Sources of bias in the RFID tag-recapture data used in the stock assessment of North East Atlantic Mackerel

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Abstract

Northeast Atlantic Mackerel (*Scomber scombrus*) is an immensely valuable fish stock for Norway and several other nations. The dynamic stock is spread throughout many nations, making the stock assessment an effort of large international cooperations. Many nations cooperating means that there will be more room for error in the estimate. IMR has made an admirable effort in assessing the mackerel stock using steel tags for over 40 years (1969-2010), with manual processes of recapturing fish from conveyor belts with metal detectors during processing at fish factories. Technological changes with the introduction of RFID tag-recapture technology in 2011, resulted in more automatic processes, more effective data handling and a much larger proportion of the catch scanned. With mackerel being the important resource that it is, errors and biases in the stock assessment could have large implications. It is therefore essential to detect the possible sources of errors. This thesis uses data gained from RFID-tags from various nations and factories, as well as data from the old steel tag series to assess the possible sources of biases in the tag-recapture time series as input to the current assessment model. One source of bias is related to the use of age-length key (ALK) at release to estimate age at recapture in the RFID data, compared with actual age reading from otoliths of recaptured fish in the old steel tag time series. The results showed that the estimated age from ALK is slightly higher than the actual age reading of the mackerel per length group, suggesting a bias. Tagging mortality due to crowding, waves and presence of birds was evaluated so see if it affected the stock estimate. In general there was no effect of tagging mortality. Spatial factors such as region, country and factory were also compared to each other to see if stock estimates of mackerel varied between them. In general region provided similar estimates, but estimates varied from each other when going into country and factory level. Norwegian factory Pelagia Austevoll seemed to have the largest variation in estimates when compared to other factories. Variations might be due to different levels of mixing of year classes in spawning and fishing areas. RFID is a new approach to estimating mackerel stock and is still lacking a certain level of accuracy. The initial assessment indicates that the RFID-tags will provide a consistent estimate and that data needs to be evaluated over a longer period of time to pinpoint the sources of bias more accurately.

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Introduction

Mackerel biology

The North East Atlantic (NEA) mackerel (*Scomber scombrus,* L) is a pelagic schooling species of the Scombridae family. It is the most common and abundant species of the Scombridae family and is found from the west coast of Portugal and the Bay of Biscay to the north of Norway (Iversen et al., 2002, Nøttestad et al., 2015b) , making it the most northern species in the family. It is also the most abundant migratory fish species in the North East Atlantic (Pitois et al., 2015). The NEA mackerel is an ectothermic fish, making its body temperature vary between 1 to 2°C above the surrounding water temperature (Clark et al., 2009). Amphipods, plankton and small fish are the main food sources for the Atlantic mackerel, with the respective prey varying with seasons and distribution (Ringuette et al., 2002, Olaso et al., 2005). The mackerel builds up high energy reserves in the spring and summer period and utilizes these reserves for the winter migration and gonad development (Lockwood, 1988).

The age of complete maturity for the NEA mackerel occurs after three to four years. At this age the mackerel is capable of producing between 200,000 to 800,000 pelagic eggs, divided over time and place (Piling, 2009). The spawning period ranges from May to July (Lockwood, 1988). A recognizable trait for the mackerel is the absence of a swimming bladder, hence making stock abundance estimates by the use of acoustic methods complicated (Korneliussen, 2010). The absence of a swimming bladder consequently means that the mackerel must remain swimming at all times to avoid sinking.

The growth curve for mackerel larvae through to the juvenile stage (100 mm +) is sigmoidal, as typically found for many fish species (Bartsch and Coombs, 2001). NEA mackerels are 3.5 mm at hatching and grow to be maximally 65cm in length (Figure 1) (Nøttestad, 2005) and 2 kg in weight (Graves, 1998).

Figure 1: Atlantic mackerel *Scomber scombrus* (Linnaeus 1758). Source: nergard.no

Geographical distribution, population structures and migratory pattern

The North East Atlantic (NEA) mackerel population is composed of three separate spawning components, of which the first one originates west of Ireland and the UK, the second southern component originating in Spain and Portugal and thirdly, the component originating in the North Sea (ICES, 2015b). However, the NEA mackerel is assessed and managed as one stock mainly due to the mixing that occur in the fishery during the feeding and wintering season (Seafish, 2017). The age of complete maturity of the NEA mackerel occurs after three to four years. The spawning period ranges from May to July (Lockwood, 1988) and the timing is affected by the sea surface temperatures (Jansen and Gislason, 2011). After spawning in the western and southern waters the respective stocks migrate north towards the Norwegian Sea and the northern part of the North Sea (Nøttestad et al., 2015a). In recent years, the distribution of mackerel (Figure 2a-b) has expanded west and northwards, with mackerel having been recorded as far north as Svalbard (Berge et al., 2015, Nøttestad et al., 2015b). The length and weight of the NEA mackerel has been shown to be negatively proportional to the stock size, indicating a presence of density dependent growth (Olafsdottir et al., 2015). The NEA mackerel is highly migratory and is capable of covering vast distances over a short period of time, with swimming speeds reaching up to 3.5 body lengths per second (Wardle and He, 1988). The North Sea component has the shortest migration route of the three stocks, it spends the winter in the Norwegian trench and migrates to the south of the North Sea during springtime. After spawning in the North

Sea the northern, western and southern components share a mutual feeding area in the northern North Sea and southern Norwegian Sea (Figure 2a-b) (Lockwood, 1988).

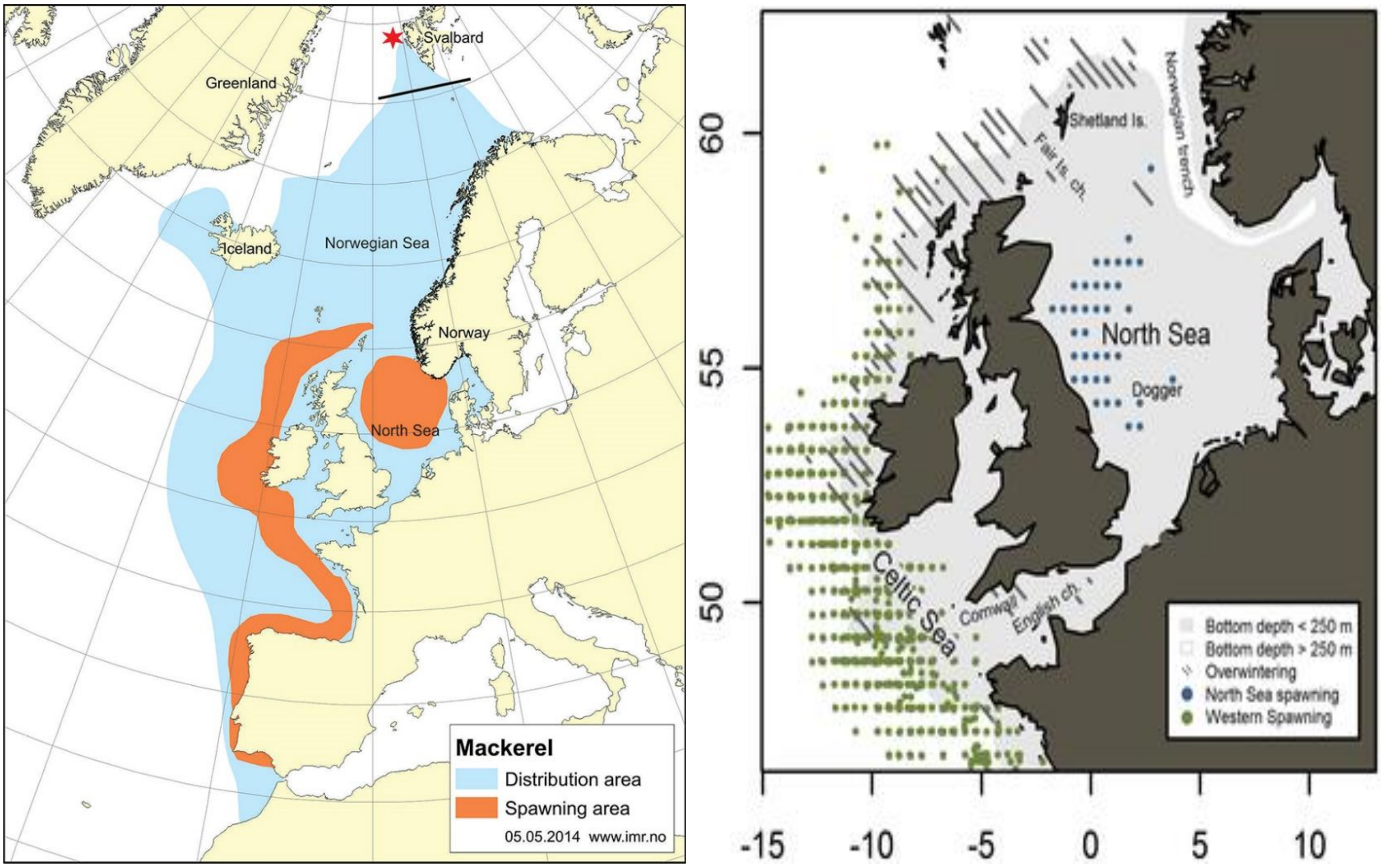


Figure 2a-b**: **a. Distribution area of the North East Atlantic mackerel (blue) and spawning areas (orange). Source: imr.no
b. Spawning areas of the NEA mackerel around the North-west European shelf (dots) and overwintering areas (stripes). The dots indicate 50+ eggs/m^2 per day (Jansen and Gislason, 2013).

Mackerel fisheries

The North East Atlantic (NEA) mackerel is distributed over a large area in Europe, making it a shared resource, fished by many nations including Norway, Iceland, Greenland, Denmark, Faeroes, Ireland, United Kingdom, Spain, France, Germany and the Netherlands (ICES, 2015a). Norway starts its fishing season in early August and focuses mainly on the mackerel overwintering close to the Norwegian coastline. The timing of fishing ensures that the mackerel has grown to maturity, providing a higher price on the market (Piling, 2009). The mackerel are fished using freezer trawlers, purse seiners, pelagic trawlers, hand line fleets and gillnets. In Norway, the purse seine is favoured and is used to haul in 88% of the total catch (Piling, 2009).

Mackerel has been a valuable resource for Norway, and the rest of Europe for a long time due to the fisheries industry and profits from exports. Since 2001 mackerel fisheries have comprised between 20-50% of the total fisheries turnover (Figure 3) (Sildesalgslag, 2017), sometimes providing the majority of the national total turnover or coming in second to Herring, another important national resource for Norway (Sildesalgslag, 2017).

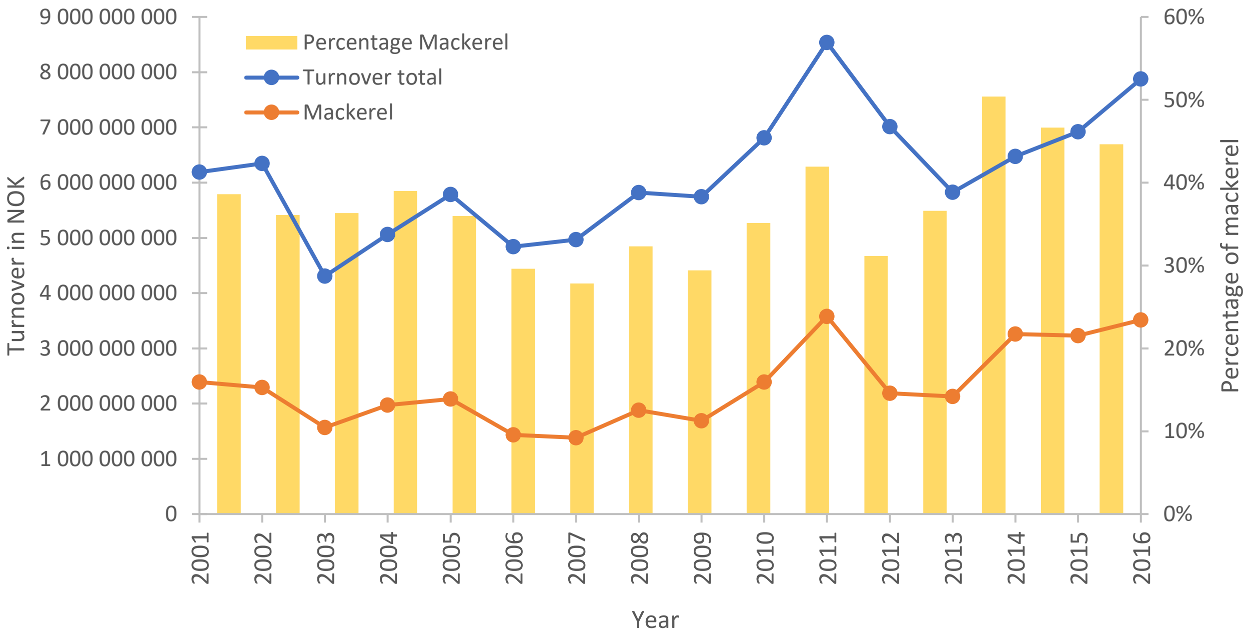


Figure 3:*Turnover of mackerel in NOK compared to total national turnover of the following species; Herring, Horse mackerel, Capelin, Blue whiting, Sand lance, Pout and Sprat combined in NOK. Data gathered from Norsk Sildesalgslags Turnover statistics from 2001-2016,* *https://www.sildelaget.no/en/catches-and-quotas/statistics/turnover/*

The mackerel fishery experienced an increase in the 1960's on account of a decrease in the herring population, in 1967 the total catch for mackerel reached 840.000 tonnes. The increased pressure on the population caused a drastic decline in numbers, estimates put the spawning stock biomass at 400.000 tonnes in the early 80's and a continuing decrease put the population at a mere 50.000 tonnes in 1986 (Pethon, 1994). Norway's pelagic fishery industry consists of Capelin, Norwegian pout, Blue whiting, Sand lances, Atlantic horse mackerel, North east Atlantic mackerel, Atlantic herring, European sprat and other miscellaneous species (Sandberg, 2009, Sandberg, 2016, Sandberg, 1999). Compared to the total pelagic catch, mackerel makes up somewhere between 7-22% of the total catch in tonnes. Recent years showed an increase of mackerel as a part of the total catch (Figure 4).

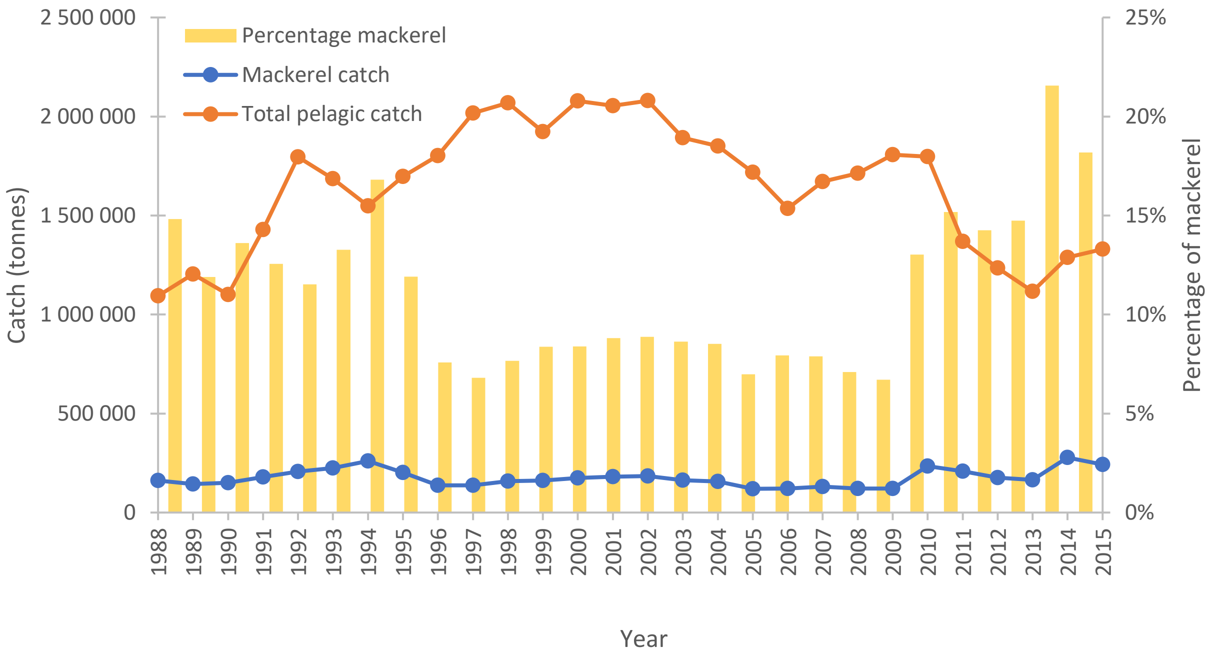


Figure 4: Total pelagic catches and mackerel catches in tonnes from 1988-2005. Percentage of mackerel catches compared to total pelagic catches for the respective year. Data gathered from Fiskeridirektoratet (2017) http://www.fiskeridir.no/Yrkesfiske/Statistikk-yrkesfiske/Statistiske-publikasjoner/Noekkeltall-for-de-norske-fiskeriene

Mackerel fisheries are growing and data is becoming more readily and easily available. In 2012 the catches from Icelandic and Faroese waters contributed to about half of the total landings, whereas almost no catches were reported from this region prior to 2008 (ICES, 2014). The majority of catch caught in the first quarter is caught off the west coast of Ireland and Scotland, the second quarter catch is the smallest of all catches and is caught in the southern and northern part of the North Sea, the third quarter catch is mainly caught in the northern North Sea and around Iceland and the fourth quarter catch is caught North of the UK and southwest of the Norwegian coast (ICES, 2015b). A total allowable catch (TAC) involving Norway, Faroes and the EU for 2015-2020 was set up in 2014 (ICES, 2015b). This TAC agreement does however not involve other fishing parties, resulting in complications surrounding agreements. ICES has set the catch quota for NEA mackerel at 667 385 tonnes for 2016, based on the maximal sustainable yield approach (ICES, 2015a). According to ICES the total catch of NEA mackerel was 135 608 tonnes in 2015 (ICES, 2015a).

Stock assessment

With mackerel being such an important economical resource it is crucial that it the stock is managed in a sustainable way. Overexploitation or underexploitation of the stock will result in a smaller yield or even a collapse of the stock (O'Brien, 2012, Nielsen and Berg, 2014). Measures to obtain a sustainable and regulated fishery of mackerel has been in place since 1970 (Pethon, 1994). Currently, the mackerel stock is estimated using a SAM (State-space Assessment Model) -model. The SAM-model is a full stochastic model that allows selectivity to vary gradually with time, using fewer model parameters than full parametric models (Cadigan, 2015). The model is based on a common cohort model in which the abundance at age X in year Y is equal to that cohort abundance in the previous year times the survival rate, which is expressed in terms of the total mortality rate. Year classes caught per year need to be followed over several years to get an accurate estimate of the stock (Cadigan, 2015). Besides these parameters the model, like most modern stock assessment models, also includes observation equations and errors, as well as process errors. The most commonly modelled process error is temporal variation in recruitment, which is treated as a random effect in the SAM-model and hence integrated out (Maunder and Piner, 2015). The output from the SAM-model will be used in the estimation of international mackerel stock and consequently the management of the stock. A more accurate insight into the stock dynamics will in turn provide a more sustainable utilization of the stock (Cash et al., 2003). The annual catch advice for 2015, 2016 and 2017 has been based upon the MSY approach which has been determined by using the SAM model output (ICES, 2017).

Mackerel is a challenging stock species to estimate due to its lack of a swimming bladder and therefore low backscattering coefficient whilst using acoustic methods (Foote, 1980).

Other methods to estimate the stock must therefore be used. In addition to fisheries dependent data, triannual egg surveys were conducted and used to estimate the stock. Catch data has not always yielded the most accurate estimates, resulting in the workinggroup looking for additional methods for stock assessment (ICES, 2006, ICES, 2015b, ICES, 2014, ICES, 2013).

During the benchmark of February 2013, the estimate for the 2012 recruitment showed a huge increase, almost 100 times that of previous estimates. To get more realistic numbers for the 2012 recruitments the integrated catch at age model (ICA) was run with different modifications. The Working Group on Widely Distributed Stocks (WGWIDE) decided to reject the updated assessment using the modified ICA settings and use the egg survey index as a basis on which advice was based in stead (ICES, 2013).
The assessment suffered from scarcity of data, underestimated catches, changes in fishing practices and uncertainties in numbers-at-age. The ICA-model relies on assumptions of correct catch and constant selectivity in the last 12 years, which in the case of the NEA mackerel, have been violated. To resolve these complications with the estimate a new and more accurate data set needs to be used to produce an estimate, and this is where the new RFID technology comes in (ICES, 2013).

During the benchmark workshop on widely distributed stocks (WKWIDE) in 2017, data from 2016 was used to provide an estimate based on catch-at-age data from 1980 until 2015 for ages 0 to 12. The survey indices were the triannual egg survey, International Bottom Trawl Survey (IBTS) conducted in the 1st and 4th quarter on the European shelf providing a recruitment index (Jansen and Burns, 2015), International Ecosystem Summer Survey in the Nordic Seas (IESSNS) as well as steel tags from release year 1980 to recapture year 2006 (ICES, 2017).

From steel tags to RFID tags

There are currently five sources of catch independent data used in the assessment of NEA mackerel; (1) A triannual international egg survey with, the aim to estimate the spawning stock biomass, (2) tag-recapture data from the steel series from 1984-2006 showing abundance of year classes, (3) trawl surveys in the Norwegian sea providing information on year class abundance, (4) recruitment estimates from IBTS showing the abundance of a yearclass at age 0 and finally (5) the RFID-series from 2011-2016 (and onwards) providing information concerning abundance of yearclasses, on which assessments and advice is based (ICES, 2015b, ICES, 2006, ICES, 2014, ICES, 2015a, ICES, 2017, ICES, 2013),

The institute of Marine Research (IMR) in Bergen (Norway) has been using internal steel tags for over 40 years, starting in 1969 and ending in 2010 (Tenningen et al., 2011). The steel tags have been released and recaptured, providing useful data on migration, population dynamics, mortality and abundance of the mackerel species. The process of using steel tags has proven to be beneficial in gaining insight into the dynamics surrounding the mackerel population, and interests has been showed in maintaining the tagging and recapture process. After using steel tags for 40 years the system proved to be tedious in manual labour and data processing. Methods for retrieving steel tags have, considering modern technology, become outdated, demanding excessive amounts of manual labour and human control with diminished results. In 1994 recaptures were as low as 129 recaptures over a period of 10 years for 26,934 marked individuals released (Tenningen et al., 2011). The results gained from the tagging and recapture experiment did not seem to align with the official ICES projections on the mackerel stock (Tenningen et al.,2011). ICES has therefore encouraged the continuation of tagging and recapture of mackerel, the notion has been second by the Norwegian fisheries industry. For an increased effectivity and efficiency, a more modern system was to be developed and implemented, requiring less manual labour and room for human errors. In 2011, the Norwegian Seafood Research Fund (FHF), Norges Sildesalgslag and IMR joined forces to develop and incorporate Radio Frequency IDentification (RFID) system into the process of tagging and recapturing mackerel. Collectively, IMR,FHF and Norges Sildesalgslag invested 11.6 million NOK for the incorporation of RFID tags into the tagging and recapturing of mackerel (Forskningsfond, 2013). The new system is more effective and the recapture numbers are higher compared to the previously used steel tag approach. The main difference between the steel tag methodology and the RFID approach, is that steels tagged fish were always removed from production and analysed off location, at IMR in Bergen, Norway, where measurements were taken together with age. The RFID tagged fish are never removed from production, data is simply automatically updated in a database in Bergen continuously as tagged fish are recaptured at a factory, with information linked to data at release.

Potential sources of bias in the tagging data

It is crucial to understand what, how and to what extent the biases influence the estimation of biomass. If the stock seems to be varying substantially from one year to the next it is essential to know if it is an actual decrease/ increase or if it is caused by a bias in the processing of catches, for instance, including a factory that isn't accurate in its reporting.

The new and improved method of using RFID tags is very efficient but does however also raise certain questions around potential errors. There are two types of errors, uncertainties and biases. Uncertainties have a probabilistic basis and reflect the incomplete knowledge of the quantity value. A larger sample size could help lower uncertainties. Biases are systematic measurement errors that skew data, they can usually be contributed to non-standardized methods. Biases can lead to an inaccurate estimate, even though the uncertainties are small. Uncertainties and biases can occur along many steps of the process of stock assessment. This thesis will mainly focus on biases as the source for errors; bias in estimation of numbers tagged and recaptured per year class, bias in RFID tagging index related to spatial and temporal changes in the catch scanned and the bias in RFID tagging data related to tagging mortality.

1. <u>Bias in estimation of numbers tagged and recaptured per year class</u>

Both steel tagged and RFID tagged fish are length measured alive, and quick, not really in the same way with pinched tail as with regular sampling; in a sense, pinched tail body length is more estimated than measured. This can cause a bias in the age length key (ALK), where each fish aged is length measured more accurately. In addition, there has been a change in methodology of estimating numbers recaptured per year class from the steel tagging until the RFID tagging. Using steel tags meant that the individual fish were shipped back to the IMR headquarters in Bergen, where they were manually identified, analysed and aged. The current system does not have the same manual approach and checking, it solely relies on the assumption that the previously produced ALK is accurate. The RFID tagged mackerel at a given length are linked to the previously constructed age length key (ALK) at time of release.

Hence, the steel tags were aged to one specific age group whilst the RFID tags have a larger distribution of ages with decimals compared to whole integers for the steel tags (ICES, 2017).

2. <u>Bias in the RFID tagging data related to tagging mortality</u>

It is an underlying assumption that the tagging mortality, i.e. number of fish dying due to the handling in terms of catch, holding in tanks and tagging process, is stable between releases, experiments and expeditions. If the tagging mortality is varying significantly from year to year, then changes in an abundance index based on the tags may likely be due to this. There are two potential factors that may cause differences in the tagging mortality. One is the weather conditions, where it is expected that high waves and lots of wind increased the handling stress on the mackerel being jigged. The other factor is occurrence of predators, hereunder, the gallons, the most common bird predator. Both these factors are recorded using a subjective scale for each release (one day, one position). FishWeb also offers filters for the observed presence of waves and birds during tagging experiments, making it possible to see whether these factors are effecting recapture rates and final estimates of abundance. Potentially the presence of birds and turbulent waves could influence the survival of the tagged and released mackerel, hence causing a bias in the stock estimate.

3. <u>Bias in RFID tagging index related to spatial and temporal changes in the catches scanned</u>

The project started off with only Norway, but as it has grown so has the scope of countries involved, now including Iceland, Faroe Islands, Denmark, and Great Britain. It could potentially lead to biases in the estimation of the stock if there are different efficiencies at factories, hereunder assuming that the antenna-reader system does not recapture 100% of the tagged mackerel at all factories. In addition, the various countries don't share fishing areas or fishing seasons equally. Hence, fish of a certain year class tagged at spawning grounds of Ireland and Scotland may not mix equally in all catch areas if there are different components having different migration routes between spawning and feeding areas. The FishWeb programme is designed to be able to filter the results based on experiment, factory (country), time of year and location, which makes is suitable for analyses of such potential biases in the tagging data.

Aims and objectives

Based on the above mentioned information, the main objective of the present thesis is to give a thorough description the RFID technology and method used, and the potential sources of bias in the tag-recapture data to be used in the NEA mackerel assessment from 2017 onwards.

Material and Methods

The tagging of mackerel, for the purpose of stock assessment, was initiated in 1986 using steel tags. The steel tags were used for 24 years, up until 2010, (Tenningen et al., 2011), after which smaller RFID tags were used to replace them. The RFID tags provide a more in depth look into the individual tagged mackerel, information on the tagger, abiotic conditions, date, length in cm, weight in grams, sex, year class, ship, expedition number, release number, sample number, fish number, maturity, catch gear used and the country of capture are recorded (http://tracid-fishweb.imr.no:9000). One of the main purposes of this thesis is to test whether the estimated age, based on the length and an age-length-key, is accurate and therefore the steel tag series as well as the RFID tag series are used.

Tagging (Steel tags)

The steel tags that were used in the period between 1986 to 2010 were tagged using a hired purse seine boat where the mackerel was caught by manual jigging using four to five wheels alongside a boat (Antsalo, 2006). The mackerel with reduced physical fitness due to handling were used to gather biological data (such as age, length, weight) and discarded whilst the fitter individuals were length measured, tagged and released as soon as possible to minimize handling time. The tail of the mackerel was not pinched during length measures, making the length data more of an estimate than actual measured length. The steel tags inserted were individual pieces of 20mm long, 4mm wide and 1mm thick pieces of steel with a serial number etched into it (Figure 5).
A "Gunderson's tagging pump" was used to insert the steel tag into the abdominal cavity or muscle of the mackerel.

In 1982 metal detectors were installed in factories to detect the steel tags inserted into both mackerel and herring. The steel tags (released in 1977-2009) were screened as part of processing of commercial catches for human consumption at factories with conveyor belt systems. For each catch scanned the length of 100-200 fish was measured and mean weight estimated. Mean weight was used to estimate number of fish screened, and the length measures were used in combination with an age-length key for adult fish, to age the catches.The process of detecting tags was tedious, the metal detector alerted to the steel tag, however not providing the specific fish being tagged. If a steel tag was detected it resulted in 50 fish being removed from the assembly line, individually scanned by a hand-held metal detector, and fish with tags were frozen and sent to IMR. Once at IMR the tag and consequent biological data was extracted and registered.

The steel tags were work intensive, demanding many hours for processing data during recapture. The recapture ratio for steel tags was low, and combined with the high work intensity required to process the data during recapture resulted in the termination of steel tagging.

Biological sampling was carried out during tagging experiments to construct age-length-keys, providing the distribution of age per length groups, this key was used to give the mackerel an estimated age after measuring the length.

Figure 5: A steel tag with individual serial number, inserted in the abdominal cavity of mackerel and detected by metal detectors at the factories processing the catches.

The RFID tag

In 2011 the Norwegian Seafood Research Fund (FHF), Norges Sildesalgslag and IMR joined forces to develop and incorporate Radio Frequency IDentification (RFID) system into the process of tagging and recapturing mackerel.

Radio Frequency IDentification (RFID) tags, as the name might suggest, use radio frequencies to transfer data from an electronic tag, through an antenna, to a RFID-reader, which subsequently recognizes the unique code and links it back to the individual tag.

The dimensions of the RFID tag are quite similar compared to the previously used steel tags, having the dimensions of 3.85mm in width and 23mm in length (Slotte, 2013).

The glass encased tag is scanned and processed, inserted into the abdominal cavity, the length of the mackerel is measured and the mackerel is released (Figure 6). The data can then be extracted by scanning the abdomen of the fish using a hand-held personal digital assistant (PDA). The PDA registers the individual tagging code, date, time and GPS-position. The individual length of the fish is entered manually. The data are synced to the to the FishBase database on daily basis through internet or GPRS network (Figure 7) (TracID, 2013a).

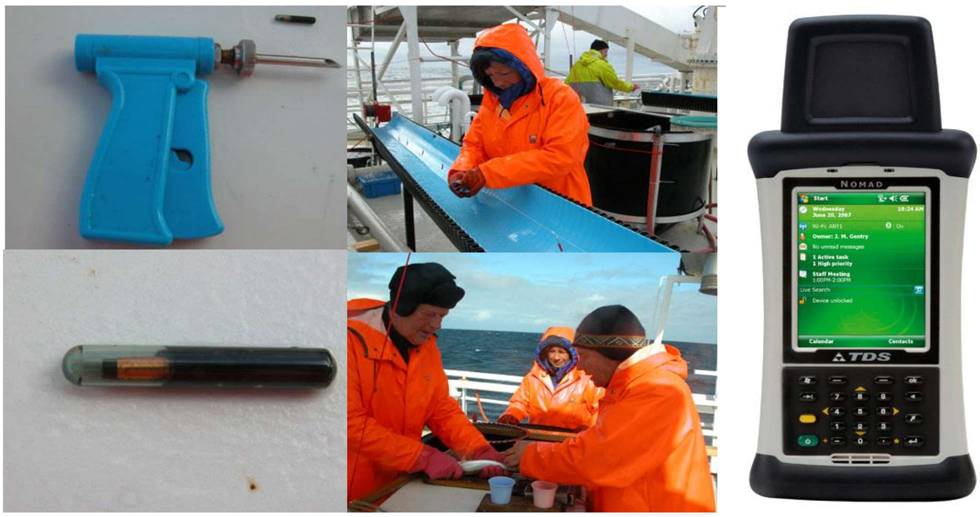


Figure 6: The tools used to insert RFID tag (top left), the glass encased RFID tag (bottom left), the slide used to release mackerel after tagging (top right) and the handling of the mackerel (bottom right) collectively show the process of tagging and releasing an individual. The data can be read and edited using the handheld PDA.

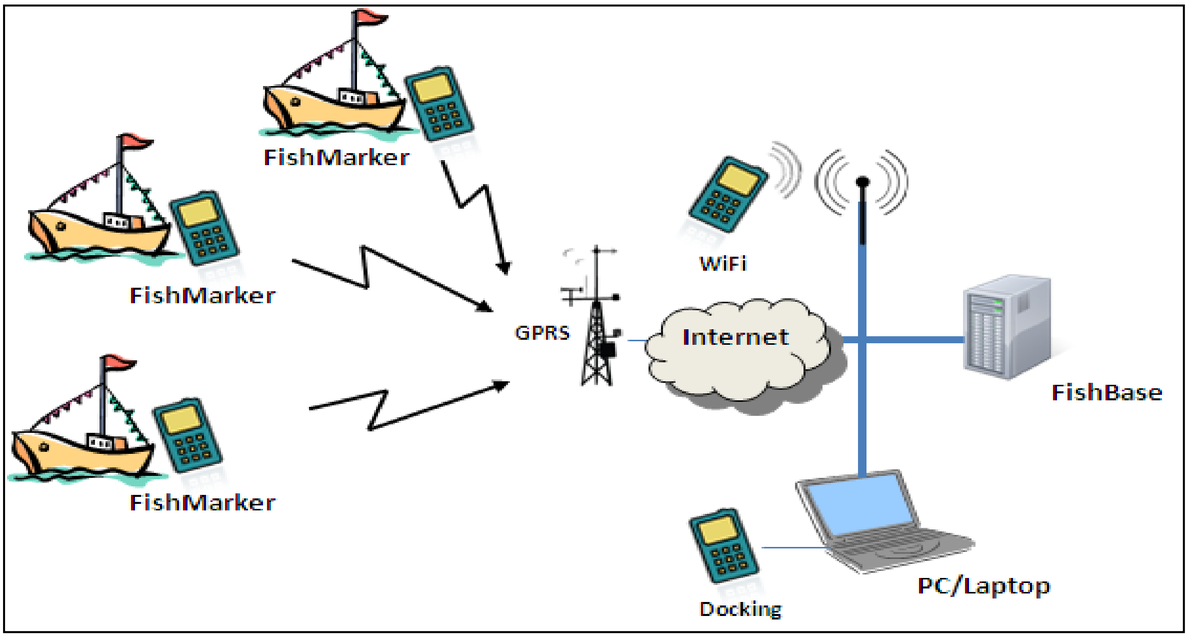


Figure 7: Schematic overview showing how data is transferred from the vessels to the database

Since the beginning of the RFID-tagging experiment started a total of 247893 tags have been released over the past six years. This is more than twice what was released in the last six years of tagging using steel tags. More tags are recaptured with the RFID method compared to the steel tags (Figure 8), mainly due to heavily increased biomass screened (Figure 9).

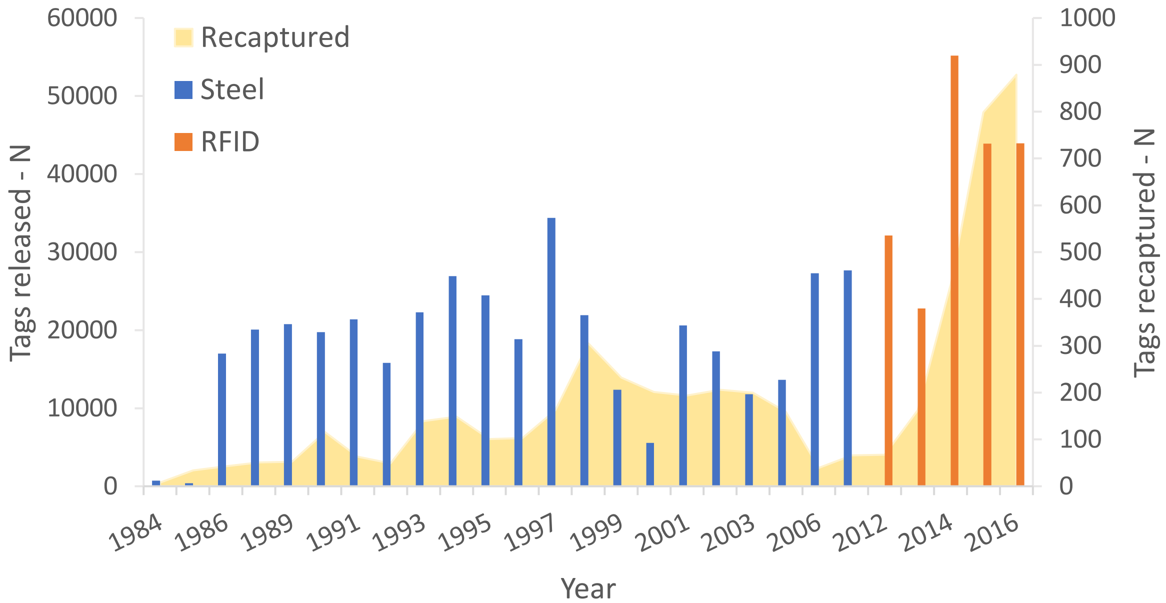


Figure 8: On average, close to 2.3 times more mackerel have been tagged per year using the RFID tags compared to the steel tags. After switching to RFID tags recaptures of tagged individuals has increaed.

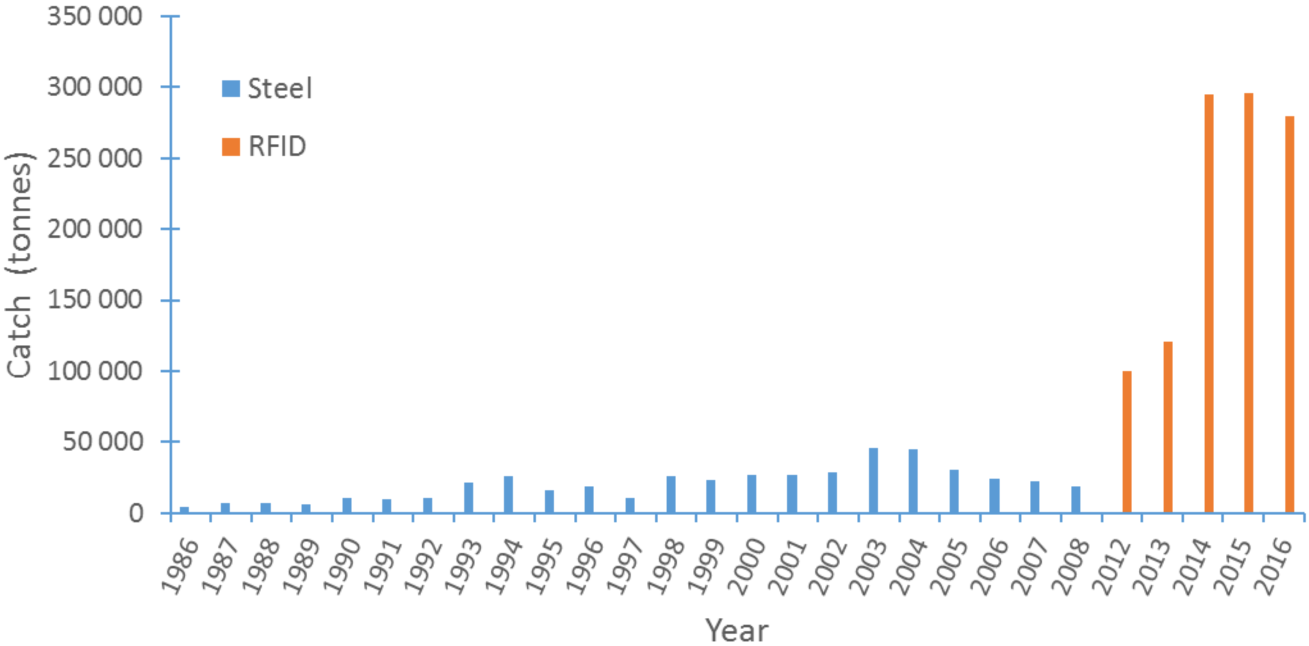


Figure 9: An overview of the catches screened per year, with steel tags used from 1986-2008 and RFID tags used from 2009 and onwards. There is an increase in the amount of catches screened since the transition to RFID tags.

The new RFID system makes it possible to see the release and recapture numbers based the year and experiment at which they were released (Figure 10 & 11, Figure S6-S9). In general, the graphs show that there is a relationship between the amount of releases and the number of recaptures.

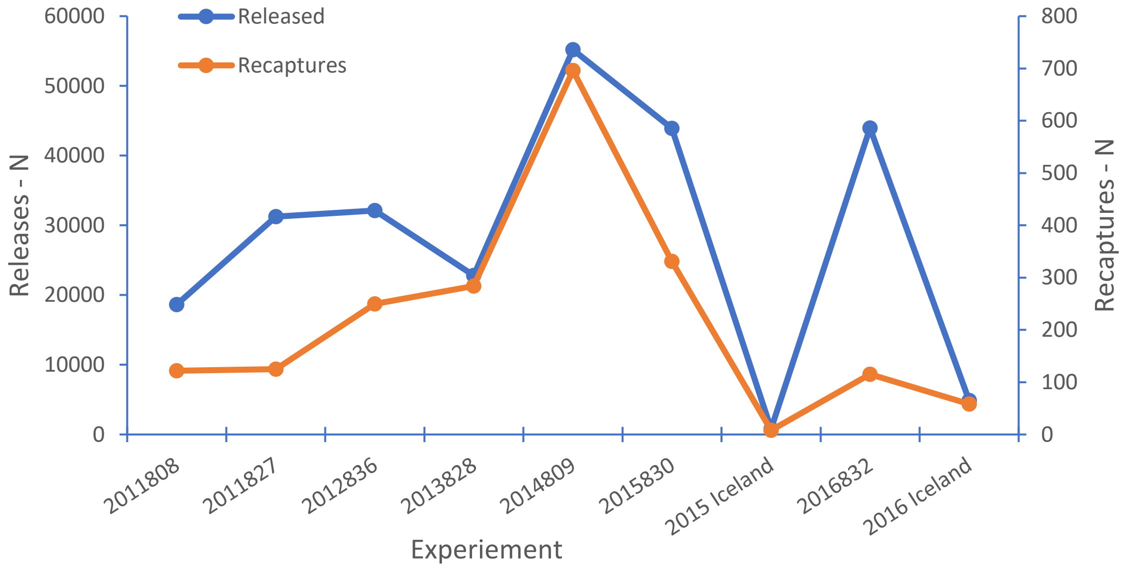


Figure 10: The number of released individuals and recaptured individuals per experiment. The blue line indicates the released individuals while the orange line indicates the number of recaptured individuals.

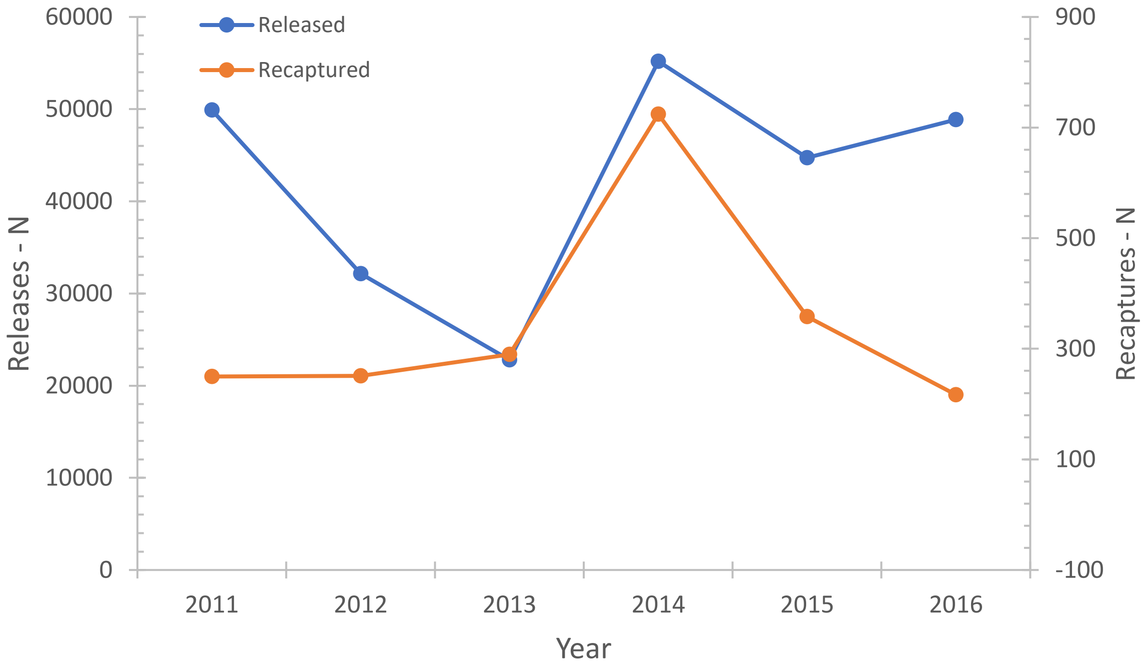


Figure 11: The relationship between the number of tagged individuals released and the amount of tagged individuals recaptured.

Age-composition of the population provides information on cohort strength and recruitment and has therefore been divided into years and quartiles. The first quartile includes mackerel caught from January to March, the second quartile includes catches from April to June, the third quartile includes catches from July to September and the forth quartile includes catches from October to December. Catch years 2012, 2013, 2014, 2015 and 2016 are shown in the respective supplementary figures S1-S5. Age-compositions vary from year to year and season to season due to recruitment variability and migration.

Screening and reading data from RFID tags

Since the transition from steel tags to RFID tags there has been an increase in the catches screened per year due to an increase in factories that have installed detectors. This automatic detection and data processing makes the process cheaper and more effective compared to the previous steel tags, making it possible to install more detectors and process a larger part of the catch.

Fishing vessel deliver their landings to factories where they are put on a conveyor belt and processed. The factories that are cooperating with the tag-recapture study have had an RFID antennae mounted on top of the conveyor belt (Figure 12).

Figure 12: Antennae mounted to the assembly line, reading internal RFID tags in marked individuals

The hardware for the factories consists of two parts; an RFID antenna (Figure 12), which is placed on top of the conveyor belt and reads the signals from the tags, and a reader station, a small metal cabinet that is used to translate the antenna signal to a binary code and transmitting it to the IMR database using a network connection (Figure 13) (TracID, 2013a, TracID, 2012). The main reading direction of tag to antennae is perpendicular, and to ensure optimal detection and reading of the tag the antennae has a geometrically arrow shape. A correct set up is essential to avoid a loss of signal and data.

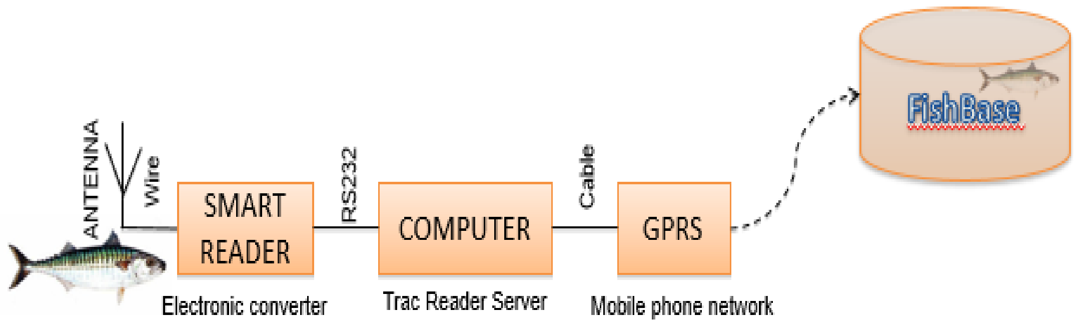


Figure 13: The process of 'reading' a marked mackerel to incorporating the data into FishBase. The antenna reads the tag, the singal get converted to the proper format using the Smart reader, the data gets incorporated into the server and goes online through the GPRS network, entering FishBase (TracID, 2013a).

A total of 16 countries have incorporated RFID readers into their assembly line, conveying data from catches directly back to the FishBase database (http://tracid-fishweb.imr.no:9000/). The RFID antenna has been incorporated in several factories internationally (Figure S9). Norway composes up to 50% of the total factories, respectively followed by Great Britain, Iceland and Faroe Islands. The largest biomass of all catches are scanned by Norwegian factories Pelagia Selje, Pelagia Egersund Seafood and Brødrene Sperre. Norway is closely followed by Great Britain with Lerwick Shetland Catch scanning the largest proportion of the biomass (Figure 14). The RFID method is proving to be an efficient method, with an increase of recaptured tags every year. Great Britain has the highest recaptured individuals, followed by Norway, Iceland, Faroe Islands and Denmark respectively (Figure 15).

There are several factors that could potentially cause reading errors, mainly if the distance between antennae and tag is too large, the presence of metals, misaligning of the tag, an excess amount of fish present on the conveyor belt, the conveyor belt moving too quickly or the tag itself failing (TracID, 2013b). Upon testing the system it showed that most systems read all of the data, giving an overall accuracy of 99.81% (TracID, 2014). The most noticeable point of weakness was the reading of tags adjacent to the side of the conveyor belt.

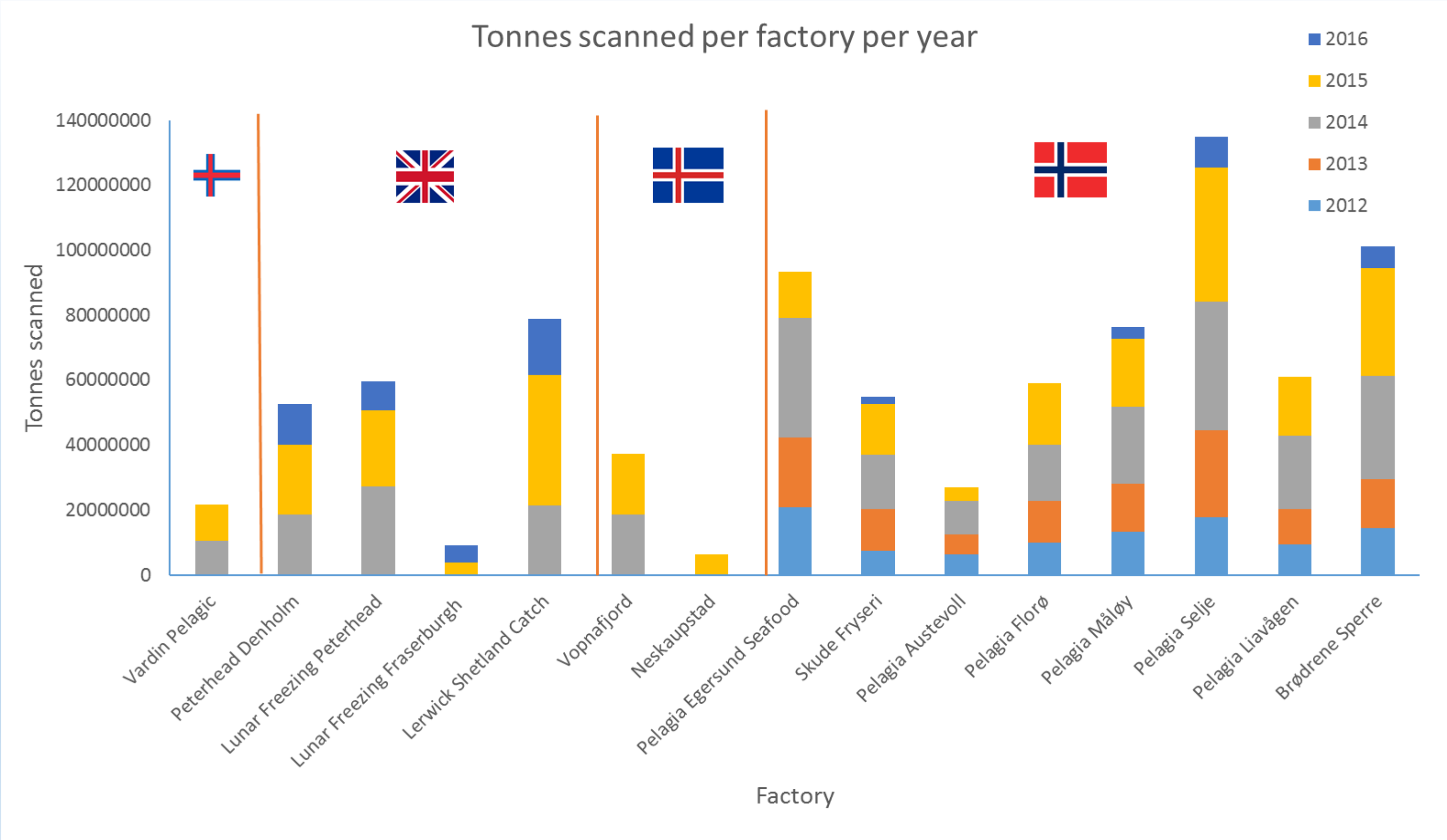


Figure 14: The amount of mackerel scanned per factory for each year, sorted by nations. Data includes catches from 2012 and the beginning of 2016. Norwegian factories scan a larger amount of mackerel than the other three nations, closely followed by Great Britain, Iceland and Faroe Islands.

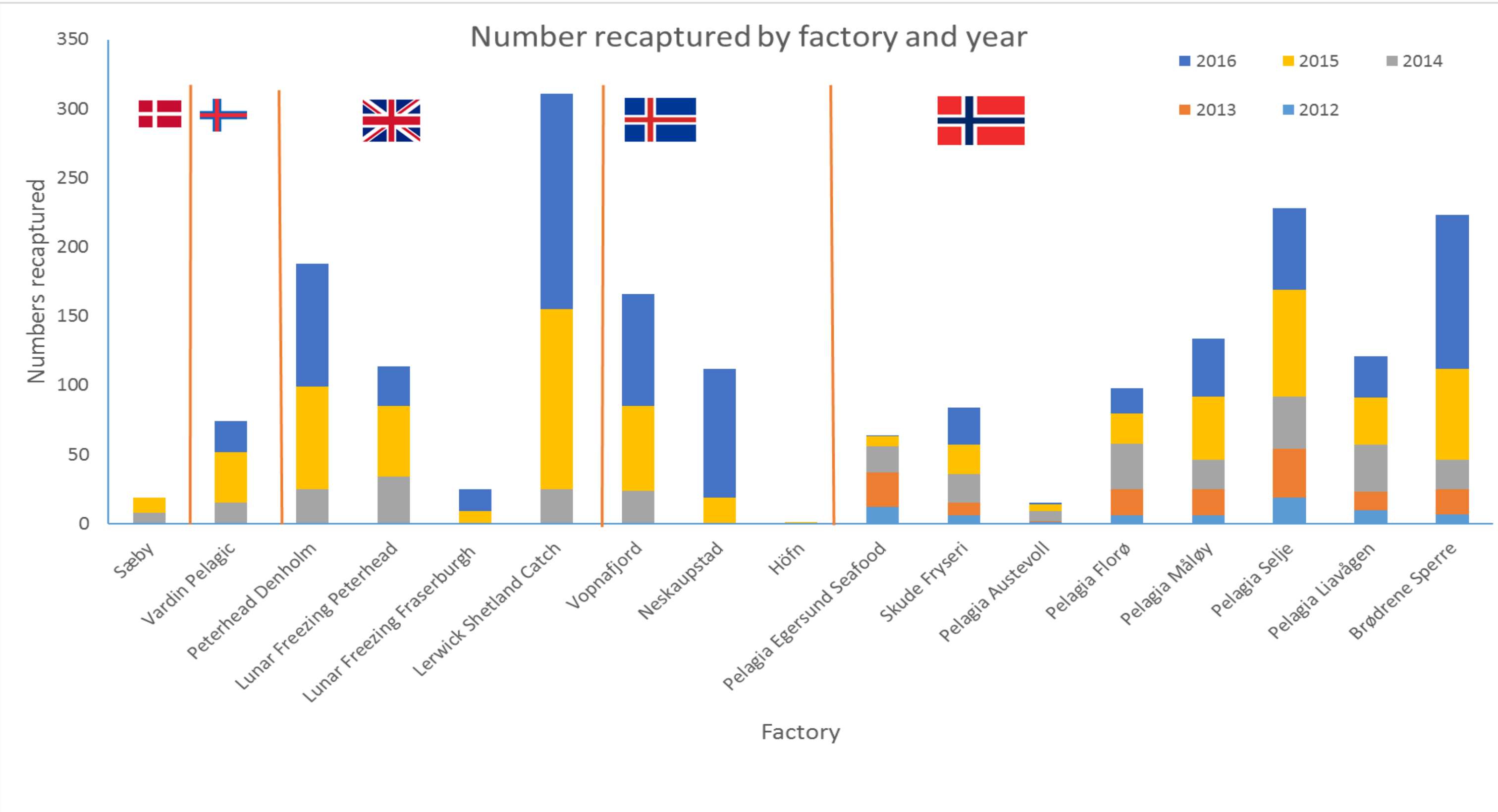


Figure 15: Number of recaptures for each factory per year. There is an increase in recaptured individuals in recent years. Data includes numbers recaptures in 2012 to 2016. Great Britain has the highest amount of recaptured individuals, scanned at the Lerwick Shetland Catch factory. Norway has the second highest number of recaptures scanned at their factories, followed by Iceland, Faroe Islands and Denmark respectively.

Data processing

Determining age of several individuals has proven to be time consuming and expensive (otoliths need to be removed and studied manually). Therefore, an age-length-key (ALK) is often used to link a certain length of individuals to an age, making it possible to deduce age from measuring the length of the fish (Berg and Kristensen, 2012).
The data used to check the age-length key from the steel tag series was previously collected and processed by Tenningen (Tenningen et al., 2011). Samples from each year were used to create an age-length key for that specific year (Figure 16). The average age for each length group was calculated and compared to the actual age collected at recapture. Whilst tagging and releasing fish will experience stress and physical injury due to crowding (Digre et al., 2016) and handling (Brattey and Cadigan, 2004). The individuals with a reduced fitness (15-20%) a day were used to make an age-length-key for each year (Tenningen et al., 2011).

The steel tag series used by Tenningen et al., in 2011 recorded the length at tagging time, the age of recapture and the time in between these two measurements. The age at recapture was measured by reading the ring increments on the otoliths. Together with the time between marking and recapture, this would give provide the age at tagging.
Negative ages were excluded from the dataset. However, the observed 0 to negative ages themselves clearly indicate a potential bias from age reading, a problem not covered in this study.

PL041X Ver_0398 Tabulering av pr›ver Art : MAKRELL 02/07-1999

F›lgende serienr. er med: 20017-90 20018-90 20003-90 20004-90 20005-90 20006-90 20007-90 20008-90 20009-90 20019-90 20020-90 20021-90

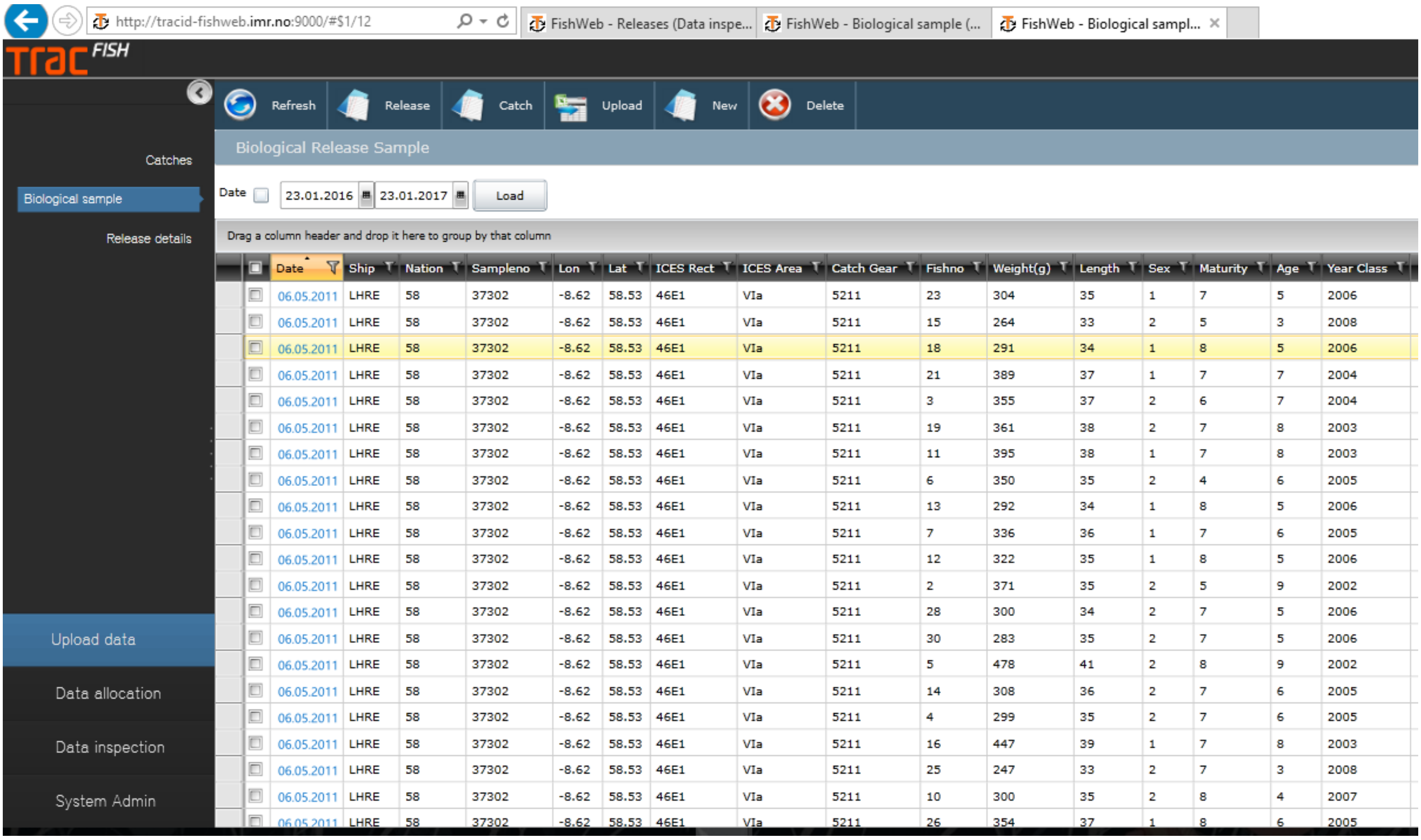
Lengde (cm)/Alder Samfengt

Lengde (cm)/Alder	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15+	Sum	Ubs	Sum	%
18.0			1														1		1	.1
19.0		4															4		4	.4
20.0		18															18		18	1.7
21.0		9															9		9	.9
22.0		13															13		13	1.2
23.0		14															14		14	1.3
24.0		8															8		8	.8
25.0		1	15														16		16	1.5
26.0			63														63		63	6.0
27.0			57	2													59		59	5.6
28.0			41	14													55		55	5.2
29.0			15	70	5												90		90	8.5
30.0			12	104	14	2											132		132	12.5
31.0			3	111	13	2	4										133		133	12.6
32.0				75	19	5	1	1	1								102	1	103	9.8
33.0				59	14	13	5		1		2						94		94	8.9
34.0				26	14	5	2		1		1						49		49	4.7
35.0				9	8	2	9		1	2	1	2					34		34	3.2
36.0				4	3	1	4		3	3	1	2					21	2	23	2.2
37.0					3	2	12	2	2	2	5	1		1			30	1	31	2.9
38.0						2	8	1	1	2		2			1		17		17	1.6
39.0							5	3	3	4	5	3	1			1	25	2	27	2.6
40.0				1			2		4	1	1		1	1		2	13	1	14	1.3
41.0									1	10	3	2				2	18		18	1.7
42.0								1	2	6		3				2	14	1	15	1.4
43.0										2	1	1	1			1	6	1	7	.7
44.0									1	1						1	3		3	.3
45.0										1							1	1	2	.2
46.0																	0	1	1	.1
Sum	0	67	207	475	93	34	52	8	21	34	20	16	3	2	1	9	1042	11	1053	99.9
%	.0	6.4	19.9	45.6	8.9	3.3	5.0	.8	2.0	3.3	1.9	1.5	.3	.2	.1	.9	100.1			
L	.0	22.2	27.6	31.6	32.9	33.9	36.5	38.4	38.6	40.5	38.4	39.4	41.2	39.0	38.5	41.8	31.5	40.0	31.6	
S(L)	.0	1.6	1.5	1.7	2.0	2.0	2.4	2.8	3.1	2.6	2.7	2.7	2.1	2.1	.0	1.6	4.6	4.2	4.7	

Figure 16: An age-length distribution used to construct an age-length key. The same age-length distribution was made for every year, this specific example is from 1999. It provides the length groups (cm) in the left column and the ages in the top row, the numbers in the cross table indicate how many individuals are within each age and length category. From this table the average age for each length group can be calculated.

The data from the RFID tags that gets collected from the landings are stored on an online database called FishWeb, accessible using the Microsoft Silverlight plug-in and a personalized account, through the weblink: http://tracid-fishweb.imr.no:9000/.

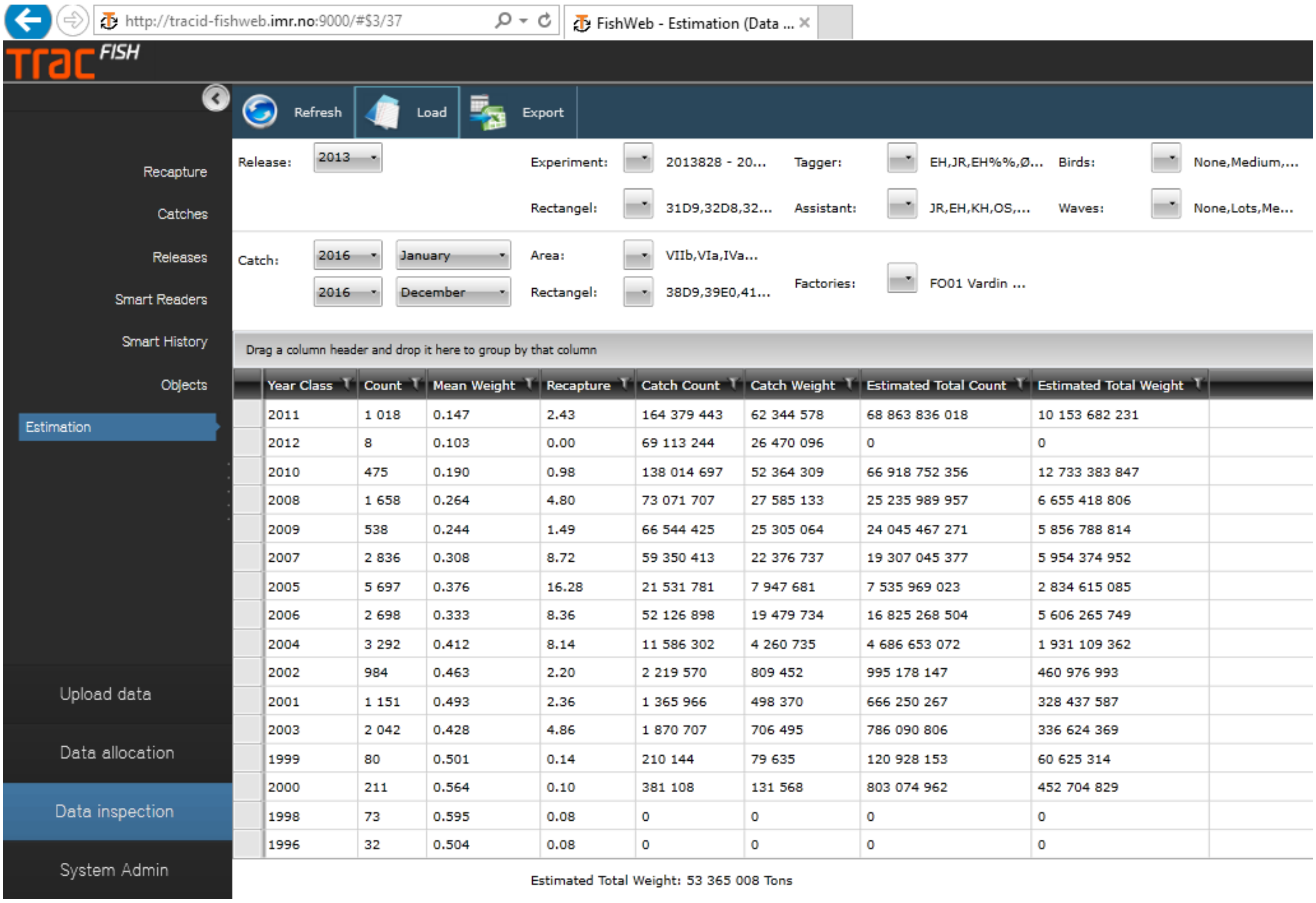
The data is arranged in three separate tabs; upload data, data allocation and data inspection. Data are usually showed as releases, catches and recaptures, with information varying from averages to individual data. The datasets can be filtered to show certain periods and the showed sets can be further sorted, filtered or summaries by adjusting and dragging the column names (Figure 17). The data can easily be exported to Excel using the copy-paste function.



Date	Ship	Nation	Sampleno	Lon	Lat	ICES Rect	ICES Area	Catch Gear	Fishno	Weight(g)	Length	Sex	Maturity	Age	Year Class
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	23	304	35	1	7	5	2006
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	15	264	33	2	5	3	2008
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	18	291	34	1	8	5	2006
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	21	389	37	1	7	7	2004
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	3	355	37	2	6	7	2004
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	19	361	38	2	7	8	2003
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	11	395	38	1	7	8	2003
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	6	350	35	2	4	6	2005
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	13	292	34	1	8	5	2006
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	7	336	36	1	7	6	2005
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	12	322	35	1	8	5	2006
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	2	371	35	2	5	9	2002
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	28	300	34	2	7	5	2006
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	30	283	35	2	7	5	2006
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	5	478	41	2	8	9	2002
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	14	308	36	2	7	6	2005
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	4	299	35	2	7	6	2005
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	16	447	39	1	7	8	2003
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	25	247	33	2	7	3	2008
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	10	300	35	2	8	4	2007
06.05.2011	LHRE	58	37302	-8.62	58.53	46E1	VIa	5211	26	354	37	1	8	6	2005

Figure 17: The online database used to store and extract data for analysis, weblink: http://tracid-fishweb.imr.no:9000/.

Data can easily be investigated further by using the estimate function provided by FishWeb. By changing factors like the presence of birds or waves, include or exclude certain experiments or compare catches per factory, it is possible to compare if this would influence the amount of recapture or catches (Figure 18).



Year Class	Count	Mean Weight	Recapture	Catch Count	Catch Weight	Estimated Total Count	Estimated Total Weight
2011	1 018	0.147	2.43	164 379 443	62 344 578	68 863 836 018	10 153 682 231
2012	8	0.103	0.00	69 113 244	26 470 096	0	0
2010	475	0.190	0.98	138 014 697	52 364 309	66 918 752 356	12 733 383 847
2008	1 658	0.264	4.80	73 071 707	27 585 133	25 235 989 957	6 655 418 806
2009	538	0.244	1.49	66 544 425	25 305 064	24 045 467 271	5 856 788 814
2007	2 836	0.308	8.72	59 350 413	22 376 737	19 307 045 377	5 954 374 952
2005	5 697	0.376	16.28	21 531 781	7 947 681	7 535 969 023	2 834 615 085
2006	2 698	0.333	8.36	52 126 898	19 479 734	16 825 268 504	5 606 265 749
2004	3 292	0.412	8.14	11 586 302	4 260 735	4 686 653 072	1 931 109 362
2002	984	0.463	2.20	2 219 570	809 452	995 178 147	460 976 993
2001	1 151	0.493	2.36	1 365 966	498 370	666 250 267	328 437 587
2003	2 042	0.428	4.86	1 870 707	706 495	786 090 806	336 624 369
1999	80	0.501	0.14	210 144	79 635	120 928 153	60 625 314
2000	211	0.564	0.10	381 108	131 568	803 074 962	452 704 829
1998	73	0.595	0.08	0	0	0	0
1996	32	0.504	0.08	0	0	0	0

Figure 18: An example of estimates provided by the Fishweb, the estimate can be individually tailored to include certain experiments, presence of birds and waves, factories etc.

In addition to the FishWeb database the catches, releases and recaptures are graphically summarized online using maps at the following site: http://tracid-fishmap.imr.no/map.aspx. The site provides options to show selected years of release, recapture and catches with the option of selecting factories where landings were processed (Figure 19).

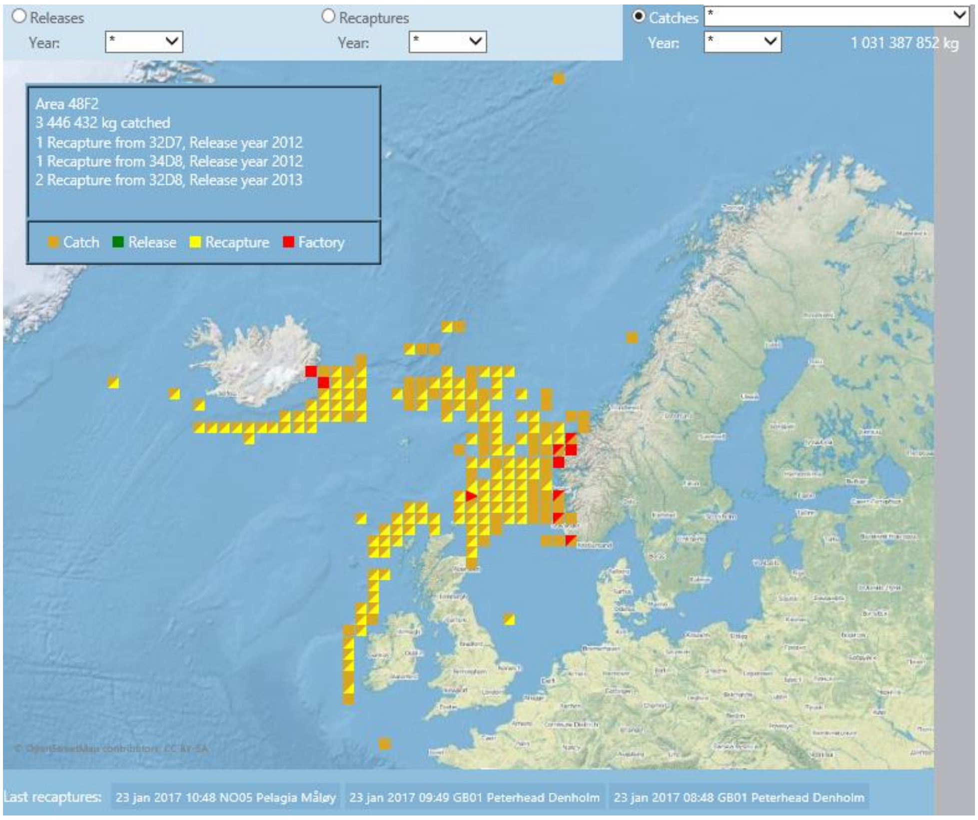


Figure 19: An example of a map from http://tracid-fishmap.imr.no/map.aspx, showing the geographical location of data gathered, with the option of selecting year of release, recapture, catches and/or factory. By selecting a point on the map information corresponding with that specific point will be displayed in the top left corner. The last recaptures are always displayed at the bottom of the map.

Possible errors

As mentioned earlier, stress due to crowding and handling could influence the mortality of fish (Berg and Kristensen, 2012, Digre et al., 2016). Tagging of mackerel with RFID tags occurs in different years and expeditions, with varying numbers of mackerel being tagged, released and recaptured for each expedition. It is important to determine whether there is an effect of sample size on the number of recaptures. Theoretically, if mortality is excluded, a larger number of tags being released, would result in a large number of tags being recaptured. A negative effect could indicate that there is an increased mortality due to crowding or a longer handling time with larger samples being tagged.

Besides number of mackerel tagged per experiment, there may be other factors affecting number of mackerel recapture. The RFID series provides extra information on environmental factors, like the condition of the sea (many/medium/few waves), the presence of birds as well as the name of the individual and assistant tagging the mackerel. The potential bias related to these factors were explored in the thesis.

Since the start of using RFID tags the number of factories included has increased, also increasing the chances of potential errors. Total count estimates of the population are based upon the recapture rates detected by the different factories, it is therefore important to identify possible errors or biases as a result of including or excluding certain factories. One potential likely error is related to the fact that each country has specific catch areas and main fishing season, and if the tagged fish does not mix equally in all areas and seasons one may end up with a bias in the data. Hence, present analyses tested for differences in estimated numbers of fish between countries as well as factories.

Statistical analysis

All statistical analyses were performed using the programmes Dell Inc. (2015). Dell Statistica (data analysis software system), version 13 (software.dell.com) or RStudio Version (2016) 0.99.903 (https://www.rstudio.com/). An alpha value of 0.05 was maintained for all statistical analyses.

Comparing actual age obtained from otolith readings to estimated age from the ALK was done using a linear model ANOVA in RStudio and a t-test using Statistica. An alpha of 0.05

was used for both tests. This statistical test was picked because the data was normally distributed.

A linear model was used to test for density dependence during release and its effect on the recapture. Hereunder it was assumed that handling time and density in tanks increased with higher number of fish tagged in an experiment/release. A normal linear model was the best fit for the data, providing the least residuals. Tests were done using RStudio and an alpha of 0.05 was maintained for statistically significant results.

A non-parametric Kruskall-Wallis ANOVA was used to test if there was an effect of the presence of predators in terms of birds and weather in terms of waves for the estimated biomass of mackerel. Hereunder assuming that newly tagged fish may have higher mortality with increasing presence of predators and rougher handling under bad weather conditions. The data was arranged per release year and all of the recapture years after this. The test analyses if the different groups differ from each other, in this case the groups would be no birds present, medium amount of birds present and lots of birds present during release. When only two categories were available (release year 2014) a non-parametric test for two variables was used, Kolmogorov-Smirnov. All tests were done using Statistica and an alpha of 0.05 or less was assumed as significant in both tests.

A non-parametric Kruskall-Wallis ANOVA was used to test if there was an effect of the presence of waves for the estimated biomass of mackerel.
The data was arranged per release year and all of the recaptures after this. The test analyses if the different groups differ from each other, in this case the groups would be no waves present, medium waves present and lots of waves present during release. When only two categories were available (release year 2016) a non-parametric test for two variables was used, Kolmogorov-Smirnov. All tests were done using Statistica and an alpha of 0.05 or less was assumed as significant in both tests.

To test whether there was an effect of both waves and birds being present at the same time a non-parametric Kruskall-Wallis ANOVA was used to test the difference between lots of waves with lots of birds, no waves or birds and finally medium amount of waves and birds. An alpha of 0.05 or less was assumed as significant. Data was only available for 2015 and 2016.

Effects of country and factory on the total estimated count were tested using a Kolmogorov–Smirnov test and a Kruskall-Wallis non-parametric test and respectively. All tests were done using Statistica, and an alpha of 0.05 or less was assumed as significant for both tests.

Results

Ageing of recaptured fish

The estimated age from the steel tag series, based on the age-length key, provides a slightly higher age when compared to the age found from the actual otolith readings after recapture for all data collected from 1984 to 2007 (Figure 20). The relationship between the actual age and the estimated age is shown in figure 21, showing a R^2 of 0.6. For all data combined from 1984 to 2007, there was a statistical difference between actual age retrieved from the otoliths and estimated age based on the ALK (p= 2.2e-16).

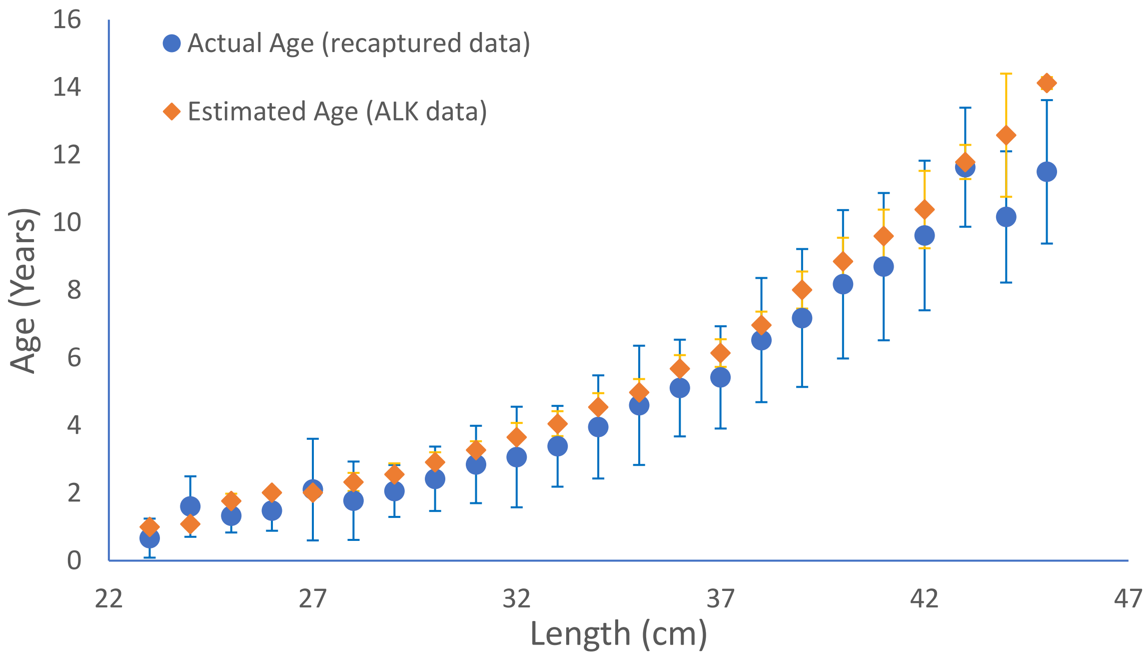


Figure 20: The estimated age, derived from the age-length key from the steel tag series, compared to the actual length-age relationship from otolith readings after recapture, standard error for both are indicated by the error bars. Data was collected from 1984 through 2007. A significant difference in age was found between actual and estimated age for lengths 26cm and 28-42cm (p<0.05) using the t-test.

The same trend of a slightly higher estimated age was displayed for the 80's, 90's and 2000's when the data was divided into decades versus compiling all data from 1984 to 2007 (Figure 20).

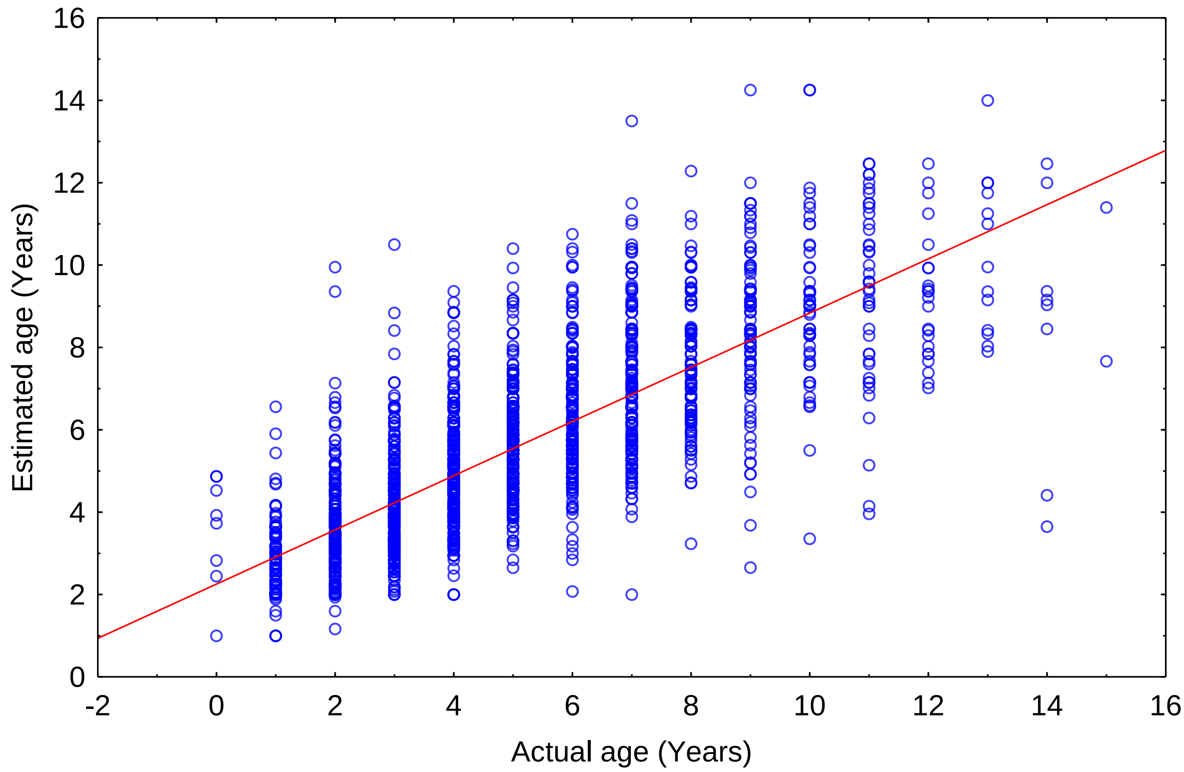


Figure 21: Actual ages derived from otolith readings compared to estimated ages from all mackerel measured from 1984-2007. R^2 is 0.60

Collecting data over 33 years means that there might be a variation in protocols and therefore variations over the year. The data collected from 1984 to 2007 has therefore been split up into three separate chunks of data, one for the 80's, one for the 90's and one for data collected from 2000-2007. The data collected in the 80's show a large variation of the data points between the actual age from otoliths and the estimated age (Figure 22) as well as a low R^2 of 0.4672 (Figure 23). There was a statistical difference between actual age retrieved from otoliths and estimated age from the ALK (p= 1.268e-06). The large spread in confidence interval in the graph is caused by the limited amount of data point (length 39cm and 42cm only have two data points).

There was a statistical difference in actual age retrieved from otoliths and estimated age for mackerel at length 28, 29, 30, 33, 34, 36 and 40 (p<0.05 using the t-test).

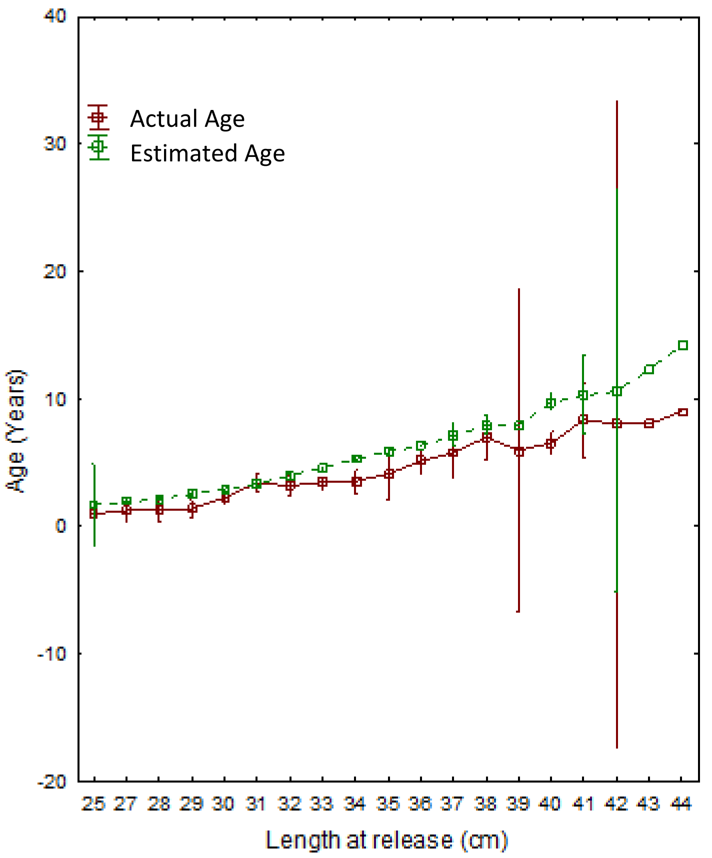


Figure 22: The actual age vs estimated age for several lengths of release during the 80's. There was a significant difference between estimated and actual age for lengths at release 28, 29, 30, 33, 34, 36 and 40.

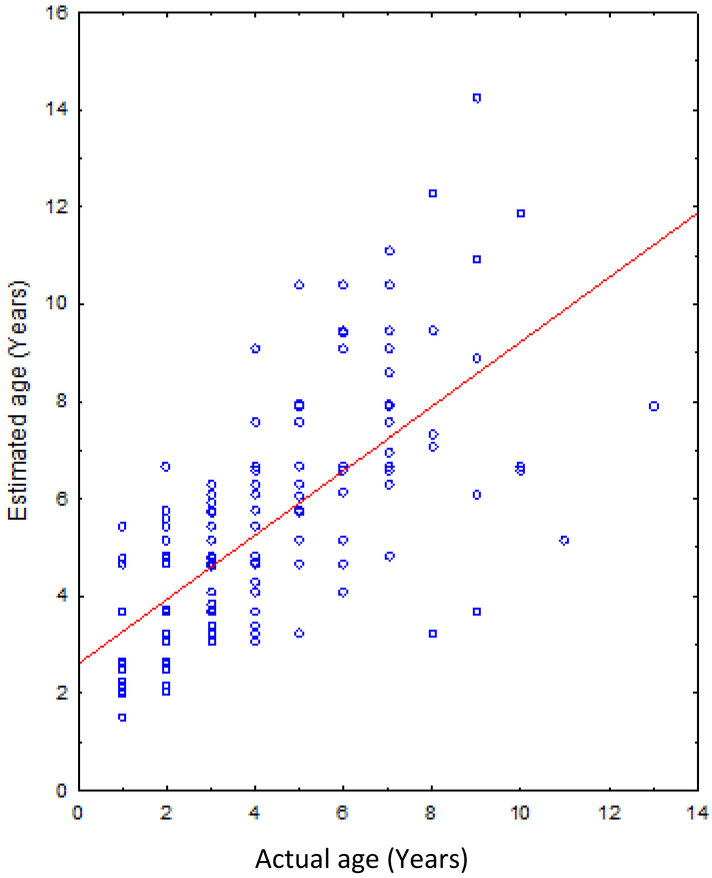


Figure 23: Graph showing the regression line and relationship between actual age and estimated age. The data points show a large spread, giving a R^2 of 0.47.

During the 90's more mackerel was measured (a total of 1245 mackerel were used to compose the ALK). There was a statistical difference between actual age retrieved from otoliths and estimated age from the ALK (p= 3.71e-07). The statistical test show that there was a difference in actual age retrieved from otoliths and estimated age for the following length of mackerel; 26, 28-34 and 36-42 (p-value< 0.05) (Figure 24). The R^2 of the regression line in the scatterplot is however at 0.81, indicating a strong correlation between the two variables (Figure 25).

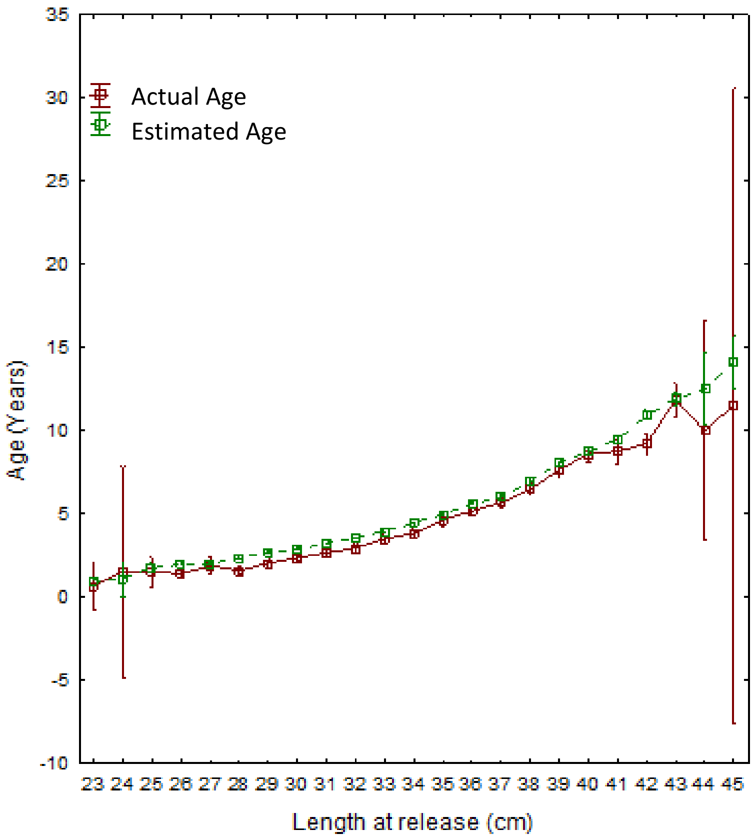


Figure 24: The actual age vs estimated age for several lengths of release during the 90's. There was a significant difference between estimated and actual age for lengths at release 26, 28-34 and 36-42.

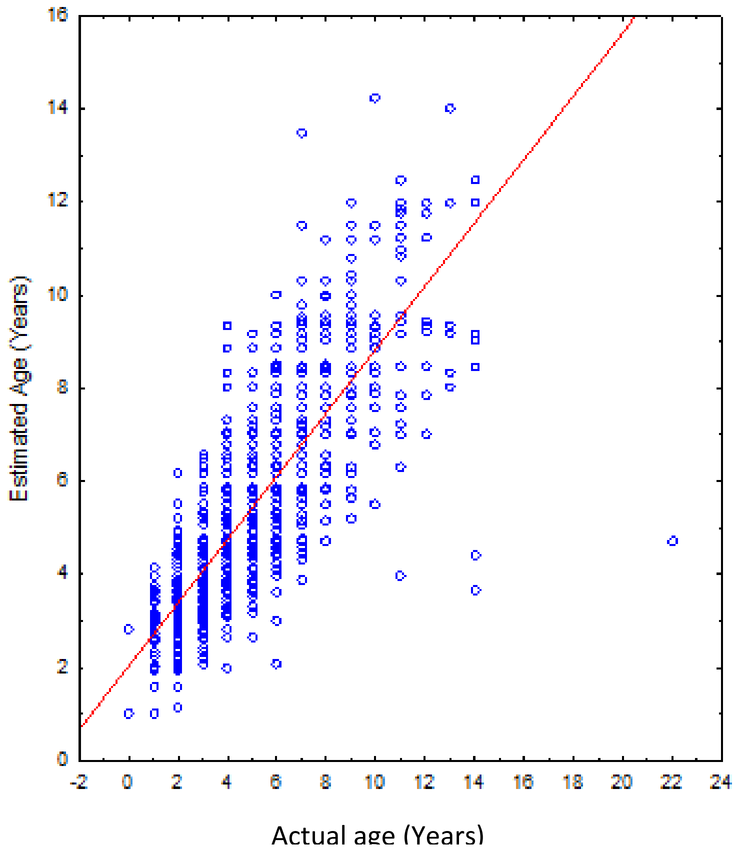


Figure 25: Graph showing the regression line and relationship between actual age and estimated age for the 90's. The data points show a less varied spread compared to the 80's. R2 is at 0.81.

In the years between 2000 and 2007 a total of 980 mackerel were used to produce the ALK. There was a statistical difference between actual age retrieved from otoliths and estimated age from the ALK (p= 4.71e-08). Of these 980 mackerel, there was a significant difference between actual age retrieved from otoliths and estimated age for the mackerel lengths of 32-39cm and 41cm (p-value<0.05 using a t-test) (Figure 26).

The scatterplot shows quite some variation in the estimated ages compared to the actual age retrieved from otoliths (Figure 27). The regression line shows a R^2 of 0.5158.

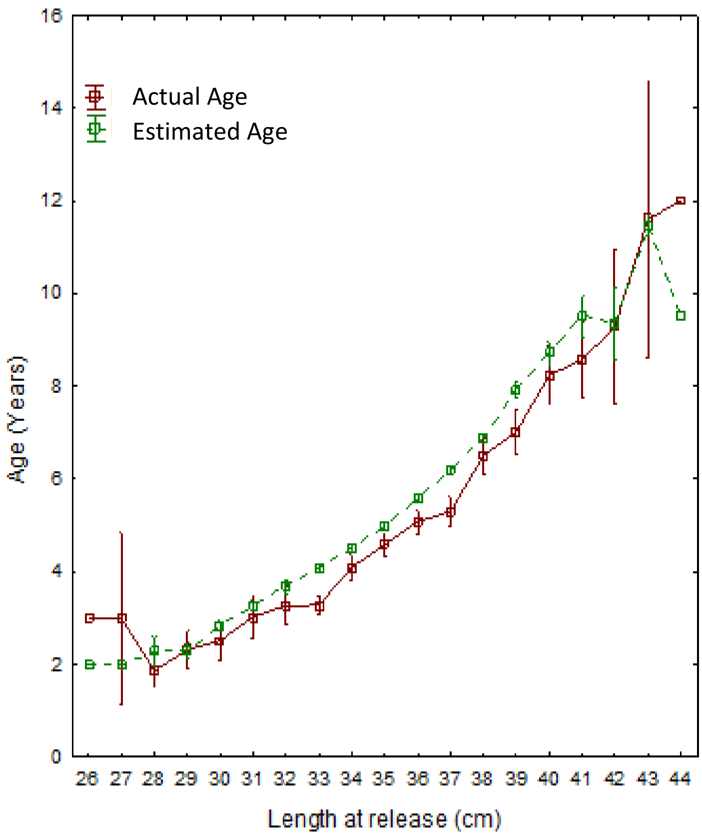


Figure 26: The actual age vs estimated age for several lengths of release during the 2000's. There was a significant difference between estimated and actual age for lengths at release 32-39cm and 41cm

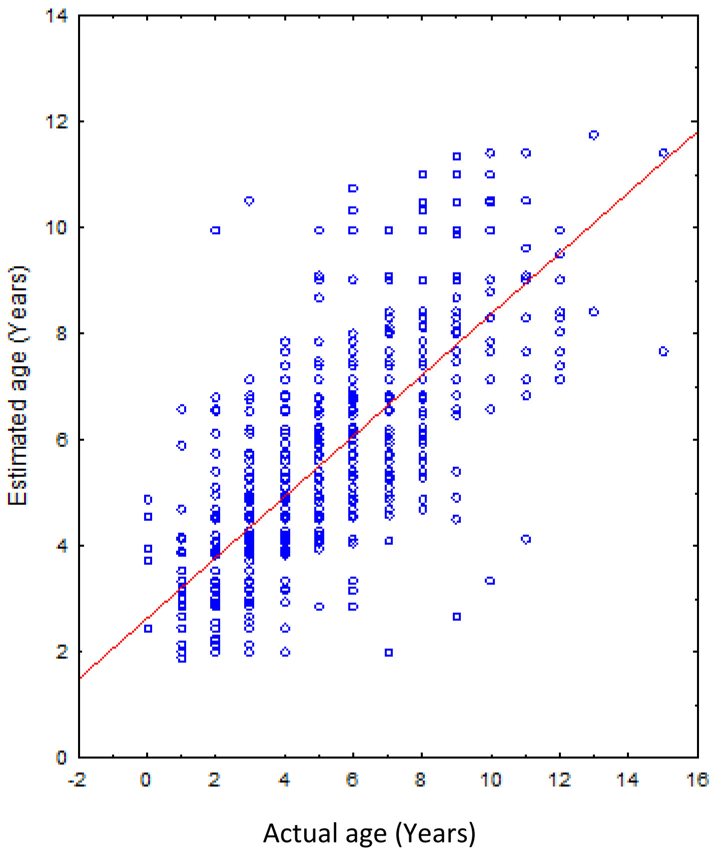


Figure 27: Graph showing the regression line and relationship between actual age and estimated age for the 2000's. The data points show a larger spread compared to the 90's. This is reflected in the R^2, which is at 0.52.

One would assume that the readings are more accurate when time between tagging and recapture is shortest (there is less time for other factors to play a role and growth is more linear over a shorter period of time).

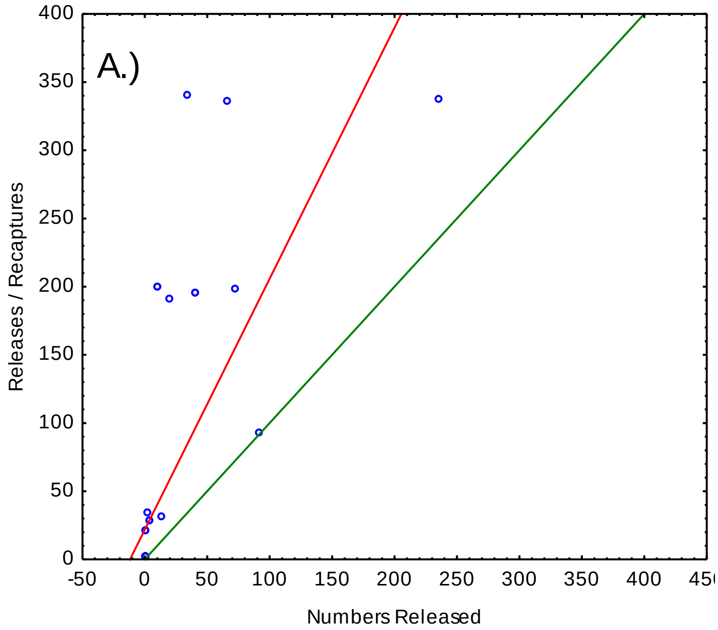
The time between tagging and recapture could be a possible source of error. The time between release and recapture has therefore been divided into three time categories for each decade (Figure 28). There is no correlation between the time between tagging and recapture and the accuracy of the ALK (Figures S10-S12).

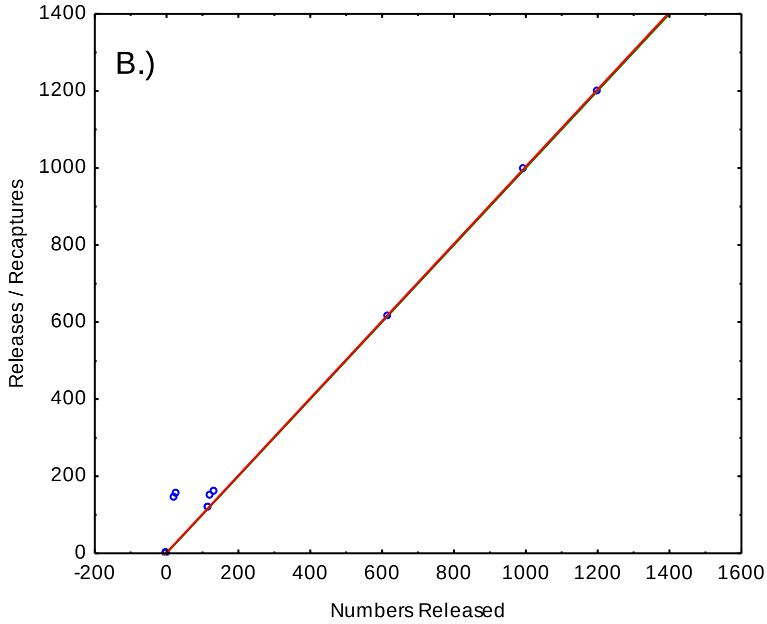
Decade	0-2 years	3-5 years	5-7 years	8+ years
80's	42%	8%	17%	NA
90's	28%	65%	28%	50%
2000's	11%	44%	57%	33%

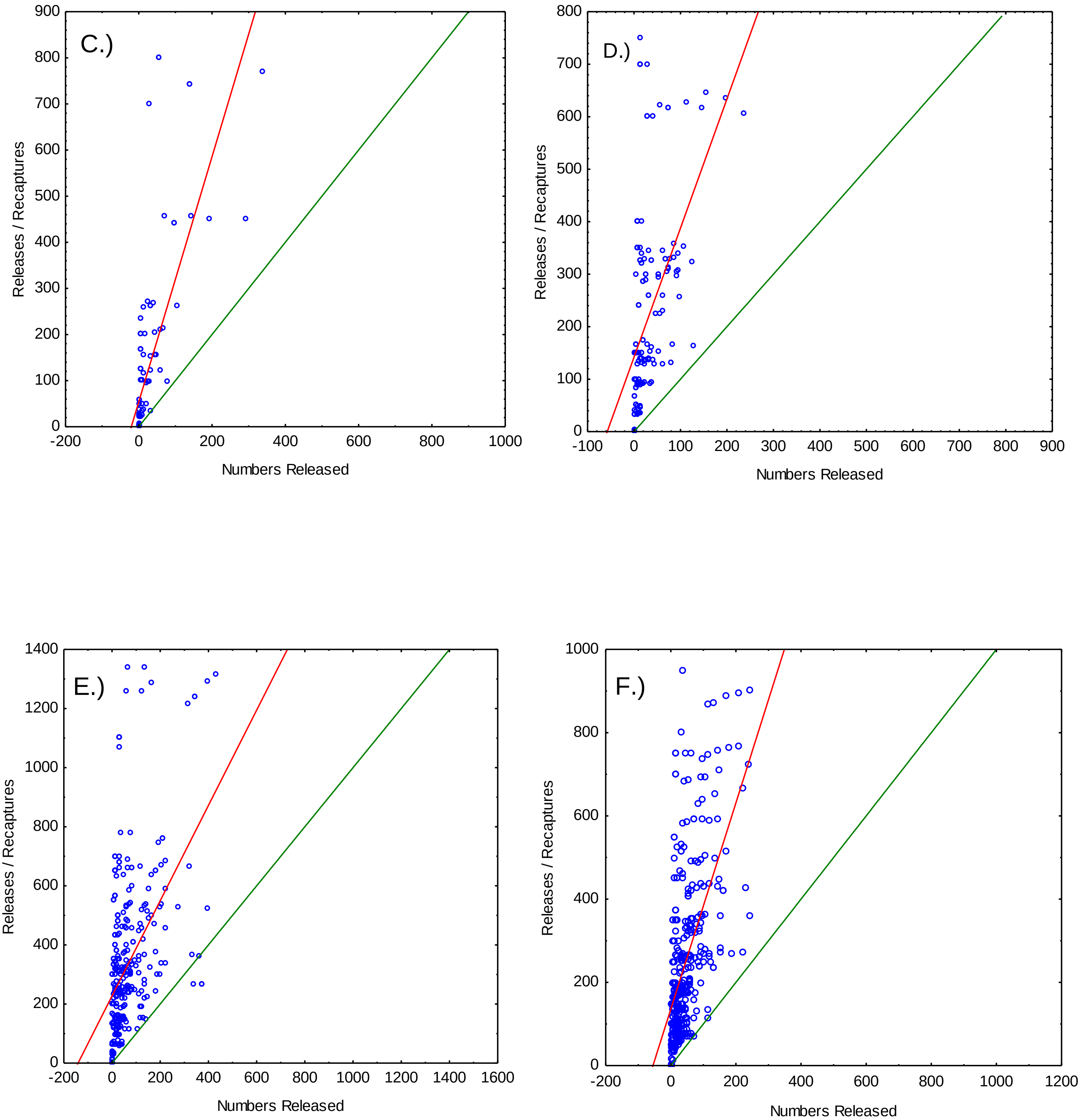
Figure 28: Table showing the percentage of estimated and actual ages derived from otolith readings that statistically vary from each other per decade and time period between release and recapture

Density dependent releases and recaptures

Due to crowding during capture, tagging and releasing, there is an potential hypothetical bias that survival rate will decrease if larger amounts are released at the same release. A larger number of fish being released may result in more stress, physical damage due to crowding and a longer handling time (Digre et al., 2016, Huse and Vold, 2010). To test if there is an effect of number of individuals being released per experiment the number of fish released is plotted against the recapture rate (number of fish recaptured relative to total number released in a release or experiment) (Figure 29a-g). The graphs are divided into the various expeditions, showing number of mackerel released on the X-axis and the recapture rate on the Y-axis. The graphs show that more fish need to be released to recapture one individual when numbers released is increased. This could potentially indicate a negative relationship between survival and numbers of fish released during an experiment. There was however no statistical support for the effect of density dependence, with the exception of expedition 2015830 (p-value= 0.04). The expeditions in Iceland were left out of the analysis because the amount of releases were very low (Iceland 2015: 13 releases at most, and Iceland 2016: 55 releases at most).






C.)
D.)
E.)
F.)
Releases / Recaptures
Numbers Released

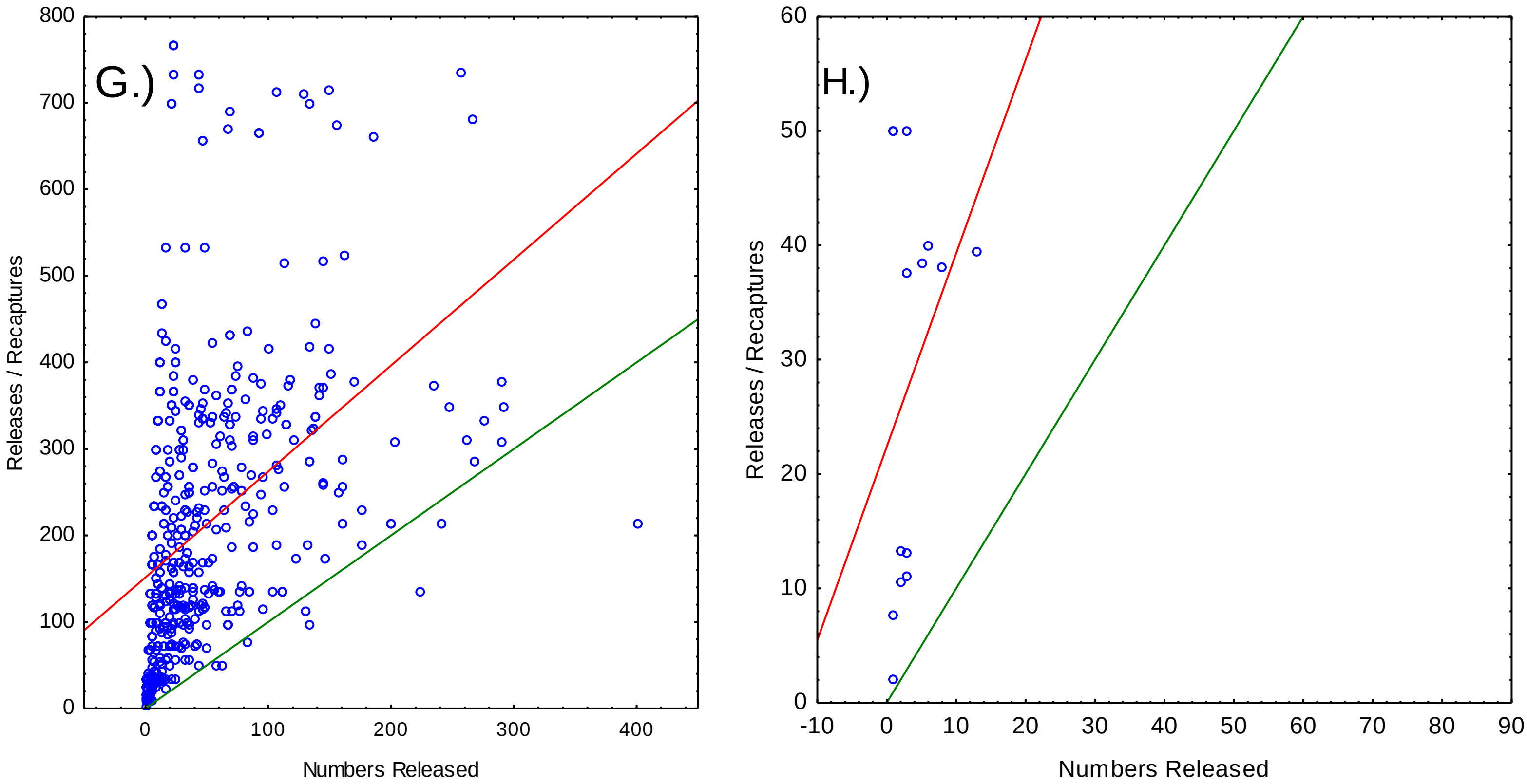


Figure 29 a-g : Graphs showing the relationship between number of fish released per tagging experiment and the recapture rate. A higher number of releases/recapture shows a lower recapture rate. Figure A-F are respectively expedition numbers 2011808, 2011827, 2012836, 2013828, 2014809, 2015830 and 2016832. The red line shows the relationship between numbers released and the recapture rate. The green line shows the ideal 1:1 relationship between numbers released and recapture rate. There is no statistical proof of an effect of density dependent releases on recapture, with the exception for expedition 2015830 ($p< 0.05$).

Effect of weather and birds

Fishing vessels attract birds, the fish are closer to the surface and therefore easier prey for the birds. The presence of birds during tagging and release was expected to have a negative effect on the recapture of fish due to predation occurring during capture and release. There was however no effect of presence of birds in most years, only a small effect was found in 2016 ($p<0.05$). The effects of the presence of birds was tested using a non-parametric Kruskall-Wallis.

Mackerel tagged and released in 2013 showed no effect of the presence of birds during the release on the estimated biomass of the stock (Figure 30).

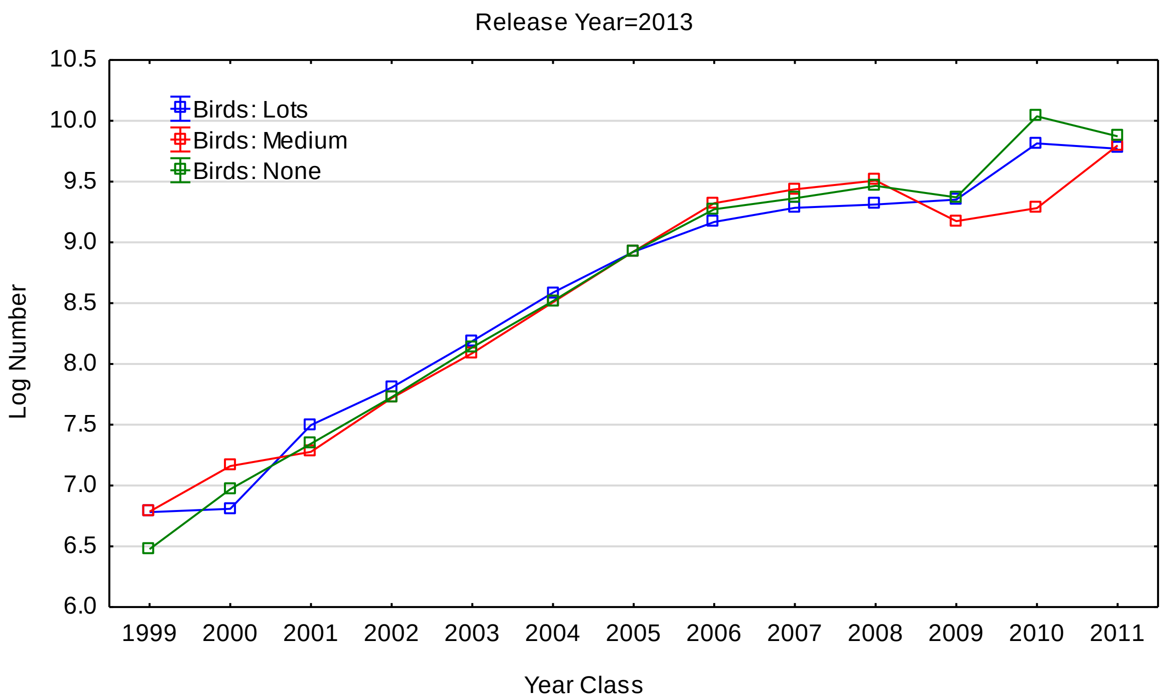


Figure 30: The effect of the presence of birds during tagging and releasing of mackerel in 2013 and recaptures in all following years. No statistical difference on mackerel stock estimates between the various amounts of birds present during tagging (p= 0.9025).

Data collected on releases in 2014 did not include conditions where there were no birds present (Figure 31), comparing the estimated biomass between release conditions with lots of birds and medium amount of birds present did not show a statistical difference in estimated stock between the two conditions (p=0.45).

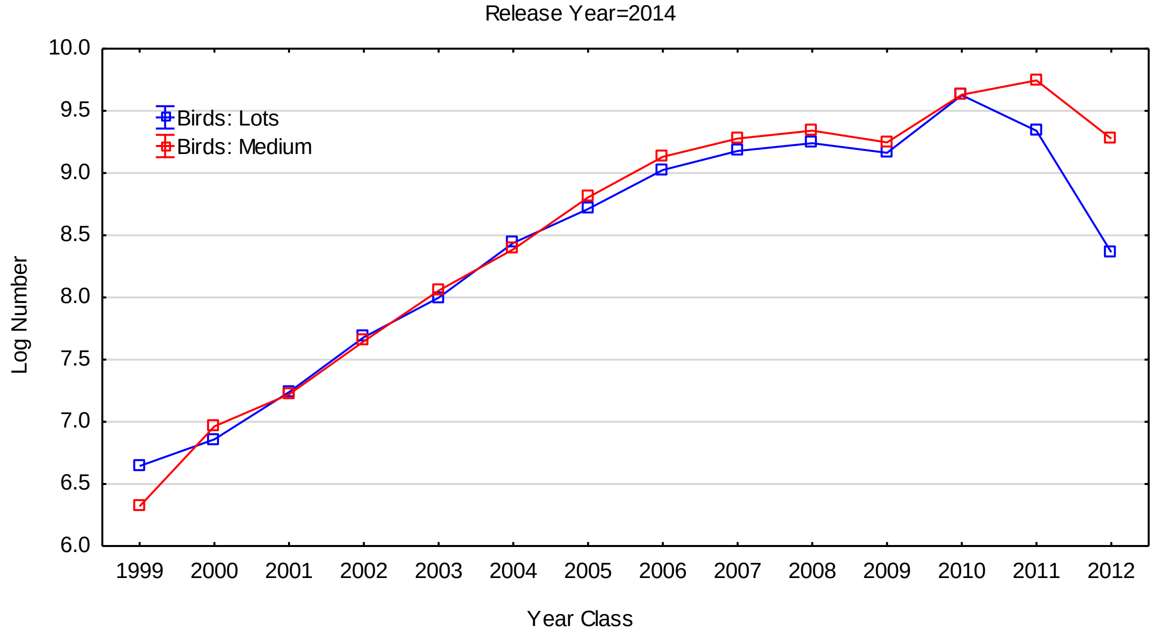


Figure 31: The effect of the presence of birds during tagging and releasing of mackerel in 2014 and recaptures in all following years. No statistical difference on mackerel stock estimates between the various amounts of birds present during tagging (p= 0.4497).

During releases in 2015 all conditions for birds present were registered. There was still no effect of the presence of birds on the estimated stock(p= 0.75) (Figure 32).

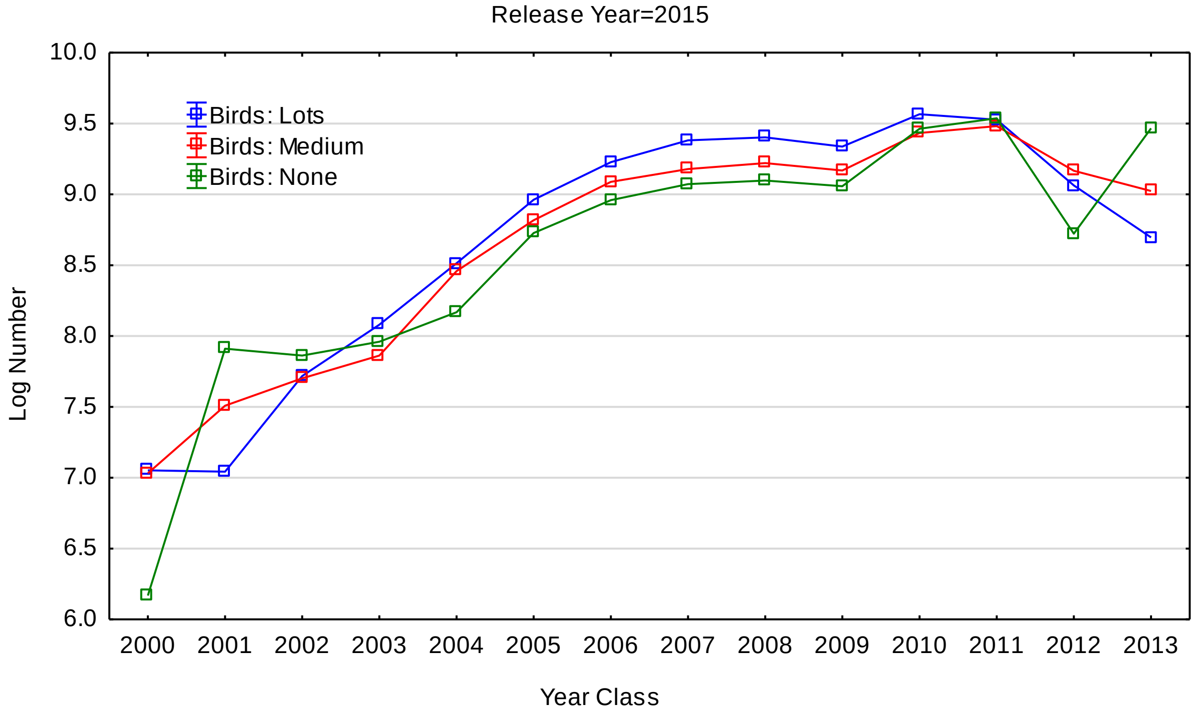


Figure 32: The effect of the presence of birds during tagging and releasing of mackerel in 2015 and recaptures in all following years. No statistical difference on mackerel stock estimates between the various amounts of birds present during tagging (p= 0.7515).

Releases in 2016 (Figure 33) showed an effect of the presence of birds on the estimated mackerel stock, the difference was found between lots of birds and no birds present (p=0.01).

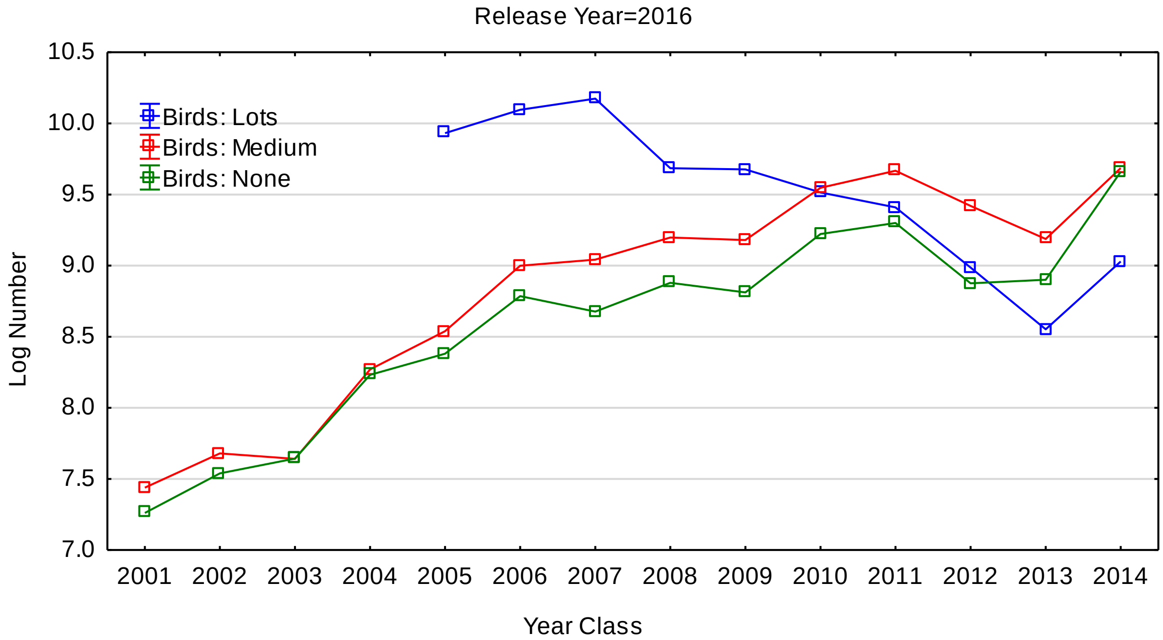


Figure 33: The effect of the presence of birds during tagging and releasing of mackerel in 2016 and recaptures in all following years. Statistical difference, p=0.05. The main statistical difference was found between lots of birds present and no birds present (p=0.005).

Turbulent oceans could potentially affect the survival of the tagged and released mackerel. The effect of weather is therefore measured by the presence of waves, which are divided into three categories, no waves, medium waves or lots of waves present. The data, just like the data on the presence of birds, was arranged by release year and the estimated biomass from all the following recapture years. There was however no data collected on waves during release year 2013. Releases from 2014 show that there was no effect of the presence of waves on the estimated stock based on the recaptures (p>0.05) (Figure 34).

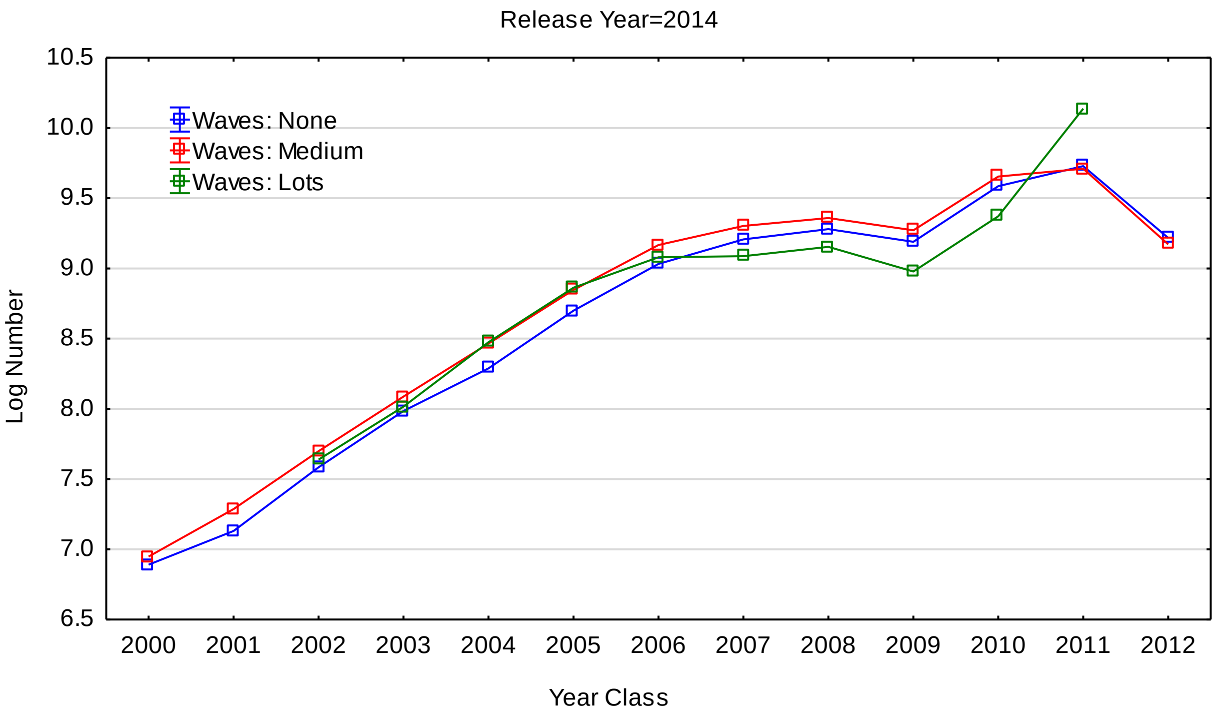


Figure 34: The effect of the presence of waves during tagging and releasing of mackerel in 2014 and recaptures in all following years. There was no effect of the presence of waves on mackerel stock estimates between the various amounts of waves present during tagging (p> 0.05).

There was no effect of waves on the estimated stock for release year 2015 or release year 2016 (Figure 35-36).

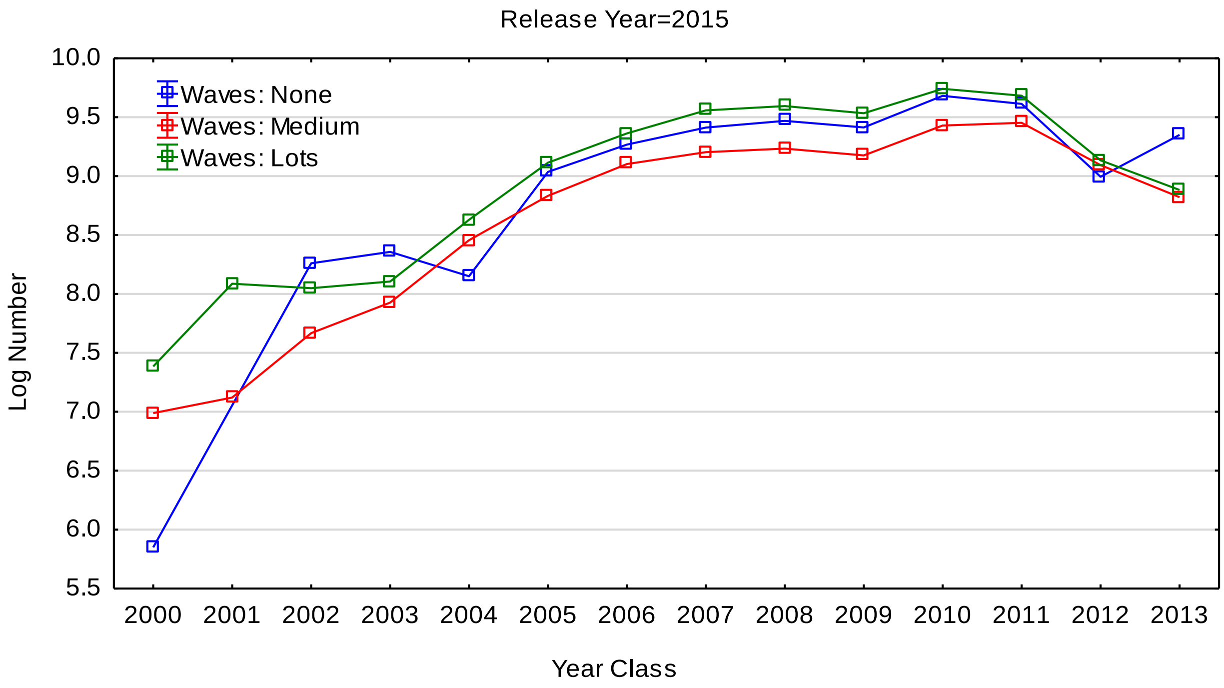


Figure 35: The effect of the presence of waves during tagging and releasing of mackerel in 2015 and recaptures in all following years. There was no effect of the presence of waves on mackerel stock estimates between the various amounts of waves present during tagging (p> 0.05).

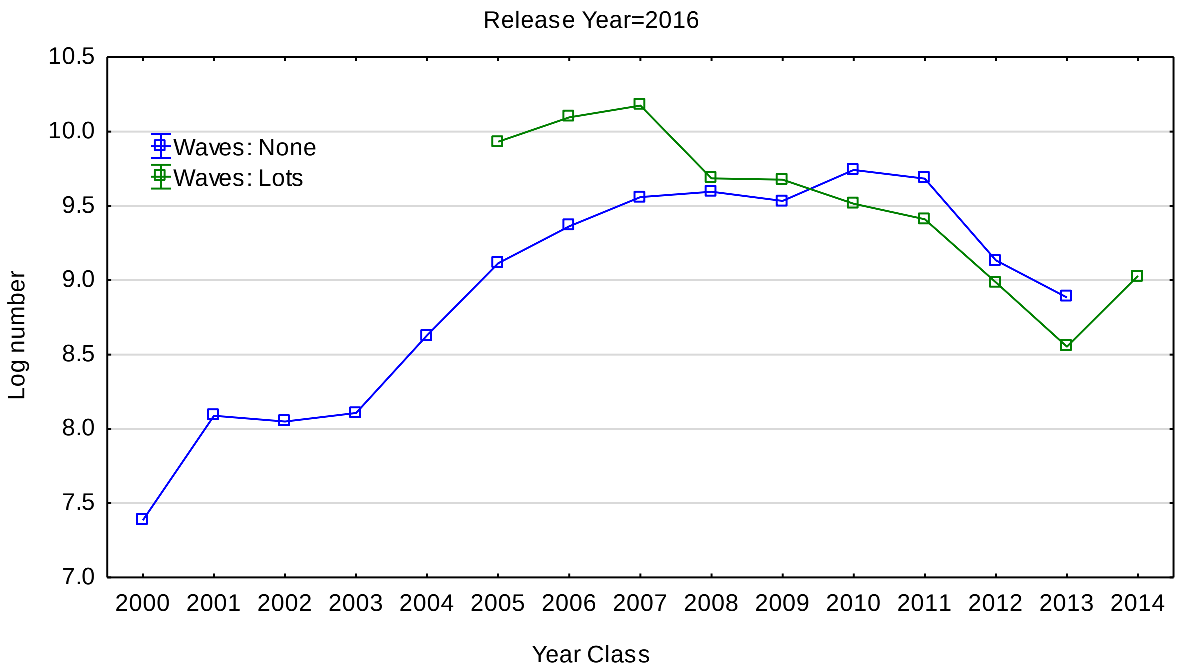


Figure 36: The effect of the presence of waves during tagging and releasing of mackerel in 2016 and recaptures in the following year. There was no effect of the presence of waves (p> 0.05). The same insignificant result was found when year classes younger than 2005 were excluded.

There might not have been a clear individual effect of presence of waves or birds. To see whether the two factors combined have an effect the conditions lots of birds together with lots of waves was compared to medium birds and waves, and no birds and no waves. Data was available for release years 2015 and 2016. Release year 2015 indicated that there was no significant difference between the combination of birds and waves ($p<0.05$) (Figure 37).

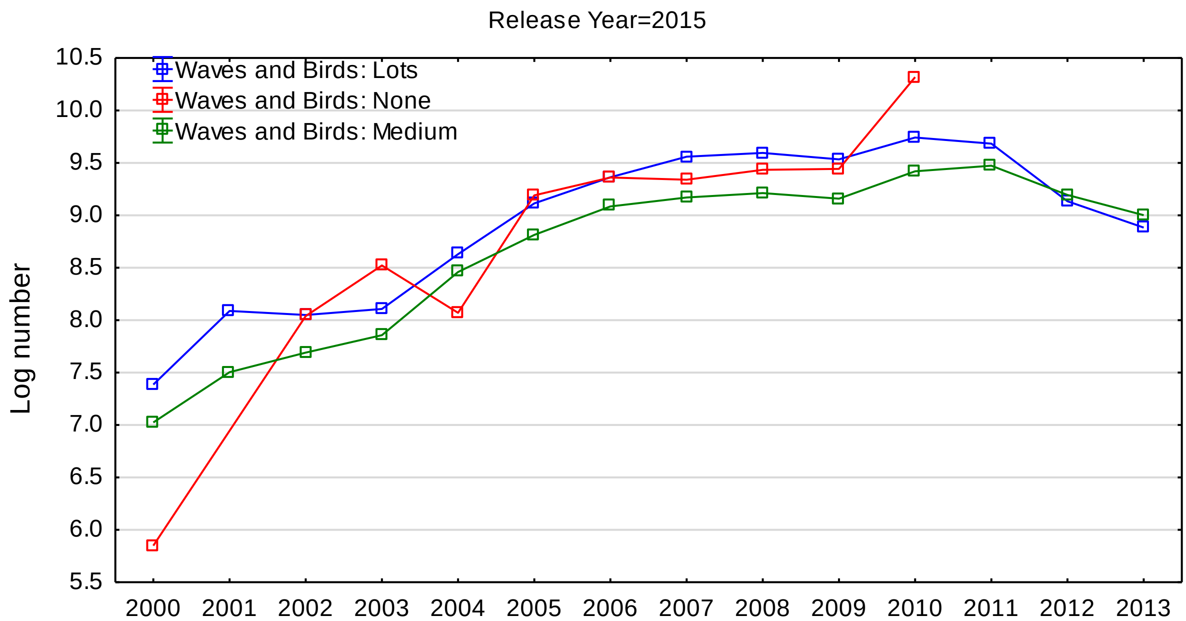


Figure 37: The effect of lots of waves and birds, no birds and waves, and medium birds and waves present on the estimated log number for releases in 2015. There was no significant effect (p<0.05).

Release year 2016 showed that there was a significant difference between stock estimates when lots of birds and waves present were compared to when none and medium birds and waves were present. Lots of birds and waves compared to medium birds and waves had a significant difference (p=0.044) and lots of birds and waves compared to no birds and waves showed a significant difference of p=0.012 (Figure 38).

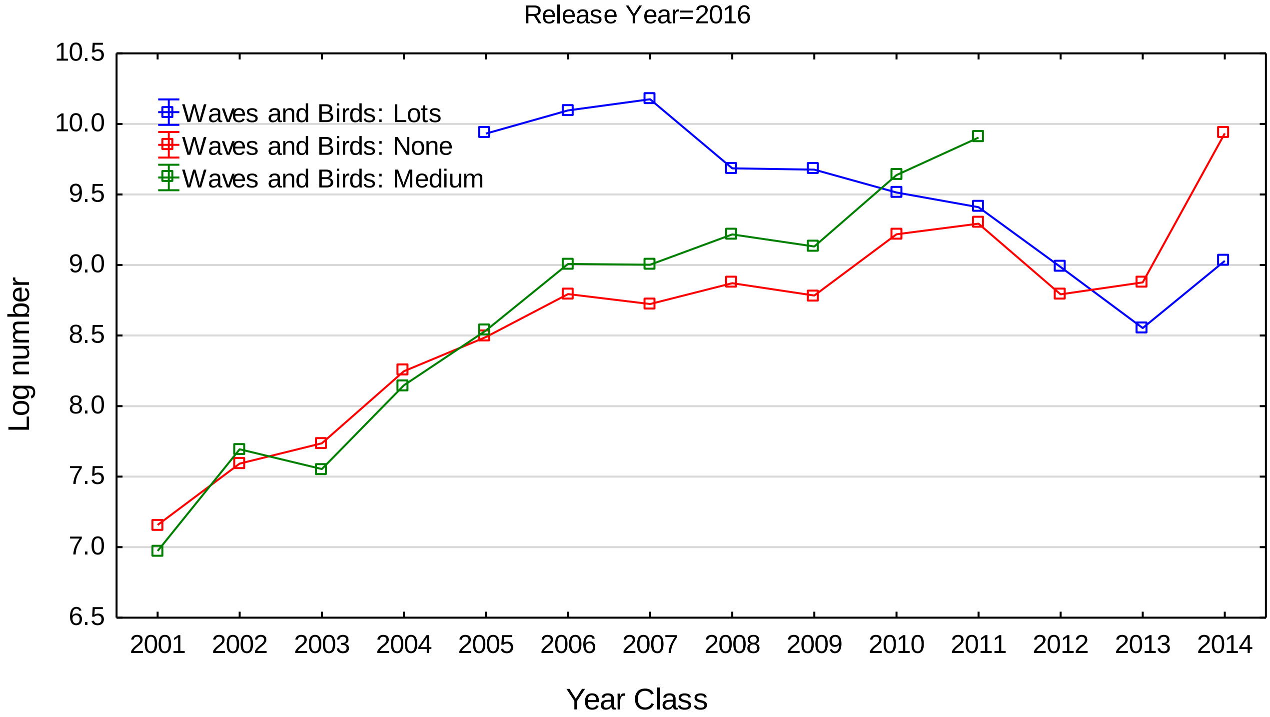


Figure 38: The effect of lots of waves and birds, no birds and waves, and medium birds and waves present on the estimated log number for release year 2016. There was a significant difference between lots of birds and waves compared to medium birds and waves (p=0.044) and between lots of birds and waves and no birds and waves (p=0.012). There was no significant difference between none and medium presence of birds and waves.

Effect of region, country and factory

At the benchmark meeting data was presented indicating that there are differences in recapture rates within same year classes between factories, and to some extent between countries (ICES, 2017). It was however decided that is was better to merge data from all factories to not over complicate the parameterization of the model. It is still important to identify where the biases occur.

Looking at the year classes caught and the estimated total count derived from the recaptures from both Norway and the rest of the nations (Great Britain, Faroe Island and Iceland) for each release year (Figure 39-44), statistical differences between Norway and Great Britain, Faroe Island and Iceland combined were found for release years 2014 and 2015 ($p<0.05$) using the Kolmogorov–Smirnov non-parametric test. The data included year classes from 2000 and above and mackerel from 2 years and older.

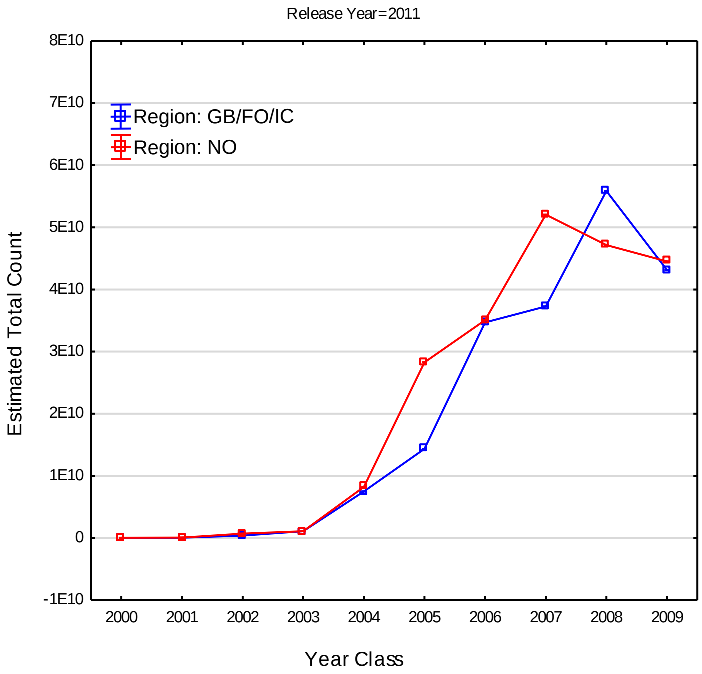


Figure 39: Estimated count for release year 2011, comparing Norway with combined data from Great Britain, Faroe Islands and Iceland. The data included year classes from 2000 and above and mackerel from 2 years and older. There was no statistical difference between the two estimates.

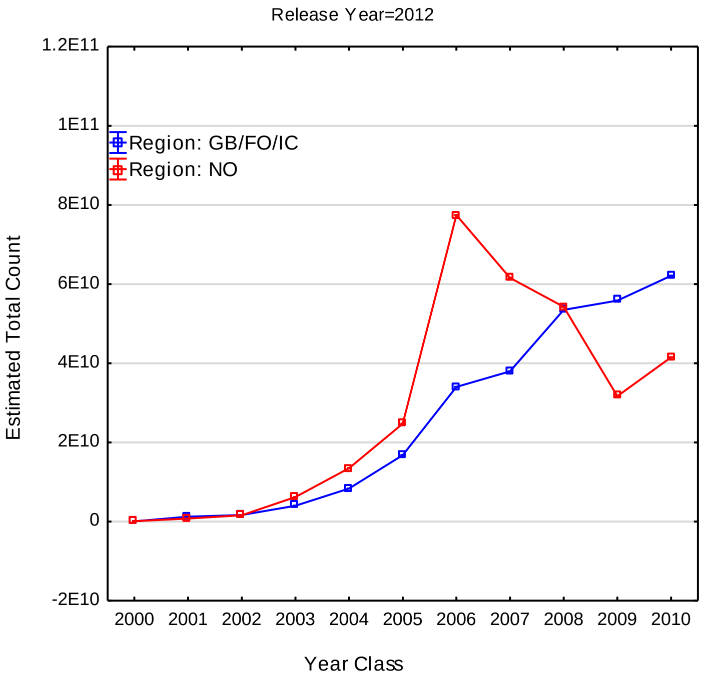


Figure 40: Estimated count for release year 2012, comparing Norway with combined data from Great Britain, Faroe Islands and Iceland. The data included year classes from 2000 and above and mackerel from 2 years and older. There was no statistical difference between the two estimates.

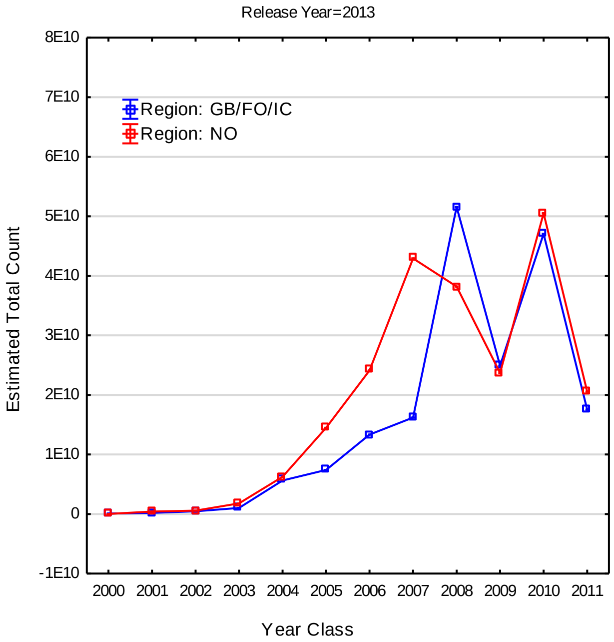


Figure 41: Estimated count for release year 2013, comparing Norway with combined data from Great Britain, Faroe Islands and Iceland. The data included year classes from 2000 and above and mackerel from 2 years and older. There was no statistical difference between the two estimates.

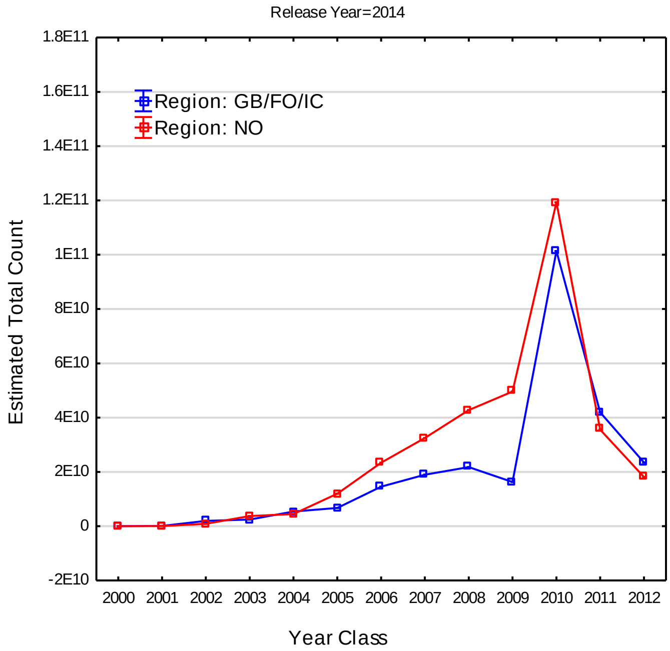


Figure 42: Estimated count for release year 2014, comparing Norway with combined data from Great Britain, Faroe Islands and Iceland. The data included year classes from 2000 and above and mackerel from 2 years and older. There was a statistical difference between the two estimates (p<0.05).

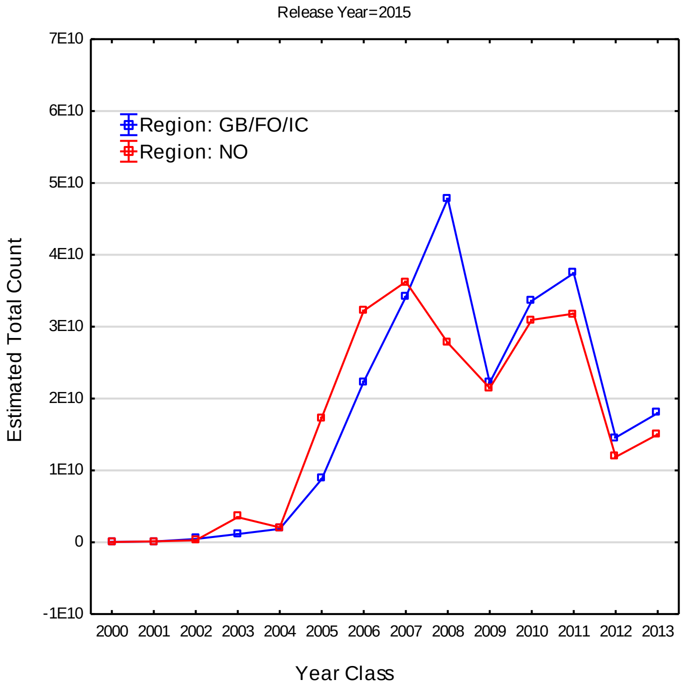


Figure 43: Estimated count for release year 2015, comparing Norway with combined data from Great Britain, Faroe Islands and Iceland. The data included year classes from 2000 and above and mackerel from 2 years and older. There was a statistical difference between the two estimates (p<0.05).

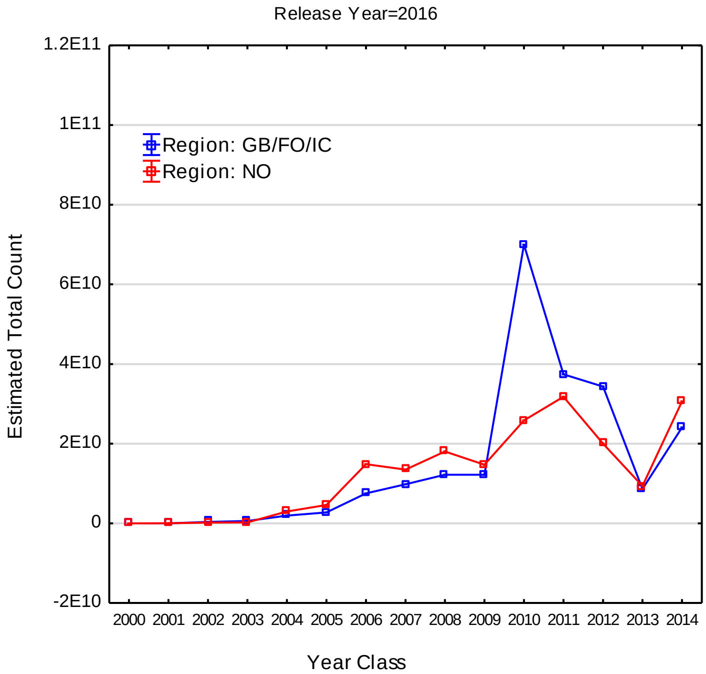


Figure 44: Estimated count for release year 2016, comparing Norway with combined data from Great Britain, Faroe Islands and Iceland. The data included year classes from 2000 and above and mackerel from 2 years and older. There was no statistical difference between the two estimates.

To look at the estimates in further depth the regions have been split up to show the individual countries (Figure 45-50). Statistical tests were performed to compare estimates between various countries per release year and all recapture years. There was no statistical difference between estimated total count between countries for release year 2011 (Figure 45). Release year 2012 showed a significant difference in estimated total count between Norway and Iceland (p=0.03), and between Great Britain and Iceland (p=0.003) (Figure 46). Release year 2013 showed a significant difference between Great Britain and Faroe Islands (p=0.003) (Figure 47). Release years 2014, 2015 and 2016 showed no significant difference in estimated total count for any of the countries (Figure 48-50).

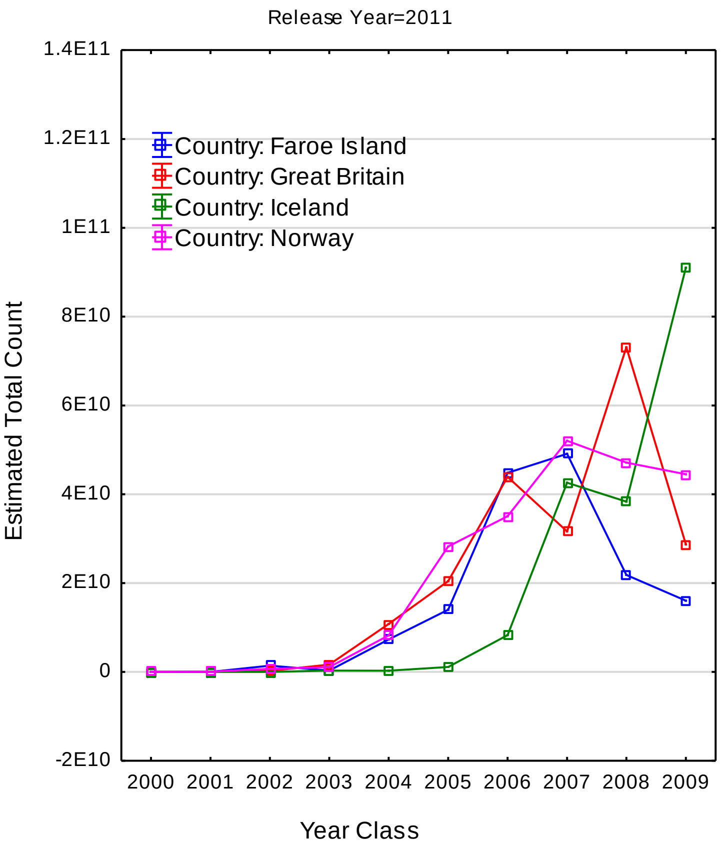


Figure 45: Estimated total count compared per country for release year 2011 and all recapture years. Yearclasses below 2000 and mackerel younger than 2 years old were excluded from the dataset. There was no statistical difference between countries.

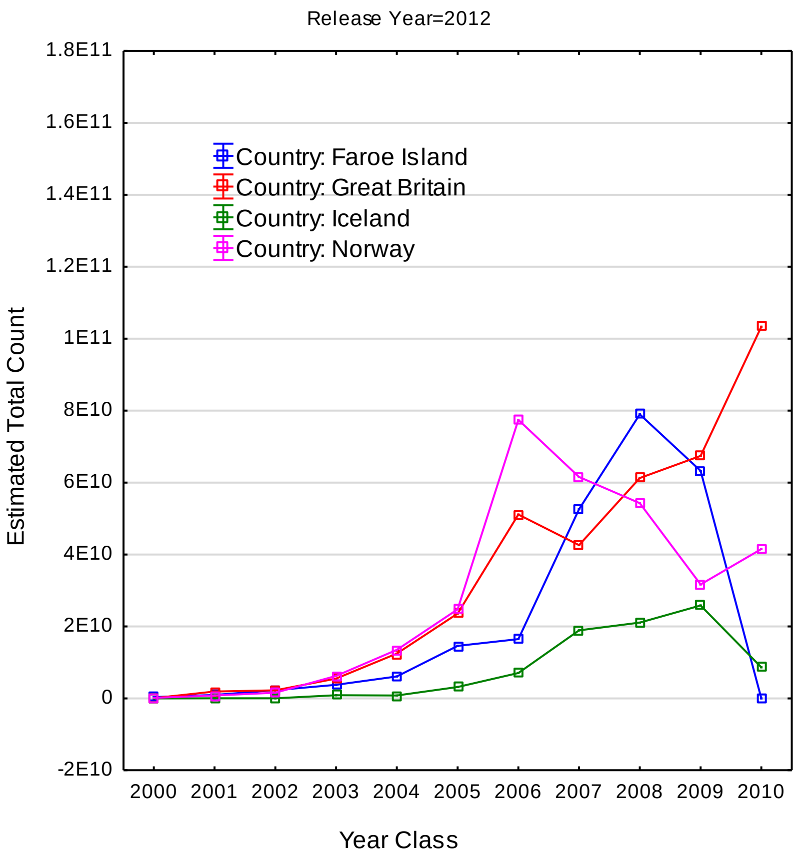


Figure 46: Estimated total count compared per country for release year 2012 and all recapture years. Yearclasses below 2000 and mackerel younger than 2 years old were excluded from the dataset. There was a statistical difference between Norway and Iceland (p=0.03), and between Great Britain and Iceland (p=0.003).

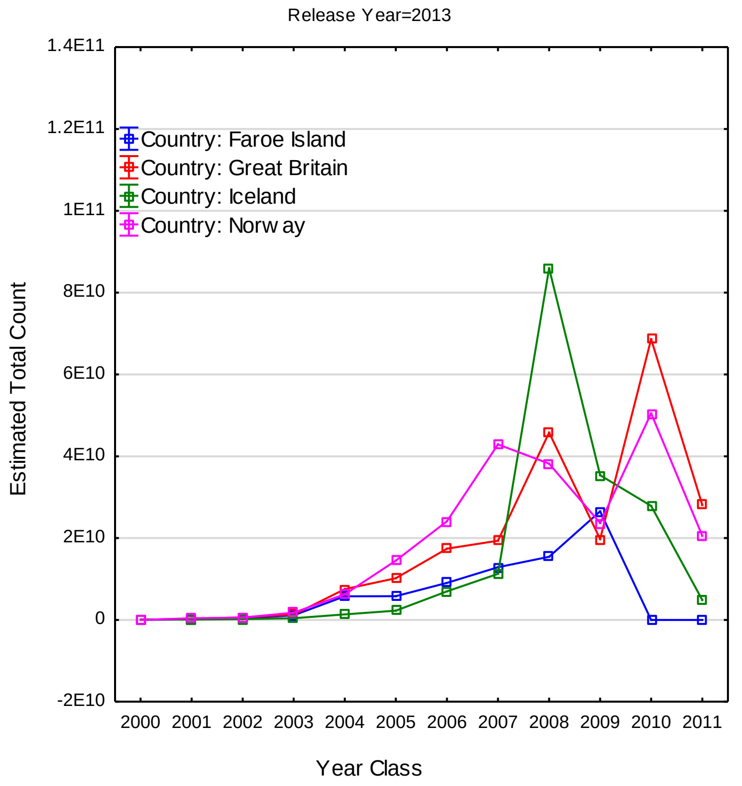


Figure 47: Estimated total count compared per country for release year 2013 and all recapture years. Yearclasses below 2000 and mackerel younger than 2 years old were excluded from the dataset. There was a statistical difference between Great Britain and Faroe Islands (p=0.003).

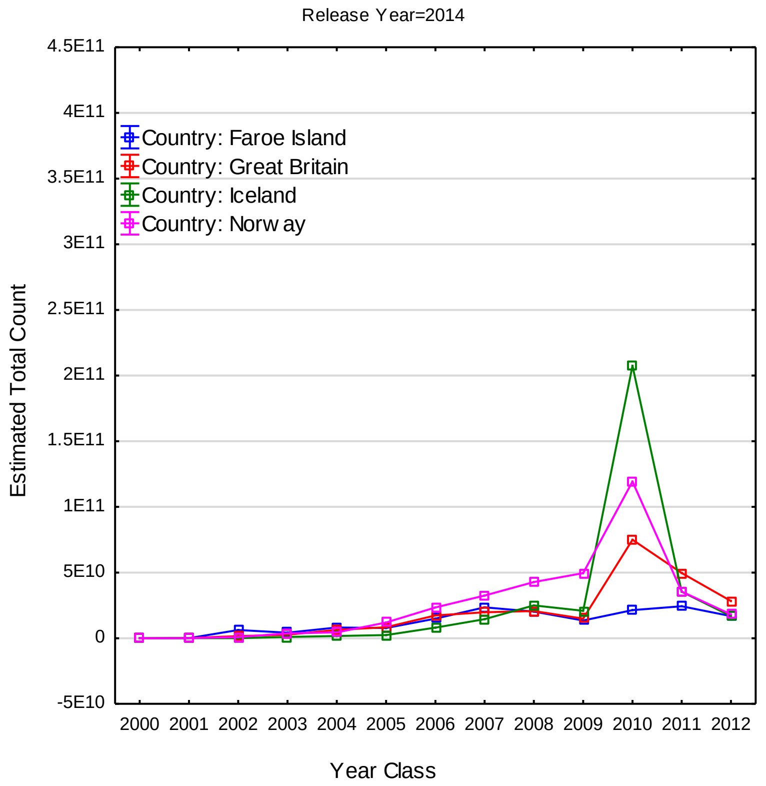


Figure 48: Estimated total count compared per country for release year 2014 and all recapture years. Yearclasses below 2000 and mackerel younger than 2 years old were excluded from the dataset. There was no statistical difference between countries.

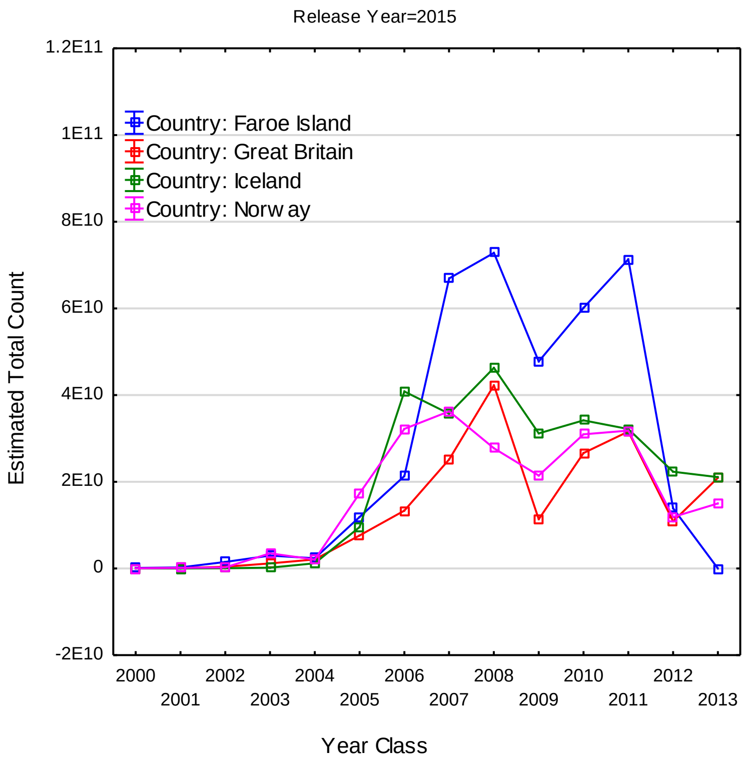


Figure 49: Estimated total count compared per country for release year 2015 and all recapture years. Yearclasses below 2000 and mackerel younger than 2 years old were excluded from the dataset. There was no statistical difference between countries.

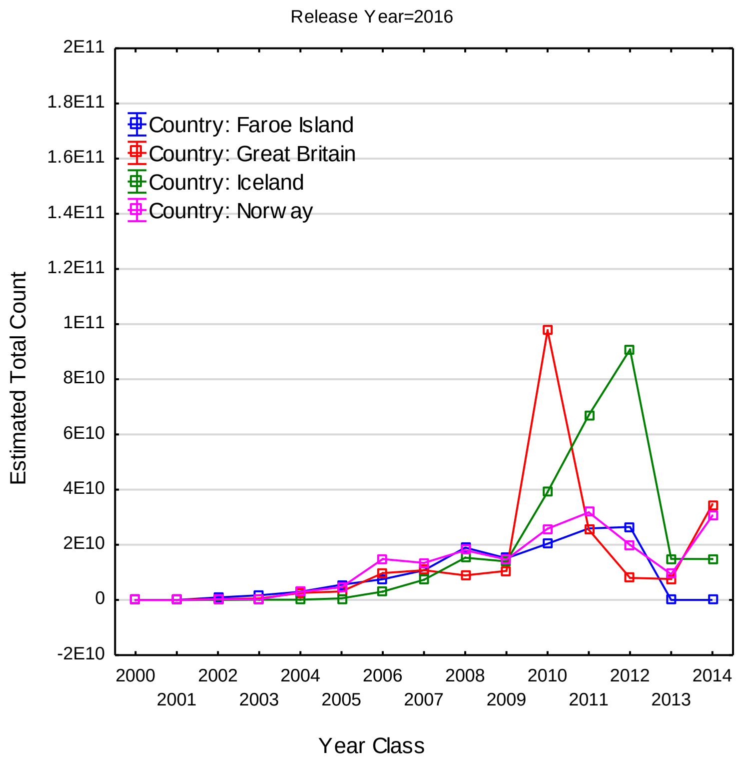


Figure 50: Estimated total count compared per country for release year 2016 and all recapture years. Yearclasses below 2000 and mackerel younger than 2 years old were excluded from the dataset. There was no statistical difference between countries.

To get an even more accurate insight into the differences in total estimated count the countries can be further divided into factories and statistically compared to each other per release year. Statistical differences were found between total estimated count in factories Lunar Freezing Faserburgh (GB02) and Lerwick Shetland Catch (GB04) (p=0.003) and Pelagia Austevoll (NO03) (p=0.017) in release year 2011. Lunar Freezing Faserburgh and Lerwick Shetland Catch (p=0.0008), Pelagia Måløy (NO05) (p=0.005), Pelagia Selje (NO06) (p=0.0007) and Brødrene Sperre (NO08) (p=0.02) varied statistically in total estimated count in 2011. Pelagia Austevoll varied statistically in total estimated count from Pelagia Måløy (p=0.002), Pelagia Selje (p=0.0001) and Brødrene Sperre (p=0.01) in 2011 (Figure 51).

In release year 2012, total estimated count varied statistically between Pelagia Austevoll and all other factories with the exception of Lunar Freezing Freserburgh, Vopnafjord (IC01), Neskaupstad (IC02), Skude Fryseri (NO02) and Pelagia Florø (NO04). Neskaupstad varied statistically in total estimated count from Peterhead Denholm (p=0.0012), Lunar Freezing Peterhead (p=0.007), Pelgia Måløy (p=0.05), Pelagia Selje (p=0.001) and Brødrene Sperre (0.002). Skude Fryseri and Pelagia Austevoll varied statistically from each other in total estimated count as well (p=0.02) (Figure 52).

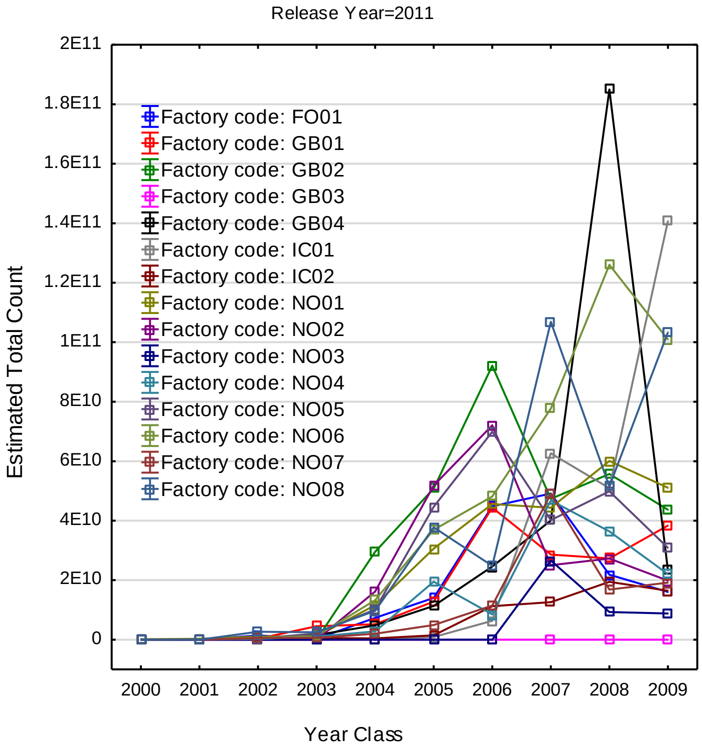


Figure 51: Estimated Total count per factory from release year 2011 and all following recapture years. Statistical differences were found between total estimated count in factories Lunar Freezing Faserburgh, between Lerwick Shetland Catch and Pelagia Austevoll. Lunar Freezing Faserburgh and Lerwick Shetland Catch, Pelagia Måløy, Pelagia Selje and Brødrene Sperre varied statistically in total estimated count. Pelagia Austevoll varied statistically in total estimated count from Pelagia Måløy, Pelagia Selje and Brødrene Sperre.

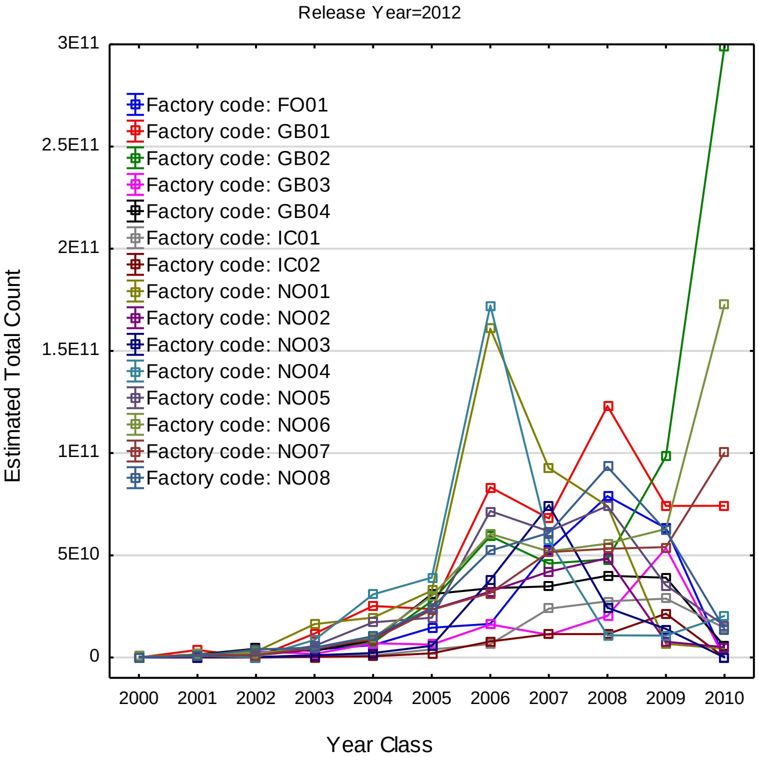


Figure 52: Total estimated count varied statistically between Pelagia Austevoll and all other factories with the exception of Lunar Freezing Freserburgh, Vopnafjord, Neskaupstad, Skude Fryseri and Pelagia Florø. Neskaupstad varied statistically in total estimated count from Peterhead Denholm, Lunar Freezing Peterhead, Pelgia Måløy, Pelagia Selje and Brødrene Sperre. Skude Fryseri and Pelagia Austevoll also varied statistically from each other.

In release year 2013, total estimated count varied statistically between Pelagia Austevoll and Peterhead Denholm (GB01) (p=0.04), Lunar Freezing Peterhead (p=0.01), Lerwick Shetland Catch (p=0.002), Pelagia Måløy (p=0.00003), Pelagia Selje (p=0.02) and Brødrene Sperre (p=0.0002). Vardin Pelagics'(FO01) total estimated count varied statistically from Brødrene Sperre (p=0.02). Pelagia Måløy varied statistically in total estimated count from Vardin Pelagia (p=0.004), Skyde Fryseri (0.02), Pelagia Austevoll (p=0.0003) and Pelagia Liavågen (NO07) (p=0.03) (Figure 53).

There were no statistical differences in total estimated count between factories in release year 2014 (Figure 54).

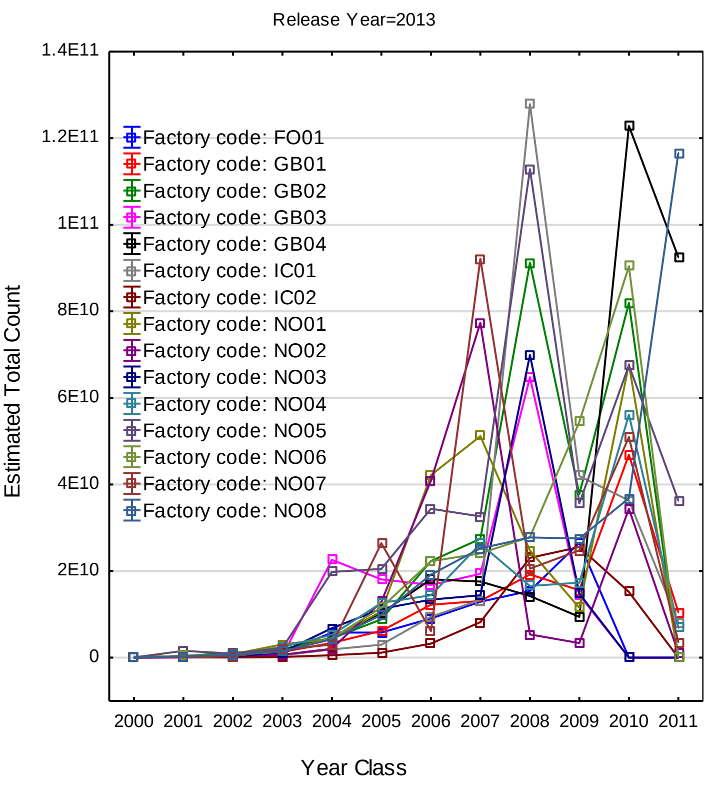


Figure 53: Estimated Total count per factory from release year 2013 and all following recapture years. Total estimated count varied statistically between Pelagia Austevoll, Peterhead Denholm and Lunar Freezing Peterhead, Lerwick Shetland Catch, Pelagia Måløy,, Pelagia Selje and Brødrene Sperre. Vardin Pelagics' total estimated count varied statistically from Brødrene Sperre. Pelagia Måløy varied statistically in total estimated count from Vardin Pelagia, Skyde Fryseri, Pelagia Austevoll and Pelagia Liavågen.

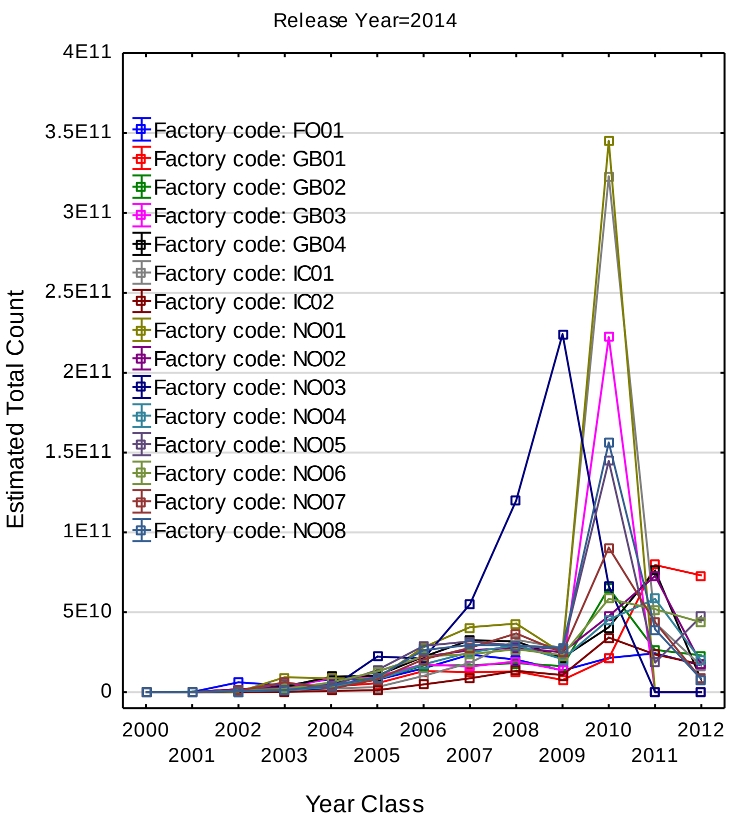


Figure 54: Estimated Total count per factory from release year 2014 and all following recapture years. There were no statistical differences in total estimated count between factories in release year 2014.

In release year 2015, the majority of statistical varieties were found for total estimated counts for factories Pelagia Egersund Seafood (NO01), which varied from all other factories except for Lunar Freezing Fraserburgh and Pelagia Austevoll. Pelagia Austevoll aslo varied statistically from all other factories (except Pelagia Egersund Seafood) when comparing total estimated counts (Figure 55).

In 2016, Pelagia Egersund Seafood and Pelagia Austevoll both varied statistically in total estimated count for the same factories; Peterhead Denholm, Lunar Freezing Peterhead, Vopnafjord, Pelagia Florø, Pelagia Måløy, Pelagia Selje, Pelagia Liavågen and Brødrene Sperre (Figure 56).

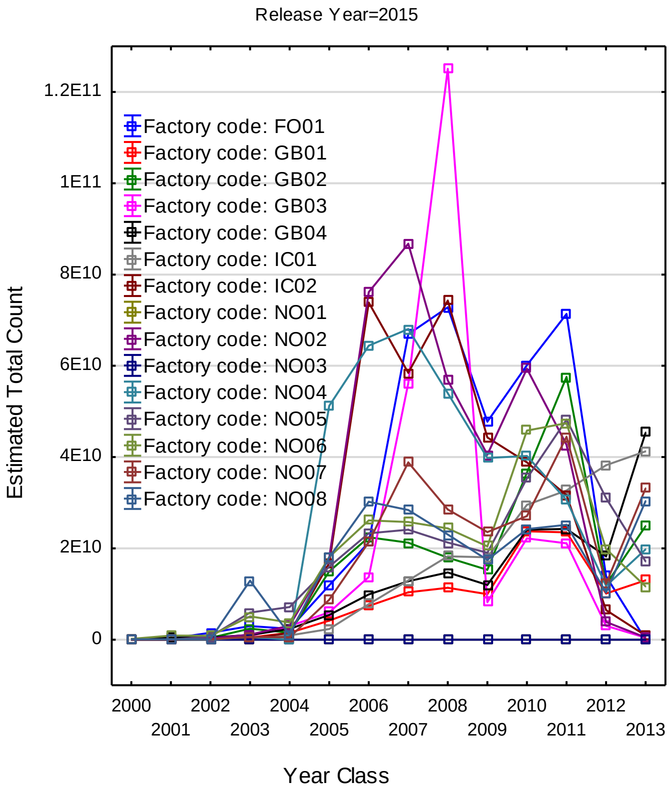


Figure 55: Estimated Total count per factory from release year 2015 and all following recapture years. Total estimated counts for factories Pelagia Egersund Seafood (NO01) varied from all other factories except for Lunar Freezing Fraserburgh and Pelagia Austevoll. Pelagia Austevoll aslo varied statistically from all other factories (except Pelagia Egersund Seafood) when comparing total estimated counts.

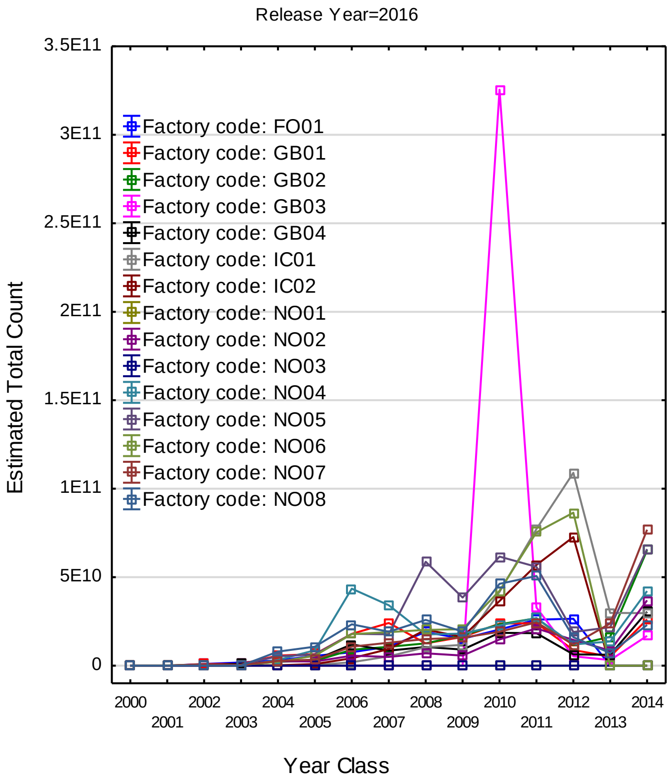


Figure 56: Estimated Total count per factory from release year 2016 and all following recapture years. Pelagia Egersund Seafood and Pelagia Austevoll both varied statistically in total estimated count for the same factories; Peterhead Denholm, Lunar Freezing Peterhead, Vopnafjord, Pelagia Florø, Pelagia Måløy, Pelagia Selje, Pelagia Liavågen and Brødrene Sperre

Discussion

Biases in models can be eliminated or reduced by standardizing protocols and/ or instruments. Knowing where the sources of biases occur make it easier to take them into account when running a model and producing an estimate. In this thesis, I have focused on three possible sources of biases in data used as input in the SAM-model to estimate the stock of NEA mackerel; bias in estimation of numbers tagged and recaptured per year class, the bias in RFID tagging data related to tagging mortality and the bias in RFID tagging index related to spatial and temporal changes in the catch scanned.

Bias in estimation of numbers tagged and recaptured per year class

Age-composition data is generally considered to provide information on the strength of the cohort (recruitment). Composition data, collected from fisheries or other surveys, are commonly used in the assessment of major fish stocks, including NEA mackerel. Length-composition data are the most common because it can be converted to age composition using an ALK. Age compositions of a stock are widely used to describe a population and are often used when the ageing procedure is well established. Producing ALKs is expensive and tedious, including shipping of mackerel and manually deducing age from otoliths if done properly. There seems to be large uncertainties with variability as a result from using different ageing techniques such as otoliths, scales or length-composition analysis (Chang and Maunder, 2012). The biological data collected both from the previous steel tagging surveys and current RFID tagging surveys were used to make an age-length-key, providing the distribution tagged fish per age. In the case of RFID tagging time series, when the recaptured fish were not manually removed from the catch, this key was also used to give the mackerel an estimated age after at recapture. An age-length-key does become less and less accurate as the growth curve changes (Figure 57), giving larger room for error while estimating age from length (Francis et al., 2016, Aires-da-Silva et al., 2015). Mackerel tagged with RFID tags have an age distribution from the ALK. It means that a tagged fish recaptured, which was released at a given length, has a distribution of ages attached at proportions between 0 and 1 and summing up to 1. This is clearly different compared to the steel tagged mackerel which were estimated to a specific age group by aging of the fish at the lab. This results in the fact that numbers of recaptured mackerel by year class from the

RFID series being will always be in decimals whilst numbers of recaptures in the steel tagged individuals were in whole numbers (ICES, 2017).

Statistical analyses of the present thesis show that there are differences between actual age derived from otoliths and estimated age from ALK, but the graphs showed a similar trend between the two. The large variability in the data was in most cases due to a small sample size, often only two or three data points.

It would therefore be beneficial to incorporate more mackerel into the production of the ALK. The steel tag series was not based on ALKs where fish were samples length stratified, resulting in few small and large fish in the ALK, and hence more uncertain estimates of released ages in the youngest and oldest fish. The RFID time series had, however, started to use length stratification, now at least 20 mackerel from each 1 cm length group is aged as a rule. Hence ALKs today, are more accurate and less uncertain for the small and large fish then in the steel tag time series.

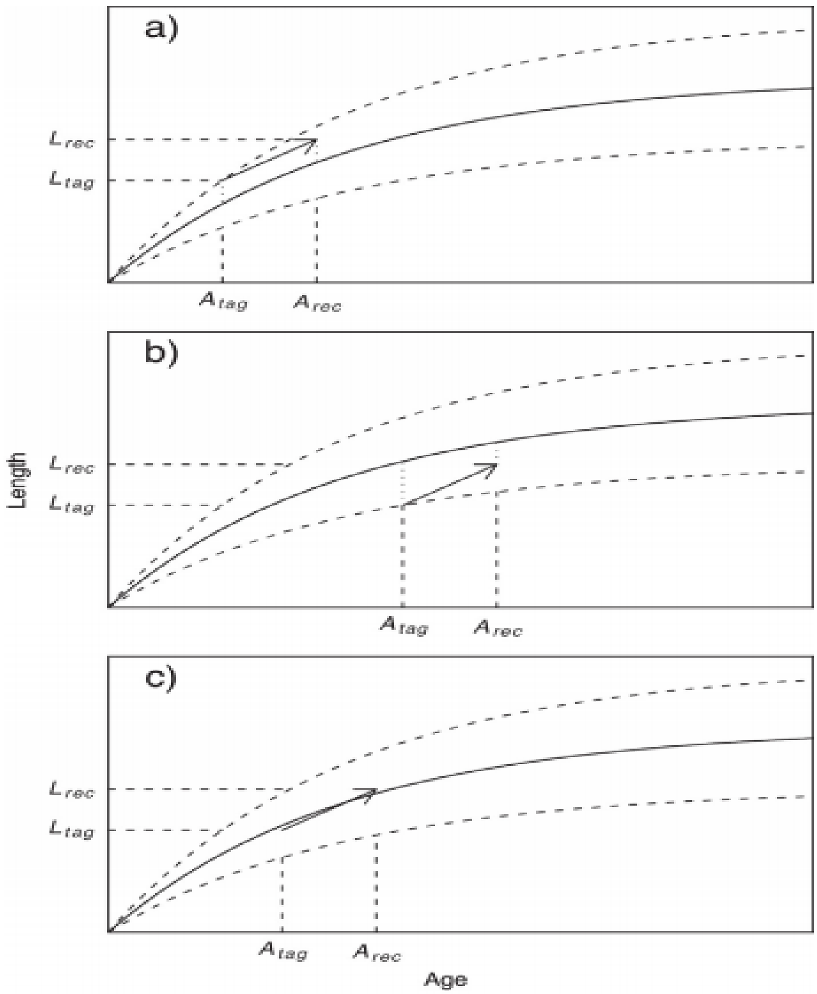


Figure 57: In each graph, the solid curved line describes the mean length at a given age and the dashed curved lines are 95% confidence bounds for length at age. The arrow shows a possible trajectory for the tagged fish. The length varies, shown by the vertical dotted lines: (a) for the smallest likely value of age at tagging; (b) for the largest likely value of Age at tagging and (c) for an intermediate value of Age at tagging.

Random sampling and manual processing of mackerel may be more accurate compared to deducing age from the ALK. Still, age reading of tagged fish being out for years is also not straight forward. There are errors and biases, increasing with the size of the fish. This is also why the steel tag time series data used from Tenningen individuals showed ages of -1 or even -2 at release based on the aging from otoliths at recapture and back calculated age at release. It clearly points at potential aging problems with otoliths, here the case of overestimating age. These obvious errors were excluded from the dataset, but there might have been less obvious errors which remained incorporated in the dataset. For instance, cases where the age from otoliths is underestimated, which are included in the data set. Hence, it is not conclusive whether there is more or less bias in the data when simply trusting the ALK instead compared with actual age reading of recaptured fish.

Bias in RFID tagging data related to tagging mortality

The SAM model has shown that there has been a significant difference in post-release survival rates between the steel and RFID-tags. The steel tag survival rate was approximately 40% whilst the newer and improved RFID tags had a survival rate around 10% (ICES, 2017). This difference in survival rate is most likely due to a rougher handling when tagging with RFID tags. The system is more automated using jigging machines, dragging the jigged fish into pipes onboard, which probably increases the mortality, it does however assumingly give a more constant mortality rate compared to the steel tags where tags and jigging was done manual with jigging wheels and a variety of fishers handling the fish differently. Hence, the idea is that the automated catching process with jigging machines is reducing variation between the experiments, and thereby reducing this potential bias on tagging mortality (ICES, 2017).

Mortality is difficult to estimate in an open system, there are several factors which may influence the stock estimation. Migration, tag shedding, natural predation, tag screening and mortality due to handling can cause a shift in the stock estimation. If tags get lost after insertion in the fish due to any of the previously mentioned reasons it would skew the stock estimate. It would be beneficial to know the exact tagging mortality so that this could be incorporated into the model. Tag shedding is assumed to be low because the RFID tags are not external. To see if there is any tag shedding one could tag individuals with two tags and observe the proportion of mackerel recaptured with only one tag (Hearn et al., 1991).

Data on the presence of waves and predators is available on the online database, categorized into none, medium and lots for both categories. The results showed that there was no effect on the estimation of stock numbers for these factors. There was a slight effect when the two factors were combined, a variation between estimates of stock was found between many waves in combination with many birds when compared to when there were no waves and no birds. There is however a lack of data over a longer period of time. There is no data on birds or waves before 2013 and 2014, comparisons of combined factors was also only possible for 2015 and 2016. This makes it difficult to compare and see the true effect of including weather and natural predators over a longer time period. In future studies, it would be beneficial if all expeditions provided data on waves and birds, which is the plan. So, in a few years the data available for such analyses will be larger and then results may be different.

Bias in RFID tagging index related to spatial and temporal changes in the catch scanned

With the project going international and including more factories it also allows room for more errors in processing catches and detecting tags. The project started off with only Norwegian factories and grew to include the RFID system in many other countries. It is essential to standardize processing techniques to reduce biases in the stock estimate. If some conveyor belts and detectors are not working at the same efficiency and accuracy, causing tags to pass by undetected, it will skew the final estimate. Previously, using the steel tags meant that there was a human component present, manually examining the fish back at IMR after detecting it at the factory. Full atomisation is highly effective for processing a larger catch quickly and at a lower cost but there might be a trade-off between accuracy and efficiency, although the systems are assumed to be 100% efficient. There were some differences between Norway and the other nations combined for release years 2014 and 2015. When countries were examined more in depth there were varying estimates between Iceland and Norway and Great Britain for release year 2012 and between Great Britain and Faroe Islands in 2013. There were no statistical differences in other years.

On a factory level, certain factories stood out due to their varying estimates when compared to other factories. One of these factories was Pelagia Austevoll, which varied in total count estimates from other factories in almost all release years. Pelagia Egersund Seafood showed the same behaviour in the last two years. It would be recommended to follow up with these factories to check their protocols and efficiency of their tag detector.

Differences between countries and factories could possibly be explained by lack of equal mixing of year classes in all catch areas and seasons. For instance, it is possible that some spawners off Ireland and Scotland may choose to migrate to Iceland-Greenland to feed, taking a route back and forth south of Faroes, thereby not entering the main fisheries north off Faroes by Faroese fishermen, and further east by Norwegian fishermen. It is too early to make such conclusions, but it seems more likely that different efficiencies in the factories as testing at factories haves shown close to 100% efficiency in all countries. However, such tests should be carried out regularly at least in the beginning and end of fishing seasons at all factories, to make sure that there is no bias related to efficiency. This is an easy task compared to testing potential bias related to unequal mixing of a year class over the catch area and seasons. If differences are found in survival rates between countries, and one can assure that the landed catch quantum in accurately reported, and efficiency is 100%, unequal mixing is a likely explanation. More years with data are needed prior to being more conclusive, and perhaps the Icelandic tagging experiments carried out during August in Icelandic waters med shed more light on this potential bias after a few more years of data.

Conclusions and points to consider

The biases present in the RFID-tag data are relatively small and it is believed that with time the errors will decrease. The RFID-system has only recently been implemented and with more time the procedures will improve, errors will be fixed and the system will improve in general. Being able to study and compare estimates over a longer time will pinpoint the errors more accurately, hopefully more concretely to a factory level.

Mackerel being tagged, released and recaptured within one year should not be included into the dataset used in the assessment because it might not be representative for the rest of the population. The individual might not have had sufficient time to mix with the rest of the population. This is the reason behind the decision to exclude in year data for future assessments in the 2017 benchmark process (ICES, 2017). Here it was also decided to use data from tagged fish 2 years old and older, despite some indications of different survival rates in 2 year olds. Survival chances for most fish increases as they get older and are more capable of avoiding natural predators. However, for tagging mortality it may be opposite, of advantage to be small when jigged, causing less damages and stress, small fish requires less space and less oxygen etc, so they could be less impacted by the process of handling, tagging and release. Also 2 year olds are not fully recruited to the spawning stock, and hence one may have mixing issues. When more years of data in the RFID time series have been obtained, one should look more into potential differences in survival rates between 2 year olds and older fish.

At present RFID data are collected in several countries of which have smaller quotas, or fewer factories scanning mackerel catches, resulting in a small proportion of total catch scanned, like the Faroes and Iceland. This leads to more uncertain data from their catch areas and seasons in comparisons of for instance survival rates between countries. Still such data are highly valuable, and in the future on should try to estimate the uncertainly related to variable scanned biomass between countries, so that comparisons are more statistically correct.

Analogously, it is very important contributions, when tagging and releasing expeditions also occur in other countries. However, if for instance comparing survival rates between experiments occurring during feeding in August, with that during spawning of Ireland and Scotland in March, one also has to take into account the numbers released. Experiments in Iceland 2015 and 2017 have such low release numbers that it would be bias to include these in the density dependent release analysis, also one should stick to a time series from the same area for use in the assessment. However, for other purposes such as looking at migrations and potential differences in survival it of value, but one should have uncertainty included in the estimates to make the comparisons more statistically correct.

Some factories were also missing estimated and recapture numbers due to processing errors. Such errors need to be detected at an early stage so the period of problems could be deleted from the time series. It is therefore of importance that there is an improved surveillance and testing of factories in the future, to make sure that such errors do not occur.

This thesis has focused on the potential sources of errors individually and not combined the cumulative effects of sources of errors. It would be interesting to combine different combinations, looking at different combinations of taggers and assistant taggers. The new system has a lot of data filtering available, making many different combinations of possible error sources possible.

There are also several other factors which could be included in the data, like the handling time, temperature, wind, time of day etc. The indications from the early stage analyses of the present study, although showing high significance, clearly suggest that one should follow up on this in the future years when more data has been collected. Then more of these potential sources of biases may in fact found to be statistically significant.

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Appendix

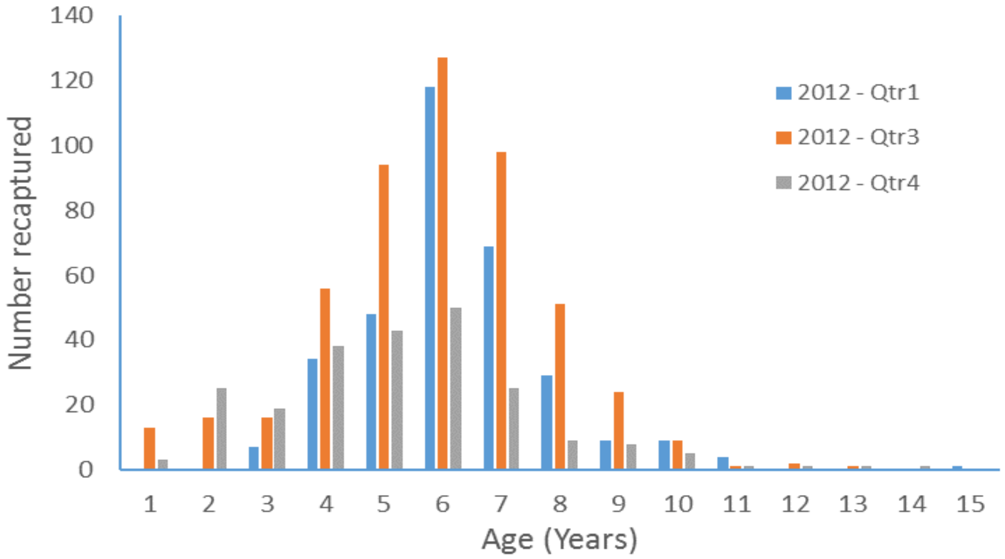


Figure S1: The distribution of ages in the various quartile catches of 2012. Quartile 1 includes catches from January (N=328), quartile 3 includes catches from September (N=508) and quartile 4 includes catches from October and November (N=229). The average age of mackerel caught in 2012 was 5.9 years old.

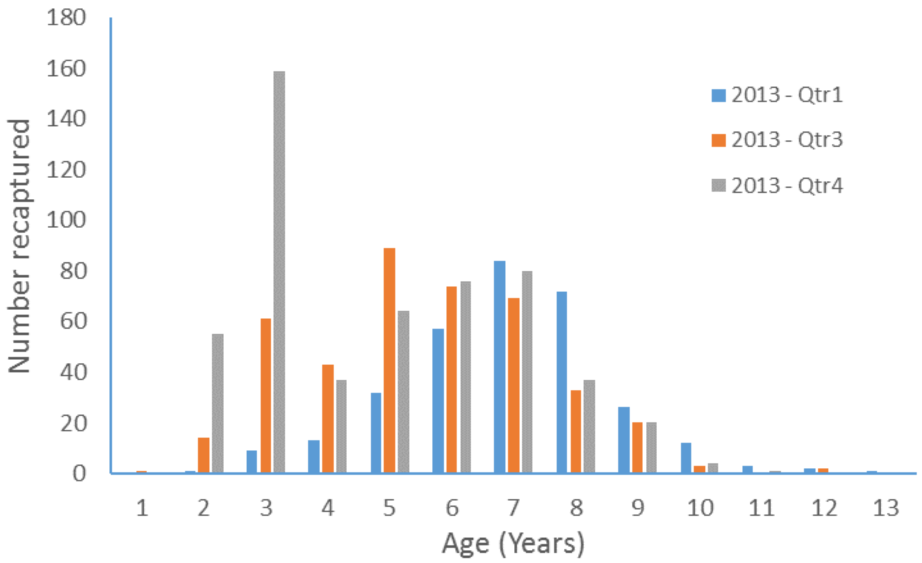


Figure S2: The distribution of ages in the various quartile catches of 2013. Quartile 1 includes catches from January (N=312), quartile 3 includes catches from September (N=409) and quartile 4 includes catches from October (N=533). The average age of mackerel caught in 2013 was 5.6 years old.

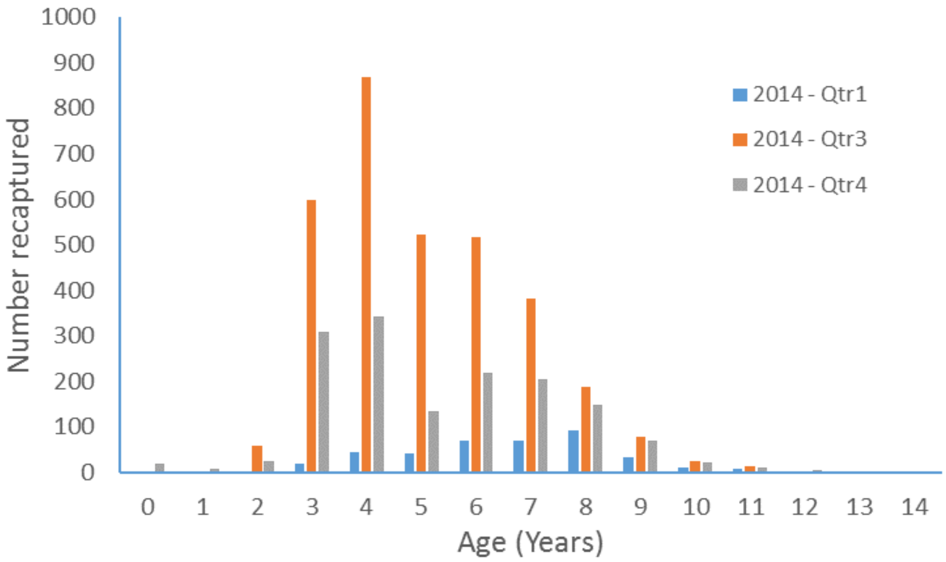


Figure S3: The distribution of ages in the various quartile catches of 2014. Quartile 1 includes catches from January and February (N=396), quartile 3 includes catches from July, August and September (N=3252) and quartile 4 includes catches from October and November (N=1515). The average age of mackerel caught in 2014 was 5.2 years old.

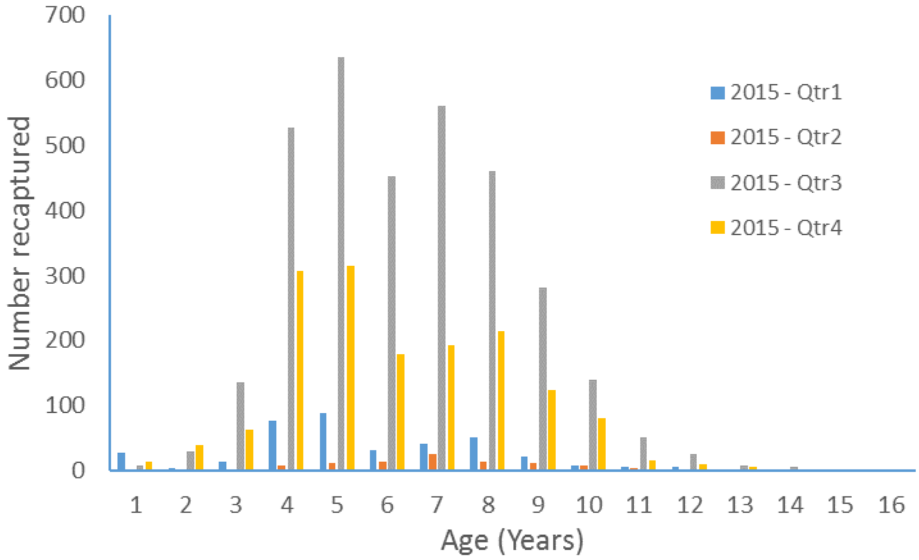


Figure S4: The distribution of ages in the various quartile catches of 2015. Quartile 1 includes catches from January and February (N=371), quartile 2 includes catches from April (N=96), quartile 3 includes catches from July, August and September (N=3321) and quartile 4 includes catches from October, November and December (N=1560). The average age of mackerel caught in 2015 was 6.2 years old.

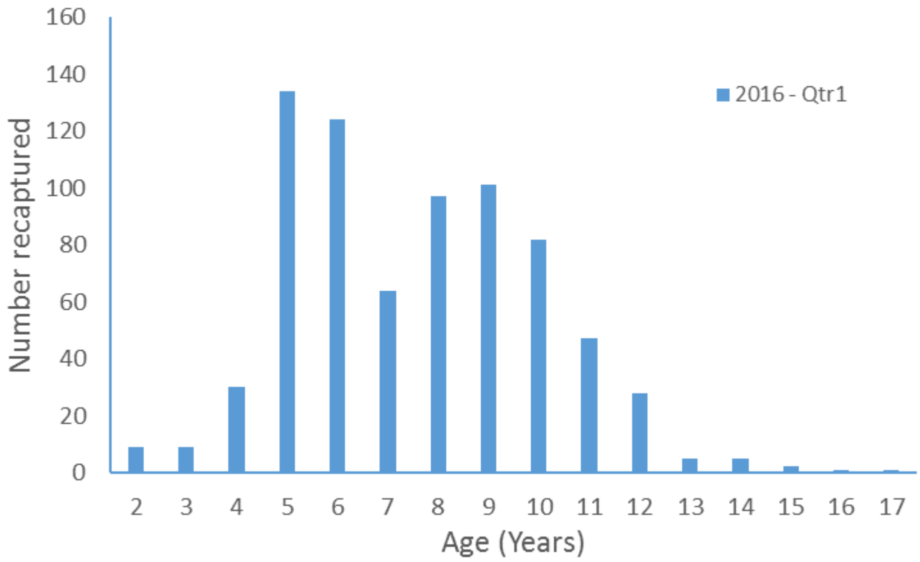
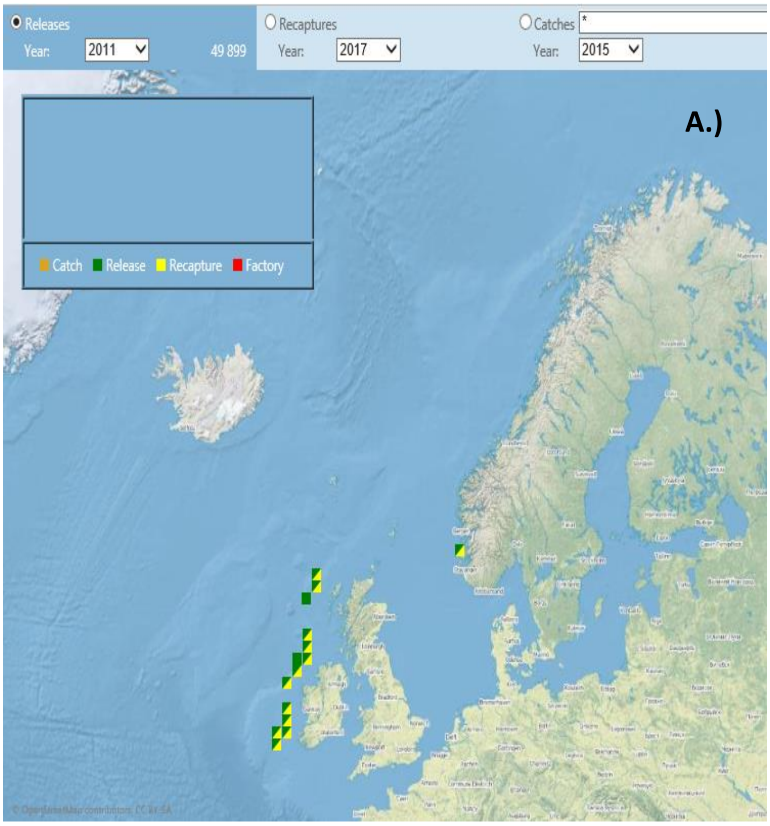
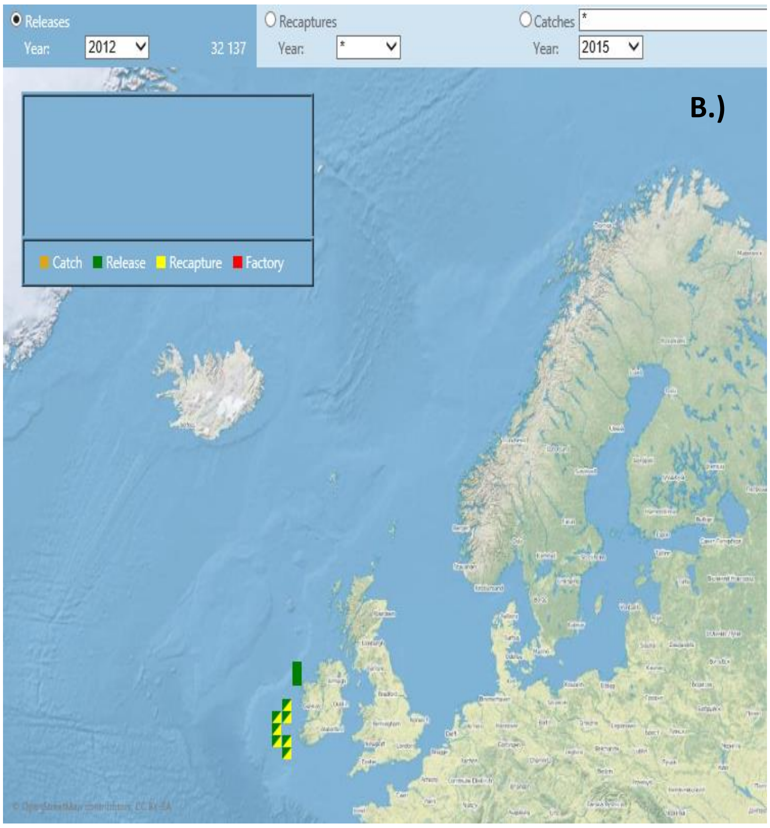
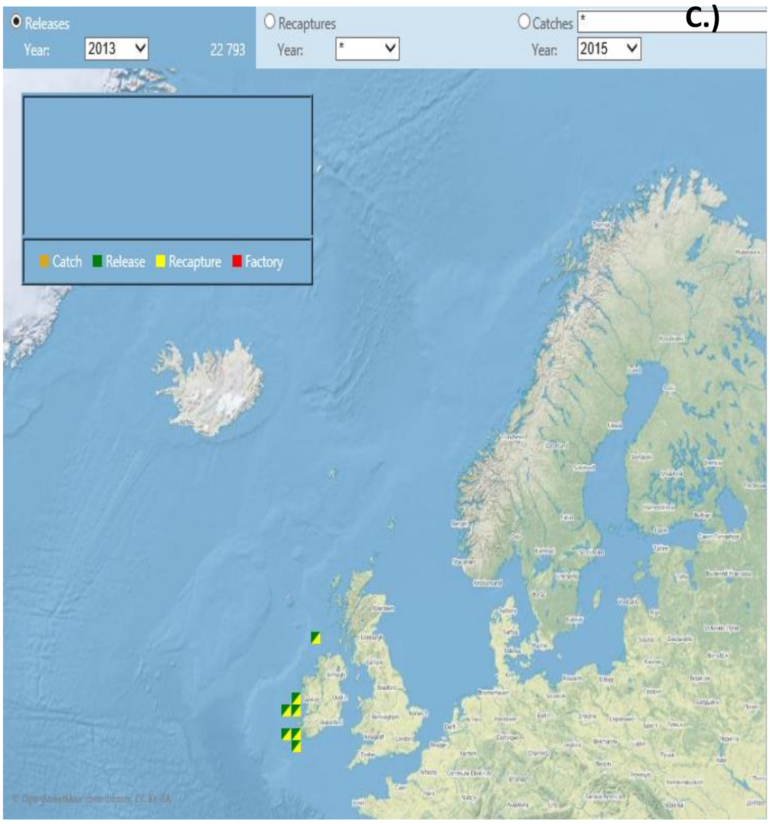


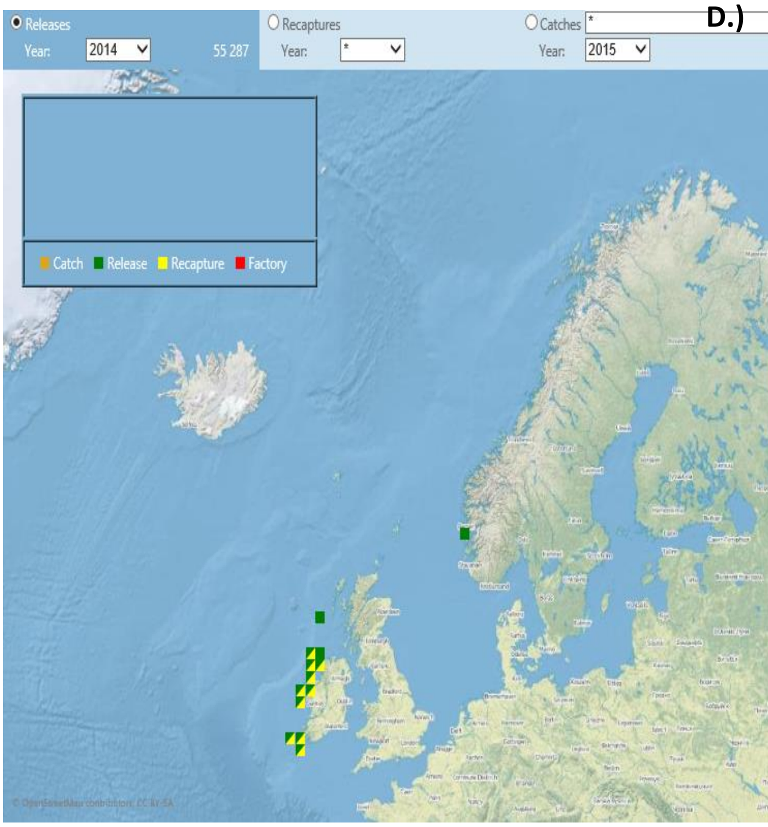
Figure S5: The distribution of ages in the various quartile catches of 2016. Quartile 1 includes catches from January and February (N=739).

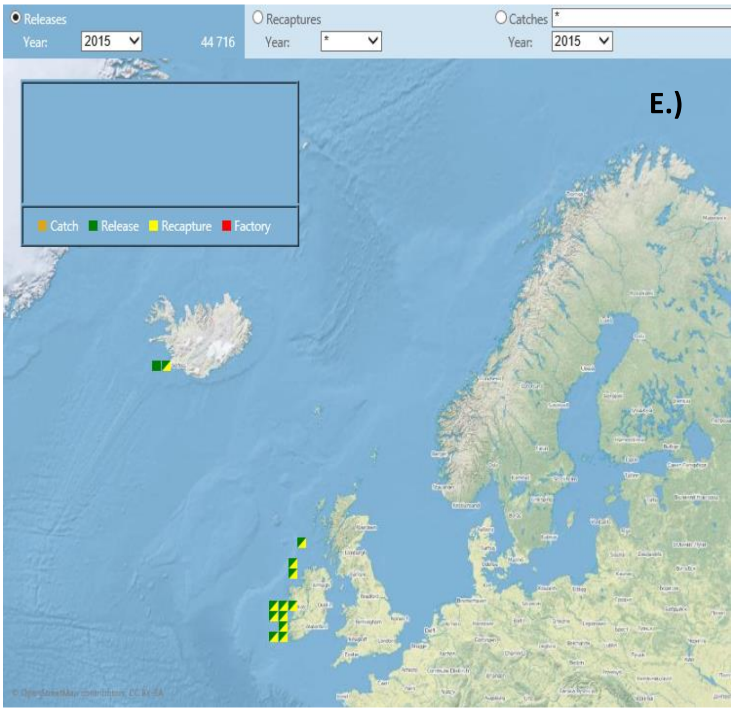
Releases 2011-2016

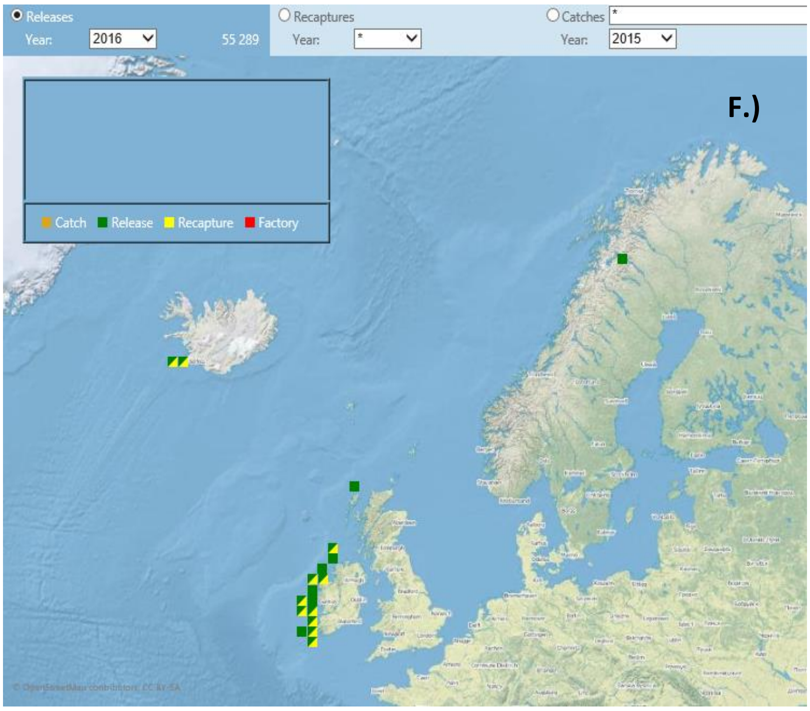












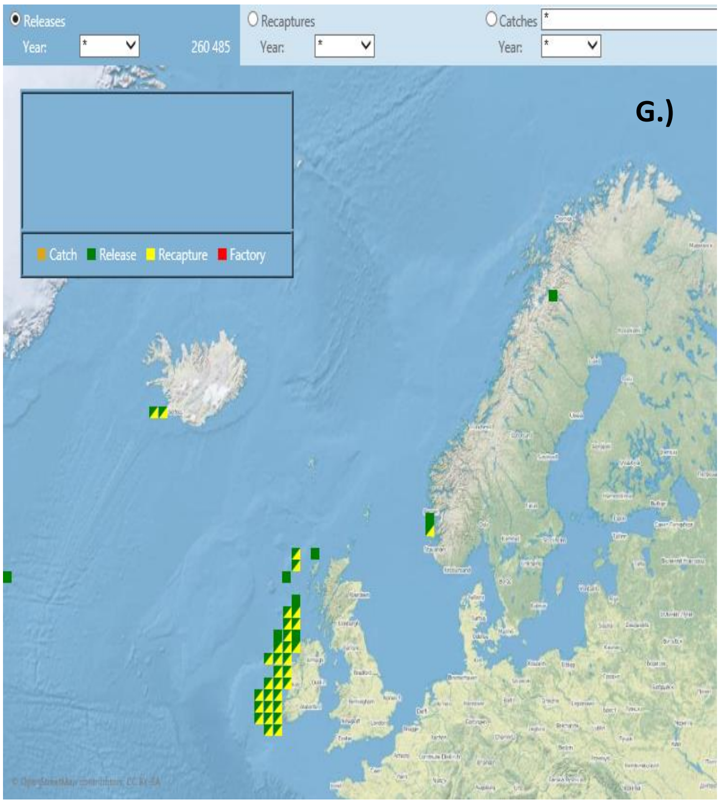
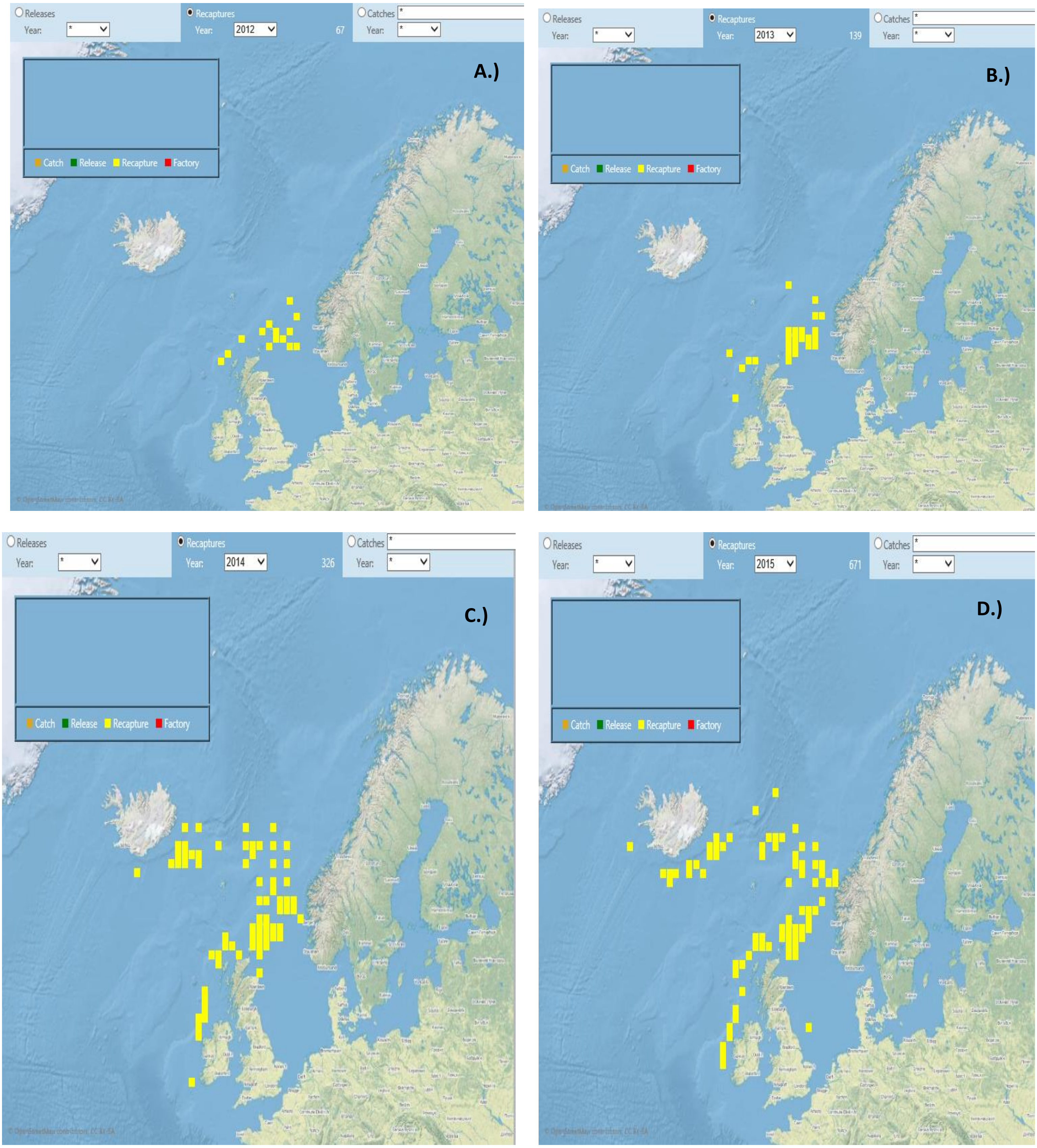


Figure S6: Releases from 2011-2016 (A-F respectively). Map G shows all releases from all years combined. Maps made from http://tracid-fishmap.imr.no/map.aspx. Green squares show releases and yellow squares show recaptures.

Recaptures 2012-2016



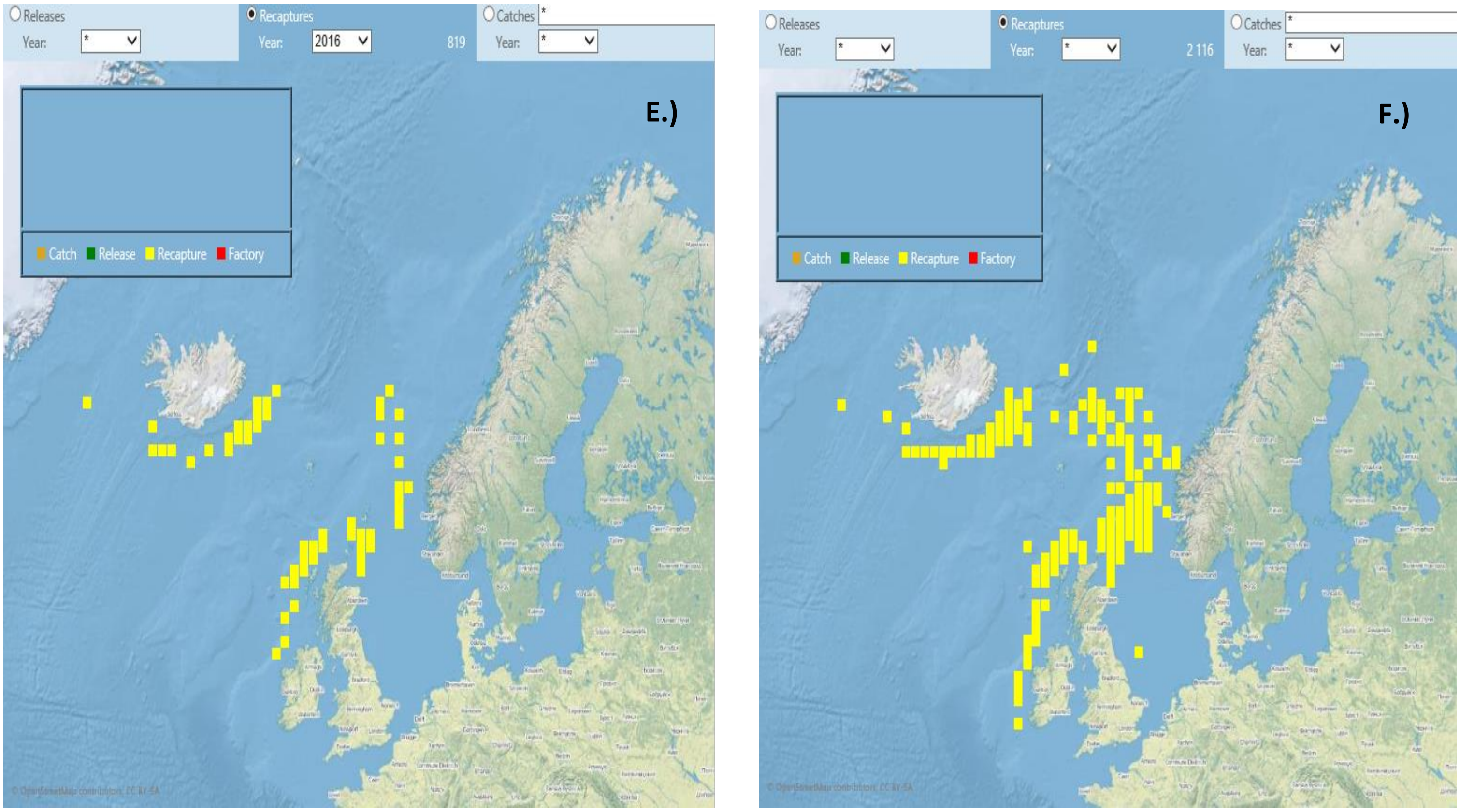
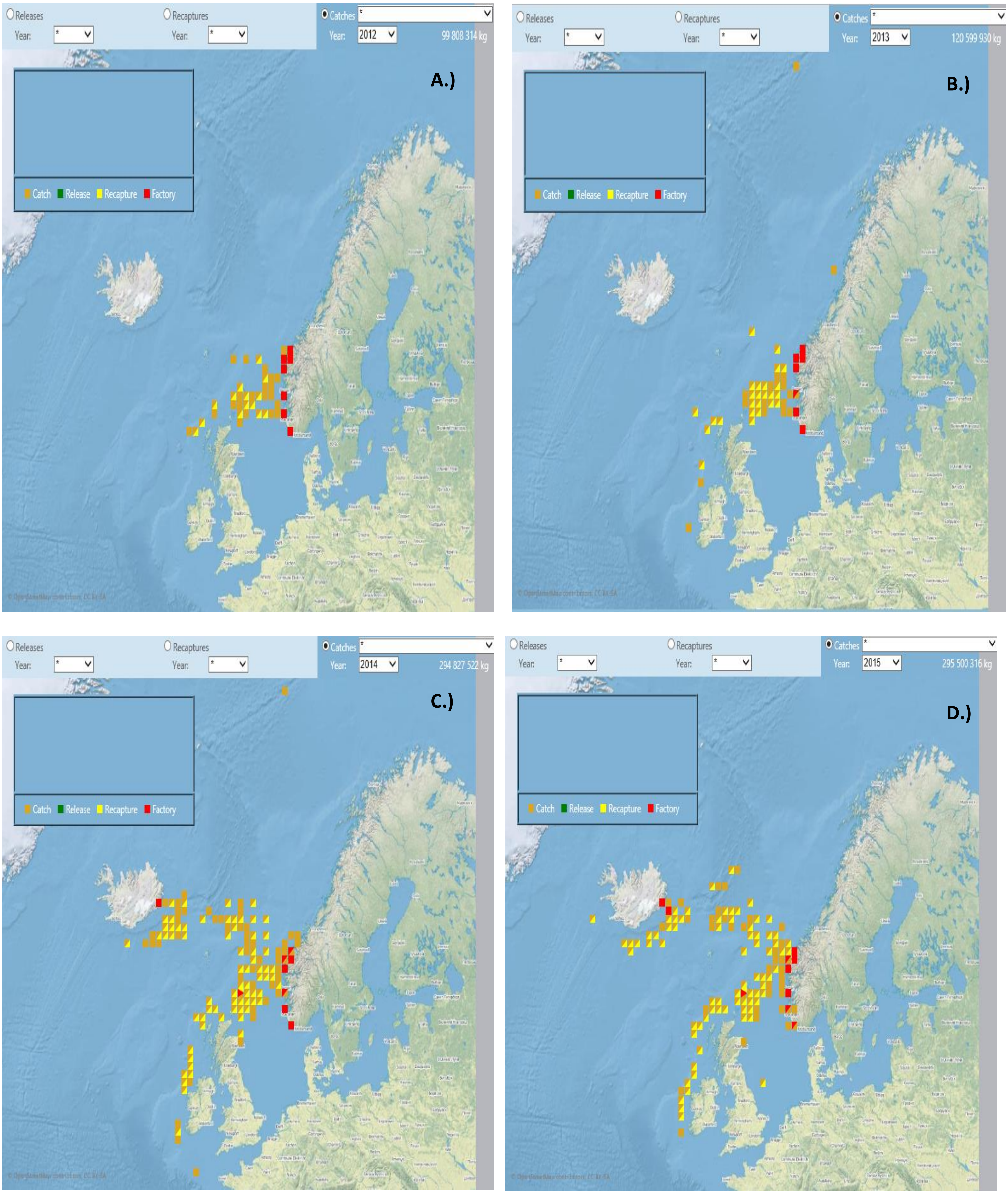


Figure S7: Recaptures from 2012-2016 (A-E respectively). Map F shows all recaptures from all years combined. Maps made from http://tracid-fishmap.imr.no/map.aspx. Yellow squares show location of recaptures.

Catches 2012-2016



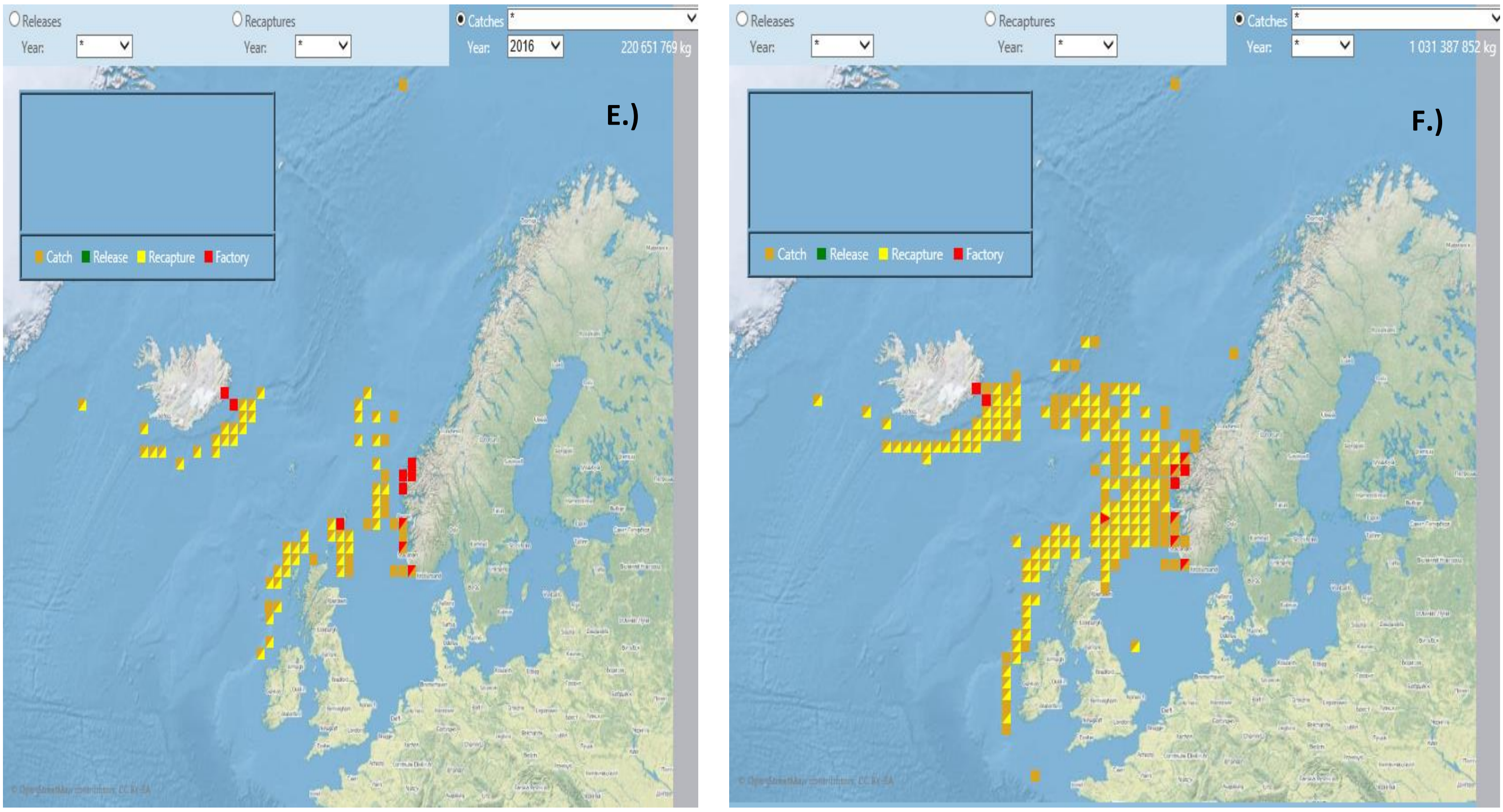
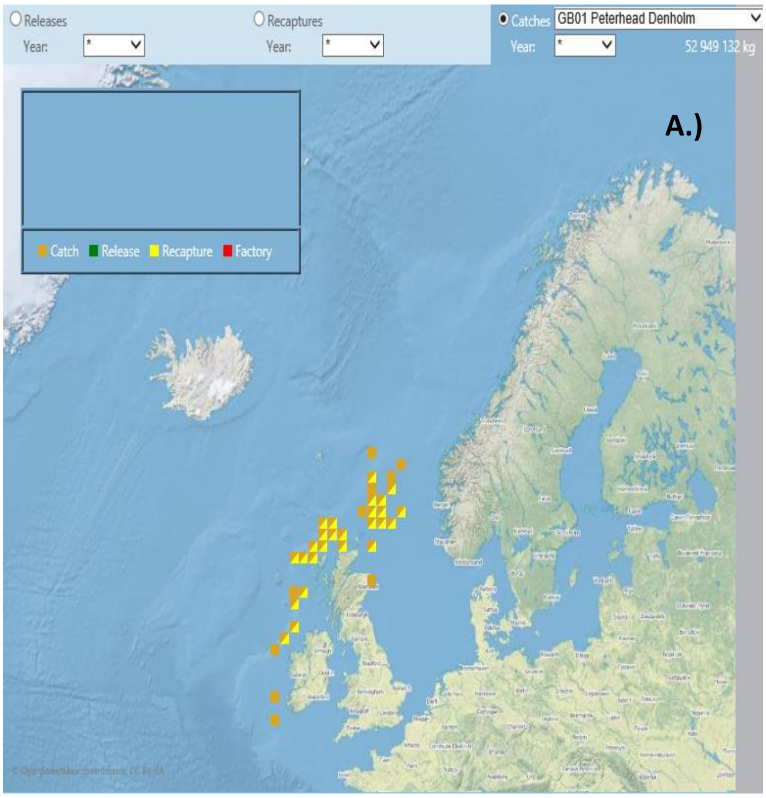
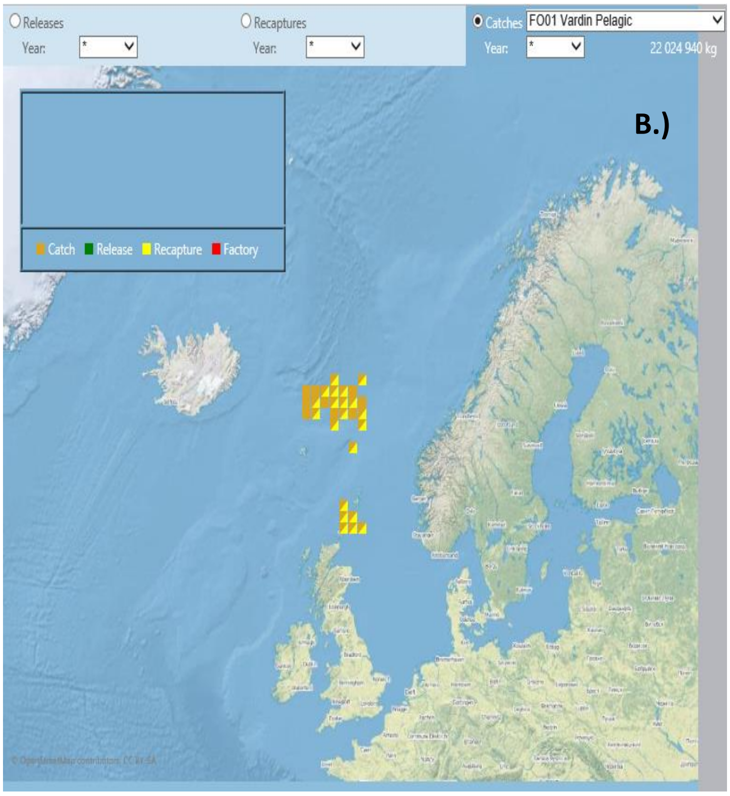
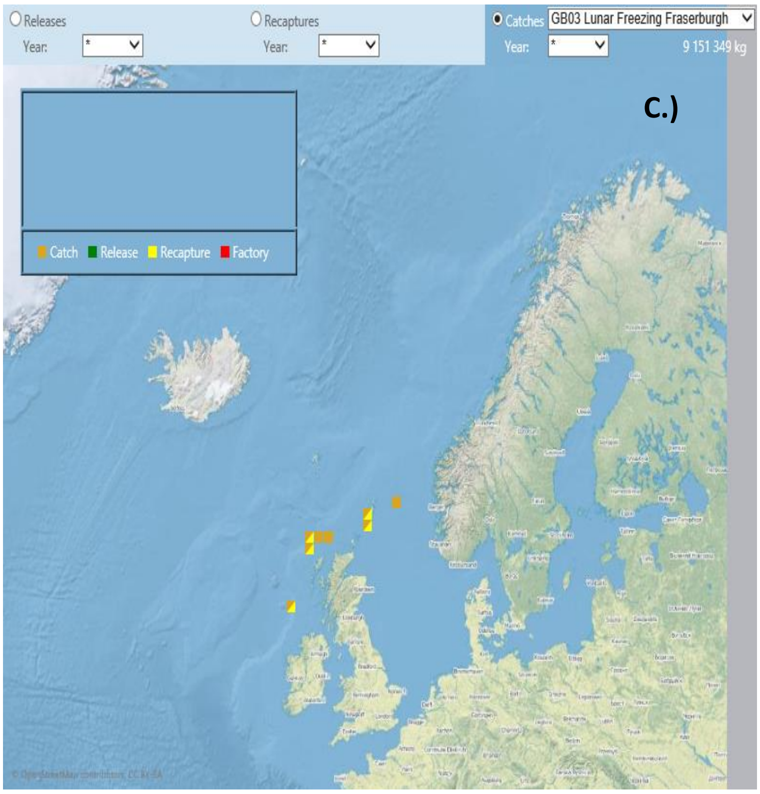


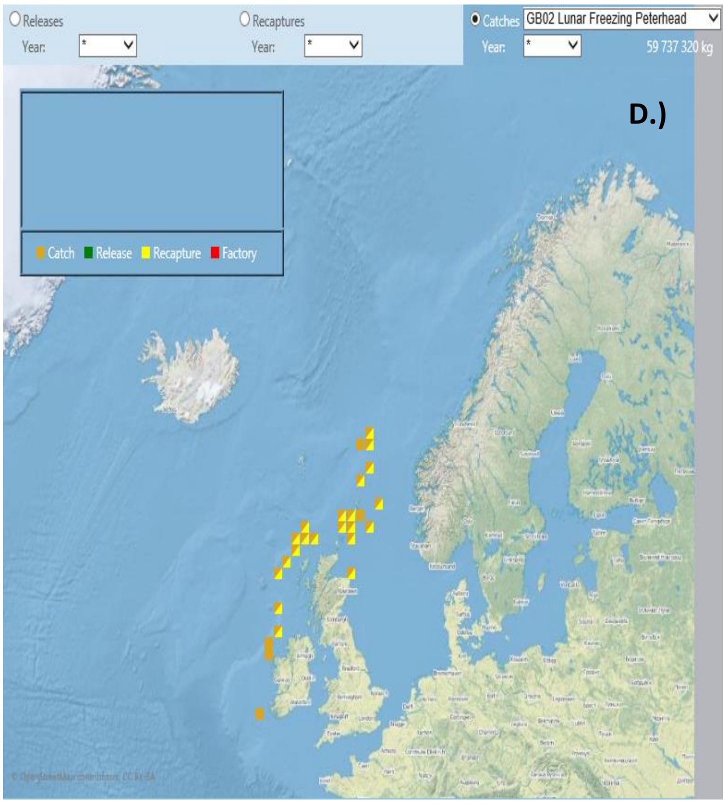
Figure S8: Catches from 2012-2016 (A-E respectively). Map F shows all catches from all years combined. Maps made from http://tracid-fishmap.imr.no/map.aspx. Yellow squares show location of recaptures, orange squares show catch location and red squares show the location of the factories where catch is processed.

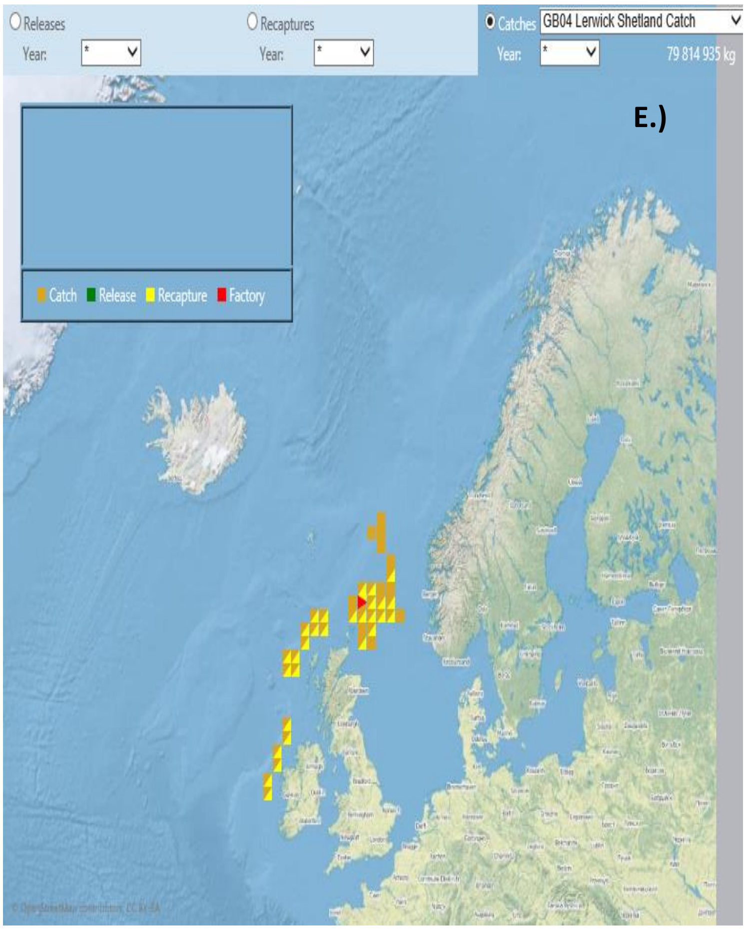
Catches per factory

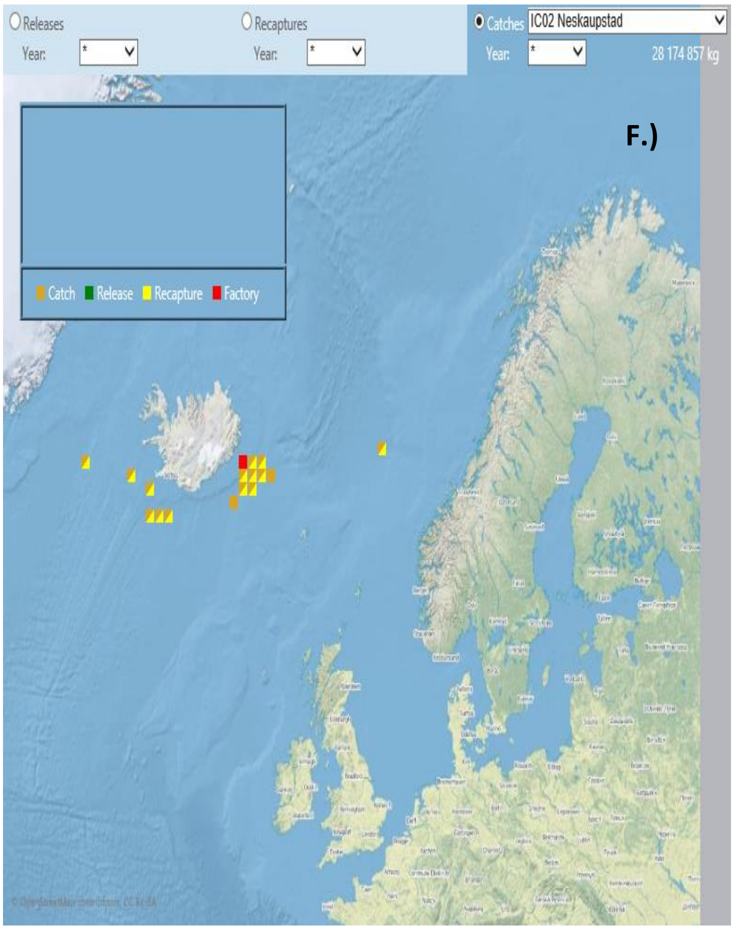


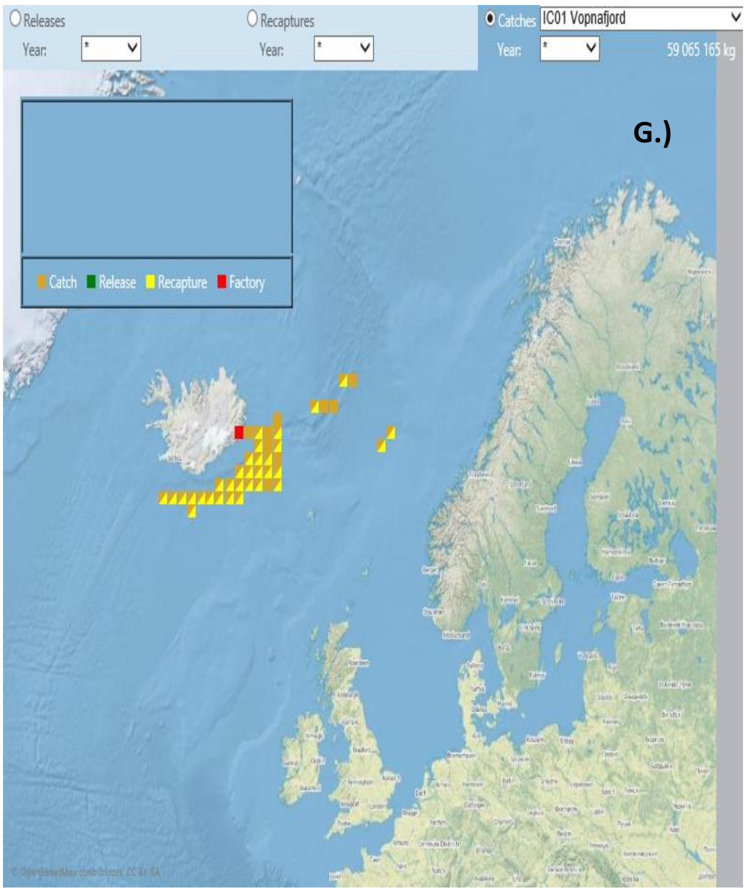


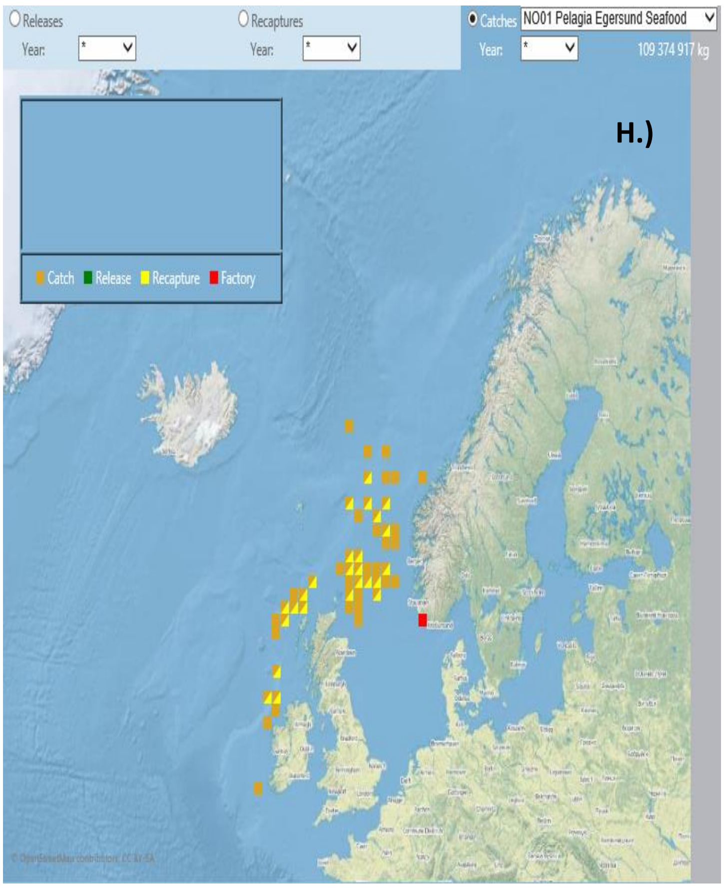


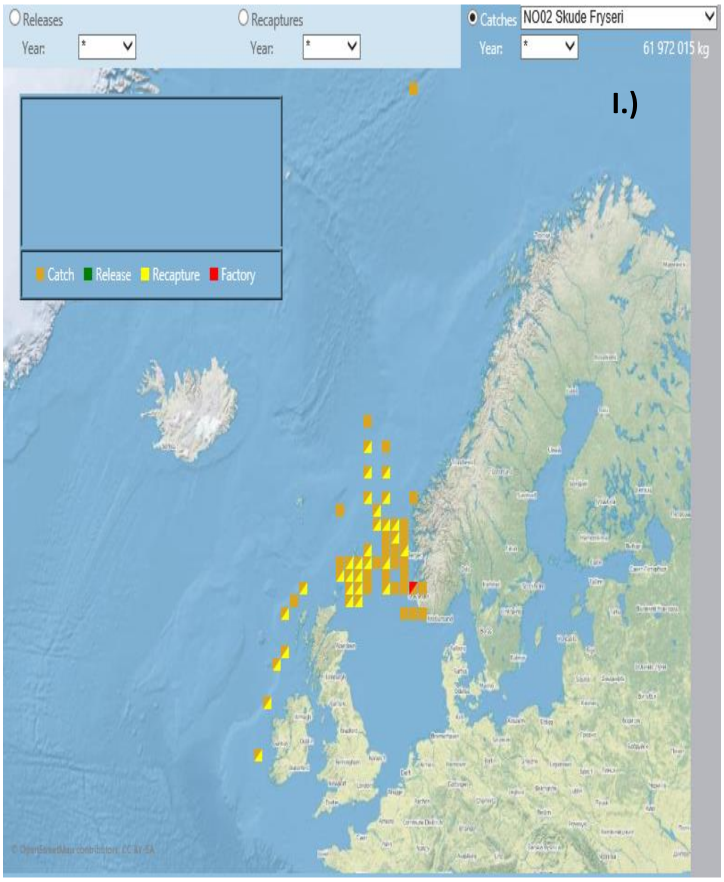


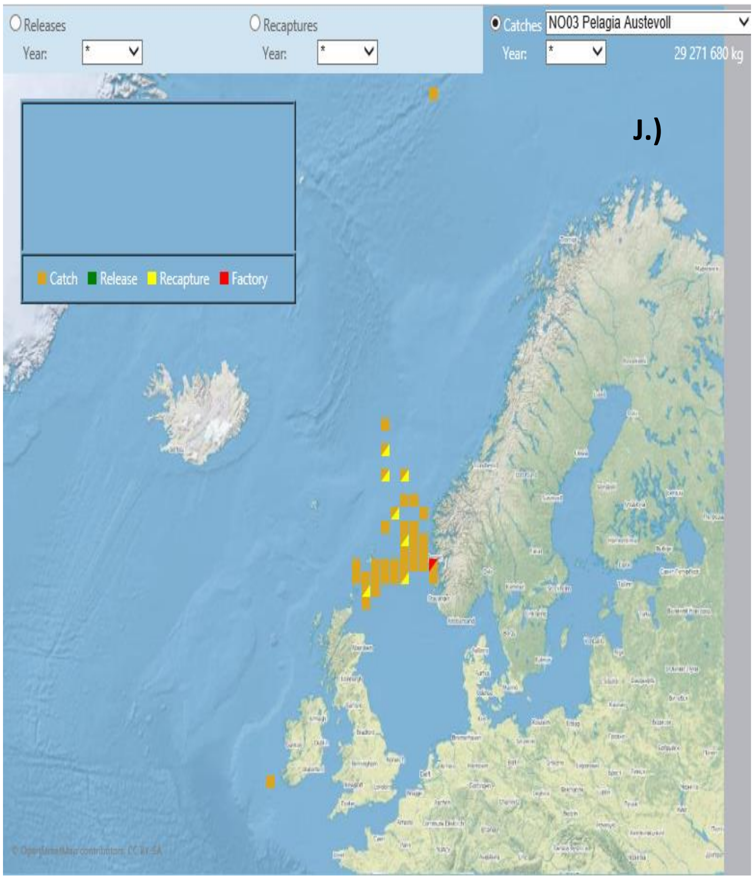

Releases
Year:
Recaptures
Year:
Catches
GB04 Lerwick Shetland Catch
Year:
79 814 935 kg
E.)
Catch
Release
Recapture
Factory

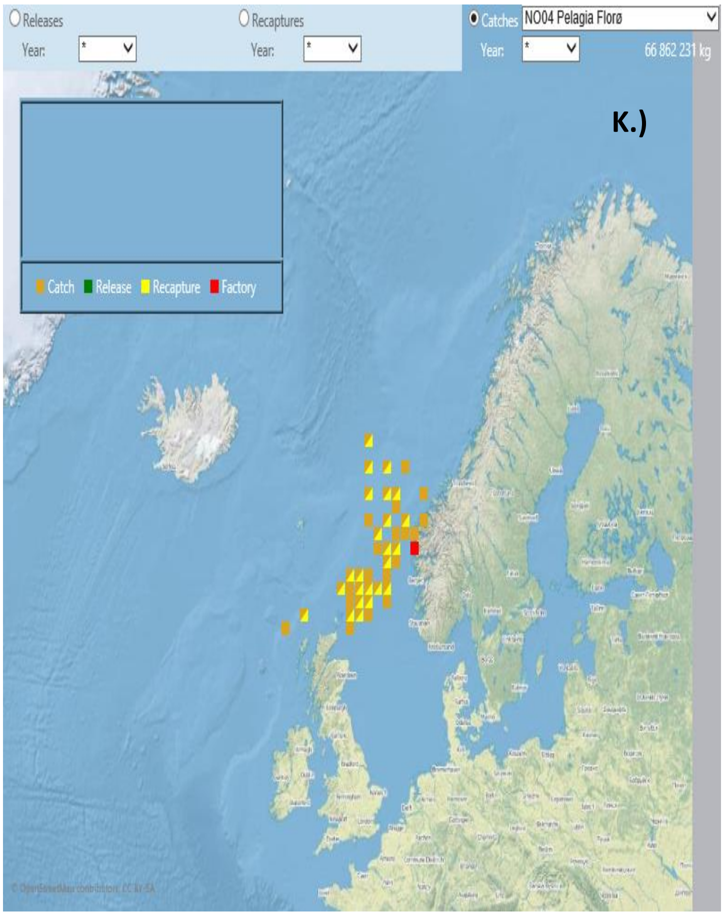

Releases
Year:
Recaptures
Year:
Catches
IC02 Neskaupstad
Year:
28 174 857 kg
F.)
Catch
Release
Recapture
Factory

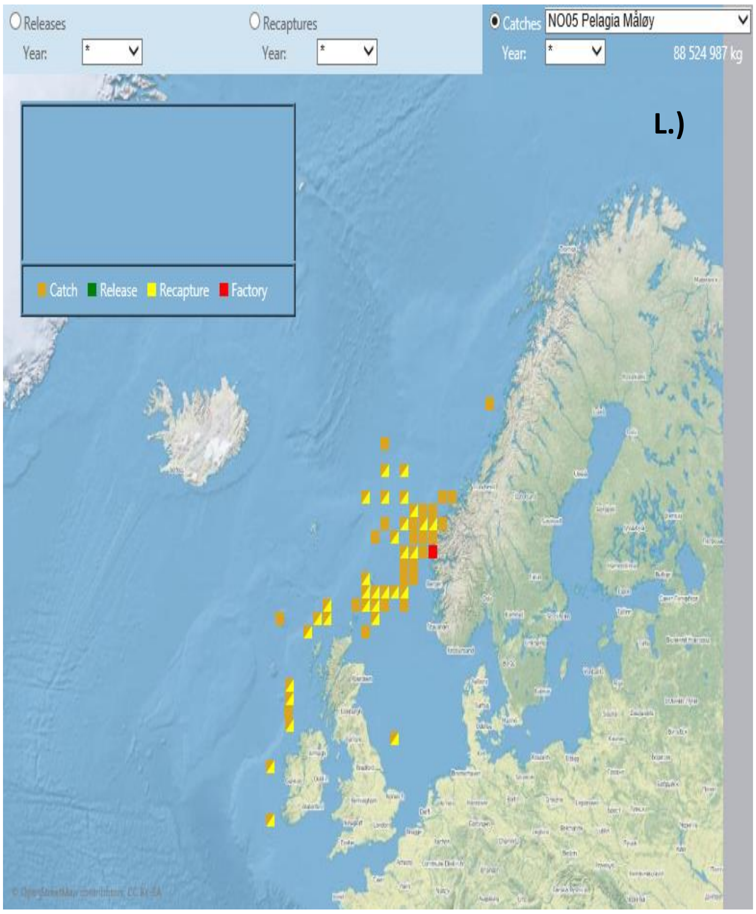

Releases
Year:
Recaptures
Year:
Catches
IC01 Vopnafjord
Year:
59 065 165 kg
G.)
Catch
Release
Recapture
Factory

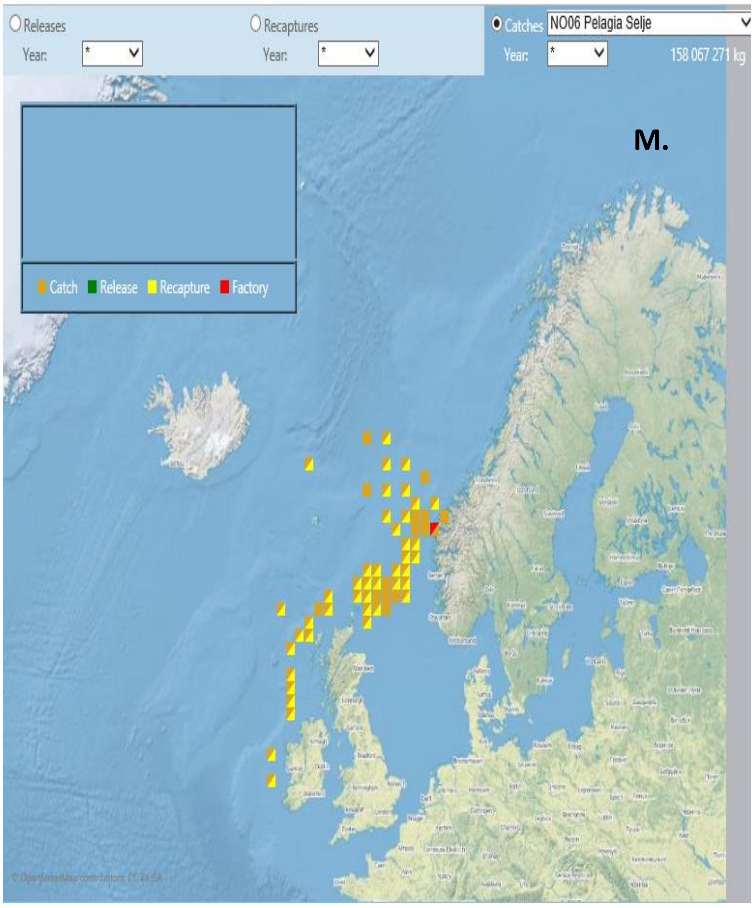

Releases
Year:
Recaptures
Year:
Catches
NO01 Pelagia Egersund Seafood
Year:
109 374 917 kg
H.)
Catch
Release
Recapture
Factory

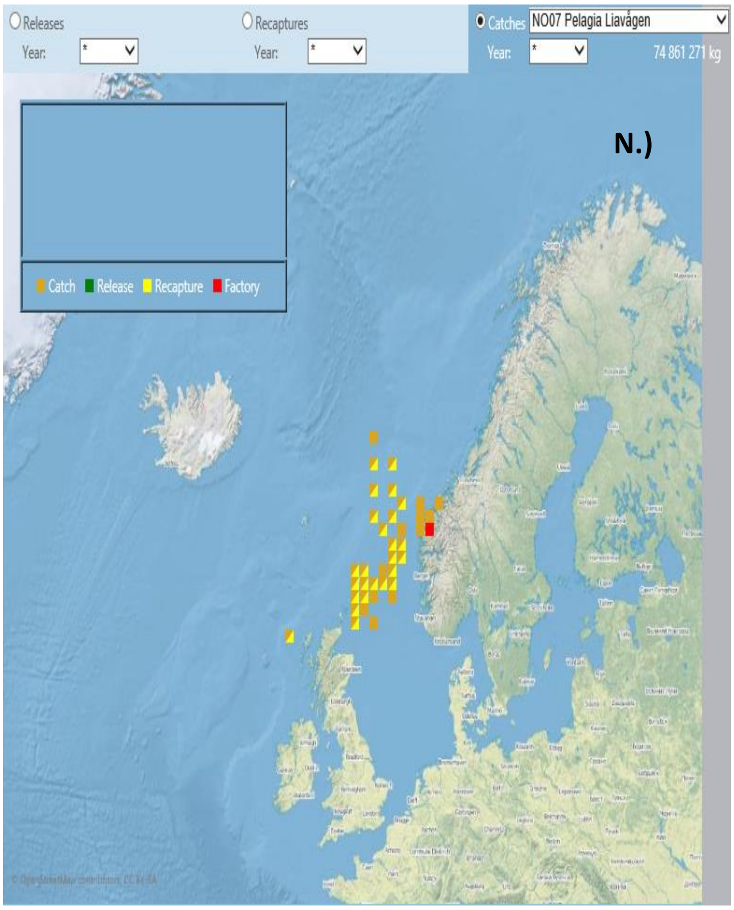

Releases
Year:
Recaptures
Year:
Catches
NO02 Skude Fryseri
Year:
61 972 015 kg
I.)
Catch
Release
Recapture
Factory


Releases
Year:
Recaptures
Year:
Catches
NO03 Pelagia Austevoll
Year:
29 271 680 kg
J.)
Catch
Release
Recapture
Factory


Releases
Year:
Recaptures
Year:
Catches
NO04 Pelagia Florø
Year:
66 862 231 kg
K.)
Catch
Release
Recapture
Factory


Releases
Year:
Recaptures
Year:
Catches
NO05 Pelagia Måløy
Year:
88 524 987 kg
L.)
Catch
Release
Recapture
Factory





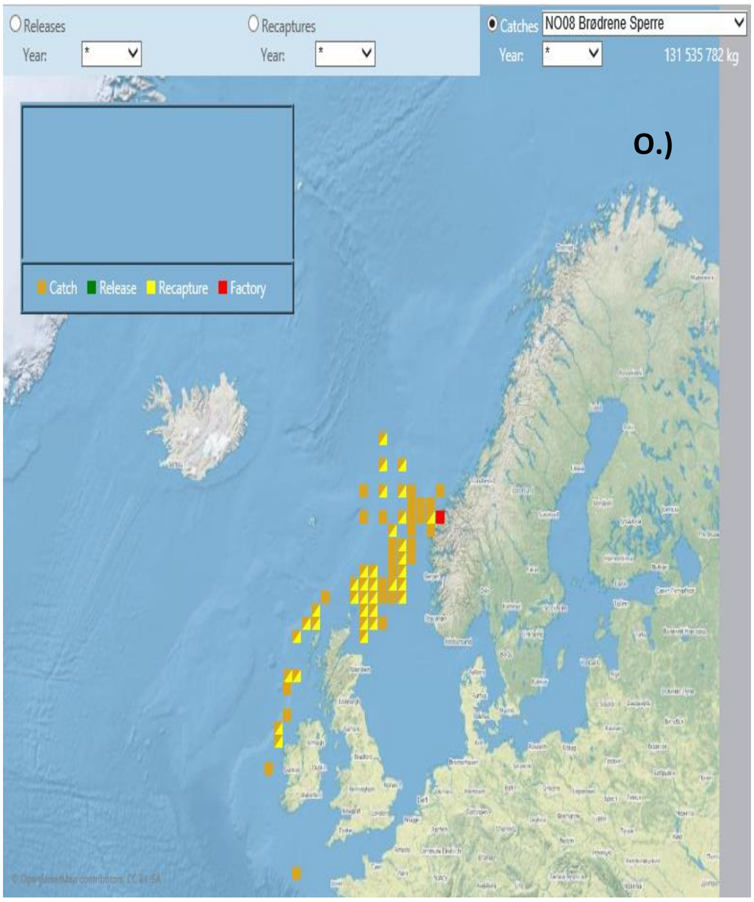
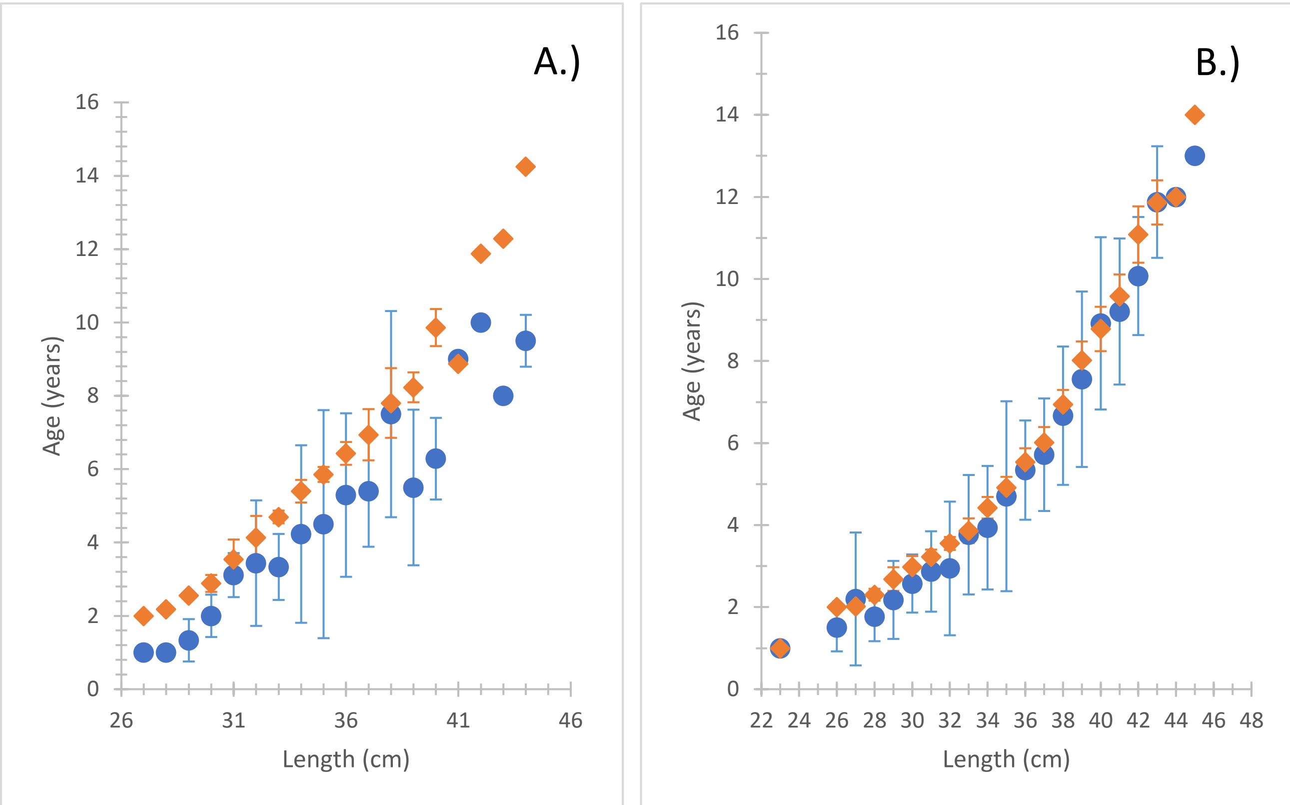


Figure S9: Recaptures and catches from 2011-2016 for each factory. A.) is for factory Peterhead Denholm (GB), B.) is for factory Vardin Pelagic (FO), C.) is for factory Lunar Freezing Frasenburgh, D.) is for factory Lunar Freezing Peterhead E.) is for factory Lerwick Shetland Catch, F.) is for factory Neskaupstad (IC), G.) is for factory Vopnafjord (IC), H.) is for factory Pelagia Egersund Seafood, I.) is for factory Skude Fryseri, J.) is for factory Pelagia Austevoll, K.) is for factory Pelagia Florø, L.) is for factory Pelagia Måløy, M.) is for factory Pelagia Selje, N.) is for factory Pelagia Liavågen and O.) is for factory Brødrene Sperre. Maps made from http://tracid-fishmap.imr.no/map.aspx. Yellow squares show location of recaptures, orange squares show catch location and red squares show location of the factories.



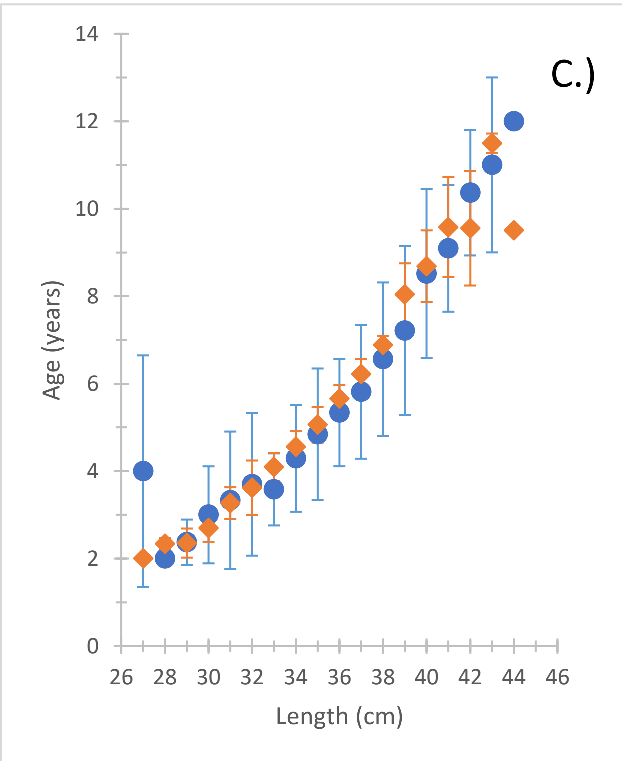
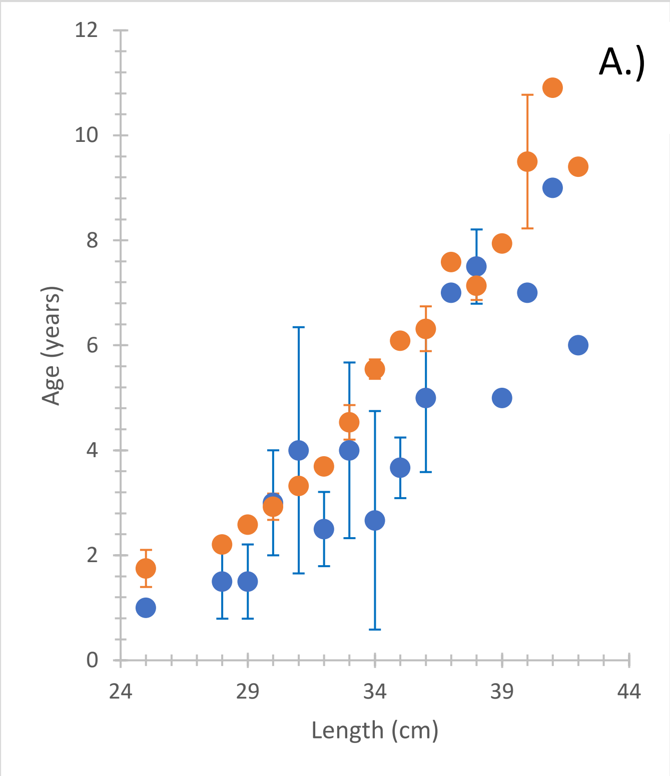
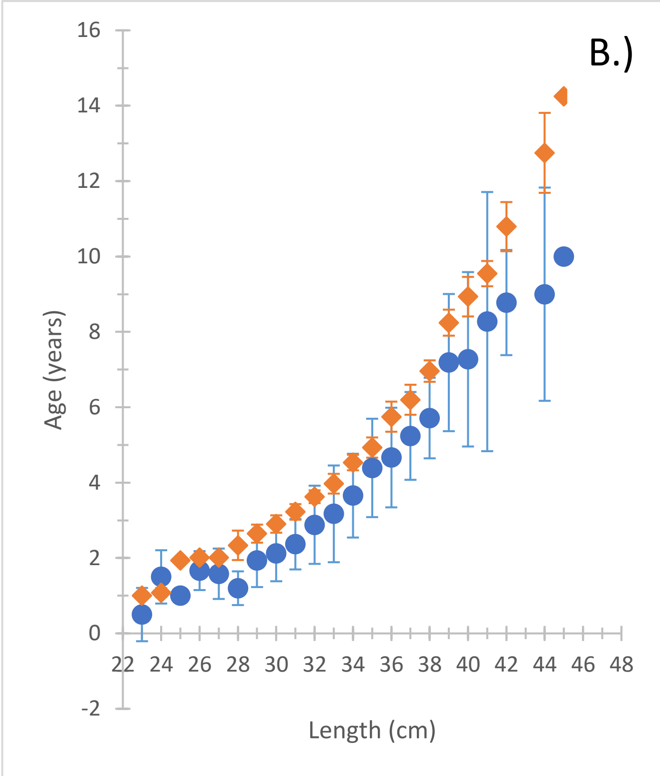


Figure S10: Showing the difference in estimated age and actual age for fish tagged and recaptured within 2 years, error bars indicate the S.D. Graphs A,B and C show different decades, 80's, 90's and 2000's respectively. The orange rectangles indicate the estimated age based on the ALK whilst the blue circles show the actual age.





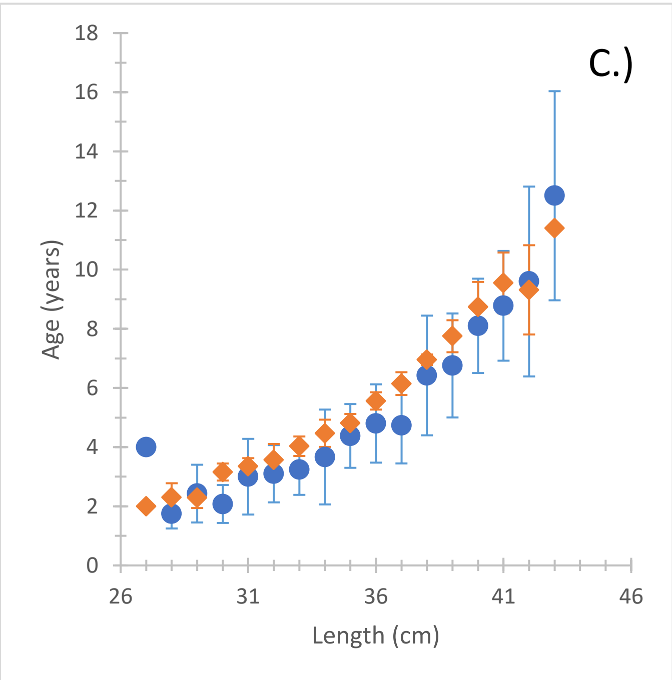
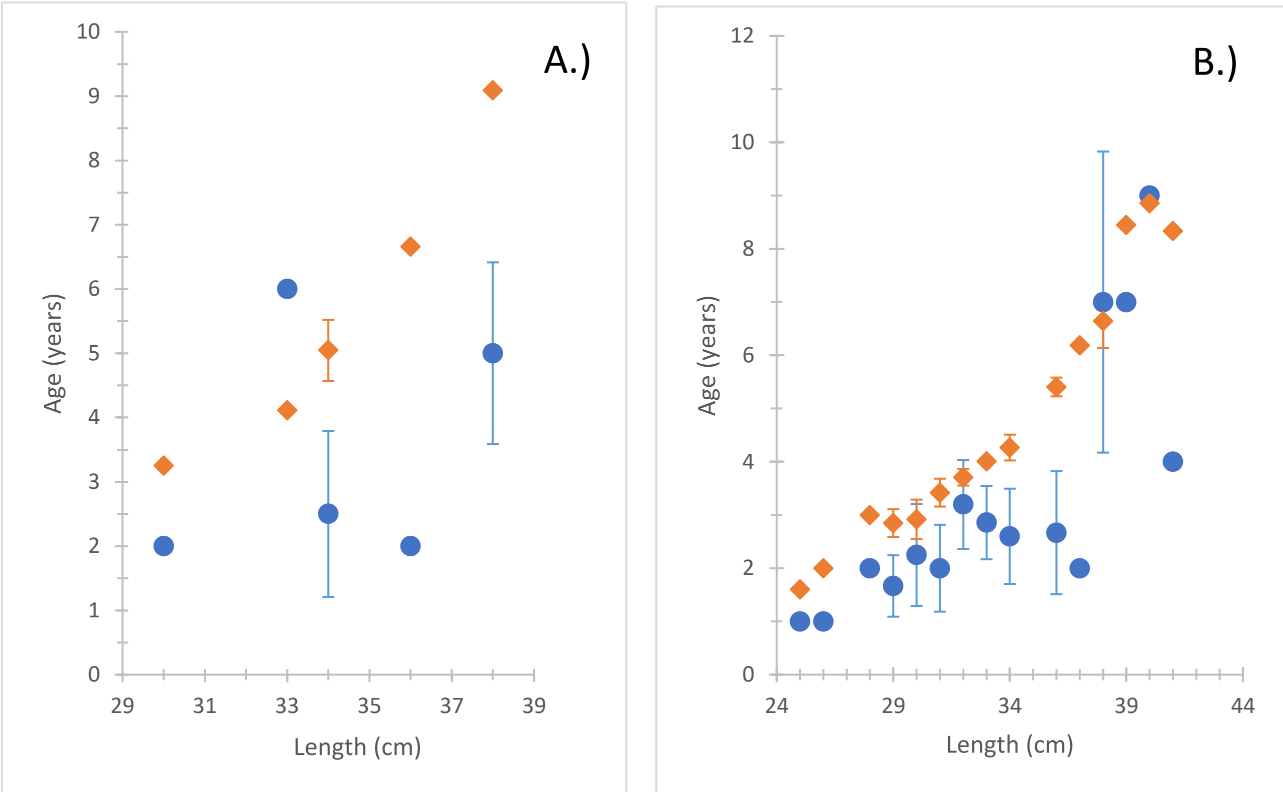


Figure S11: Showing the difference in estimated age and actual age for fish tagged and recaptured within 3 to 5 years, error bars indicate the S.D. Graphs A,B and C show different decades, 80's, 90's and 2000's respectively. The orange rectangles indicate the estimated age based on the ALK whilst the blue circles show the actual age.



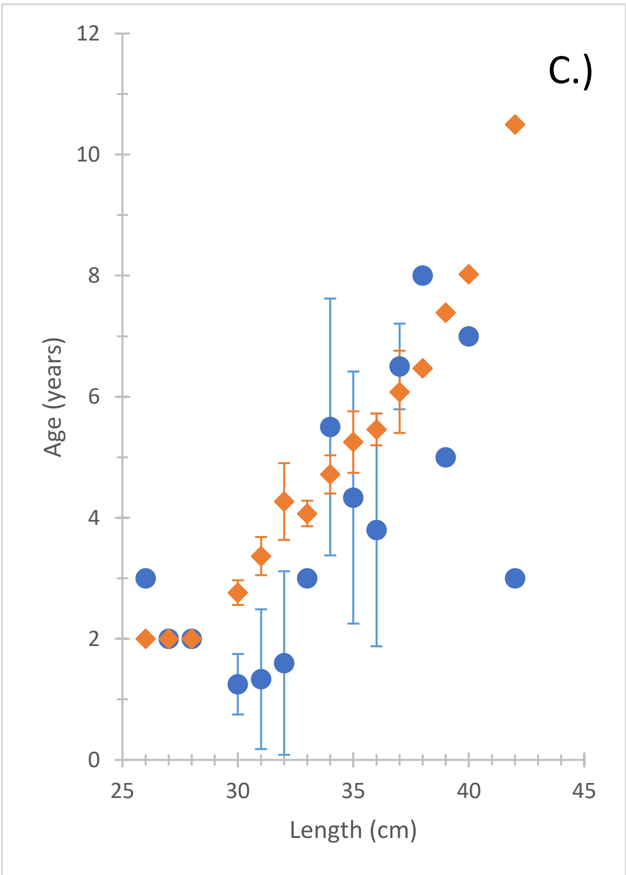


Figure S12: Showing the difference in estimated age and actual age for fish tagged and recaptured after 8+ years, error bars indicate the S.D. Graphs A,B and C show different decades, 80's, 90's and 2000's respectively. The orange rectangles indicate the estimated age based on the ALK whilst the blue circles show the actual age.