Predicted times and areas of interaction risk between harbour seals and coastal gillnet fisheries in Norway

Master thesis

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Abstract

Incidental take of non-target species by fisheries, also referred to as bycatch, is a major concern for management of species in the marine megafauna. In Norway, 555 harbour seal (*Phoca vitulina*) die as the result of bycatch each year. The majority of these bycatch events occur in gillnet fisheries. To increase our understanding of harbour seal bycatch events along the Norwegian coast, time and areas of potential interaction risk can be identified, referring to incidents when and where harbour seal foraging and fishing effort overlap. To compensate for the lack on dispersal and movement data on harbour seals in Norway, harbour seal distribution were simulated from their primary moult site to an at-sea location. Overlapping abundances of simulated harbour seal and fishing effort were then used to calculate the relative interaction risks between seals and fisheries in defined Statistical Sea Locations (SSLs), in each season. Seasonality in interaction risk was related to the Northeast arctic cod fisheries, with interaction risks relatively high during winter and particularly spring. Two areas in north and one in west Norway were categorised as Consistently High or moderate Interaction Risk (CHMIR). The relative interaction risk was highest in Vesterålen and Senja (CHMIR2) in north Norway. The CHMIR-areas in general, and particularly CHMIR2 in north Norway, are expected to be the areas where the majority of bycatch events occur in Norway. The method predicts spatial and temporal probabilities for interaction between harbour seals and coastal gillnet fisheries. The located times and areas of interaction risk can be used in management practises to increase our understanding of bycatch events along the Norwegian coast, and to possibly implement mitigation efforts in times and areas with largest effect.

Introduction

Marine resources have probably been considered to be endless since the dawn of time. As Roberts and Hawkins (1999) pointed out, two of the 18th and 19th centuries greatest thinkers, Jean Baptiste de Lamarck and Thomas Huxley, claimed that humanity could not cause extinctions in the marine environment. This is a belief that may still be commonly shared by many people today (Roberts and Hawkins 1999). History has, however, shown that several marine species have suffered significant depletions from unsustainable harvesting, which still occurs today (Garcia and de Leiva Moreno 2003). Populations of cod (*Gadus morhua*) in Canada, Norwegian spring-spawning herring (*Clupea harengus*), North Atlantic right whales (*Balaena glacialis),* and blue whales (*Balaenoptera musculus*), have all been severely depleted by anthropogenic activity, and have recovered to various degrees (Hamre 1994, Walters and Maguire 1996, Reeves et al. 1998, Kraus et al. 2005). However, some marine species have been extirpated locally and globally by anthropogenic activity. In total, 19 marine animal species are categorized as extinct (EX) by the International Union for Conservation of Nature (IUCN) (IUCN 2021). Of the 19 marine animals, four marine mammals are classified as extinct in the red list; these are the stellar sea cow (*Hydrodamalis gigas*), Caribbean monk seal (*Neomonachus tropicalis*), Japanese sea lion (*Zalophus japonicus*), and sea mink (*Neovison macrodon*) (IUCN 2021). With 868, 444, and 225 marine animals categorized as vulnerable (VU), endangered (EN) and critically endangered (CR), respectively, combined with expected increased anthropogenic activity in the future, more species are expected to be categorised as extinct (EX). Regional extinction (RE), which is far more likely to occur than global extinction, affects the local ecosystems by removing the ecological services that the extirpated species provided. Regional extinction may also result in the loss of genotypes from the species gene pool (McCauley 1991, Hare et al. 2011)

Many species in the marine megafauna are especially vulnerable to overexploitation and represent a large proportion of marine animals categorized as EX by the IUCN. Their large size and life-history strategies make them particularly vulnerable to overexploitation (Williams 1966). Typically, a life history strategy in the marine megafauna is low fecundity, which is compensated with a long lifespan and an iteroparous reproductive strategy. Sub-adult and adult survival rates are naturally high, which makes such life-history strategies vulnerable to exploitation and other human encroachments that affect survival.

In the marine realm, coastal environments are hot-spots for anthropogenic activity, with over 50% of the global human population living within 60km from the coast (DeMaster et al. 2001). Coastal environments are subject to a vast amount of anthropogenic pollution and other stressors that all contribute to lowering the quality of the ecosystems and the organisms inhabiting them (Vikas and Dwarakish 2015). Marine biodiversity is richest in the coastal neritic zone, and approximately 95% of marine fish catches come from the continental shelf (Roberts and Hawkins 1999). Fishing activity is intense in the coastal region, and fisheries may deplete the targeted species and reduce the abundance of non-target species that incidentally get entangled in the fishing gear. This incidental capture of non-target species is referred to as bycatch. Bycatch may also refer to incidental catch of non-target size or age classes of the target species (e.g. juveniles or large females).

Since the 1970s, bycatch has been increasingly recognized as a factor that may limit and reduce marine mammal populations (Read 2005, Reeves et al. 2013). Individuals incidentally caught can either be unharmed, released with injuries, or killed (Lewison et al. 2004). Animals may also be injured, captured, or killed in discarded fishing gear or other marine debris (Hess et al. 1999). Bycatches impose a major threat to the marine megafauna, where different taxa are vulnerable to different types of gear (Hall et al. 2000, Lewison et al. 2004). Marine mammals have a foraging behaviour and overlapping habitat use with coastal fisheries, making them vulnerable to gillnet fisheries (Woodley and Lavigne 1991, Bjørge et al. 2002c, Read et al. 2006, Niemi et al. 2012). In the US, gillnet fisheries were responsible for 84% of cetacean and 98% of pinniped bycatch mortality (Read et al. 2006). Of the total 34 species in Pinnipedia, 66% of species are recorded to be killed as bycatch (Reeves et al. 2013). Woodley and Lavigne (1991) concluded that bycatch had contributed to declines in populations of harbour seal (*Phoca vitulina*) in the North Pacific, harp seal (*Pagophilus groenlandica*) in the Barents Sea, and northern fur seals (*Callorhinus ursinus*) in the North Pacific. Conflicts between marine mammals and commercial fisheries are increasing in frequency and are expected to do so in the future (DeMaster et al. 2001).

The harbour seal is the world’s most widely distributed pinniped species (Teilmann and Galatius 2018). They occur in coastal areas of the temperate and sub-arctic regions in the Northern Hemisphere and are divided into three recognized subspecies: Atlantic harbour seal (*Phoca vitulina vitulina*), Ungava harbour seal (*P.v. mellonae*), and Pacific harbour seal (*P.v. richardii*) (Berta and Churchill 2012). *P.v. vitulina* inhabits the northeast

Atlantic Ocean, spanning coastal areas from northern France (30°N) to Svalbard (78.5°N) (Teilmann and Galatius 2018). The population in Svalbard is the northernmost population of harbour seals in the world. In Norway, preliminary results from DNA analyses indicated that there are regional genetical differences between populations (Nilssen et al. 2020). Further, their distribution in coastal regions all along the Norwegian coast makes harbour seals vulnerable to coastal fisheries.

The harbour seal is an opportunistic, central place forager that forages solitarily, close to land, in shallow waters (Riedman 1990, Pierce et al. 1991, Bjørge et al. 1995, Frost et al. 2001, Lowry et al. 2001, Rosing-Asvid et al. 2020). Harbour seals frequently use haul-out sites for various reasons such as resting, predator avoidance, thermoregulation, pupping and moulting (Watts 2011, London et al. 2012). Their semiaquatic behaviour and frequent use of haul-out site makes harbour seals frequently exposed to disturbances and anthropogenic activity along the coast. Their diets vary geographically and temporally in a relatively predictable way related to prey availability (Riedman 1990) and generally consist of small specimens or species of demersal fish (Härkönen 1987, Olsen and Bjørge 1995, Tollit and Thomas 1996, Berg et al. 2002). Many commercial and non-commercial fish are represented in their diet, but harbour seals mainly target the younger life stages of commercial fish species (Olsen and Bjørge 1995). The preferred size of prey suggests that interaction between fisheries and harbour seals should be minimal. However, harbour seals may aggregate near fishing gear or fishing activity to feed on discards (Wickens 1994), entrapped fish (Read 2005), or exhausted fish released alive (Stanley and Shaffer 1995). Depredation on fish entangled in fishing gear may increase the probability of getting entangled. Also, harbour seals travel to or at foraging sites near the bottom while searching for prey (Bjørge et al. 1995), which makes them exposed to incidentally get caught in benthic fishing gear while travelling or foraging.

Various codfish and monkfish (*Lophius piscatorius*) fisheries use bottom-set gillnets with large mesh sizes, and the largest proportion of harbour seal bycatch is taken in such fisheries (Bjørge et al. 2017). Bycatch and depredation by marine mammals have been demonstrated to have severe economic costs for some fisheries (Yano and Dahlheim 1995, Ashford et al. 1996, Tixier et al. 2021), which derive from a reduction in the value of the reduced catch and damage to the gear itself.

In Norway, fishing intensity is high along the entire coast, and the potential for interactions between seals and fisheries is high. Politically, harbour seals are managed to ensure viable populations within their natural range along the Norwegian coast (Meld. St. 27 (2003-2007)). Population growth is regulated with hunting quotas to mitigate damage and interaction between seals and fisheries. The total population is stabilized around 7000 recorded seals in the moulting seasons, which is estimated to give a total population of about 10 000 individuals (Ries et al. 1998, Anon 2010, Meld. St. 46 (2008-2009)). To manage the populations at the desired size, the Institute of Marine Research (IMR) performs nationwide surveys every fifth year and recommends quotas annually to the Directorate of Fisheries (DoF). In recent years, between 300-500 harbour seals have been hunted annually. In addition, it is estimated that 555 harbour seals were taken as bycatch annually between 1997-2014, which is considered to unsustainable (Bjørge et al. 2017).

In Norway, harbour seals were categorized as vulnerable (VU) in 2006 by the Norwegian red list (Kålås et al. 2006), mainly because of high hunting quotas set by the DoF. Today, after the implementation of the new management regime in 2010, harbour seals are surveyed and managed with a more scientific approach. The population has recovered and is currently listed as Least Concern (LC) by the Norwegian Red list (Henriksen and Hilmo 2015). However, as part of an evaluation of the Norwegian management of coastal seal conducted by North Atlantic Marine Mammal Commission, it has been recommended that harbor seal surveys should cover the whole Norwegian coastline more frequently than every fifth year. This should be done to avoid sudden population declines that may go unnoticed for several years (Nilssen et al. 2020). Also, hunting is stopped if a population drops below 0.5 of the desirable population size, and NAMMCO suggests that this threshold should be increased to 0.7 to compensate for the uncertainty between the surveys. The administrative management units used to set quotas are set at county level and are not based upon science. This makes small and/or endemic colonies within a county at risk to be overharvested. While harbour seals are not threatened as a species, small populations can be vulnerable to mortalities, which may have demographic effects and result in population decline. Small populations are also more vulnerable to genetic drift, which may remove genetic variation by stochastic genetic processes and cause fixation of alleles (Hare et al. 2011). The largest proportion of human-induced mortalities is caused by unregulated mortalities caused by bycatch, and a greater understanding of bycatch may be crucial for the health of small and/or endemic populations.

It is widely accepted that estimates of bycatch rates in any fishery require an independent observer scheme (Read et al. 2006). In the absence of detailed data on bycatch, knowledge of the spatial and temporal distribution of fishing effort and the non-target species can be used to construct predictive models of bycatch risk (Roe et al. 2014). Predictive models can then be used to identify times and areas of potential interaction to inform bycatch mitigation strategies (Žydelis et al. 2011, Harden and Williard 2012)

This thesis will integrate information on the seasonal distribution of harbour seal and seasonal fishing effort along the Norwegian coast. Due to lack of data on harbour seal dispersal patterns in Norway, harbour seal distribution will first be simulated from their moult-site to an at-sea location. Information on harbour seal moult-site locations and abundances were obtained from the IMR and are used together with literature data on harbour seal movement to model their distribution at sea during different seasons. The simulation aims to distribute seals at sea across Statistical Sea Locations (SSLs) (see figure 1), which the IMR and DoF use to register fisheries landing statistics. Fishing effort varies seasonally, and interaction between fisheries and seals is expected to be greatest during periods with high fishing effort. The relative distribution of harbour seals and fishing effort is then used to predict areas and times of strong and potentially fatal interactions. The results are aimed at increasing our understanding of harbour seal bycatch risk in Norway, and ultimately informing management decisions.

Material and methods

In Norway, harbour seals are distributed along the coast, with large colonies and congregations of colonies in the west and north (see figure 1). They are generally located within 50km from their primary haul-out site (Peterson et al. 2012), which is where they moult. Seals may, however, travel vast distances over several days on foraging trips, but return to their core area within their home range to haul out (Lowry et al. 2001, Rosing-Asvid et al. 2020). Sub-adults show reduced fidelity to their primary haul-out site until they reach maturity and are the age-classes that travel furthest away from the primary haul-out site (Lowry et al. 2001, Dietz et al. 2013). Harbour seals generally visit the same feeding grounds during their foraging trips before returning to their last used haul-out site, and they may use multiple haul-out sites over a year, reflecting seasonality or depletion of prey abundance (Thompson 1989, Bjørge et al. 1995, Tollit et al. 1998, Lowry et al. 2001, Cordes et al. 2011). In Scotland, less than 1% of foraging trips ended at a different haul-out site than where the trip started (Thompson et al. 1998). Their site fidelity and foraging behaviour make harbour seal a good candidate to have their movement at sea modelled.

Data collection and preparation

Statistical Sea Locations

The Directorate of Fisheries (DoF) and the Institute of Marine Research (IMR) use Statistical Sea Areas (SSAs), which are subdivided into Statistical Sea Locations (SSLs) to register landing data (see figure 2; e.g., SSL 28-41, is location 41 in SSA 28). There are nine SSAs along the Norwegian coast. The shape and area of SSLs can be divided into two shape categories: coastal and offshore cells. All offshore cells are 0.5° x 1° (latitude x longitude) grid cells. This corresponds to ~55.5km from north to south, whereas the length from west to east varies from ca. 35 – 59km. Coastal SSLs vary in shape and area depending on the shape of the coastline, islands and fjords. For example, the 205km long Sognefjorden is represented by one SSL. Some coastal SSLs have only a small proportion of the cell adjacent to the coast. Such cells have their largest proportion defined as offshore, if offshore is considered as 9miles (14.49km) from the coast. Such cells are defined as offshore-coastal SSLs. The shape-files (Data files used in Geographical Information System (GIS)) retaining data on the polygonal shape and size of SSAs and SSLs were obtained from the IMR.

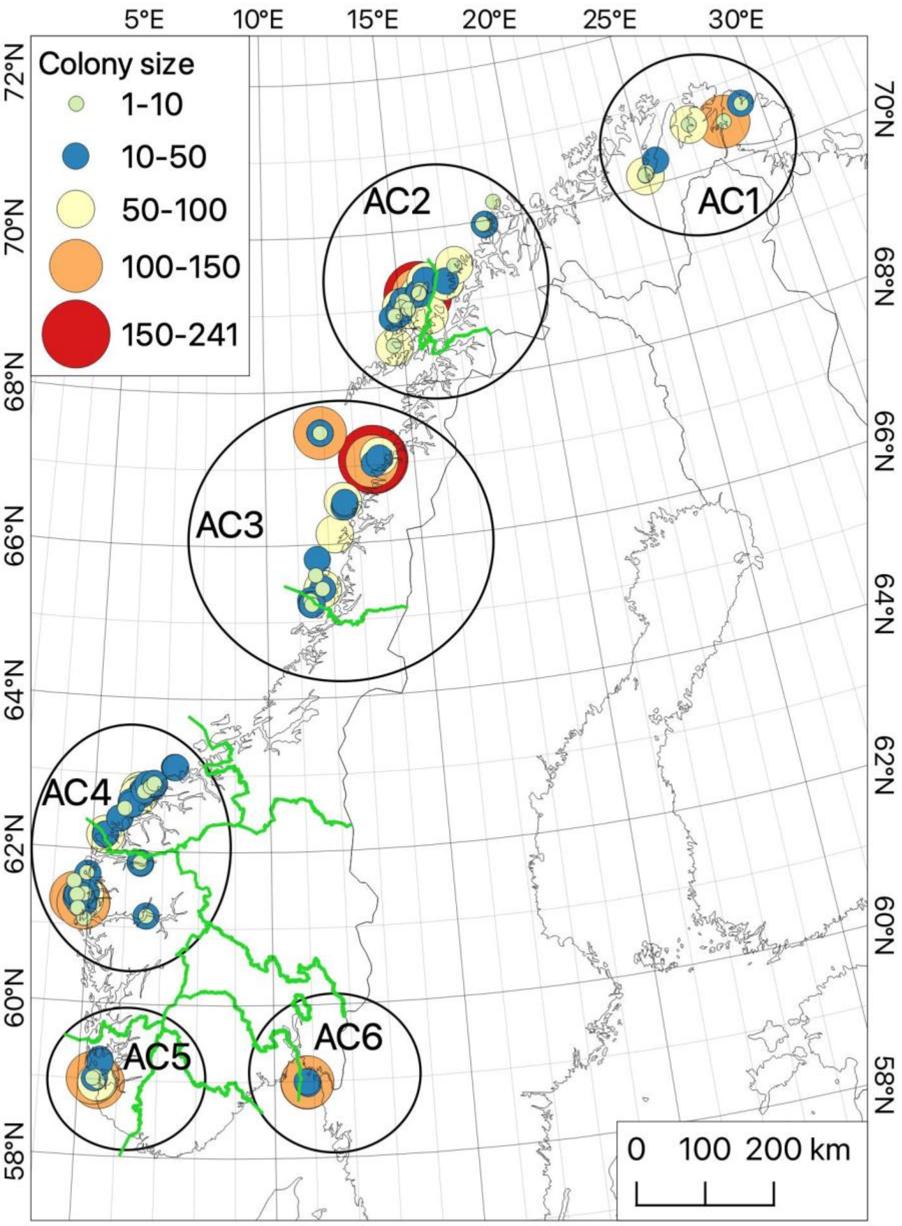


Figure 1. Distribution and abundance of harbour seal colonies along the Norwegian coast. A total of 6012 harbour seals are distributed in 171 colonies. Colony sizes are categorized into five categories depending on their size, with smaller colonies plotted on top of the larger ones. Colonies in close proximity to one another are expected to have continuity of home-range between them, and colonies are defined into six aggregation of colonies (AC), defined as AC1, AC2, AC3, AC4, AC5, and AC6. Green lines represent county borders. Data are obtained from the Institute of Marine Research and includes count surveys from

Seal surveys

To simulate harbour seals movement and thus movement at sea, available data on harbour seal moulting sites was used. The data included information on size, date, locality (divided into county, municipality, region, and location), and coordinates of the surveyed colony. Nationwide surveys are performed over several years by the IMR, aimed to cover all known harbour seal moult sites within five years. The dataset used included surveys between 1994-2020, where some counties were surveyed multiple times in different years. If a county was surveyed two or more times in different years, only data from the latest annual survey were used. However, several municipalities in the county Nordland were missing in the latest surveys, and surveys from multiple years were therefore used to describe the abundance of seals in Nordland, see table 1. Within an annual survey, each colony was surveyed between 1-3 times during moult season. Colonies that were

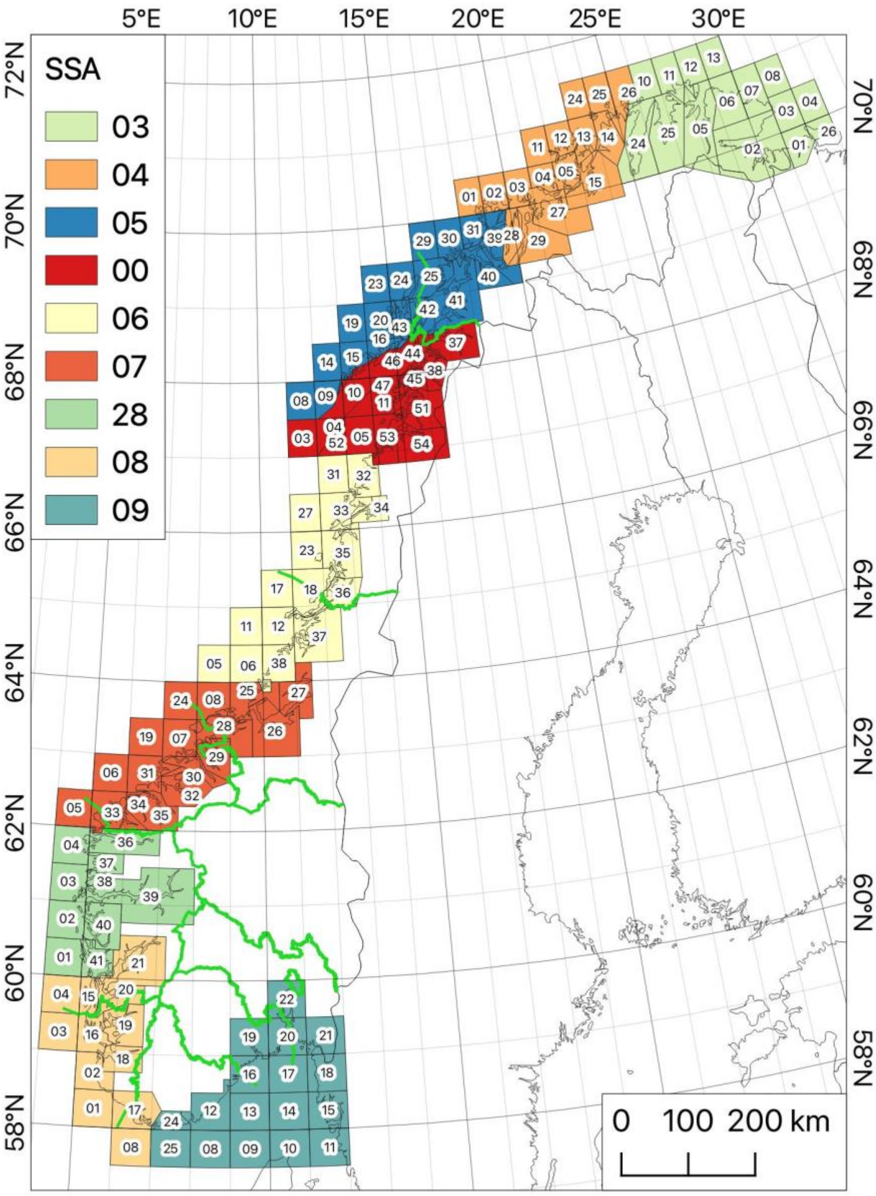


Figure 2. Statistical sea Areas and locations (SSA and SSL). Statistical Sea Areas (SSAs), coloured areas, are subdivided into smaller cells referred to as Statistical Sea Locations (SSLs). The presented SSLs are those used in the simulation. Coastal SSLs have their borders drawn upon the mainland for better visualization of the extent of the cells. Green lines represent county borders.

surveyed multiple times had their highest number of observed seals used. In some cases, the data lacked complete information about which colony it was observing, and the number of colonies surveyed between days differed. In those cases, dates with the highest number of observed seals were used. Some colonies and localities lacked coordinates and were assigned coordinates from adjacent colonies. The dataset retrieved was not a complete representation of the Norwegian harbour seal colonies. The counties Vestfold, Vest-Agder, Øst-Agder, Telemark, and Sør-Trøndelag were not included in the dataset. The names of the counties used in the dataset are stated as they were before the merger in 2020.The final cleaned dataset included 6012 seals distributed over 171 count sites, see figure 1.

Table 1. Overview of surveys retained to represent the abundance of harbour seals along the Norwegian coast. Years represent the time of the survey used to represent a given county. The names of the counties are stated as they were before the merger in 2020.

Finnmark	Møre og Romsdal	Nord-Trøndelag	Nordland	Rogaland	Sogn og Fjordane	Troms	Østfold
2012	2018	2019	2012, 2019, 2020	2011	2018	2012	1998

Fishery data

To estimate the relative probability of interaction between harbour seals and coastal fisheries using bottom-set gillnets, landing statistic for the Norwegian fisheries were used as a measure of fishing effort. These data are available as CSV files on the DoF webpage: https://www.fiskeridir.no/Tall-og-analyse/AApne-data/AApne-datasett/Fangstdata-seddel-koblet-med-fartoeydata . The data had over 100 columns of information on landing statistics, where the most relevant information for the present thesis was date, SSA, SSL, type of gear used, and catch weights of each species of fish caught. Landing statistics between 2006-2018 were used and filtered to include statistics for small vessel coastal fisheries (overall boat length < 15m) using bottom-set gillnets. A total of 5190 vessels using bottom-set gillnets were registered in the given period. Catch of cod (northeast arctic and the coastal cod populations) and monkfish accounted for respectively 71.3 and 2.9% of the total catch in small coastal vessels using bottom-set gillnets, respectively. I assumed that hauls where over 50 percent of the catch included the species pollock (*Pollachius pollachius*), common ling (*Molva molva*), cusk (*Brosme brosme*), haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*), cod, Atlantic halibut (*Hippoglossus hippoglossus*) and/or monkfish were from fishing trips with risk of entanglement of harbour seal. These trips were retained and used for later analysis. Trips where other species was recorded as the main catch were removed. This procedure removed 6.67% of the fishing trips and resulted in a total of 774393 fishing trips between 2006-2018 that were used for further analysis.

Average seasonal fishing effort ($effort_{it}$) was estimated as the number of fishing trips that occurred in an SSL i during season t between the years 2006-2018, using the following equation:

$$effort_{it} = \frac{\sum_{i=1}^{n}\sum_{t=1}^{4} trips_{it}}{13} \quad (2.1)$$

Simulation of harbour seal distribution

The simulation aimed to distribute harbour seals from their primary haul-out site, the site where harbour seals are counted during moult in late summer, to at-sea locations. Individual seal dispersal was simulated using a Monte Carlo simulation. The resulting distribution of seals was used to estimate the abundance of harbour seals within SSLs. The relative probability of seals and the relative probability of fishing effort could then be used to calculate the relative interaction probability between harbour seals and bottom-set gillnets categorized with risk of entanglement.

Harbour seals and coastal fisheries are expected to operate in productive water, and foraging and fishing sites are therefore assumed to overlap. All coastal and offshore SSLs with registered activity of fisheries using bottom-set gillnets were retained for further analysis. However, some extra SSLs with no registered fishing activity were also retained, to even out the sampling ground/SSLs used to simulate harbour seals in, compare SSL in figure 2 (selected SSL used in the simulation) to figure 4 (SSL where coastal fisheries are registered).

Harbour seal dispersal from their primary haul-out site is expected to increase from short-range dispersal during summer to long-range dispersal during winter (Dietz et al. 2013). The simulation used three variables to represent seasonality in harbour seal dispersal. Due to similar results during testing, spring and autumn variables were combined into one intermediate dispersal distance. Summer and winter dispersal distances represent short- and long-range dispersal. Each seasonal dispersal variable was defined based on the literature on harbour seal movement (table 2). Multiple studies were used to account for the variation and quality between the studies, and to explain the variation expected to occur along the Norwegian coast.

Table 2. The mean and standard deviation (SD) of harbour seal seasonal dispersal distance from their primary haul-out site, used in the simulation to explain seasonality in mobility. The quantiles explain the proportion of the simulations expected to occur within the presented distance, e.g., 50% of the simulated seals with summer variables are expected to occur within 9.99km from their primary haul-out site. The expected value is the mean for the truncated normal distribution with 0 as the lower limit. All values are in km.

Season	Mean	SD	50%	95%	99.9%	Expected value
summer	5	11.60	9.99	26.27	42.22	11.32
Spring/autumn	15	26.90	24.95	63.54	100.81	27.91
Winter	35	49.30	49.94	122.02	181.09	54.94
Framework Literature		(Thompson and Miller 1990, Lowry et al. 2001, Bjørge et al. 2002b, Bjørge et al. 2002c, Cunningham et al. 2009, Cordes et al. 2011, Lesage and Kovacs 2011, Peterson et al. 2012, Sharples et al. 2012, Dietz et al. 2013, Blanchet et al. 2014, Aarts et al. 2016, Rosing-Asvid et al. 2020)				

To simulate seal movement from one colony, the GPS coordinates of its moult site were used to create a sampling space of discretised points with a density of one point every kilometre. The points were constructed by first creating 180 line-segments that originated in the initial point coordinate and ended a maximum of 191.3km away. Each line was 2 degrees offset from the previous one. Points were then created at 1km intervals along those lines and named based on the concentric ring they belong to, again originated from the initial point. Points along the 180 lines located on land were removed. Seals were distributed along a random line using a truncated normal distribution. A truncated normal distribution functions as a normal distribution, but with a predefined range, which in this case was 0-191,3km. The maximum distance of 191.3km represents the 99.9% quantile for the largest seasonal dispersal distance (mean: 35km and SD: 49.94km) with a lower limit set at 0 and with no upper limit. If a seal ended up in a location outside the boundaries of any SSL, it was registered in the SSL closest to that location, based on geodesic distance. For each set of parameters, the simulation was run 1000 times. The average seasonal abundance of seals in each SSL was then calculated from replicates within a season. A more detailed description of the script and functions used in the simulation is presented in Appendix 2.

Calculating Entanglement Risk

To estimate the relative probability of interaction between harbour seal and coastal fisheries, I used the same method as Roe et al. (2014). First, relative density estimates were converted to relative probabilities by calculating the likelihood that seals occupied SSL i at season t relative to all other SSLs n across the four seasons, using the following equation:

$$P_{rel}(seal)_{it} = \frac{density_{it}}{\sum_{i=1}^{n}\sum_{t=1}^{4} density_{it}} \quad (2.2)$$

Similarly, the probability of fishing effort in SSL i during the tth season relative to all other SSL n across the four seasons is:

$$P_{rel}(fishing)_{it} = \frac{effort_{it}}{\sum_{i=1}^{n}\sum_{t=1}^{4} effort_{it}} \quad (2.3)$$

Finally, an interaction index was computed for SSL i during the tth season relative to all other SSL n across the four seasons using the equations:

$$P_{rel}(interaction)_{it} = \frac{P_{rel}(seal)_{it} \times P_{rel}(fishing)_{it}}{\sum_{i=1}^{n}\sum_{t=1}^{4}(P_{rel}(seal)_{it} \times P_{rel}(fishing)_{it})} \quad (2.4)$$

In equation 2.4 all SSL probabilities in the four seasons combined sum to one, allowing for more intuitive relative comparisons to be made across time periods.

Interaction values and risk categories

The interaction values derived from equation 2.4 ranged from a minimum of $5.49*10^{-10}$ to a maximum of 0.069. Interaction values were categorized and binned using a semi-logarithmic scale. Four main categories defined with very low, low, medium, and high interaction risk between harbour seal and coastal fisheries were used. The categories low, medium, and high were categorized using a logarithmic scale, whereas the very low category gathered all values < $1.0*10^{-4}$. Each main division in a logarithmic scale, for example, $1.0*10^{-4}$ to $1.0*10^{-3}$ is called a cycle. Interaction values above $1.0*10^{-4}$ were binned using three cycles: $1.0*10^{-4}$ to $1.0*10^{-3}$; $1.0*10^{-3}$ to $1.0*10^{-2}$; and $1.0*10^{-2}$ to $1.0*10^{-1}$, respectively referring to the interaction risk categories low, medium, and high. Each logarithmic cycle used was also subdivided into two halves for comparisons within cycles/main categories. The main category "low interaction risk" consists of Risk Category 2 (RC2) and RC3, whereas the main category "medium interaction risk" consists of RC4 and RC5. The main category "high interaction risk" consists of RC6 and RC7. The very low category was also defined as RC1. See table 3 for a detailed overview of the categorization of the interaction risk values. SSLs predicted with Consistently High or Moderate Interaction Risk were defined as CHMIR. SSLs categorised as CHMIR adjacent to one another were defined CHMIR-areas, three such areas were located next to the Aggregation of Colonies (ACs): AC2, AC3, and AC4.

Software, script and packages

R and RStudio were used to tidy and prepare the datasets retrieved from the IMR and the DoF. Maps were produced using QGIS. Packages and script used in the simulation are presented in the Rmarkdown file in appendix 2.

Results

Simulated harbour seal distribution

A total of 18 036 000 (6012x3x1000) harbour seal positions were simulated. Harbour seals were simulated in 361 of the total 414 Season and Statistical Sea Location Combinations (SSSLCs) used in the model. The average abundance of seals in each SSSLCs ranged from 0.001 to 763.19, see figure 4. The Statistical Sea Locations (SSLs) with occurrences of seals can be divided into two main categories: source and sink SSLs. Source-SSLs have their maximum abundance of seals during summer when short-range dispersal distances were used. The abundance of seals in source-SSL may then decline as the dispersal distances increased from short to intermediate dispersal distances. Source-SSLs have their smallest abundance of seals during large dispersal distances in winter. Sink-SSLs function opposite to source SSLs and have their abundances of seals increased as dispersal distances increase. A total of seven SSLs had their minimum or maximum abundances of harbour seals when the intermediate seasonal distances were used. See estimated minimum, maximum, and average seasonal abundances in all SSLs in figure I.2 in appendix 1. With short summer

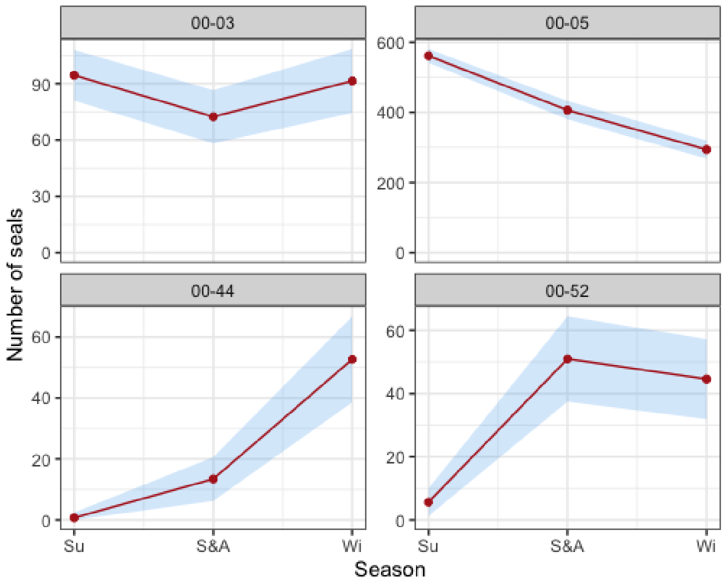


Figure 3. Overview of how harbour seal abundances develop as dispersal distances is increased. The title of the plots describes which SSL that are presented. Along the y-axis, the number of simulated harbour seals. Along the x-axis, the seasonal distances Su (summer), S&A (spring and autumn), and Wi (winter). Top-right and bottom-left represent source and sink -SSLs, respectively. Top-left and bottom-right show examples when highest or lowest abundances are obtained with intermediate dispersal distance. The graphs decrease as emigration from the cell exceeds immigration, and vice versa. Similar plots with all SSLs are presented in figure I.2, in appendix 2.

dispersal distances, harbour seal distribution and abundance were concentrated in the SSL that the colonies were counted in or in adjacent SSLs. With the intermediate (spring and autumn) and large (winter) dispersal distances, harbour seals were dispersed over a larger area. The larger area of dispersal resulted in fewer individuals from a given colony representing the colonies SSL of origin.

The relative density estimates of harbour seal, used to represent the seasonal proportion of harbour seals in a given SSL (derived from equation 2.2), can be inspected in figure 5. The relative probabilities of seals occupying a SSL are highest during summer in SSLs with registered colonies. SSLs with registered colonies of seals have their relative probabilities decreased with the increase of dispersal distances, and spread the relative probabilities of seals occupying a SSL to adjacent SSLs. The relative probabilities used to represent spring and autumn are equal since they use the same seasonal distance to simulate their seasonal dispersal. They were, however, used individually to weight the relative probabilities over four seasons when the relative interaction risks were calculated.

Fishing trips and effort

An annual average of 59 568 (SD: 6557) fishing trips were used to represent fishing effort. Seasonality in fishing effort was explained by the annual average registered trips within a season, with 16321 (SD: 2704), 26944 (SD: 2841), 5527 (SD: 1253), and 10777 (SD: 1761) trips in winter, spring, summer, and autumn, respectively, see figure 4. Spring is when the majority of fishing trips occurs along the Norwegian coast, and represent 45% of the annual average fishing trips registered between 2006-2018. Combined, winter and spring represent 73% of the fishing effort defined with risk of entanglement for harbour seals. Fishing effort was high along the entire coastline during spring. Almost every SSL had their highest number of registered fishing trips occurring during spring. However, some SSLs located north of Lofoten peak during winter. Summer was the season with the lowest abundance of fishing trips, with a high share of SSLs north of 65°N having under 100 trips. The highest proportion of fishing effort during autumn occurred in central and northern Norway. The relative probabilities of fishing trips, used to represent the seasonal proportion of fishing effort in a given SSL (derived from equation 2.3), can be inspected in figure 5.

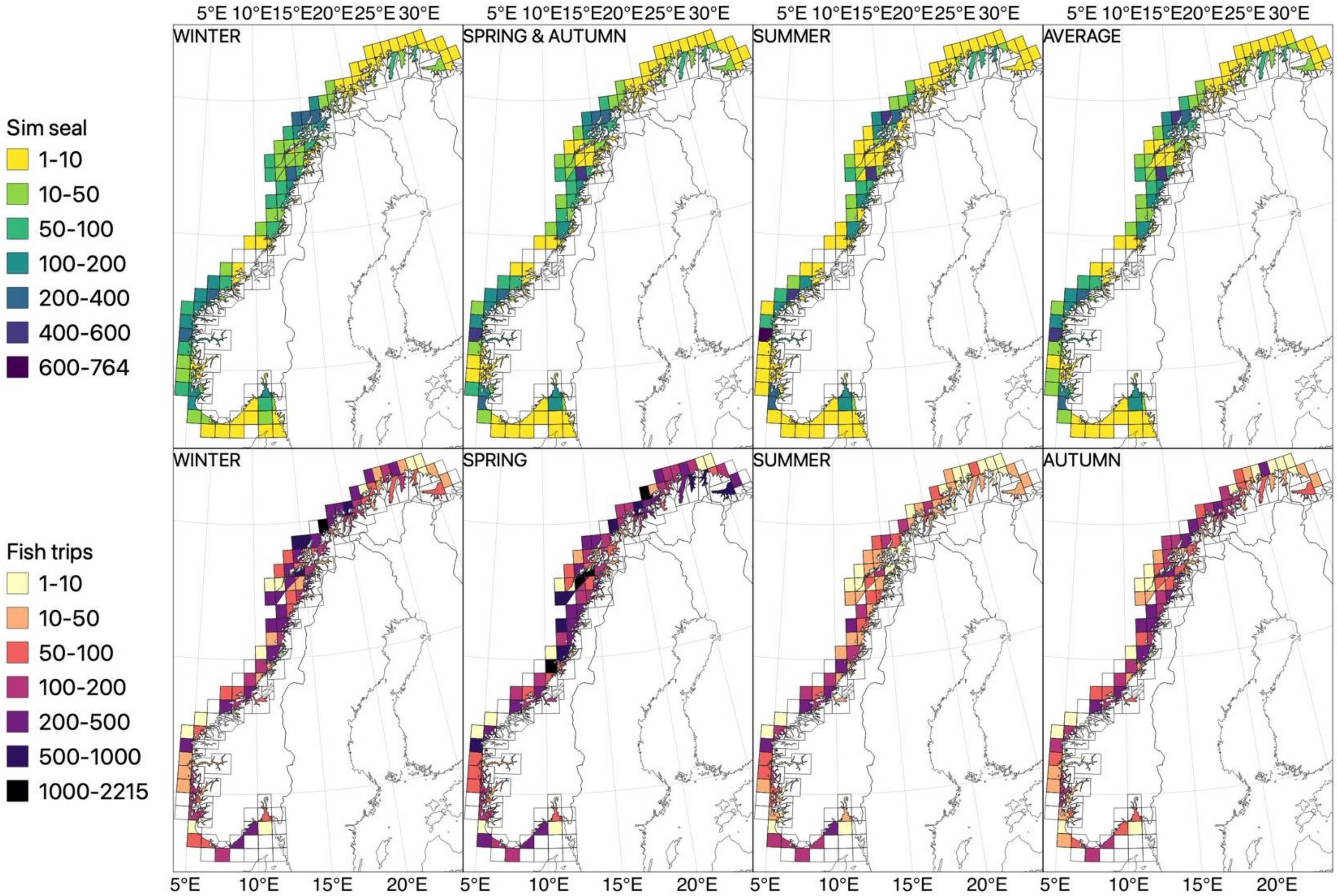


Figure 4. The distribution of simulated harbour seals (above) and fishing trips (below) in the Statistical Sea Locations (SSLs). Both seals and fishing trips were categorized into seven categories, see legends to the respective map to the left. Harbour seals were distributed with seasonal distances defined in table 2, from left winter, spring and autumn and winter distances. The map tagged average, is the average abundance of the three seasonal distances. The distribution of fishing trips (below), shows the average amount of registered fishing trips using bottom-set gillnets, between 2006-2018, using gear categorized with risk of entanglement for harbour seal. White cells are SSLs without simulated seal or registered fishing trips.

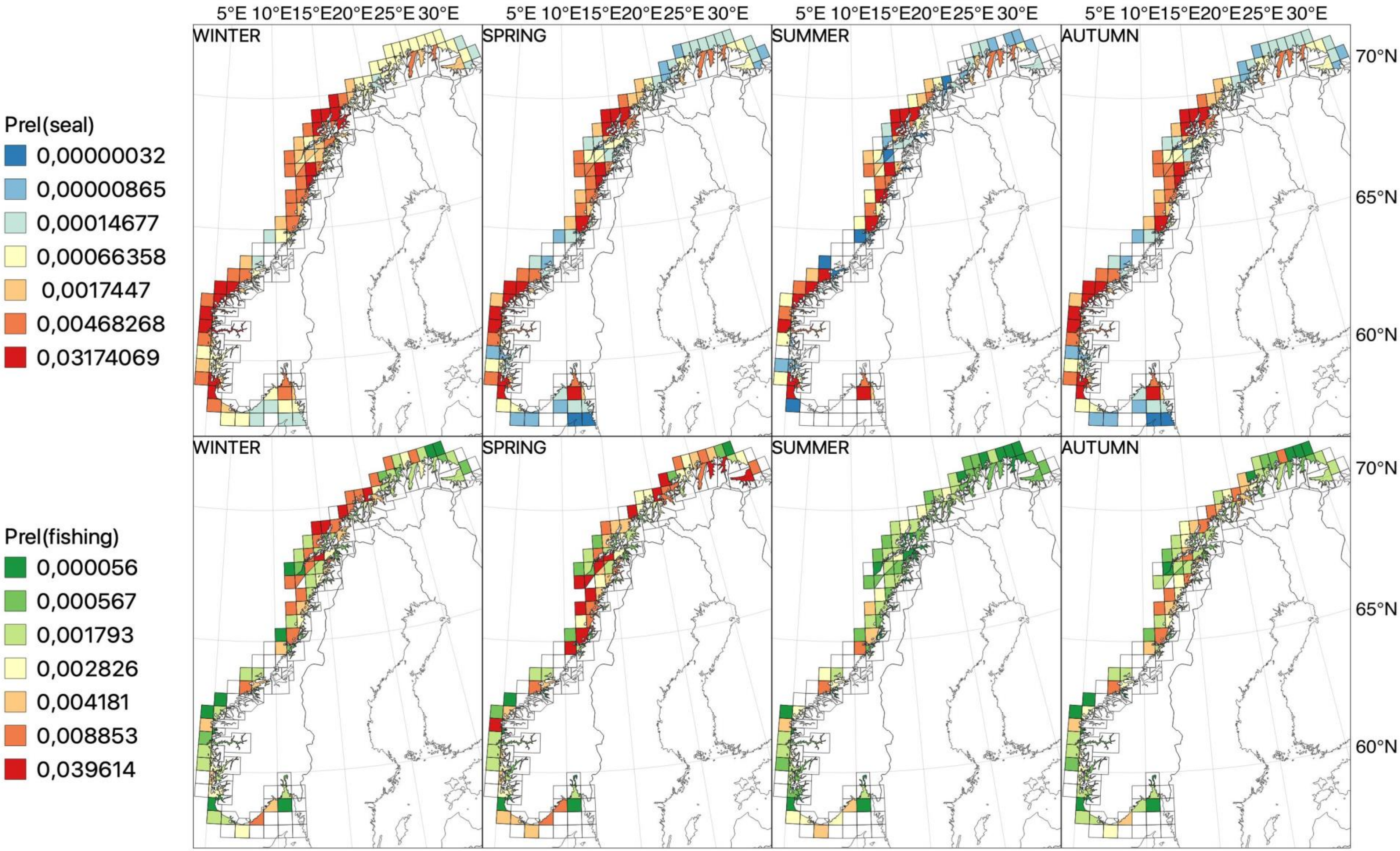


Figure 5. The relative probability of simulated harbour seal (above) and fishing effort retrieved from equation 2.4 and 2.3, respectively. Both maps are categorized into seven categories using an equal count (quantile) to define the categories, and presented by the each season, winter, spring, summer and autumn. All SSLs across the four seasons are equal to one, for both Prel(seal) and Prel (fishing). Prel(seal) use the same values for spring and autumn and are equal to one another.

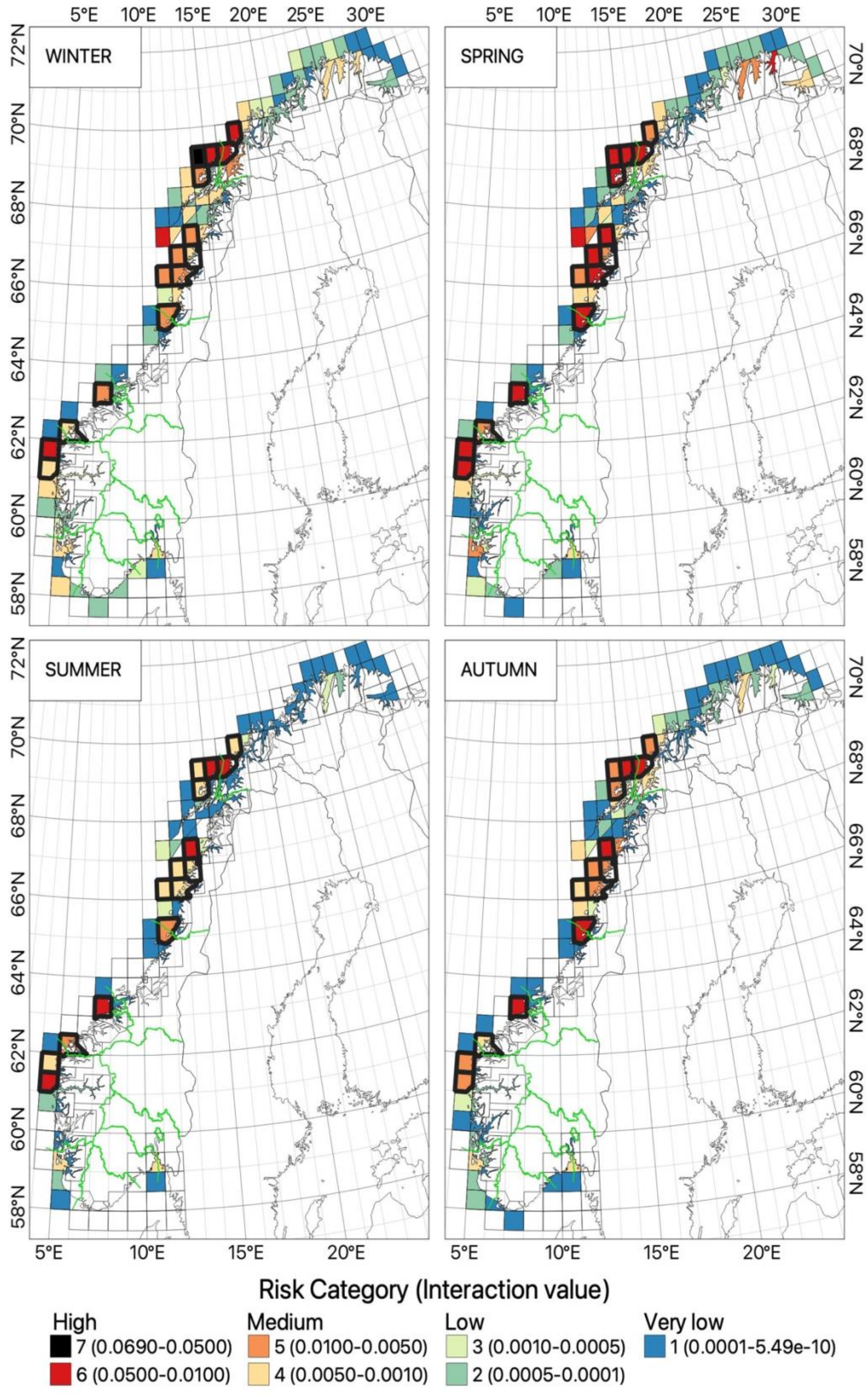
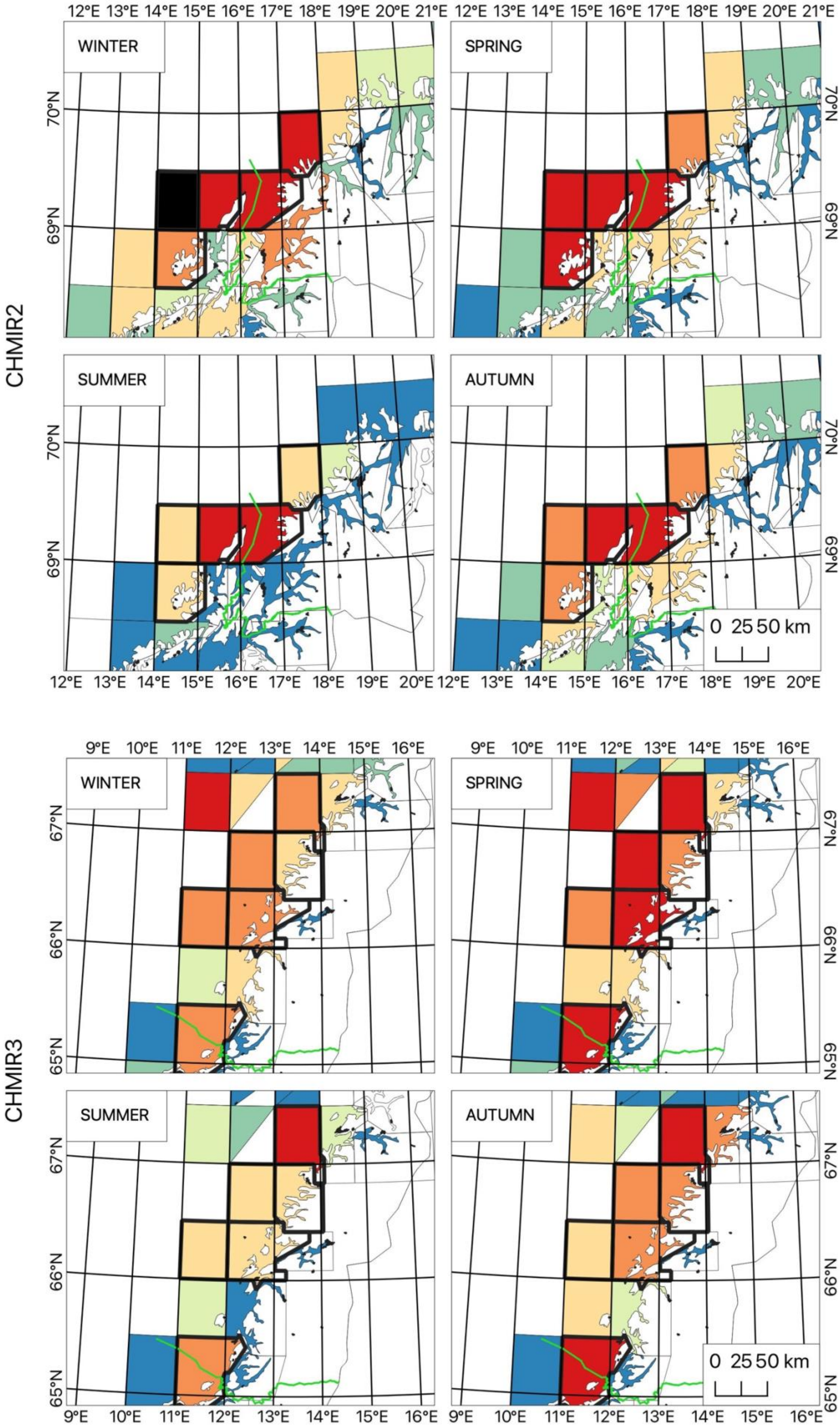


Figure 6. Predicted interaction risk along the Norwegian coast between harbour seals and fisheries using bottom-set gillnets categorized with risk of entanglement. Values are derived from the interaction index, equation 2.5, and represent the relative proportion of bycatch risk for each season and SSL combination, such that all SSLs across the four seasons sum to one. The seven Risk Categories (RCs) represent four main categories defined by a semi-logarithmic scale, blue (very low), light and dark green (low), light and dark orange (medium), and red and black (high). Cells with thick borders are SSLs with consistently high or moderate interaction risk (CHIMR). Green lines represent county borders.


CHMIR2
WINTER
SPRING
SUMMER
AUTUMN
12°E 13°E 14°E 15°E 16°E 17°E 18°E 19°E 20°E 21°E
12°E 13°E 14°E 15°E 16°E 17°E 18°E 19°E 20°E
70°N
69°N
0 25 50 km
CHMIR3
WINTER
SPRING
SUMMER
AUTUMN
9°E 10°E 11°E 12°E 13°E 14°E 15°E 16°E
67°N
66°N
65°N
0 25 50 km

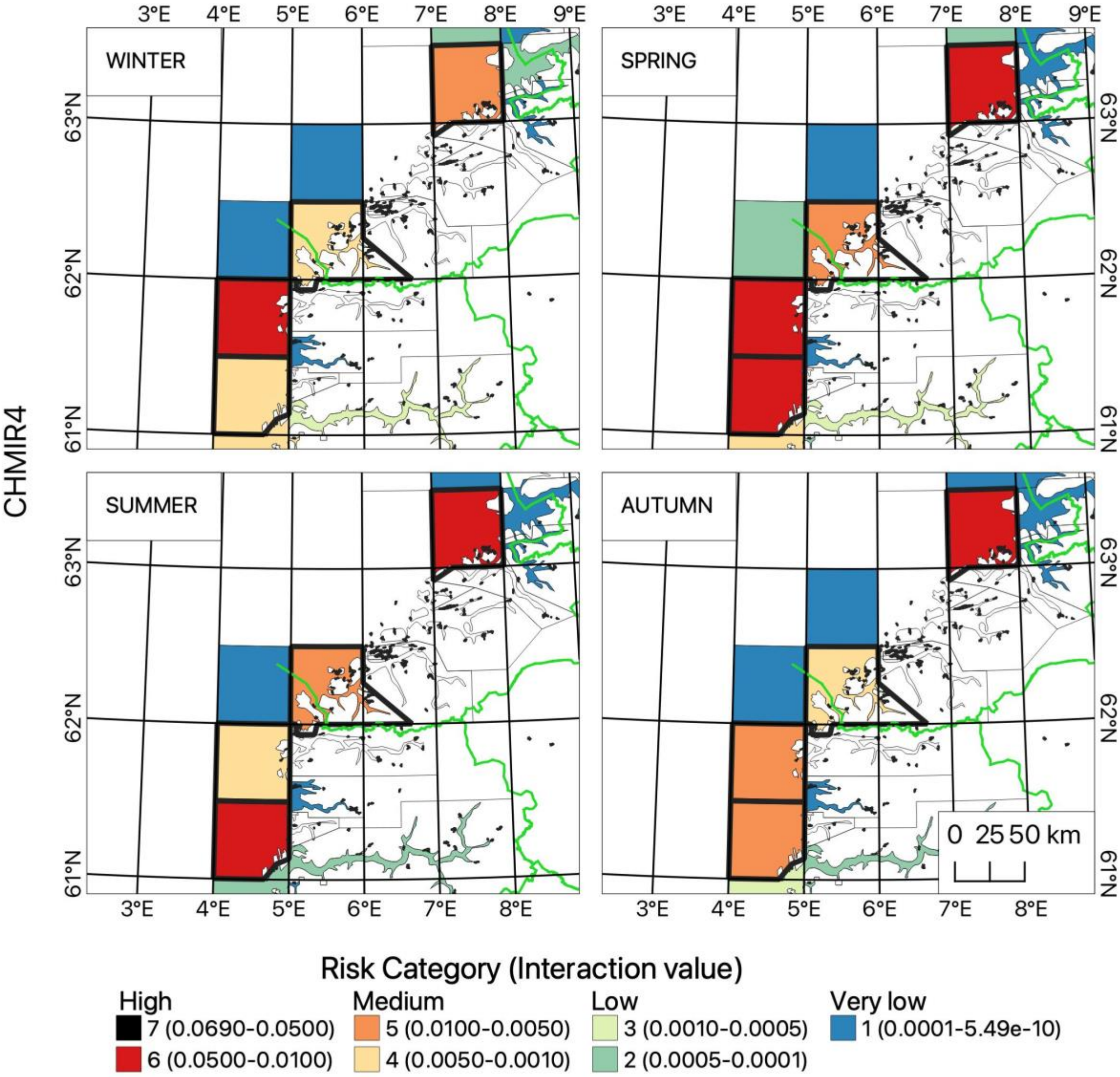


Figure 7. Overview of the CHMIR-areas. From top to bottom, CHMIR2, CHMIR3, and CHMIR4. The green line represents the county boarders. Black markers represent towns with a minimum population of 200 and maximum 50m between houses. The seven Risk Categories (RCs) represent four main categories defined by a semi-logarithmic scale, blue (very low), light and dark green (low), light and dark orange (medium), and red and black (high). Cells with thick borders are SSLs with consistently high or moderate interaction risk (CHIMR). CHMIR2 covers coastal areas in north-Nordland and south Troms og Finnmark county. CHMIR3 covers coastal areas in central Nordland and south Trøndelag county. CHMIR4 cover coastal areas in north Vestland and Møre og Romsdal county.

Harbour seal and fishery interaction

A total of 29, 84, 105, 169 SSSLCs were defined with high, medium, low, and very low bycatch risk, respectively. All interaction values used to describe seasonal and temporal variation between harbour seals and bottom-set gillnet fisheries are presented in figure I.3.

SSSLCs predicted with high interaction risk can be inspected in table 4. Seasonality in interaction risk was predicted with interaction values in winter, spring, summer, and autumn at 0.3139, 0.3532, 0.1248, 0.2081 of the total interaction risk, respectively.

Three areas were predicted to have Consistently High or Moderate Interaction Risk (CHMIR). These areas were defined as CHMIR2, CHMIR3, and CHMIR4, which corresponds to the areas with constant high risk for the aggregation of colonies AC2, AC3, and AC4, respectively. SSLs with thick borders in figure 6 represent the SSLs defined as CHMIR. From north to south, CHMIR2 includes a cluster of five SSLs (05-30, 05-23, 05-24, 05-25, and 05-20). All SSLs in CHMIR2 are located between 68.5-70°N, with Senja (southwest in Troms and Finnmark county) in the north and Vesterålen (north in Nordland county) in the south. CHMIR2 explains 36.9% of the predicted interaction risk over all seasons. CHMIR3 includes a cluster of five SSLs (00-05, 06-31, 06-32, 06-27, 06-33) between 66-67.5°N, in central Nordland county. CHIMR3 also includes one SSL (06-18) 0.5° south of the cluster, on the border between Nordland and Trøndelag county. CHMIR3 explains 21.2% of the total predicted interaction risk over all seasons. CHMIR4 includes a cluster of three SSLs (28-03, 28-04, 07-33) between 61-62.5°N, located in the northern range of Vestland county and the southern range of Møre og Romsdal county. CHIMR4 also includes one SSL (07-07) 0.5° north of the cluster, in the northern range of Møre og Romsdal county. CHMIR4 explains 18.6% of the total predicted interaction risk over all seasons.

CHIMR-areas are generally predicted with the highest interaction risk during spring and winter when fishing effort is relatively high along the entire coast, see figure 3. Two SSLs in CHMIR2, 05-24 and 05-25 (between 15-17°E and 69-69.5°N), were the only SSLs predicted with high risk (interaction value > 0.01) in all seasons. At the same latitude in spring, SSL 05-23 was predicted to be the seasonal SSL combination (SSSLC) with the overall highest interaction value of ~ 0.069.

In the two smaller aggregations of colonies in southern Norway, AC5 and AC6, moderate interaction risk was predicted consistently in one SSL adjacent to each AC. Both SSLs of concern are located between 59-59.5°N. One SSL (08-16) is located between 5-6°E, north in Rogaland county. The other SSL (09-20) lies between 10-11°E, on the border between the counties Viken and Vestfold og Telemark. For the northernmost aggregation of colonies, AC1, high and moderate risk was predicted to occur in four SSLs during spring, with low-moderate bycatch risk in three of them during winter. The four SSLs (03-24, 03-25, 03-05, and 03-02) are located between 70-71°N and 25- 31°E, in Troms og Finnmark county.

The CHMIR-areas include the majority of SSSLCs defined with high risk. Combined they explain 76.6% of the total predicted interaction risk. Outside the CHIMR-areas there are two SSLs predicted to have high interaction risk. SSL 00-03 (between 11-12°E and 68-68.5°N) west of CHIMR3, including the island Røst south of Lofoten in Nordland county, is estimated to have a high interaction value during winter and spring. SSL 03-05 (located between 28-29°E and 70.5-71°N), including Tanafjorden in Troms og Finnmark county, is predicted to have high interaction risk during spring. Both SSLs show strong seasonality.

Table 4. An overview of Statistical Sea Locations (SSLs) predicted with high interaction risk (RC6 and RC7). A total of 14 SSLs were predicted with high interaction risk in a minimum of one season. A total of 29 season and SSL combinations (SSSLCs) were predicted with high interaction risk. Each SSL is divided in the season predicted with high bycatch risk, where W=winter, Sp=spring, Su=summer, and A=autumn. Harbour seals represent the simulated abundance of harbour seal in a given SSSLC. Trips are the average abundance of trips in a given SSSLC. The interaction values are derived from equation 2.4. The ten highest interaction values are underlined.

SSL	season	Harbour seal	Trips	HS/Trips	Interaction value
00-03	W	91	331	0.28	0.0103
	Sp	72	714	0.10	0.0175
00-05	Sp	406	108	3.77	0.0149
	Su	560	57	9.77	0.0109
	A	406	142	2.87	0.0196
03-05	Sp	85	554	0.15	0.0161
05-20	Sp	157	199	0.79	0.0106
05-23	W	248	818	0.30	0.0688
	Sp	200	261	0.77	0.0177
05-24	W	240	523	0.46	0.0425
	Sp	398	222	1.79	0.0300
	Su	586	102	5.74	0.0203
	A	398	184	2.15	0.0249
05-25	W	248	298	0.83	0.0251
	Sp	320	170	1.89	0.0185
	Su	375	88	4.27	0.0112
	A	320	327	0.98	0.0355
05-30	W	44	1287	0.03	0.0194
06-18	Sp	113	580	0.19	0.0222
	A	113	380	0.29	0.0145
06-31	Sp	84	497	0.17	0.0142
06-33	Sp	96	495	0.19	0.0161
07-07	Sp	87	478	0.18	0.0141
	Su	115	394	0.29	0.0154
	A	87	400	0.21	0.0118
28-03	Sp	547	95	5.77	0.0176
	Su	763	87	8.76	0.0226
28-04	W	172	215	0.80	0.0125
	Sp	150	594	0.25	0.0302

Discussion

Interaction risk

The present thesis presents a broad-scale perspective on the overall spatial and temporal interaction risk between Norwegian harbour seals and coastal fisheries using bottom-set gillnets categorized with risk of entanglement. All Statistical Sea Locations (SSLs) predicted with high interaction risk are shown in table 4 and include 14 SSLs with a total of 29 season and SSL combinations (SSSLCs). SSLs categorized with high interaction risk contribute to over 60% of the predicted interaction risk between harbour seals and coastal gillnet fisheries, see table 3. The majority of the interaction was predicted to occur in winter and spring, where both seasons combined account for 66.7% of the predicted interaction risk. Both seasons explain 73% (winter: 31.4%, spring: 35.3%) of the average annual fishing effort. All SSLs predicted with high interaction risk, except for SSL 00-03, had spring as one of the seasons with high risk.

Regionally, harbour seals are predicted to have high interaction risk with the coastal gill net fishery near the Aggregation of Colonies (ACs) AC2 and AC3 in north Norway, and AC4 in west Norway. The Statistical Sea Areas (SSAs) in which the three ACs occur include over 80% of the harbour seals used in this thesis. Some SSLs in proximity to AC2, AC3, and AC4, are also defined as Consistently High or Medium Interaction Risk (CHMIR). The CHMIR-areas have the largest abundances of harbour seals and fishing effort. CHMIR-areas are expected to include a large proportion of the annual bycatch events occurring along the Norwegian coast. The two SSLs 05-24 and 05-25, covering the coastal areas near Vesterålen and Senja, are both predicted to have high interaction risks in all seasons, and combined they account for 20.8% of the total predicted interaction risk. Combined with SSL 05-23, which has the SSSLC with the overall highest predicted risk, these three SSLs account for 30.5% of the interaction risk when all seasons are included. These three cells are the central SSLs in CHMIR2.

The relative interaction risk in the high-risk category varied between 0.0103 to 0.0688. Within the high-risk category, the highest SSSLC has about six times higher probability of interaction between harbour seals and fisheries than the lowest one. While the method used does not describe the bycatch rate within the cells, it is assumed that bycatch rates will be higher in cells with higher interaction values. The ratio between harbour seal abundance and fishing effort seen in table 4 varied from 0.03 to 9.77. This ratio portrays different scenarios within the SSLs predicted to have high interaction risk. Different mitigation efforts may be more effective in cells with a high ratio compared to low, and vice versa.

The large size of the SSL makes the predicted interaction risk uncertain in terms of where in the cell interaction may occur. The fishing effort may be aggregated in one part of a SSL, while harbour seals may forage in the other, and in such a case, the interaction risk would be 0 if the model used smaller cells. The predicted interaction risk assumes that forage and fishing effort overlap within SSLs. In a study in Sandøy and adjacent waters in north Norway, harbour seals and fisheries were observed to exploit the same habitats, especially deep-water basins and plains between 100-200m of depth (Bjørge et al. 2002a). The overlapping areas exploited by seals and fisheries were just outside the archipelago and adjacent shelf water. Another small-scale study in Norway observed that harbour seal pups were more likely to exploit deep-water basins under 100m depth within the archipelago (Bjørge et al. 2002b). A study in Ireland found that distance from haul-out sites significantly affects harbor seal bycatch rates, with bycatch events expected to be more common in close vicinity to harbor seals' haul-out sites., and bycatch events are expected to be more common in close vicinity to harbour seals haul-out sites (Luck et al. 2020). These studies suggest that within SSSLC predicted with interaction risk, bycatch events will occur near haul-out sites proximate to the archipelago, in deep-water basins. However, the Norwegian coastal waters are complex with variable depths and a range of habitats within short distances (Bjørge et al. 2002a), and regional differences in forage localities can be expected.

The predicted interaction risk increases as the abundance of harbour seal or fishing effort, or both, increases, and it is assumed that this relationship is equal across seasons and areas. However, harbour seals are more likely to get incidentally entangled during their first months after birth, and pups (0-1y) represent the largest proportion of bycatch of any age stage (Bjørge et al. 2002c). This suggests that if harbour seal abundance and fishing effort were equal across all seasons, a larger proportion of the interaction risk should be calculated in the months after pupping. Reducing bycatch events during summer and autumn could considerably increase pup survival and reduce bycatch along the Norwegian coast. By examining table 4, seven SSLs are predicted with high interaction risk during summer or autumn, or both. These seven SSLs are 00-03, 00-05, 05-24, 05-25, 06-18, 07-07, and 28-03. Summer and autumn are also the two seasons with the lowest fishing effort. SSLs with small breeding populations may also benefit from mitigation efforts in summer and autumn, to enhance pup survival and population growth. SSL 06-18 and 07-07 are both predicted with high interaction risk during summer and/or autumn and have an abundance of harbour seals below 150 in those seasons. These populations might be more vulnerable to bycatch due to their low abundance, and the predicted time and area of high interaction might be of interest in management of population health. Mitigation efforts like time and area restriction can be expected to impact the economic aspects of fisheries less in these seasons due to the relative low fishing effort, while pup survival can be expected to increase considerably.

Harbour seals haul out more frequently during summer and early autumn when they breed and moult. Time used to haul-out decreases towards winter, where it reaches a minimum, and increases again towards summer (Hamilton et al. 2014). However, pups are born with adult fur (Riedman 1990) and do not moult after parturition. Subadults do not breed. Both of these subadult life-stages do not haul out as extensively as adults during summer and autumn. In Greenland, seals were observed hauling out between 7-9 hours a day in moult season, which gradually shifted towards 4 hours of hauling out every second day (Rosing-Asvid et al. 2020). This behaviour may increase harbour seals' exposure to entanglement in months and seasons with short haul-out length. However, lengthy periods in water were often close to haul-out sites in the Netherlands (Sharples et al. 2012), and may limit seals' exposure to entanglement. Winter and spring are the two seasons with the shortest observed haul-out lengths (Sharples et al. 2012, Hamilton et al. 2014, Rosing-Asvid et al. 2020). Even though the haul-out length was not accounted for in the model, these seasons were predicted to have the highest interaction risk.

Interaction risk probabilities were assessed based on overlap in the spatial and temporal distribution of fishing effort and harbour seal and changed in response to the spatial and temporal variability in fishing effort and harbour seal dispersal and abundance.

Study design

Fishing effort

The average number of trips within a combination of season and SSL was used as a measure for fishing effort, and all trips were assumed to have an equal risk of entanglement for harbour seals in the calculation of the interaction risk. However, trips, and especially trips from different fisheries can be expected to differ depending on gear size, length, soak time, and depth of placement. These are all factors that are expected to impact bycatch (Cosgrove et al. 2016, Tixier et al. 2021). A total of seven fish species were used to define fisheries with risk of entanglement for harbour seals. Cod and monkfish fisheries are the fisheries expected to impose the greatest risk for harbour seals and other marine mammals along the Norwegian coast (Moan 2016, Bjørge et al. 2017). The other species are considered as bycatch in cod and monkfish fisheries, but are also targeted in their respective fisheries. Fishing effort varies seasonally due to fish availability and fishery regulations.

The Northeast Arctic Cod fisheries are the major contributor to interaction risk and seasonality in fishing effort. Fisheries targeting the Northeast Arctic cod are active from January to the end of April, with the highest fishing effort registered in March. The Northeast Arctic Cod is the world's largest cod population. They migrate from the Barents Sea along the Norwegian coast to their respective spawning ground located between Stadt in Vestland county in the west, to Troms og Finnmark county in the north. The main spawning grounds are in Lofoten (SSA 00 and 05) and Vesterålen (SSA 05) in the northern range of Nordland county. Around 40% of the Northeast Arctic cod are caught in Lofoten and Vesterålen. Other known spawning grounds are in central Nordland county (SSA 06), south-east and central Troms of Finnmark county (SSA 05 and 04), and north of Vestlandet county (SSA 28).

Monkfish constitute 2.3% of the total catch of bottom-set gillnet fisheries. Monkfish is protected from fishing activity using nets north of 64°N between 20. December and 20. May, and fishing therefor occurs in summer and autumn. Atlantic halibut, which may be caught as bycatch in monkfish fisheries (and vice versa), are protected between January and late March. Monkfish fisheries use larger mesh size than cod fisheries, and larger mesh size is demonstrated to increase bycatch events (Cosgrove et al. 2016). In recent years have monkfish and Atlantic halibut fisheries increased in frequency north of 62°N, and are expected to increase harbour seal bycatch as well (Bjørge et al. 2017). In the calculation of the interaction risk, the small proportion of monkfish fisheries are treated equally to the more common cod fisheries, but are expected to impose a greater risk of entanglement. Alternatively, monkfish fisheries could have been weighted so that the interaction risk would be greater where and when they occur.

Coastal cod fisheries and fisheries targeting, cusk, common ling, and pollock impose a near-constant threat of entanglement in all seasons. Except for cod, the other species named are also often taken as bycatch in cod fisheries. In southeast Norway, coastal cod populations have been protected since 15 June 2019. The protection includes a total ban on all cod fishing activity, and a ban on the use of bottom set gillnet from Telemark in southeast Norway and eastwards to the border of Sweden, and out to 1 nautical mile from the coast. The results of the thesis do not consider the ban, as data on fishing effort prior to the ban is used. The already low interaction risk and possible bycatch events in southeast Norway may be expected to be even lower today, as restrictive measures have been put in place. However, the protection of the southeast cod population has resulted in an increased hunting quota on harbour seal in the area.

Simulation of harbour seal dispersal

The simulations distributed harbour seals over an area expected to lie within a given colony's fundamental niche and used seasonal dispersal distances from their primary moulting site and colony abundances to do so. The simulation design accounted for the uncertainty of harbour seal dispersal directions by evenly distributing harbour seals in all directions from their primary haul-out site to an at-sea location. The model assumes that all SSLs are equally productive and accessible for all harbour seals, which, in reality, may not be the case.

Norway is one of the largest exporters of fish in the world, and the opportunistic harbour seal is assumed to find suitable foraging grounds in all coastal SSLs. However, SSLs can be expected to differ in their productivity and abundance of prey. Simplified, fishing effort in a given SSL can be interpreted to reflect productivity in the cell. Figure 3 shows the heterogeneity of fishing effort and may also reflect the heterogeneity in the abundance of harbour seal's prey. Harbour seals in any given colony are observed to spread from their moult site in all directions along the coast (Dietz et al. 2013). Their opportunistic foraging behaviour probably makes harbour seals less picky when searching for the forage sites with the highest abundance of prey. Studies have documented that individual seals repeatedly visit the same foraging sites (Tollit et al. 1998), and the relative abundance of prey have shown a low correlation to their contribution to diets (Hall et al. 1998, Lesage and Kovacs 2011). This suggests that individual harbour seals may have a few preferred species, and specialise to forage on them specifically. Other studies have documented that harbour seal may switch prey when the abundance is high (Olsen and Bjørge 1995). If seals were to disperse to a highly productive SSL with an abundance of preferred prey throughout the year, seals in such cells can be expected to limit their range to stay within this highly productive SSL. In Vesterålen, harbour seals were observed to prey mainly on saithe over a year (Berg et al. 2002), which this may represent an area where harbour seals don't necessarily need to migrate between seasons. Seals that encounter areas that may be depleted of preferred prey or are dependent on seasonal abundance of prey, can be expected to travel further and have a larger home range. Since the model does not consider heterogeneity in prey abundance, harbour seal abundance may be underestimated in highly productive cells and overestimated in less productive cells.

The simulation of harbour seals dispersal assumed that suitable haul-out sites were present within the retained SSLs. While the large area covered by each SSLs increases the likelihood that seals would encounter suitable haul-out sites, anthropogenic disturbances and settlements, and general lack of suitable haul-out sites, may affect dispersal to certain SSLs. Harbour seals are highly mobile and expected to avoid areas heavily influenced by anthropogenic activity (Andersen et al. 2012). Figure 7 shows the distribution of towns and cities within or near the CHMIR-areas, haul-out sites are not expected to be in close proximity to these locations and should be considered when interpreting the results. For example, SSL 07-07 (between 7-8°E and 63-63.5°N) in Møre og Romsdal, have most of its coastal areas covered with human settlements (Kristiansund). This would force the seals simulated to forage and haul out in this cell to do so in the Northeast or southwest, where towns and expected anthropogenic disturbance is limited or absent. Similarly, offshore and offshore-coastal SSLs may lack suitable haul-out sites, and seals simulated to forage in such cells may use haul-out sites in adjacent cells. The calculation of the interaction values assumes that harbour seals only occupy the SSL with a registered abundance of seals, whereas in reality, harbour seals may forage in offshore and offshore-coastal SSLs and haul out in another coastal SSL. Such cases would expose harbour seals to interaction with fisheries in multiple SSLs, which is not accounted for.

Harbour seal colonies located on the northeast side of Lofoten had their sampling space include areas southeast on the other side of Lofoten in the south. In figure I.1, colony 4 first replicate is shown and two of the 15 seals in that replicate are simulated on the southeast coast of Lofoten. In reality, seals would swim about 400km around Lofoten to get to the site of the simulation. While such extensive dispersals are observed (Bjørge et al. 2002b), they are not common and were not aimed for in the simulation. Such errors in the dispersal of harbour seals in the simulation are minimal but present. SSL 00-44 in the inner part of the Lofoten and mainland Norway, is the most obvious example when it comes to such dispersal errors. Dispersal errors would reduce the interaction risk in the cells seals should be simulated within, and increase it in SSLs they were wrongly simulated to.

Not all known colonies were accounted for in the model, and some of the colonies used included outdated harbour seal count surveys. By including the colonies that were left behind, the relative interaction risk should increase near the colonies in the counties Vestfold og Telemark, Agder, and south of Trøndelag (Sør-Trøndelag county prior the merger in 2020) and decrease elsewhere. However, SSLs in south Trøndelag have no registered fishing effort, and no interaction risk would be calculated there. Nevertheless, the addition of more seals would lower the relative measure for harbour seal abundance in other areas and affect the calculation elsewhere. If this study was to be repeated, it should include all colonies, and the data from previous surveys should be updated to increase the predictability in regard to the current situation.

Setting the parameters for the simulation

Literature on harbour seal dispersal combined with an ecological understanding of the species were used to set the seasonal dispersal distances used in the simulations. There were multiple challenges linked to this procedure. Firstly, the parameters (mean distance and SD) used in the simulation represented all harbour seal colonies along the Norwegian coast. Norwegian harbour seal colonies are expected to differ in their home range due to different habitats, feeding grounds and/or preferred regional prey. Harbour seal inhabiting rocky steep habitats are also expected to have a smaller home range than seals using sandy flat habitats (Sharples et al. 2012). Seasonality in dispersal may also increase from south to north due to more environmental variation which may disperse seals further from their primary haul-out site (Blanchet et al. 2014, Rosing-Asvid et al. 2020). Secondly, the different studies differed in the number of seals, regions, seasons, habitats, age and sex composition of the observed seals. These factors may all affect the observed dispersal and movement of harbour seals (Lowry et al. 2001, Peterson et al. 2012, Sharples et al. 2012). Thirdly, studies used different metrics when describing harbour seal movement. These methodological differences made it difficult to directly compare the studies drawn upon, and to transform values to the parameters (mean distance and SD) used in the simulation. The selected variables represent a vast amount of uncertainty regarding harbour seal dispersal along the Norwegian coast. They are however considered to represent a large amount of variation that is expected to occur within and between colonies.

Statistical Sea Locations

The average size of the SSLs used in this thesis are 1622km^2 (SD:922). The large area covered by each SSL is suitable for the study design due to the uncertainty in the harbour seal dispersal range along the Norwegian coast. Harbour seals home range may include several SSLs along the coastline. The length and area of SSLs function as a buffer for uncertainty associated with their dispersal range, however differences in the size and shape of the SSLs have not been accounted for. Large cells have a higher probability to include a larger proportion of fishing effort and abundance of seals than smaller cells, if these measurements were equally dispersed along the coast. The expected correlation between size and fishing effort was tested by using Kendell's rank tau and were found insignificant with a p-value of 0.067 when a threshold of 0.05 was used. The margins to be significant was small, and rescaling of the abundance of fishing effort should be considered if the simulation was to be repeated. Rescaling fishing effort based on the area of a given SSLs cover was done in testing. The scaled vs not-scaled fishing effort rearranged the order of the interaction values within each category, and a few interaction values of SSSLCs moved up or down one risk category. The two methods significantly correlate with Kendall's rank correlation, with a p-value of $2.2*10^{-16}$, and represent each other well.

Bycatch mitigation and future studies

Mitigation efforts to reduce unwanted mortalities may be crucial to have viable populations of marine megafauna near concentration of anthropogenic activity. Identifying times and areas of high encounter risk can also help direct the spatial planning and fishery regulations. Research to modify fishing gear aimed at increasing gear selectivity may contribute to minimizing catch of non-target species. However, gillnets are limited in how they can be adjusted and modified to reduce unwanted catch, unlike fishing gear such as cod-traps and fyke nets where gear modifications are more successful (Königson et al. 2015).

Different mitigation efforts implemented to reduce the risk of bycatch have been studied, with various results. The use of Acoustic Deterrent Devices (ADDs) has had a significantly positive effect on bycatch of cetaceans, which scares the animals away from the nets (Kraus et al. 1997, Palka et al. 2008). Similar devices have been tested for pinnipeds, where sound devices may scare them, but have also attracted seals to the nets (Williams 1999). Luck et al. (2020) found a significant relationship between water turbidity and increased bycatch rate in Ireland, suggesting that increased visibility of gillnets may reduce bycatch in those cases where depredation is not the cause of entanglement. Increased visibility by adding shark shapes or replacing the top portion of a net with a thicker twine has reduced bycatch of turtles and seabirds (Melvin et al. 1999, Wang et al. 2010, Luck et al. 2020). Visual deterrents have not been studied regarding bycatch within Pinnipedia and should be further investigated.

The most effective measure to reduce bycatch of harbour seals and other species may be time and area restrictions. To protect the critically endangered Saimaa ringed seal (*Phoca hispida saimensis*), pup survival is enhanced by a ban on gillnets in the most critical season (spring) when pups are born (Niemi et al. 2012). Ban and time restriction may be the only reasonable mitigation effort to reduce bycatch in gillnet fisheries when needed. Such mitigation efforts may be particularly useful for the management of small breeding populations, which are more vulnerable to mortalities due to their population size alone.

While mitigation efforts in SSLs predicted with high interaction risk are expected to be more beneficial than mitigation effort in cells with low interaction risk, one type of mitigation effort could be more effective in SSSLCs that have a low abundance of fishing effort and high abundance of harbour seals, or vice versa. The harbour seal and fishing effort ratios could help inform management decisions regarding which mitigation efforts that would be the most beneficial given the circumstances. Similarly, seasonal fisheries and constant fisheries could benefit from different mitigation efforts. Scare tactics may be used on seasonal fisheries, as this may reduce habituation of the tactic used. Time and area restriction may be more useful for fisheries that impose a more constant risk over seasons. As mitigation efforts have economic consequences which would affect the livelihood for fisheries and fishers, the presented maps and results can be used as a tool to locate time and areas that would minimize the cost while bycatch is reduced.

Similar predictions of interaction between wildlife and bottom-set gillnets should be considered to increase the knowledge of potential areas with high interaction risk between multiple species and fisheries. Grey seals (*Halichoerus grypus*) and harbour porpoise (*Phocoena phocoena*) are also taken in large-mesh gillnet fisheries (Moan 2016). Identification of areas of high risk of interactions among fisheries and multiple species of megafauna would facilitate decision-making processes and enable policymakers to establish area and time closures for gillnet fisheries. The identification of areas predicted with interaction risk between fisheries and multiple species would have a larger ecologically effect by considering multiple species at once, and would minimize the cost by concentrating mitigation efforts effectively. Vesterålen, the area in this study with the overall highest interaction risk, may be one of these areas with high bycatch rates of marine mammals.

Conclusion

This thesis predicts spatial and temporal trends in interaction risk by exploring the overlap in seasonality and abundances of harbour seal and fishing effort along the Norwegian coast. The interaction risk was predicted to be highest during winter and especially spring due to the seasonality in fishing effort highly influenced by the Northeast Arctic cod fisheries. Three areas were predicted to have Consistently High or Moderate Interaction Risk (CHMIR). These areas were defined as CHMIR2, CHMIR3, and CHMIR4, which corresponds to the areas with constant high risk for the three largest aggregation of colonies AC2, AC3, and AC4, respectively. CHMIR2 is located in Nordland and Troms og Finnmark county, CHMIR3 in Nordland and Trøndelag county, CHMIR4 in Vestland and Møre og Romsdal county. Vesterålen and Senja in CHMIR2 are the regions with the highest predicted interaction risk overall. The CHMIR-areas are expected to constitute the majority of the bycatch events in

Norway, with water near Vesterålen and Senja functioning as the major hotspot for potential fatal interaction. Mitigation efforts require knowledge of where and when the bycatch risk may be greatest in order to be effective, and the results presented here are aimed at increasing our understanding of harbour seal bycatch risk in Norway, and ultimately informing management decision making.

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Appendix I: Additional figures and table

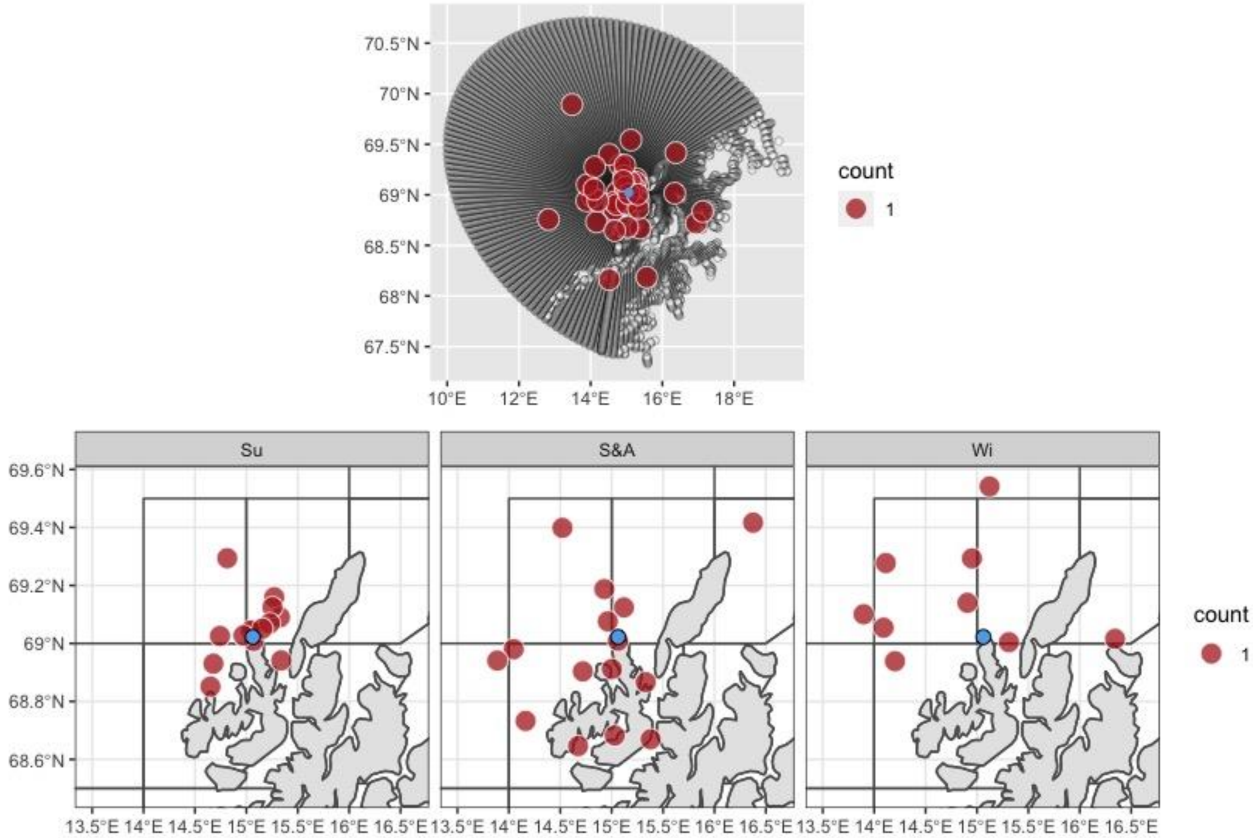
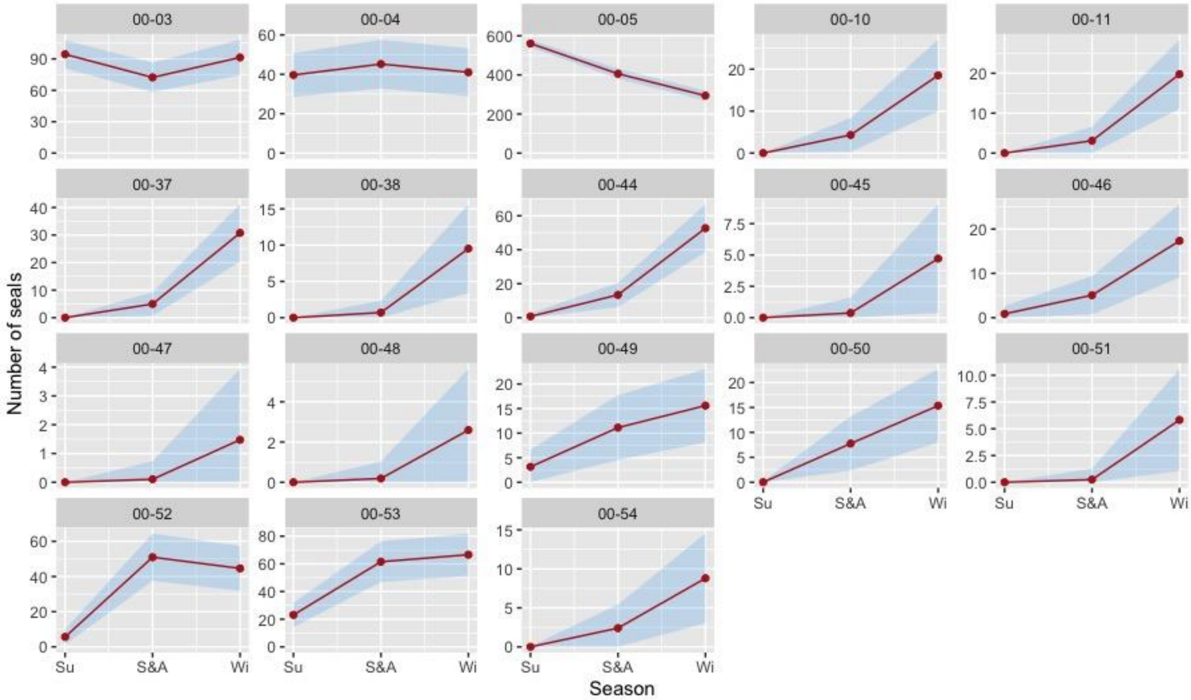


Figure I.1. A representation of how seals and colonies were simulated from their moult site. The figure represents the first replicate (of a thousand) of colony 4, a colony in Vesterålen Lofoten. A total of 15 seal were registered in colony 4. The blue dot is the registered moult site for the colony, and red dots represent simulated seals. The first row (above) shows the sampling space used for colony 4. All three seasonal distances are represented, which are divided in the figures at the second row (below). The second row (below) shows the seasonal distances used, Su (summer), S&A (spring and autumn), and Wi (winter). Not all seals are presented in Wi, since seals were simulated outside the boundaries of the figure.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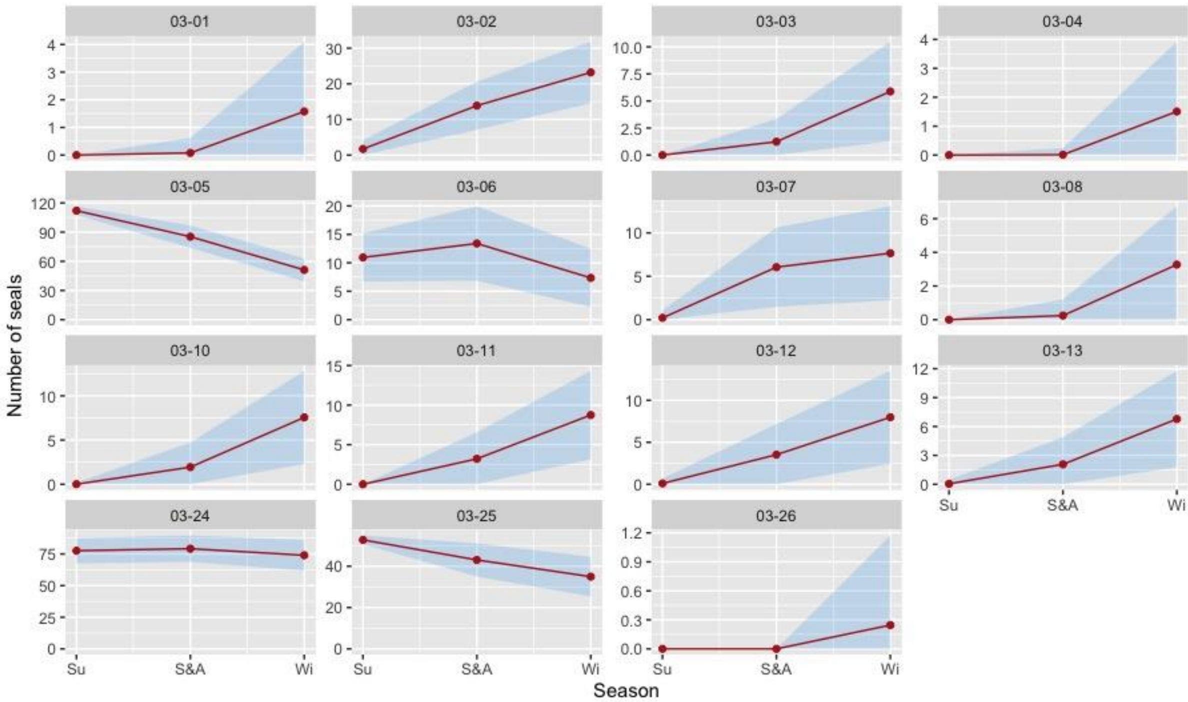
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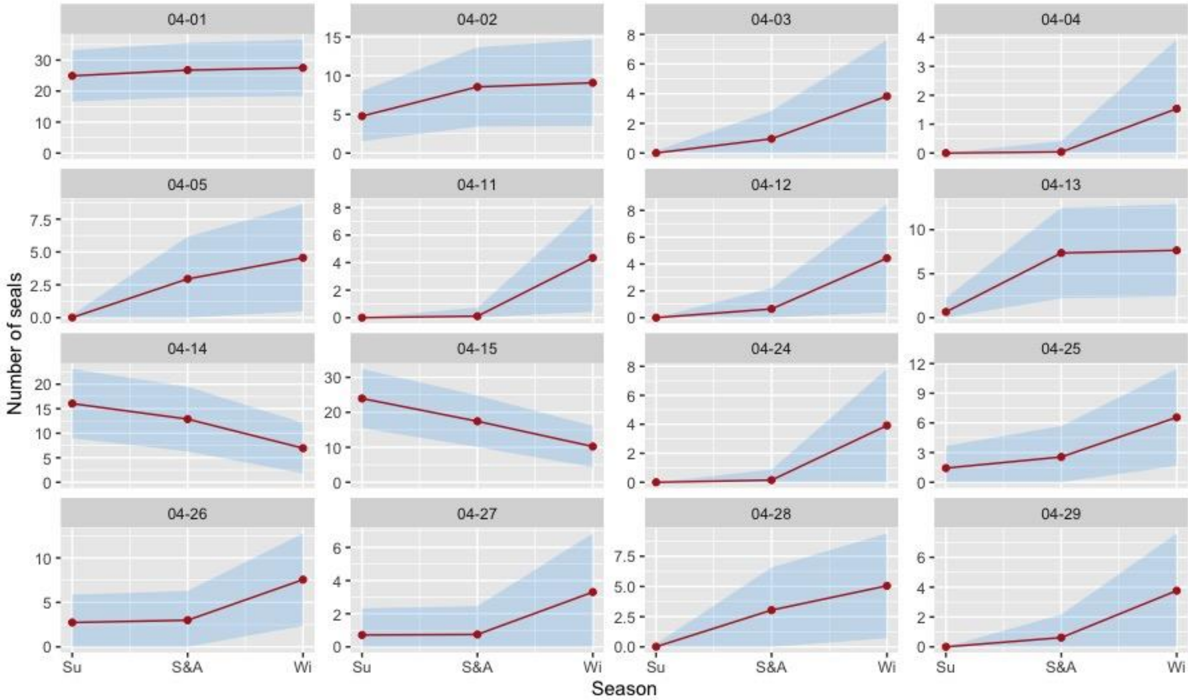
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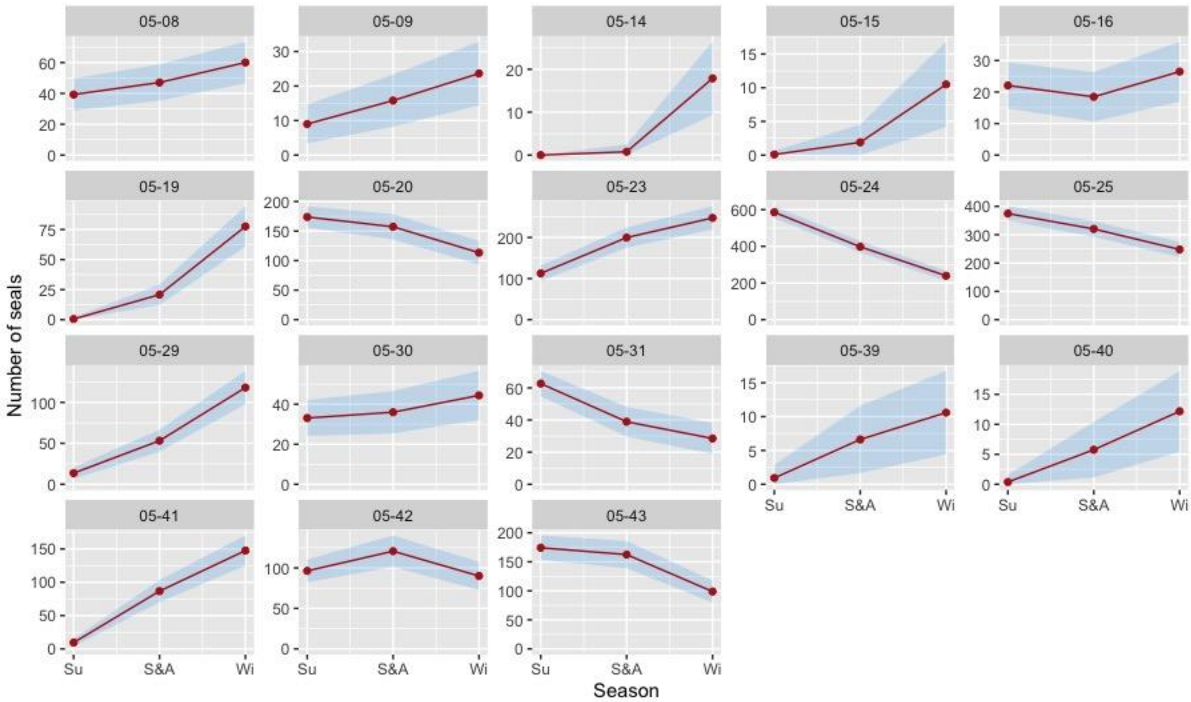
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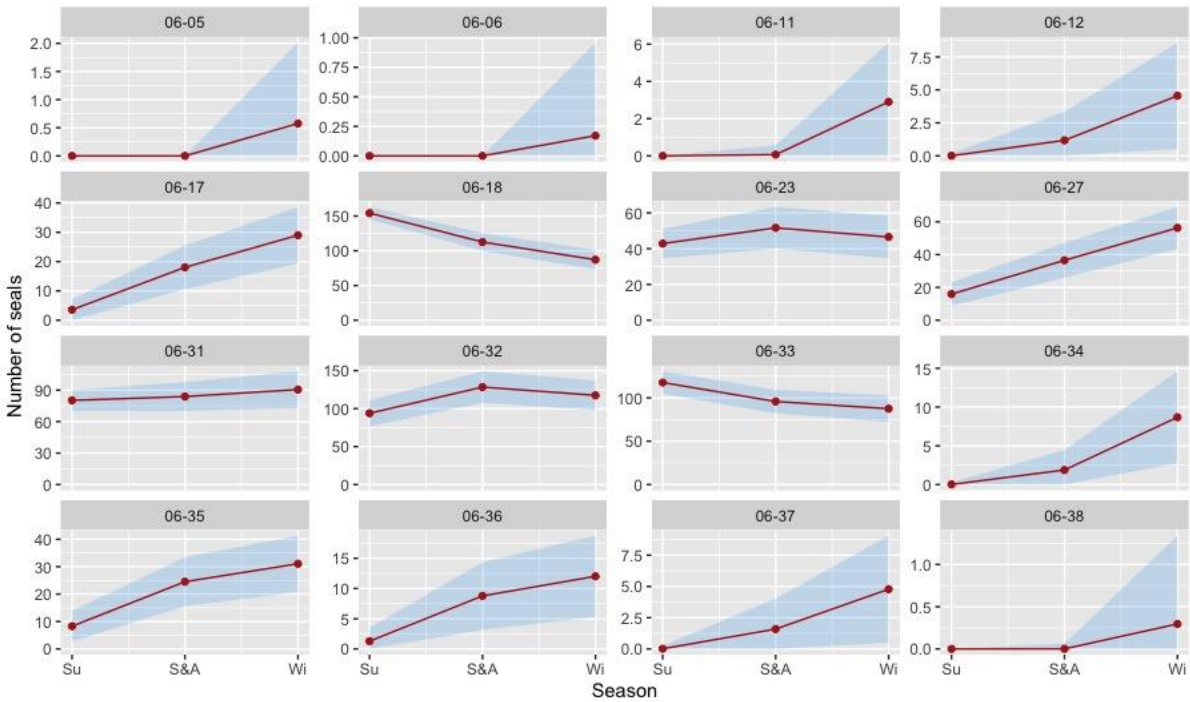
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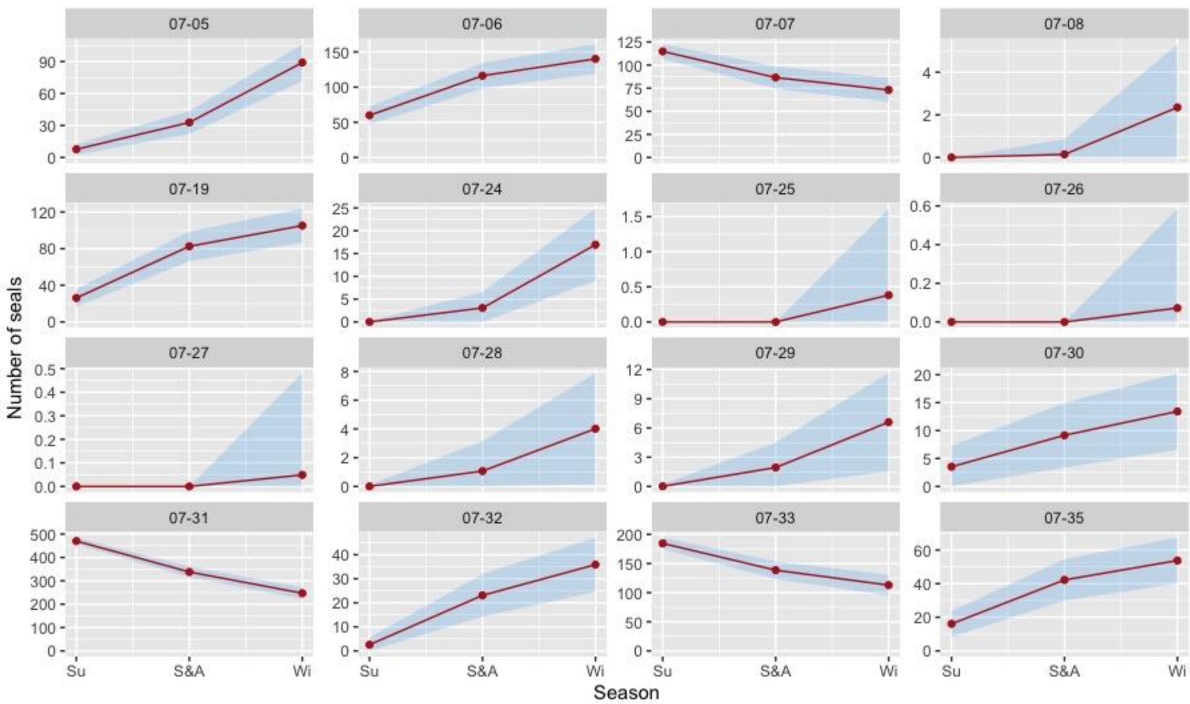
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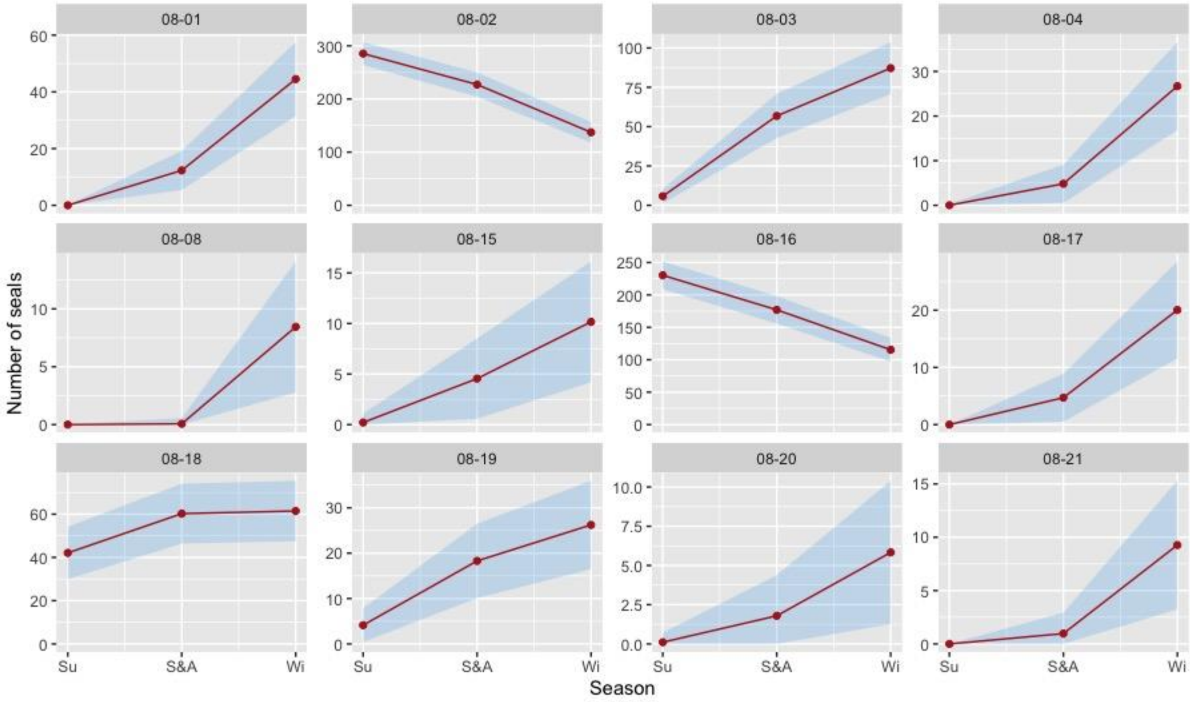
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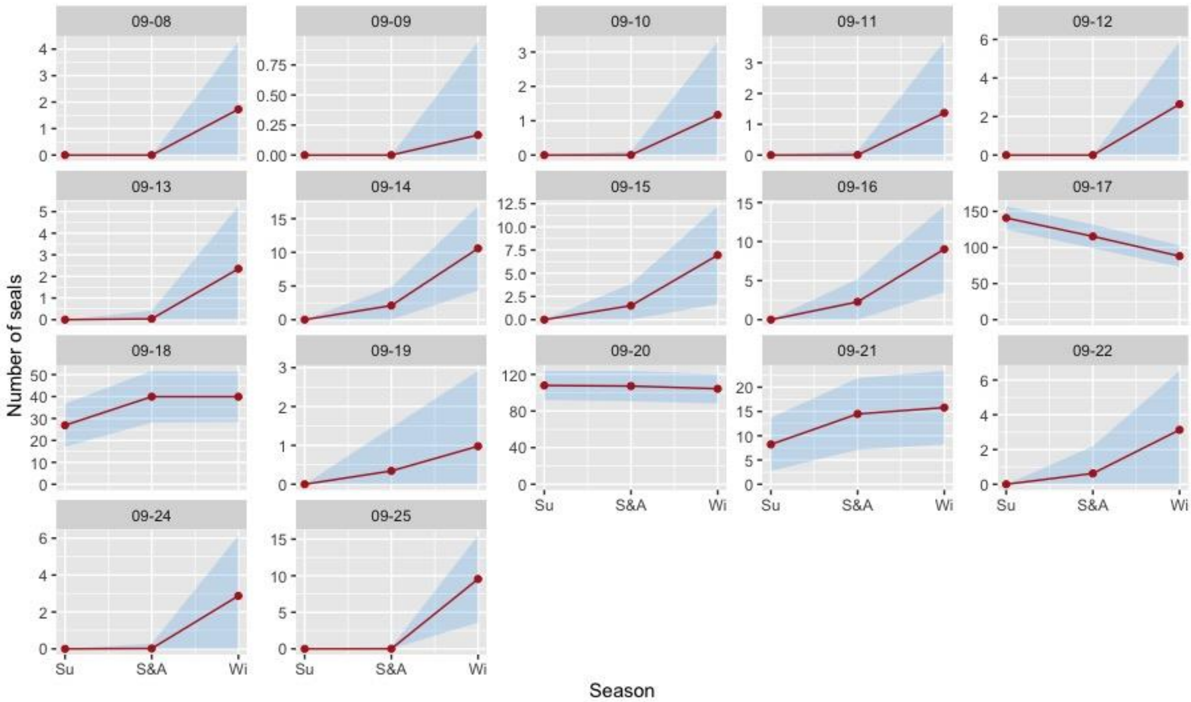
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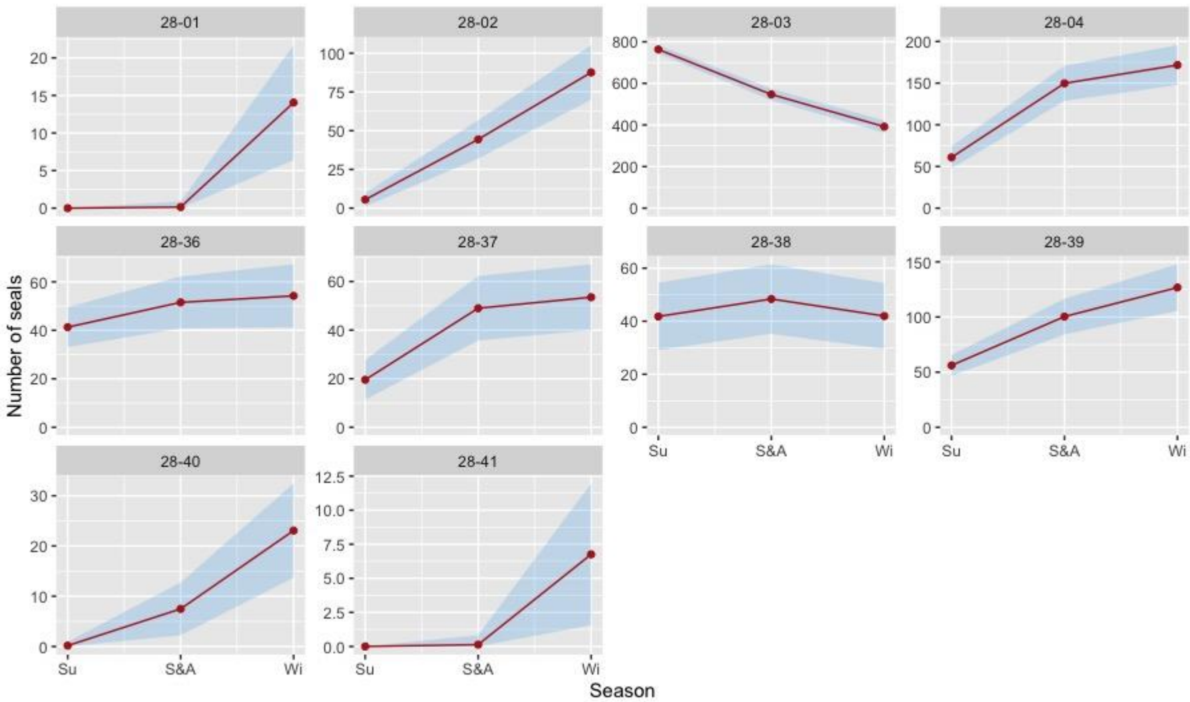

Figure I.2. An overview of simulated abundances of harbour seals in each Statistical Sea Locations (SSLs). A total of 138 SSLs were used in the simulation. The title of the plots describes which SSL that are presented. E.g., SSL 28-41 is location 41 in SSA 28. Along the y-axis, the number of simulated harbour seals. Along the x-axis, the seasonal distances Su (summer), S&A (spring and autumn), and Wi (winter). The values used for each seasonal distances are presented in table 2. Each seasonal distance was used to simulate in total 6012 seals from their primary haul-out site to a SSL, 1000 times. The average abundance of simulated harbour seals in a given SSL are represented by red dots. Shaded blue area represent the variance simulated within a SSL, from minimum to maximum abundance.

Table I.1 Overview of all SSLs predicted with interaction risks in a given season. W=winter, Sp=spring, Su=summer, A=autumn. Risk and RC define the interaction value and Risk Category used to portray the SSSLCs in figure 6.

SSL	W risk	W RC	Sp risk	Sp RC	Su risk	Su RC	A risk	A RC
00-03	1.03e-02	6	1.75e-02	6	7.99e-04	3	1.04e-03	4
00-04	4.15e-03	4	8.96e-03	5	2.00e-04	2	5.15e-04	3
00-05	8.00e-03	5	1.49e-02	6	1.09e-02	6	1.96e-02	6
00-10	1.85e-03	4	1.49e-03	4	1.73e-08	1	1.44e-04	2
00-11	3.05e-04	2	8.57e-05	1	0	0	9.14e-05	1
00-37	1.60e-04	2	3.60e-05	1	5.23e-09	1	2.78e-05	1
00-38	3.11e-05	1	2.73e-06	1	0	0	4.14e-06	1
00-44	2.16e-03	4	4.73e-04	2	3.06e-07	1	3.60e-04	2
00-45	3.89e-04	2	2.05e-05	1	0	0	2.64e-05	1
00-46	3.57e-03	4	3.82e-03	4	3.08e-05	1	5.28e-04	3
00-47	2.77e-05	1	1.55e-05	1	0	0	9.27e-07	1
00-48	2.83e-04	2	9.37e-05	1	0	0	1.44e-05	1
00-49	3.67e-06	1	2.67e-05	1	0	0	1.16e-06	1
00-50	2.51e-04	2	5.18e-04	3	2.44e-08	1	7.63e-05	1
00-51	4.53e-04	2	2.32e-05	1	0	0	1.33e-05	1
00-53	3.41e-03	4	4.05e-03	4	5.22e-04	3	6.59e-03	5
00-54	3.68e-05	1	1.79e-05	1	5.49e-10	1	4.27e-06	1
03-02	4.46e-04	2	3.20e-03	4	1.67e-05	1	4.63e-04	2
03-03	3.93e-05	1	1.28e-04	2	0	0	1.47e-05	1
03-05	1.28e-03	4	1.61e-02	6	7.91e-05	1	6.02e-04	3
03-06	2.44e-05	1	3.51e-04	2	6.58e-06	1	1.51e-05	1
03-07	9.84e-05	1	3.25e-04	2	1.08e-06	1	7.95e-05	1
03-10	7.95e-04	3	1.72e-04	2	1.84e-07	1	1.67e-04	2
03-11	1.09e-04	2	1.77e-04	2	0	0	2.69e-06	1
03-12	2.29e-06	1	5.07e-06	1	5.27e-08	1	1.84e-07	1
03-13	7.08e-07	1	1.41e-06	1	2.46e-09	1	1.08e-07	1
03-24	2.39e-03	4	9.97e-03	5	6.85e-04	3	2.30e-03	4
03-25	1.30e-03	4	8.20e-03	5	1.82e-04	2	3.85e-04	2
04-01	2.71e-03	4	1.17e-03	4	5.08e-05	1	6.90e-04	3
04-02	9.41e-04	3	4.06e-04	2	6.00e-05	1	3.08e-04	2
04-03	7.19e-04	3	2.20e-04	2	2.31e-07	1	1.16e-04	2
04-04	6.90e-05	1	3.40e-06	1	0	0	2.34e-06	1
04-05	1.32e-04	2	2.63e-04	2	8.31e-08	1	1.03e-04	2
04-11	4.11e-04	2	4.59e-05	1	0	0	6.80e-06	1
04-12	7.41e-06	1	3.57e-06	1	0	0	1.70e-07	1
04-13	2.00e-04	2	3.09e-04	2	5.81e-06	1	2.39e-04	2
04-14	5.53e-05	1	5.97e-04	3	1.80e-05	1	1.72e-04	2

04-15	1.15e-04	2	4.79e-04	2	7.26e-05	1	1.65e-04	2
04-24	5.29e-04	3	2.39e-05	1	0	0	4.81e-06	1
04-25	1.06e-04	2	1.06e-04	2	2.81e-06	1	1.66e-05	1
04-26	2.76e-04	2	1.98e-04	2	2.36e-06	1	9.71e-06	1
04-27	1.79e-04	2	6.32e-05	1	9.42e-06	1	5.06e-05	1
04-28	1.78e-04	2	1.29e-04	2	2.79e-07	1	9.62e-05	1
04-29	1.37e-04	2	2.41e-05	1	0	0	4.11e-05	1
05-08	3.14e-06	1	6.77e-05	1	0	0	0	0
05-09	3.77e-05	1	3.38e-04	2	8.70e-06	1	1.69e-05	1
05-14	4.37e-04	2	2.16e-05	1	0	0	1.44e-06	1
05-15	1.48e-03	4	2.00e-04	2	1.33e-06	1	5.51e-05	1
05-16	7.79e-04	3	3.94e-04	2	3.08e-04	2	1.03e-03	4
05-19	1.57e-03	4	2.24e-04	2	4.38e-06	1	3.15e-04	2
05-20	9.82e-03	5	1.06e-02	6	2.83e-03	4	5.67e-03	5
05-23	6.88e-02	7	1.77e-02	6	2.42e-03	4	7.92e-03	5
05-24	4.25e-02	6	3.00e-02	6	2.03e-02	6	2.49e-02	6
05-25	2.51e-02	6	1.85e-02	6	1.12e-02	6	3.55e-02	6
05-30	1.94e-02	6	9.59e-03	5	1.14e-03	4	5.33e-03	5
05-31	3.68e-03	4	1.87e-03	4	7.60e-04	3	2.44e-03	4
05-39	6.17e-05	1	7.65e-05	1	1.78e-06	1	5.02e-05	1
05-40	2.49e-04	2	3.64e-05	1	7.82e-07	1	7.67e-05	1
05-41	8.23e-03	5	1.81e-03	4	1.53e-05	1	1.73e-03	4
05-42	2.47e-03	4	4.30e-03	4	7.30e-05	1	1.31e-03	4
05-43	4.65e-04	2	1.58e-03	4	7.28e-05	1	9.25e-04	3
06-12	2.59e-04	2	4.75e-04	2	5.60e-07	1	6.96e-05	1
06-17	6.07e-06	1	3.49e-05	1	1.40e-05	1	4.86e-05	1
06-18	9.79e-03	5	2.22e-02	6	8.56e-03	5	1.45e-02	6
06-23	6.13e-04	3	1.98e-03	4	5.56e-04	3	1.66e-03	4
06-27	5.05e-03	5	6.27e-03	5	1.12e-03	4	3.28e-03	4
06-31	9.01e-03	5	1.42e-02	6	4.10e-03	4	9.94e-03	5
06-32	3.47e-03	4	8.83e-03	5	1.01e-03	4	5.33e-03	5
06-33	6.36e-03	5	1.61e-02	6	2.00e-03	4	7.48e-03	5
06-34	1.73e-05	1	3.98e-06	1	1.25e-09	1	5.02e-06	1
06-35	1.21e-03	4	2.34e-03	4	5.83e-05	1	9.93e-04	3
06-36	2.29e-05	1	4.93e-05	1	5.69e-07	1	2.75e-05	1
06-37	4.85e-05	1	4.46e-05	1	1.31e-07	1	2.54e-05	1
07-05	6.75e-05	1	1.05e-04	2	1.20e-06	1	2.58e-06	1
07-06	4.76e-05	1	1.52e-05	1	0	0	6.07e-06	1
07-07	9.49e-03	5	1.40e-02	6	1.54e-02	6	1.18e-02	6
07-08	5.27e-05	1	3.63e-06	1	0	0	4.61e-06	1
07-24	4.71e-04	2	1.04e-04	2	3.14e-07	1	6.26e-05	1

07-28	2.40e-04	2	6.44e-05	1	1.13e-07	1	5.19e-05	1
07-29	1.02e-05	1	8.13e-07	1	7.47e-09	1	1.42e-06	1
07-33	3.11e-03	4	9.63e-03	5	7.79e-03	5	4.82e-03	4
08-01	1.19e-03	4	9.78e-04	3	1.55e-07	1	1.86e-04	2
08-02	9.69e-05	1	2.97e-05	1	1.94e-04	2	1.48e-04	2
08-15	6.11e-04	3	2.65e-04	2	4.57e-06	1	1.85e-04	2
08-16	3.94e-03	4	9.12e-03	5	2.20e-03	4	1.93e-03	4
08-17	3.81e-04	2	3.13e-04	2	0	0	8.78e-05	1
08-18	3.37e-05	1	1.73e-05	1	7.70e-06	1	1.57e-06	1
08-19	1.10e-03	4	8.14e-04	3	6.48e-06	1	3.70e-04	2
08-20	1.30e-04	2	3.87e-05	1	8.70e-07	1	2.55e-05	1
08-21	1.09e-04	2	8.78e-06	1	0	0	6.40e-06	1
09-12	2.83e-04	2	0	0	0	0	0	0
09-16	6.69e-04	3	2.43e-04	2	0	0	7.00e-05	1
09-17	2.76e-05	1	7.53e-05	1	2.21e-05	1	1.81e-05	1
09-20	2.46e-03	4	2.91e-03	4	1.75e-03	4	2.41e-03	4
09-22	3.60e-06	1	6.69e-07	1	0	0	4.24e-07	1
09-25	4.68e-04	2	8.23e-07	1	0	0	5.93e-07	1
28-01	2.10e-04	2	2.78e-06	1	0	0	1.05e-06	1
28-02	1.22e-03	4	1.04e-03	4	1.11e-04	2	7.25e-04	3
28-03	3.39e-03	4	1.76e-02	6	2.26e-02	6	9.70e-03	5
28-04	1.25e-02	6	3.02e-02	6	4.39e-03	4	9.15e-03	5
28-37	4.20e-06	1	3.71e-05	1	4.09e-06	1	7.68e-06	1
28-39	5.80e-04	3	5.69e-04	3	1.64e-04	2	2.39e-04	2
28-40	1.01e-03	4	4.64e-04	2	5.52e-06	1	3.20e-04	2
28-41	3.21e-04	2	7.10e-06	1	0	0	5.93e-06	1

Appendix II: Harbour seal simulation script

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The following Rmarkdown file displays the packages and script used to simulate the harbour seal distribution from their primary haul-out site to an at-sea location. The simulated sites are then used to estimate the abundance of harbour seals in Statistical Sea Locations (SSLs). The script is divided into four sections: Read in data, Functions, Simulation, and Results. The following Rmarkdown-file only displays the script used in the simulation. Explanatory results from the script can be viewed in Appendix

Packages used for data management, simulation and plot

```
library(sf) # reading and manipulating spatial data
library(ggplot2) # plotting
library(ggspatial) #plotting
library(rnaturalearth) # administrative borders
library(rnaturalearthhires) # administrative borders, with higher resolution
library(grid)
library(gridExtra)
library(truncnorm) # truncated normal distribution
library(geosphere) # destPoint function
library(data.table) #data management
```

Data.table is also used for its significantly faster rbindlist function [as an alternative to do.call(rbind, var)) – because it can concatenate rows in a dataframe without copying the whole dataframe for each concatenation operation… which would take a lot longer. Also, fread is from data.table, and has the same advantage of being much faster.

Read in data

Get polygons for all the countries in our study region. We need other countries besides Norway because some locations intersect with the coastline for those countries.

```
scandinavia <- ne_countries(country = c("Norway", "Sweden","Finland","Russia"
), scale = "large", returnclass="sf")
scandinavia <- st_transform(scandinavia, crs = 4326) # convert to latlong
scandinavia <- st_crop(scandinavia, xmin = 0, xmax = 35, ymin = 55, ymax=72)
# crop to region of interest
scandinavia <- st_transform(scandinavia, crs = 2163) # transform back to plan
ar
scandinavia <- st_union(scandinavia) # combine all country polygons into one
single big "landmass" polygon
```

```
scandinavia <- st_sf(scandinavia)
st_agr(scandinavia) <- "constant"
```

SSLs were obtained from the Institute of Marine Research. SSLs retained for further analysis were preselected in Qgis, landmass were also removed from the polygons. See figure 2 for an overview of which SSLs that were selected. Retained SSLs are here downloaded into R and given central coordinates.

```
#coastal SSL and adjecent offshore SSL have been selected in qgis and saved a
s "SSL coastal 2.0.shp"
locations <- st_read("~/OneDrive - Universitetet i Oslo/master/Q/shp data/SSL
 coastal 2.0.shp")
# get centers for all cells, but in latlong coordinates
locations[,c("center.X", "center.Y")] <- st_coordinates(st_transform(st_centr
oid(locations), crs = 4326))
st_agr(locations) <- rep("constant", times = ncol(locations))
```

Read in harbour seal count data retrieved from the IMR and prepare it for the simulation.

```
hss <- fread("~/OneDrive - Universitetet i Oslo/master/R/data/excel csv/telle
data.csv", dec=",")
hss$LAT <- as.numeric(hss$LAT)
hss$LON <- as.numeric(hss$LON)
hss <- with(hss, {
    pts <- lapply(seq_len(length(COUNT)), function(i) st_point(c(LON[i], LAT[
i])))
    pts <- do.call(st_sfc, args = list(... = pts, crs = 4326))
    st_sf(data.frame(colony = 1:length(COUNT), location = NA, count = COUNT),

          geometry=st_geometry(pts),
          agr = rep("constant", 3))
})
hss <- hss[!is.na(hss$count),]
hss <- st_transform(hss, crs = 2163) #planar
hss$location <- locate(hss)
hss$colony <- 1:nrow(hss)
st_agr(hss) <- rep("constant", 3)
```

Functions

Functions used in the simulation and data management.

The function mkss() takes a sf object with point coordinates as features, and creates a sampling space of discretized points of the given density (e.g. if the sf unit is in meters, a density of 0.001 would correspond to one point per kilometer, and a density of 1 would be one point per meter). Points are constructed by first creating 180 line segments that all originate in the intial point coordinates, and end 192.3 km away, each with an angle 2 degrees offset from the previous one. Points are then created at regular intervals along those lines, and named based on the concentric ring they belong to, again originating from the initial point coordinate.

```
mkss <- function(x, density = 0.001) {
  ss <- st_buffer(x, 191300, nQuadSegs = 45) # sampling space
  ss <- st_cast(ss, "POINT")
  ss <- st_union(ss, x, by_feature = T)
  ss <- st_cast(ss, "LINESTRING")
  s2 <- sapply(seq_len(nrow(ss)), function(i) st_line_sample(ss[i,], density=
density))
  s2 <- do.call(st_sfc, args=list(...= s2, crs = 2163))
  s2 <- st_sf(data.frame(id = 1:nrow(ss), geometry=s2))
  s2 <- st_cast(s2, "POINT", warn=F)
  s2$ring <- rep(sum(s2$id==1):1, times = max(s2$id))
  s2 <- s2[which(!st_intersects(s2, scandinavia, sparse=F)),]
  s2
}
```

locate() - determines which location cell a given point falls into.

```
locate <- function(dest) {
    dist <- st_distance(locations, dest)
    j <- apply(dist, 2, which.min)
    locations$LOKREF[j]
}
```

groupify() - takes a given total number of animals and distributes them into groups so that the numbers of members in the groups are normally distributed with the given mean and standard deviation.

```
groupify <- function(total, mean = 2, sd = 2) {
    lapply(total, function(x) {
        if (x == 1) {
            g = 1
        } else {
            g <- round(rtruncnorm(n = x, a = 1, b = x, mean = mean, sd = sd))
            g <- g[cumsum(g) <= x]
            while (sum(g) != x) {
                b <- x - sum(g)
                if (b > 1) b <- round(rtruncnorm(n = 1, a = 1, b = b, mean =
mean, sd = sd))
```

```
                if ((sum(g) + b) <= x) g <- c(g, b)
            }
        }
        g
    })
}
```

disperse() - this function takes count data for a colony (x) and a corresponding sf sampling space (ss), and simulates the break-up of a colony into individual groups and dispersal away from the colony site, based on the simulation parameters. The function is vectorized, so x and ss can both be data frames. Returns an sf object with the new positions for each group, the number of individuals in that group, and the fishery statistics cell that that new position corresponds to.

```
disperse <- function(x, ss, probs) {
    g <- groupify(x$count, mean = group_size_mean, sd = group_size_sd)[[1]]
    direction <- sample(unique(ss$id), size = length(g), replace=T)
    s <- lapply(direction, function(dir) {
        i <- which(ss$id == dir)
        if (length(i)==1) return(ss[i,])
        p <- probs[ss$ring[i]]
        if (sum(p) == 0) {
            p <- rep(1/length(i), length(i))
        } else {
            p <- p/sum(p)
        }
        j <- sample(i, size = 1, replace=T, prob = p)
        ss[j,]
    })
    s <- st_sf(do.call(rbind, s))
    s$colony <- x$colony
    s$count <- g
    s$location <- locate(s)
    s
}
```

sim_get_probs() - convenience function to drop impossible dispersal probabilities. Needed to handle islands, fjords and jagged coastlines in the sampling space.

```
sim_get_probs <- function(ddm, dds) {
  sapply(c(0, seq(500, 191300, 1000)), function(i) {
    j <- ifelse(i == 0, 500, 1000)
    ptruncnorm(q = i+j, a = 0, b = dispersal_distance_max, mean = ddm, sd = d
ds)-
      ptruncnorm(q = i, a = 0, b = dispersal_distance_max, mean = ddm, sd = d
ds)
```

```
  })
}
```

sim_run() - function for running the simulation

```
sim_run <- function(season, N = 1) {
    ddm <- dispersal_distance_mean[season]
    dds <- dispersal_distance_sd[season]
    p <- sim_get_probs(ddm, dds)
    x <- replicate(N, mapply(disperse, hss.list, ss, MoreArgs = list(probs =
p), SIMPLIFY=F), simplify=F)
    setattr(x, "N", N)
    setattr(x, "ddm", ddm)
    setattr(x, "dds", dds)
    x
}
```

sim_run_batch - runs the simulation in batches of some number of replicates, as specified in saveFreq (e.g. 50) and saves all progress by the end of each batch.

```
sim_run_batch <- function(N = 1000, saveFreq = 2, savePath) {
    if (!file.exists(savePath)) stop(sprintf("Path '%s' not found.", path))
    if (saveFreq > 100) warning("A save frequency greater than 100 may cause
data loss and is not recommended.")
    savePath <- gsub("/$", "", "~/OneDrive - Universitetet i Oslo/master/R/da
ta/sim")

    progress <- file.path(savePath, "progress.Rdata")
    data <- file.path(savePath, "step%d.RData")

    if (file.exists(progress)) {
        step <- readRDS(progress) + 50
        print(sprintf("Restarting simulation from step %d (If you would like
to restart the simulation, please delete the progress file '%s')",
                      step, progress),quote=F)
    } else {
        step <- 1
        print("Starting a new simulation...")
    }

    while (step <= N) {
        print(sprintf("Running replicates %d - %d... ", step, step+saveFreq-1
))
        pb <- txtProgressBar(min = 0, max = 12, style = 2)
        res <- lapply(c(season = 1:3), function(season) {
            x <- sim_run(season = season, N = saveFreq)
            setTxtProgressBar(pb, season)
```

```
            return(x)
        })
        close(pb)
        saveRDS(res, file = sub("%d", step, data, fixed=T))
        saveRDS(step, file = progress)
        cat(sprintf(" done! Progress saved in '%s'\n", sub("%d", step, data,
fixed=T)))
        step <- step + saveFreq
    }
}
```

Simulation

The simulation use parameters defined in the script to simulate dispersion of harbour seal at sea from their location of moult. The parameter used are the mean travel distance to an at sea location with standard deviation.

Set the mean and standard deviation for harbour seal average distances from haul-out site to an at sea location. The group size was set to 0.01, to represent solitary foraging behavior.

```
# set up the simulation parameters

#mean
dispersal_distance_mean <- c(5000, # summer
                             15000, # spring & autumn
                             35000) # winter

#sd
dispersal_distance_sd <- c(11600, # summer
                           26900, # spring & autumn
                           49300) # winter

dispersal_density <- 0.001 # sampling space resolution (1 = 1m, 0.001 = 1km)
dispersal_distance_max = Inf # maximum dispersal distance (meters)
group_size_mean = 1 # average group size
group_size_sd = 0.01 # standard deviation of group size
N <- 1000 # number of simulation replicates (as many as possible, and at leas
t 1000)
```

set up the sampling space for each colony

```
hss.list <- split(hss, 1:nrow(hss))
ss <- lapply(hss.list, mkss, density = dispersal_density)
```

Run the simulation in batches.

```
sim_run_batch(saveFreq = 50, savePath = "~/OneDrive - Universitetet i Oslo/ma
ster/R/data")
```

The Results are now ready, but need to be combined into one large dataset. Combine the batches saved by savefrequenzy. The savefrequenzy was set to 50, and a total of 20 batches of R-objects need to be combined into one large R-object. Each R-object with 50 iterations are 2.4GB and are added togheter five at a time. Then the workspace is deleted to add the next five batches togheter. The workspace should be deleted so that the computers RAM are not overloaded.

```
# combine the results into one list
dat1 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/step
1.Rdata") #9.226s
dat2 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/step
21.Rdata")
dat3 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/step
41.Rdata")
dat4 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/step
61.Rdata")
dat5 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/step
81.Rdata")
dat6 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/step
101.Rdata")
dat7 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/step
121.Rdata")
dat8 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/step
141.Rdata")
dat9 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/step
161.Rdata")
dat10 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/ste
p181.Rdata")
res1av5 <- do.call(mapply, args = list(c, dat1, dat2, dat3, dat4, dat5, dat6,
 dat7, dat8, dat9, dat10,  SIMPLIFY = F)) saveRDS(res1av5, "~/OneDrive - Univ
ersitetet i Oslo/master/R/data/sim/sim/res1av5.Rdata")
rm(list=ls()) #clear workspace


# This procedure was repeated to include all samples


res1av5 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/r
es1av5.Rdata")
res2av5 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/r
es2av5.Rdata")
res3av5 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/r
es3av5.Rdata")
```

```
res4av5 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/r
es4av5.Rdata")
res5av5 <- readRDS("~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/r
es5av5.Rdata")

#Combine into one large file
res <- do.call(mapply, args = list(c, res1av5, res2av5, res3av5, res4av5, res
5av5, SIMPLIFY = F)) #res4av5, res5av5,
saveRDS(res, "~/OneDrive - Universitetet i Oslo/master/R/data/sim/sim/res.Rda
ta")
```

Results and plots

sim_calc_averages - calculates the mean and standard deviation of simulated seals for each Statistical Sea Location. The function also puts seals simulated outside the bounderies of the retained SSLs used, to the closest SSLs of the simulated point. Results are plottet by the later function “plot_abundance_by_season”.

```
sim_calc_averages <- function(x, collapse = TRUE) {
    R <- 1:length(x[[1]])
    y <- cbind(data.frame(location = locations$LOKREF),
               iter=matrix(0, ncol = length(R), nrow = nrow(locations)))
    y2 <- vector(mode = "list", length = length(R))
    y2 <- lapply(1:3, function(season) cbind(data.frame(season = season), y))

    nil <- sapply(1:3, function(season) {
        sapply(seq_len(length(x[[season]])), function(iter) {
            m <- rbindlist(x[[season]][[iter]])
            m <- m[,.(count = sum(count)), by = location]
            j <- match(m$location, y2[[season]]$location)
            y2[[season]][j,iter+2] <<- m$count
        })
    })
    y2 <- rbindlist(y2)
    i <- seq(3, 2+length(R), 1)
    y2$mean <- rowMeans(y2[,i,with=F], na.rm=T)
    y2$sd <- apply(y2[, i, with=F], 1, sd, na.rm=T)
    y2$lower <- pmax(0, y2$mean + y2$sd * qnorm(0.025))
    y2$upper <- y2$mean + y2$sd * qnorm(0.975)
    if (collapse == TRUE) {
        y2[,.SD,.SDcols = c(1:2,(ncol(y2)-3):(ncol(y2)))]
    } else {
        y2
    }
}

res.avg <- sim_calc_averages(res)
```

```
saveRDS(res.avg, "~/R/res.avg.Rdata")
res.avg <- readRDS("~/R/res.avg.Rdata")
```

plot_dispersal() - plots a selected replica of a given colony in the sampling space defined for the colony. plot_dispersal2() - plots a selected replica of a given colony in the sampling space by the seasonal distances used. Results can be inspected in Appendix 1, figure I.1.

```
plot_dispersal <- function(x, replicate = 1, colony, months = 1:3) {

    d <- lapply(months, function(month) {
        cbind(data.frame(replicate = replicate, colony = colony, month = mont
h),
              res[[month]][[replicate]][[colony]])
    })
    d <- rbindlist(d)
    d <- st_as_sf(d)
    ggplot(data = d) +
        geom_sf(data = ss[[colony]], shape = 21, fill = "white", color = "bla
ck", alpha = 0.25) +
        geom_sf(data = d, aes(size = count), shape=21, color="white", fill="f
irebrick", alpha = 0.75) +
        geom_sf(data = hss[colony,], colour = "steelblue2") +
        coord_sf(crs = 4326)
}

plot_dispersal2 <- function(x, replicate, colony, months = 1:3) {
    len_r <- length(x[[1]])
    if (replicate > len_r) stop(sprintf("Max replicate is %d", len_r))

    d <- lapply(months, function(month) {
        cbind(data.frame(replicate = replicate, colony = colony, month = mont
h),
              res[[month]][[replicate]][[colony]])
    })
    d <- rbindlist(d)
    d <- st_as_sf(d)
    d$month <- factor(d$month, labels = c("Su", "S&A", "Wi")) #Wi, S&A, Su #m
onth.name[1:3]
    bb <- st_bbox(st_transform(st_buffer(hss[colony,], 60000), crs = 4326))

    ggplot(data = d) +
        geom_sf(data = scandinavia) +
        geom_sf(data = locations, fill = NA) +
        geom_sf(data = d, aes(size = count), shape=21, color="white", fill="f
irebrick", alpha = 0.75) +
        geom_sf(data = hss[colony,], shape = 21, size = 3, fill  = "steelblue
2", color="black") +
        coord_sf(xlim=bb[c(1,3)], ylim = bb[c(2,4)], crs = 4326, expand=T) +
```

```
        theme_bw() +
        theme(plot.background = element_rect(fill="white")) +
        facet_wrap(~month)
}

#plot
#first replica of colony 4
a <- plot_dispersal(x = res.avg, colony = 4, replicate = 1)
a1 <- plot_dispersal2(x = res, replicate = 1, colony = 4, months = 1:3)
grid.arrange(a, a1, ncol = 1) #Plot both plots in one frame, see figure A.1

#second replica of colony 4
b <- plot_dispersal(x = res.avg, colony = 4, replicate = 2)
b1 <- plot_dispersal2(x = res, replicate = 2, colony = 4, months = 1:3)
grid.arrange(b, b1, ncol = 1) #Plot both plots in one frame, see figure A.1
```

plot_abundance_by_season - plot results with the mean and standard deviations for every SSL with simulated seals in them. Results can be inspected in Appendix 1, figure I.2.

```
plot_abundance_by_season <- function(x, area) {
  i <- grep(sprintf("^%02s", area), x$location)
  if (!length(i)) stop("Area not in data")

  d <- x[i,][!is.nan(mean),]
  valids <- d[,.(valid=sum(mean)!=0), location]
  valids <- valids$location[valids$valid]
  d <- d[location %in% valids,]
  title <- sprintf("Simulated location use through an average year in area %0
2s (w/%d replicates)", area, attr(x, "N"))

  ggplot(data = d, aes(x = month, y = mean)) +
    geom_ribbon(aes(ymin = lower, ymax = upper), fill="steelblue2", alpha = 0
.25) +
    geom_point(color = "firebrick") +
    geom_line(color = "firebrick") +
    #expand_limits(y = 0) +
    ylim(c(0, NA)) +
    ylab("Number of seals") +
    scale_x_continuous("Season", breaks = c(1, 2, 3), labels = c("Su", "S&A",
 "Wi")) +
    ggtitle(title) +
    facet_wrap(~location, scales = "free_y")
}

#plot
plot_abundance_by_season(x = res.avg, area = 0)
# This procedure was repeated to include all Statistical Sea Locations
```