Mapping the interaction risk between harbour seals (*Phoca vitulina*) and coastal gillnet fisheries in Norway: An Individual-Based Modelling approach

MIA PERNILLE RUBIN WOLLAN

Thesis submitted for the degree of
Master of Science in Marine Biology and Limnology
60 credits

Department of Bioscience
Faculty of Mathematics and Natural Sciences

UNIVERSITY OF OSLO

November 2023

Mapping the interaction risk between harbour seals (*Phoca vitulina*) and coastal gillnet fisheries in Norway: An Individual-Based Modelling approach

Supervisors:

Øystein Ole Gahr Langangen[1]
André Moan[2]
Arne Bjørge[2]

[1]Department of Biosciences, University of Oslo
[2]Department Marine Mammals, Institute of Marine Research

Title: Mapping the interaction risk between harbour seals (*Phoca vitulina*) and coastal gillnet fisheries in Norway:
An Individual-Based Modelling approach

Author: Mia Pernille Rubin Wollan

http://duo.uio.no/

Print: Reprosentralen, University of Oslo

Abstract

Bycatch poses a common concern for management. It is estimated that 5% of the entire harbour seal (*Phoca vitulina*) population dies in Norway because of this phenomenon (Bjørge et al., 2016). An initial step in reducing bycatch events can be to identify areas and times of year of high interaction risk. These interaction risks represent probabilities of overlap between harbour seals and coastal gillnet fisheries.

An individual-based model (IBM) that was designed for harbour seals, was set up for three study areas: Sør-Trøndelag, Nordland, and Rogaland. The IBM simulated movements of individual harbour seals and included multiple patterns such as turning angles, memory procedures, and environmental factors. In this thesis, this IBM was used with data on haul-out locations and harbour seal counts, and fishery data to identify areas and times of high interaction risk. From the results of this thesis, the highest predicted interaction was observed during winter and spring. Notably, the county of Nordland (location cell 05-24) was predicted to have a high interaction risk. This observation can be related to the Northeast Arctic cod (*Gadus morhua*) fisheries. High interaction risk was also observed for the location cells 07-25 and 07-08 in Sør-Trøndelag. The results were further compared with previous studies that used a different approach to simulate the distribution of seals at sea. The results were similar for Sør-Trøndelag and location cell 05-24 in Nordland but inconsistent with Rogaland.

This research has provided a deeper understanding of areas and times of the year with predicted high interaction risk. The located times and areas of high risk can further be used in management and conservation to increase our understanding of bycatch events. Additionally, the study sets the stage for future research to ensure viable harbour seal populations.

Acknowledgements

These two past years have been fun, instructive, and interesting but also quite difficult. Firstly, I want to thank Arne Bjørge for giving me the opportunity to write my thesis about marine mammals. It is my dream to one day work with them, and you have provided me with both wisdom during sampling and correction, and kind words that I will bring with me in the future. I also want to thank him for guiding me in the direction of comparing my study with one of your previous students. It has been a rewarding experience.

I can truly say that I did not start my thesis with much coding experience, and I am still not sure how I ended up with two different languages to learn, both R-studio and NetLogo. Therefore, I have to express my gratitude to André Moan for the countless hours he helped me get through with the coding, but also for your constructive feedback when proofreading my thesis. I also want to thank Øystein Langangen, for contributing a lot to the modelling aspect, giving constructive feedback, and believing in me when I thought my results and thesis were ruined. This thesis would not have been accomplished without the two of you. Additionally, I must thank all three of you for letting me explore the world when I was an exchange student in Australia. Thank you for seeing the opportunities, and not stressing me with my thesis during this time. I think this has helped me to achieve the results I have today.

I also have to say thank you to Magda Chudzinska and Jacob Nabe-Nielsen for providing the IBM I based my thesis on. Additionally, Jonas Oliver Elnes has let me use his thesis for inspiration, which has greatly contributed to this thesis. I also want to thank Carla Freitas Brandt for letting me use her photo. Furthermore, I want to give a special thank you to all of my friends, and my boyfriend. You have been there for me through my ups and downs and always encouraged me to write and never give up. A special thanks go to Emma Å, Emma H, Lone, Amanda, and Celina for motivating words, laughter, smiles, and help in the office. It has helped bring my thesis to a whole. Especially thanks to Lone, Emma Å, and Celina for the coding help, IBM discussion, and proofreading. I also want to thank my best friend Norunn for providing some helpful corrections and proofreading during the end stage of the thesis.

Finally, I must thank my family, who has always been by my side, thanks for believing in me, and for guiding me through this rollercoaster with motivating words. You are everything to me.

Pernille Rubin Wollan

Oslo, November 2023

TABLE OF CONTENTS

Acronym explanation

IMR	Institute of Marine Research
DoF	Directory of Fisheries
IUCN	The International Union for Conservation of Nature
IBM	Individual-based model
ODD	‘Overview’, ‘Design concepts’ and ‘Details’
“The original model”	The harbour seal IBM that this thesis is built upon. Based on the Scottish harbour seal population by Chudzinska et al. (2021)
FSA	Fishery statistical area
FSL	Fishery statistical location
Lokref cell	FSA+FSL combined (also called location cell)
Preluse	Predicted relative use (Number of timesteps seals occupy each location cell)
Prelcatch	Predicted relative fishing effort in each location cell
HSI	Habitat suitability index
RC	Risk categories (Used for describing the predicted interaction between coastal gillnet fisheries and harbour seals). Ranging between 1-6, where 1 indicate very low interaction risk and 6 is very high interaction risk

1 INTRODUCTION

1.1 EXPLOITATION OF MARINE RESOURCES DUE TO ANTHROPOGENIC ACTIVITIES

Human activities have significantly altered the structure and function of many marine ecosystems (Bryhn et al., 2020; Halpern et al., 2015). Marine resource depletion has occurred in several oceanic regions that were previously thought to be inexhaustible resources (Roberts & Hawkins, 1999). Coastal regions are often nutrient-rich and hot spots for human activities, as over half of the global human population lives within 60km of the coast (DeMaster et al., 2001; Roberts & Hawkins, 1999). Activities such as pollution, habitat fragmentation, overfishing, and many other stressors contribute to lowering the quality of marine ecosystems across the globe. Approximately 95% of fish catches derive from the continental shelf (Roberts & Hawkins, 1999).

History has shown that humans have engaged in unsustainable harvesting of many marine populations globally (Garcia & Moreno, 2003). This unsustainable harvesting has led to a severe depletion of many species worldwide. Norwegian spring-spawning herring (*Clupea harengus*) is the largest herring stock in the world and was close to commercial extinction in the late 1960s due to overexploitation. After strict fishing regulations, the stock fully recovered in the early 2000s (Engelhard & Heino, 2004; Toresen & Østvedt, 2000). Similarly, the Canadian cod (*Gadus morhua*) population collapsed in the early 1990s due to overfishing (Hutchings & Rangeley, 2011; Myers et al., 1997), and has still not recovered to previous levels (Brander, 2005). Larger marine mammal populations, such as the blue whale (*Balaenaoptera musculus*) were hunted to near extinction, and their populations have not fully recovered (Branch et al., 2004). Pinnipeds (sea lions and seals) have also been negatively affected by human exploitation, resulting in some cases of extinction events (Härkönen et al., 2012). The International Union for Conservation of Nature (IUCN) 2022 reported the ‘extinction’ of several marine species. Some were marine mammals, including the Caribbean Monk seal (*Neomonachus tropicalis*), Japanese Sea Lion (*Zalophus japonicus*), Sea mink (*Neovison macrodon*), and the Steller’s sea cow (*Hydrodamalis gigas*) (Hilton-Taylor & Brackett, 2000). Anthropogenic activities continue to cause depletion (Garcia & Moreno, 2003), with numerous marine species still categorized as ´critically endangered´ in the latest IUCN report reflecting decreasing population trends.

Over the years, various management plans have been developed for different marine mammal species. These plans can include catch quotas, culling programs, or other regulations (Bjørge, 1993). However, even well-managed sustainable fisheries can still have negative demographic effects on non-target species. The effect is especially negative for the marine megafauna including sharks, sea birds, sea turtles, pinnipeds, and cetaceans (porpoises and whales/dolphins) (Lewison et al., 2004). These species are vulnerable to incidental catches because of their large sizes, their life history strategies, and feeding habits. Marine mammals play a crucial role in maintaining a healthy food web and ecosystem. As keystone species, their presence can significantly impact the resilience of the food web and affect other species (Jordan, 2009; Rupil et al., 2022). Depletion of their population can lead to changes in species composition potentially resulting in cascading effects throughout the marine food webs (Harwood, 2001). Therefore, it is important to manage their populations to ensure that they remain viable, while also considering the potential problems they can cause for coastal fisheries (Bjørge, 1993).

1.2 BYCATCH AS SOURCE OF ANTHROPOGENIC DRIVERS

Bycatches are known as incidental catches from fisheries and are common in modern fishing gears, such as gillnets. Different taxa are however seen to be vulnerable to various types of gears. If marine mammals become entangled, they may be unable to reach the surface to breathe, leading them to drown or suffocate and potentially die if they can't get loose (Moan, 2016; Moore & van der Hoop, 2012). Gillnets are intended to target one type of fish but may still incidentally catch marine mammals or other fish species of the same size. The impact of bycatch in gillnet fisheries is especially crucial for the long-lived, and K-selected species including sharks, pinnipeds, cetaceans, and seabirds. They typically have life history strategies based on slow growth, and low reproductive rates, with survival rates increasing with age.

Individuals who have reached reproductive maturity will have the most significant effect on the population if they get caught (Soykan et al., 2008; Williams, 1966). There is little information on how they become trapped, but factors such as nondetection, food preference, and curiosity may be contributing factors (Moan, 2016). Entanglements are almost always fatal for marine mammals. Populations that experience bycatch may eventually decline over decades, without detection (Moan, 2016; Reeves et al., 2013). One species subjected to fishery bycatches is the harbour seal (*Phoca vitulina*) (Bjørge et al., 2002a)

1.3 THE HARBOUR SEAL

The harbour seal, also known as the common seal, is a widespread species, being the most widely distributed pinniped of the northern hemisphere (Blanchet et al., 2021). They are long-lived marine mammals found in the family Phocidae. There are estimated to be more than 600 000 individuals worldwide, distributed over different waters and countries (Bjørge & Nilssen, 2020). They inhabit coastal ecosystems in the North Atlantic and North Pacific and their adjacent seas, indicating that they are a diverse species. This expansive geographical range leads to different behavior and feeding ecology throughout the various habitats (Blanchet et al., 2021). Their habitats include bays, lakes, estuaries, rivers, and sea ice where they use solid substrates during nursing, resting, and moulting (Blanchet et al., 2021; Vincent et al., 2010). The species is also typically non-migratory and stays within the littoral zone (Bjørge et al., 1994).

Adult males are larger than females, with an average length of 150cm weighing between 70-100kg (Bjørge et al., 2010a). Females become sexually mature between the ages of 4 to 6 and continue to grow until the age of 10 (Boulva & Mclaren, 1979). Their longevity is at least 30 years and males tend to die at a greater rate after reaching sexual maturity (Ridgway & Harrison, 1981). The northernmost population at Svalbard is an exception where seals become no older than 16 years, which is surprising as there is limited negative human-seals interaction for this population (Leclerc et al., 2012). As they are iteroparous, they can reproduce multiple times throughout their lifespan. The breeding season occurs in June and early July, with a peak in mid-June (Thompson, 1988). During breeding seasons, the females give birth to one pup annually on land (Bigg, 1981; Boyd, 1991; Ridgway & Harrison, 1981).

Harbour seals have a variety of diets. It is reported that adult harbour seals can consume between 3.8-4.8kg of fish per day when actively foraging (Brkljacic, 2007; Chudzinska et al., 2021; Härkönen & Heide-Jørgensen, 1991). The adults feed opportunistically on a wide variety of fish, cephalopods, and crustaceans. Feeding typically occurs during the daytime. Their diet consists of commonly eaten fish including herring, sand lance (*Ammodytes dubius)*, fishes of the cod family (Gadidae), flatfishes (Pleuronectiformes), ballan wrasse (*Ctenolabrus rupestris*), pollock (*Pollachius pollachius*), common ling (*Molva molva*), haddock (*Melanogrammus aeglefinus*) and cusk (*Brosme brosme*) (Ridgway & Harrison, 1981; SMRU, 2017).

The seals were earlier exploited for food, trade, and fur and were considered a renewable resource for coastal communities (Bjørge, 1993). Fishers were allowed to shoot approaching seals, to protect their fishing gear from depredation of seals. Today, seal hunting is regulated, and the demand for seal products has decreased since the mid-1970s (Bjørge, 1993). The Norwegian harbour seal population categorized as 'vulnerable' by the Norwegian Red List was in 2006 due to high hunting quotas. However, after a new management plan was implemented in 2010, the population has recovered (Henriksen & Hilmo, 2015). The population is currently listed as 'least concerned' globally in the most recent assessment of the IUCN Red List, as well as on the Norwegian national Red List. Due to stricter hunting regulations, other seal populations worldwide have shown an increasing trend. For example, grey seal (*Halichoerus grypus*) (Bowen, 2016), harp seal (*Pagophilus groenlandicus*) (Kovacs, 2015), New Zealand fur seal (*Arctocephalus forsteri*) (Chilvers & Goldsworthy, 2015) and Northern elephant seal (*Mirounga angustirostris)* (Hückstädt, 2015) are showing increasing population trends.

1.4 INTERACTION BETWEEN HARBOUR SEALS AND COASTAL GILLNET FISHERIES

Both seals and coastal fisheries operate in productive waters. Seal foraging behaviour can therefore lead to an overlap with fishing sites, making them vulnerable to entanglements (Bjørge et al., 2002a; Niemi et al., 2012). As both fisheries and harbour seals compete for the same resource, seals are at a higher risk of getting caught. Harbour seals are especially observed to be bycaught in gillnet fisheries particularly for monkfish (*Lophius piscatorius*) and cod (Moan, 2016).

Multiple studies support the hypothesis that gillnet fisheries are responsible for bycatch mortality. Woodley and Lavigne (1991) study stated that bycatch contributed to declines in several seal populations, including the harbour seal in the North Pacific, northern fur seal (*Callorhinus ursinus*) in the North Pacific, and harp seal in the Barents Sea A study by Tixier et al. (2021) found that static nets accounted for 55% of bycatch of pinnipeds (Tixier et al., 2021). Interaction between commercial fisheries and marine mammals will continue to increase in the future (DeMaster et al., 2001).

1.5 NORWEGIAN HARBOUR SEALS AND INTERACTION TRENDS

Resources along the Norwegian coast have been harvested and farmed extensively for years (Bjørge et al., 2002a). The Norwegian coast stretches over 100 000km and is one of the longest coastlines in the world (Breili, 2022). The coast consists of both large and smaller islands with islets and skerries, making it a complex system. Fishery effort along the coast varies in both space and time and the interaction risk between fisheries and harbour seals is expected to be greatest when fishing effort is high. This means that an area with high fishing effort may not necessarily have a high interaction risk if there are no seals present. High interaction risk is therefore correlated with both high fishing effort and high seal movement.

Harbour seals can be found in local populations along the entire Norwegian coast. They form large colonies that exhibit limited migration. There are estimated to be approximately 10 000 individuals as recently assessed by The Institute of Marine Resources (IMR) (Bjørge & Nilssen, 2020). The seals can undertake foraging trips that can last for days but typically remain within 50km of their native colony/haul-out site. A study from Scotland has shown that less than 1% of foraging trips end up in non-origin sites (Thompson et al., 1998). When foraging they tend to revisit their preferred feeding grounds before returning to the last haul-out site (Bjørge et al., 1994; Cordes et al., 2011; Lowry et al., 2001). While they feed on species of a variety of depths and habitats, their preference is for benthic species of younger life stages. This, however, varies geographically and temporally among seals (Olsen & Bjørge, 1994). As they dive and forage near the bottom, they increase their entanglement risk in the bottom-set gillnets (Bjørge et al., 1994; Chudzinska, 2009). Additionally, feeding on discards and injured fish released from fishing boats increases their interaction risk. Harbour seals spend most of their time in the water foraging, but also frequently haul out on sandbanks, rocks, and beaches (Cunningham et al., 2009). When hauling out, they moult, breed, digest, and seek shelter from predators (Peterson et al., 2012). They haul out more frequently during summer and early autumn due to the breeding and moulting seasons, and haul out less frequently during the winter (Hamilton et al., 2014).

There is evidence that bycatch has occurred in Norwegian coastal fisheries. Based on the recovery of tagged harbour seals in Norway, it is estimated that around 6% have incidentally drowned due to fishing gear, and 2% have been shot when approaching fish farms (Bjørge et al., 2002a; Bjørge et al., 2002b). Another study using harbour seal abundance from 2015 with measurements from coastal reference vessels between 2006-2020 showed that these vessels bycaught 292 seals. Among them, 88% were identified as harbour seals, although there were uncertainties in the species identification. The study divided the Norwegian coast into three regions: north, mid, and south. The study concluded that bycatch rates were high in the mid-region of Norway and lower in the southern part of the country (Moan & Bjørge, 2021). Another study by Bjørge et al. (2016) found that 555 individual harbour seals were accidentally caught between 1997 and 2014 which represented 5% of the entire population.

1.6 ELNES (2021) STUDY OF INTERACTION RISK ON NORWEGIAN HARBOUR SEALS

Calculating overlap, also termed interaction risk with coastal fisheries and Norwegian harbour seals has been conducted before. Elnes (2021) research used a simple method to simulate harbour seal movement. Harbour seal counts and fishery data were obtained from the IMR and The Directorate of Fisheries (DoF). In short, the study simulated individual harbour seal movement using a Monte Carlo simulation. This was achieved by estimating the distance from moult site for individual harbour seals to at-sea locations. The distribution of seals was used to estimate the abundance of harbour seals within location cells along the Norwegian coast. The simulation accounted for seasonality in harbour seal dispersal and included seasonal age-specific vulnerability using age-specific bycatch events from Bjørge et al. (2002b). The relative probability of seals and fishing effort was later used for calculating relative interaction probabilities along the Norwegian coast. A close comparison of the results from Elnes' study will be followed throughout this thesis. This will allow for a comprehensive examination of interaction risk between Norwegian harbour seals and fisheries.

1.7 THE USE OF INDIVIDUAL-BASED MODELS IN ECOLOGY

Individual-based models (IBMs) are widely used in ecology when dealing with complex systems (DeAngelis & Mooij, 2005; Grimm & Railsback, 2005). These models operate as simulation models that use ‘agents’ to represent individual organisms or groups of similar organisms with varying traits. IBMs have been used in various fields including ecology (DeAngelis & Grimm, 2014), economics (Scheffer et al., 1995), and demographic work. IBMs have particularly been useful in studies on how environmental factors such as pollution, predation, and resource availability can affect a population (Boyles & Brack Jr, 2009; Grimm & Railsback, 2005; Hall et al., 2006; Schmitt et al., 2016).

IBM has also been an important tool in capturing individual movements. Movement can be simulated based on ecological principles such as optimal foraging and learning (Chudzinska et al., 2021; Nabe-Nielsen et al., 2018; Railsback & Grimm, 2019). Before implementing an IBM that aims to capture movement, data of initial state variables for a population including energy levels, sex, age, and food availability are often collected and evaluated. Compared to other ecological models, IBMs tend to be more realistic (Grimm & Railsback, 2012). The use of IBMs has earlier succeeded in reproducing the foraging movement of marine mammals (Chudzinska et al., 2021; Dodson et al., 2020; Nabe-Nielsen et al., 2013).

Grimm et al. (2006) implemented a standard protocol to clarify how an IBM works, the ODD protocol. It is based on seven elements in three broad categories ('Overview', 'Design concepts', and 'Details'). See Table 1.1 for a visualization of the protocol. Since its original publication, this protocol has been updated twice and is widely used by ecological modellers (Grimm et al., 2020; Planque et al., 2022). The protocol aims to first provide general information (Overview). This is followed by strategic considerations that can be used for predicting future conditions (Design concepts). Finally, the protocol aims to describe the processes in detail (Details) (Grimm et al., 2006).

Table 1.1: Overview of the seven elements grouped into the three blocks of the ODD protocol.

Overview	Purpose State variables and scales Process overview and scheduling
Design concepts	Design concepts
Details	Initialization Input Submodels

Modelling with IBM has some disadvantages. These models are typically more complex than classical analytical models. This is because they usually include many entities, heterogeneities, and spatial scales. This complexity is especially apparent when the models are used to capture individual traits and their adaptations through learning and interacting with their environment (Jørgensen & Fath, 2011). Additionally, IBM modelling requires sufficient computer and coding skills. The models are also generally more difficult to analyze and understand compared to classical analytical models, as the latter has a general language of the mathematics (Grimm et al., 2006; Grimm et al., 1999).

1.8 AIMS AND OBJECTIVES

This thesis applied a simple movement model (IBM) to study the movement behaviour of Norwegian harbour seals based on central-place foraging movements. The aim was to increase our understanding of the spatial distribution of bycatch trends in Norway by using harbour seal haul-out locations and movement behaviour from an IBM, and fishery data from the DoF. The analyses were conducted by quantifying the time seals spent in each location cell in a discretised landscape. By similarly assessing fishing efforts, it was possible to estimate the interaction risk between harbour seals and Norwegian coastal gillnet fisheries. The results were further used to compare with previous studies that used a different movement approach to simulate the distribution of seals at sea. This gave the following objectives:

1. Identify location cells of high interaction risk at different times of the year.
2. Compare interaction risk estimates based on movements generated using a complex IBM and a simpler model that used only distance from haul-out to generate movements.

2 MATERIALS AND METHODS

Estimating the relative probability of interaction between coastal gillnet fisheries and harbour seals followed a multi-step approach. Initially, data was obtained from both fishery and harbour seal surveys. The landscape of the study areas was further modified using the software programming language for statistical graphics, R-studio. The data collection and preparation were implemented into an IBM in NetLogo where the output from the simulations was used for estimating overlap in R-studio.

STUDY AREA

This thesis focused on three distinct areas along the Norwegian coast. Nordland (67°N 12°E), is found in the northern region. Sør-Trøndelag (63°N 10°E), is located in the middle part of Norway. At last Rogaland (59°N 6°E), located in the south-western region of Norway (see Figure 2.1). Nordland was further divided into a lower (64.5-67.3°N) and an upper (66.5-69.5°N) area. This created an overlap between those two areas, but was accounted for prior to interaction risk calculations. Sør-Trøndelag and Nordland were selected as the greatest concentration of harbour seals are located in these areas (Bjørge et al., 2010b). Rogaland was studied to include colonies of a smaller size.

2.1 DATA COLLECTIONS

2.1.1 Fishery statistical areas and locations

The Directorate of Fisheries (DoF) collects data from coastal fisheries along the Norwegian coastline using fishery statistical areas (FSAs). These FSAs are further divided into locations cells called fishery statistical location (FSL) cells, see Figure 2.1. The FSAs span from the Russian border up north to the Danish and Swedish borders. The FSLs represent specific location cells at sea that can be categorized into coastal and offshore cells. Coastal cells vary in shape and are based on the shape of the coastline. Whereas all offshore cells are 0.5° x 1° (latitude x longitude) grid cells. FSA and FSL combined are called lokref cells. An example of a lokref cell was 06-31, where

06 represented the FSA of lower NL with 31 for its specific FSL (see Figure 2.1). To estimate interaction risk, only fishery data from FSLs that intersected with the study area were considered.

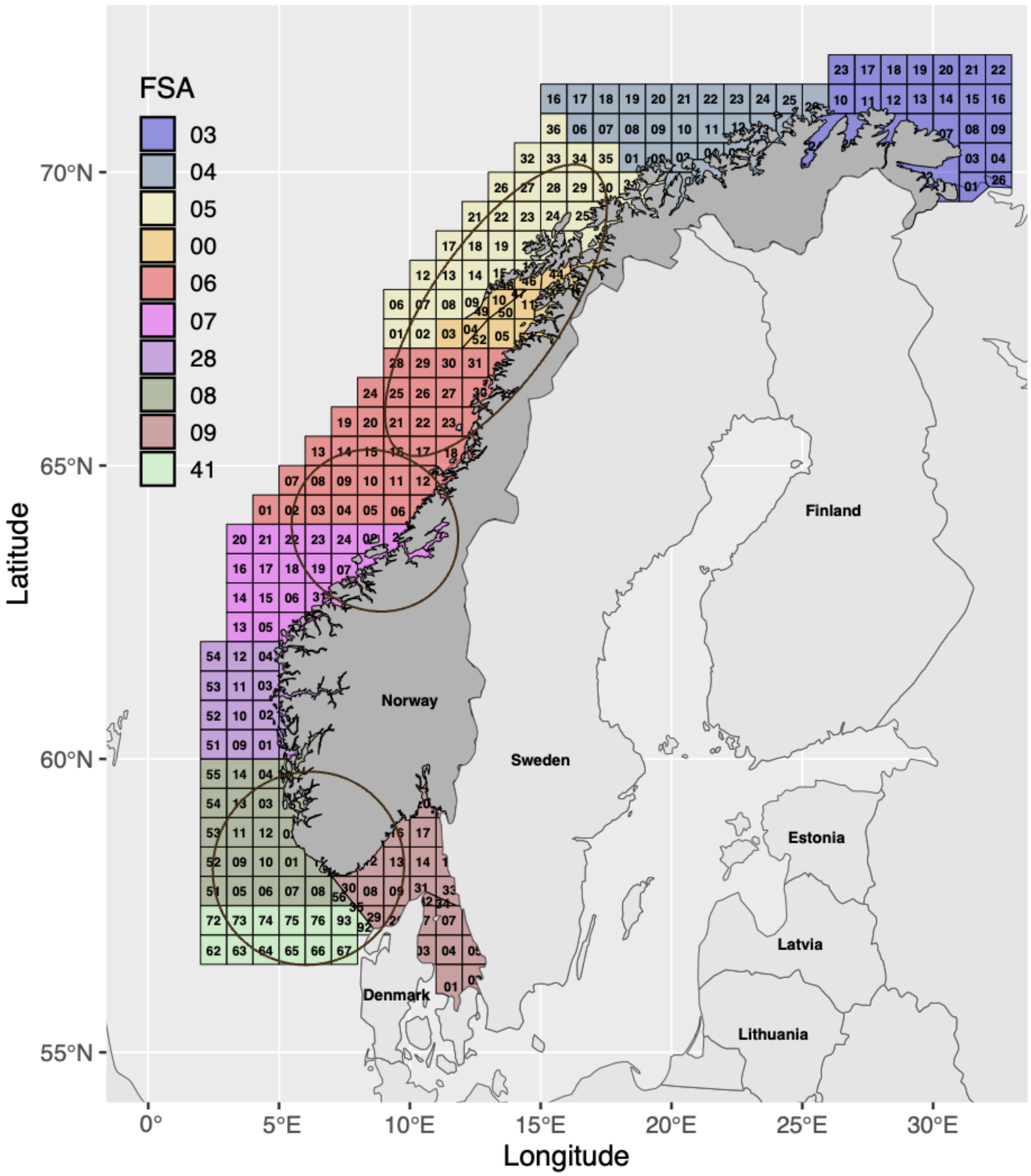

Figure 2.1. Display of ten fishery statistical areas (FSAs), with their corresponding locations (FSLs) along the Norwegian coast. Seven out of those ten were used in this study. These together create lokref cells. All FSAs are represented by their own colour, where the brown circles represent the study areas.

2.1.2 Fishery data

Fishery data for the three areas circled in Figure 2.1 were collected. This was achieved by using landing statistics of Norwegian fisheries as a measure of fishing effort. Landing statistics are comprehensive electronic records used for fishery management with details about species caught, boat types, and equipment used, offering an overview of Norwegian marine fisheries. The DoF conducts the landing statistics and uses the lokref cells for data registration. The data was collected as CSV on the DoF website: https://www.fiskeridir.no/Tall-og-analyse/AApne-data/Fangstdata-seddel-koblet-med-fartoeydata. Data used for Rogaland and Sør-Trøndelag correspond with the latest harbour seal survey in the areas; 2017 and 2019 respectively. Due to circumstances caused by the global COVID-19 outbreak, the total catch in Nordland was lower in 2020 than for the remaining years in the period 2017-2022 (Sluttseddelregisteret, 2023a). On the basis of this, fishery data from 2019 was used (see Table 2.1). Although the landing statistics consisted of more than 100 data columns, only information about month, year, lokref, equipment (gillnets), fish species, and the total catch for each species were used.

The fishery data required further correction to accurately link the fishing effort to each lokref cell and the degree of overlap of the study areas. To achieve this, the number of catches for each lokref cell was adjusted with the proportion of spatial overlap of the defined study area. This was essential as catches within each lokref cell were uniformly distributed, which was an unrealistic assumption. The adjustment was also necessary because some lokref cells were cropped to be less than 1 (see Figure A-6). The adjusted data was used to calculate the relative probability of fishing effort (prelcatch) in each lokref cell. For example, let’s imagine that a lokref cell had a proportion of 0.92 with a total catch of 2000 tons. When calculating the catches in that cell, the proportion was multiplied by the fishing effort, which would give a result of 1840 tons. This calculation was applied to all lokref cells for the three study areas.

2.1.3 Harbour seal survey data

The Institute of Marine Research (IMR) conducts mosaic surveys to count harbour seals along the coastline. The survey covers separate parts of the coast in successive years, completing one full survey cycle once every fifth year. Survey data contained information about the date, a location description (county, municipality, area), and coordinates (latitude and longitude) of haul-out sites where seals were observed, as well as counts (number of observed individuals, not corrected for availability bias). This dataset included counts from the latest survey cycle, between 2016-2022. Figure 2.2 visualizes the distribution of harbour seals in the three study areas, and Table A-1 contains a description of each haul-out site. The survey conducted in Nordland from 2019 and 2020 included a total of 1620 harbour seals, distributed over 11 colonies (divided into lower and upper areas in Table 2.1). Harbour seal counts for Sør-Trøndelag in 2019 resulted in 790 seals distributed over 3 colonies, whereas Rogaland counts from 2017 included 492 seals distributed over 6 colonies (see Table 2.1). A deeper insight of the data is found in Table A-1. These haul-out sites were further used in the individual-based model for movement simulation in NetLogo, to capture the relative use (preluse) that seals spent in each lokref cell.

Table 2.1: Overview of harbour seal abundance of the three study areas retained from the IMR. The years represent the time of the survey of a given county. Nordland is represented as lower and upper with corresponding haul-out IDs.

County	Sør-Trøndelag	Rogaland	Lower Nordland	Upper Nordland
Survey years	2019	2017	2019, 2020	2020
Observed individuals	790	492	660	960
Number of haul-out sites	3	6	6	5
Haul-out ID	19-21	2-5,47,48	22-26,28	29-33

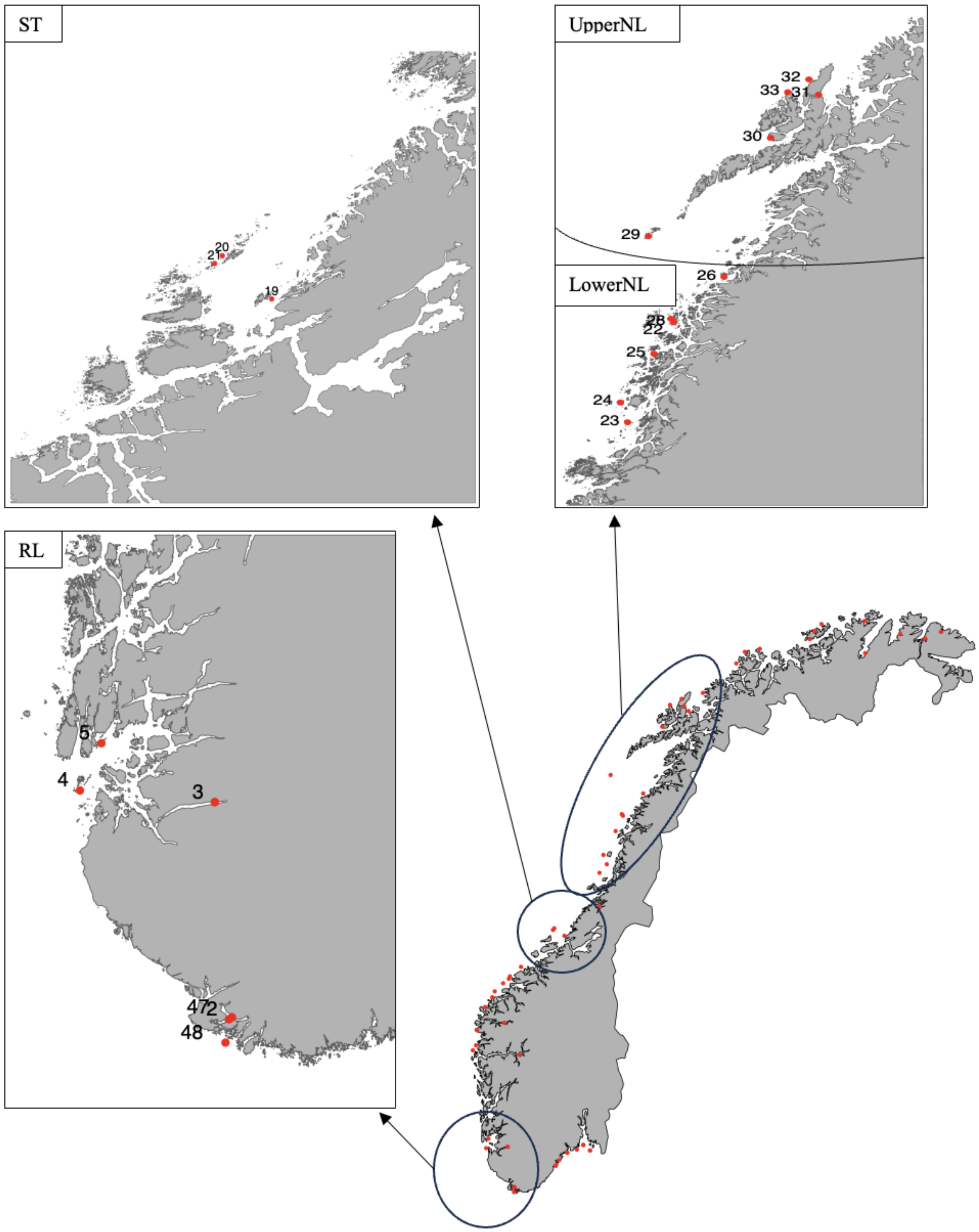

Figure 2.2. Seal colonies along the Norwegian coast with a zoomed-in map of the three study areas, ST=Sør-Trøndelag, NL=Nordland, and RL =Rogaland. Red dots represent haul-out sites/colonies for all areas. Each red dot has a specific haul-out ID, which is presented as a number next to the haul-out site. Nordland is divided into upper and lower areas visualized with a black line between haul-out ID 29 and 26. Haul-out ID 22-26+28 refers to the lower area and id 29-33 represents the upper NL. Haul-out colonies 19-21 are found in ST, where 2-5+ 47 and 48 are colonies of RL.

2.2 MODEL SETUP

2.2.1 Creating the landscape

Before running the seal movement simulation in NetLogo, the landscape of the three areas was modified. Preliminary model runs indicated that the original IBM of Chudzinska et al. (2021) was not suited for areas with jagged coastlines, narrow fjords, and islands because the seals often got stuck when trying to forage. To counter this issue, the landscape of the three areas was modified by smoothing the coastline and removing (some) islands. Fjords that were too narrow were expanded by changing some land cells to water cells. These land cells were given a constant chosen depth. Moreover, bathymetric files were used to generate distance-to-coast raster files. These files were generated to add the distance to the nearest point on the coastline for each water cell. This was important for seals' dispersal movement as they moved away from or along the coast during the dispersal (Nabe-Nielsen et al., 2014; Åslein, 2023). Each study area was smoothed multiple times, and both the smoothed maps of Figure 2.3b and 2.3c were tested in the IBM. Finally, Figure 2.3c, representing a highly smoothed area, was used for all simulations. The smoothed landscape of Rogaland and upper Nordland can be found in Figure A-4.

Figure 2.3. The landscape of Sør-Trøndelag before (a) after first smoothing (b) and how it was implemented in the IBM (c). The green areas represent water patches while the grey areas show land. The differences in which patches became water and land can be seen when comparing a and c.

Due to the method of using highly smoothing areas, some seals were simulated to move in areas that originally were land but were later smoothed to be water (see Figure A-8). To address this issue, all original land locations where seals were simulated to be moving, were given a neighbouring lokref fishery cell in water. This step was accounted for before preluse, prelcatch, and interaction risk data. This modification improved the reliability of the data, allowing for the estimation of predicted interaction risk between harbour seals and coastal gillnet fisheries.

2.2.2 Habitat suitability index

Habitat suitability index (HSI) was used to assess the habitat preference of harbour seals and observe the impact on seal movement. The HSI approach involved identifying environmental factors that can influence distribution of the seal population. HSI serves as an indicator of habitat quality and food resources. The HSI framework employed in this thesis was based on the approach by Moan et al. 2023 (Moan et al. unpublished data) developed by Carter et al. (2020). In short, to estimate HSI, a generalized additive modelling approach was used. The models of Carter were fitted based on tracking data of harbour and grey seals in UK waters. These models were further used for running predictions based on Norwegian surveys and environmental data. The environmental data included factors such as bathymetric depth, rugosity, winter sea-surface temperature, stratification, seafloor sediment type, and distance to the coast and were sourced from EMODnet. These were chosen as they correlate with biological relevance to seals and their prey (Carter et al., 2020). The environmental data was used to prepare a prediction grid centred on each harbour seal haul-out site, along with a radius of the maximum observed foraging distances found to be 237km (Moan et al. 2023, unpublished data). Carter's model of the UK was then applied to the prediction grid to estimate expected occupancy for each raster cell, where the resulting predictions were considered as habitat suitability indices (HSIs). To simplify the interpretation, HSI values were normalized within the range of 0-1, which has been done in other studies as well (Chudzinska et al., 2021). A higher index would indicate a better habitat. Figure 2.4 provides an overview of HSI along the Norwegian coast, with a zoomed-in map of the study area of lower Nordland.

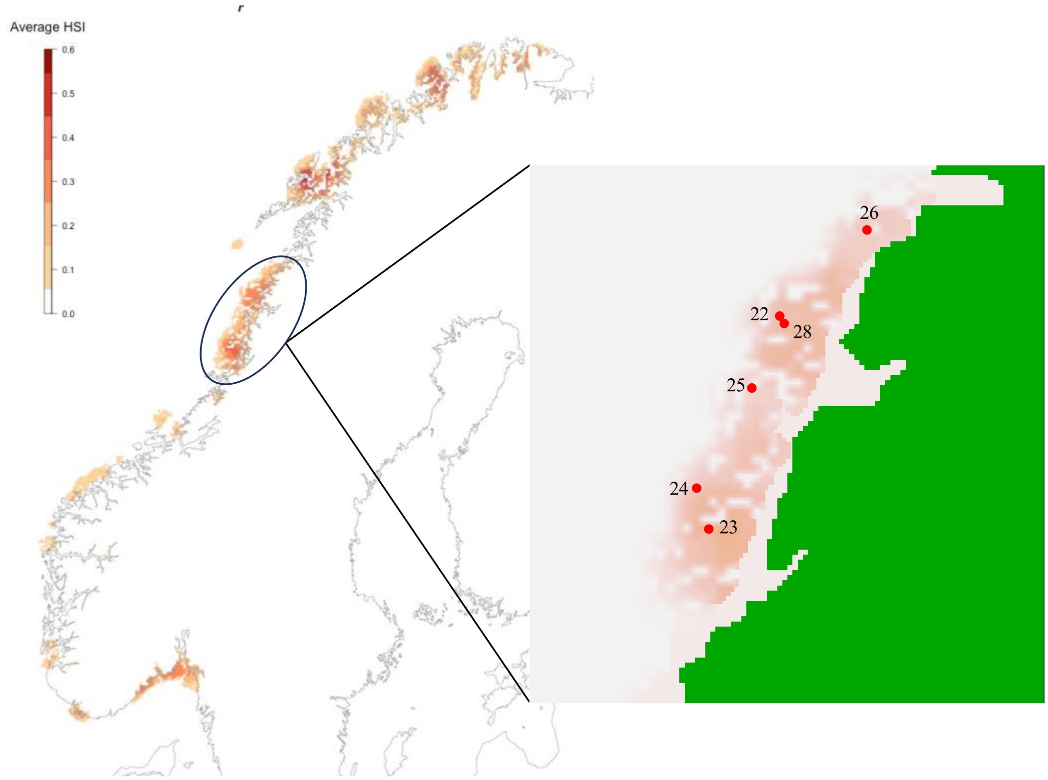

Figure 2.4. Habitat suitability index for harbour seals of the Norwegian coast with a zoomed-in map of the smoothed lower Nordland area. The red areas indicate the HSI of the area. The stronger the colour, the better the quality. Colony IDs are represented as red dots, where the green area is land, and the grey area is water.

2.3 INDIVIDUAL-BASED MODEL TO STUDY THE MOVEMENT OF HARBOUR SEALS

The highly smoothed landscape of the three study areas, including files of haul-out sites and HSI, was applied to an Individual-based model (IBM). All areas were modelled separately with three replicates for each area.

2.3.1 Introduction

Previous studies have examined the movement of harbour seals along the Norwegian coast using a simpler method (Elnes, 2021). For this thesis, an IBM of harbour seals was applied. The IBM followed a harbour seal IBM on the East coast of Scotland. A description of how the model works is described in detail by Chudzinska et al. (2021) and is referred to as 'the original model' throughout this thesis. The original model was adapted to fit the three study areas, as described above. The next section provides a general description of how model works and follows the ODD protocol.

2.3.2 Model description

PURPOSE

The purpose of the model is to simulate adult harbour seal movements using an IBM that incorporated central place foraging. The aim is to use the simulated movements in the study areas, Sør-Trøndelag, Rogaland, and Nordland (upper and lower) to estimate overlap with gillnet fishing activities. Improving our understanding of the spatial distribution of entanglement risk is essential to monitor, address, and mitigate bycatch issues in fisheries.

STRUCTURE

The model structure followed the original model design but is adapted to consider the geographical features of the study areas. The landscape in each study region is comprised of grid cells that divides land and water patches. Sør-Trøndelag is divided into a grid with 222 x 228 cells, Rogaland into a grid with 270 x 285 cells, lower Nordland into a grid with 303 x 318 cells, and finally, upper Nordland into a grid with 364 x 390 cells. Each cell is covering 1 x 1 km projected in UTM33N (PSG code 32633). The cell is characterized by the following properties: distance to land and distance to each haul-out site, with a HSI value. The water patches are further grouped into blocks of 5 x 5 km and 25 x 25 km used for memory procedures. One timestep in the model is 15 minutes.

State variables describe the structure of the system and include the seals, their haul-out sites, and landscape patches. In the model system, there are two types of agents: adult male and female harbour seals. The modelled seals have state variables of a unique ID, sex, stomach capacity, and length. Other variables considered include location, speed, movement direction, mass (total and reserves), behaviour (resting or foraging), net energy level, and a list of memorized patches and haul-out sites. The haul-out sites have the following variables: location, unique ID, and the proportion of observed seals occupying a haul-out site (Chudzinska et al., 2021).

To simulate realistic behaviour, the model uses various patterns. One pattern is *energetics*, which explains the energy intake and expenditure of the seals over the year. Another pattern is *body reserves*, including fine-scale movement describing turning angle and step length. Activities during the day like resting and foraging, and site fidelity are also part of the body reserve pattern as it explains movement patterns. The activities seals perform in the model include foraging, short resting at sea, long resting at sea, hauling out, land avoidance, and travelling from the moment seals decide to haul, to the actual haul-out-site.

PROCESSES

The processes include six procedures, foraging (a), time to rest (b), time to haul out (c), rest at sea (d), go to haul-out-site (e) and haul-out (f), and follows the flow chart diagram shown in Figure A-5. The order individual seals perform a given procedure is randomized at each time step. To maintain consistency with the original model, and due to the absence of Norwegian population values, the model uses the same parameters for energy level, movement, and state variables. Each of the model processes is described in the following paragraphs:

Foraging

A foraging trip is defined as seal movement between haul-out events over a period that exceeds 6 hours, as suggested by Sharples et al. (2012). Harbour seals search for food based on a correlated random walk and spatial memory behaviour related to HSI (Bartumeus et al., 2005). The seals move slower in areas with high food availability (high HSI) and transit faster where food availability is low (low HSI). The seals remember earlier visited patches and the amount of food captured in these patches and update their memory of haul-out sites passed within a distance. While foraging, they consume fish (*intake energy)*. They also expend energy (*Energy expenditure*) depending on the activity performed for each time step. Besides the times seals are hauling out, they turn to avoid land. Avoiding land procedures is, therefore, a modelling practice rather than a behaviour-driven procedure. The design of land avoidance is described in detail by Dalleau (2013) and has later been implemented in models of Liukkonen et al. (2018) and Chudzinska et al. (2021).

Time to rest

Seals will either go to rest at sea or go to a haul-out site to digest based on recently consumed food. This is performed as the activity “short resting at sea” for emptying their stomach or “long resting at sea” for digestion. The duration of resting at sea is defined by their digestion capabilities. Seals do not change their location while resting at sea.

Time to haul-out

If the seals have not hauled out for a while, they will travel to a haul-out site. However, if they are in poor condition, they are less likely to haul out because foraging can improve their condition.

Go to haul-out site

The movement towards haul-out sites is influenced by the distances to various sites and seals memory of these locations. The seals have two types of memories in the model. One for patches passed by and one for already visited patches, derived from Nabe-Nielsen et al. (2013) and modified by Chudzinska et al. (2021). The seals use correlated random walk if they are far from shore. Otherwise, they choose to follow the shortest path along the shore to reach a haul-out site when they are close to shore.

Haul-out

Hauling out can occur for digestive or non-digestive reasons. At the end of a haul-out event, the seals evaluate which food patch to head to next based on memory and their previous energy intake.

The primary goal of the seals is to maximize their net energy intake. This is calculated at the end of each time step as the difference between intake energy and energy expenditure. If the net energy intake is greater than 0, seals convert their excessive energy into storage (blubber). Conversely, if the net energy intake is less than 0, the seals burn fat, resulting in a loss of body mass. The seals die when the mass of blubber decreases below 5% of total body weight. This is the only way a harbour seal can die in the model as factors such as age distribution and other stressors are not considered.

SUBMODELS

A detailed description of the submodels for each procedure, their function, and how each parameter is calibrated is specified by Chudzinska et al. (2021) in the TRACE document, section 1.7.

DESIGN CONCEPT

The model assumes that seals would optimize their foraging movements by increasing the time spent in good-quality habitats (cells with high HSI). They memorize visited habitat patches and are more likely to return to the profitable ones. Using harbour seal movement can increase our understanding of interaction risk between the seals and fishing fleets based on data from the Directorate of Fisheries (DoF).

INITIALIZATION

The study areas are simulated separately, each with three replicates as outlined in Table 2.2. To initiate each model, super-individuals of harbour seals are placed on their respective haul-out sites. Super-individuals are simple solutions when modelling larger populations on an individual basis (Scheffer et al., 1995). One super-individual in the model represents a total of 10 seals. This resulted in 79 modelled seals for Sør-Trøndelag, 49 for Rogaland, 66 for lower Nordland, and 98 for upper Nordland (see Table 2.2). All individuals in the model are adults, with a random distribution of males and females. The model started on the 1st of October outside the breeding season and was simulated for one year. The simulations did not account for seasonal variation, and parameters remained the same for all study areas. All seals started the simulation from their native haul-out site. Therefore, for seals to learn the environment and distribute naturally, the first five days were excluded prior to the calculation of preluse, prelcatch, and interaction risk.

Table 2.2: Overview of the twelve simulated models, with three replicates for each area. Super individuals modelled, and the start date, ddmmyy of the model simulation is also illustrated. The output of the three replicates for each area was used to find the mean value of preluse, prelcatch, and interaction. The number of super-individuals remained the same for the replicates.

Study area	Simulation	Replicate	Super-individuals	Start date for simulation
	1	1		
Upper Nordland	2	2	98	1.10.19
	3	3		
	4	1		
Lower Nordland	5	2	66	1.10.19
	6	3		
	7	1		
Sør-Trøndelag	8	2	79	1.10.19
	9	3		
	10	1		
Rogaland	11	2	49	1.10.17
	12	3		

2.4 ESTIMATING INTERACTION RISK

After running all simulations and replicates in NetLogo, the output-files were used for assessing the relative risk of interaction between coastal fisheries and harbour seals. The same three-step methodology outlined by Roe et al. (2014) and Elnes (2021), adapted from the work of Vanderlaan et al. (2008) was used. The approach involved a calculation of three metrics and was calculated in R-studio. The metrics involved relative use (preluse), relative catch (prelcatch) and the degree of overlap between the two variables (interaction). Preluse was determined by converting density estimates into relative probabilities and was achieved by calculating the probability of seals being present in a specific lokref cell i relative to all other lokref cells n across the seasons t. This probability was derived from N, represented as ticks (timesteps) in NetLogo that denoted the amount of time seals spent in a given lokref cell (equation 2.1). The next step involved calculating the probability of fishing effort occurring in each lokref cell i during various seasons, compared to the other lokref cells n (equation 2.2). It was calculated by taking the catch of each cell and dividing it by the total catch from Norwegian fishery data from the DoF. Finally, an interaction index was computed to determine the extent of overlap by combining the two equations 2.1 and 2.2. These metrics were calculated and the mean value from the three replicates for each area was used to describe preluse, prelcatch, and interaction for the seasons Autumn, A, Winter, Wi, Spring, Sp, and Summer, Su. An overview of the different variables is found in Table 2.3.

Table 2.3: Definition of different variables used in the equations (2.1-2.3).

i	Specific lokref cell
n	Total number of lokref cells
t	Seasons
N	Timestep (density) (seal-presence in a lokref cell)

$$P_{rel}(Seal, use)_{it} = \frac{N_{it}}{\sum_{i=1}^{n}\sum_{t=1}^{4} N_{it}} \quad (2.1)$$

$$P_{rel}(Fishing, catch)_{it} = \frac{effort_{it}}{\sum_{i=1}^{n}\sum_{t=1}^{4} effort_{it}} \quad (2.2)$$

$$P_{rel}(Interaction, overlap)_{it} = \frac{P_{rel}(Seal,use)_{it} \times P_{rel}(Fishing,catch)_{it}}{\sum_{i=1}^{n}\sum_{t=1}^{4} P_{rel}(Seal,use)_{it} \times P_{rel}(Fishing,catch)_{it}} \quad (2.3)$$

Interaction values were determined using equation 2.3. The values were binned and categorized using a semi-logarithmic scale. Five categories representing the interaction risk between harbour seals and coastal fisheries were defined as very low, low, medium, high, and very high interaction risk. The medium risk was further subdivided into two halves for comparison with Elnes' research (3 medium and 4 medium). The Risk Category (RC) of very low was applied to the lowest interaction risk value and was termed RC1. The rest were using a logarithmic scale when possible. Interaction values above the lowest number were binned as followed: 0 to 10^{-3}, 10^{-3} to 10^{-2}, 10^{-2} to 10^{-1}, $10^{-}1$ to $25*10^{-1}$, $>25*10^{-1}$, corresponding to the interaction risk categories of low, 3medium, 4medium, high and very high. The low interaction risk was defined as RC2, the moderate interaction risk consisted of RC3 and RC4 whereas the high and very high interaction risk involved RC5 and RC6.

2.5 SENSITIVITY ANALYSIS

Sensitivity analyses are simulation experiments that can analyse rigorous models. The analyses examined how the results varied based on different inputs and how different processes influenced the model (Chudzinska et al., 2021). The sensitivity analyses were implemented for lower Nordland focusing on two model modifications related to food depletion and memory. Food depletion involved whether fish numbers available were changing per patch or remained the same. Memory was modified to test if visited patches could affect movement, or if seals followed a correlated random walk toward haul-out sites. The two modifications could either be turned ON or OFF in NetLogo. They were tested with 33 super individuals to make the model run faster. Both scenarios were tested over three months where the rest of the parameters remained untouched. The sensitivity analyses were tested for mean blubber (%), number of seals alive, and daily energy expenditure (MJ/day) as visualized in Figures A-1 and A-2. Another test was performed to see how long it took for seals to distribute naturally in the landscape since most seals started their movement with the activity of foraging from their native haul-out site at the beginning of the simulation. A detailed description of the sensitivity analyses can be found in the appendix.

2.6 SOFTWARE USED

The IBM of the three study areas was implemented in NetLogo version 6.2.2. RStudio version 2021.09.1, R version 4.1.2 (Core, 2008) was used to prepare model input files (e.g., spatial data/raster files), analyse the model output, and visualize the simulation results. The input files were created by generating multiple raster files. They represent different aspects of the landscape including water depth (bathymetry), distance to coast which showed the distance from each at-sea patch to the coast, and HSI files. The packages of *raster* (Hijmans, 2022), and *sf (Pebesma, 2018)* generated the raster data. Bathymetric depth was downloaded from EMODnet (EMODnet, 2020). For data preparation, the packages of *data.table* (Dowle & Srinivasan, 2021), *dplyr* (Wickham et al., 2022), *tidyr (Wickham & Girlich, 2022),* and *rnaturalearth* (South, 2017) were used. To generate plots, the packages of *ggplot2* (Wickham, 2016), *patchwork* (Pedersen, 2022), and *RColorBrewer* (Neuwirth, 2022) were used. To help with plotting, Chat.openAI, GPT-3.5 was used (OpenAI, 2023). All R scripts used in this thesis are publicly available at a permanent GitHub repository located at https://github.com/pernillerw/Master-thesis-2023.git.

The TRACE document of Chudzinska et al. (2021) can be found using this link:
https://github.com/MagdaChu/AgentSeal/blob/master/AgentSeal%201.0%20TRACE_2020.pdf

3 RESULTS

3.1 SIMULATED SEAL MOVEMENT IN NETLOGO AND THEIR ACTIVITIES

A total of 2902 harbour seals were simulated with 292 super-individuals representing 10 individuals each across the three study areas. Throughout the simulations and across the three replicates, the super-individuals exhibited consistent movement behaviour. This trend was observed for all study areas. Figure A-10 illustrates the movement of the super-individuals in upper Nordland across the three replicates. The seals generally remained close to their haul-out site for the majority of the year. They engaged in various activities including foraging, hauling out, land avoidance, long resting at sea, short resting at sea, and travelling from the moment the seals decide to haul-out to the actual haul-out site, each occurring at different scales. Figure 3.1 displays the activity proportions of the simulated super-individuals of lower Nordland, focusing on one of the replicates throughout the model simulation. The predominant activity was foraging constituting 58.8% of the total. Hauling out accounted for 25.3% of the overall activity proportions. However, it is worth noting that the hauling-out activity was excluded before interaction risk calculation as haul-out sites are on land and will not contribute to interaction occurrences. Similar patterns in activity distribution were observed across the other areas.

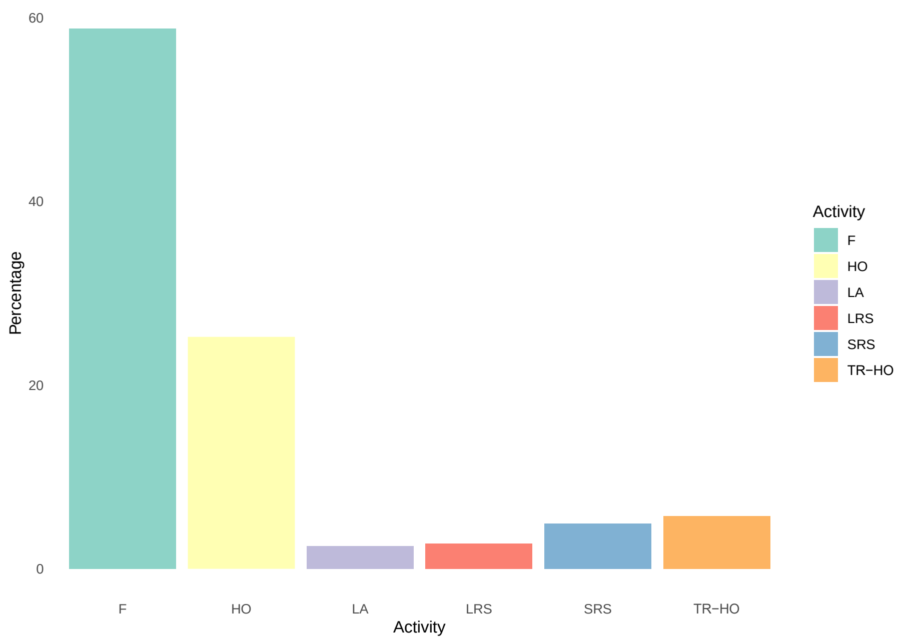

Figure 3.1. Overview of the activities seals performed throughout the simulation of lower Nordland. The proportion of the different activities is visualized as percentages. F=foraging (58.8%), HO=haul-out (25.3%), LA=land-avoidance (2.5%), LRS=long resting at sea (2.8%), SRS=short resting at sea (4.9%), TR-HO=travelling to HO (5.8%).

The amount of lokref cells visited by each individual seal varied over the model simulations. Some seals predominantly stayed in a few lokref cells, while others were more active, moving between various haul-out sites. Figure 3.2 illustrates two simulated harbour seals in lower Nordland. One seal (red) primarily stayed in lokref cell 06-33 near haul-out ID 25 but was observed to travel between haul-out sites in lokref 06-31. In contrast, the other seal (turquoise) travelled between several haul-out sites, including haul-out ID 22, 28, and 26. The movement behaviour of seals in areas where haul-out sites were located in the smaller fjords is visualized in Figure A-8.

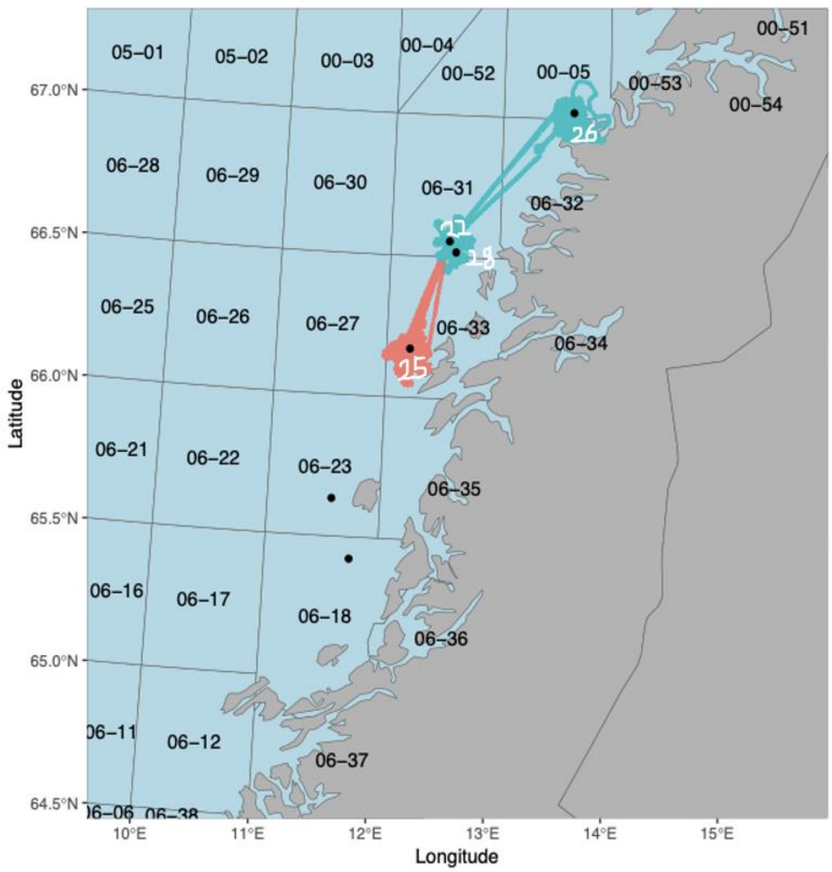

Figure 3.2. Two harbour seals movement throughout the model simulation of lower Nordland. The haul-out ID is displayed as white numbers next to black dots representing the haul-out sites. One of the seals (red) is showing site fidelity to haul-out ID 25 in lokref cell 06-33, while the other seal (turquoise) travelled and foraged in between several haul-out sites. The grey area illustrates land areas, while the blue displays lokref cells both close to the shore, and offshore.

3.2 RELATIVE USE OF THE THREE STUDY AREAS

The relative use of harbour seals (preluse), derived from equation 2.1 represents the proportion of harbour seals occupying lokref cells throughout different seasons as illustrated in Figure 3.3. Preluse reflects the seal's movement over the entire year, with consistent parameter values across the seasons. A higher relative use was observed for the seasons of autumn, winter, and spring. The summer season had a lower relative use due to the inclusion of only the month of June. Values that ranged from 0.026 to over 0.09 fell into the categories of high relative use and were represented with the colours red and black respectively in Figure 3.3. Winter and spring were observed to have a generally higher proportion of movement compared to autumn and summer. Summer showed a higher proportion of moderate use compared to the other seasons. The preluse of category 1, indicating little to zero movements, was less evident for lokref cells closer to the shore but more prevalent offshore lokref cells. The visualization of the preluse for all seasons is illustrated in Figure 3.3. A detailed description of the relative use in the three study areas is provided in the following section:

Relative use of Nordland

In upper Nordland, seals moved the most within lokref cell 05-24 for all seasons with the two highest categories. Adjacent lokref cells of 05-23 and 05-25 had both 3 and 4 medium degrees of movement indicating a moderate use. Lokref cell 05-20 of Langøya, had category 5 of relative use. Seal movement of lower Nordland was predominant in lokref cells 00-03, 06-31, and 06-33 with categories 5 and 6 for all seasons except summer. The adjacent cells showed varying degrees of use.

Relative use of Sør-Trøndelag

Most of the movement was concentrated in the lokref cells surrounding a haul-out site, particularly lokref cells 07-08 with haul-out IDs 20 and 21, and 07-25 with haul-out ID 19. The majority of movements were observed in these cells compared to any other lokref cell of the area. These two lokref cells consistently had a preluse of a category of 6 (illustrated with black colour) for all seasons except summer. Summer was categorized as 5, still showing high use. Adjacent cells were categorized as 3 medium, indicating activity performance at a moderate scale. Additionally, the highest movement in the adjacent cells was exhibited in the winter season, however as category 2, indicating lower movement activity.

Relative use of Rogaland

Seal movement was predominant in winter and spring. Lokref cell 08-17 consistently had a very high use (category 6) for all seasons except summer (category 5). The lokref cells of 08-02, 08-16, and 08-18, associated with haul-out sites, showed moderate to very high use with preluse categories ranging from 4-6 across the seasons. However, seals also utilized adjacent cells, but with a lower to moderate movement activity of the categories 2 and 3.

3.3 RELATIVE CATCH FROM FISHING EFFORT

Calculated from equation 2.2, fishing effort, or the relative predicted catches (prelcatch), was determined by dividing the catch per lokref cell by the total catch in all cells. The catches encompassed all species recorded by the DoF in gillnet fisheries. Spring was the season when most fishing trips occurred along the Norwegian coast, visualized in Figure 3.4.

Prelcatch (fishing effort) varied across the study areas. During spring, fishing efforts consistently fell into the high and very high categories for all coastal areas. The only offshore cell categorized as very high throughout all seasons was for lokref cell 41-75 of Rogaland, situated closer to the Danish border. Winter showed a generally high fishing effort, particularly in lokref cells 05-23 and 05-24 of upper Nordland. Autumn and spring had the highest fishing effort for Sør-Trøndelag. The lokref cell of 07-25 exhibited high effort during autumn, while lokref cells 06-06 and 06-12 were categorized as high during both autumn and spring. Winter and spring had the highest fishing effort for Nordland in both the upper and lower areas. Spring had the highest fishing effort for Rogaland. Rogaland was the only area that did not receive a category 6 for lokref cells closer to the coast. Summer recorded the lowest fishing effort for all areas, mainly represented by categories 2 and 3.

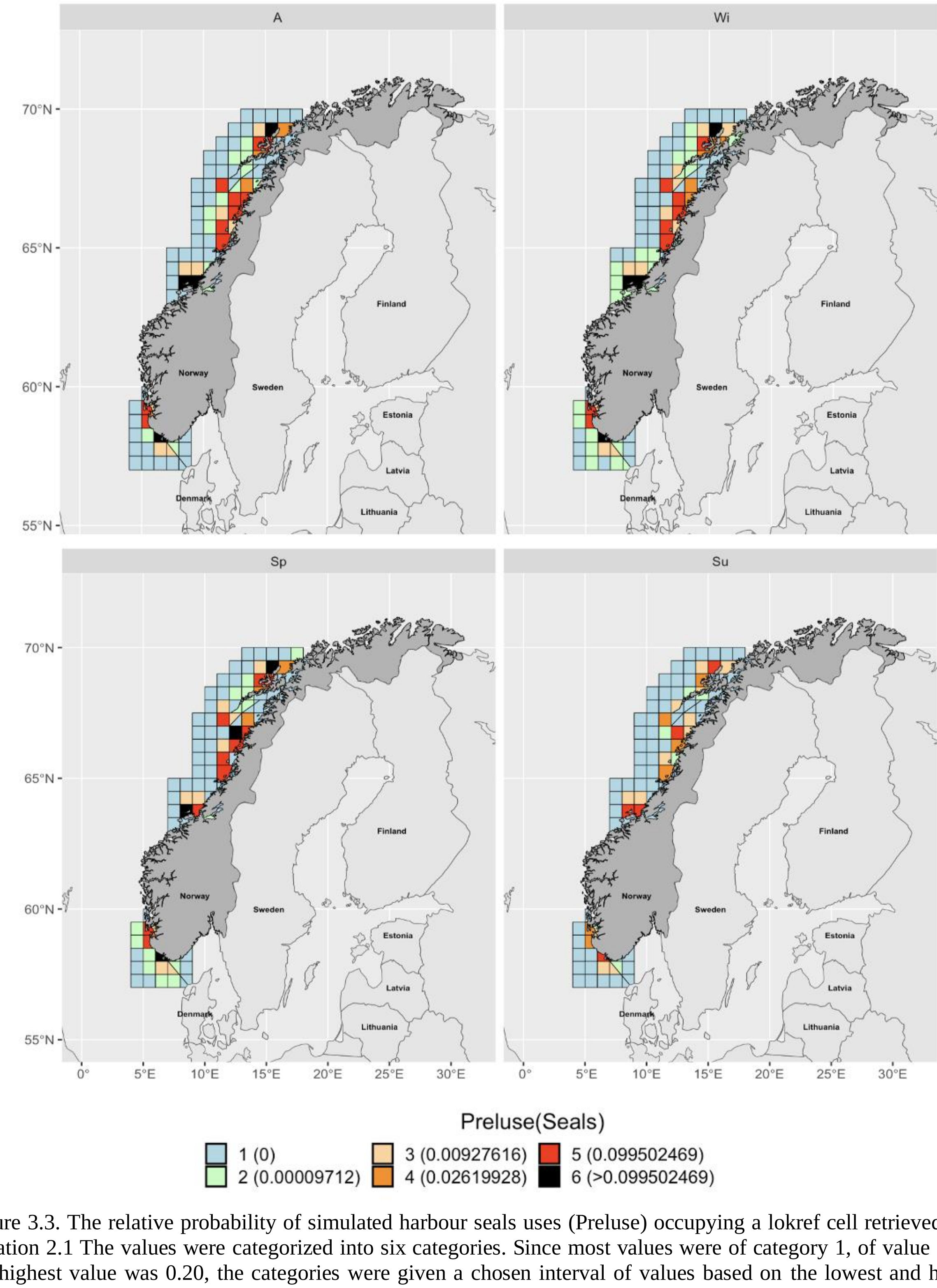

Figure 3.3. The relative probability of simulated harbour seals uses (Preluse) occupying a lokref cell retrieved from equation 2.1 The values were categorized into six categories. Since most values were of category 1, of value 0, and the highest value was 0.20, the categories were given a chosen interval of values based on the lowest and highest value, which was representative of the different categories. The darker the colour, the higher the use. All maps display the seasons, A =Autumn, Wi = Winter, Sp= Spring, and Su=Summer.

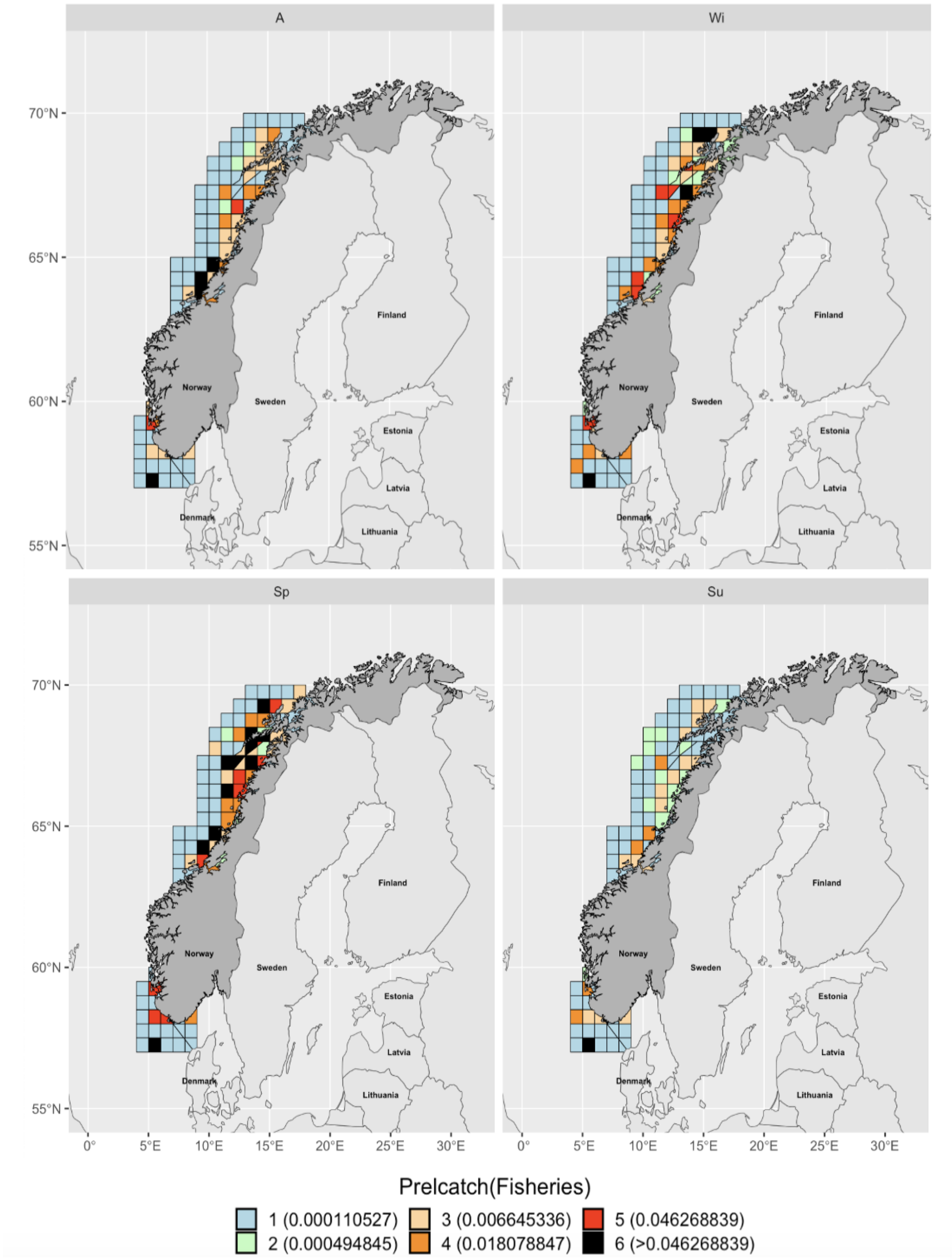

Figure 3.4. The predicted fishing effort, (Prelcatch) was retrieved from equation 2.2 of the three study areas. Values were categorized into six categories. The categories were given a chosen interval of values based on the lowest and highest value, of 0 and 0.31 respectively that was representative of the different categories. The darker the colour, the higher catch. All maps display the seasons, A =Autumn, Wi = Winter, Sp= Spring, and Su=Summer.

3.4 INTERACTION BETWEEN HARBOUR SEALS AND COASTAL GILLNET FISHERIES

Interaction risk categories were calculated and defined from equation 2.3, using a semi-logarithmic scale to define the Risk Categories (RC). The distribution comprised a total of 3, 12, 24, 20, 64, 322 lokref cells classified as very high (RC6), high (RC5), 4 medium (RC4), 3 medium (RC3), low (RC2) and very low (RC1) interaction risk, respectively. Table 3.1 provides an overview of lokref cells with interaction values of RC5 and RC6. Figure 3.5 illustrates the predicted interaction risk between harbour seals and fisheries based on category intervals, across all four seasons of the study areas along the Norwegian coast.

The interaction risk categories showed variability across the study areas. The three lokref cells of 05-24 in upper Nordland, 07-25 in Sør-Trøndelag, and 08-17 in Rogaland consistently received RC6 in different seasons. Specifically, lokref cells 05-24 had the highest RC in winter, 07-25 in autumn, and 08-17 in spring. These cells encompassed haul-out IDs of 30-32 in Nordland, 19 in Sør-Trøndelag, and 2,47, and 48 in Rogaland. The highest predicted risk through all study areas occurred in the winter season of lokref cell 05-24 with an overall interaction risk value of 0.383. Lokref cells that showed a relatively high to moderate interaction for all seasons except summer included 00-03 with the island of Røst in Lofoten, 00-05, located outside of Bodø, 05-24, located close to Andøya, and 06-31, and 06-33 in lower Nordland. These areas were predicted to be of high risk during winter and spring when fishing efforts were high. Rogaland composes a smaller proportion of harbour seal individuals than Nordland, which has over 30% more individuals. However, interaction risk was still predicted to be high to moderate for all seasons in lokref cells with haul-out sites (08-16, 08-17) of Rogaland. In Sør-Trøndelag, the islands of Frøya and Hitra, situated in lokref cell 07-08 with haul-out ID 19 had a predicted RC5 for winter, and RC4 for the other three seasons. The neighbouring lokref cell of 07-25 had RC6 for autumn, RC5 for spring and winter, and was predicted with RC4 for summer, indicating that entanglement risk can be relatively high in these areas. While RC3 to RC6 was observed for many lokref cells, most cells fell within RC1. However, most of these cells were offshore cells, where harbour seals are seldom observed. Figure 3.6 provides a detailed visualization of all study areas with interaction risk categories 1-6. Additional details about preluse, prelcatch, and interaction values can be found in Table A3. Information about harbour seals with haul-out IDs and corresponding lokref cells for all areas is found in Figure A-6.

Table 3.1: Overview of 9 lokref cells with a high RC of category 5 or 6. The three lokref cells with RC6 are outlined with a darker blue colour. Each lokref is divided into seasons predicted with interaction risk. Preluse represents harbour seal use in each lokref cell and prelcatch is the relative fishing effort in each lokref cell. Sp=spring, Wi=winter, A=autumn.

Study area	Lokref	Season	Preluse	Prelcatch	Interaction	RC
Nordland	00-03	Sp	0.0507694	0.0545602	0.1527443	5
Nordland	00-05	Sp	0.0188698	0.1060309	0.1201999	5
	05-24	Sp	0.1144636	0.0319841	0.1989134	5
Nordland	05-24	Wi	0.1082934	0.0635550	0.3833801	6
	06-31	A	0.0938315	0.0214961	0.1092058	5
Nordland	06-31	Sp	0.1141446	0.0412888	0.2480899	5
Nordland	06-33	Sp	0.0692867	0.0317218	0.1233048	5
Sør-Trøndelag	07-08	Wi	0.1787570	0.0139568	0.1422584	5
	07-25	Wi	0.1194523	0.0331575	0.2174156	5
Sør-Trøndelag	07-25	Sp	0.0938282	0.0362424	0.1894405	5
	07-25	A	0.1016817	0.0550437	0.3035505	6
	08-16	A	0.0781519	0.0414699	0.1915965	5
Rogaland	08-16	Wi	0.0824343	0.0412749	0.2024997	5
	08-16	Sp	0.0768179	0.0400321	0.1786305	5
Rogaland	08-17	Sp	0.1585753	0.0348618	0.3248742	6

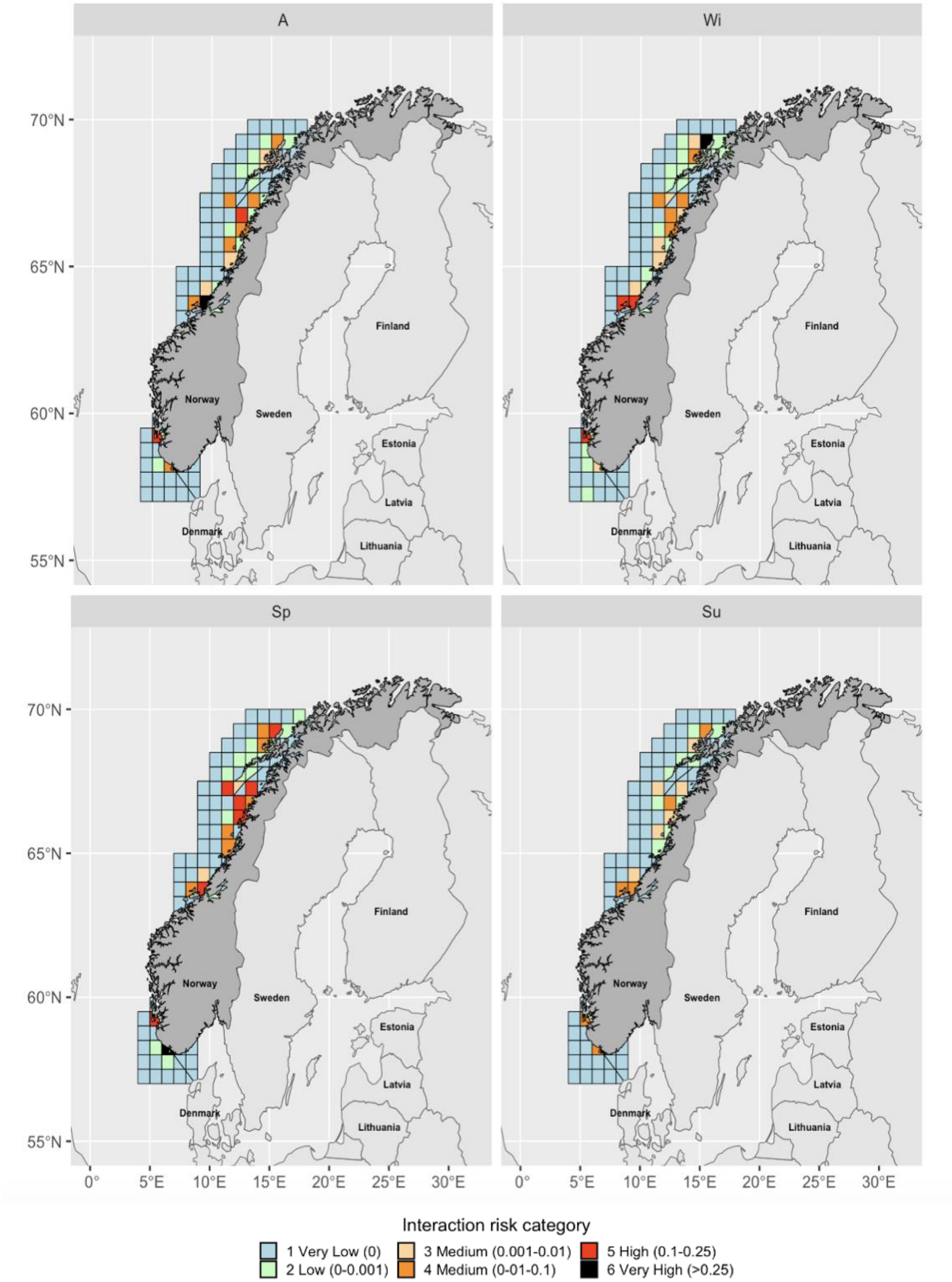

Figure 3.5. Predicated interaction risk between harbour seals and coastal gillnet fisheries retrieved from equation 2.3 for the three study areas along the Norwegian coast. Six Risk Categories (RC) were assigned the values of every lokref cell across all four seasons. RC1 represented very low, while low interaction risk was defined as RC2. Moderate interaction risk consisted of RC3 and RC4 whereas the high and very high interaction risk involved RC5 and RC6.

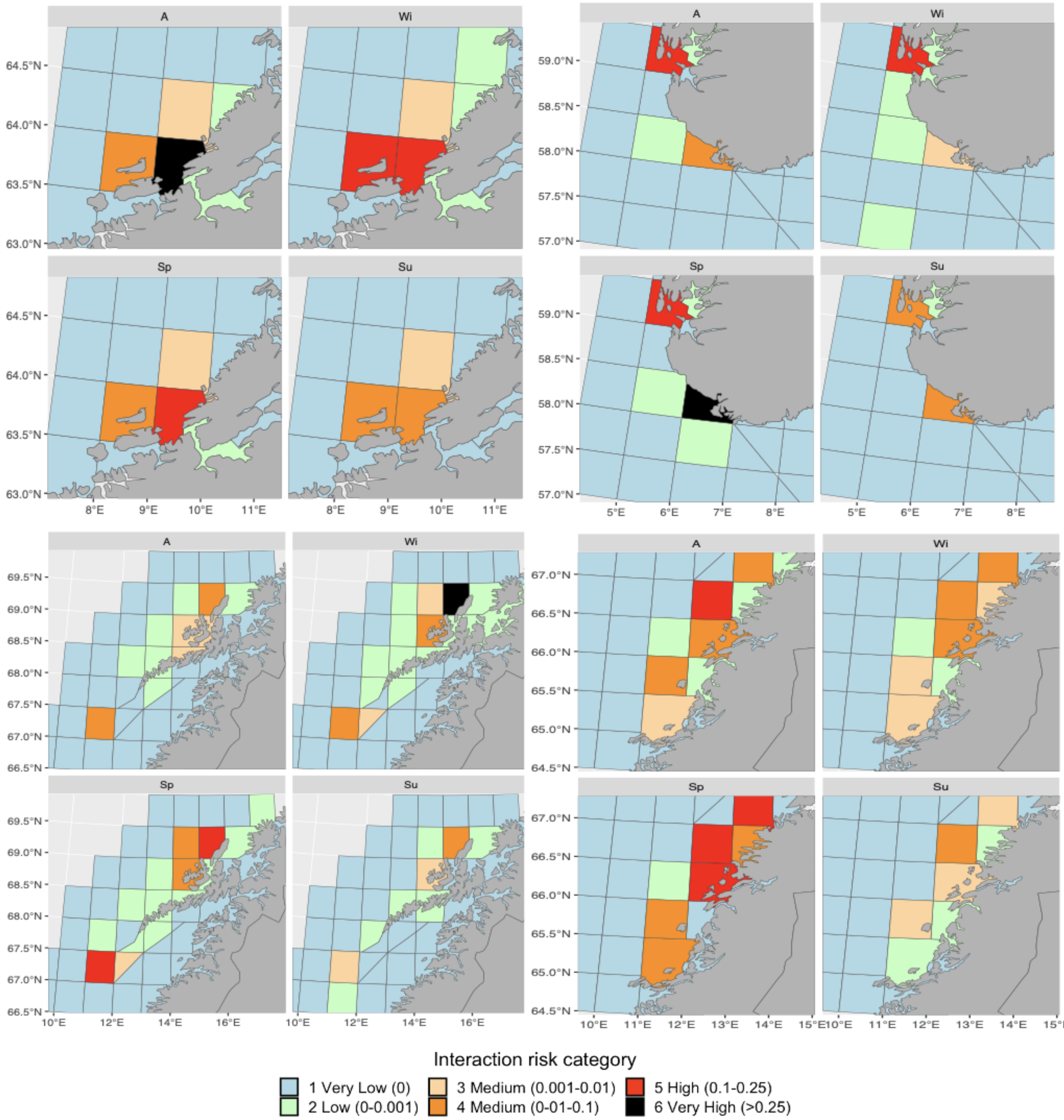

Figure 3.6. A closer insight into the study areas with corresponding interaction risk categories. The upper left illustrates Sør-Trøndelag risk categories for all seasons, with an overall moderate to high predicted risk. The upper right shows Rogaland's interaction risk for all seasons. The two bottom pictures illustrate upper (left) and lower (right) Nordland. Interaction risk was predicted to be high for seasons winter and spring, especially for lokref 05-24. Lokref cell 00-03 in upper Nordland showed a high predicted interaction risk during spring.

3.5 COMPARISON WITH ELNES (2021) STUDY

The estimated interaction risk from this study revealed both similarities and disparities in comparison with the research of Elnes (2021). Details on how predicted interaction risk categories were defined for both studies are provided in Table 3.2. The category of very low interaction risk was defined as RC1 for both studies. The category of low interaction risk was defined as RC2 for this thesis and RC2+3 for Elnes' study. Medium interaction risk was RC3+4 for this thesis and RC4+5 for Elnes' study. The categories of a high interaction risk were within RC5+6 for this thesis and RC6+7 for Elnes' study. A detailed comparison of risk categories for the different lokref cells can be found in Table 3.3, allowing for an insight into the variation observed.

Table 3.2: Overview of how interaction risk categories between harbour seals and coastal gillnet fisheries were defined for this study and the research of Elnes (2021) with risk categories (RC) ranging between 1-7 from very low to high.

Interaction risk category (RC)	Very low	Low	Medium	High
This thesis	1	2	3+4	5+6
Elnes study	1	2+3	4+5	6+7

The observed result for Nordland was both correlating and showing dissimilarities between the two studies as visualized in Table 3.3. Elnes (2021) predicted an overall interaction risk category of 4-6 for lower Nordland, while this thesis found the area to be within RC3-RC5 suggesting a correlation. Upper Nordland was observed to have the biggest contrast between the two studies. Particularly for the lokref cells of 05-23 and 05-25 adjacent to lokref cell 05-24. Elnes predicted a generally high interaction risk for those cells based whereas this thesis predicted a relatively low to moderate risk. Elnes predicted the lokref cells of 05-24 and 05-25 to fall within RC6 for all seasons except spring of 05-24 (RC5). This thesis found lokref cell 05-24 to be RC4 for autumn and summer, RC6 for winter, and RC5 for spring. Notably, the spring and winter seasons showed similar interaction risk assessments for the two studies in lokref cell 05-24. Lokref cell 05-25 on the other hand was in this thesis predicted to be within the lowest interaction risk category, indicating dissimilarities. Lokref cell 00-03 of lower Nordland was predicted with RC4 for autumn and winter, RC5 for spring, and RC3 for summer in this thesis. Conversely, Elnes' study found this lokref cell to be within RC5 for spring, RC4 for winter, and a lower risk category, RC2 for summer and autumn. These findings indicate both similarities but also some differences between the two interaction risk studies when studying Nordland.

Table 3.3: Overview of the risk category (RC) of the two studies. The lokref cells illustrated are mostly within the high RC category, but some are from adjacent cells (08-01, 08-02). RC from the Elnes' study is retrieved from the 2021 study, with the RC from Sør-Trøndelag from the updated version of 2023. The predicted interaction risk of the high categories is highlighted in blue for both studies. The seasons are defined A=autumn, Wi=winter, Sp=spring, Su=summer

		RC for each season, this study				RC for each season, Elnes' study			
Study area	*Lokref cell*	***A***	***Wi***	***Sp***	***Su***	***A***	***Wi***	***Sp***	***Su***
Nordland	00-03	4	4	5	3	4	6	6	3
Nordland	00-05	4	4	5	2	6	5	6	6
Nordland	05-23	1	3	4	1	5	7	6	4
Nordland	05-24	4	6	5	4	6	6	5	6
Nordland	05-25	1	1	1	1	6	6	6	6
Nordland	06-31	5	4	5	4	5	5	6	4
Nordland	06-32	1	3	4	1	5	4	5	4
Nordland	06-33	4	4	5	3	5	5	6	4
Sør-Trøndelag	07-07	1	1	1	1	6	5	6	6
Sør-Trøndelag	07-08	4	5	4	4	5	5	5	6
Sør-Trøndelag	07-25	6	5	5	4	6	6	6	7
Rogaland	08-01	1	1	1	1	2	4	3	1
Rogaland	08-02	1	1	1	1	1	1	2	2
Rogaland	08-16	5	5	5	4	4	4	5	4
Rogaland	08-17	4	3	6	4	2	2	1	1

Elnes et al. (2023) predicted lokref cell 07-08 in Sør-Trøndelag to fall within RC5 during all seasons except summer, indicating a moderate risk. Summer was predicted with RC6 of high interaction risk. In contrast, this thesis projected the same lokref cell to be classified as RC4 indicating a moderate risk for all seasons except winter, where it was assigned RC6 of high interaction risk. Regarding the adjacent cell, Elnes classified the lokref cell of 07-25 as RC6 and RC7 for all seasons, while this thesis predicted the interaction risk to be within RC5 and RC6 for all seasons except summer (RC4). The area of Sør-Trøndelag was generally similar in both studies, but some differences were observed.

Elnes (2021) predicted a generally relatively low interaction risk for most lokref cells of Rogaland. The exception was for lokref cell 08-16 which was consistent with moderate interaction risk across the seasons. This was dissimilar to this thesis that predicted a high interaction risk, RC5 for 08-16 for all seasons except summer (RC4). Furthermore, lokref cell 08-17 showed inconsistency, where the RC varied between RC3 to RC6 across the different seasons. An illustration of the risk category (interaction risk) map from Elnes' research can be found in Figure A-12.

4 DISCUSSION

This thesis mapped interaction risk between Norwegian harbour seals and coastal gillnet fisheries. Even though overlap does not necessarily lead to bycatches, it still serves as a valuable indicator for encounter risk. An initial measure towards mitigating these problems can be to identify areas and times of high interaction risks. The following section aims to elaborate on the findings related to the first objective of identifying areas and times of the year of high interaction risks using an IBM to capture seal movement.

4.1 INTERACTION RISK

4.1.1 Location cells with predicted high interaction risk

The estimated interaction risk was predicted to be highest during spring and winter. A total of nine lokref cells were predicted to have high interaction risk (risk category, RC5+6). Among these were four lokref cells observed to have high interaction risk for multiple seasons. For example, lokref cell 05-24 in Nordland had a high interaction risk for both winter and spring. The lokref cell of 07-25 in Sør-Trøndelag had a high interaction risk for winter, spring, and autumn, with the highest risk during autumn. Similarly, the lokref cell of 08-16 in Rogaland demonstrated a high predicted interaction risk during winter, spring, and autumn. In total, spring accounted for eight of the highest interaction risks, followed by winter (four) and autumn (three) (see Table 3.1). Among all lokref cells in the study, spring emerged as the season with the highest interaction risk constituting 42.4% of the total. Winter accounted for 32%, autumn 21%, and summer 4.57% of the total. Elnes (2021) found that spring accounted for 45% of annual average fishing trips along the Norwegian coast between 2006-2018. This supports that both a high relative use and relative catch for winter and spring can indicate why interaction risks were observed to be high. Similar results were observed for bycatch events in Ireland, where winter and spring accounted for most bycatch risk, and the risks were lower during summer and autumn (Luck et al., 2020).

The high-risk categories varied between 0.1092058 (RC5) and 0.3833801 (RC6) (see Table 3.1). Among these were lokref cell 05-24 observed to have the highest relative interaction risk, approximately three times greater than the lowest (high) value located in lokref cell 06-31, both located in Nordland. Even though interaction risk does not describe the bycatch rate directly within a cell, it still assumes that the bycatch rates will be higher in cells of higher interaction values (Murray et al., 2021).

4.1.2 High predicted interaction risk explained by fishing efforts

Fishing efforts showed seasonal variation and differences across the study areas. Data from the Directorate of Fisheries (DoF) revealed that Nordland had a total weight (tons) of catches of 131085 in 2019. Sør-Trøndelag weighted catches of 3790 tons in 2017 (no data registered for 2019), and Rogaland measured 3242 tons in 2017 as shown in Table A2. These data included gillnet but also other conventional fishery equipment. However, previous studies state that bycatch is not always proportional to fishing effort (Moan, 2016; Rochet & Trenkel, 2005). These studies suggest that there should be a stronger correlation between fishing trips and bycatch events than between catch and bycatch. Nevertheless, landing statistics from the DoF were still used as a proxy for fishing effort, acknowledging potential limitations in capturing the true correlation between catch and interaction risk events.

Interaction risk was in this thesis predicted to be high for lokref cells in Nordland. Other studies support the findings that northern Norway is predicted to have a high interaction risk. An unpublished study by Moan et al. (2023) applied HSI to the Norwegian coast, and estimated interaction risk between seals and fisheries. The study identified one of the highest risks to be in Vesterålen/Hinnøya in upper Nordland, consistent with the observation in this thesis. Upper Nordland, particularly lokref cells 05-23 and 05-24 had high and moderate interaction risk during winter and spring which can be explained by the significant fishing effort. This increased risk is attributed to the importance of the Northeast Arctic cod, which is not only the largest cod population but also a notable part of a harbour seal diet. The gillnet fishery for Northeast Arctic cod is the major contributor to seasonal fishing efforts and occurs from January to April. The cod population typically migrates from the Barents Sea, along the Norwegian coast where they spawn between the Finnmark county in northern Norway to Møre & Romsdal in the west (Bogstad, 2019). Their main spawning ground occurs in Vesterålen/Lofoten, and high fishing efforts were observed in the lokref cells adjacent to this area.

There is however evidence suggesting that cod spawning grounds have shifted further north over time due to climate change. Temperature can directly affect spawning distribution or cause a shift in their prey distribution (Fossheim et al., 2015; Langangen et al., 2019). A study by Langangen et al. (2019) found that the size of spawners increased with increasing latitude, and decreased with decreasing latitude. Their study also suggested spawning locations over time to be located further north. If spawning grounds of the Northeast Arctic cod continue to shift northward, it could potentially impact the interaction trends found between harbour seals and fisheries. This is because fisheries typically target larger fish, as they yield a better price per kilogram compared to smaller fish (Zimmermann & Heino, 2013). A northward shift in cod distribution could therefore lead to a northward shift in fisheries. This shift could possibly reduce the risks of interaction around Vesterålen/Lofoten in the future, as harbour seals tend to prefer smaller to medium-sized cod and other prey species (NAMMCO, 2021). This is supported by a study by Moan and Bjørge (2021) that found that bycatch levels have shifted northward over the last 15 years. Bycatch events in the region of mid-Norway including Sør-Trøndelag, lower Nordland, and upper Nordland to the island of Langøya, have been observed to shift towards the region of north Norway, from the region of Andøya in upper Nordland and further north (Moan & Bjørge, 2021).

There is also evidence that the monkfish fisheries show a high interaction risk with harbour seals along the Norwegian coast (Bjørge et al., 2016; Elnes, 2021; Moan, 2016). Monkfish fisheries typically use a larger mesh size than cod fisheries. It is demonstrated that the larger mesh sizes can increase the probability of bycatching marine mammals (Cosgrove et al., 2016; Elnes, 2021). In contrast to cod fisheries, the fishery for monkfish typically starts in April, and reaches a maximum in September, with a gradual decline towards December (Moan, 2016). Moan (2016) studied the impact of cod and monkfish fisheries on harbour seals. Their study revealed that cod fisheries predominantly occurred in FSA 04, 05, and 00 (including Nordland), with decreasing levels further south. Monkfish fisheries conversely were most prominent in FSA 06 and 07 corresponding to Sør-Trøndelag, with the lowest levels found in FSA 08 and 09 corresponding to Rogaland. These findings support the predicted interaction risk in the different location cells found for this thesis. Monkfish and cod fisheries can therefore explain some of the high interaction risks observed for the study areas.

4.1.3 Mitigating bycatch events by focusing on location cells close to haul-out sites

One of the most effective measures in reducing bycatch events of harbour seals and other marine species has been observed to be spatial and temporal restrictions (Elnes, 2021; Luck et al., 2020).

A study by Niemi et al. (2012) banned specific fishing gear and used time and area restrictions to increase recruitment of the critically endangered Saimaa ringed seal (*Pusa hispida saimensis*). The mitigation efforts in location cells with high interaction risk were observed to be more beneficial than mitigation efforts in areas of lower risk in the study.

This thesis found areas of higher interaction risk to be located within lokref cells close to haul-out sites, with declining trends towards the continental shelf. Many lokref cells of predicted high risk were consistent with reported actual bycatch events by gillnet-fisheries close to haul-out sites (Bjørge et al., 2002b), especially for lokref cells 07-08, 07-25, and 05-24 for Sør-Trøndelag and Nordland respectively. A high interaction risk was also observed close to haul-out sites of lokref cells 00-03, 00-05, 06-33, 06-31, 08-16 and 08-17 (see Figure A-6). These findings are supported by several studies such as Moan (2016), Murray et al. (2021), and Luck et al. (2020). Murray et al. (2021) found that the highest areas of interaction risk between grey seals and Canadian fisheries occurred adjacent to major pupping colonies and close to haul-out sites. Luck et al. (2020) observed that distance from haul-out sites would significantly affect bycatch rates of the grey seal population of Ireland. Focusing on fishing restrictions closer to major seal colonies where they typically haul-out in larger numbers, offers an effective approach to minimizing bycatch events. This facilitates conservation efforts while simultaneously being less restrictive to fishing efforts over spatial scales (Luck et al., 2020).

4.2 INDIVIDUAL-BASED MODEL TO CAPTURE CENTRAL-PLACE FORAGING

The next section aims to discuss how the IBM captured harbour seal movement, (preluse). This will also include how HSI influenced the observed movement patterns.

4.2.1 Distribution of activities

Harbour seals were observed to perform various activities in the IBM. As displayed in Figure 3.1, it was evident that foraging was the most frequently performed activity. Harbour seals along with other pelagic predators depend on resources that are patchy distributed (Boyd, 1996). They typically feed close to their haul-out sites usually within 50 km (Frost et al., 2001; Härkönen & Harding, 2001) which fairly well corresponded with the movement simulation in this study. Consequently, they invest their energy in exploitation of multiple prey during each foraging trip (Chudzinska, 2009; Robinson et al., 2007). However, changes in prey distribution due to fisheries management actions or environmental changes may potentially alter the foraging patterns of seal (Robson et al., 2004). Individual seals are also suggested to have separate foraging areas (Chudzinska, 2009), a general feature for harbour seals (Boyd, 1996; Staniland et al., 2004). A high concentration of several central place foragers may cause local depletion of resources leading individuals to develop specific tactics and foraging routes for minimizing competition (Chudzinska, 2009; Dolman & Sutherland, 1997; Staniland et al., 2004). However, the IBM applied in this thesis did not include social structure, grouping, or other direct interactions that could lead to competition (Chudzinska et al., 2021). For future studies, these factors should be considered as they have the potential to influence the distribution of activities.

The results revealed that hauling out (presented as HO in Figure 3.1) was the second most frequent activity for the seals, which aligns with realistic expectations. As previously mentioned, harbour seals use haul-out sites for various reasons. A haul-out duration is observed to vary among sexes. They typically have a longer haul-out duration in the summer due to the moulting seasons. Consequently, they are more dispersed during autumn, winter, and spring where they use the haul-out sites for resting in between foraging trips (Härkönen, 1987). The seals used their memory and experience to remember visited haul-out sites. This memory did not decay over the simulation duration. They also remembered patches with lower quality, enabling them to avoid those areas in their next timestep. Sensitivity analyses revealed that keeping the patch memory turned 'on' resulted in more realistic site fidelity, which is typical for a harbour seal (Chudzinska et al., 2021; Nabe-Nielsen et al., 2013). This haul-out memory in seals is consistent with findings from other studies. Mackey et al. (2008) and Cordes and Thompson (2015) found that seals have the potential to remember and return to a haul-out site even after several years. It is however noteworthy, that the activity of hauling-out was removed from the dataset prior to the calculation of interaction risk. This is because interaction risk between fisheries is equal to zero when seals haul-out on land.

Activities such as short resting at sea and long resting at sea (SRS and LRS in Figure 3.1) were performed less frequently and were based on seals recent consumption of food. The mechanisms of resting either on land, at the sea surface, or the sea bottom are poorly understood in ecology, especially for wild seals, and need to be studied more in the future (Chudzinska et al., 2021; Mikkelsen et al., 2019; Ramasco et al., 2014). The distribution of seal activities for the Norwegian study areas aligned with the original model of Chudzinska et al. (2021) (see Figure A-9). These similar results validated the application of the IBM to the Norwegian coast.

4.2.2 Habitat suitability index (HSI) influence on seal movement

To understand the foraging ecology of predators like harbour seals, it is crucial to acquire information about the conditions in which they forage (Chudzinska, 2009). Foraging behaviour typically follows prey (Chudzinska et al., 2021). The choice of prey depends on dive bouts, and other factors including, local bathymetry and maximizing their net energy intake (Chudzinska, 2009; Tollit et al., 1998). This indicates that the feeding area can affect the behaviour of a seal (Madden et al., 2008).

HSI was originally developed for terrestrial species (Carter et al., 2020; Manly et al., 2007), but has also been applied for marine species, e.g. cetacean surveys (Hammond et al., 2013). This thesis used a UK model, developed by Carter et al. (2020) modified to fit Norwegian harbour seal habits by Moan et al. (2023, Unpublished data). However, the application of the UK model to Norwegian waters had some limitations. The landscape of UK waters differs from the Norwegian waters. UK waters are characterized by a broad underwater plateau, whereas Norwegian waters are longer and narrower with deeper fjords. The distribution estimates in this thesis were based on an overall habitat preference, indicating that all activities had the same habitat preference relationship, which may not be the case in reality. These relationships of different activities vary regionally in a species-specific manner, as harbour seals exhibit discrete foraging and travelling movement behaviour (Carter et al., 2020).

Distance to haul-out sites are important covariates in harbour seal models (Carter et al., 2020). This factor alone might be more representative for Norwegian harbour seal HSI models than using a range of different covariants which was used in this thesis (Moan et.al 2023., Unpublished data). Considering seals regularly return to land for hauling out events between foraging trips (Aarts et al., 2008), the distance to coast tends to be a crucial drivers of distribution.

Seals movement was observed to be concentrated around areas of strong HSI. These areas were typically in lokref cells close to haul-out sites (see Figure A-7). This is supported by Carter et al. (2020), where individual seals of the Scottish population were observed to forage at the east coast of St. Andrews Bay, with repeated trips to Wee Bankie, a sandeel fishing ground, while other seals tagged in the Firth of Forth remained in areas close to their primary haul-out site. This variation in habitat preference among individuals show how HSI can influence movement. Both repeated foraging trips and stationary behaviour were observed for the simulated seals in this thesis as well (see Figure 3.2).

Since Nordland was divided into two areas due to technical difficulties, an overlap was observed for certain lokref cells. This affected the HSI, as it was apparent for both areas. This division raised the possibility of seals moving within the same lokref of different modelled areas. For example, lokref cells 06-30 and 06-31, 00-05, and 00-03 for both upper and lower Nordland showed an overlap (see Figure A-6). Seal colonies are located in lokref cells 06-31, 00-03, and 00-05, where the seal colonies in lokref cells 06-31 and 00-05 were added for lower Nordland, while the colonies for 00-03 were simulated in upper Nordland. HSI was observed to be high in areas adjacent to lokref cell 00-05. This should initially have made the seal colonies located in lokref cell 00-03 of upper Nordland forage to the areas of high HSI of lower Nordland. However, this was not observed. The overlap did not cause calculation problems as the seals of lower Nordland did not travel to lokref cell 00-03 and had a preluse of 0 for all seasons. Upper Nordland showed similar patterns where the seal colonies in lokref cells 00-05 and 06-31 had a preluse of 0. Considering this, the overlapping lokref cells led to no additional corrections. It is however important to note that incorporating the entire area of Nordland into the IBM in future studies will be necessary for mitigating these uncertainties.

4.3 COMPARING THE INDIVIDUAL-BASED MODEL TO ELNES SIMPLER MODEL

The next section aims to discuss the second objective. This will elaborate advantages and disadvantages of capturing the observed seal movement using an IBM approach compared to a Monte Carlo simulation. Moreover, compare the results from the two studies. A short description of Elnes' study is outlined in section 1.6.

4.3.1 Modelling movement differences

The use of an IBM offers several advantages over simpler models, such as the Monte Carlo simulation of Elnes (2021) and Elnes et al. (2023). Firstly, IBM simulates individual harbour seals, with unique rules, parameters values, behaviour, and interactions (Grimm & Railsback, 2005; Grimm & Railsback, 2012; Nabe-Nielsen et al., 2014). This thesis simulated 292 super individuals with specified static entities like sex, stomach capacity, length, and a unique ID. Elnes simulated a total of 7.362 individuals, without individual-specific rules or parameters leading to a less realistic representation of individuals' behaviour.

Furthermore, while Elnes' research used direction and distance from haul-out to determine movement, the IBM in this thesis considered multiple movement-oriented patterns. These patterns included HSI, prey availability, turning angles, frequently remembered haul-out sites and duration trips, a distribution of at-sea positions, and distance from haul-out site and site. Using distance from the haul-out site as the only proxy for movement does not account for variation between the modelled individuals, their preferences, and responses to environmental factors. Additionally, the IBM incorporated sensing abilities for the individuals, allowing them to detect land and distinguish patches of higher and lower HSI. The seals were also not naive at the beginning of the simulations, where they used knowledge of food distribution in each study area. Moreover, an IBM can incorporate environmental factors more precisely allowing for a better comprehension of how environmental changes can influence individual movement of seals. These various environmental factors are typically represented as HSI for marine top predators like seals (Carter et al., 2020; Chudzinska et al., 2021; Grecian et al., 2018). The IBM also captured the distribution of activities as described in the previous section; a feature not included in the simpler model. This relates to seal movement behaviour in the real world which enhances that IBM is a more suitable model when studying the movement of seals.

An important difference between the two model approaches is that the Monte Carlo simulation accounted for seasonal variety in the movement simulation. The IBM on the other hand did not include any seasonal behaviour, and as previously mentioned, the parameters remained the same for all seasons. This is an important factor to include if the IBM is to be further developed. This is because the harbour seal dispersal from their primary haul-out site is expected to increase from a short-range dispersal during summer to a longer-range dispersal during winter (Dietz et al., 2013; Elnes et al., 2023). For Elnes' study, the seasonal variety gave a different total abundance of seals in all lokref cells for the various seasons which reflects reality.

There are some practicalities of using Monte Carlo simulations. The method is typically more straightforward, simpler to implement, and computationally less demanding compared to an IBM that employs more complex modelling techniques (Elnes, 2021). The Monte Carlo simulation was also run over 1000 times. Simulating multiple times allows for assessing variability and makes the results more reliable. The IBM on the other hand, had a total of 12 simulations with three replicates for each area. Modelling with IBMs can take several hours, and this thesis had simulations lasting over 12 hours. A smaller number of runs may provide uncertainties in the results as it only gives an insight into the results. Having more replicates generally enhances the reliability of model outcomes and should be accounted for in future studies. Consequently, the trade-off between the two models is between computational efficiency and details with realistic representations of individual movement behaviours. The choice between a Monte Carlo simulation and an IBM will therefore depend on the research goal. This implies that an IBM, incorporating complex individual behaviour, offers a more realistic depiction of seal movement when evaluating interaction risk with fisheries. This holds even when the model excluded seasonality and had fewer simulations and replicates.

4.3.2 Comparing predicted interaction risks

The interaction risk results from Elnes et al. (2023) and this study showed to be similar for some location cells and differ in others. Firstly, the two methods used different risk categories (RCs), which can be viewed in Table 3.2. Both studies predicted spring and winter to have the highest interaction risk. Moreover, location cells with high fishing effort were observed to have higher interaction risk, especially for colonies in north Norway. Interaction risk was highest in areas close to haul-out sites for both studies, which corresponds with evidence of actual bycatch events. The highest predicted interaction risk in the Elnes' study was in Sør-Trøndelag, lokref cell 07-25 for all seasons. Vesterålen and Senja in Nordland also had a high predicted risk. It is noteworthy that Elnes included a seasonal relative age-specific vulnerability for representing every season and had more simulated seals than this thesis. A noteworthy finding in this thesis that did not align with other data, is that some specific lokref cells from all areas showed high interaction risk during autumn. This is noteworthy as fishing effort is low during autumn. Lokref cells 06-31, 07-25, and 08-16, for lower Nordland, Sør-Trøndelag, and Rogaland respectively showed high risk during autumn, with the highest risk for Sør-Trøndelag and Rogaland. These results were inconsistent with Elnes' study, showing a lower interaction risk for those lokref cells (Elnes et al., 2023). This can be explained by the highly smoothed landscape, where seals were given a neighbouring at-sea lokref cell when swimming on land areas. These adjustments would most certainly increase the preluse of those cells and influence the observed high interaction risk. Table 3.3 presents an overall description of the main findings of interaction risk between using the two different methods. After comparing the results, both methods were observed to be useful in determining areas of high interaction risk between Norwegian harbour seals and coastal gillnet fisheries. However, the overall findings between the two studies suggest that the method of using an IBM yielded more realistic movement results. The IBM incorporated individual behaviour data as previously mentioned, which enhances the reliability of the observed interaction risk.

4.4 IMPLICATIONS FOR MANAGEMENT AND CONSERVATIONS

Mapping interaction risk using an IBM approach can potentially help with harbour seal management and fishery regulations. Especially by identifying the areas and times of year of highest predicted interaction risk. This identification has been observed to be the most effective measure in reducing bycatch events for marine mammals (Elnes et al., 2023; Gormley et al., 2012). Results from this thesis revealed that the majority of seals remained close to haul-out sites while foraging. Preserving location cells of seal colonies may be appropriate for management and may ensure effective conservation of harbour seal populations. Primarily for location cells observed to have the highest interaction risks, which were found to be lokref cells 05-24 in Nordland and 07-25 in Sør-Trøndelag from both this study and Elnes' research. The influence of the Northeast Atlantic cod populations might affect interaction risks in the future as there has been observed a northward shift. This can potentially minimize the observed high interaction risk for seal populations located in the northern part of Norway.

While many researchers tend to focus on marine mammal populations only when they show decreasing trends, it is crucial to control and monitor other populations even when their population sizes seem to stay stable. Population fluctuation arises from various factors including variations in life history traits such as survival, fecundity, migration, fishing effort, and dispersal. Reducing bycatch mortality of marine mammals is critical for sustaining viable populations within their range of distribution. This is particularly important when considering the challenges that seals impose on coastal fisheries, hence the damage to fishing gear, loss of catches (ghost fishing), unintended catches, and transmission of parasites to fish. Since many seal populations are showing increasing trends worldwide, it can lead to elevated levels of interaction risk with fisheries (Cosgrove et al., 2016).

Bycatch remains one of the most significant global barriers to fisheries sustainability (Dodson et al., 2020). This causes an urge for innovation in effective fishery management to reduce the ecological impacts that fisheries have on fisheries that unintentionally catch marine mammals in their gillnets. Hazen et al. (2018) used a multispecies dynamic ocean management approach that aimed to reduce bycatch while simultaneously supporting sustainable catch rates for fisheries. By studying Californian swordfish fisheries, and tracking daily oceanographic conditions, Hazen et al. (2018) could access closed fishing areas and still protect leatherback turtles. The problem with this management approach is that species distribution shifts with the changing climate, so using historical species distribution data for designing closed fishing areas, puts those areas at risk of losing the ecological relevance (Hazen et al., 2018; McLeod et al., 2009).

Many mitigation efforts have successfully contributed to reducing bycatch risk. For example, modern fishing gears aim to minimize bycatch risk. Some of these include specialized hooks in longlines, biodegradable polymers, and acoustic deterrent devices. Longlines can now use hooks designed to reduce incidental catches, whereas biodegradable polymers have been suggested as a solution for reducing discarded fishing gear (ghost fishing) (Kim et al., 2016; Wilcox & Hardesty, 2016). Acoustic deterrent devices have been developed to deter echolocating animals from approaching the gillnets. Yet, for gillnet fisheries particularly, it is limited in how these gears can be modified and adjusted (Elnes et al., 2023).

4.5 LIMITATIONS OF APPLYING AN IBM TO FIT THE NORWEGIAN COAST

Despite contributing to understanding potential bycatch events, this thesis encountered limitations reflected by the highly smoothed landscape of the study areas. This is noteworthy as it can disrupt the reliability of the findings in this thesis. Firstly, the study areas were smoothed multiple times. In the first smoothing scenario, a smaller portion of land areas were changed into water patches and vice versa (Figure 2.3b and Figure A-4b, A-4e). When simulating this scenario in the IBM, over half of the seals died. Moreover, the activity of land avoidance was observed to be more frequent which does not correspond with reality (see Figure A-11). The seals were modelled to be able to detect land areas, but this was, however, not observed for the first scenario. Three of the four areas were therefore further smoothed to a high extent (see Figure 2.3c, section 2.2.1 for smoothing details). This was due to the technical difficulties that emerged since the Norwegian coast is more complex than the study area of the original model of Chudzinska et al. (2021). A larger proportion of land areas was changed into water patches, and some water patches were removed to become land. This allowed for a more fluent movement without the disruption of smaller bays and the death of seals. However, these highly smoothed areas could result in unrealistic seal behaviour, as the seals moved “on land”. This raises uncertainties about how realistic the results are.

The highly smoothed areas caused problems for colonies located in the smaller fjords. For instance, haul-out ID 3, within Lysefjorden in Stavanger of Rogaland comprises over 100 individuals. Also, haul-out IDs 47 and 48 are located within Lyngdalsfjorden. These fjords are extremely small, and initial model runs resulted in seals getting stuck, unable to forage. This happened even though the IBM included a land avoidance routine. These implications demonstrate that the current form of the IBM is limited as it cannot be applied for areas with narrow fjords and similar features as the complex Norwegian coast. However, this limitation could be addressed in future versions of the IBM. The IBM still succeeded in producing a realistic central-place foraging movement of harbour seals because it showed a similar distribution of activities as the original model of Chudzinska et al. (2021).

4.6 FUTURE IMPROVEMENTS

The individual-based model (IBM) also posed some other limitations than applying the smoothed landscape. The following section outlines some improvements that could be considered if the model were to be further developed. The following adjustments could affect movement, and make the model more realistic, which in turn would produce more realistic interaction risk estimates.

Besides the discussed smoothing challenges, incorporating details about seasonal variations is important for the development of this IBM. Seasonality should be considered for both prey availability and harbour seal movement, as dispersal distances vary. The original model by Chudzinska et al. (2021) on which the IBM in this thesis is based, was simulated for only three months and did not consider seasonality. Seasonality was, therefore, not further developed for the IBM in this thesis. The seal's relative use in each location cell was based on movement over the whole year. The seasons were applied when months were divided into seasons in the relative use equation (section 2.4, equation 2.1). This method assumed that seals moved in the same way throughout the simulations. The IBM did, therefore, not consider the biological variations in seals corresponding to the different seasons. This assumption resulted in an almost equal movement distribution for the seasons autumn, winter, and spring, whereas summer had a lower relative use because it only included the month of June (see Figure 3.5). A study of harbour seals in Southeast Scotland found a similar pattern, where seal movement was observed to be highest during the autumn and winter seasons of November, December, and January. The summer months of June and July, on the other hand, showed more stationary behaviour as the probability of hauling out was higher (Sharples et al., 2009). The assumption can, therefore, not be realistically true in this thesis as seals typically haul-out during summer and early autumn. Seasonality was, however, applied in the study of Elnes et al. (2023) as shortly described in section 4.3.1. As this thesis aimed to compare results with Elnes' study, adding seasonality to IBM could potentially have enhanced the reliability of the results. Moreover, considering seasonal variation could further highlight the suitability of using an IBM for studying movement behaviour compared to the simpler model by Elnes et al. (2023).

Age-specific distribution is another aspect that should have been considered in the IBM. Elnes et al. (2023) included age-specific bycatch events in all seasons in the simple Monte Carlo model. This should have also been considered in this thesis because the predicted interaction risk is expected to be higher for younger harbour seals (Bjørge et al., 2002a). Particularly for pups of ages 0-1 years during their first month after birth (Bjørge et al., 2002a). This is supported by the study of Murray et al. (2021) which found a significant pattern of interaction between younger grey seals and gillnet fisheries. There has previously been suggested that different sexes and age groups have different hauling out behaviours. Information about age distribution is of vital importance as it can affect the relationship between counts of seals and total population dynamics. Moreover, age distribution can affect seasonal behaviour and should be accounted for if the study were to be repeated (Cunningham et al., 2009; Härkönen & Harding, 2001; Härkönen et al., 1999).

The entire Norwegian harbour seal population should be further investigated. One approach could be to use satellite trackers on the individuals along the coast to study movement closely to provide information on whether the simulated seal movement in this model would align with actual harbour seal movement. The three study areas in this thesis included 2903 harbour seals, corresponding to approximately 30% of the overall population of 10 000 individuals (Bjørge et al., 2010b). This left out a huge proportion of both larger and smaller seal colonies on the Norwegian coast. This could influence relative predicted interaction risk as it is expected to be increased in Vestfold and Telemark, Troms and Finnmark (Elnes et al., 2023). If the study were repeated, the entire coast including all colonies would have been included. The model should also be tested for a longer period in future studies to investigate how interaction risk could impact the population over time.

Seals are top predators, but they are also preyed upon. One would expect the foraging movement to differ if predation was considered. A study by Jourdain et al. (2017) found that 19 out of 23 observed predation events of killer whales (*Orcinus orca*) on seals resulted in the killing and consumption of prey. Observations included attacks on both grey seal and harbour seals of various age classes (Jourdain et al., 2017). Adding the killer whale as an individual agent in the IBM could alter seal behaviour in response to the killer whale's presence. This would have captured a realistic scenario of the real world. Additionally, the IBM should also include other marine species that are known to be captured by gillnet-fisheries, such as the grey seal or the harbour porpoise (*Phocoena phocoena*).

Seals are also facing other threats that have not been considered in this thesis but should be covered in future studies. This includes climate changes, maritime development, and hunting pressure. Diseases and parasites can also have an impact on harbour seals (Dietz et al., 2013) as they can generate stochastic mortality fluctuations within the population.

5 CONCLUSION

This study aimed to increase our understanding of the spatial distribution of gillnet entanglement risk along the Norwegian coast. An Individual-based model (IBM) was used to identify areas and times of the year with predicted high interaction risk along three areas of the Norwegian coast. The highest predicted interaction risk occurred during the spring and winter, particularly in the northern areas. This can be explained by the Northeast Arctic cod fisheries. Notably, the areas of the highest interaction risk aligned with haul-out sites, especially for lokref cells 05-24, 07-25, and 08-16. This information can be valuable for management as an initial step in reducing bycatch incidents.

The thesis further elaborated on interaction risk results and movement approaches between the individual-based model (IBM) and the simpler Monte Carlo simulation conducted by Elnes et al. (2023). Both studies found lokref cells 07-08 and 07-25 of Sør-Trøndelag to be predicted with high interaction risk. Variation was observed for lokref cells 08-16 in Rogaland and 05-25 in Nordland. This thesis emphasizes the significance that the areas of Nordland and Sør-Trøndelag are expected to be primary locations for bycatch events in Norway. Particularly highlighting Vesterålen/Lofoten as major hotspots for fatal interactions with fisheries. The IBM demonstrated more realistic movement behaviour compared to the simpler model. While the IBM included various factors like sensing, memory, habitat suitability index, distance from haul-out site, turning angles, and prey availability to model movement, the simpler model relied solely on the distance from haul-out as a proxy for movement. Moreover, the IBM incorporated individual entities such as unique ids, sex, and stomach capacity that were considered during the seal's movement decisions. These differences justify the effectiveness of an IBM in capturing the movement behaviour of harbour seals over a Monte-Carlo simulation.

Nonetheless, the IBM had some limitations, that should be considered for further development. Firstly, the model would benefit from being simulated multiple times. The simulations of this thesis had three replicates for each area which can underestimate variation. Additionally, extending the simulation period could investigate how interaction risk would affect the harbour seal population over time. Furthermore, the IBMs should be developed in a way that includes complex landscapes, as the study areas of this thesis were smoothed to an extreme. The smoothed areas could influence the accuracy of interaction risk, especially in the smaller fjords. Achieving these improvements would enable the model to record the interaction risk of the entire Norwegian coast.

In conclusion, despite certain limitations, this thesis succeeds in adapting an existing IBM to suit the Norwegian coast for studying harbour seal movement. This made it possible to successfully identify location cells of high interaction risk between seals and fisheries. This can be beneficial as it serves as an initial step to potentially reduce bycatch in the future. Even though a high overlap between harbour seals and fisheries does not necessarily lead to bycatch events, it still serves as a valuable indicator of encounter risk.

REFERENCES

Using Endnote 20, APA 7th Style

Bartumeus, F., da Luz, M. G. E., Viswanathan, G. M., & Catalan, J. (2005). Animal search strategies: A quantitative random-walk analysis. *Ecology*, *86*(11), 3078-3087. https://doi.org/https://doi.org/10.1890/04-1806

Bigg, M. (1981). Harbour seal *Phoca vitulina* linnaeus, 1758 and Phoca largha pallas, 1811. *Handbook of Marine Mammals: Seals.*, *2*, 1-28.

Bjørge, A. (1993). *The harbour seal, Phoca vitulina L., in Norway and the role of science in management* Department of Fisheries and Marine Biology, University of Bergen]. Bergen.

Bjørge, A., Bekkby, T., Bakkestuen, V., & Framstad, E. (2002a). Interactions between harbour seals, *Phoca vitulina* , and fisheries in complex coastal waters explored by combined Geographic Information System (GIS) and energetics modelling. *ICES Journal of Marine Science*, *59*(1), 29-42. https://doi.org/10.1006/jmsc.2001.1137

Bjørge, A., Desportes, G., Waring, G. T., & Rosing-Asvid, A. (2010a). Introduction: the harbour seal (*Phoca vitulina*) - a global perspective. *NAMMCO Scientific Publications*, *8*, 7-11. https://doi.org/10.7557/3.2668

Bjørge, A., Lydersen, C., Skern-Mauritzen, M., & Wiig, Ø. (2010b). Sjøens pattedyr 2010. *[Marine mammals] Fisken og havet*, *2-2010*. https://imr.brage.unit.no/imr-xmlui/bitstream/handle/11250/113960/Sjoens-pattedyr-2010.pdf?sequence=1

Bjørge, A., Moan, A., Nilssen, K. T., Tor, & Øigård, A. (2016). Bycatch of harbour and grey seals in Norway. *NAMMCO Scientific Publications*, *CSWG*, 1-15.

Bjørge, A., & Nilssen, K. T. (2020, 2021/07/26). *Harbour seals | Institute of Marine Research*. https://www.hi.no/en/hi/temasider/species/harbour-seals

Bjørge, A., Thompson, D., Hammond, P., Fedak, M., Bryant, E., Aarefjord, H., Roen, R., & Olsen, M. (1994, Nov 29-Dec 01). Habitat use and diving behaviour of harbour seals in a coastal archipelago in Norway.*Developments in Marine Biology* [Whales, seals, fish and man]. International Symposium on the Biology of Marine Mammals in the North-East Atlantic, Tromsø, Norway.

Bjørge, A., Øien, N., Hartvedt, S., Bøthun, G., & Bekkby, T. (2002b). Dispersal and bycatch mortality in gray, *Halichoerus grypus*, and harbor, *Phoca vitulina*, seals tagged at the Norwegian coast. *Marine Mammal Science*, *18*(4), 963-976. https://doi.org/10.1111/j.1748-7692.2002.tb01085.x

Blanchet, M.-A., Vincent, C., Womble, J. N., Steingass, S. M., & Desportes, G. (2021). Harbour Seals: Population Structure, Status, and Threats in a Rapidly Changing Environment. *Oceans*, *2*(1), 41-63. https://doi.org/10.3390/oceans2010003

Bogstad, B. (2019, 02.06.22). *Topic: Cod- Northeast Arctic* https://www.hi.no/en/hi/temasider/species/cod--northeast-arctic

Boulva, J., & Mclaren, I. A. (1979). Biology of the harbor seal, *Phoca vitulina*, in Eastern Canada. *Bulletin of the Fisheries Research Board of Canada*(200), 1-24. https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/919.pdf

Bowen, D. (2016). *Halichoerus grypus*. The IUCN Red List of Threatened Species 2016: e. T9660A45226042. In.

Boyd, I. (1991). Environmental and physiological factors controlling the reproductive cycles of pinnipeds. *Canadian Journal of Zoology*, *69*(5), 1135-1148. https://doi.org/10.1139/z91-162

Boyd, I. (1996). Temporal scales of foraging in a marine predator. *Ecology*, *77*(2), 426-434.

Boyles, J. G., & Brack Jr, V. (2009). Modeling survival rates of hibernating mammals with individual-based models of energy expenditure. *Journal of Mammalogy*, *90*(1), 9-16. https://doi.org/10.1644/08-MAMM-A-205.1

Branch, T. A., Matsuoka, K., & Miyashita, T. (2004). Evidence for increases in Antarctic blue whales based on Bayesian modelling. *Marine Mammal Science*, *20*(4), 726-754. https://doi.org/10.1111/j.1748-7692.2004.tb01190.x

Brander, K. (2005). *Spawning and life history information for North Atlantic cod stocks*. ICES Cooperative Research Reports (CRR).

Breili, K. (2022). Evolution of sea-level trends along the Norwegian coast from 1960 to 2100. *Ocean Dynamics*, *72*(2), 115-136. https://doi.org/10.1007/s10236-021-01492-7

Brkljacic, M. (2007). *Population Dynamics of Harbour Seals, Phoca vitulina L* https://www.duo.uio.no/handle/10852/11653

Bryhn, A., Kraufvelin, P., Bergström, U., Vretborn, M., & Bergström, L. (2020). A Model for Disentangling Dependencies and Impacts among Human Activities and Marine Ecosystem Services. *Environmental Management*, *65*(5), 575-586. https://doi.org/10.1007/s00267-020-01260-1

Carter, M. I., Boehme, L., Duck, C. D., Grecian, W. J., Hastie, G. D., McConnell, B. J., Miller, D. L., Morris, C. D., Moss, S., & Thompson, D. (2020). Habitat-based predictions of at-sea distribution for grey and harbour seals in the British Isles. *Sea Mammal Research Unit, University of St Andrews, Report to BEIS, OESEA-16-76/OESEA-17*, *78*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_ data/file/959723/SMRU_2020_Habitat-based_predictions_of_at-sea_distribution_for_grey_and_harbour_seals_in_the_British_Isles.pdf

Chilvers, B., & Goldsworthy, S. (2015). *Arctocephalus forsteri*. The IUCN Red List of Threatened Species 2015: e. T41664A45230026. In.

Chudzinska, M. (2009). *Diving behaviour of harbour seals (Phoca vitulina) from the Kattegat* https://bios.au.dk/fileadmin/bioscience/Videnudveksling/Myndigheder_billeder/Master_thesis_Magda_Chudzinska_FINAL.pdf

Chudzinska, M., Nabe-Nielsen, J., Smout, S., Aarts, G., Brasseur, S., Graham, I., Thompson, P., & McConnell, B. (2021). AgentSeal: Agent-based model describing movement of marine central-place foragers. *Ecological Modelling*, *440*, 109397-109397, Article 109397. https://doi.org/10.1016/J.ECOLMODEL.2020.109397

Cordes, L. S., Duck, C. D., Mackey, B. L., Hall, A. J., & Thompson, P. M. (2011). Long-term patterns in harbour seal site-use and the consequences for managing protected areas. *Animal Conservation*, *14*(4), 430-438. https://doi.org/10.1111/j.1469-1795.2011.00445.x

Cordes, L. S., & Thompson, P. M. (2015). Mark-resight estimates of seasonal variation in harbor seal abundance and site fidelity. *Population Ecology*, *57*, 467-472. https://doi.org/10.1007/s10144-015-0496-z

Core, R. T. (2008). *R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical*. https://www.R-project.org/

Cosgrove, R., Gosch, M., Reid, D., Sheridan, M., Chopin, N., Jessopp, M., & Cronin, M. (2016). Seal bycatch in gillnet and entangling net fisheries in Irish waters. *Fisheries Research*, *183*, 192-199. https://doi.org/10.1016/j.fishres.2016.06.007

Cunningham, L., Baxter, J. M., Boyd, I. L., Duck, C. D., Lonergan, M., Moss, S. E., & McConnell, B. (2009). Harbour seal movements and haul-out patterns: implications for monitoring and management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *19*(4), 398-407. https://doi.org/10.1002/aqc.983

Dalleau, M. (2013). *Écologie spatiale des tortues marines dans le Sud-ouest de l'océan Indien: apport de la géomatique et de la modélisation pour la conservation* La Réunion].

DeAngelis, D. L., & Grimm, V. (2014). Individual-based models in ecology after four decades. *F1000Prime Reports*, *6*(39). https://doi.org/10.12703/P6-39

DeAngelis, D. L., & Mooij, W. M. (2005). Individual-based modeling of ecological and evolutionary processes. *Annu. Rev. Ecol. Evol. Syst.*, *36*, 147-168.

DeMaster, D. P., Fowler, C. W., Perry, S. L., & Richlen, M. F. (2001). Predation and Competition: The Impact of Fisheries on Marine-Mammal Populations Over the next one Hundred Years. *Journal of Mammalogy*, *82*(3), 641-651.

Dietz, R., Teilmann, J., Andersen, S. M., Rigét, F., & Olsen, M. T. (2013). Movements and site fidelity of harbour seals (*Phoca vitulina*) in Kattegat, Denmark, with implications for the epidemiology of the phocine distemper virus. *ICES Journal of Marine Science*, *70*(1), 186-195. https://doi.org/10.1093/icesjms/fss144

Dodson, S., Abrahms, B., Bograd, S. J., Fiechter, J., & Hazen, E. L. (2020). Disentangling the biotic and abiotic drivers of emergent migratory behavior using individual-based models. *Ecological Modelling*, *432*, Article 109225. https://doi.org/10.1016/j.ecolmodel.2020.109225

Dolman, P. M., & Sutherland, W. J. (1997). Spatial patterns of depletion imposed by foraging vertebrates: theory, review and meta-analysis. *Journal of Animal Ecology*, 481-494. https://doi.org/10.2307/5943

Dowle, M., & Srinivasan, A. (2021). *data. table: Extension of 'data. frame'* Version 1.14.2). https://CRAN.R-project.org/package=data.table

Elnes, J. O. (2021). *Predicted times and areas of interaction risk between harbour seals and coastal gillnet fisheries in Norway* https://www.duo.uio.no/bitstream/handle/10852/87822/Oppgaven-4-1.pdf?sequence=1

Elnes, J. O., Moan, A., Nilssen, K., Vøllestad, A., & Bjørge, A. (2023). Temporal and Spatial Distribution of Harbour Seal (*Phoca vitulina*) Risk Entanglement in Gillnets Along the Norwegian Coast. *Aquatic Mammals 2023*, *49-6*, 11. https://doi.org/10.1578/am.49.6.2023.508

EMODnet. (2020). *EMODnet High Resolution Seabed Mapping project II* Retrieved 17 from https://emodnet.ec.europa.eu/geoviewer/#!/

Engelhard, G. H., & Heino, M. (2004). Maturity changes in Norwegian spring-spawning herring *Clupea harengus*: compensatory or evolutionary responses? *Marine Ecology Progress Series*, *272*, 245-256. https://doi.org/10.3354/meps272245

Fossheim, M., Primicerio, R., Johannesen, E., Ingvaldsen, R. B., Aschan, M. M., & Dolgov, A. V. (2015). Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nature climate change*, *5*(7), 673-677. https://doi.org/10.1038/NCLIMATE2647

Frost, K. J., Simpkins, M. A., & Lowry, L. F. (2001). Diving behavior of subadult and adult harbor seals in Prince William Sound, Alaska. *Marine Mammal Science*, *17*(4), 813-834. https://doi.org/10.1111/j.1748-7692.2001.tb01300.x

Garcia, S. M., & Moreno, I. d. L. (2003). *Global overview of marine fisheries* (Vol. 10).

Gormley, A. M., Slooten, E., Dawson, S., Barker, R. J., Rayment, W., du Fresne, S., & Bräger, S. (2012). First evidence that marine protected areas can work for marine mammals. *Journal of Applied Ecology*, *49*(2), 474-480. https://doi.org/10.1111/j.1365-2664.2012.02121.x

Grecian, J., Masden, E., Hammond, P., Owen, E., Daunt, F., Wanless, S., & Russell, D. (2018). Man-Made Structures and Apex Predators: Spatial Interactions and Overlap (MAPS). *Final Report to INSITE*. http://static.insitenorthsea.org.s3.amazonaws.com/files/MAPS_INSITE_revised_report_submitted.pdf

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S. K., Huse, G., Huth, A., Jepsen, J. U., Jørgensen, C., Mooij, W. M., Müller, B., Pe'er, G., Piou, C., Railsback, S. F., Robbins, A. M., . . . DeAngelis, D. L. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, *198*(1), 115-126. https://doi.org/10.1016/j.ecolmodel.2006.04.023

Grimm, V., & Railsback, S. F. (2005). *Individual-based modeling and ecology*. Princeton university press.

Grimm, V., & Railsback, S. F. (2012). Pattern-oriented modelling: A 'multi-scope' for predictive systems ecology. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1586), 298-310. https://doi.org/10.1098/RSTB.2011.0180

Grimm, V., Railsback, S. F., Vincenot, C. E., Berger, U., Gallagher, C., DeAngelis, D. L., Edmonds, B., Ge, J., Giske, J., & Groeneveld, J. (2020). The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. *Journal of Artificial Societies and Social Simulation*, *23*(2). https://doi.org/10.18564/jasss.4259

Grimm, V., Wyszomirski, T., Aikman, D., & Uchmański, J. (1999). Individual-based modelling and ecological theory: synthesis of a workshop. *Ecological Modelling, 115*(2-3), 275-282. https://doi.org/10.1016/S0304-3800(98)00186-0

Hall, A. J., McConnell, B. J., Rowles, T. K., Aguilar, A., Borrell, A., Schwacke, L., Reijnders, P. J., & Wells, R. S. (2006). Individual-based model framework to assess population consequences of polychlorinated biphenyl exposure in bottlenose dolphins. *Environmental Health Perspectives*, *114*(Suppl 1), 60-64. https://doi.org/10.1289/ehp.8053

Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., Longo, C., Lowndes, J. S., Rockwood, R. C., Selig, E. R., Selkoe, K. A., & Walbridge, S. (2015). Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature communications*, *6*(1), 7615. https://doi.org/10.1038/ncomms8615

Hamilton, C. D., Lydersen, C., Ims, R. A., & Kovacs, K. M. (2014). Haul-Out Behaviour of the World's Northernmost Population of Harbour Seals (*Phoca vitulina*) throughout the Year. *PLoS ONE*, *9*(1), Article e86055. https://doi.org/10.1371/journal.pone.0086055

Hammond, P. S., Macleod, K., Berggren, P., Borchers, D. L., Burt, L., Cañadas, A., Desportes, G., Donovan, G. P., Gilles, A., Gillespie, D., Gordon, J., Hiby, L., Kuklik, I., Leaper, R., Lehnert, K., Leopold, M., Lovell, P., Øien, N., Paxton, C. G. M., . . . Vázquez, J. A. (2013). Cetacean abundance and distribution in European Atlantic shelf waters to inform conservation and management. *Biological Conservation*, *164*, 107-122. https://doi.org/10.1016/j.biocon.2013.04.010

Harwood, J. (2001). Marine mammals and their environment in the twenty-first century. *Journal of Mammalogy*, *82*(3), 630-640. https://doi.org/10.1644/1545-1542(2001)082<0630:MMATEI>2.0.CO;2

Hazen, E. L., Scales, K. L., Maxwell, S. M., Briscoe, D. K., Welch, H., Bograd, S. J., Bailey, H., Benson, S. R., Eguchi, T., & Dewar, H. (2018). A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances*, *4*(5), Article eaar3001. https://doi.org/10.1126/sciadv.aar3001

Henriksen, S., & Hilmo, O. (2015). *Norsk rødliste for arter 2015*.

Hijmans, R. J. (2022). *raster: Geographic data analysis and modeling* Version 3.5-15). https://CRAN.R-project.org/package=raster

Hilton-Taylor, C., & Brackett, D. (2000). 2000 IUCN red list of threatened species.

Hutchings, J. A., & Rangeley, R. W. (2011). Correlates of recovery for Canadian Atlantic cod (*Gadus morhua*). *Canadian Journal of Zoology*, *89*(5), 386-400. https://doi.org/10.1139/Z11-022

Hückstädt, L. (2015). *Mirounga angustirostris*. The IUCN Red List of Threatened Species 2015: e. T13581A45227116. In.

Härkönen, T. (1987). Influence of feeding on haul-out patterns and sizes of sub-populations in harbour seals. *Netherlands Journal of Sea Research*, *21*(4), 331-339. https://doi.org/10.1016/0077-7579(87)90007-X

Härkönen, T., & Harding, K. (2001). Spatial structure of harbour seal populations and the implications thereof. *Canadian Journal of Zoology*, *79*(12), 2115-2127. https://doi.org/10.1139/cjz-79-12-2115

Härkönen, T., Harding, K. C., Wilson, S., Baimukanov, M., Dmitrieva, L., Svensson, C. J., & Goodman, S. J. (2012). Collapse of a marine mammal species driven by human impacts. *PLoS ONE*, *7*(9), Article e43130. https://doi.org/10.1371/journal.pone.0043130

Härkönen, T., & Heide-Jørgensen, M. P. (1991). The harbour seal *Phoca vitulina* as a predator in the skagerrak. *Ophelia*, *34*(3), 191-207. https://doi.org/10.1080/00785326.1991.10429695

Härkönen, T., Hårding, K. C., & Lunneryd, S. G. (1999). Age- and sex-specific behaviour in harbour seals *Phoca vitulina* leads to biased estimates of vital population parameters. *Journal of Applied Ecology*, *36*(5), 825-841. https://doi.org/10.1046/J.1365-2664.1999.00434.X

Jordan, F. (2009). Keystone species and food webs. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1524), 1733-1741. https://doi.org/10.1098/rstb.2008.0335

Jourdain, E., Vongraven, D., Bisther, A., & Karoliussen, R. (2017). First longitudinal study of seal-feeding killer whales (*Orcinus orca*) in Norwegian coastal waters. *PLoS ONE*, *12*(6), Article e0180099. https://doi.org/10.1371/journal.pone.0180099

Jørgensen, S. E., & Fath, B. D. (2011). Individual-based models. In *Developments in Environmental Modelling* (Vol. 23, pp. 291-308). Elsevier. https://doi.org/10.1016/B978-0-444-53567-2.00009-0

Kim, S., Kim, P., Lim, J., An, H., & Suuronen, P. (2016). Use of biodegradable driftnets to prevent ghost fishing: physical properties and fishing performance for yellow croaker. *Animal Conservation*, *19*(4), 309-319.

Kovacs, K. M. (2015). *Pagophilus groenlandicus*. The IUCN Red List of Threatened Species 2015: e.T41671A45231087. In.

Langangen, Ø., Färber, L., Stige, L. C., Diekert, F. K., Barth, J. M., Matschiner, M., Berg, P. R., Star, B., Stenseth, N. C., & Jentoft, S. (2019). Ticket to spawn: Combining economic and genetic data to evaluate the effect of climate and demographic structure on spawning distribution in Atlantic cod. *Global change biology*, *25*(1), 134-143. https://doi.org/10.1111/gcb.14474

Leclerc, L.-M. E., Lydersen, C., Haug, T., Bachmann, L., Fisk, A. T., & Kovacs, K. M. (2012). A missing piece in the Arctic food web puzzle? Stomach contents of Greenland sharks sampled in Svalbard, Norway. *Polar Biology*, *35*(8), 1197-1208. https://doi.org/10.1007/s00300-012-1166-7

Lewison, R. L., Crowder, L. B., Read, A. J., & Freeman, S. A. (2004). Understanding impacts of fisheries bycatch on marine megafauna. In *Trends in Ecology and Evolution* (Vol. 19).

Liukkonen, L., Ayllón, D., Kunnasranta, M., Niemi, M., Nabe-Nielsen, J., Grimm, V., & Nyman, A.-M. (2018). Modelling movements of Saimaa ringed seals using an individual-based approach. *Ecological Modelling*, *368*, 321-335. https://doi.org/10.1016/j.ecolmodel.2017.12.002

Lowry, L. F., Frost, K. J., Ver Hoep, J. M., & Delong, R. A. (2001). Movements of satellite-tagged subadult and adult harbor seals in Prince William Sound, Alaska. *Marine Mammal Science*, *17*(4), 835-861. https://doi.org/10.1111/j.1748-7692.2001.tb01301.x

Luck, C., Cronin, M., Gosch, M., Healy, K., Cosgrove, R., Tully, O., Rogan, E., & Jessopp, M. (2020). Drivers of spatiotemporal variability in bycatch of a top marine predator: First evidence for the role of water turbidity in protected species bycatch. *Journal of Applied Ecology*, *57*(2), 219-228. https://doi.org/10.1111/1365-2664.13544

Mackey, B. L., Durban, J., Middlemas, S., & Thompson, P. M. (2008). A Bayesian estimate of harbour seal survival using sparse photo-identification data. *Journal of zoology*, *274*(1), 18-27. https://doi.org/10.1111/j.1469-7998.2007.00352.x

Madden, K., Fuiman, L., Williams, T., & Davis, R. (2008). Identification of foraging dives in free-ranging Weddell seals *Leptonychotes weddellii*: confirmation using video records. *Marine Ecology Progress Series*, *365*, 263-275. https://doi.org/10.3354/meps07396

Manly, B., McDonald, L., Thomas, D. L., McDonald, T. L., & Erickson, W. P. (2007). *Resource selection by animals: statistical design and analysis for field studies*. Springer Science & Business Media.

McLeod, E., Salm, R., Green, A., & Almany, J. (2009). Designing marine protected area networks to address the impacts of climate change. *Frontiers in Ecology and the Environment*, *7*(7), 362-370. https://doi.org/10.1890/070211

Mikkelsen, L., Johnson, M., Wisniewska, D. M., van Neer, A., Siebert, U., Madsen, P. T., & Teilmann, J. (2019). Long-term sound and movement recording tags to study natural behavior and reaction to ship noise of seals. *Ecology and Evolution*, *9*(5), 2588-2601. https://doi.org/10.1002/ece3.4923

Moan, A., & Bjørge, A. (2021). *Bycatch of coastal seals in Norwegian gillnet fisheries conducted by coasal fishing vessels*.

Moan, A. G. (2016). *Bycatch of harbour porpoise, harbour seal and grey seal in Norwegian gillnet fisheries* http://urn.nb.no/URN:NBN:no-56897

Moore, M. J., & van der Hoop, J. M. (2012). The Painful Side of Trap and Fixed Net Fisheries: Chronic Entanglement of Large Whales. *Journal of Marine Biology*, *2012*, 230653. https://doi.org/10.1155/2012/230653

Murray, K. T., Hatch, J. M., DiGiovanni Jr, R. A., & Josephson, E. (2021). Tracking young-of-the-year gray seals *Halichoerus grypus* to estimate fishery encounter risk. *Marine Ecology Progress Series*, *671*, 235-245.

Myers, R. A., Hutchings, J. A., & Barrowman, N. J. (1997). Why do fish stocks collapse? The example of cod in Atlantic Canada. *Ecological applications*, *7*(1), 91-106.

Nabe-Nielsen, J., Sibly, R. M., Tougaard, J., Teilmann, J., & Sveegaard, S. (2014). Effects of noise and by-catch on a Danish harbour porpoise population. *Ecological Modelling*, *272*, 242-251. https://doi.org/10.1016/j.ecolmodel.2013.09.025

Nabe-Nielsen, J., Tougaard, J., Teilmann, J., Lucke, K., & Forchhammer, M. C. (2013). How a simple adaptive foraging strategy can lead to emergent home ranges and increased food intake. *Oikos*, *122*(9), 1307-1316. https://doi.org/10.1111/j.1600-0706.2013.00069.x

Nabe-Nielsen, J., van Beest, F. M., Grimm, V., Sibly, R. M., Teilmann, J., & Thompson, P. M. (2018). Predicting the impacts of anthropogenic disturbances on marine populations. *Conservation Letters*, *11*(5), Article e12563. https://doi.org/10.1111/conl.12563

NAMMCO, N. A. M. M. C. (2021, July 2021). *Harbour seal*. https://nammco.no/harbour-seal/#1670770907469-36a19759-f5c8

Neuwirth, E. (2022). *ColorBrewer palettes* Version 1.1-3). https://CRAN.R-project.org/package=RColorBrewer

Niemi, M., Auttila, M., Viljanen, M., & Kunnasranta, M. (2012). Movement data and their application for assessing the current distribution and conservation needs of the endangered Saimaa ringed seal. *Endangered Species Research*, *19*(2), 99-108. https://doi.org/10.3354/esr00468

Olsen, M., & Bjørge, A. (1994, Nov 29-Dec 01). Seasonal and regional variations in the diet of harbour seal in Norwegian waters.*Developments in Marine Biology* [Whales, seals, fish and man]. International Symposium on the Biology of Marine Mammals in the North-East Atlantic, Tromsø, Norway.

OpenAI. (2023). *ChatGPT* Version 3.5). https://chat.openai.com/chat/

Pebesma, E. J. (2018). *Simple features for R: standardized support for spatial vector data*.

Pedersen, T. L. (2022). *Patchwork: The Composer of Plots* Version 1.1.2). https://CRAN.R-project.org/package=patchwork

Peterson, S. H., Lance, M. M., Jeffries, S. J., & Acevedo-Gutiérrez, A. (2012). Long distance movements and disjunct spatial use of harbor seals (*Phoca vitulina*) in the inland waters of the Pacific Northwest. *PLoS ONE*, *7*(6), Article e39046. https://doi.org/10.1371/journal.pone.0039046

Planque, B., Aarflot, J. M., Buttay, L., Carroll, J., Fransner, F., Hansen, C., Husson, B., Langangen, Ø., Lindstrøm, U., Pedersen, T., Primicerio, R., Sivel, E., Skogen, M. D., Strombom, E., Stige, L. C., Varpe, Ø., & Yoccoz, N. G. (2022). A standard protocol for describing the evaluation of ecological models. *Ecological Modelling*, *471*, 110059. https://doi.org/10.1016/j.ecolmodel.2022.110059

Railsback, S. F., & Grimm, V. (2019). *Agent-based and individual-based modeling: A Practical introduction, Second Edition*. Princeton University Press. https://www.perlego.com/book/822780/agentbased-and-individualbased-modeling-a-practical-introduction-second-edition-pd

Ramasco, V., Biuw, M., & Nilssen, K. T. (2014). Improving time budget estimates through the behavioural interpretation of dive bouts in harbour seals. *Animal Behaviour*, *94*, 117-134. https://doi.org/10.1016/j.anbehav.2014.05.015

Reeves, R. R., McClellan, K., & Werner, T. B. (2013). Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research*, *20*(1), 71-97. https://doi.org/10.3354/esr00481

Ridgway, S. H., & Harrison, R. J. (1981). *Handbook of marine mammals* (Vol. 2: Seals). Academic Press Incorporated.

Roberts, C. M., & Hawkins, J. P. (1999). Extinction risk in the sea. *Trends in Ecology & Evolution*, *14*(6), 241-246. https://doi.org/10.1016/S0169-5347(98)01584-5

Robinson, P., Tremblay, Y., Crocker, D., Kappes, M., Kuhn, C., Shaffer, S., Simmons, S., & Costa, D. (2007). A comparison of indirect measures of feeding behaviour based on ARGOS tracking data. *Deep Sea Research Part II-Topical Studies in Oceanography*, *54*(3-4), 356-368. https://doi.org/10.1016/j.dsr2.2006.11.020

Robson, B. W., Goebel, M. E., Baker, J. D., Ream, R. R., Loughlin, T. R., Francis, R. C., Antonelis, G. A., & Costa, D. P. (2004). Separation of foraging habitat among breeding sites of a colonial marine predator, the northern fur seal (*Callorhinus ursinus*). *Canadian Journal of Zoology*, *82*(1), 20-29. https://doi.org/10.1139/Z03-208

Rochet, M.-J., & Trenkel, V. M. (2005). Factors for the variability of discards: assumptions and field evidence. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*(1), 224-235. https://doi.org/10.1139/F04-185

Roe, J. H., Morreale, S. J., Paladino, F. V., Shillinger, G. L., Benson, S. R., Eckert, S. A., Bailey, H., Tomillo, P. S., Bograd, S. J., & Eguchi, T. (2014). Predicting bycatch hotspots for endangered leatherback turtles on longlines in the Pacific Ocean. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1777), 20132559. https://doi.org/10.1098/rspb.2013.2559

Rupil, G., Angelini, R., Rodrigues Filho, J., Roman, J., & Daura-Jorge, F. (2022). The role of mammals as key predators in marine ecosystems. *Marine Ecology Progress Series*, *684*, 211-222. https://doi.org/10.3354/meps13962

Scheffer, M., Baveco, J., DeAngelis, D., Rose, K. A., & van Nes, E. (1995). Super-individuals a simple solution for modelling large populations on an individual basis. *Ecological Modelling*, *80*(2-3), 161-170. https://doi.org/10.1016/0304-3800(94)00055-M

Schmitt, W., Auteri, D., Bastiansen, F., Ebeling, M., Liu, C., Luttik, R., Mastitsky, S., Nacci, D., Topping, C., & Wang, M. (2016). An example of population-level risk assessments for small mammals using individual-based population models. *Integrated Environmental Assessment and Management*, *12*(1), 46-57. https://doi.org/10.1002/ieam.1640

Sharples, R. J., Mackenzie, M. L., & Hammond, P. S. (2009). Estimating seasonal abundance of a central place forager using counts and telemetry data. *Marine Ecology Progress Series*, *378*, 289-298. https://doi.org/10.3354/meps07827

Sharples, R. J., Moss, S. E., Patterson, T. A., & Hammond, P. S. (2012). Spatial Variation in Foraging Behaviour of a Marine Top Predator (*Phoca vitulina*) Determined by a Large-Scale Satellite Tagging Program. *PLoS ONE*, *7*(5), e37216. https://doi.org/10.1371/journal.pone.0037216

Sluttseddelregisteret, F. (2023a). *Rundvekt (tonn) fordelt på landingsfylke Norske fartøy*. https://www.fiskeridir.no/Yrkesfiske/Tall-og-analyse/Fangst-og-kvoter/Fangst/Fangst-fordelt-paa-landingssted

Sluttseddelregisteret, F. (2023b). *Rundvekt (tonn) fordelt på landingsfylke og redskap Norske fartøy*. https://www.fiskeridir.no/Yrkesfiske/Tall-og-analyse/Fangst-og-kvoter/Fangst/Fangst-fordelt-paa-landingssted

SMRU. (2017). Scientific Advice on Matters Related to the Management of Seal Populations: 2017 Contents. *Special Committee on Seals (SCOS)*. http://www.smru.st-andrews.ac.uk/files/2018/01/SCOS-2017.pdf

South, A. (2017). *rnaturalearth: World Map Data from Natural Earth* Version 0.1.0). https://CRAN.R-project.org/package=rnaturalearth

Soykan, C. U., Moore, J. E., Ždelis, R., Crowder, L. B., Safina, C., & Lewison, R. L. (2008). Why study bycatch? An introduction to the Theme Section on fisheries bycatch. *Endangered Species Research*, *5*(2-3). https://doi.org/10.3354/esr00175

Staniland, I. J., Reid, K., & Boyd, I. L. (2004). Comparing individual and spatial influences on foraging behaviour in Antarctic fur seals *Arctocephalus gazella*. *Marine Ecology Progress Series*, *275*, 263-274. https://doi.org/10.3354/meps275263

Thompson, P. (1988). Timing of mating in the common seal (*Phoca vitulina*). *Mammal Review*, *18*(2), 105-112. https://doi.org/10.1111/j.1365-2907.1988.tb00080.x

Thompson, P. M., Mackay, A., Tollit, D. J., Enderby, S., & Hammond, P. S. (1998). The influence of body size and sex on the characteristics of harbour seal foraging trips. *Canadian Journal of Zoology*, *76*(6), 1044-1053. https://doi.org/10.1139/cjz-76-6-1044

Tixier, P., Lea, M. A., Hindell, M. A., Welsford, D., Mazé, C., Gourguet, S., & Arnould, J. P. (2021). When large marine predators feed on fisheries catches: global patterns of the depredation conflict and directions for coexistence. *Fish and Fisheries*, *22*(1), 31-53.

Tollit, D., Black, A., Thompson, P., Mackay, A., Corpe, H., Wilson, B., Van Parijs, S., Grellier, K., & Parlane, S. (1998). Variations in harbour seal *Phoca vitulina* diet and dive-depths in relation to foraging habitat. *Journal of zoology*, *244*(2), 209-222.

Toresen, R., & Østvedt, O. J. (2000). Variation in abundance of Norwegian spring-spawning herring (*Clupea harengus*, Clupeidae) throughout the 20th century and the influence of climatic fluctuations. *Fish and Fisheries*, *1*(3), 231-256.

Vanderlaan, A. S., Taggart, C. T., Serdynska, A. R., Kenney, R. D., & Brown, M. W. (2008). Reducing the risk of lethal encounters: vessels and right whales in the Bay of Fundy and on the Scotian Shelf. *Endangered Species Research*, *4*(3), 283-297. https://doi.org/10.3354/esr00083

Vincent, C., McConnell, B. J., Delayat, S., Elder, J.-F., Gautier, G., & Ridoux, V. (2010). Winter habitat use of harbour seals (*Phoca vitulina*) fitted with Fastloc™ GPS/GSM tags in two tidal bays in France. *NAMMCO Scientific Publications, 8*, 285-302.

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis* Springer-Verlag New York. https://ggplot2.tidyverse.org

Wickham, H., François, R., Henry, L., & Müller, K. (2022). *dplyr: A Grammar of Data Manipulation* Version 1.0.8). https://CRAN.R-project.org/package=dplyr

Wickham, H., & Girlich, M. (2022). Tidyr: Tidy Messy data. *R package version*. https://CRAN.R-project.org/package=tidyr

Wilcox, C., & Hardesty, B. D. (2016). Biodegradable nets are not a panacea, but can contribute to addressing the ghost fishing problem. *Animal Conservation*, *19*(4), 322-323. https://doi.org/10.1111/acv.12300

Williams, G. C. (1966). Natural selection, the costs of reproduction, and a refinement of Lack's principle. *The American Naturalist*, *100*(916), 687-690. https://www.journals.uchicago.edu/doi/abs/10.1086/282461?casa_token=aue9sgmaiywAAAAA:eBfcVaoLykA8vs6ZBogDFSG98SFibjXNqjxDztYC8jq-C2noQ_KHazpMcxnng6lK6NuAkxEhDVU

Woodley, T. H., & Lavigne, D. M. (1991). *Incidental Capture of Pinnipeds in Commercial Fishing Gear* (Vol. 91-01). Citeseer.

Zimmermann, F., & Heino, M. (2013). Is size-dependent pricing prevalent in fisheries? The case of Norwegian demersal and pelagic fisheries. *ICES Journal of Marine Science*, *70*(7), 1389-1395. https://doi.org/10.1093/icesjms/fst121

Aarts, G., MacKenzie, M., McConnell, B., Fedak, M., & Matthiopoulos, J. (2008). Estimating space-use and habitat preference from wildlife telemetry data. *Ecography*, *31*(1), 140-160. https://doi.org/10.1111/j.2007.0906-7590.05236.x

Åslein, E. H. (2023). *Killer whale (Orcinus orca) predation on harbour porpoise (Phocoena phocoena) in Hardangerfjord, Western Norway* https://www.duo.uio.no/handle/10852/104779

APPENDIX

SENSITIVITY ANALYSIS

Sensitivity analysis was tested to investigate which model that would reproduce the most realistic seal movement. Patch memory and food/habitat depletion were tested. In NetLogo, these could either be turned on or off, and it was the scenario memory turned ON, while keeping habitat depletion turned OFF that was used in the IBM for all of the study areas. These were the four different scenarios:

HABONPATCHON, referring to habitat depletion turned on, patch memory turned on,
HABONPATCHOFF, referring to habitat depletion turned on, patch memory turned off,
HABOFFPATCHOFF, referring to habitat depletion turned off, patch memory turned off
HABOFFPATCHON, referring to habitat depletion turned off, patch memory turned on.

They were all tested in the light of how many seals were alive after model simulation of 3 months, to check whether blubber was changed, and see how daily energy expenditure was affected by the different scenarios. The scenarios were tested for lower Nordland, where the outcome of this analysis was used for the remaining study areas of the extremely smoothed landscape. The output showed that HABOFFPATCHON was generating the best model and was further used in the model simulations. Moreover, these sensitivity analyses were also tested with the smaller fjords when first applying scenario Figure 2.3b, also for Figure-A4-e and f in the appendix. When these landscapes were used in the IBM, it created a different scenario for seals in upper Nordland, and for Rogaland, which are illustrated in A-4. The analysis of the extremely smoothed area was therefore used instead, as no seals died (Figure A-1, A-2).

Another analysis was to check how many days it took for the seals to learn the environment. This was tested by looking at the activity distribution of the seals after one-year simulation. All modelled seals were also used in this analysis. The outcome gave insight that the first five days varied from the rest of the year, indicating that these days were removed prior to all calculations in R-studio (Figure A-3).

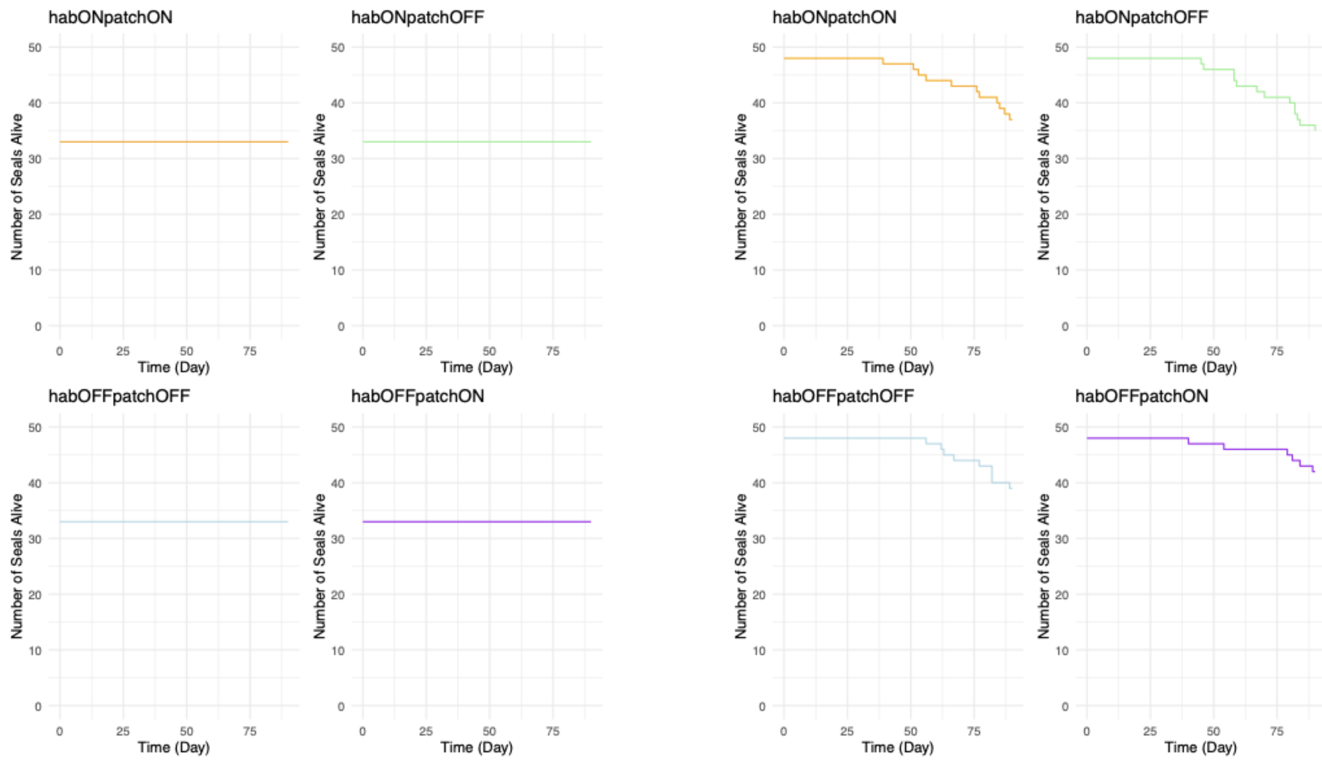

Figure A1. No changes were observed between the different scenarios when the number of seals alive was tested for the area of lower Nordland (left picture). The outcome was slightly different when testing for upper Nordland using the smoothed scenario e instead of f. Here HABOFFPATCHON was seen to generate the best model as fewer seals died after simulating for three months (right picture).

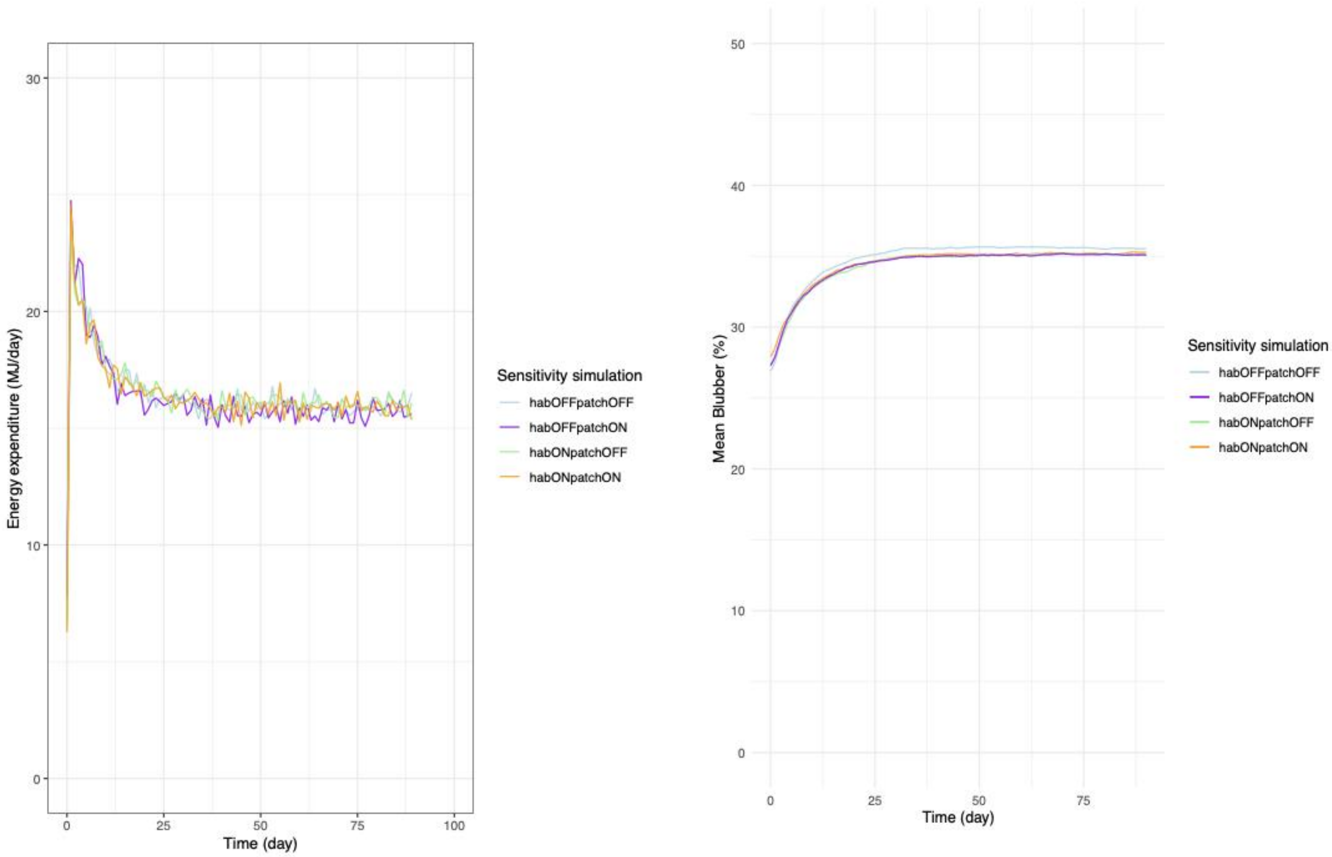

Figure A2. The left picture illustrates Energy expenditure for the different scenarios. There was little variation, but purple indicating HABOFFPATCHON was used. The right picture showed mean blubber over the simulation, with also little variation. Therefore, HABOFFPATCHON was used in the simulation model when running the whole year.

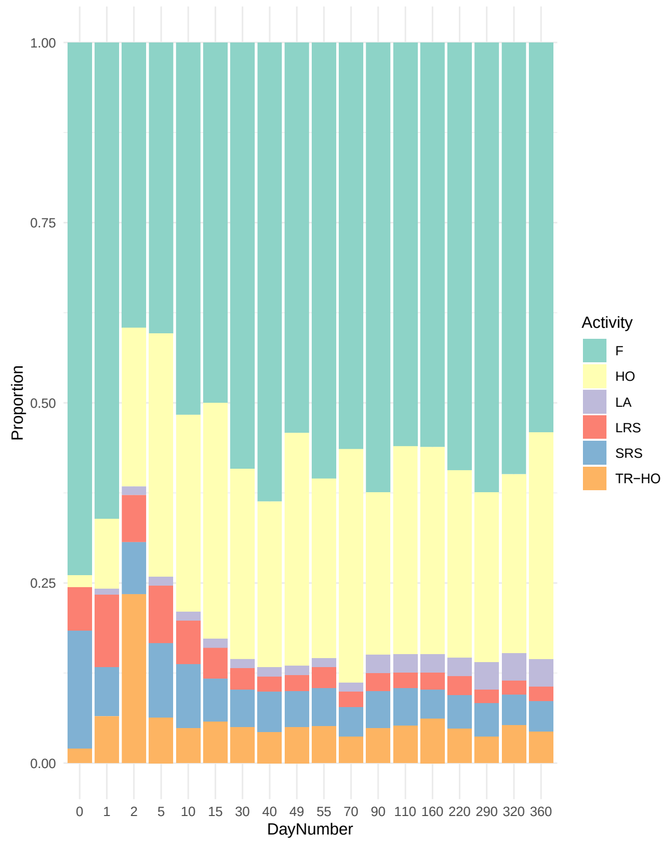

Figure A-3. Sensitivity analysis over one of the replicates of lower Nordland. It illustrates how the activity of harbour seals is distributed over the entire year. Day 0 had a large proportion of activity being foraging, and SRS, where it had more SRS after 1 day, and less activity of SRS. Seal movement in day number 0-5 was therefore discarded before calculations for all study areas, as they used these days to learn the area.

METHOD

Creating the landscape

The three study areas were smoothed to an extreme, as it was necessary prior to the implementation of the IBM as seals got stuck in the narrow fjords. Figures A-4, a-f illustrate how Rogaland and upper Nordland were prior to smoothing, a and d, after the first smoothed map, b and e, and the extremely smoothed areas of c and f. It was the extremely smoothed areas that were applied in the IBM and simulated over a year.

Figure A-4. Overview of the three different levels of smoothing. a-c illustrates Rogaland, while d-f represents upper Nordland. b and e were tested first but ended in several dead seals, and the majority of activity being LA. Plot c and f represent the extremely smoothed map and were applied to the IBM.

Harbour seal data

Harbour seal counts are visualized in Table A1. The table gives an overview of the year of count, county, municipality, location, latitude, longitude, and maximum count for each colony. The dataset is compromised to only show the three study areas and their location, with the corresponding haul-out ID, and the visualization of these haul-out sites is found in Figure 2.2.

Table A1**.** Overview of the updated version of harbour seal counts in the three study areas, modified from the original harbour seal count from IMR between 2016-2022. Haul-out ID has also been included to illustrate how many seals there are in each colony. The table corresponds with Figure 2.2. Agder V (RL) indicates that the areas were represented as Rogaland in the model simulations.

year	**county**	**municipality**	**location**	**lat**	**lon**	**Maxcount**	**Haul-out ID**	**Lokref cell**
2016	Agder V (RL)	Farsund	Lyngdalsfjorden	58.1236	6.884	35	2	08-17
2022	Agder V (RL)	Lyngdal	Lyngdalsfjorden	58.1331	6.90455	30	47	08-17
2022	Agder V (RL)	Farsund	Ystesteinen	58.0216	6.8784	16	48	08-17
2017	Rogaland		Lysefjorden	59.0426	6.54723	105	3	08-18
2017	Rogaland	Kvitsøy	Magerøya	59.013	5.42	266	4	08-16
2017	Rogaland	Tysvær	Kårstø	59.2283	5.54083	40	5	08-16
2019	Nordland	Rødøy	Nesøy sør	66.55560763	12.53460035	62	22	06-31
2019	Nordland	Brønnøy	Onstein	65.42274728	11.74884154	66	23	06-18
2019	Nordland	Vega	Fugløyvær	65.6333	11.5693	25	24	06-23
2019	Nordland	Dønna	Kuflesan	66.1724847	12.2111114	19	25	06-33
2019	Nordland	Gildeskål	Sør Fugløy	67.0208177	13.65800913	429	26	00-05
2020	Nordland	Lurøy	Nesøy	66.5177	12.5974	62	28	06-31
2020	Nordland	Røst	Røstholman SV	67.4386	11.9461	175	29	00-05
2020	Nordland	Hadsel	Ongstadvika	68.5272	14.6568	88	30	05-20
2020	Nordland	Andøy	Risøyrenna	68.9918	15.8038	118	31	05-43
2020	Nordland	Andøya Vest	Skogvoll	69.1582	15.6735	443	32	05-24
2020	Nordland	Langøya	Gisløy	69.022	15.0638	134	33	05-23
2019	S-Trøndelag	Bjugn	Tarva	63.807237	9.5231	484	19	07-25
2019	S-Trøndelag	Frøya	Sørburøy/Flesan	63.97762	8.992619	168	20	07-08
2019	S-Trøndelag	Frøya	Gjesingen/Gronga	63.9397	8.9246	138	21	07-08

INDIVIDUAL-BASED MODEL

Flow chart diagram

The flow chart diagram (Figure A-5) illustrates all model procedures that the seals executed throughout the year. A description of each part is found in section 2.3.2, processes.

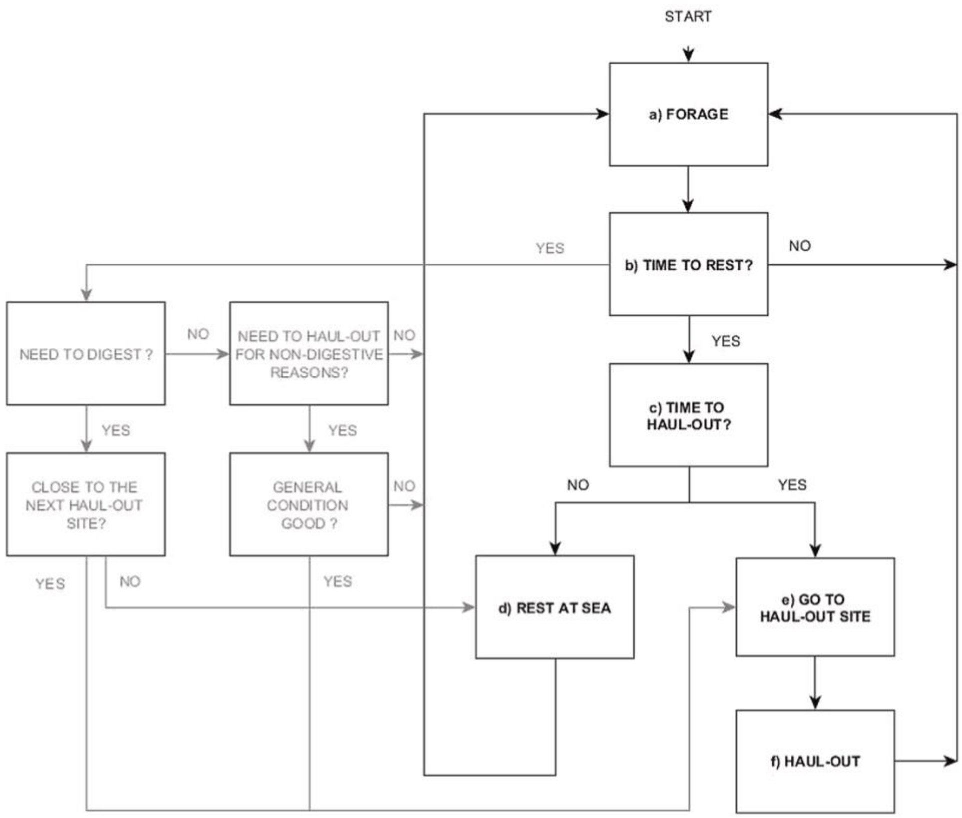

Figure A-5**.** Model procedures executed by all harbour seals at each time step of 15 minutes. The letters a–f refer to the description of these procedures in *Process overview and scheduling* section in 2.3.2. The seals forage at sea by adjusting their turning angle to the current habitat suitability index. At certain conditions, they rest for eighter digestive or non-digestive reasons. They then decide whether to rest at sea or go to haul-out-site. The grey-colored flow chart shows the more detailed decision process of harbour seals whether to rest or not, and if so where to do so. The model is retrieved from Chudzinska et.al (2021) research on harbour seal movement in the Scottish waters (Chudzinska et al., 2021).

RESULTS

This section provides an insight of several aspects of the thesis.

FISHERY DATA

Table A2 show Fishery data from DoF, of how much catch in tons the fisheries of conventional equipment, including gillnet fisheries captured in 2017 and 2019 for the three study areas (Sluttseddelregisteret, 2023b).

Area	Equipment	2017, weight tons	2019, weight tons
Rogaland	conventional	3242	4422
Nordland	conventional	142757	131085
Sør-Trøndelag	conventional	3790	

Prior to prelcatch data was the lokref cell sizes taken into consideration. The following figure present lokref cells of all areas. Some of the location cells are naturally cropped, where the proportion of the cell was less than 1. The proportion of these cells was therefore multiplied with the fishing effort in that cell. In that way, the correct number of catches was used. The red number indicate harbour seal colonies in the different lokref cells.

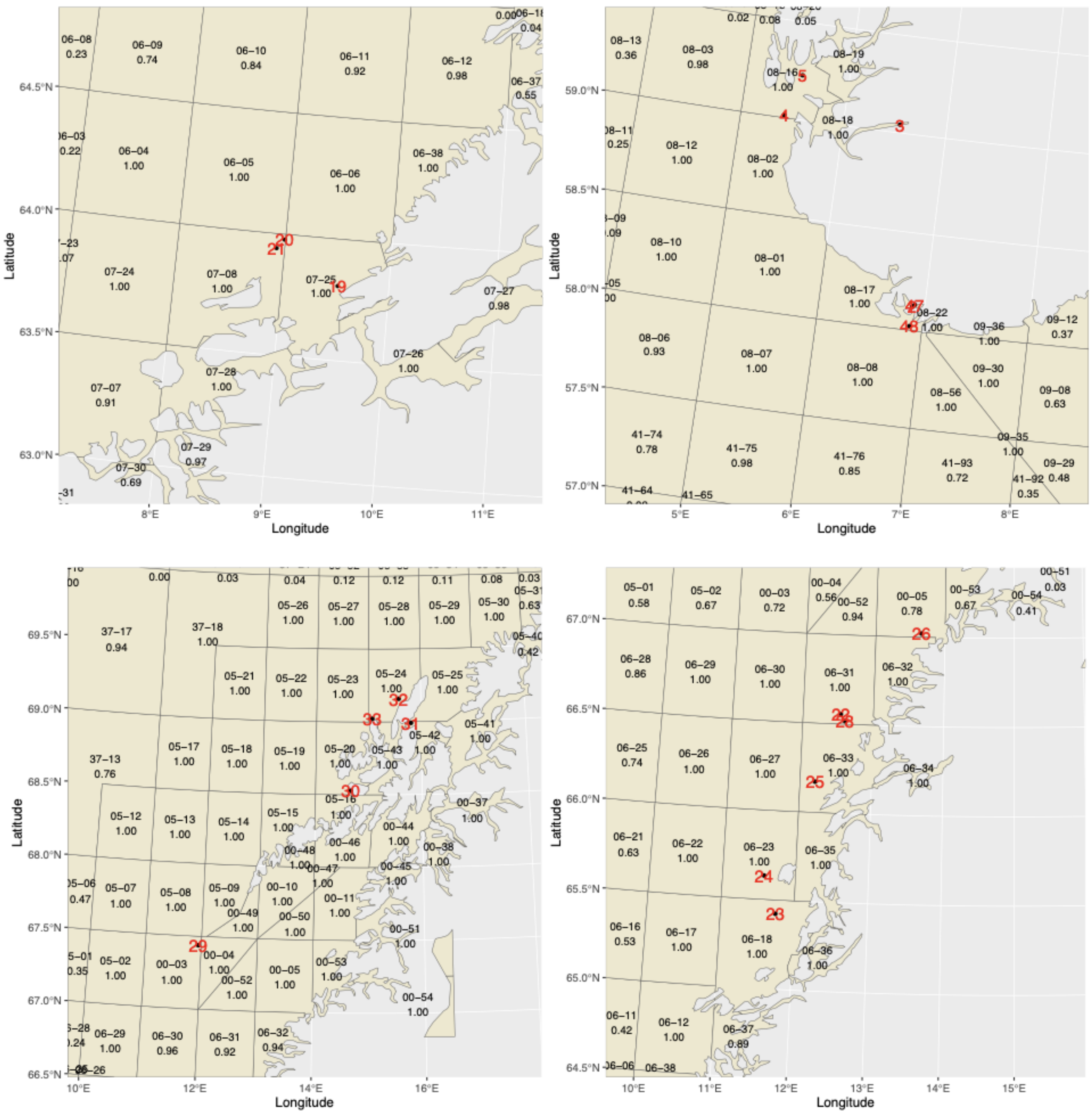

Figure A-6. Lokref cells of all areas. Upper left = Sør-Trøndelag, Upper right = Rogaland, lower left = upper Nordland, lower right= lower Nordland. The number under the lokref number illustrate the proportion of that cell. This was relevant since catches was multiplied with the proportion of the cell. The red numbers and black dots illustrate the harbour seas haul-out id in the different lokref cells.

HABITAT SUITABILITY INDEX

Figure A-7 illustrate how seals were moving in NetLogo in correlation with HSI values. The areas of darker red indicates a better quality of the habitat.

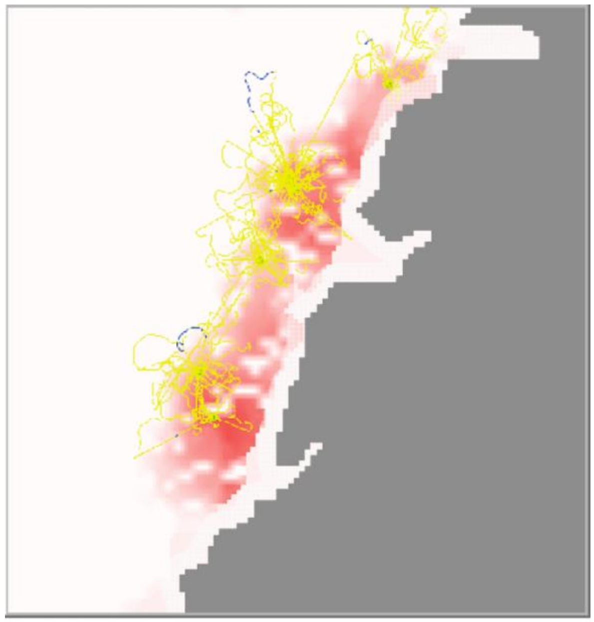

Figure A-7. Seal movement of 66 seals with HSI around the areas of Lower Nordland. The seals are foraging and traveling in areas of higher Hsi and spend shorter time in areas of lower Hsi values.

MOVEMENT OF SEALS WITH HO-SITE IN THE SMALLER FJORDS

As mentioned in the method and discussion part, most of the areas were extremely smoothed due to technical difficulties when running the simulations in NetLogo. These smoothed maps made it possible to swim on areas that in reality are land. Figure A-8 illustrate how two seals were moving in between haul-out-sites. It clearly illustrates that they swam on land. The blue areas are lokref cells representing at-sea locations and are areas where seals initially would have performed movement procedures. The grey area around lokref cells 08-19 and 08-18 are cells that have been smoothed to become water cells. When calculating the preluse and interaction risk later, the seals were given a neighbouring lokref cell of the positions they were on land, meaning that these two seals were given lokref cell 08-18 and 08-19 depending on which lokref were closest, when observed swimming on land (marked with a yellow circle).

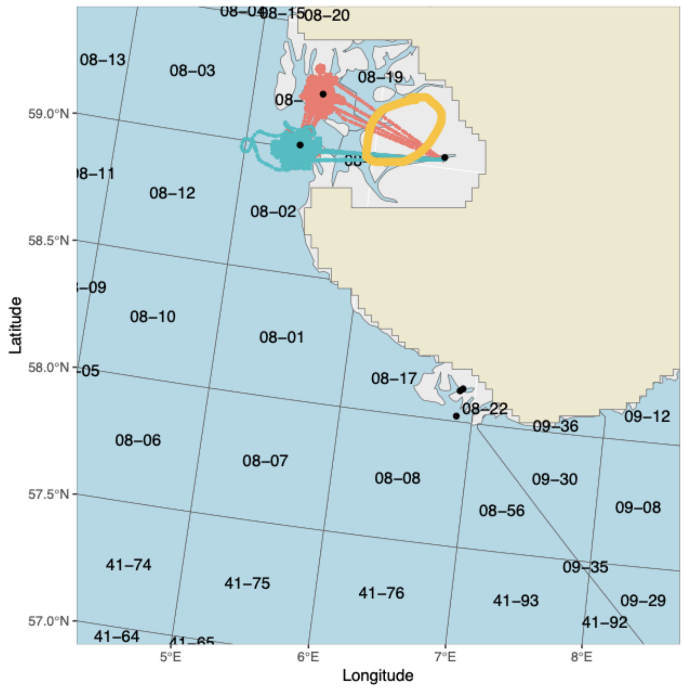

Figure A-8. Movement procedure of two super individuals of harbour seals of the study area of Rogaland. The seals are represented by different colours, red and turquoise. Black dots represent the colonies, where the three colonies used by the seals correspond to colony haul-out id 5 and haul-out-id 4 in lokref cell 08-16, and both seals were observed to travel to the colonies of haul-out id 3 in Lysefjorden of lokref cell 08-18. The yellow circle indicates how seals were travelling over the smoothed areas of original land since the fjord was too small and disrupted movement.

<u>SEAL MOVEMENT OF THE THREE REPLICATES OF UPPER NL</u>

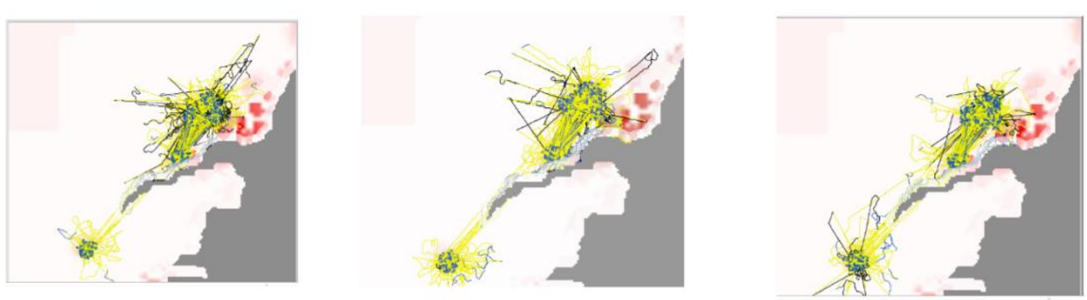

Figure A-9: Movement behaviour of 96 super individuals in the area of upper Nordland. The three pictures illustrate the three replicates and show how seal movement were similar.

DISTRIBUTION OF ACTIVITY FROM THE ORIGINAL MODEL

To validate that the model of this thesis worked properly, the model of the original model was simulated over 1 year. The original model was initially created for three months outside of breeding season but was tested over 1 year. This resulted in activity distribution similar to what this thesis observed. Foraging was the dominant activity followed by hauling out. Land avoidance was slightly higher compared to the model of the Norwegian coast. This was however dependent of the landscape since it was not a behaviour driven process. Having a similar activity distribution can indicate that the model was accurate and solid.

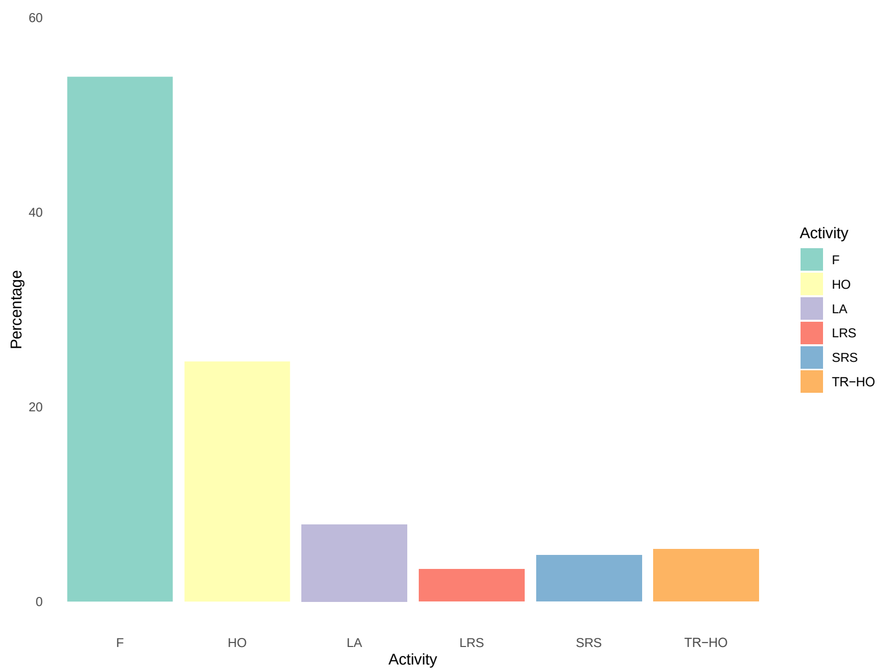

Figure A-10. Overview of seal activity distribution tested for the original model of Chudzinska et al. (2021) running over a year. This visualization correlates with the activity found for lower Nordland.

UNREALISTIC SCENARIO

The model was as previously mentioned tested many times to find a model that properly worked for the complex Norwegian coast. The following plot illustrates an unrealistic scenario where seals died as a result of land avoidance (LA). The activity plot corresponds to the simulation and shows how LA was outcompeting the other activities even before one year was simulated. This method was therefore discarded and is also an indicator of why the area was smoothed to an extreme.

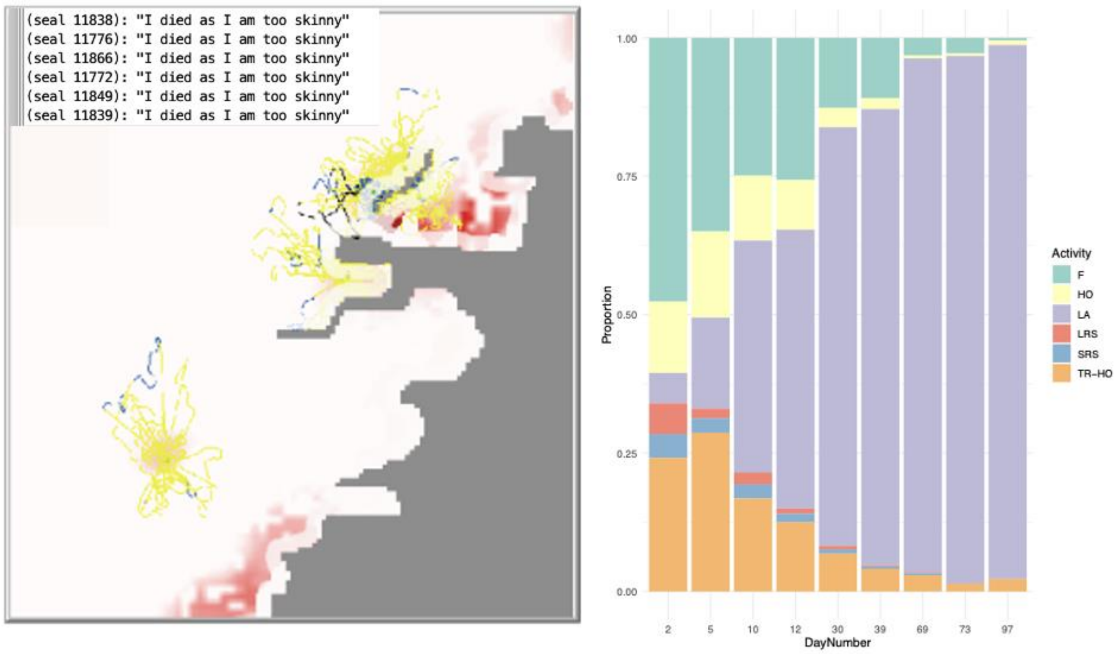

Figure 11. Seal movement of upper Nordland, simulated in NetLogo when the Figur-2.3b landscape was tested in the IBM. Several seals died before the end of the simulation. The corresponding activity plot showed how LA was the main activity after running the model for 97 days. These plots showed unrealistic seal behaviour and was therefore not used for interaction risk calculation. Red areas on the plot indicate high HSI.

INTERACTION RISK VALUES FOR ALL AREAS

Table A3. Predicted interaction risk values for all areas. All values in risk category (RC) RC1, value 0 have been removed from the dataset. Also values with a season_rel_use or a season_rel_catch value but showed 0 in interaction have also been removed to compromise the dataset.

lokref	season	season_rel_use	season_rel_catch	season_interaction
06-06	A	0.0016957	0.0918860	0.0086736
06-06	Wi	0.0013058	0.0382109	0.0027550
06-06	Sp	0.0012388	0.0649070	0.0045872
06-06	Su	0.0004491	0.0154646	0.0011624
06-12	Wi	0.0000018	0.0084744	0.0000006
06-38	A	0.0000032	0.0026076	0.0000002
06-38	Wi	0.0000090	0.0004263	0.0000002
07-08	A	0.1727282	0.0066234	0.0650394

07-08	Wi	0.1787570	0.0139568	0.1422584
07-08	Sp	0.2018719	0.0033678	0.0371999
07-08	Su	0.0724663	0.0011722	0.0142058
07-25	A	0.1016817	0.0550437	0.3035505
07-25	Wi	0.1194523	0.0331575	0.2174156
07-25	Sp	0.0938282	0.0362424	0.1894405
07-25	Su	0.0261993	0.0031584	0.0136850
07-26	A	0.0000420	0.0075610	0.0000234
07-26	Wi	0.0000052	0.0055083	0.0000024
07-26	Sp	0.0000004	0.0070051	0.0000001
08-01	A	0.0000396	0.0043522	0.0000061
08-01	Wi	0.0000269	0.0127518	0.0000449
08-01	Sp	0.0000493	0.0346569	0.0000813
08-02	Wi	0.0335008	0.0000688	0.0001511
08-08	Sp	0.0080730	0.0000482	0.0000263
08-16	A	0.0781519	0.0414699	0.1915965
08-16	Wi	0.0824343	0.0412749	0.2024997
08-16	Sp	0.0768179	0.0400321	0.1786305
08-16	Su	0.0255525	0.0122173	0.0548100
08-17	A	0.1460237	0.0016781	0.0151345
08-17	Wi	0.1591788	0.0009394	0.0087965
08-17	Sp	0.1585753	0.0348618	0.3248742
08-17	Su	0.0533039	0.0021899	0.0205786
08-18	Wi	0.0276314	0.0004949	0.0008165
08-19	A	0.0010862	0.0150481	0.0009582
08-19	Wi	0.0001940	0.0411516	0.0004488
08-19	Sp	0.0002982	0.0282416	0.0004057
08-19	Su	0.0000375	0.0000431	0.0000003
41-75	Wi	0.0000130	0.1353616	0.0001405
00-05	A	0.0172382	0.0126547	0.0115577
00-05	Wi	0.0215839	0.0607769	0.0668627
00-05	Sp	0.0188698	0.1060309	0.1201999
00-05	Su	0.0040159	0.0021379	0.0013916
00-53	A	0.0000042	0.0093163	0.0000021
06-18	A	0.0341275	0.0052387	0.0096702
06-18	Wi	0.0415369	0.0042561	0.0099386
06-18	Sp	0.0341844	0.0070642	0.0115750
06-18	Su	0.0158604	0.0000809	0.0002079
06-23	A	0.0375062	0.0050551	0.0106462
06-23	Wi	0.0340227	0.0016137	0.0028574

06-23	Sp	0.0387925	0.0091262	0.0204023
06-23	Su	0.0082393	0.0010915	0.0014576
06-27	A	0.0007891	0.0107725	0.0003391
06-27	Wi	0.0001315	0.0141798	0.0001323
06-27	Sp	0.0001273	0.0708104	0.0006402
06-31	A	0.0938315	0.0214961	0.1092058
06-31	Wi	0.0966560	0.0147261	0.0788613
06-31	Sp	0.1141446	0.0412888	0.2480899
06-31	Su	0.0417816	0.0045639	0.0309061
06-32	A	0.0267737	0.0000333	0.0000501
06-32	Wi	0.0255647	0.0070954	0.0095450
06-32	Sp	0.0263109	0.0124329	0.0177134
06-32	Su	0.0091409	0.0001324	0.0001961
06-33	A	0.0866648	0.0049797	0.0238788
06-33	Wi	0.0805594	0.0215728	0.0887070
06-33	Sp	0.0692867	0.0317218	0.1233048
06-33	Su	0.0218343	0.0004420	0.0015641
06-35	A	0.0001336	0.0015734	0.0000128
06-35	Wi	0.0002026	0.0076525	0.0000835
06-35	Su	0.0000295	0.0001977	0.0000010
00-03	A	0.0559229	0.0033241	0.0101800
00-03	Wi	0.0590610	0.0107986	0.0328926
00-03	Sp	0.0507694	0.0545602	0.1527443
00-03	Su	0.0155908	0.0024884	0.0063878
00-04	Wi	0.0018105	0.0124451	0.0019218
00-04	Sp	0.0033333	0.0379736	0.0076058
00-10	A	0.0000291	0.0014717	0.0000004
00-10	Wi	0.0000253	0.0052765	0.0000008
00-10	Sp	0.0000169	0.0666639	0.0001121
00-48	A	0.0000156	0.0050088	0.0000037
00-48	Wi	0.0000188	0.0213449	0.0000018
00-48	Sp	0.0000121	0.1610333	0.0002329
00-49	Sp	0.0000441	0.0035974	0.0000164
05-08	Sp	0.0002050	0.0000650	0.0000022
05-09	Wi	0.0012490	0.0001573	0.0000318
05-09	Su	0.0011768	0.0000700	0.0000133
05-14	A	0.0000095	0.0001658	0.0000001
05-14	Wi	0.0000082	0.0010447	0.0000006
05-14	Sp	0.0000061	0.0098354	0.0000039
05-15	A	0.0000612	0.0011126	0.0000035

05-15	Wi	0.0000954	0.0156676	0.0000421
05-15	Sp	0.0000498	0.0495137	0.0001264
05-15	Su	0.0000275	0.0015754	0.0000073
05-16	A	0.0129068	0.0015091	0.0012537
05-16	Wi	0.0138326	0.0004570	0.0003549
05-16	Sp	0.0134919	0.0003931	0.0003047
05-16	Su	0.0045592	0.0000366	0.0000287
05-19	Wi	0.0000120	0.0052957	0.0000106
05-19	Sp	0.0000223	0.0081068	0.0000000
05-20	A	0.0628861	0.0007048	0.0024383
05-20	Wi	0.0662696	0.0056690	0.0199573
05-20	Sp	0.0614642	0.0126943	0.0439606
05-20	Su	0.0183088	0.0006818	0.0021040
05-22	Wi	0.0000326	0.0003418	0.0000011
05-23	A	0.0062595	0.0030848	0.0009412
05-23	Wi	0.0048180	0.0467287	0.0085173
05-23	Sp	0.0047917	0.0462688	0.0134205
05-23	Su	0.0013879	0.0016794	0.0003908
05-24	A	0.0995025	0.0129578	0.0739375
05-24	Wi	0.1082934	0.0635550	0.3833801
05-24	Sp	0.1144636	0.0319841	0.1989134
05-24	Su	0.0396095	0.0051152	0.0335890
05-25	A	0.0127810	0.0000154	0.0000115
05-25	Wi	0.0086568	0.0007276	0.0005432
05-25	Sp	0.0132280	0.0010999	0.0008398
05-25	Su	0.0043890	0.0001105	0.0000809
05-41	Wi	0.0000218	0.0002837	0.0000010
05-42	Wi	0.0159169	0.0000133	0.0000349
05-43	A	0.0581698	0.0007359	0.0023041
05-43	Wi	0.0187983	0.0000065	0.0000204
05-43	Sp	0.0455667	0.0000879	0.0003289

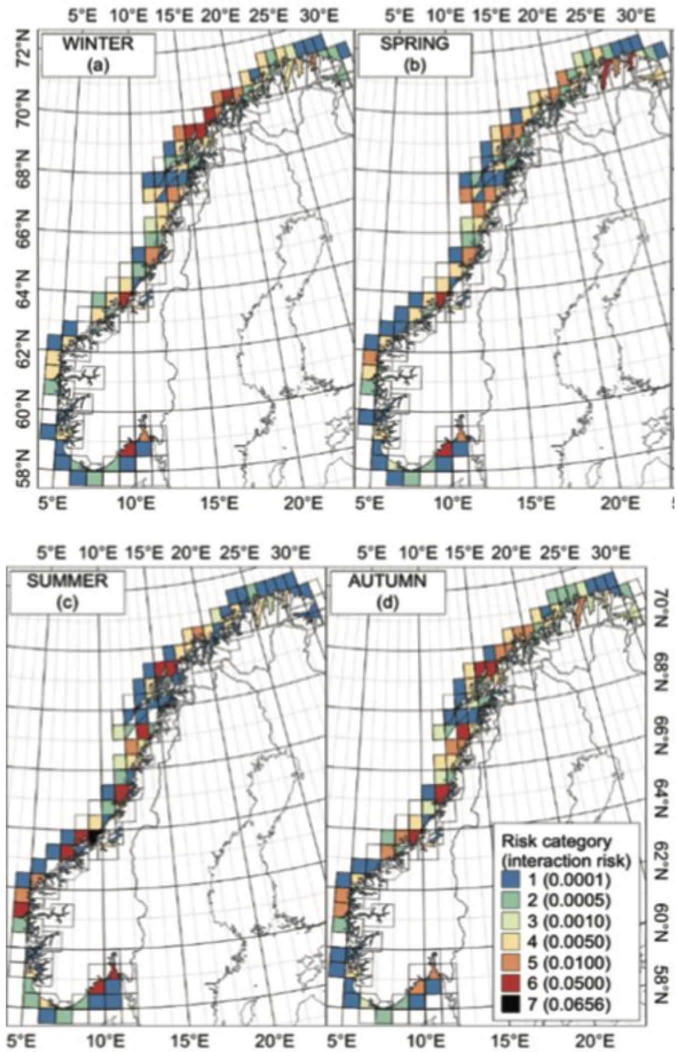

Figure 12. Predicted interaction risk along the Norwegian coast, presented with risk categories 1-7. This plot is retrieved from Elnes' study representing the results of the updated method of 2023 (Elnes et al., 2023).

Appendix literature

CHUDZINSKA, M., NABE-NIELSEN, J., SMOUT, S., AARTS, G., BRASSEUR, S., GRAHAM, I., THOMPSON, P. & MCCONNELL, B. 2021. AgentSeal: Agent-based model describing movement of marine central-place foragers. *Ecological Modelling,* 440**,** 109397-109397.

ELNES, J. O., MOAN, A., NILSSEN, K., VØLLESTAD, A. & BJØRGE, A. 2023. Temporal and Spatial Distribution of Harbour Seal (*Phoca vitulina*) Risk Entanglement in Gillnets Along the Norwegian Coast. *Aquatic Mammals 2023,* 49-6**,** 11.

SLUTTSEDDELREGISTERET, F. 2023. *Rundvekt (tonn) fordelt på landingsfylke og redskap Norske fartøy* [Online]. Fiskeridirektoratet. Available: https://www.fiskeridir.no/Yrkesfiske/Tall-og-analyse/Fangst-og-kvoter/Fangst/Fangst-fordelt-paa-landingssted [Accessed 2023]