C is released back into the environment. For primary producers this can be calculated where the equilibrium ratio of ^{14}C in a primary producer is equal to the environmental concentration and expressed as:

$$Metabolic\ decay\ rate = D_i.C_0/(\frac{C_i}{B_i})$$

Where D_i is the direct uptake rate for the primary producer i, C_0 is the DIC ^{14}C activity, C_i is the ^{14}C activity of the primary producer and Bi is the biomass. It was assumed there was no direct uptake for consumers and metabolic decay was initially estimated using model calculated respiration rates and adjusted to an equilibrium status. All Ecotracer parameters from this equilibrium model were used for both Ecosim and Ecospace Kattegat models.

2.4.1. Ecotracer in Ecosim

Ecotracer simulations ran in Ecosim treat the Kattegat marine ecosystem as a single entity and provides output that should be considered as averages for the entire area. Input of ^{14}C to the model in Ecosim was considered from both atmospheric and marine discharges. Data was provided by the Swedish Radiation Safety Authority for atmospheric discharges on an annual basis between 2002 and 2020, and monthly discharges from January 2014 to December 2020 and marine discharges of 1% of the atmospheric discharge value. For simulation periods before and after the period of known discharges, the average annual discharge between 2002 and 2020 of 0.98 TBq was used. It should be noted that due to the shutdown of two of the reactors at Ringhals nuclear power plant, it is likely that this value is an overestimate for discharges since 2020.

Using a model estimate for the average net CO_2 uptake in the Kattegat of 0.45 Tg C per year (Gustafsson et al., 2015), Kattegat uptake of atmospheric discharges of ^{14}C was estimated using the following equation:

$$u_a = \frac{\frac{R_a}{M}0.45}{A_k}$$

Where u_a is ^{14}C activity in Bq/km^2, R_a is the ^{14}C activity released to the atmosphere, M is the mass (Tg) of the atmospheric carbon pool in the form of CO_2 assuming a mass of 0.75 g CO_2/m^3 and A_k is the modelled area (57160 km). The annual mean contribution of ^{14}C to the Kattegat from atmospheric discharges was estimated at approximately 0.66 KBq/km^2. Although only a fraction of the discharged ^{14}C will enter the Kattegat marine environment, this assumes that all the discharged ^{14}C is available and is therefore likely to be an overestimate. All the marine discharges were assumed to enter the marine DIC pool providing an annual mean contribution of approximately 0.17

KBq/km^2. The annual physical removal rate of ^{14}C from the modelled environment was set using a net export rate of 9.6 Tg DIC per year or 72% of the total DIC pool (Gustafsson et al., 2017).

Using a Monte Carlo routine, 400 simulations of Ecotracer in Ecosim were conducted with small variations in the initial parameter values. The simulations ran through the calibration period of 1982 to 2009 and continued to 2025.

2.4.2. Ecotracer in Ecospace

Only the marine discharges of ^{14}C were considered in Ecospace simulations. Although the estimated contribution to total activity to enter the Kattegat from atmospheric discharges was higher, it was anticipated that the area affected by increased ^{14}C activities from marine discharges would be significantly smaller and therefore marine discharges would have a larger net contribution to the total activity in this area. Input of ^{14}C was modelled as the estimated monthly marine discharges which entered the 16 km2 km grid cell neighbouring the location of the Ringhals nuclear power plant. Due to the spatial resolution, the Bata Fjord where marine discharges occur, is not present in the model. Six regions made up of four grid cells totalling 64 km^2 were selected for specific output of all functional groups through time (Figure 2).

Following Tierney et al. (2018), ^{14}C entering the environment was dispersed within Ecospace using marine advection. An advection map for the Kattegat was created using velocity data from the Copernicus Baltic Sea Physics Reanalysis dataset (CMEMS 2022). As a result of gaps being created in the velocity data during processing, it was not possible to create a series of month averaged advection maps, and instead a mean advection map was created for the period between 1993 and 2021. This captured the general trends in Kattegat currents and in particular, a northward current in the east.

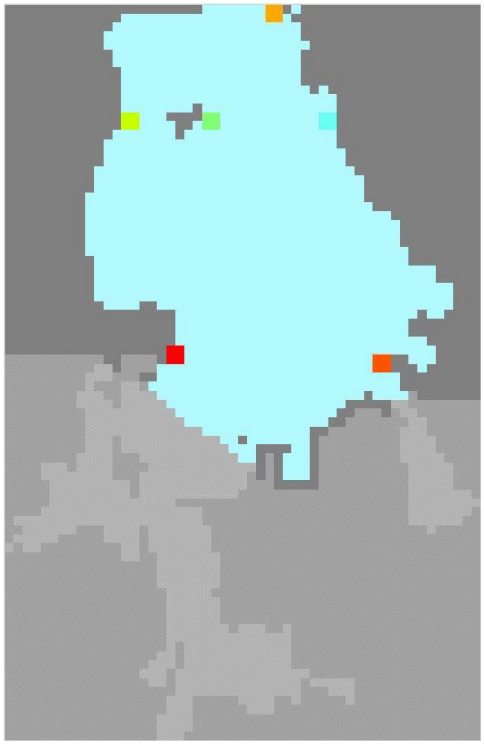


Figure 2. Ecospace map of the model area with six 64 km^2 regions for data output coloured: blue (at the source point near to Ringhals), green (east coast of Læsø), yellow (Danish coast south of Sæby), light orange (west coast of Öckerö), dark orange (near Höganäs), and red (near Boeslum, Denmark).

Ecospace simulations were conducted from 1982 to 2051. For the period from 2008, beyond the calibration extent, two different scenarios were modelled using different IPCC Representative Concentration Pathways (RCP) and nutrient loadings: 1) RCP 4.5 (greenhouse gas emissions peak in 2040) and a reduction in nutrient loading to the Kattegat; and 2) RCP 8.5 (greenhouse gas emissions continue to rise throughout the 21st century) and nutrient loading increases. These are our "best case" and "worst case" scenarios respectively for the Kattegat. This additional information was added to the model to investigate any effect these drivers could have on ^{14}C uptake as they are likely to impact biomass of primary producers. An individual run of each simulation is described in this report.

3. Results and discussion

3.1. Model balancing and fitting

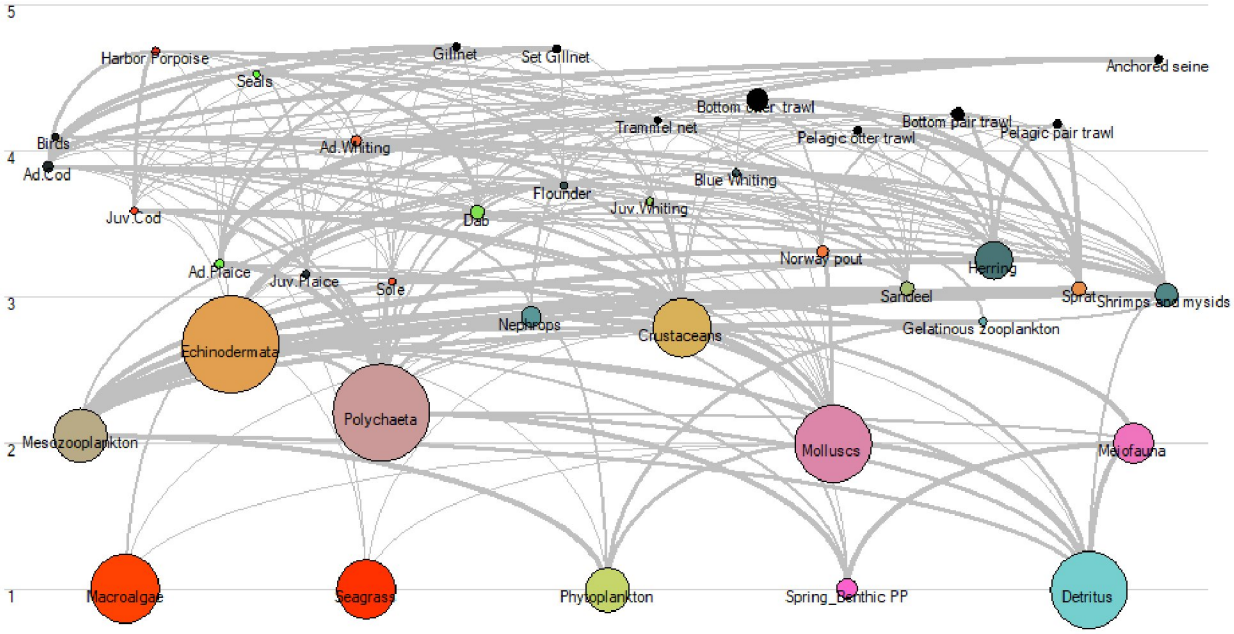


Figure 3. Food-web structure for Ecopath Kattegat model 1982 including fishing fleets.

The Ecopath food-web model describing the Kattegat marine ecosystem in 1982 was balanced after application of the PRE-BAL diagnostics (Link, 2010). The model includes 30 functional groups describing biota and, after the addition of detritus and fishing fleets, 39 nodes connected through 257 links representing the web of interactions in the Kattegat marine ecosystem (Fig. 3). In Ecosim calibration, the model reproduced the observed main trends and fluctuations relatively well and is therefore appearing to show good predicative power for the known ecosystem dynamics (Fig. 4). Spatial dynamics in Ecospace also appears to be well balanced with functional group biomass moving in time and space as expected from the environmental drivers applied (Fig. 5). These model predictions do require further testing and validation for use in Kattegat ecosystem studies, although are deemed fit for purpose to determine uptake of discharged ^{14}C.

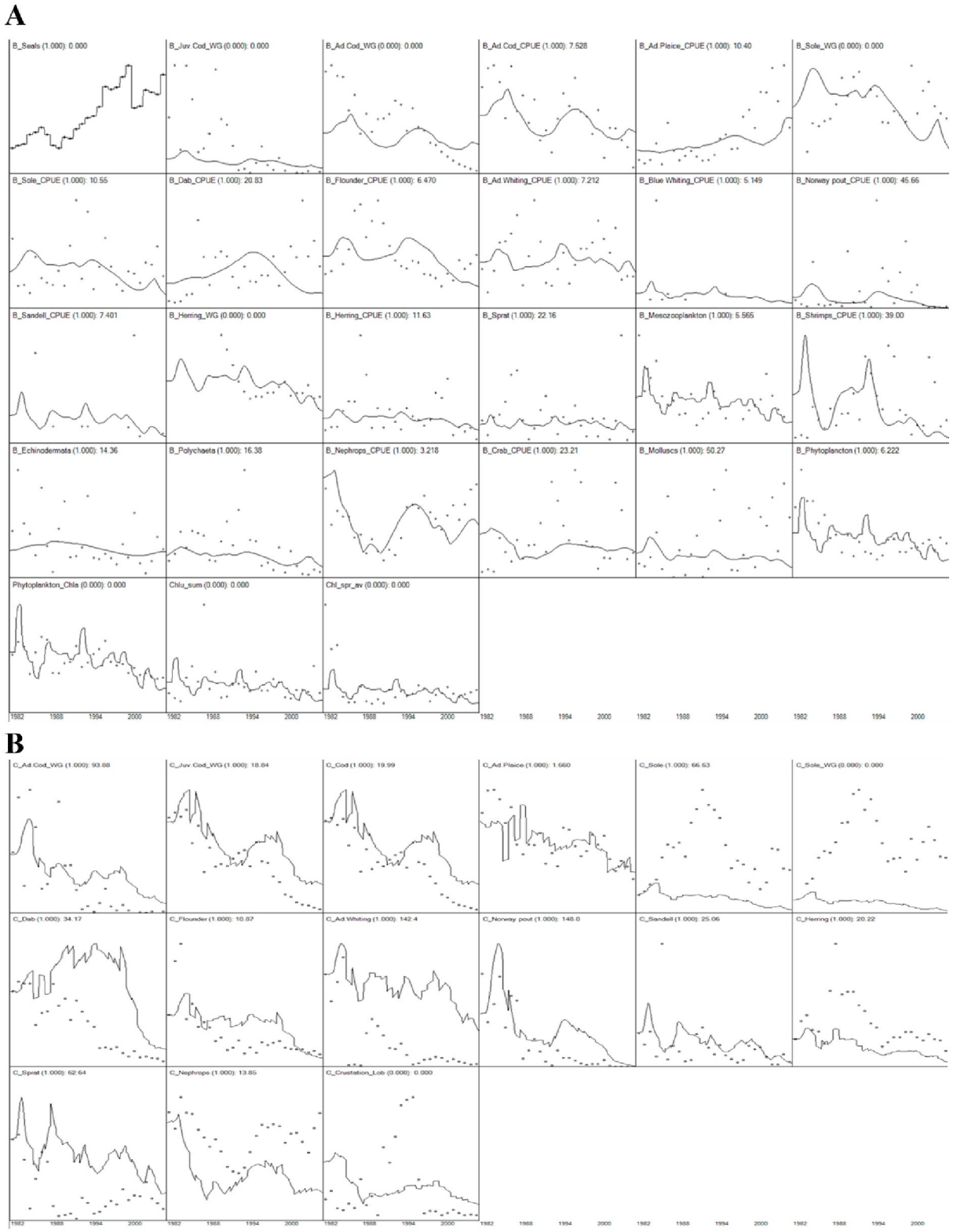


Figure 4. Kattegat Ecosim model fit from 1982 to 2009. Solid lines are model estimates and dots are observations/input data. A) fit for biomass and survey data and B) fit to fisheries landings.

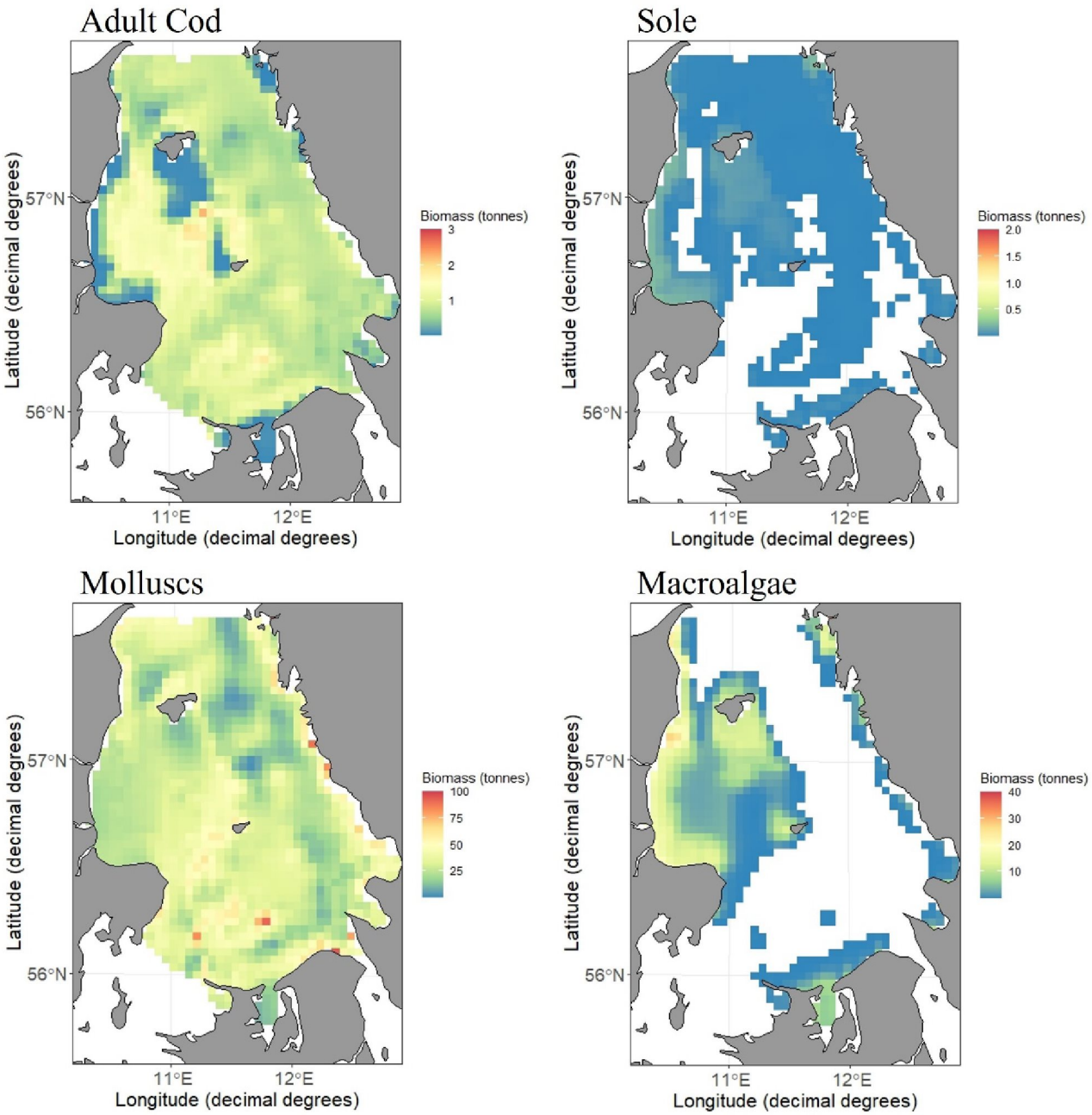


Figure 5. Selected Kattegat Ecospace biomass maps from January 1998 overlaid on a map of the Kattegat region. Note change in unit scale.

3.2. Ecotracer in Ecosim

Ecotracer ^{14}C output is in Bq per tonne of functional group wet weight. It is presented in this report as Bq $kg^{-1}C$ after conversion using carbon fractions in marine biota collected by the SUERC Radiocarbon Laboratory in prior studies (Muir et al., 2017; Tierney et al., 2017a, 2017b). Predicted ^{14}C activities ranged from approximately 2 to 20 Bq $kg^{-1}C$ across all functional groups and the 400 model runs that were completed, with a typical mean of 4 – 7 Bq $kg^{-1}C$ for all functional groups (Fig. 6). The relatively

narrow range in predicted activities was a result of the consistent input activities which only varied slightly between 2002 and 2020, and remained at the same order of magnitude throughout. As a result, it also indicates that the ecosystem model was well balanced and that the flow of ^{14}C between functional groups and out of the model environment was modelled correctly with no accumulation occurring. Some model uncertainty beyond the end of the calibration period in 2009 was shown by the increase in the range of ^{14}C activity for macroalgae as a result of larger variations in productivity for this functional group. This had a positive feedback through the food-web affecting ^{14}C activity for some consumers, i.e., echinodermata and cod functional groups.

The predicted activities are excess ^{14}C as a result of discharges from Ringhals nuclear power plant in addition to existing background and any other sources. It provides an estimate of the mean ^{14}C activity present in the entire Kattegat because of these discharges. A background activity of 249 Bq $kg^{-1}C$ (Tierney et al., 2016) would mean that these values show an increase of approximately 2-3 % over background. This is a relatively insignificant contribution on its own although other sources of ^{14}C to this environment should also be considered, i.e., releases from other nuclear power plants and the Sellafield and La Hague nuclear fuel reprocessing facilities and what the cumulative effect is. As an estimate for the entire Kattegat these values do not provide a prediction for ^{14}C activities in the vicinity of the discharge point which is shown in the Ecospace model below (Section 3.3).

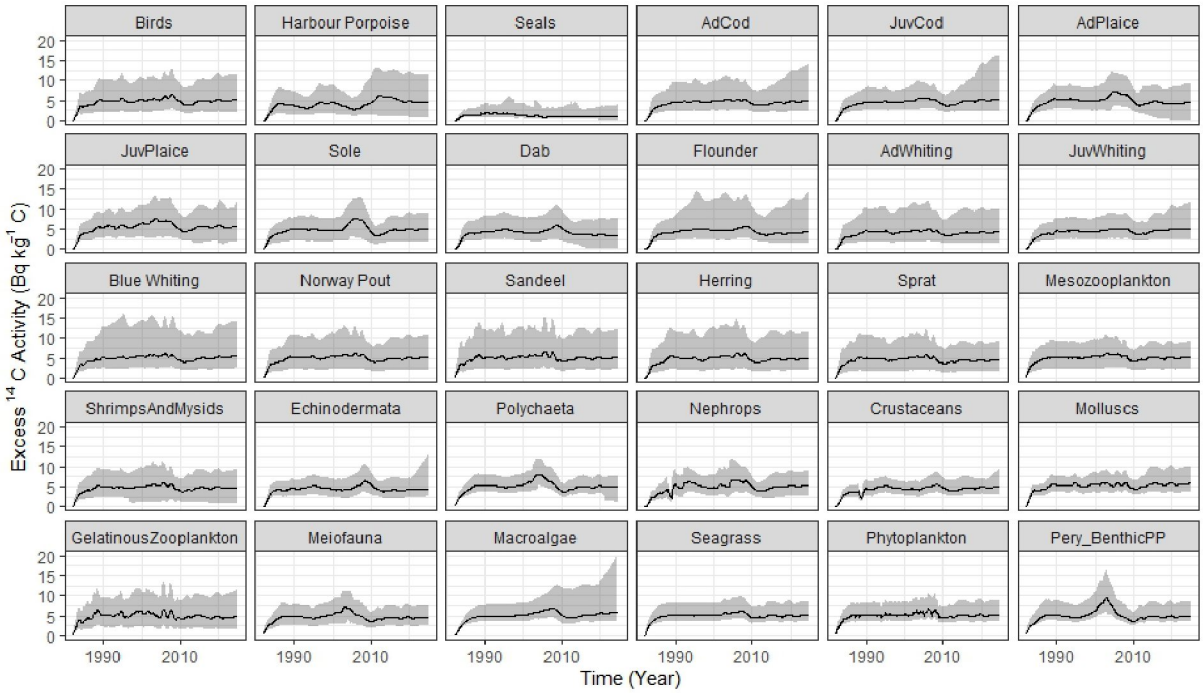


Figure 6. Results from the Kattegat Ecosim model for ^{14}C activities in all functional groups from 1982 to 2025 shwoing the range (in grey) and mean (solid black line) of 400 simulations where the input paramaters were slightly adjusted.

3.3. Ecotracer in Ecospace

In addition to map outputs for the entire model area, time-series data were output from Ecospace model simulations under RCP 4.5 and 8.5 scenarios for six pre-selected

regions. The results are averages for these regions and provide predictions for the mean ^{14}C activity for each functional group in a 64 km^2 region between 1982 and 2050. Only two regions showed a consistent increase in ^{14}C activities above 1 Bq $kg^{-1}C$, the region near to Ringhals nuclear power plant (Region 1), and the region near Öckerö (Region 2). This is consistent with ^{14}C activities being higher close to the discharge point and ^{14}C being carried northwards in the Kattegat surface current.

For primary producers in Region 1, ^{14}C activities were predicted to be between 10 and 25 Bq $kg^{-1}C$ for the duration of the model simulations in both scenarios (Figs. 7 and 8). Seagrass activities were 0 in Region 1 due to having no modelled biomass in this area. The sessile benthic periphyton activities were consistently higher than phytoplankton as the latter were more dispersed and therefore a portion of the modelled biomass was exposed to lower ambient activities. Macroalgae ^{14}C activity reduced before increasing towards the end of the simulations, which was likely a result of a decrease in biomass and production followed by an increase. This was less pronounced in the RCP 8.5 simulation where macroalgae biomass dropped to near 0 before increasingly slightly compared to a larger biomass gain in RCP 4.5.

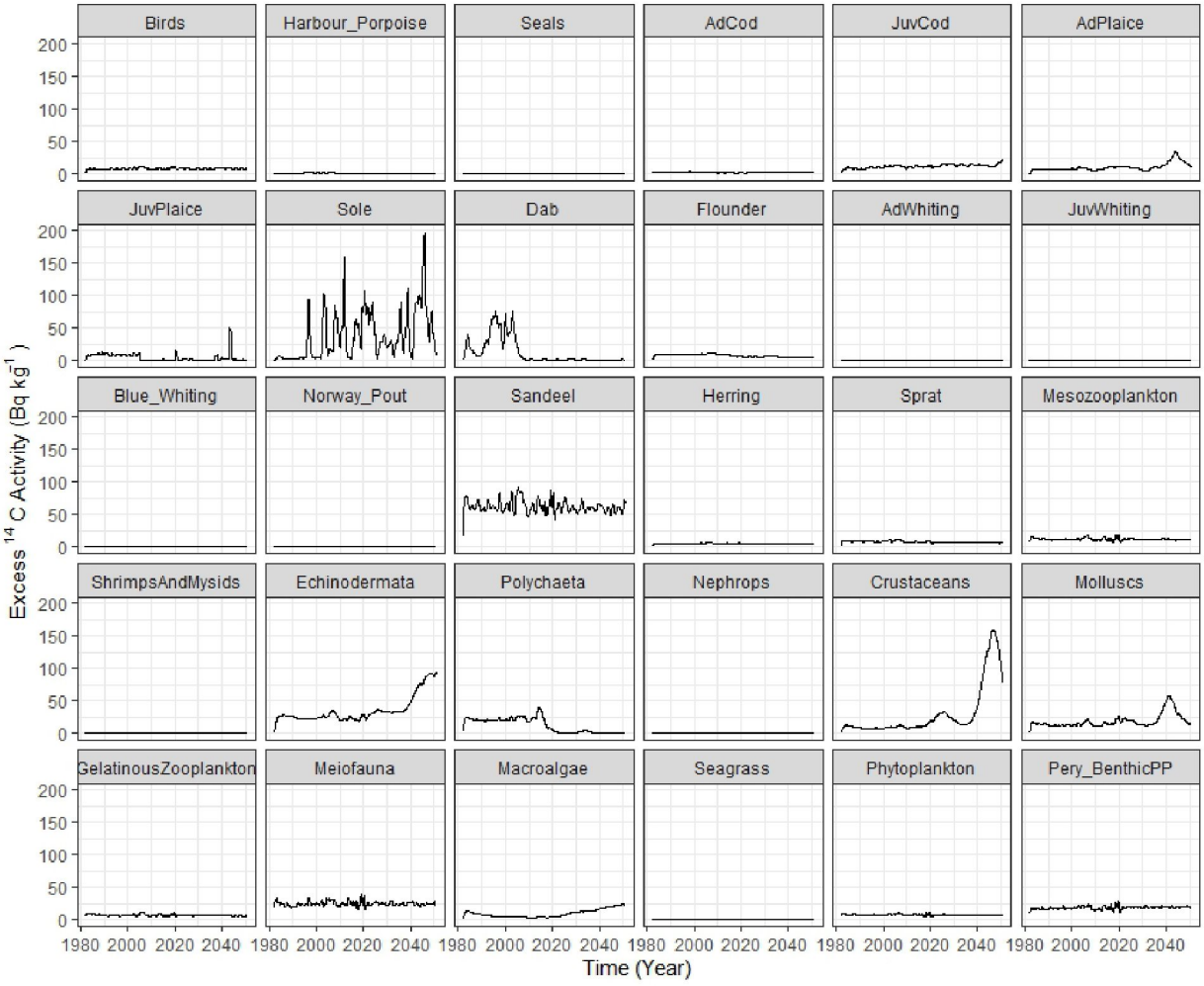


Figure 7. Results from the Kattegat Ecospace RCP 4.5 model for ^{14}C activities in Region 1 for all functional groups from 1982 to 2050. Predicted biomass for seals, adult whiting, juvenile whiting, blue whiting, norway pout, shrimps and mysids, nephrops and seagrass was consistently 0 for this region.

Most consumer functional groups with biomass present in Region 1 show a similar range in ^{14}C activities to primary producers with some exceptions. Sole predicted activities peaked at a little below 200 Bq $kg^{-1}C$ in both simulations and sandeel peaked at 125 Bq $kg^{-1}C$ in RCP 8.5 and 77 Bq $kg^{-1}C$ in RCP 4.5, significantly higher than primary producers. This is explained by some biomass of these and other functional groups moving through areas of higher ambient ^{14}C activity. Primary producers in the model area to the north of the discharge point approaching the location of Kungsbacka Fjord and past the Onsala peninsula towards the coastal region near Gothenburg had higher activities compared to Region 1 (Fig. 9). This is due to discharged ^{14}C being advected northwards in the model towards these areas and a small build-up in ambient activity occurred against the coastline. Modelled biomass that moved through this area gained a higher ^{14}C activity from foraging here before then entering areas with lower ambient activities. This is an effect of the integration of ^{14}C, where the ^{14}C activity of a tissue is directly related to an organism's diet and carbon turnover meaning that the activity in consumers may not equate with ambient ^{14}C activities at a point in time. This was particularly obvious in the results for sole ^{14}C activity where the large spikes show the transient nature of biomass moving in and out of Region 1.

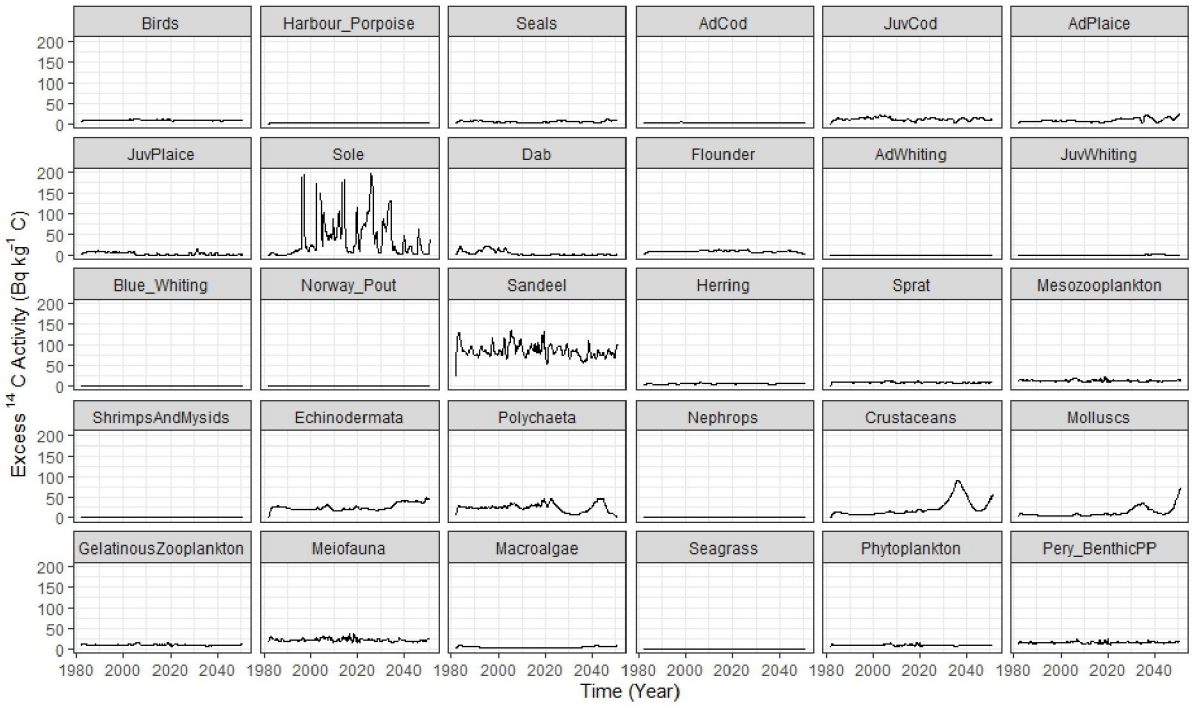


Figure 8. Results from the Kattegat Ecospace RCP 8.5 model for ^{14}C activities in Region 1 for all functional groups from 1982 to 2050. Predicted biomass for harbour porpoise, adult whiting, blue whiting, norway pout, shrimps and mysids, nephrops and seagrass was consistently 0 for this region.

Under RCP 4.5, the model predicted an increase in ^{14}C activity between 2040 and 2050 for echinodermata and crustaceans and to a lesser extent molluscs and adult plaice. This correlates with the largest peak in sole ^{14}C activity and was initially considered to relate to an increase in detrital ^{14}C activity from sole which is transferred through these benthic groups. There is no peak in sole ^{14}C activity under RCP 8.5 at 2040 and no significant increases in these other functional groups. However, the earlier peaks in sole ^{14}C activity did not result in any significant increases for these functional groups in either scenario. Further investigation revealed that this is likely an internal model

issue. Increases in uncertainty after the calibration period ended and the addition of the scenarios in Ecospace, made it more likely for biomass crashes to occur. Ecotracer and Ecospace work in different time-steps and a sudden regional crash in biomass for crustaceans and molluscs caused an increase in ^{14}C in Ecotracer for these functional groups and other groups closely linked in the food-web. This is also apparent in data from Region 2. This problem is limited to the time modelled after 2025, although it does make comparisons between scenarios difficult.

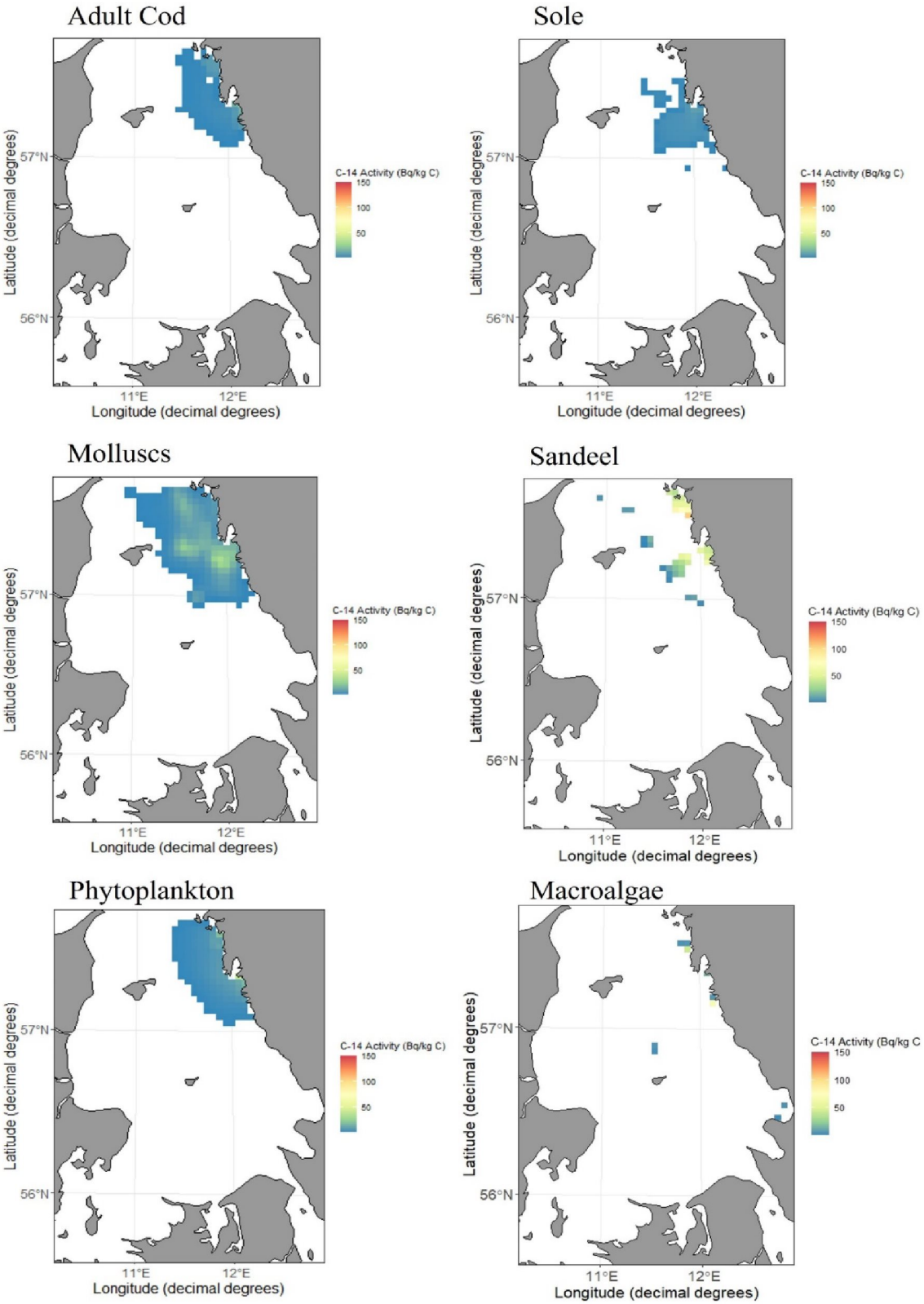


Figure 9a. Map output from the Kattegat Ecospace RCP 4.5 model for ^{14}C activities for selected functional groups from January 1998. Activities above 75 Bq $kg^{-1}C$ were predicted in both macroalage and sandeel.

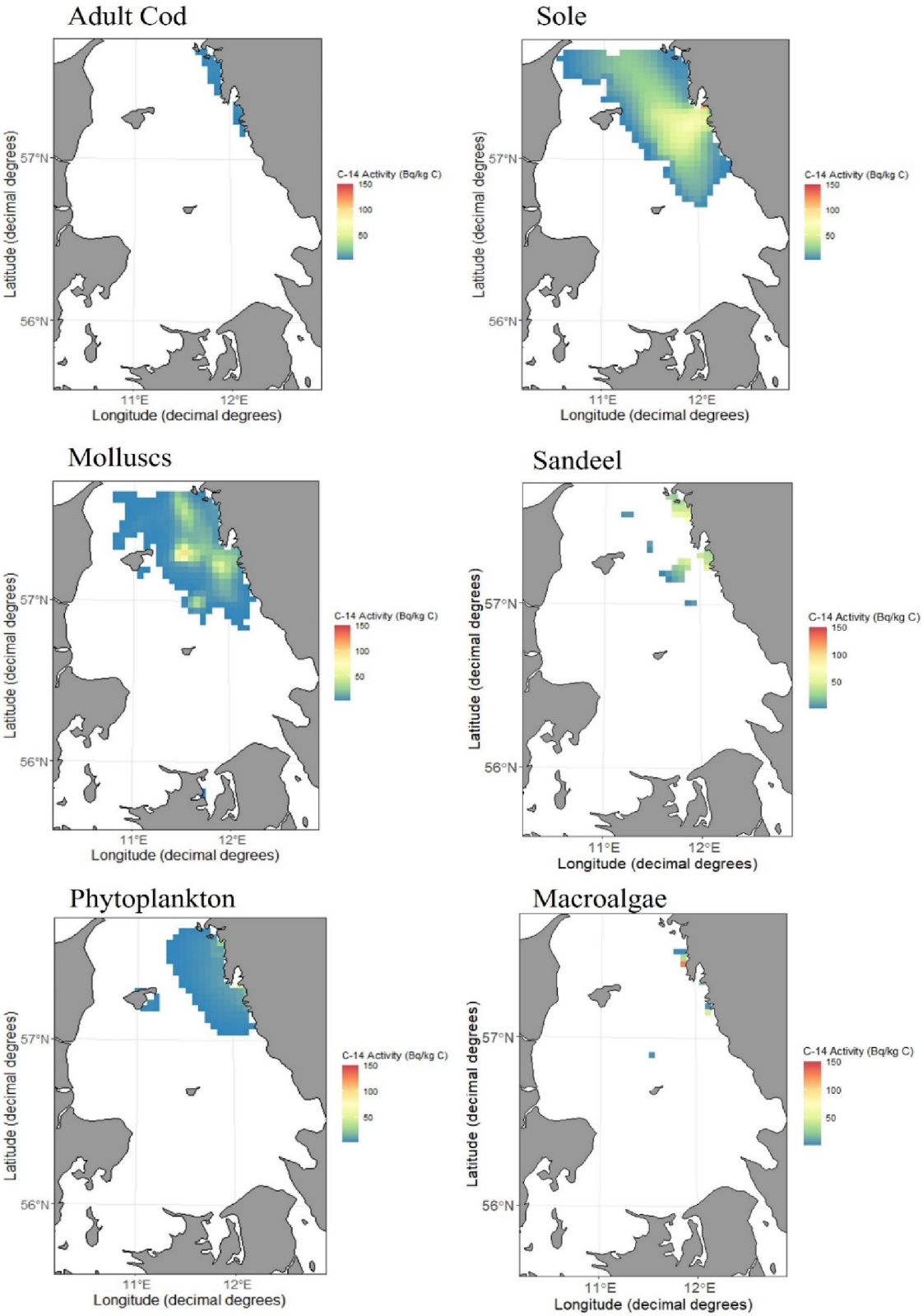


Figure 9b. Map output from the Kattegat Ecospace RCP 4.5 model for ^{14}C activities for selected functional groups from January 2018. Activities above 100 Bq $kg^{-1}C$ were predicted in macroalage, molluscs, sandeel and sole.

In Region 2, predicted ^{14}C activities for primary producers were typically between 2 and 5 Bq $Kg^{-1}C$ in both scenarios (Figs. 10 and 11). Again, there was no seagrass biomass in this region. Most consumer functional groups with biomass present remained at or below 10 Bq $kg^{-1}C$, however sandeel was consistently high again in both scenarios with activities over 40 Bq $kg^{-1}C$ in RCP 4.5 and 60 Bq $Kg^{-1}C$ in RCP 8.5. This could be a result of biomass movement patterns as discussed above although model uncertainty for sandeel should be explored in further work through conducting multiple simulations in Ecospace.

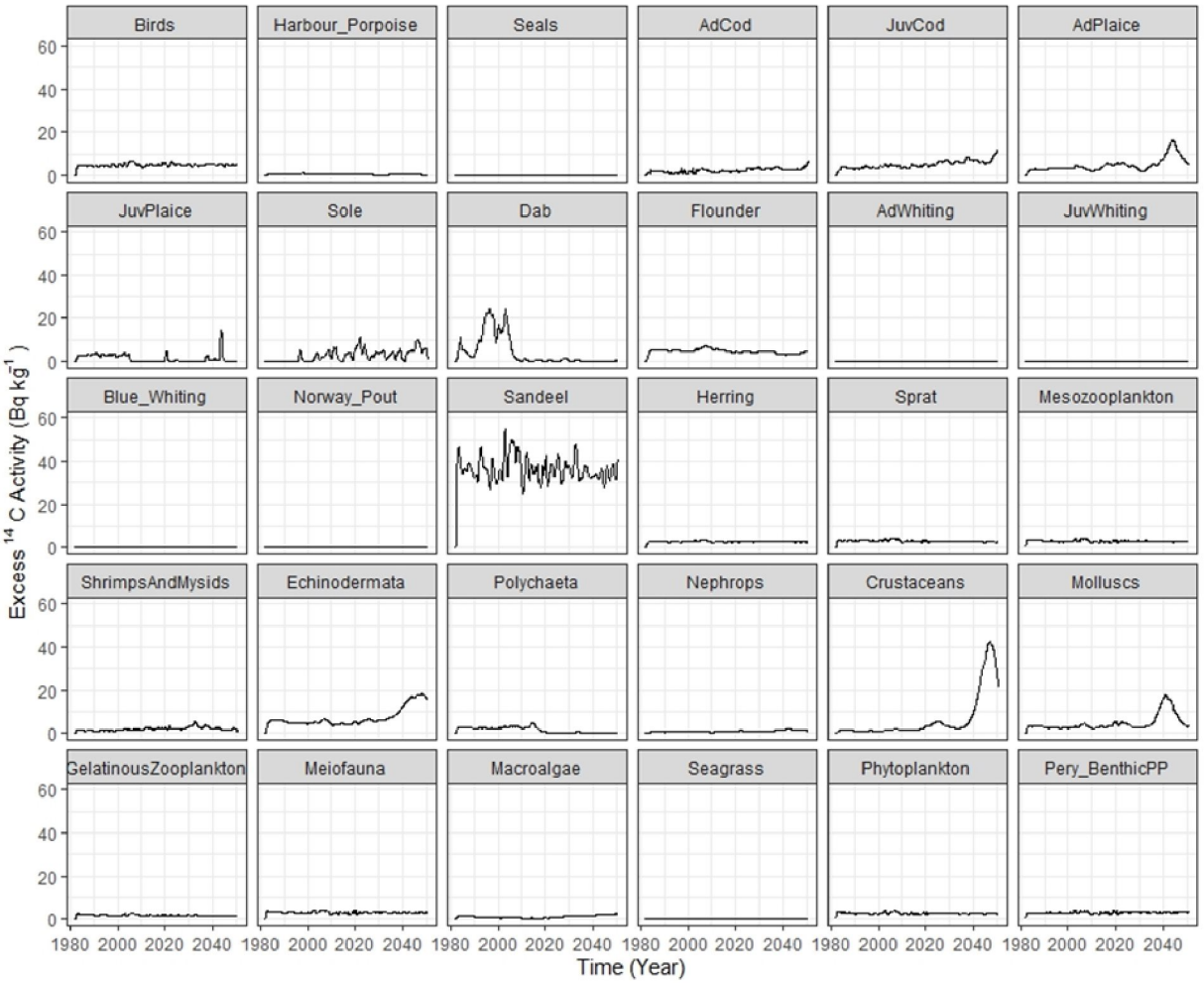


Figure 10. Results from the Kattegat Ecospace RCP 4.5 model for ^{14}C activities in Region 2 for all functional groups from 1982 to 2050. Predicted biomass for seals, adult whiting, juvenile whiting, blue whiting, norway pout and seagrass was consistently 0 for this region.

The highest predicted ^{14}C activities of between 150 and 200 Bg $kg^{-1}C$ in functional groups is less than the assumed marine background of 249 Bq $kg^{-1}C$. Typical values of less than 25 Bg $kg^{-1}C$ in Region 1 suggests that the contribution of ^{14}C from Ringhals discharges to biota is relatively low. However, a total activity of 274 – 449 Bq $kg^{-1}C$ is higher than the values obtained through measurements of macroalgae at sites south of Ringhals since 1988 (239 – 269 Bq $kg^{-1}C$) where some influence from Ringhals,

Sellafield and La Hague are expected (Mattsson et al., 2022). It should also be noted that these predicted activities do not account for discharges to the atmosphere from Ringhals, although the contribution from these discharges to marine biota is likely to be low. The contribution of atmospheric discharges to ^{14}C activities in the Ecosim model of approximately 80% and typically 3 – 6 Bq $kg^{-1}C$ could be used in addition to the Ecospace activities.

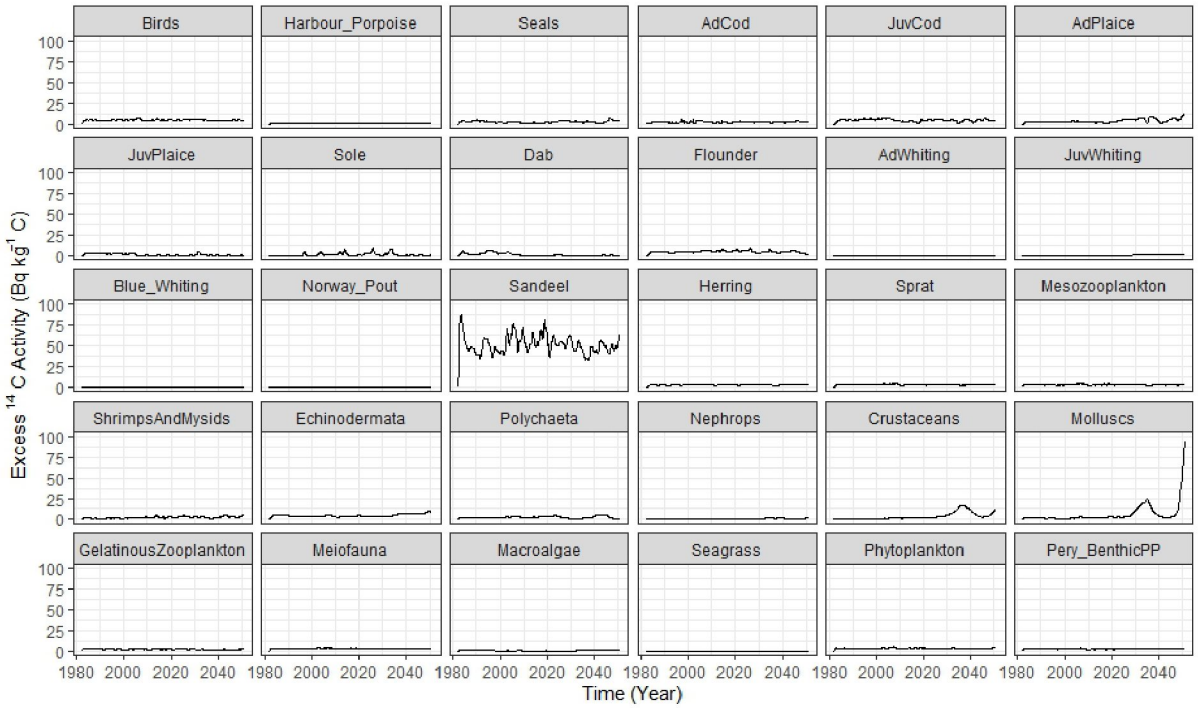


Figure 11. Results from the Kattegat Ecospace RCP 8.5 model for ^{14}C activities in Region 2 for all functional groups from 1982 to 2050. Predicted biomass for harbour porpoise, adult whiting, blue whiting, norway pout and seagrass was consistently 0 for this region.

It is expected that the contribution of ^{14}C to biota from Ringhals will increase with increasing proximity to Ringhals. Marine discharges are made to the partially enclosed Bata Fjord and therefore some accumulation of ^{14}C may occur. The Kattegat Ecospace model does not show the Bata Fjord due to the spatial resolution and so discharges are rapidly dispersed by the prevailing northward advection in the model. An accumulation in modelled ^{14}C was more apparent at the Kungsbacka Fjord and further north. The small accumulation in discharged ^{14}C in these regions could be a result of the model resolution and inability to predict an accumulation at the discharge point, however, due to the prevailing currents it is possible that an accumulation of ^{14}C has also occurred in the area to the north and Kungsbacka Fjord in particular.

4. Conclusions

Using an ecosystem model to predict radionuclide uptake and transfer in the environment is still very novel. To the authors knowledge this is the first study to model discharges of a radionuclide in a spatially resolved dynamic ecosystem model with multiple environmental drivers forcing ecosystem changes. Although further work is required to assess the modelled ecosystem dynamics, it is apparent that the model

captures the trends observed during the calibration period up to 2008. Tracing ^{14}C discharged by Ringhals Nuclear Power Plant in the time dynamic module Ecosim shows consistent output up to the end of the model simulations in 2025 indicating minimal model uncertainty. An increase in model uncertainty does appear towards the end of these simulations for some of the modelled functional groups but this was expected beyond the end of the calibration period and is handled well within Ecosim. Projecting further to 2050 in spatially resolved Ecospace with the addition of RCP scenarios and changes to nutrient loading, increased model uncertainty and caused regional crashes in biomass for functional groups. It is possible that the predicted crashes in biomass may be modelled correctly as a response to the scenarios, however, it had a problematic impact on modelled ^{14}C activities, occurring separately within the Ecotracer plug-in.

The predicted ^{14}C activities up to 2025 in both Ecosim and Ecospace appear to be reliable within the constraints of the quality of the data that were input to the model and the model limitations themselves. The small increase in ^{14}C predicted in Ecosim for the entire Kattegat ecosystem as a result of discharges from Ringhals is reasonable. Larger increases have been observed and modelled in, for example, the Irish Sea, however discharges from the Sellafield nuclear fuel reprocessing facility have historically been orders of magnitude higher. Increased activities closer to the source of discharges would be expected and are shown in the Kattegat Ecospace model and the range in values also appear to be reasonable. There are limitations such as the Bata Fjord, where Ringhals discharges occur, not being present in the model due to the spatial resolution. Instead, modelled marine discharges are rapidly advected northwards and accumulations are predicted towards Kungsbacka Fjord and further north. These accumulations resulted in ^{14}C activities in the model of up to 200 Bq $kg^{-1}C$ which may occur within the Bata Fjord.

To test the model output, a reliable dataset of ^{14}C activities in a range of biota from the region is required. Samples should be obtained from the Bata Fjord and the vicinity of Ringhals nuclear power plant. Further studies of ^{14}C in the Kattegat should also consider the coastal region north of Ringhals, including Kungsbacka Fjord. There will be contributions to ^{14}C from other sources, particularly Sellafield and the La Hague reprocessing facilities and future studies should consider how to untangle these source terms to determine the contribution from Ringhals in this environment.

Further modelling studies should initially focus on reducing model uncertainty. For modelling the very recent past and future this would involve increasing the ecosystem calibration period towards the present day. There is also additional software development required for EwE so that Ecotracer can handle extreme events in the ecosystem predictions, particularly in Ecopace as observed in this work. As a result of this project, several other software bugs were identified and fixed. Using a simpler food-web model would likely result in more consistent Ecotracer output in the current iteration of EwE, however ecosystems do change, biota presence in an area will vary and changes to the flow of a contaminant or tracer will occur as a result and to capture this requires the use of a dynamic ecosystem model.

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