Improved stock estimation for Iceland scallops (*Chlamys islandica*) in the Svalbard area

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Abstract

Iceland scallops (*Chlamys islandica*) were commercially harvested in the Svalbard fishery protection zone (FPZ) from 1986 to 1992, when the fishery ended due to overfishing. After approximately 30 years of prohibition, a trial fishery was permitted in the scallop beds around the Bear Island (Bear Island SE, Concordia and Kveitehola) in 2021. As an extension of this trial fishery, the Norwegian fishery authorities plan to open a fishery in the Moffen and Parryflaket scallop beds north of Svalbard. We, therefore, surveyed the area in autumn 2022, taking dredge samples and video recordings. The dredge samples were used to collect biological samples, while the video recordings were used to estimate the stock density. Images were randomly selected from the video recordings, and scallops on these images were counted by six individual human counters. The density was then estimated using three different approaches; a design-based swept area estimation (approach 1) and two statistical models; a regular and a spatial generalized additive mixed model (GAMM) (approaches 2a and 2b). Data from surveys in the Bear Island region was included in the models, to compare density between the scallop beds in the Svalbard area. Our main objectives were to standardize the annotation procedure, assess shell height distribution and estimate density and biomass in the Moffen region. And then compare the results with the scallop beds in the Bear Island region. Our main findings indicate recovery in shell height distribution and density. The spatial GAMM (approach 2b) provided the most precise and conservative density estimates. These estimates are expected to serve as the foundation for quota recommendations for harvesting in the Moffen region.

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1. INTRODUCTION

The exquisite taste of Iceland scallops (*Chlamys islandica*) made the species commercially valuable (Hansen and Nedreaas, 1986, Hauan, 1988). Harvesting of the scallop species started in the Svalbard fishery protection zone (FPZ) in the middle of the 1980s (Sundet and Rubach, 1988). The fishery was short-lived and closed in 1992 due to overfishing (Sundet, 2006). The Iceland scallop fishery has been closed in the Svalbard FPZ until recently; a trial fishery in the Bear Island region was permitted after development of new gear technology and based on quota advice given by the Institute of Marine Research (IMR), (Sundet and Zimmermann, 2020), producing the first catches in December 2022 (Nedrejord, 2023). The Moffen scallop bed north of Spitsbergen was considered the largest fishing ground, with the highest abundance in the Svalbard FPZ in the 1980s (Sundet and Rubach, 1988). Interest in the status of the scallop stock in this area and the potential for an expansion of the trial fishery motivated the study presented here. We surveyed the Moffen region (consisting of the two scallop beds Moffen and Parryflaket) in early autumn 2022 to assess the stock abundance and distribution, which will be the base of future quota advice for the Moffen region.

1.1 Study species: Iceland scallop (*Chlamys islandica*)

The Iceland scallop is in the order Anisomyaria and the Pectinidae family (Wiborg, 1963).

Figure 1 Picture of the Iceland scallop, Chlamys Islandica. Outside morphology (left-hand side), the mother of pearl lining inside the shell (right-hand side.).

1.1.1 Morphology

The Iceland scallop has the same general shape as most pectinids; the shell is almost circular and laterally compressed. Individuals usually reach a shell height of 80 – 110 mm (Garcia, 2006). The valves are almost identical, but the right ear on the ventral valve has a deeper incision than the left one. Both valves have tiny transversal ribs and more visible radial ribs (figure 1). The shell comes in variable colours (e.g., grey, white, violet, yellow, red), but usually in some variation of orange tones. The mother-of-pearl lining inside also varies in colour (Wiborg, 1963).

1.1.2 Ecology

The Iceland scallop is a slow-growing filter feeder (Ekman, 1953, Wiborg, 1962) found at various depths (Wiborg, 1970), in relatively cold (Wiborg, 1963, Eriksson, 1986, Pedersen, 1994) areas with strong currents (Ekman, 1953). The Iceland scallops can be found between 10, and almost 600 meters depth (Hansen and Nedreaas, 1986, Eriksson, 1986, Rubach and Sundet, 1987), but the highest densities are usually located between 10 – 100 m depth (Wiborg, 1970). The scallops seem to prefer bottom substrate consisting of gravel/sand/stones (Ekman, 1953, Wiborg, 1962), with a temperature between 1,4 and 10 °C (Wiborg, 1963, Eriksson, 1986, Pedersen, 1994). Still, they can survive temperatures above (Jonasson et al., 2004) and below (Wiborg, 1970). The Iceland scallops can lay freely on the seafloor (Soot-Ryen, 1924) and are, like other pectinids, able to swim by contracting the two valves (Wiborg, 1963). Still, the scallops are mostly found attached to the seabed by byssus threads to other shells or bottom substrate (Wiborg, 1963). The scallop beds create habitats for other species, and the scallops are commonly covered by different fouling organisms, for instance; hydroids, tubiferous annelids, sponges, bryozoans, and barnacles (Wiborg, 1963). Barnacles are generally the most dominating fouling species (Sundet, 1985, Rubach and Sundet, 1987).

The general growth in all the body parts of the scallop (viscera, gonads, and shell) takes place in the same period as the phytoplankton blooms, from the end of March to June (Vahl, 1978, Vahl, 1981a, Vahl, 1981b, Thorarinsdóttir, 1993). The age is usually determined by counting seasonal growth patterns in the ligament at shell umbo. So far it has been found specimens, determined to be older than 20 years old (Vahl, 1981a, Vahl, 1981b).

1.1.3 Reproduction and recruitment

Iceland scallops reproduce sexually during summer. Iceland scallops are dioecious, meaning the sexes are separate (Sundet and Vahl, 1981). The sex ratio seems to be approximately 1:1 (Vahl, 1981a, Eriksson, 1986, Rubach and Sundet, 1987). The gonad in sexually ripe specimen makes it simple to determine the sex; male gonads have a whitish colour, while the female gonad is more orangish in colour (Wiborg, 1963). The gonad in juvenile scallops and in spawned out individuals is often whiteish and consequently not always a useful indicator (Mottet, 1979). Sex determination may therefore be more accurate before, or some months after the spawning season. The spawning period usually lasts from the end of June to the end of July and is affected by an increase in temperature (Skreslet and Brun, 1969, Skreslet, 1973, Sundet and Lee, 1984, Eriksson, 1986, Pedersen, 1988, Oganesyan, 1994) and the nutrient availability (Arsenault and Himmelman, 1998, Thorarinsdóttir, 1993). The larva settles approximately six weeks after the spawning (Thorarinsdóttir, 1991).

The Directorate of Fisheries implemented a minimum legal size in shell height in coastal areas to ensure that individuals were not taken out of the population before they could reproduce (Vahl, 1982). There is a variation in the growth rate between different regions, which results in different sizes and ages at maturity between the locations. In coastal Norway and Iceland, the scallops usually reach maturity at age 5 – 7 years and between a shell height of 40 – 50 mm. The scallops in Greenland can be 4 – 9 years and 30 – 55 mm when becoming fertile (Wiborg, 1963, Eriksson, 1986, Pedersen, 1994). This was the main reason for implementing a minimum legal size of 65 mm in the coastal areas (Hauan, 1988), and 60 mm in the Svalbard FPZ, based on assumptions that scallops in the Svalbard area grow slower than scallops along the coastline, thus are smaller when reaching maturity (Jan H. Sundet, pers. comm.).

1.1.4 Distribution

The Iceland scallop is a sub-arctic species, which is found along western and northern Spitsbergen, Hopen Island, the Bear Island, Murman coast, west coast of Novaja Zemlja, White Sea, Kara Sea, Jan Mayen Island, East and West Greenland, Iceland, the east coast of Canada, North America and north and west in Norway (Sars, 1878, Ekman, 1953, Berg et al., 1958, Wiborg, 1963, Wiborg et al., 1974, Eriksson, 1986, Galand and Fevolden, 2000, Garcia, 2006, Jonasson et al., 2007). Along the Norwegian coast, the highest population densities are found in fjords with shallow sills and strong currents, and the populations are mainly distributed north of the Lofoten area (Wiborg, 1963).

This study surveyed the scallop beds north (around Moffen) and south (around the Bear Island) of Svalbard (figure 2).

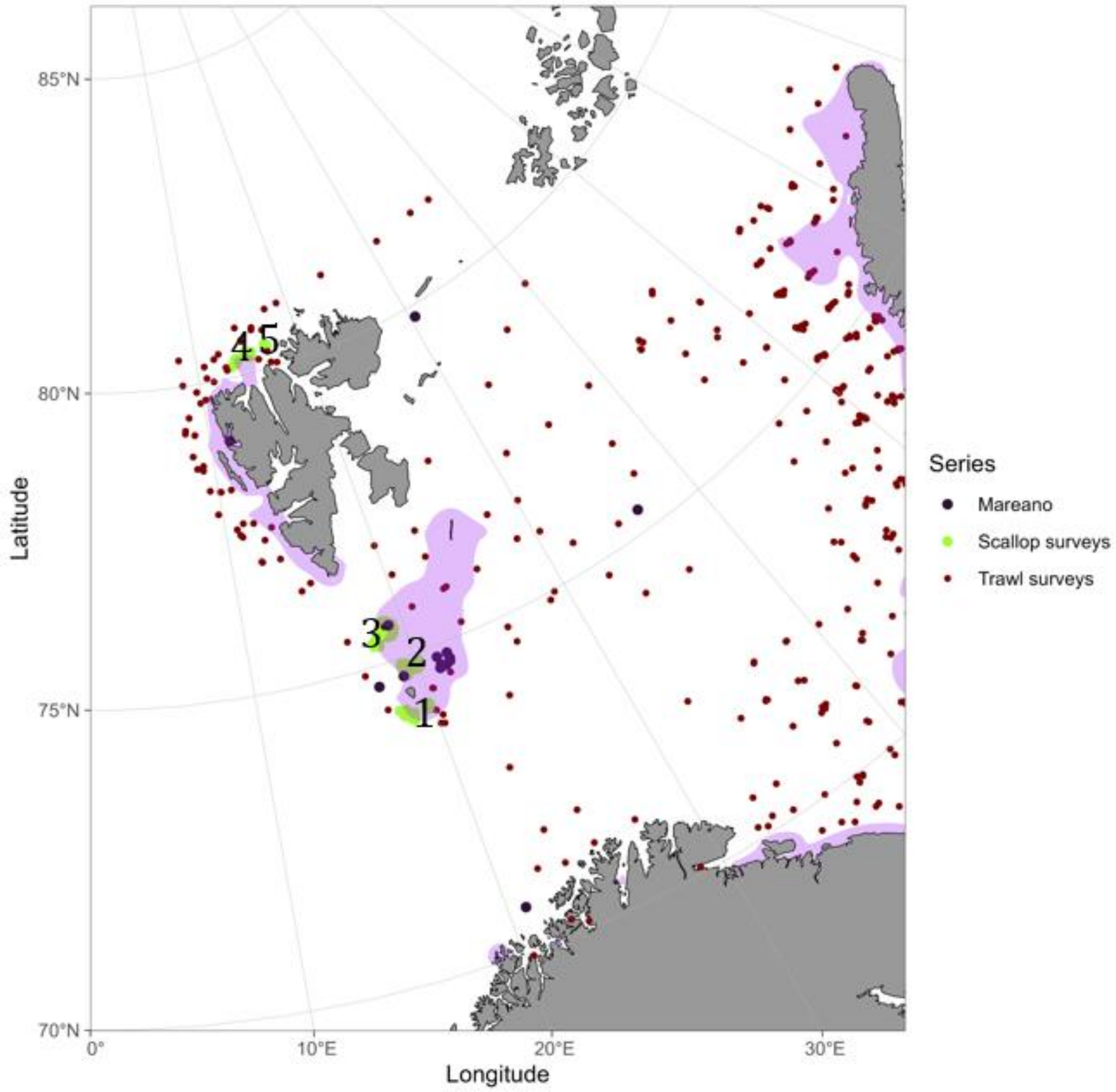

Figure 2 Map of the observed distribution of Iceland scallop from Norwegian surveys – Mareano survey (dark colour), scallop survey (green) and Institute of Marine Research (IMR) surveys (maroon). The purple polygons show known scallop beds. The numbered areas show the scallop beds we focus on in this study; 1 = Bear Island SE, 2 = Kveitehola, 3 = Concordia, 4 = Moffen and 5 = Parryflaket.

1.2 Scallop fishery

Global scallop fishery was poorly managed at the beginning of the 20th century, which led to overfishing and collapse of several stocks (Shumway and Parsons, 2016). People have harvested scallops in shallow habitats throughout centuries (Rhodes, 1991), however, other kinds of bivalves such as mussels and clams played a more important part in preindustrial fishing communities (Shumway and Parsons, 2016). Most scallop fisheries require some degree of technology and equipment, compared to preindustrial subsistence harvesting of mussels and clams. The scallop fishery is therefore a relatively "new" fishery, oriented towards a commercial market (Shumway and Parsons, 2016). Today's scallop fishery can be divided into three categories; small-scale operations (usually inshore, dredging, trawling, diving, or raking where the fishers go back and forth to shore every day), and large-scale industrial operations (often offshore, processing the catch onboard, lasting for days) and the last is sea ranching, which is a kind of aquaculture in the wild. It is important to be aware of these differences when managing scallop stocks because the different categories may require various stock regulations. For instance, quotas might be a viable option when regulating large-scale industrial fisheries, but may be difficult to enforce in a small-scale fishery (Shumway and Parsons, 2016). The neglect of proper management combined with environmental changes/disturbances have caused the collapse of several scallop stocks (Shumway and Parsons, 2016), e.g. the collapse of Queen scallop *Aequipecten opercularis* in Spain after the 1960s (Orensanz et al., 2006), New Zealand scallop *Pecten novaezelandiae* in New Zealand (north of the South Island) in the end of the 1970s (Mincher, 2008) and King scallop *Pecten maximus* in Cardigan Bay in the United Kingdom in 1980 (Ansell, 1991). Scallop stocks are usually common property and have earlier been managed as open access fishing resources or with unlimited number of licences, leading to overfishing (Brand, 2006). This was also the case when the Iceland scallop fishery started in Iceland in 1969 (Garcia, 2006), while regulations were implemented when the harvest of Iceland scallops started in Greenland in 1983: Only a few licences were issued and a yearly quota was determined. These regulatory measures have kept the catch steady through the years (Garcia, 2006).

1.2.1. The Norwegian Iceland scallop fishery

The commercial interest in Iceland scallops in the Svalbard FPZ did not occur until the mid-1980s and lasted 7-8 years. The fishery ended due to overfishing in the early 1990s (Garcia, 2006).

Until the 60s, the scallops were primarily used as fishing bait, by Northern Norwegian fishermen (Wiborg, 1963, Sundet, 1985). Wiborg conducted the first survey of Iceland scallop beds in Norwegian coastal waters in 1961/62. These preliminary surveys were conducted in Troms and Finnmark in the northern part of Norway, however, Wiborg (1963) suggested that the waters around Svalbard also could be promising for harvesting scallops. The first surveys of scallop beds in the Svalbard FPZ were at the Bear Island, in 1968/69 (Wiborg, 1970). These surveys concluded that the rough bottom conditions would make commercial fishery challenging in the area (Wiborg, 1970). The conclusion from the following survey in 1973 was more optimistic towards commercial possibilities. Wiborg (1974) found mainly Iceland scallops in the Svalbard FPZ with a shell height between 75 – 85 mm, that was 10 – 15 years old, probably because small scallops could escape through the meshes of the dredge. The gonad and muscle weight were greater around the Bear Island than north and west of Spitsbergen Island (Wiborg et al., 1974). The scallop beds in the Svalbard FPZ seemed to have a promising fishery potential (Garcia, 2006). However, it was not until 1985 that the interest in Iceland scallop harvesting started. Fishermen rebuilt their seiners and trawlers to fit the scallop fishery in the Bear Island and Spitsbergen area (Jan H. Sundet pers. comm.). Consequently, Rubach and Sundet surveyed the Bear Island, Spitsbergen and Jan Mayen in 1986 and found scallop beds suitable for dredging (Rubach and Sundet, 1987). Nonetheless, Wiborg (1970) assumed that some parts of the scallop beds were impossible to dredge and suggested that these areas could serve as undisturbed pools generating recruits to sustain the stock in harvested areas. Even so, the Iceland scallop stock declined, and the last Norwegian scallop boat stopped fishing in the Svalbard FPZ in 1992 (Sundet, 2006).

1.2.2 Gear development

Iceland scallop was harvested with heavy dredges during the commercial fishery (Wiborg, 1963, Sundet, 1985, Sundet, 2006), this is not a sustainable way to harvest, and a development of gear is required to continue harvesting (Sundet et al., 2019).

The fishing effort increased rapidly and peaked with 26 vessels in 1986 (Sundet and Rubach, 1988). Nine of these vessels were built specially for Iceland scallop fishery, while the rest were old fishing vessels rebuilt to fit scallop fisheries (Opstad, 1988, Misund et al., 2016). The vessels operated at least two dredges simultaneously – one hauled up on deck while the other fished (Sundet, 1985). The dredges weighed 3 – 7 tons each (Sundet, 2006). Video recordings from the bottom at Moffen and the Bear Island after the dredging activity showed marked furrows in the bottom sediments, probably caused by years of dredging (Sundet et al., 2019). Research on dredge effects on the sea floor ecosystem has not been conducted in this area, however, several reports have shown significant differences and disturbances in the ecosystems as a result of dredging elsewhere (Collie et al., 1997, Veale et al., 2000, Jenkins et al., 2001, Thrush and Dayton, 2002, Council, 2002, Jennings et al., 2005). Consequently, the Norwegian fishery authorities have banned dredge as a gear choice in Iceland scallop fisheries. To be able to open for Iceland scallop fishery new gear is required. Therefore Ava Ocean (formerly known as Tau tech AS) developed a new gear to minimize the impact on the sea floor, they named it "harvester". The harvester uses negative pressure to suck up scallops from the sea floor. Scallops and organisms smaller than minimal legal size are sorted out at the sea floor. This is supposed to secure the sea floor fauna, and thereby make the fishery more sustainable. Ava Ocean hired the Institute of Marine Research (IMR) and the Norwegian Institute of Water Research (NIVA) to test the "harvester". The survey gave the following results; no changes in species composition (except Iceland scallops), small/moderate fauna damage and moderate impact on bottom sediments (Sundet et al., 2019). Consequently, the harvester might be the future of Iceland scallop fisheries. However, these results were based on a single survey, thus more research is needed to understand the impact of harvesting on larger scale over time (Sundet et al., 2019).

1.2.3 Management

The fishery of Iceland scallop in the 1980s resulted in overfishing and severe impacts on the benthic habitat (Sundet, 2006), calling for more sustainable and precautionary management. Surveys were conducted in the Svalbard region before the fisheries started in the middle of the 80s, to map out the populations (Wiborg, 1970, Wiborg et al., 1974, Rubach and Sundet, 1987). Vahl (1982) suggested that the density of recruits is negatively correlated with the number of adults. This indicates that the success of recruitment might be related to population density (Vahl, 1982). Even so, with minimum legal size as the primary management measure, the population declined and Norwegian vessels stopped fishing in the Svalbard FPZ in 1992 (Sundet, 2006). Since then, the Institute of Marine Research partly surveyed Moffen and the

Bear Island areas in respectively 1994 and 1996, and both regions in 2006 - to map the population development (Sundet, 2006). A stock survey was conducted around the Bear Island in 2019, to estimate a sustainable fishing quota in the area (Sundet and Zimmermann, 2020). And Ava Ocean started a five-year trial fishery in the area at the end of 2022, with a quota of 15 000 tons of scallops per year (Nedrejord, 2023).

Total allowable catch (TAC) and rotational management are examples of management approaches that have been used to manage scallop stocks throughout the world (Shumway and Parsons, 2016). In Iceland both TAC and minimum legal size were implemented in 1978 to manage the Iceland Scallop stock, however, the stock was recruitment overfished and the fishery closed in 2003/2004 (Garcia, 2006). Rotational management and closed areas have given successful results on other scallop species (Shumway and Parsons, 2016). *Pecten. maximus* in the Isle of Man area increased in size, age and density after closing the area (Beukers-Stewart et al., 2005). The temporal openings of parts of scallop beds with individuals over minimum legal size have given profitable results (Rudders et al., 2006).

1.2.4 The commercial interest

The Iceland scallop is commercially harvested mainly because of its edible and tasty adductor muscle (Rubach and Sundet, 1987, Sundet, 2006). The muscle is the solemn target in factory manufacturing, but gonads are targeted as well in the manual processing of the scallops (Jan H. Sundet pers. comm.). In scallops at minimum legal size (60 mm) pre-spawning, the adductor muscle can make up to 20 - 25% of the total weight (Wiborg, 1963, Rubach and Sundet, 1987). The scallops are at minimum weight in early spring and reach maximum weight in the early autumn (Sundet and Vahl, 1981). The habitat depth may also influence muscle size; the scallops from the shallowest areas had the largest muscles (Rubach and Sundet, 1987). The adductor muscle store food surplus as glycogen. Low content of glycogen results in a watery and shrivelled muscle, while high levels of glycogen create a tasty and firm meat (Mottet, 1979). The glycogen accumulates in the muscle mostly during the summer and the glycogen level peaks in august (Sundet and Vahl, 1981).

1.3 Aim and objectives

Gear developments sparked an interest in re-opening the scallop beds in the Svalbard FPZ, including the beds north of Svalbard (in the Moffen region), to trial fishery.

The main aim of the project is therefore to provide improved stock estimates for Iceland scallop, *Chlamys islandica*, in the Svalbard area, based on data from the surveys covering scallop beds around the Bear Island and in the Moffen region.

Specific aims include:

- To standardize the scallop counting procedure based on video transects, using a comparative picture annotation approach to quantify the uncertainty of the scallop counting strategy.
- To map the distribution and density of Iceland scallops in the Moffen and Parryflaket scallop beds, using video transects and dredge stations. I will compare these results with previous findings from the Bear Island region.
- To estimate total abundance and biomass in the Moffen and Parryflaket scallop beds from density information and potential explanatory variables such as bottom depth using geostatistical modelling. We will include data from previous surveys (2019 and 2020) in the Bear Island region to compare results from the two regions, and between design- and model-based estimation approaches.

2. MATERIALS AND METHODS

2.1 Stock area

Surveys were conducted south of Svalbard in the Bear Island and Spitsbergenbanken area in 2019 and 2020, and north of Svalbard in the Moffen region in 2022 (figure 3). The Moffen Island is encompassed by a protected area, that covers the surrounding territorial waters (12 nm). In 2004, the limits for territorial waters was extended from 4 nm to 12 nm, which also resulted in the expansion of the protected area (Pedersen et al., 2015). Thus the area accessible to fishery has decreased since the 1980s, but the accessible scallop bed is still of a considerable size (Sundet and Zimmermann, 2020).

In this paper the "Bear Island region" is a collective term applying to all the scallop beds (Bear Island Southeast, Concordia and Kveitehola) in the Bear Island and Spitsbergenbanken area, while the "Moffen region" applies to the two scallop beds Moffen and Parryflaket.

The survey in 2019 was conducted to estimate the stock size in the Bear Island region, and provide advice on a possible trial fishery in the area (Sundet and Zimmermann, 2020). The survey in 2020 was supposed to collect samples in the Moffen region, but challenging ice conditions in the area led to sampling in the Bear Island region instead (Fabian Zimmermann pers. comm.). The stock status north of Svalbard remained therefore unknown and the region was not included in the areas open to the trial fishery approved in 2021. To close this knowledge gap, we surveyed the Moffen and Parryflaket scallop beds in 2022. The main aim of this study was to collect and analyse the survey data and estimate the scallop abundance around Moffen and Parryflaket. Data from the two surveys in the Bear Island region was included here to compare results from the two regions and test a model-based estimation of abundance that integrates data from all surveyed areas.

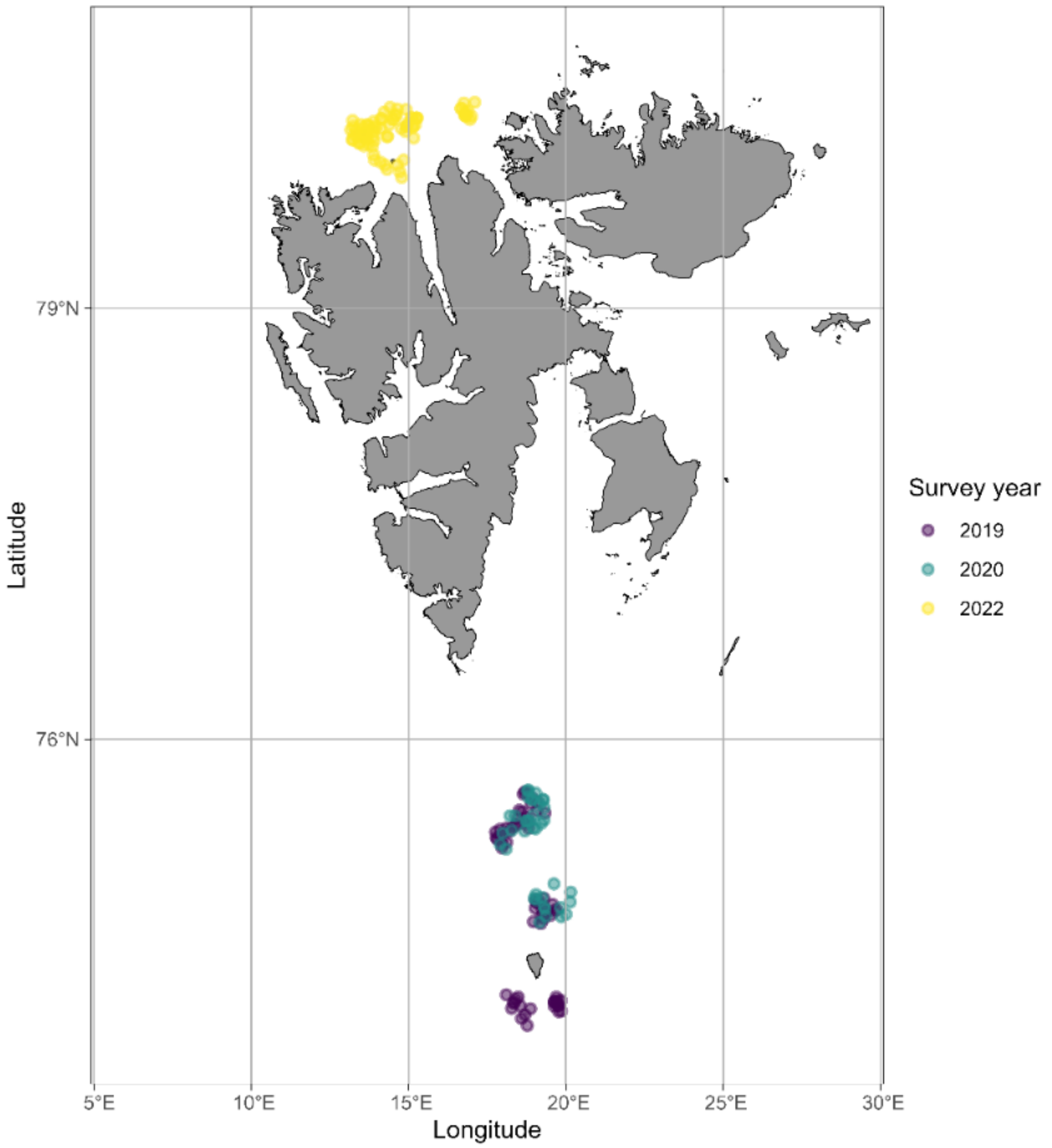

Figure 3 Overview of survey areas from Iceland scallop research cruises in 2019, 2020 (the Bear Island region) and 2022 (the Moffen region).

2.2 Survey design

The survey areas were based on survey data from 1986 and 1988, enclosing the areas around Svalbard (the Bear Island region and Moffen region) where Iceland scallops were previously observed. Data from the Bear Island region was collected on a research cruise conducted on RV Johan Hjort between 29.11.2019 – 12.12.2019 and on RV Helmer Hanssen between 15.06.2020 – 21.06.2020, and on the Moffen and Parryflaket scallop beds during a research cruise on RV Helmer Hanssen 20.09. – 26.09. in 2022.

During the research cruise on RV Johan Hjort in 2019, 44 Delta scallop dredge (duration 5 minutes) samples and 26 (duration 60 minutes) video sledge samples were taken. The video sledge was initially made to observe red king crabs (*Paralithodes camtschaticus*) and had a fibre cable connected between the vessel and the sledge to transfer live footage.

Throughout the cruise on RV Helmer Hanssen in 2020, 4 Delta scallop dredge (duration 5 minutes) samples and 35 (duration 60 minutes), video sledge samples were taken. The sledge was a simpler version of the one used in 2019, without live footage transfer, but the principle was the same – a sledge gliding along the sea floor with a recording device attached (figure 4).

During the cruise on RV Helmer Hanssen in 2022, we did 13 Delta scallop dredge (duration 5 minutes) samples and 60 (duration 20 – 30 minutes) video sledge (the same sledge as in the 2020 survey) samples (figure 5). The video recordings were half of the duration of previous years. This made it possible to do more sledge stations, thus covering more potentially various areas.

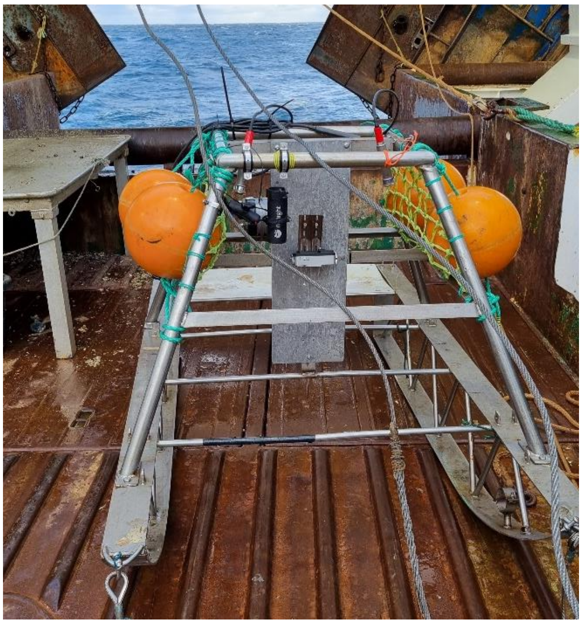

Figure 4 Picture (by Fabian Zimmermann, 2022) of the video sledge used in Iceland scallop surveys in 2020 and 2022 in the Bear Island and Moffen regions respectively.

The overall sampling structure varied between the surveys in the Bear Island region and the survey in the Moffen region. During the cruises in 2019 and 2020 (the Bear Island surveys), Delta scallop dredge and video sledge were used at different locations, which made it possible to cover larger survey areas. In contrast, in the survey in 2022, all the dredging stations were combined with video stations. At 13 positions parallel stations with video and dredge were conducted, allowing to compare observation of scallops (occurrences and densities) based on the two different gear types. The video recordings were taken first, then the dredged samples – to be able to observe/count the number of shells before removing them, in addition to avoiding disturbance in sediments, lowering the quality of the recordings. The remaining stations consisted only of video sledges. All the video recordings were saved on discs with backup copies, to be processed on shore.

2.2.1 Selection of sampling sites

Survey data from 1986 and 1988 were used to create polygons enclosing the areas around Svalbard where the Iceland scallop was previously observed. These areas were divided into substrata to separate areas inside and outside the Moffen protected area. Only video samples were taken inside the protected area, while dredge and video samples were collected outside. Sample sites were randomly selected along a nonaligned grid (by using the sp package (Pebesma and Bivand, 2005) in R (v. 4.2.3; R Core Team, 2023)), and paired with depth information based on the closest available position with known bottom depth (based on GEBCO bathymetric data and observed depth in 1986/1988). Iceland scallops mainly occur between 35 m and 100 m depth in the offshore regions (Rubach and Sundet, 1987). Thus, sampling positions were restricted to bottom depths between 20 and 150 m. The probability of selecting a site within the protected area was downweighed, to ensure that most stations were placed outside the protected area. The probability of choosing stations along the eastern border of the protected area was also down-weighted due to the suboptimal bottom substrate. The randomized selection of stations resulted in 84 stations, where half of them were considered backups.

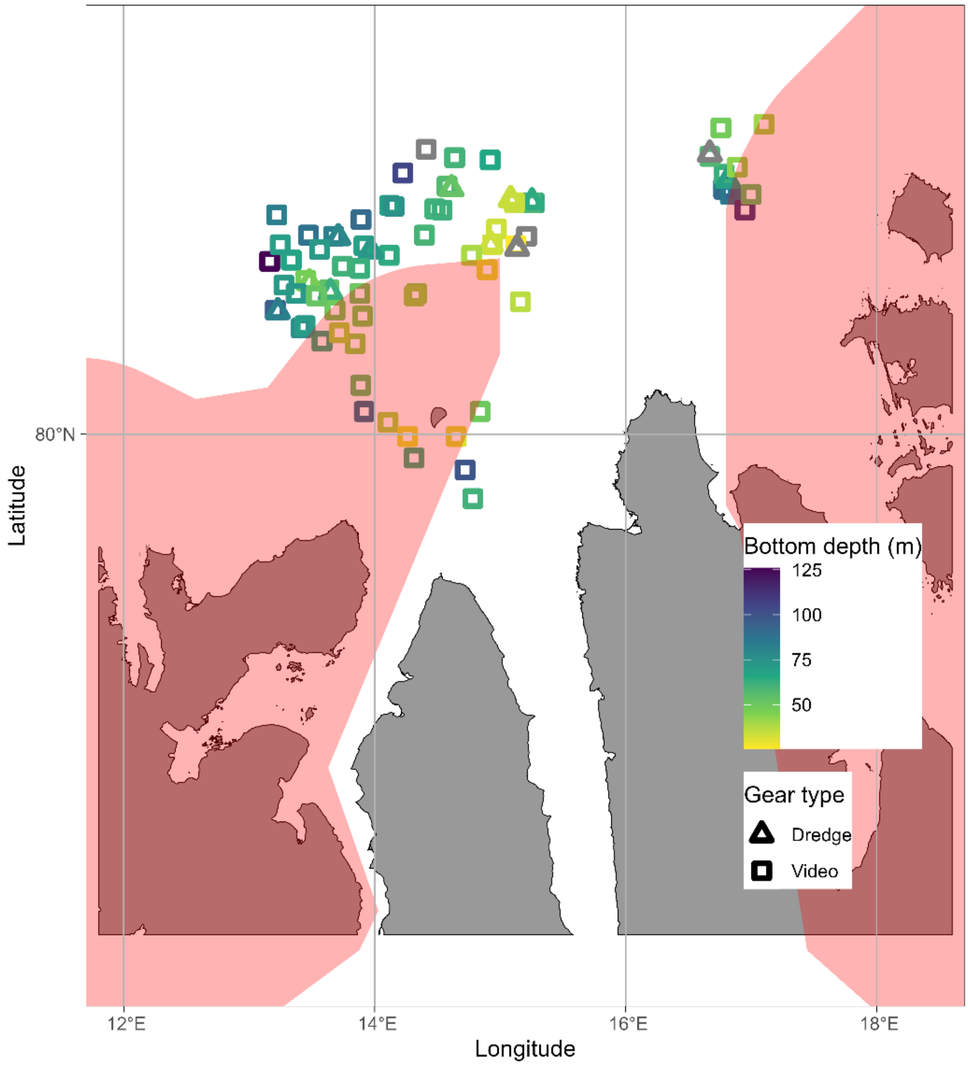

Figure 5 Overview of survey stations from Iceland Scallop survey in the Moffen and Parryflaket area (see figure 2 for locations of the two scallop beds). The colour difference indicates bottom depth (m) and the shapes indicates gear type. Protected area is shown as red polygons.

2.3 Sampling

We sorted the dredge content on deck and picked out all the Iceland scallops, and measured shell height of all the individuals, from the umbo to the shell edge. Ten individuals from each dredge were randomly selected and dissected. Tissue, mussel, digestive gland, and gonad samples were collected and conserved in a freezer to be processed onshore. The shells were then frozen for later age determination. Extra shell samples were selected to represent different sizes, hence different ages. The shells were age-determined following the procedure by Johannessen (1973).

Growth as the age-shell height relationship was estimated using the von Bertalanffy growth function (VBGF):

$$L(a) = L_{\infty} \times (1 - e^{(-k \times (a - t_0))}) \tag{2.1}$$

Where *L(a)* is the length of the scallop at age a, L_∞ is the asymptotic size, *k* the growth coefficient, *a* the age of the organism and t_0 the theoretical size at age $_0$ (Von Bertalanffy, 1938).

2.4 Video analysis

Scallop counts from video analyses were used to estimate the density and stock size in the Bear Island region and the Moffen region. Dredging of Iceland scallops is considered unsuitable for stock estimation because the area covered is challenging to standardize even with the same duration and speed, mainly because the dredge can fill up quickly in areas with larger rocks and other bottom substrate (Mann et al., 2004). We therefore used the dredge stations to collect biological samples, while the video recordings were used to determine the stock size. Each video recording from the 2019 and 2020 surveys lasted approximately 60 minutes.

The quality of the recordings varied with the speed of the sledge, in addition to the amount of marine snow, loose fine-grained sediments, and motion disturbances. The scallops were covered by barnacles, which made it difficult to separate them from rocks and other bottom substrate. It was also challenging to separate living scallops from dead, as the shells of dead scallops often remain intact over long time periods. Scallops were determined as living mostly based on visible live tissue of open scallops and their position, i.e., whether an upright position, opening angle, etc. provided clear indications of active feeding. We did not count individuals we were uncertain about, and only counted scallops that could be considered alive with high confidence. Consequently, one can assume that some living scallops were not counted, contributing to a conservative estimate.

Because differentiating (live) scallops is challenging due to their cryptic appearance on the sea floor, often together with dead shells, still-images with sufficient quality were needed. This was in a first step selected from the videos, extracting a subset of images from each video. The vessel's slow towing speed resulted in random segments of slow speed or standstill on the sea floor; the latter was suitable to extract images of sufficient quality to identify living scallops. This resulted in 32 – 285 (mean 122) single images from each station in 2019, and 1 - 317 (mean 173) images from each station in 2020. The video recordings lasted approximately 20 minutes in the survey in the Moffen region in 2022, generating 3 – 118 (mean 48) images from each station. We assumed that each image made up a random representative sub-sample of the whole station area in the further data processing.

Because of different camera systems, the images from 2019 represented an area of 0.65 × 0.65 m, while the images from 2020 and 2022 represented an area of 0.55 × 0.9 m. The area difference was standardized in further analysis to scallops per m^2. Six people identified, counted, and annotated scallops per image in the annotation program VIAME DIVE. The counting-experience varied between the counters; one can be considered an expert (counted scallops from the surveys in 2019 and 2020), three of the counters had some kind of experience with counting based on video recordings, but not on Iceland scallops, and the last two counters had no video-based counting experience. A subset of stations was assigned to each of the six counters to ensure that images from each station were annotated by two to five counters. The multiple counts per station were used to compare resulting scallop density and quantify counter bias and variation. In addition, each counter assessed individually if the images were of sufficient quality to be able to determine/count scallops, which led to a slight difference in the number of pictures per station between the counters in some of the stations.

The counting procedure used in this study was designed to 1) document the image analysis and counting procedure for transparency and reproducibility, 2) to compare and standardize counts and quantify uncertainty introduced by counter subjectivity, and 3) establish a library of annotated image for future training of image recognition algorithms based on machine learning. The goal was to improve the procedure previously used. To analyse the video data from the surveys in 2019 and 2020, one expert went through all recordings from all the stations, paused the videos when the image was clear enough to detect the scallops, and registered the number of scallops counted. These images or meta data about video location were not stored for later, nor was any comparison or cross-validation conducted.

2.5 Statistical analysis

All the analyses were conducted using R (v. 4.2.3; R Core Team, 2023), RStudio (Posit team, 2023) and the tidyverse package (Wickham et al., 2019). Statistical analysis and stock estimation were conducted with the following packages: glmmTMB (Brooks et al., 2017), sdmTMB (Anderson et al., 2022) and INLA (Bakka et al., 2018). The model residuals were checked using the DHARMa package (Hartig, 2022). ggOceanMaps (Vihtakari, 2022) was used to create maps.

Then we used three approaches to estimate the density of Iceland scallops around Moffen: A design-based swept area estimation, and two statistical models (generalized additive mixed models (GAMMs)).

2.5.1. Stock estimations

After the Bear Island region survey in 2019, the stock size was calculated using design-based approach (Approach 1) that represents a common and efficient approach to estimate stock size when assuming that observations are representative for the stock area. Here we compared the same approach with two model-based approaches, testing both a regular and a spatial GAMM (approaches 2a and 2b).

Approach 1 was a design-based swept area estimate; the density was calculated by using the mean of counted scallops per m^2 per scallop bed:

$$d = \mu_d \tag{2.2}$$

Where d is the estimated density and μ_d is the mean density of counted scallops (n/m^2). This approach was used as a baseline when comparing the three approaches.

Approach 2a and 2b were model-based stock estimations using GAMMs that differed mostly by whether they were explicitly spatial by including spatial correlation as spatial random fields (2b). Generalized models provide multiple advantages compared to approach 1, notably that they are flexible in handling non-gaussian distribution as often found with catches or densities (strictly zero-positive data, often with long right tails due to few very high observations), allow to include covariates that explain part of the observed variation such as bottom depth or environmental variables, and allow to include random effects to account for unobserved processes and clustering effects such as spatial variation or vessel or gear effects. Distribution of Iceland scallops is very patchy, and they tend to grow in clusters (Brand, 2006b), creating areas dominated by scallops and areas with few or no scallops present even on a very short spatial scale. The high degree of spatial variation represents a challenge for design-based estimates that assume representative observations from a relatively homogenously distribution population, and it also makes it difficult to stratify a scallop bed into statistically representative sub-areas. Therefore, we added geospatial information in approach 2b.

Approach 2a can be formulated:

$$E(Y) = \mu = f^{-1}(X\beta + Zu) \tag{2.3}$$

Where the expected value of Y is denoted as E(Y), μ is the mean, f is the link function, X is a model matrix for fixed effects and β is the fixed effects. The random effects model matrix is denoted as Z and u are the random effects (Hatefi, 2021).

The GAMM including spatial random fields (approach 2b) allows for inclusion of spatially auto-correlated random effects structure to account for spatial correlation and variation among data points. Approach 2b can be formulated:

$$E[y_s] = \mu_s = f^{-1}(X_s^{main}\beta + \alpha_g + X_{s,t}^{svc}\zeta_s + \omega_s) \tag{2.4}$$

Where $E[y_s]$ is the expected value of y in the point s (lowercase s stands for specific point s in the whole equation). The mean is denoted by μ_s, f is the link function, X_s^{main} and X_s^{svc} are different model matrixes (X_s^{main} is matrix for main effects and X_s^{svc} is matrix for spatially varying coefficients). β represents fixed effects, α_g represents random intercept by group g, ζ_s represents spatially varying coefficients and ω_s represents a spatial component (Anderson et al., 2022).

The mean scallop density per image per scallop bed was used to estimate density and the total amount of scallops per bed. The counted density of scallops per m^2 was the response variable, while bottom depth (with a thin-plate smooth spline restricted to three degrees of freedom) and scallop bed were included as continuous and categorical fixed effects, respectively. The sampling equipment (video sledge) differed between the first and the two other surveys, and gear type was therefore included as a random intercept to absorb potential “catchability” differences (i.e., differences in observations that might be linked to differences in camera angle or similar).

Because of the distribution of observed densities that included both zeros and positive continuous values, we modelled the response variable with a tweedie distribution with a log link.

The implementation of tweedie in glmmTMB and sdmTMB is a compound Poisson-Gamma distribution that combines Poisson for zero/non-zero and Gamma for positive-continuous values.

The tweedie distribution can be described;

$$\text{Tweedie}\ (\mu, p, \varphi)\ 1 < p < 2 \qquad (2.5)$$

Where mean is denoted μ, p is the power parameter determining the shape of the distribution and the dispersion parameter is φ. The tweedie distribution is flexible and can handle both underdispersion and overdispersion, and the dispersion parameter φ allows for flexible variance in the models (Anderson et al., 2022).

Mean densities and their standard errors were predicted from the fitted values of both GAMM implementations, either for the scallop bed effect with bottom depth set to the observed mean (approach 2a) or by predicting across integration grids for all scallop beds (approach 2b). A "simple" prediction was also done using the spatial GAMM (approach 2b), with bottom depth set to the observed mean, to compare the depth-density relationship between approach 2a and 2b. Integration grids were created as evenly spaced integration points within the scallop bed polygons, and for each integration point bottom depth was derived from GEBCO bathymetric data (www.gebco.net). The Iceland scallop usually grows between 35- and 100-meters depth in the Svalbard region (Rubach and Sundet, 1987), and regions with depths between 20 and 160 m were therefore selected. This grid was used when predicting the fitted values of the approach 2b. Predictions were done on population level, i.e., the random effect for gear was set to its mean (0). Approach 2b allows to predict across the spatial domain and therefore to estimate spatially weighted mean densities. This accounts for depth and habitat structure within a scallop bed and may provide a better representation of the spatial variation in density than a mean of observations. To represent uncertainty across the integration grid adequately, 500 simulations were generated that represent each a random draw from the joint mean and standard error estimate of the fitted model for each integration point.

We calculated the abundance (number of scallops per scallop bed) by multiplying the mean density estimates and 95% CIs from approach 1 and 2a with the area of the scallop beds. The harvestable biomass was calculated by multiplying the abundance larger than the minimum legal size (60 mm) with 0.07 kg (the mean total weight of Iceland scallops larger than 60 mm (Sundet and Zimmermann, 2020)).

3. RESULTS

In the first section the uncertainty of the counting method is described and assessed, to quantify the variation between counter and, thus, determine if the procedure gives a reliable mean count, that can be used in further density estimations. As important demographic characteristics of a population, shell height distribution and growth (fitted with VBGF) are presented and compared between the Moffen and the Bear Island regions. The ratio of scallops larger or equal to 65 mm in data from 2019, 2020 and 2022 surveys is contrasted with data from 1986 and 1987 in the two areas. The surveys from 1986 and 1987 are used as a baseline, to be able to comment on the development of shell height distribution in the two regions. Lastly, I compare three approaches (design based swept area, generalized additive mixed model (GAMM) and GAMM including spatial correlation) to estimate the density of Iceland scallop in the five scallop beds in the Moffen and the Bear Island regions.

3.1 Uncertainty in count estimates

The mean of observed/counted scallops varied between the counters. The variation in number of counted scallops did not have a counter-specific bias, that is mean counts did not follow a specific pattern related to the counter. The exception was one counter who had a tendency towards higher counts than those of the others (figure 6). The absolute uncertainty (standard deviation SD) tended to be higher on stations with higher mean count (n scallops/image), as expected, while the coefficient of variation (CV = standard deviation/mean of counted density) did not follow this trend. The CV was highest in stations with few scallops (see table A1, in appendix 1). The number of scallops seemed to be related to the number of images per station – the higher the number of pictures, the higher the number of scallops. Even though, this did not apply to all the stations (table 1); high number of images from areas with low scallop density did not increase the mean density count.

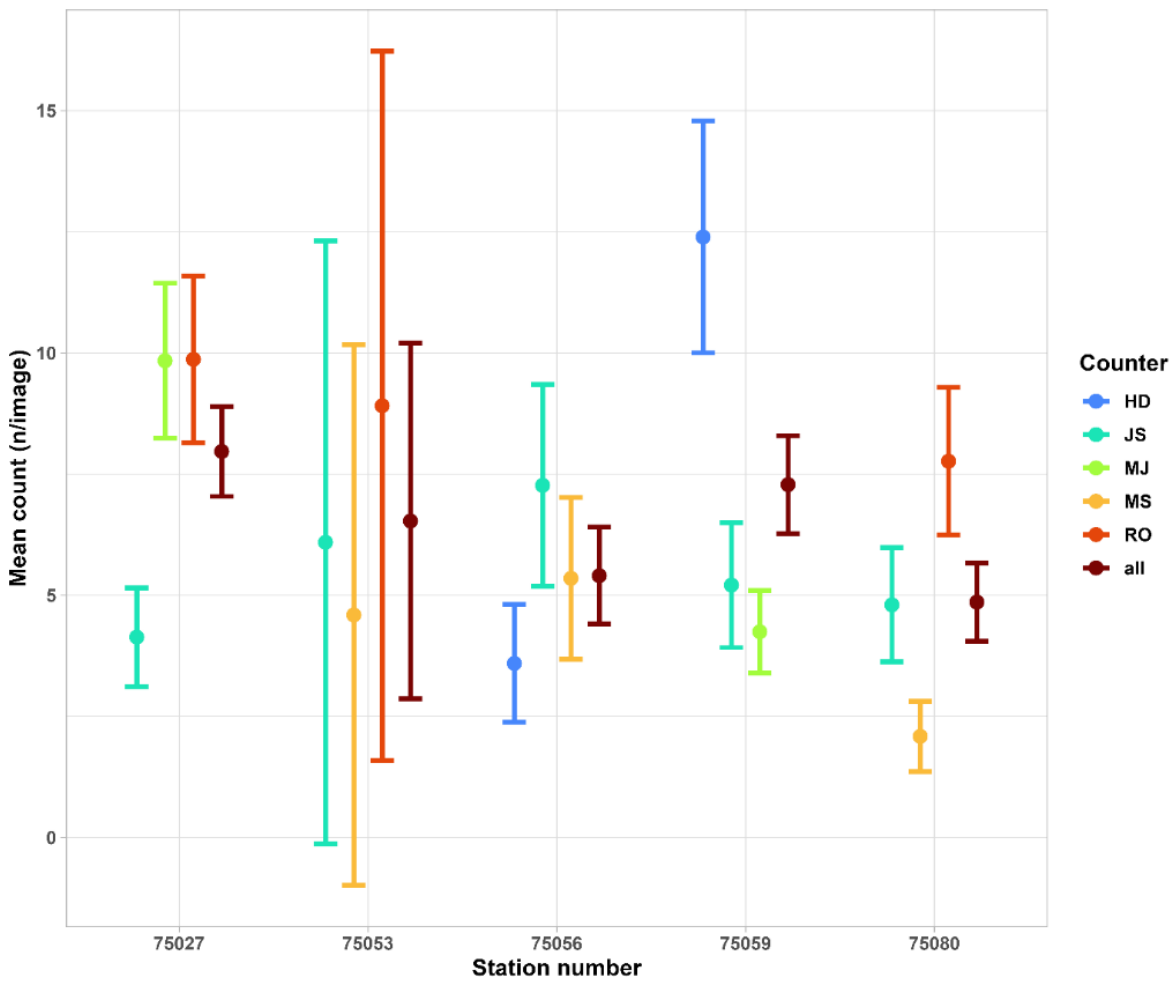

Figure 6 The mean of counted density of Iceland scallops (n/image), with error-bars showing 95% confidence level, based on five human counters. The stations with highest mean densities were selected, to illustrate the high absolute uncertainty in mean density counts between the counters.

The stations with the highest standard deviation in the scallop count per image were 75027, 75059 and 75080. All these stations had a high mean count (across the counters); over 4.8 scallops per image (figure 6). The stations with the lowest standard deviation, e.g., station 75021 and 75076, had a low mean count (less than one scallop per image) (table 1). 38 of 60 stations had a mean count of one scallop per image (see figure A1 in appendix 1).

Table 1 Overview of video-stations (with the highest and lowest standard deviation) in the Moffen region; counter ID, the number of counted Iceland scallops and number of images per station.

Station number	Counter ID	Scallops (n)	Images (n)
75021	HD	0	34
75021	JS	1	34
75021	MJ	1	34
75021	MS	1	34
75027	JS	277	67
75027	MJ	669	68
75027	RO	671	68
75059	HD	1 673	135
75059	JS	703	135
75059	MJ	573	135
75076	HD	3	70
75076	JS	3	70
75076	MS	1	70
75080	JS	168	35
75080	MS	73	35
75080	RO	264	34

The stations with the highest CV were the following stations: 75039, 75043 and 75082, with a CV between 1.18 and 1.73 (figure 7). The median CV per picture per station was 0.562. Station 75006 and 75014 had the lowest CV; 0.14 and 0.08. Both stations had a high mean count, while the stations with the highest CV had a relatively low mean count of scallops (across counters), (see table A1 in appendix 1).

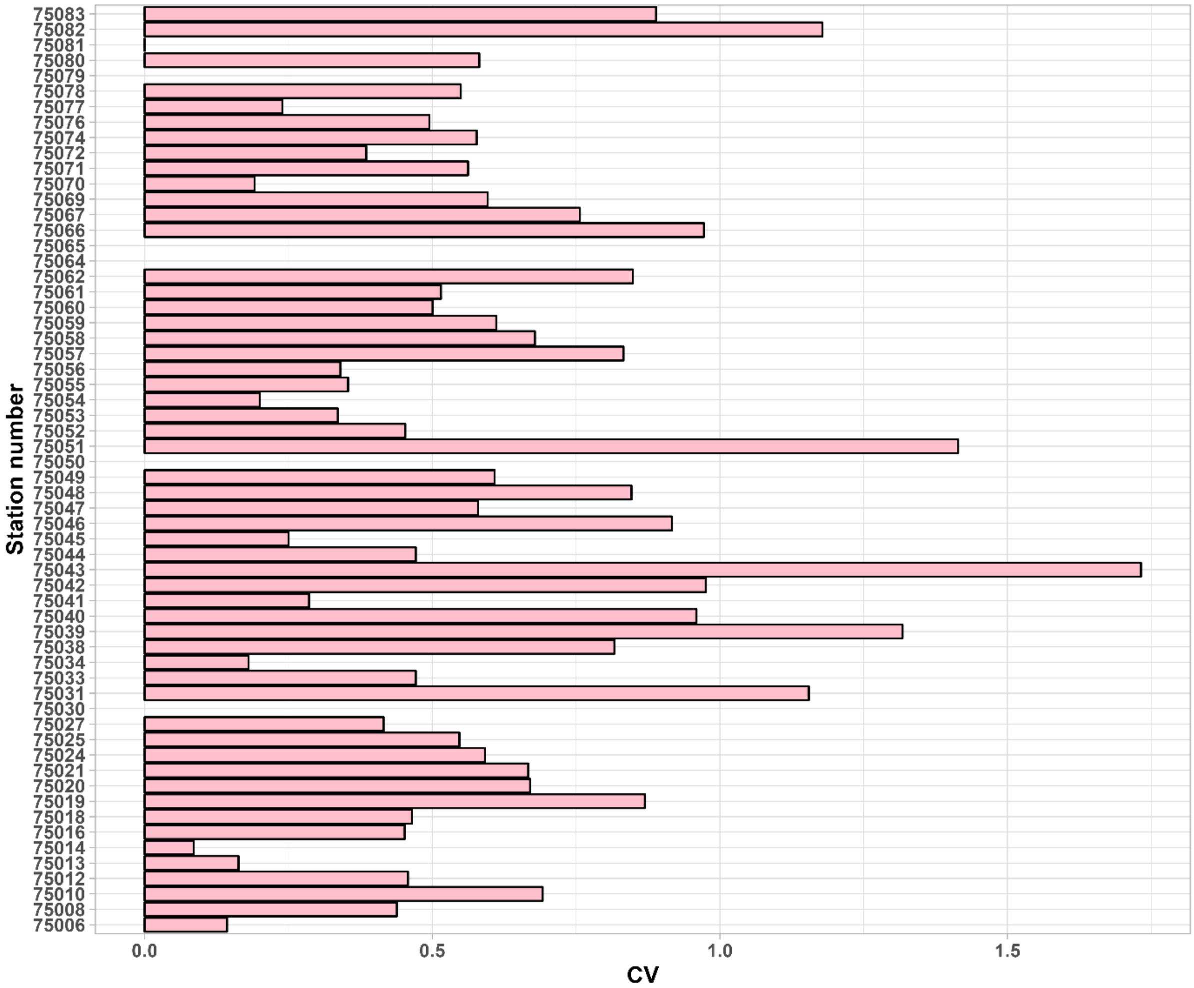

Figure 7 The mean coefficient of variation (CV = standard deviation/mean of counted density of Iceland scallops) per image per video-station. From survey in the Moffen and Parryflaket scallop beds north of Svalbard autumn 2022.

Despite the varying scallop count between the six counters, there was a clear common trend throughout all the stations; all the counters generally annotated high scallop density on the same images, and low density on the same images (figure 8). However, there were some exceptions; for instance, the counters annotated scallops in entirely different pictures in station 75049 (figure 8). Few scallops were annotated ($1<n<5$) in this station. Stations with more scallops had a more precise count pattern; the counters "agreed" on high-density images. Even so, there was still a large difference in the counts from images with the highest densities. An image from station 75059 for instance, has gotten approximately 90 scallop annotations from counter "HD", while "MJ" and "JS" counted less than 50 scallops in the same image (figure 8).

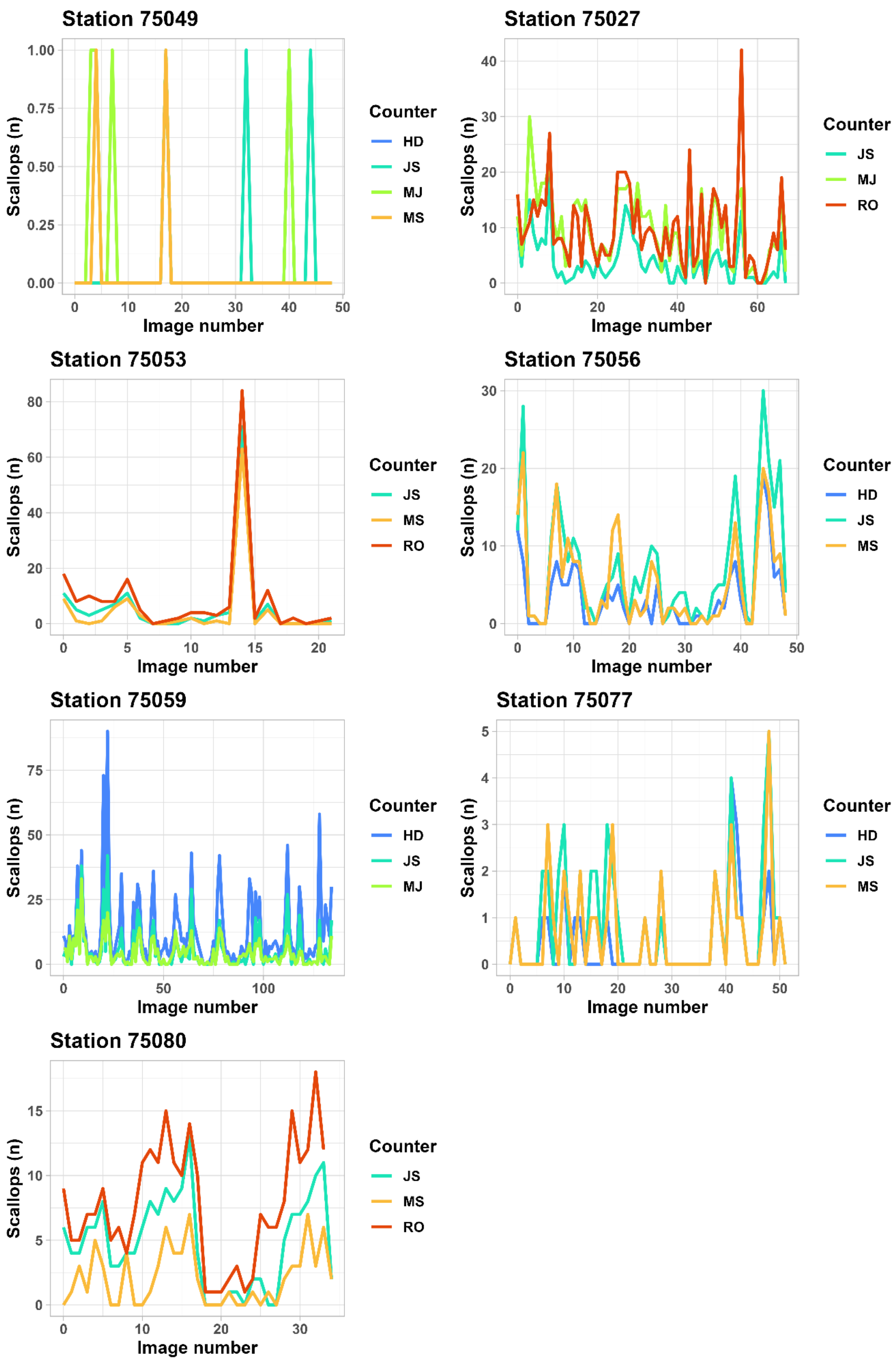

Figure 8 Selected video-stations from survey in the Moffen region. The number of Iceland scallops annotated per image, and counter (colours).

3.2 Population structure

Shell height distribution and age-shell height relationship were used to examine the population structure of Iceland scallop in the Bear Island and Moffen regions. I decided to look at the regional scale, because the growth and shell height distribution were very similar among the scallop beds within each region (see figure A2 and figure A3 in appendix 1).

3.2.1 Shell height distribution

Most of the scallops sampled in the Moffen region had a shell height between 50 mm and 75 mm. Few small scallops were caught, and no individuals larger than 100 mm were found, which resulted in a shell height distribution with a slight left skew (figure 9). 72% of the measured individuals had a shell height larger than the minimum legal size of 60 mm, while 15% were smaller 60 mm. 13% of the measured individuals had a shell height of exactly 60 mm.

The shell height distribution in the Bear Island region was also left skewed, with a longer tail of individuals smaller than mean shell height, than individuals larger than mean height (figure 9). The scallops in the Bear Island region were generally higher than the scallops in the Moffen region.

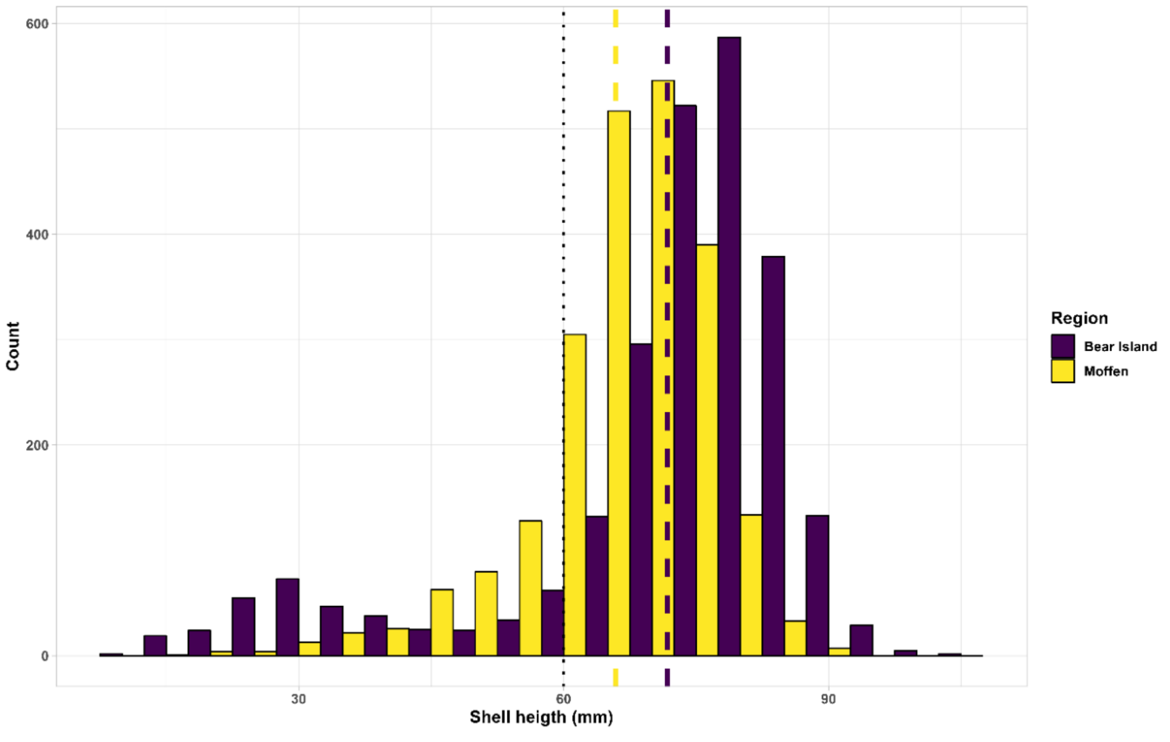

Figure 9 Shell height distribution of Iceland scallop in the Bear Island region (purple) and the Moffen region (yellow). Dashed lines show the means; the yellow line shows the mean in the Moffen region, and the purple line shows the mean in the Bear Island region. The dotted line shows the minimum legal size (60 mm).

The mean (66 mm) and maximum (90 mm) shell heights were lower in the Moffen and Parryflaket scallop beds than in the Bear Island region, where mean height was between 79 mm and 69 mm in the belonging scallop beds. Maximum shell height was between 100 mm and 105 mm in the beds in the Bear Island region (table 2). The highest individual was found in Kveitehola (105 mm), while the scallop bed southeast of the Bear Island had the highest mean size (79 mm).

Table 2 Shell height (mm) of Iceland scallops from scallop beds within the Moffen and the Bear Island regions in the Svalbard area.

Region	Scallop bed	Min	Mean	Max
Bear Island	Bear Island SE	13	79	103
	Concordia	10	69	100
	Kveitehola	15	73	105
Moffen	Moffen	15	66	90
	Parryflaket	27	66	90

3.2.2 Shell height and age distribution

There was a clear age and shell height relationship in the Iceland scallops in the Moffen region: The shell height increased rapidly in younger individuals, with an almost linear relationship for ages younger than 10, before it started to level off in scallops reaching 15 – 20 years of age. The older scallops found around the Bear Island were larger than in the Moffen area (figure 10). In addition, several individuals older than age 15 were registered in the Bear Island regions, with one individual determined to be 27 years old. In contrast, only one individual in the Moffen region was above 15 years old, representing the registered maximum age of 18.

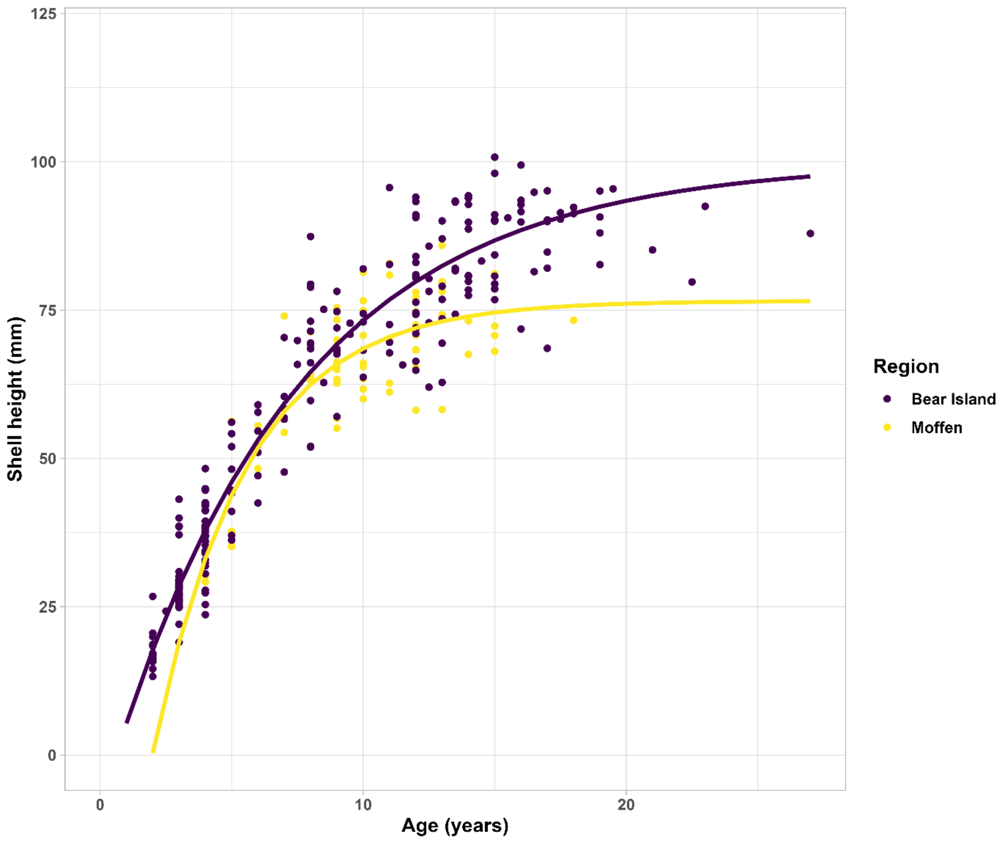

Figure 10 The relationship between shell height and age of Iceland scallop in the Moffen region (yellow) and the Bear Island (purple) region, fitted by von Bertalanffy growth functions.

According to fitted values from the von Bertalanffy growth function; the estimated asymptotic size in the Moffen region was 76.6 mm (95% CIs: 72.5 – 83.0 mm), compared to 100 mm in the Bear Island region (95% CIs 94.5 – 107 mm). The estimated growth rate K and the theoretic age at zero size (t_0) were found to be higher in the Moffen region (0.281 mm/year and 1.99 years) compared to the Bear Island region (0.141 mm/year and 0.609 years), (table 3).

Table 3 The von Bertalanffy growth function outputs for Iceland scallops in the Bear Island and Moffen regions.

Bear Island region			
Term	**Estimate**	**CI05**	**CI95**
Sinf	100	94.5	107
K	0.141	0.115	0.169
t0	0.609	0.159	0.997
Moffen region			
Term	**Estimate**	**CI05**	**CI95**
Sinf	76.6	72.5	83.0
K	0.281	0.193	0.383
t0	1.99	0.970	2.60

3.3 Historical comparison of population structure

The only historic reference for the population structure in the Moffen region is the proportion above minimum landing size registered during the surveys in 1986 and 87 (figure 11). The minimum legal size of 60 mm was not implemented in the Svalbard area when the surveys in 1980s were conducted, instead the minimum legal size implemented along the Norwegian coast (65 mm) was used to estimate the percentage of scallops of harvestable size. Therefore, we calculated here the proportion of the observed population above 65 mm when comparing the shell height rations from recent surveys with ratios from the surveys in the 1980s.

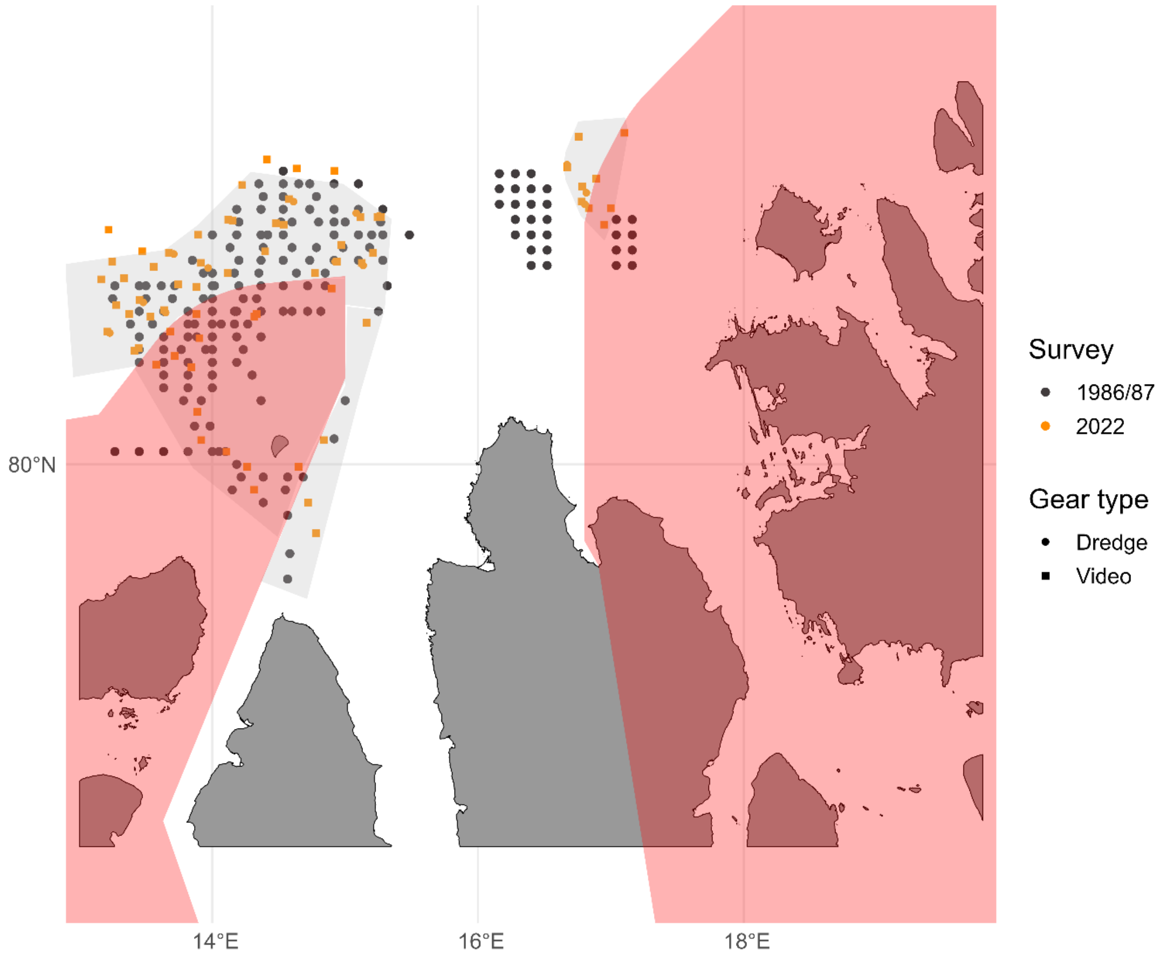

Figure 11 Map of planned stations from surveys in 1986 and 1987 (grey), and stations from the survey in 2022 (orange), in the Moffen region. Gear types used at each station are indicated by shape, and survey areas (scallop beds) through grey shading. Red areas show the protected zones.

The ratio of shell height ≥ 65 mm around the Bear Island region in 2019 and 2020 was approximately on the same level as in 1986 and 1987, while the ratio had increased from the

80s in the Moffen region. 55.8% of the sampled scallops had a shell height ≥ 65 mm in 1986, and the ratio decreased with 12.6% before the next survey and was only 43.2% in 1987. In 2022, samples from the Moffen region showed that 71.1% of the scallops had a shell height of 65 mm or greater (table 4).

Table 4 The percentage of Iceland scallops ≥ 65 mm, in the Svalbard area (Moffen and the Bear Island regions) from surveys in 1986, 1987, 2019, 2020 and 2022.

Year	Region	Ratio of shell height ≥ 65 mm (%)
1986	Bear Island	91.5
1986	Moffen	55.8
1987	Bear Island	87.6
1987	Moffen	43.2
2019	Bear Island	80.7
2020	Bear Island	85.8
2022	Moffen	71.1

3.4 Stock and biomass estimates

The scallop density and the biomass were calculated by three approaches; swept area estimate (approach 1), a nonspatial/regular GAMM (approach 2a) and a GAMM including spatial correlation (approach 2b). Table with the model estimates and standard errors from approach 2a and 2b (in addition to matern range, and spatial standard deviation from approach 2b) can be found in appendix 1 (table A2).

The Iceland scallops had a patchy spatial distribution. This patchiness was found on large-scale (figure 12), and on small-scale (e.g., different density within images from the same video station, figure 8). The density varied between 0 – 10 scallops per m^2 within the Moffen scallop bed (figure 12), according to estimations from the spatial GAMM.

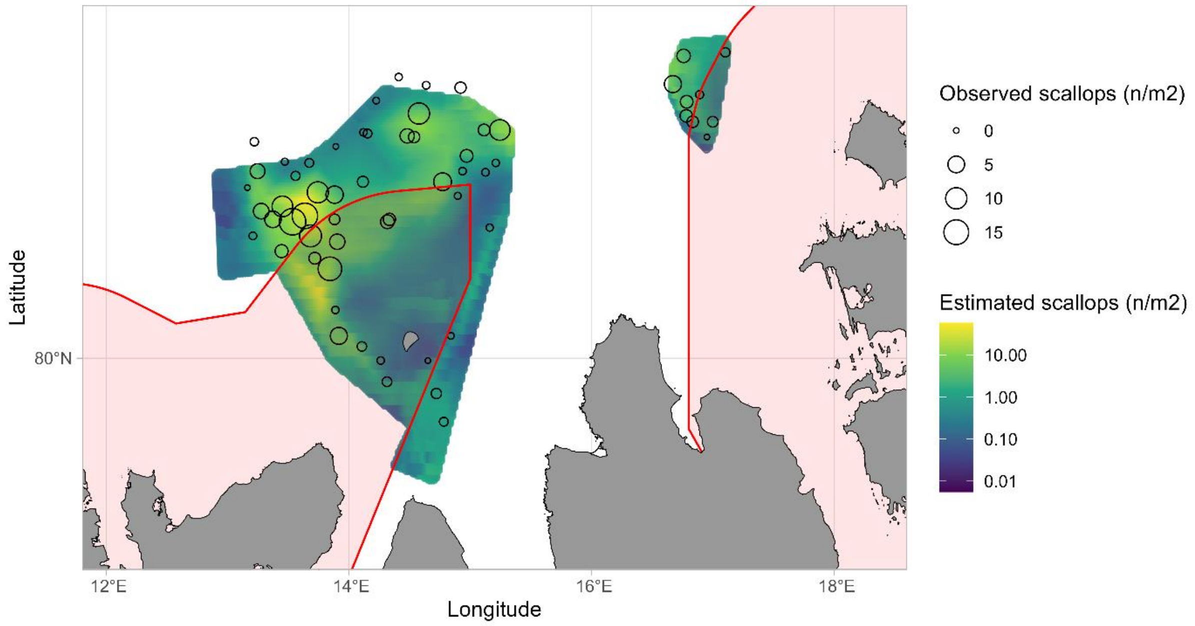

Figure 12 Map of the predicted density of scallops in the Moffen and Parryflaket region using a geospatial model (approach 2b; spatial GAMM implemented in sdmTMB). The colour scale shows the predicted scallop density per cell of the integration grid (note the logarithmic scale), while the size of black circles represents the observed scallop density per station. Red line, and red polygons show the protected area in the region.

The maximum density in the Bear Island region was one scallop per m^2 according to the spatial GAMM, while the observed scallop density (corresponds to swept area estimates) was up to 5 scallops per m^2 (see figure A4 in appendix 1).

The three approaches were consistent in the overall trend, estimating highest density of scallops in the Bear Island SE, Moffen and Parryflaket scallop beds (figure 13). There are, however, clear deviations in the absolute estimates and the corresponding uncertainty. For Bear Island SE, the model-based estimates were more conservative than the design-based estimate. For Moffen and Parryflaket, on the other hand, the highest estimates were from the nonspatial GAMM, relatively clearly deviating from the other two approaches. The confidence intervals overlapped in all cases, suggesting that none of the differences were significant.

According to the three approaches, the density in the Moffen bed (outside of the protected area) was between 1.4 (spatial GAMM) and 4.3 scallops (regular GAMM) per m^2. The density in the Parryflaket bed was between 1.7 (swept area approach) and 3.9 (regular GAMM) scallops per m^2. Whereas the scallop bed southeast of the Bear Island contained the highest density in the Bear Island region (density between 1.1 (regular GAMM) – 2.2 (swept area approach).

Concordia and Kveitehola had the lowest density with 0.2 (spatial GAMM) – 0.5 (swept area) scallops per m^2 and 0.3 (spatial GAMM) – 0.6 (swept area) scallops per m^2 respectively.
The spatial GAMM produced, in general, the lowest estimates (except for the Parryflaket bed, where the design-based estimate was the lowest). The regular GAMM gave the highest density estimates in the Moffen and Parryflaket beds, while the design-based estimates were highest in the Concordia, Kveitehola and Bear Island SE beds compared to the other two approaches. The regular GAMM estimates had the largest uncertainty as represented by the 95% confidence intervals.

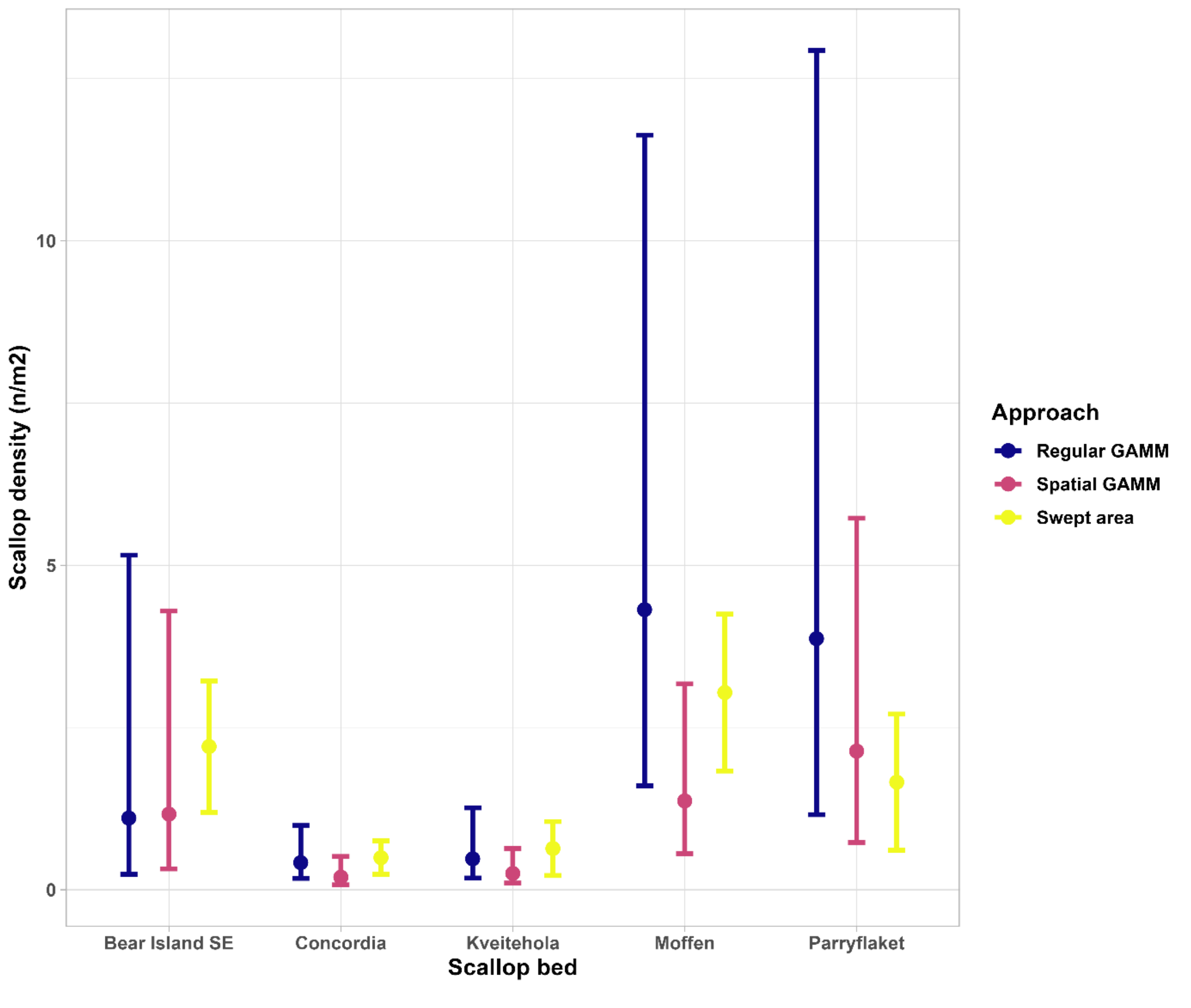

Figure 13 The density estimates of Iceland scallop (n /m^2), with error bars showing 95% confidence level, per scallop bed. Based on three estimation approaches; design based swept area, regular generalized linear mixed effects model (GAMM fitted with glmmTMB) and a spatial GAMM (fitted with sdmTMB).

The highest density was found in the Moffen scallop bed. The Moffen bed also covered the largest area and, as abundance is the product of density and area, Moffen also had the highest total estimated abundance (see figure A5 appendix 1). In addition to the highest harvestable abundance (between 1 015 × 10^6 (spatial GAMM) and 3 164 × 10^6 (regular GAMM) scallops in the bed). The harvestable biomass in the Moffen bed was therefore higher than in any of the other four scallop beds (figure 14). Parryflaket and Bear Island SE also had a high density, but the harvestable biomass was much lower than Moffen because of the smaller size of the two scallop beds. The Concordia and Kveitehola beds cover a larger area than the Parryflaket and Bear Island SE beds, thus containing approximately the same amount of biomass as Bear Island SE and Parryflaket. According to the three estimation approaches, the harvestable biomass in the Moffen bed was between 71.1 × 10^3 tons (spatial GAMM) and 221.5 × 10^3 tons (regular GAMM), and 15.4 × 10^3 tons (swept area) - 6.59 × 10^3 tons (regular GAMM) in the Parryflaket bed. In the scallop beds around the Bear Island, the estimated harvestable biomass based on the three approaches were respectively 14.2 - 28.4 × 10^3 tons, 17.8 - 44.6 × 10^3 tons and 10.4 - 25.7 × 10^3 tons in Bear Island SE, Concordia and Kveitehola. The exact density, harvestable biomass and harvestable abundance estimates can be found in table A3 in appendix 1.

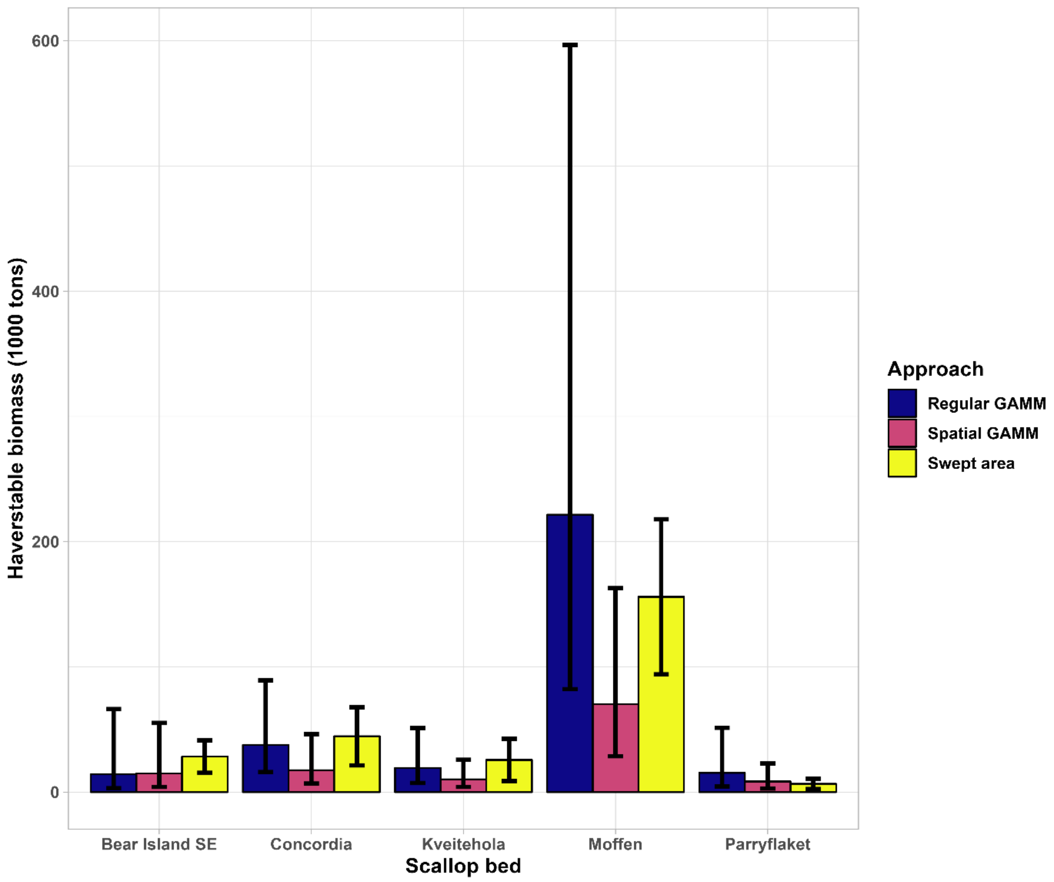

Figure 14 The estimated biomass (1000 tons) of Iceland scallop, with error bars showing 95% confidence level, per scallop bed. Based on three estimation approaches; a design based swept area, a regular generalized linear mixed effects mode (GAMM fitted with glmmTMB) and a spatial GAMM (fitted with sdmTMB).

According to the regular GAMM was the scallop density in the Moffen scallop bed highest at approximately 60 meters depth, with a density higher than 5 scallops per m^2 (figure 15), while the predictions from the spatial GAMM showed that the density was highest at approximately 70 meters depth, with a density around 2.5 scallops per m^2 (figure 15). We did not have sufficient depth samples to be able to assess the depth-density relationship in Bear Island SE, Concordia and Kveitehola.

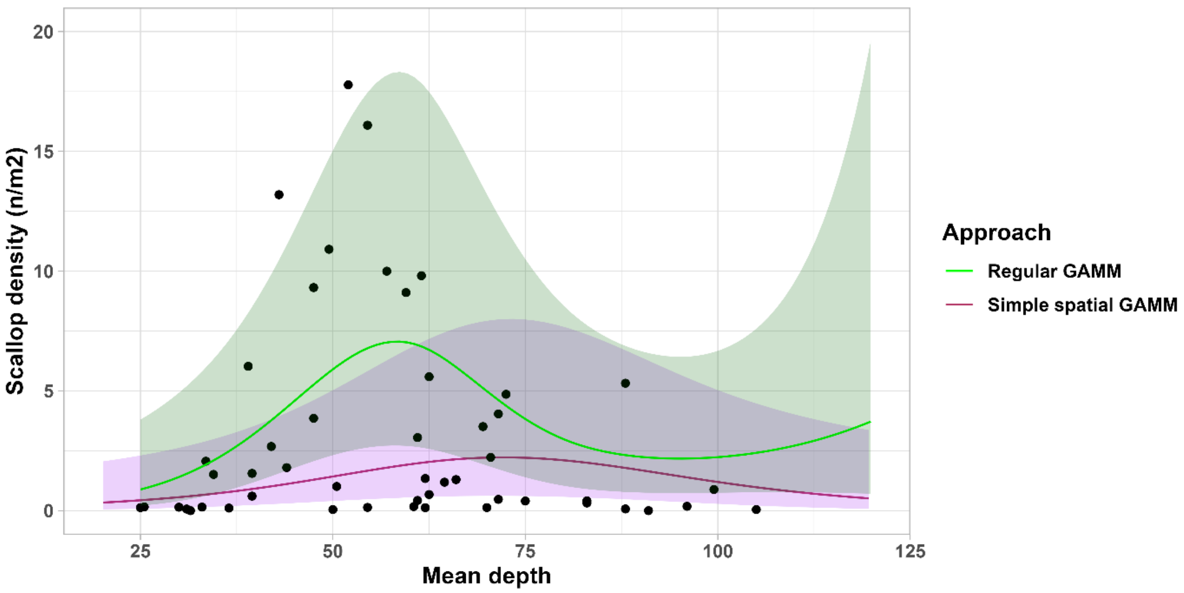

Figure 15 The estimation of Iceland scallop density (scallop/ m^2) based on mean station depth per scallop bed, with shaded area showing 95% confidence level. Estimations were based on a "simple" (based on mean of observed depth) spatial GAMM prediction (fitted with sdmTMB), and a regular GAMM (fitted with glmmTMB). The scatter points show the number of scallops counted pr m^2.

4. DISCUSSION

The relative uncertainty in count estimates was assessed by calculating the coefficient of variation (CV), which showed that the mean counts from stations with low density had the largest relative uncertainty, while stations with high density had a lower relative uncertainty (figure 7 and table A1 in appendix 1). Thus, mean counts in areas with higher density might be more accurate, than in low-density areas.

According to the two demographic characteristics we assessed (shell height and growth) were the scallops in the Bear Island region larger than the ones in the Moffen region (figure 10), while the scallops in the Moffen region grew faster (table 3). Comparison of shell height with historical references showed that the ratio of scallops ≥ 65 mm was either larger than the ratio in 1986/87 (Moffen region), or slightly lower (Bear Island region), (table 4).

The three approaches (approach 1; a design based swept area, approach 2a; a regular generalized additive mixed model (GAMM) and approach 2b; a spatial GAMM), were consistent in the overall trend, estimating highest density of scallops in the Bear Island SE, Moffen and Parryflaket scallop beds (figure 13).

4.1 Uncertainty in count estimates

We chose to have several counters to rule out bias and hopefully reduce the uncertainty in the scallop counts. The higher the number of scallops counted per station, the higher the standard deviation (SD) between the different counters, as expected. However, the relative variability, quantified as the coefficient of variation (CV), deceased with higher number of scallops, and increased with low scallop density. Stations with high scallop density contain a lot of scallops and consequently a lot of reference points when assessing whether an individual is living/dead, while stations scarce of scallops contain few reference points, which could a reason of the high CV in stations with few scallops. The variability in counts might also be a result of different experience or fatigue (Franklin et al., 1980, Giguère and Brulotte, 1994). Counting from video recordings have proved to be time consuming and fatiguing. The maximum time a counter could keep full focus is approximately 15 min, according to Rosenkranz and Byersdorfer (2004). Nevertheless, if the difference in mean count was a result of focus-problems, one would assume that there would be a pattern between variation in counting and the number of still-images - that stations with many images would have a higher CV, which we do not see. However, Giguère and Brulotte (1994) counted during the recording, which might be harder on the concentration, than looking at still-images.

There is a visible difference in the number of counted scallops per still-image between the counters, however, there was limited systematic bias. Instead, trends were mostly the same; pictures with high density had high counts, while pictures with low density had low counts (figure 8). This indicates that intra-picture variation among the counters tends to average each other out across all pictures of a station. Estimating the density from the 2019 and 2020 surveys, only one person counted and chose the relevant still images used for the density estimation. It was the same counter in both surveys, and this "experienced" counter also counted scallops in this survey, in addition to five other counters. The agreement was that we only annotated/counted scallops that we considered living scallops, to get a conservative count. However, the different counters had varied experience with scallop counting, and might also have different assumptions when determining living scallops. Some scallops were planted with the umbo attached to the bottom substrate, and the shell rim upwards, with the shell open. In these cases, it was easy to see the mantel edge with eyespots, thus easy to see that the individuals were alive, while some individuals were placed with the umbo upwards, and therefore harder to assess. One could assume that scallops with the rim down in the sediment might be dead, as it would obstruct free flow of water and nutrients from the surrounding waters. However, this was considerations the counters could have assessed differently based on the varied experience. The counters might have had different assumptions when counting, consequently the number of scallops per picture might vary with the counter. The results here show that there are subjective differences that may result in additional uncertainty through the counting process if only one person was to process a station. More standardization is therefore needed to reduce this effect; all the counters should probably compare, discuss, and have a clearer agreement of what signs should be considered alive/dead in future surveys.

Although counter-specific bias was limited, there was one counter with a tendency towards a higher count per still-image compared to the other counters. Other scallop studies using video recordings to estimate scallop density, noticed more accurate counting with experience (Franklin et al., 1980, Rosenkranz and Byersdorfer, 2004). Based on this, one would assume that the counter who processed the survey in 2019 and 2020 and was also included in this study, had most Iceland scallop counting experience and therefore produced the most accurate counts. However, the consistency of counters themselves was not assessed here. Rosenkranz and Byersdorfer (2004) made each of the counters count a subset of the stations twice to inspect for bias, we did not have time to do this in this study, but this should perhaps be implemented in future studies. Furthermore, the library of annotated images could be used to develop a machine-learning approach to automatic scallop detection to support counters in the future and contribute to standardize counting performance.

4.2 Population structure

Truncated size distributions towards smaller individuals are a typical sign of strong fishing pressure and, possibly, overfishing (Berkeley et al., 2004). Comparing current size distribution with an unfished reference can therefore provide indications on the population status. The shell height distribution in the Moffen region suggests, accordingly, a recovery of the populations on the scallop beds. The distribution of the shell height samples shows that 84.9% of the sampled scallops in the Moffen area had a shell height of minimum legal size (60 mm) or larger (figure 9). To be able to compare these results with the earlier distributions (surveys from 1986 and 1987) the ratio of scallops equal to or over 65 mm was also calculated. The size structure can be affected by several factors, such as environmental variation and disease (Lyles and Dobson, 1993, Stenseth, 1999, Ciannelli et al., 2004). However, unharvested Iceland scallop beds are usually "accumulated populations", which means that the population contains mostly larger/older individuals. The stock size is strongly determined by density dependent factors (Vahl, 1982, Sundet, 2006) such as available substrate (Underwood and Denley, 1984, Gaines and Roughgarden, 1985). In addition, it has been suggested that the feeding mode of Iceland scallops, filter feeding, may lead to ingestion of own offspring when population density is high (Sundet and Zimmermann, 2020). Combined, these density-dependent factors may strongly limit recruitment in an unfished population, resulting an over-compensatory, Ricker-type stock-recruitment relationship (Ricker, 1954, Zimmermann et al., 2018).

Based on the observed size structure, one could argue that the stock has grown back to this aggregated state that was found before the fishing started. The shell height distribution resembles the distribution before the fishery started in 1986. In fact, the number of scallops over the height of 65 mm was 15.3% higher than in 1986 in the Moffen region (table 4). The survey in 1987 showed the start of a decreasing trend in shell height that led to the closing of Iceland scallop harvest in 1992 (Sundet, 2006). Given that we found a higher proportion of scallops above 65 mm, we can assume that the size distribution and, thus, the population in the Moffen area might have recovered. This conclusion is constrained by a limited sample size, given that at only 13 stations biological samples were collected. None of those was within the

protected area that was sampled in the survey of 1986 and 1987. Additional samples from outside and inside the protected area could help to strengthen the assessment of the stock status and help to uncover possible spatial variation in the size composition.
In contrast to the Moffen region, the ratio of scallops larger than 65 mm in the Bear Island region was 10.8% lower in 2019 compared to 1986. This decrease can be a result of the past overfishing – the stock has might not recovered to its former distribution. Medina et al. (2007) suggested that the failed recovery in the scallop species *Argopecten ventricosus* in the Los Angles could be lack of available substrate for larvae settlement, predation, or environmental variation - perhaps these factors can apply for Iceland scallop recovery as well. However, given the relatively small difference it might be caused by observation uncertainty due to the limited sample size. We cannot know for sure that the current ratio of individuals over 65 mm is over or under the ratio in 1986, however the distributions might be used together with density estimates as an indicator that the population in the Bear Island region, as in the Moffen region, has increased to what one might expect after 30 years without harvesting. Our results are in line with the conclusions from (Sundet and Zimmermann, 2020). Compared to the survey in 1986, the year after a fishery commenced in the Svalbard area, the size distribution seems to be restored.

The survey showed a difference in shell height between the Bear Island region and the Moffen area; the mean shell height was lower in the Moffen area (table 2). This has also been registered in earlier research. The difference in size could be a result of temperature differences between the two regions (Sundet, 2006); however, currents bring "warmer" Atlantic water both to the Bear Island region (Wiborg, 1970, Loeng, 1991) and the Moffen region (Sundet, 2006, Piechura, 2009). During the survey in 1986, Sundet and Rubach recorded the surface and bottom temperatures both in the Bear Island and Moffen region. The bottom temperatures were respectively between 2.09 – 2.99 °C and between 3.07 – 4.97 °C in September 1986. The estimated growth rate K and the theoretic age at zero size (t_0) were found to be higher in the Moffen region (0.281 mm/year and 1.99 years) compared to the Bear Island region (0.141 mm/year and 0.609 years), (table 4). The higher growth rate (mm/year) in the Moffen region could be a result of the higher temperatures. However the growth rate (mm/year) was lower in the scallops in the Moffen region compared to the Bear Island region, from the survey where temperatures were measured in 1986 (Rubach and Sundet, 1987). The higher growth rate K in the Moffen region is most likely caused by few to no samples of the smallest and youngest individuals, that gave an inaccurate t_0-value (age at year 0), and t_0 should have been fixed to zero instead. Research on growth of Iceland scallops showed that the scallop growth is mainly nutrient limited (Sundet and Vahl, 1981, Blicher et al., 2010) and that temperature is not that important in relation to growth (Sundet and Vahl, 1981), which means that if the growth (mm/year) truly is higher in the Moffen region, it could has been by change in nutrition availability compared to the 1980s. However, the scallops in the Bear Island region grew larger than the scallops in the Moffen area, where the shell height growth trend declines around the age of 15 years (figure 10). Since research shows that nutritional conditions affect the growth more than the temperature (Vahl, 1978, Wallace and Reinsnes, 1985, Thorarinsdóttir and G, 1994), the lower shell height in the Moffen area might be limited by nutritional shortage. Considering the Moffen region is at a higher longitude (~ 80° N) than the Bear Island region (~ 74° N), this will affect the day-length in the two regions, which again will affect primary production in the area. Since the Bear Island is farther south, it will get longer periods with light, hence longer periods with primary production (Smith Jr and Sakshaug, 2013). Which could contribute to the shell height difference in the two regions. The size pattern seems to be the same as in the 1980s; the scallops grew lager in the Bear Island region compared to the Moffen area (Rubach and Sundet, 1987).

4.3 Stock and biomass estimates

Estimated density (scallop/m^2) in the Moffen and Parryflaket region was highest independent of the approach (figure 13). Because the scallops in this region were generally smaller than in the Bear Island region, this might lower the abundance of individuals over minimum legal size. Even though, the individuals generally have higher shell hight in the Bear Island region, the difference in percentage over/equal to 60 mm was not that large; 84.9% in the Moffen region and 85.1% in the Bear Island region. The shell height in the Moffen region had a minimal effect on the abundance of scallops over/equal to 60 mm. Thus, the abundance of individuals over minimum legal size were larger in the Moffen region than in the Bear Island region (see figure A5 in appendix 1). Moffen is, in addition, the largest scallop bed, which results in the highest scallop abundance and biomass. Since the Moffen is both the largest scallop bed (in the Svalbard region) and seems have the highest density of Iceland scallop per m^2, the estimated harvestable biomass was considerable larger in this area compared to the other beds despite a slightly lower proportion of scallops above minimum landing size. Parryflaket also had a high density, however the number of samples were low compared to the Moffen area, thus the density estimations are more uncertain around Parryflaket. Even though, the density might be as high as around Moffen, the Parryflaket bed is considerable smaller in size, and the total abundance is therefore comparatively low.

The mean density estimations based on the surveys in 1986 and 1987 were based on counts from photos taken with Benthos underwater camera. The method, photo quality and number of photos differ too much from the ones used in this study, to be able to compare the estimated densities then and now – but the general trend is the same; the density was higher in the Moffen region than in the Bear Island region. Moffen was also the bed with the highest occurrence of Iceland scallop in the Svalbard FPZ (Sundet and Rubach, 1988).

4.4 Uncertainty in density and biomass estimates

All the three approaches (a swept area estimate, a regular generalized additive mixed model (GAMM) and a spatial GAMM) used to assess the stock, are based on the mean of the counted scallops per m^2, because the data from 2019 and 2020 contained only the mean value of scallops per m^2. However, the counting data from the survey in 2022 allowed us to check how using the median of the count density affected the density estimations. The median values gave more conservative estimates, and consequently lower scallop abundance. Since we compare our results from the 2022 survey with the data and estimates from the 2019 and 2020 data, we decided to keep using the mean value in our estimations. However, the choice of mean or median as predictor variable should perhaps be scrutinized more in future stock estimates.

The three estimation approaches calculated highest density of scallops in the Moffen region (the two scallop beds; Moffen and Parryflaket), and the bed southeast of the Bear Island (figure 13). The spatial GAMM gave the most conservative estimates (except for the swept area estimated around Parryflaket). The regular GAMM gave estimates with the highest uncertainty, while the spatial GAMM and the swept area estimates had less uncertainty. The spatial GAMM estimates include more data points, explaining more of the variance than the other models (Anderson et al., 2022), resulting in estimates with lower uncertainty. The swept area model is the simplest one, assuming uniform distribution and no random effect. The model did not take the scallops patchy distribution or depth relation into consideration. Even though the swept area estimates have lower uncertainty than the regular GAMM, the assumptions of the swept area approach make it inadequate to fit the clustered distribution of Iceland scallops. However, this approach was used in earlier stock estimations, and consequently interesting to check when considering method-based differences in distribution in earlier studies compared to newer statistical models. The swept area estimates varied compared to the other models; the swept area density is highest (compared to the density of the two statistical models), in the scallop bed Southeast of the Bear Island, in Concordia and Kveitehola, while giving the lowest density estimate in Parryflaket and second highest density around Moffen. To conclude; the swept area model does not estimate density in a specific direction compared to the other models.

The sdmTMB models needs a large quantity of environmental data to make accurate predictions on species distributions (Anderson et al., 2022). Estimates of the design-based and the nonspatial GAMM approaches depend on the assumptions that observed mean density is representative for the entire scallop bed, with assumptions on mean bottom depth acting in addition as scaling factor in the nonspatial GAMM. The latter could be partially resolved by taking the depth distribution within a scallop bed more explicitly into account, like the integration grid used for the spatial GAMM. The uncertainty in the nonspatial GAMM estimates were largest for the three scallop beds: Bear Island SE, Parryflaket and Moffen. The large uncertainty reflects partly the low sample sizes in connection with large variation in density, especially on Bear Island SE and Parryflaket. This also indicates that the design-based approach might not represent uncertainty adequately. Confidence intervals in the design-based approach were based on standard errors of the mean density, which implicitly – and given the distribution of observations, incorrectly, assumes a normal distribution of observations. The spatial GAMM provides therefore an adequate solution, as it allows to account for spatial correlation in the distribution in addition to depth-related variation. Using a geostatistical approach such as the spatial GAMM presented here to estimate scallop abundance is therefore recommended. The density estimates from the spatial GAMM are lower than the other model estimates (expect in the Parryflaket bed), illustrating that including explanatory variables and spatial variation tends to give more conservative estimates. Considering that we can assume it the most credible of the three approaches we use, this illustrates that simpler approaches might easily overestimate scallop density. Thus, accounting for spatial variation in abundance estimates will help to reduce risks for future quota advice. The approach is, furthermore, flexible to expand the model configuration with habitat and environmental information as well as temporal correlation if more data becomes available in the future (Anderson et al., 2022).

When comparing to a “simple” prediction from the spatial GAMM that assumes a fixed mean depth, as in the nonspatial GAMM, one can see that including the depth information affects the estimation of the density and its uncertainty. Without an explicit spatial prediction of density across an integration grid, the result of the spatial GAMM resembles therefore much more the ones from the nonspatial GAMM (see figure A6 appendix 2). The potential bias of not explicitly account for (variation in) bottom depth becomes especially clear for estimates within the protected Moffen area, where it is relatively shallow.

Stock estimations based solely on a few research cruises contain a lot of uncertainty from both the sampling and counting process in addition to the choice of statistical models. Consequently, stock estimates from surveys are normally only used to assess relative changes in abundance through time, instead of determining absolute stock units (abundance, density and biomass), (Hart et al., 2008). As relative few observations are extrapolated to a large stock area, minor inaccuracies and uncertainties in density estimates can easily scale to substantial deviations in absolute stock size. Our assumptions on the representativeness of observations might be also problematic given the many sources of observation errors. The video sledge's random pausing on the sea floor gave a random assemblage of still-images. Yet, when watching the videos and selecting these still-images, it becomes evident that the pausing of the sledge may not be representative for the video transect, and, subsequently, the scallop bed. Based on observation, I am under the impression that the sledge seldomly paused in areas with the highest scallop densities. Scallops prefer areas with complex bottom sediment and stronger currents (Ekman, 1953, Wiborg, 1962), where visibility is poorer and it's harder for the vessel to keep a good pace. However, this might just contribute to a conservative estimate. Factors as marine snow and flowing sediment distributions also influenced the picture selection. Nevertheless, an earlier assessment of video and dredge technics regarding density estimation of scallops, showed that the video samples gave more accurate estimates (Giguère and Brulotte, 1994). Video surveying is, furthermore, less invasive, as its impacts on the bottom substrate and benthic organisms are very minor compared to dredging (Rosenkranz and Byersdorfer, 2004). Further strengthening video surveys by improving the quality of data collected is therefore recommended. Future surveys should therefore explore possibilities to collect images of high quality more consistently and comprehensively. Possible options are either to focus fully on a still-image approach, for instance with drop camera, or explore new technology that potentially allows for better quality from videos or image reels. The latter might be provided by automated underwater vehicles specifically designed for this purpose.

4.5 Future work

Given the limited resources to survey a species such as Iceland scallop and the need to provide advice on a potential reopening in the Moffen region, the data from the survey in 2022 should contribute to as much background information on the stock as needed, to be able to compare future stock assessments with the current stock conditions. I therefore propose using the data from the 2022 survey to the following research:

1) The density estimations in this survey will be the base when determining a sustainable harvesting quota. Considering the uncertainties within stock estimations, I would suggest using the same measure as used when determining the quota for the Bear Island region in 2019; instead of using the maximum sustainable yield (MSY), rather use a more precautionary measure such as the "Pretty Good Yield" (PGY), which is at least 80% of possible MSY (Hilborn, 2010). Further, the uncertainty in stock estimates should be thoroughly propagated and explored in a management strategy evaluation framework. Accounting for the spatial dimension of both the stock distribution and the fishery will be important for the advisory process.
2) Since the video samples from the survey from 2022 always were coupled with dredge samples from the same area, the data can be used to look at the "catchability" of video or dredge gear to potentially calibrate the gear types against each other and use dredge data in future estimates of the stock size. Dredge is known as a semiquantitative method, because of a lot of uncertainties even with fixed sampling conditions, e.g., the dredge might fill up in the start of the dredge station not having room for more substrate or get stuck and not cover the distance as planned (Mann et al., 2004). In addition, the calculations based on video-counting have shown to give more accurate density estimations (Giguère and Brulotte, 1994). However, it could be interesting to determine how comparable observations are between the two methods.
3) The video samples within the protected area provide information on the distribution and state inside and outside of the protected area. This baseline can be used to follow the development of densities outside and inside the protected area if fishing outside of the protected area is restarted.

We did not weigh the scallops during the survey in 2022, which I would recommend in future surveys. Here, as in previous reports, biomass calculations were based on scaling abundance above minimum landing size with an observed mean weight for this part of the stock. However, this ignores variation in weight both linked to stock structure and among regions. Collecting individual weight data systematically would allow to estimate region- or bed-specific length-weight relationships and estimate biomass more precisely. Other future improvements would be that the counter discuss and evaluate each other's counting or going through a selection of stations once more to rule out counting bias.

4.6 Conclusion

This study aimed at quantifying person-specific uncertainty and bias in annotations of Iceland scallops in images from video footage, using scallop densities from annotated images to estimate the stock size, and determining the stock status from size distribution and age data. The following main results and conclusions were attained:

1) Using more people to count the number of scallops on still-images from video recordings showed variation between the counters, but only limited differences in mean densities or systematic bias. *This entails that it is not ideal to have only one counter, although that is the most feasible given limited capacity. For future improvement a suggestion would be to repeat this kind to counting comparison and standardization exercise and repeated counting of a subset of stations to rule out bias. Furthermore, the annotated images could be used to develop a machine-learning approach to automatic scallop detection to support counters in the future and contribute to standardize counting performance.*
2) The ratio of scallops with shell height of 65 mm or over was 71.1% in the Moffen area, while this ratio before the harvesting started in 1986 was 55.8%. *This indicates that the stock in the Moffen area might have recovered to the original shell height distribution before the harvesting started.*
3) The mean density of scallops in the Moffen scallop bed was higher than the Bear Island region, as before the fisheries in the 1980s. *This means that the Moffen scallop bed is still the most abundant scallop bed of the ones we have looked at, in the Svalbard region. The combination of recovery of shell height distribution and abundance indicate that the Moffen scallop bed can be opened for harvesting.*

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6. APPENDICES

6.1 Appendix 1: Additions to results

Table A1 Overview of video-stations from Iceland scallop survey in the Moffen region, with standard deviation (SD), mean, coefficient of variation (CV) of the mean values across counters, number of images (n) and counted scallops (n) and per station.

SERIALNUMBER	SD	MEAN	CV	IMAGES (N)	COUNTED SCALLOPS (N)
75006	0.65	4.53	0.14	41	14
75008	0.33	0.75	0.44	56	2
75010	0.06	0.09	0.69	36	0
75012	0.47	1.02	0.46	94	4
75013	0.49	2.98	0.16	76	12
75014	0.42	4.95	0.09	98	20
75016	0.69	1.52	0.45	95	5
75018	0.41	0.89	0.46	49	3
75019	0.52	0.60	0.87	85	1
75020	0.04	0.06	0.67	37	0
75021	0.01	0.02	0.67	34	0
75024	1.64	2.77	0.59	44	11
75025	0.11	0.20	0.55	43	1
75027	3.30	7.95	0.42	68	24
75030	0.00	0.00	NaN	3	0
75031	0.10	0.09	1.15	17	0
75033	0.94	2.00	0.47	3	4
75034	0.83	4.61	0.18	101	14
75038	0.05	0.07	0.82	15	0
75039	0.40	0.30	1.32	25	1
75040	0.32	0.33	0.96	16	1
75041	0.12	0.44	0.29	8	2
75042	0.21	0.21	0.98	43	1
75043	0.04	0.02	1.73	102	0
75044	0.03	0.05	0.47	28	0
75045	0.23	0.93	0.25	40	2
75046	0.06	0.06	0.92	53	0

75047	0.37	0.64	0.58	94	2
75048	0.07	0.08	0.85	65	0
75049	0.04	0.06	0.61	49	0
75050	0.00	0.00	NaN	44	0
75051	0.10	0.07	1.41	14	0
75052	1.19	2.63	0.45	10	8
75053	2.19	6.53	0.34	22	20
75054	0.27	1.33	0.20	72	3
75055	0.66	1.87	0.35	6	4
75056	1.84	5.40	0.34	49	16
75057	0.92	1.10	0.83	64	2
75058	2.51	3.71	0.68	47	11
75059	4.45	7.28	0.61	135	22
75060	0.81	1.61	0.50	115	5
75061	0.09	0.17	0.52	82	1
75062	0.03	0.04	0.85	70	0
75064	*NA*	0.68	*NA*	117	1
75065	0.00	0.00	NaN	18	0
75066	0.53	0.54	0.97	72	1
75067	0.76	1.00	0.76	96	2
75069	0.07	0.12	0.60	60	0
75070	0.05	0.28	0.19	66	1
75071	0.69	1.23	0.56	20	4
75072	1.01	2.63	0.39	86	8
75074	0.04	0.08	0.58	118	0
75076	0.02	0.03	0.49	70	0
75077	0.16	0.66	0.24	52	2
75078	0.11	0.20	0.55	64	1
75079	0.00	0.00	NaN	56	0
75080	2.84	4.88	0.58	35	15
75081	0.00	0.23	0.00	30	0
75082	0.64	0.55	1.18	10	1
75083	0.68	0.77	0.89	42	2

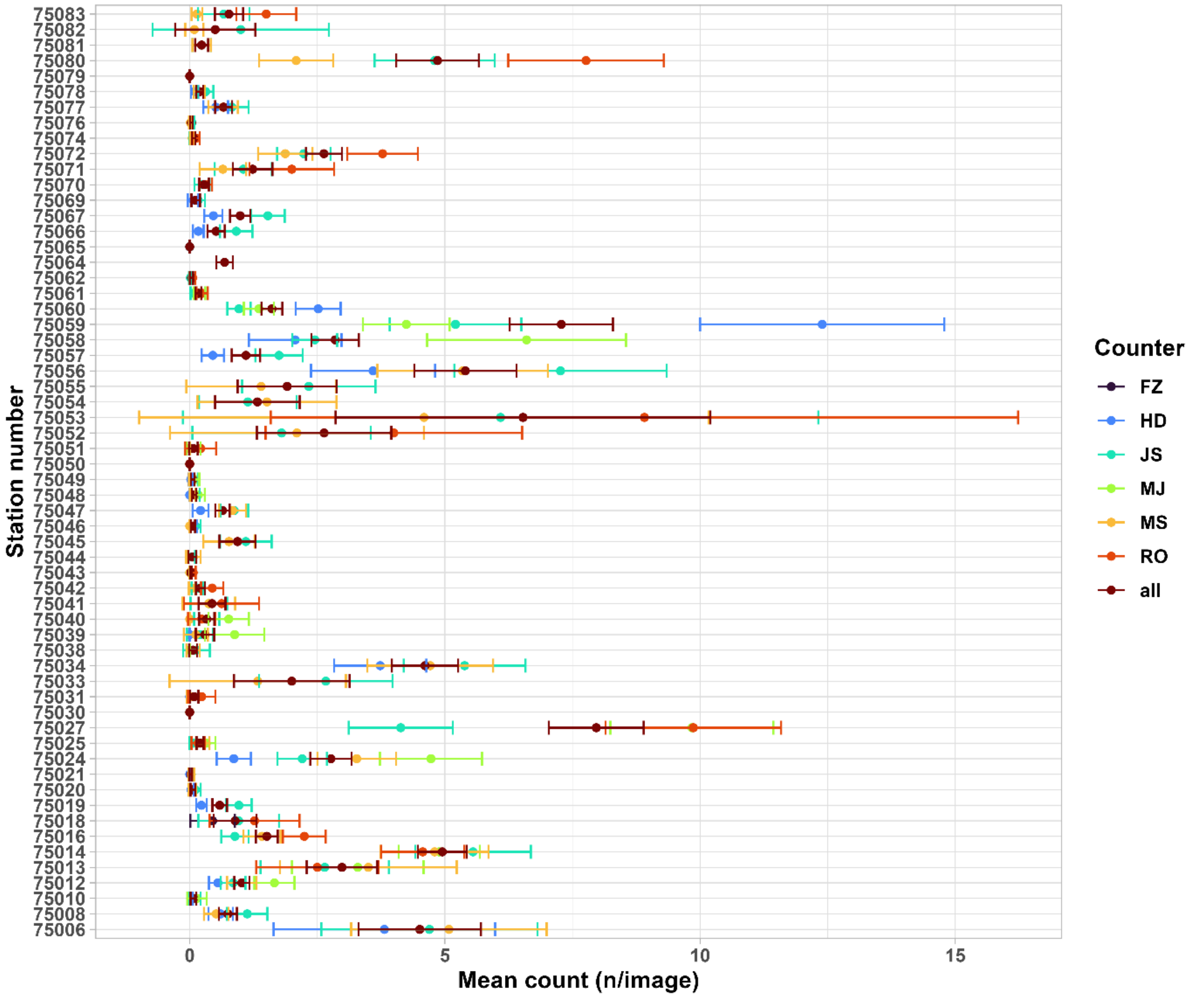

Figure A1 The mean number of Iceland scallops per video-station, based on the six different counters. Survey conducted in the Moffen and Parryflaket scallop beds north of Svalbard autumn 2022.

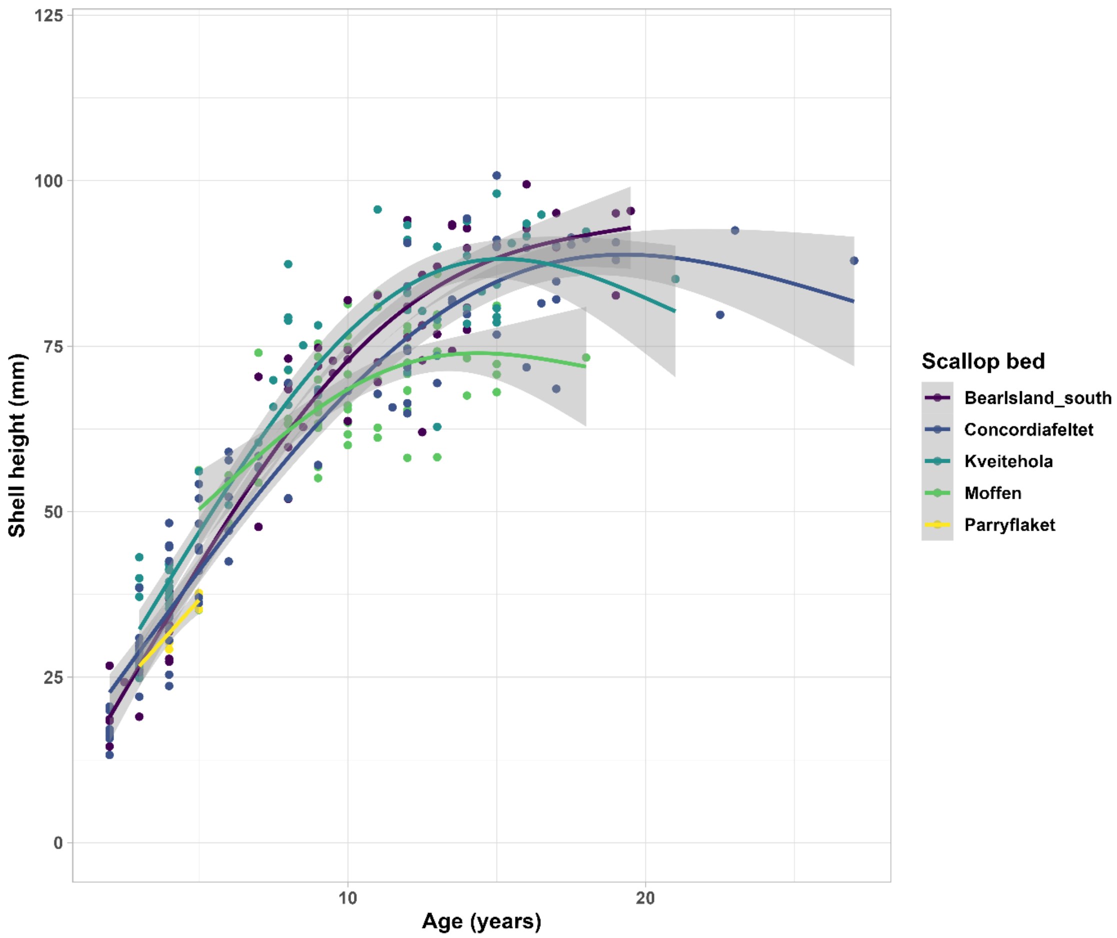

Figure A2 Relationship between shell height (mm) and age (years) (fitted by geom_smoother) in Iceland scallops in the scallop beds in the Bear Island region and Moffen region.

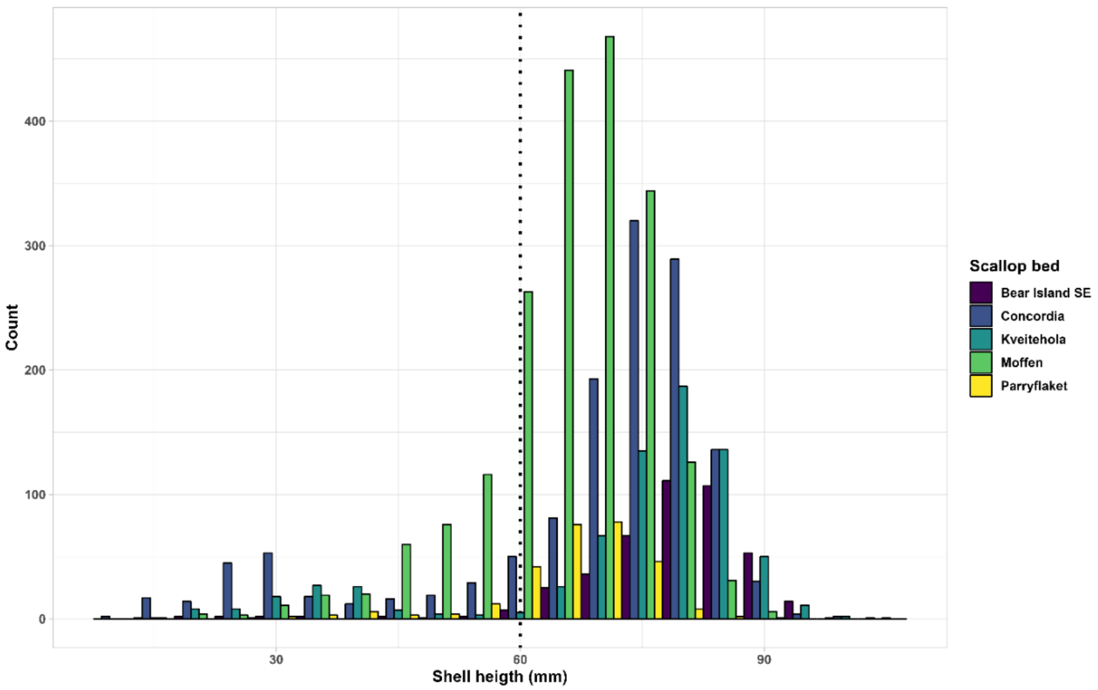

Figure A3 Shell height distribution of Iceland scallop in the scallop beds in Bear Island and the Moffen regions. The dotted line shows the minimum legal size (60 mm).

Table A2 Model estimates with belonging standard errors (SEs) from the two Generalized additive mixed models (GAMMs); a regular GAMM (approach 2a) and spatial GAMM (approach 2b), used to estimate the density of Iceland scallops in the Moffen and Bear Island regions. In addition to matern range and spatial standard deviation (SD) output from the spatial GAMM.

Approach	*Parameter*	*Estimate*	*SE*	*Matern range*	*Spatial SD*
Approach 2a	*splines::ns(depth_std, df = 3)1*	*- 0.7146*	*0.6419*		
Regular GAMM	*splines::ns(depth_std, df = 3)2*	*3.6075*	*1.5098*		
	splines::ns(depth_std, df = 3)3	*0.1834*	*0.9941*		
	Bear Island SE	*- 0.9318*	*1.0151*		
	Concordia	*- 1.8773*	*0.7815*		
	Kveitehola	*- 1.9187*	*0.8130*		
	Moffen	*- 0.1241*	*0.7443*		
	Parryflaket	*- 0.7180*	*0.8576*		
Approach 2b	*sdepth_std*	*- 0.06*	*0.18*	*6.72*	*1.94*
Spatial GAMM	*Bear Island SE*	*0.10*	*1.14*		
	Concordia	*- 1.42*	*0.66*		
	Kveitehola	*- 1.51*	*0.78*		
	Moffen	*0.42*	*0.64*		
	Parryflaket	*0.66*	*1.00*		

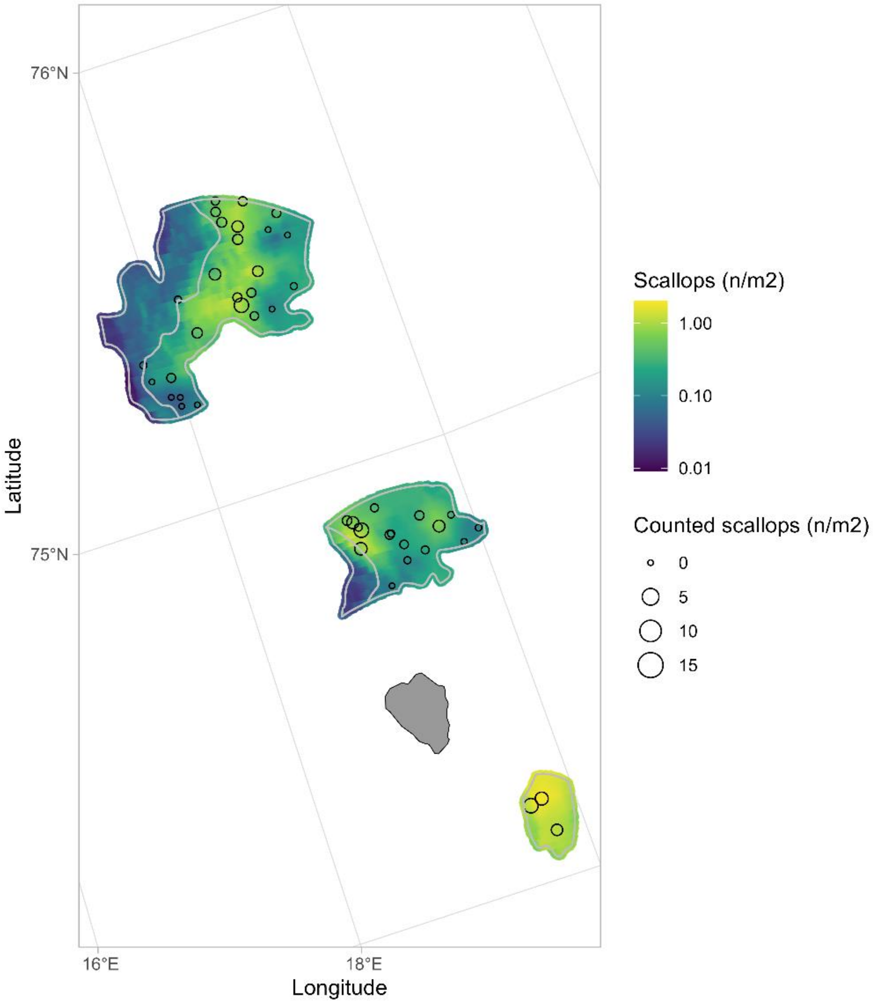

Figure A4 Map of the predicted density of Iceland scallops (log-scale) in the Bear Island region, using a geospatial model (GAMM implemented in sdmTMB). The colour scale shows the predicted scallop density per cell of the integration grid, while the size of black circles represents the observed scallops density per station. Grey lines indicate the strata borders, with strata corresponding to scallop beds Bear Island SE, Kveitehola and Concordia (from south to north). Kveitehola and Concordia are subdived into 50-100m and 100-150m depth strata, whereas Bear Island SE consists of only one stratum.

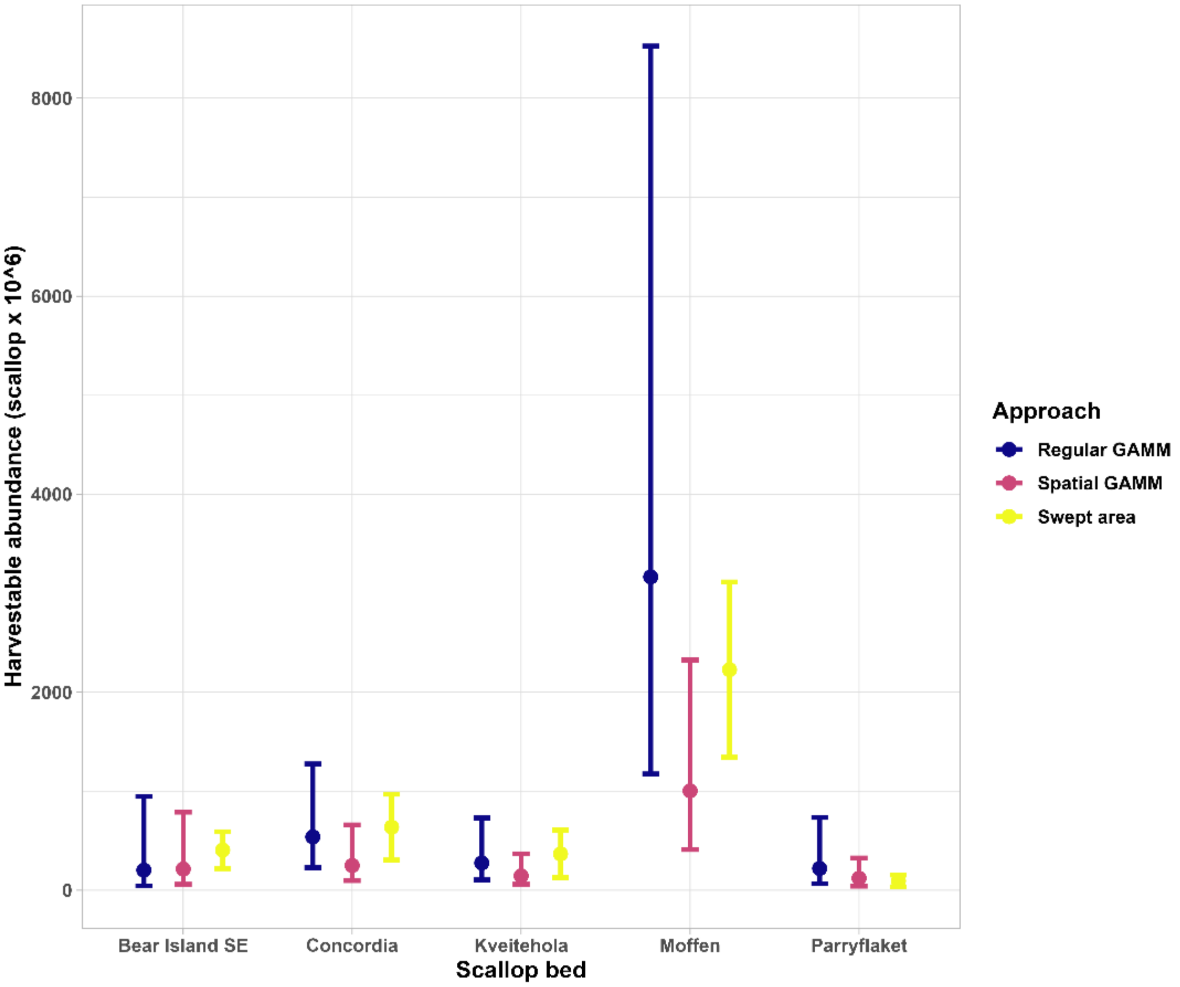

Figure A5 The estimate of harvestable abundance of Iceland scallop (n ≥ 60 mm x 10^6), with error bars showing 95% confidence level, per scallop bed based three different approaches; design based swept area, a regular generalized linear mixed effects model (GAMM fitted with glmmTMB) and a spatial distribution model (spatial GAMM fitted with sdmTMB).

Table A3 The estimate of density (n scallop/m^2), abundance (n scallop x 10^6), abundance over legal size (n scallop x 10^6) biomass over legal size (tons x 10^3), with respective CI05 and CI95 (in the same unit as the beloning categories) of Iceland scallops pr scallop bed in the Moffen and Bear Island regions based on three different density estimation approaches.

Scallop_bed	Model	Density	Density_CI05	Density_CI95	Abundance (x 10^6)	Abundance CI05	AbundanceCI95	Abundance (x 10^6) legal size	Legal size CI95	Legal size CI05	Legal size biomass (1000 tonn)	Biomass CI95	Biomass CI05
Bear Island SE	Regular GAMM	1.10	0.24	5.16	211.19	45.26	985.47	202.96	947.05	43.49	14.21	66.29	3.04
Concordia	Regular GAMM	0.42	0.18	0.99	657.48	277.89	1,555.57	538.84	1,274.86	227.75	37.72	89.24	15.94
Kveitehola	Regular GAMM	0.48	0.18	1.26	320.66	120.99	849.83	275.36	729.77	103.90	19.28	51.08	7.27
Moffen	Regular GAMM	4.32	1.60	11.63	3,753.61	1,393.42	10,111.55	3,164.81	8,525.42	1,174.84	221.54	596.78	82.24
Parryflaket	Regular GAMM	3.87	1.16	12.93	246.68	73.81	824.45	219.75	734.46	65.75	15.38	51.41	4.60
Bear Island SE	Spatial GAMM	1.08	0.35	3.76	205.66	66.40	718.65	197.64	690.62	63.81	13.83	48.34	4.47
Concordia	Spatial GAMM	0.19	0.08	0.51	297.29	119.78	798.27	243.64	654.22	98.17	17.05	45.80	6.87
Kveitehola	Spatial GAMM	0.25	0.10	0.60	167.46	65.18	405.57	143.80	348.27	55.97	10.07	24.38	3.92
Moffen	Spatial GAMM	1.39	0.50	3.32	1,205.25	439.03	2,891.31	1,016.19	2,437.77	370.16	71.13	170.64	25.91
Parryflaket	Spatial GAMM	2.06	0.75	6.10	131.21	47.58	388.96	116.89	346.51	42.38	8.18	24.26	2.97
Bear Island SE	Swept area	2.21	1.19	3.22	421.76	228.07	615.46	405.32	591.47	219.17	28.37	41.40	15.34
Concordia	Swept area	0.49	0.24	0.75	777.36	372.38	1,182.35	637.09	968.99	305.18	44.60	67.83	21.36
Kveitehola	Swept area	0.64	0.22	1.05	427.47	147.68	707.27	367.08	607.35	126.82	25.70	42.51	8.88
Moffen	Swept area	3.04	1.83	4.25	2,642.44	1,592.17	3,692.70	2,227.94	3,113.45	1,342.42	155.96	217.94	93.97
Parryflaket	Swept area	1.66	0.61	2.71	105.72	38.82	172.61	94.18	153.77	34.59	6.59	10.76	2.42

6.2 Appendix 2: Additions to discussion

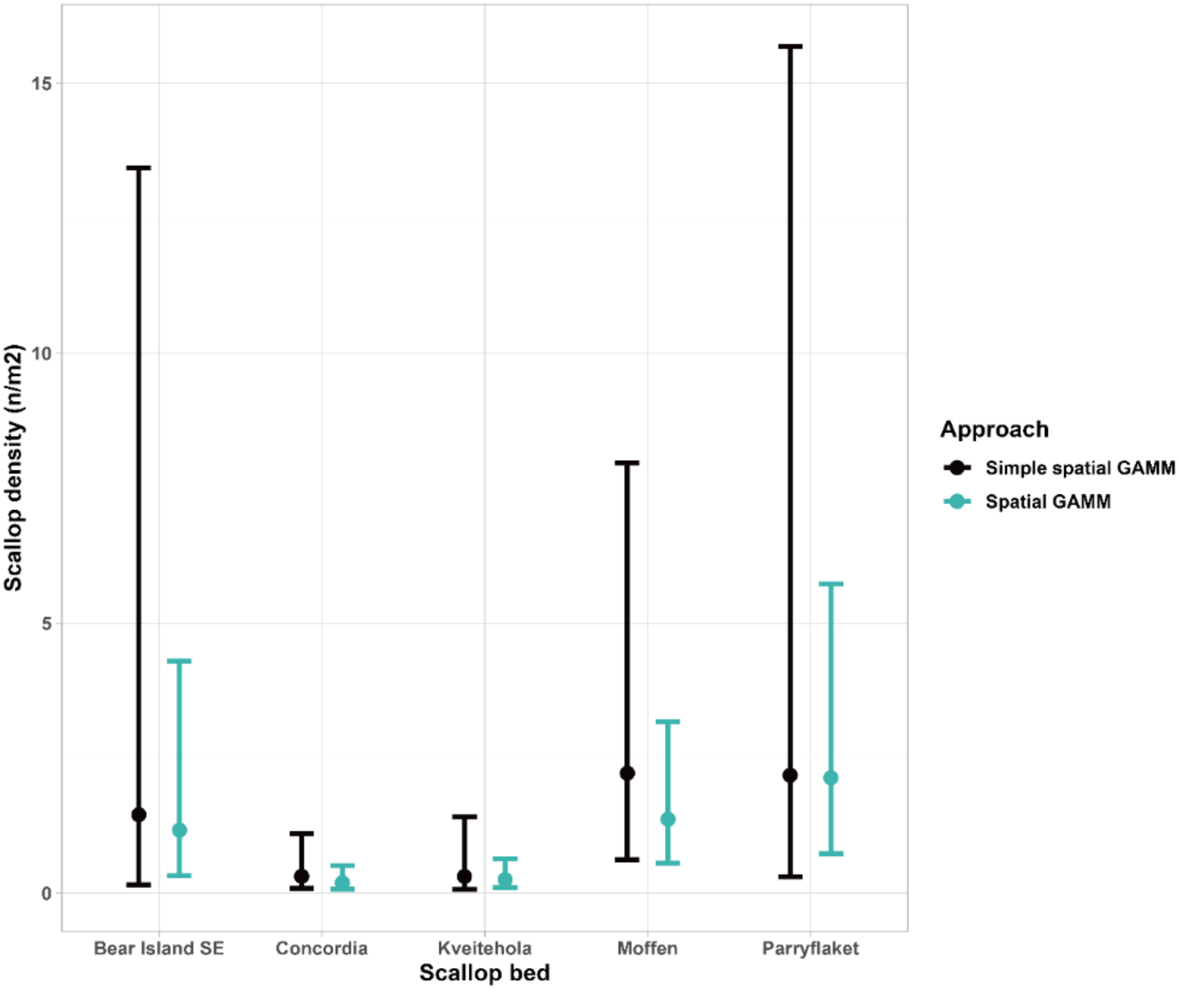

Figure A6 The estimated density of Iceland scallops (n/m^2) per bed, with error bars showing 95% confidence level, using a geospatial GAMM implemented in sdmTMB to predict densities with a spatial integration grid (spatial GAMM) and fixed effects only (simple spatial GAMM, based on categorical scallop bed effect and mean observed bottom depth).