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A novel probabilistic survey method for at sea sampling in pelagic fisheries – the Norwegian catch sampling lottery

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ABSTRACT

Reliable information on the age- and size-structure of the annual harvest of major commercial fish stocks is crucial input to analytical stock assessments. Such information is usually obtained from landing data (census of biomass) combined with biological sampling of selected landings. In this paper we describe a novel catch sampling method that we have developed and implemented for the major Norwegian pelagic fisheries that have annual landings around 1 million tonnes in recent years. The new sampling regime gradually implemented from 2018 is based on three pillars; probabilistic sampling of hauls, use of electronic logbook, and co-sampling. By a minor modification of the electronic logbook the vessels in the pelagic fishery now report the catch quantity at haul level immediately after each catch operation. This electronic report is automatically submitted to the Institute of Marine Research (IMR), where a random draw by computer in real time determines if a small sample of fish should be taken from that haul by the fishermen and be frozen and transported to IMR for analysis. Nearly 100% of the hauls annually goes through this “lottery”, and compliance (fraction of samples received) is currently around 60% and increasing. The sampling regime has been operationalized in cooperation with the fishing industry.

1. Introduction

The pelagic fishery in the northeast Atlantic is among the largest fisheries in the world both in terms of biomass landed and value (Nielsen et al., 2017; Rybicki et al., 2020). Annual landings of three abundant and widespread pelagic species in this region, namely blue whiting (Micromesistius poutassou Risso), mackerel (Scomber scombrus L.) and herring (Clupea harengus L.) were between 2.5 and 4.3 mill tonnes in the years 2006–2019 (ICES, 2021a, Fig. 1). The spatiotemporal distribution of these species is highly dynamic, and the fishery follows general triangular migrations between specific spawning, feeding, and wintering areas over a yearly cycle (ICES, 2021b; c). These species interact during the feeding season (Huse et al., 2012a), with partly overlapping distributions in time and space, both horizontally and vertically (Huse et al., 2012b; Utne and Huse, 2012; Nøttestad et al., 2016). There may be large spatial variations in the size of pelagic fish as their migration distance is observed to be size-dependent during feeding (Nøttestad et al., 1999) and spawning migration (Slotte, 1999; Slotte and Fiksen, 2000). The size structure itself may affect the distribution through individual learning and numerical domination for establishment of migration routes (Huse et al., 2010). Adding to the complexity, herring are also manged as several different stocks with different spawning grounds, but with overlapping feeding areas (Pampoulie et al., 2015; Berg et al., 2017).

The pelagic stocks in the northeast Atlantic may be managed differently by the nations that are involved in the fishery. Most of the pelagic stocks in this region are “data-rich”, and generally subject to analytical stock assessments based on input data from fisheries-dependent and fisheries-independent monitoring programs. In general, all pelagic stocks are assessed within the ICES framework using state-space, age-based modelling, where the main input data for the assessments is the estimated catch in numbers-at-age matrix, supported by information from scientific surveys (Aeberhard et al., 2020). Reliable age-based assessments depend on knowledge about the age structure of the population over time, and accurate estimates of how many individuals from each age group that are removed (fished) each year. The census landings data are provided as biomass, and not in numbers, and

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therefore biological sampling programs that cover all or most part of the fishery in a statistically sound way are required to estimate mean weight, and catch in numbers of fish by length and age. Such sampling programs are typically based on onboard catch sampling or sampling of landings by trip at the fishery ports (ICES, 2014).

The highly complex spatiotemporal dynamics of these migratory pelagic fish species pose significant challenges in designing and running biological sampling regimes that provide representative estimates of annual catch in numbers at age for each stock. Since these migratory resources are spread across many EEZs and harvested by several European countries, there are very different strategies for the monitoring of fisheries to estimate catch at age. It should be noted that Norway has overall the highest catch of these shared resources (Fig. 1), and hence Norwegian input data to the catch-at-age matrix may have substantial influence on final stock assessment outputs and quota advice. Norway has therefore spent significant resources to develop monitoring programs that are cost-effective and lead to precise estimates of catch at age while minimizing bias.

Biological sampling of fish harvested by a fishery is generally conducted in multiple stages by default. For instance, a port-day and a landing site, or a trip and a haul must be selected before a sample of individual fish can be obtained. Clearly, sampling frames based on primary sampling units (PSUs) defined as all trips or hauls annually, for example, would not be known in advance. Expert groups in ICES (2014) identified four classes of sampling designs that represent hierarchies of the most common multi-stage sampling programs for at-sea and onshore catch sampling in Europe. These sampling programs typically employ sampling frames that are based on lists of landing sites or vessel to define PSUs, or some combination of sites or vessels crossed with time, for instance port-day (site*time) or trip (vessel*time) (e.g. Azevedo et al., 2021). After the selection of a PSU in the first sampling stage, several intermediate selections will be required before a biological sample of fish is taken. For instance, for at-sea sampling programs a selection of trips (secondary sampling units, SSUs) may be obtained from a selection of vessels (PSUs), and then a selection of hauls (tertiary sampling units, TSUs) within each selected trip, before finally being able to select a sample of fish from a selected haul. These multi-stage designs are motivated by practical considerations related to how catches can be accessed to collect samples of fish. The selection of the PSUs, and the subsequent intermediate selections contribute to clustering of the sample of fish. When fish that are sampled from the same PSU tend to be more like each with respect to characteristics such as length- and age, compared to fish collected from different PSUs, then the PSU is said to cluster the selection. Such clustering will often result in a reduced effective sample size (Kish, 2003), and less precise characterization of the total harvest. Several studies (e.g., Pennington and Vølstad, 1994; Thompson, 1997; Nelson, 2014; Azevedo et al., 2021) have shown that this is not merely a theoretical concern, and that the information content in both fisheries samples and fisheries independent surveys tend to be mainly limited by the number of PSUs they sample, not the number of individual fish (Pennington and Vølstad, 1994; Aanes and Pennington, 2003; Pennington and Helle, 2011). That is, for these multi-stage sampling designs little is gained from increasing the overall number of fish sampled, unless this is achieved by increasing the number of PSUs sampled. It is therefore generally desirable to eliminate sampling stages when possible, and sample wide (many PSUs) rather than deep (many individual fish) (see Azevedo et al., 2021).

In this paper we describe a probability-based sampling system that minimizes clustering by gaining access to collecting biological catch samples from pelagic fisheries in real time directly at the haul level, without the need for prior selection of vessels or trips. This is achieved by utilising co-sampling (often called self-sampling) (Kraan et al., 2013) in close collaboration with the fishing industry, and by modifying existing infrastructure for mandatory catch reporting through electronic logbooks (ERS).

Probability-based sampling is considered the “gold standard” in surveys (see, e.g, Bacher et al., 2019) because it eliminates bias related to the selection of samples and supports the unbiased estimation of

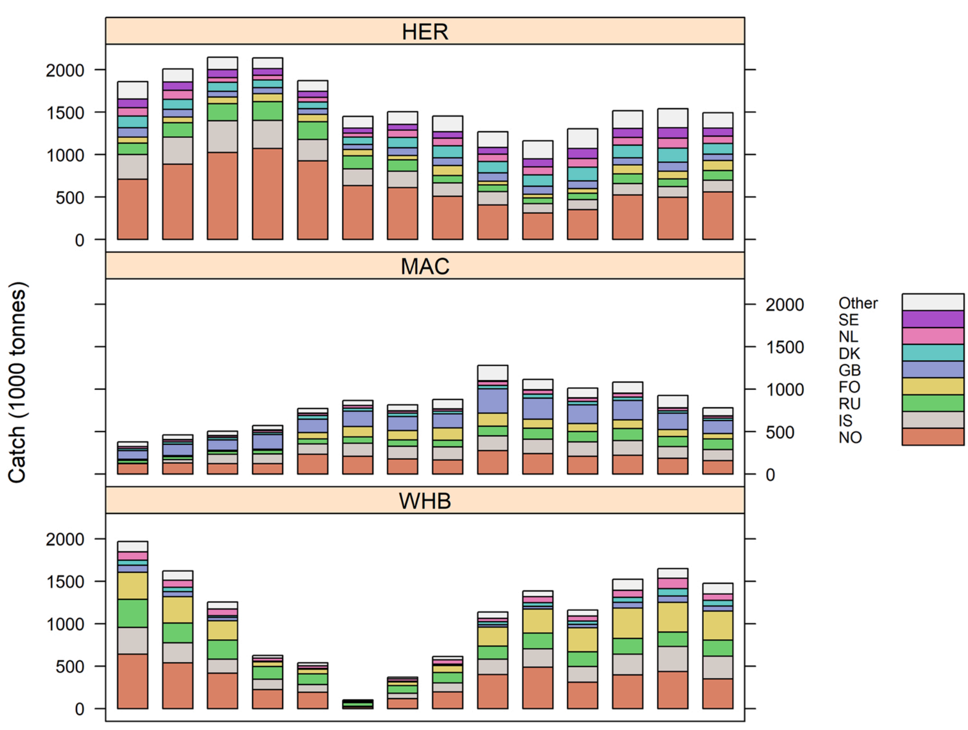

Fig. 1. Yearly catch of blue whiting (WHB), mackerel (MAC) and herring (HER) in FAO area 27 by nation.
Date is taken from Official Nominal Catches 2006–2019. Version 15–10–2021. Accessed 20–04–2022 via http://ices.dk/data/dataset-collections/Pages/Fish-catch-and-stock-assessment.aspx ICES, Copenhagen.

variance (precision) of the resulting estimates.

The large Norwegian pelagic fishing fleet is highly complex, with 200 + active vessels ranging from small coastal purse seiners (<50 m) to large (50–100 m) trawlers or purse seiners operating offshore. Catch from each fishing operation is recorded instantaneously and reported daily through a mandated electronic logbook system (ERS). A small fraction of the coastal fleet (boats < 15 m) is not currently mandated to report their catches through ERS at sea, and the catch by trip is reported at landing. Selection of catch samples from the Norwegian pelagic fleet by trip or haul to quantify length- and age composition of total annual catches has traditionally been done by expert judgement. Staff from Institute of Marine Research (IMR) with strong knowledge of the fisheries have used their extensive network to recruit vessels or buyers to provide at-sea and on-shore samples of fish in a manner they consider representative of the fishery. From a statistical point of view this can cause bias and complicates analysis, requiring strong assumptions of probabilistic sampling (for design-based estimators) or assumptions of independent and identically distributed error terms (model-based estimators). Yet rigorous probabilistic sampling is only preferable if it can also be confidently considered to be more efficient and yield more accurate estimates than the pragmatic options. That is, allowing some selection bias may be better than unbiased sampling that results in estimates of the length- and age composition of total catches in individual years with low precision. For these highly dynamic fisheries, the expert selection approach has had the benefit of being reactive in ways that rigorous sampling programmes based on pre-determined sampling frames often cannot be. Still, the fact that each catch is reported instantaneously through the electronic logbook systems (ERS) opens for a more automatic statistical approach for selecting representative samples through direct communication with vessel using this system, avoiding potential bias issues through subjective expert selection.

The main objective of this paper is to describe the development of a novel statistically sound, transparent, and effective sampling system that avoids the need for a priori allocation of sampling effort to spatio-temporal strata. We achieved this by using the electronic logbook as means for communication to conduct Poisson sampling based on data from real-time reports of catches, and a good a-priori proxy of total annual catch (the TAC). Even though the system is developed for sampling the Norwegian pelagic fishery, the use of probabilistic sampling in combination with electronic logbook system is applicable in most countries with an industrialised fishing fleet. We therefore focus on typical challenges that we experienced, and that can be expected when developing and implementing such as sampling system in close cooperation with the fishing industry. Throughout the rest of the paper, we use the term “sample”, either referring to the haul (PSU) that has been selected for sampling or the box of ~30 individuals that the fishermen sub-sampled from a selected haul and provided to IMR. The methods for sub-sampling individuals from a haul is only covered briefly in the present paper.

2. Material and methods

2.1. The Norwegian pelagic fishery

In the present paper we will focus on three of the most important shared pelagic species in the Northeast Atlantic, herring, mackerel, and blue whiting, even though other species also are included in the catch sampling lottery.

The three pelagic fish species are harvested during different parts of their seasonal migration cycles, while they are spreading over large areas (Fig. 2). The blue whiting is mainly targeted during its spawning migration along Ireland and British Isles February-April, with a minor part being harvested in the mixed industrial fisheries as immatures along the west side of the Norwegian Trench in the North Sea. The mackerel is to a large degree harvested while returning from the feeding migration in the Norwegian Sea into the wintering areas east of Shetland in the northern North Sea. The herring is composed of two different stocks – the North Sea herring and Norwegian Spring spawners, with different stock assessments and management regimes. The North Sea herring is normally fished during the feeding season from May—June in central North Sea, and to some degree during the autumn spawning closer to British Isles. The Norwegian Spring spawning herring is mainly exploited while returning from feeding in the Norwegian Sea to their oceanic wintering areas off northwestern Norway and coastal wintering areas in northern fjords, a fishery that continues over the winter and during the subsequent spawning migration southwards along the Norwegian coast

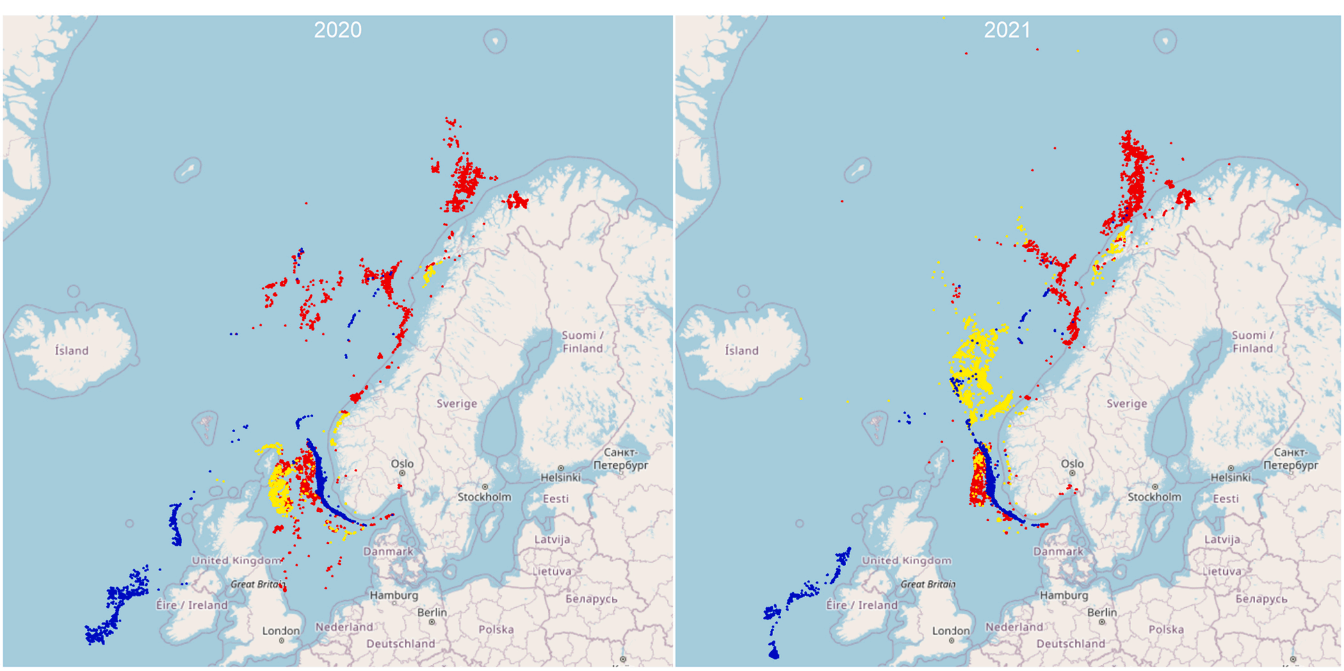

Fig. 2. Geographical distribution of Norwegian catches of herring (red), mackerel (yellow) and blue whiting (blue) in 2020 and 2021. Each point is one catch operation with catch above 2 tons of the respective species as recorded by the electronic logbook.

in January-February. Note that the spatial distribution of the fisheries for both blue whiting, mackerel and North Sea herring is highly dependent on international quota regulations within national economic zones, which varies over time. Currently Norway is not allowed to fish mackerel in UK waters, so they instead target this species during their feeding in the Norwegian Sea. The same is the case for blue whiting that now must be targeted farther south (Irish waters) and west (international waters), and for North Sea herring where only a minor proportion is allowed to be fished in UK waters.

The Norwegian pelagic fleet is large and structured as an oceanic fleet above 60 m that currently contains 67 vessels, and a coastal fleet below 60 m, with 121 vessels in the segment 15–60 m, and 133 vessels in the segment < 15 m (Fig. 3). Note that this structure applies for the herring fishery, which historically is Norway's most important fishery, with a fishing fleet where the majority of vessels use a purse seine only, and a smaller proportion combine both purse seine and trawls. The smallest vessels < 15 m may take large catches with their purse seines, but they store their catches in net pens at the catch sites until they are collected by a large vessel that transports the fish to landing sites. Most vessels targeting herring are also targeting mackerel, but a lower proportion of vessels in the ocean fleet use trawl for this purpose. Fishing for herring with trawl by the ocean fleet is mostly conducted in the North Sea stock, where it is difficult to target fish effectively with purse seine as schools are generally small during the feeding season. Note that in the

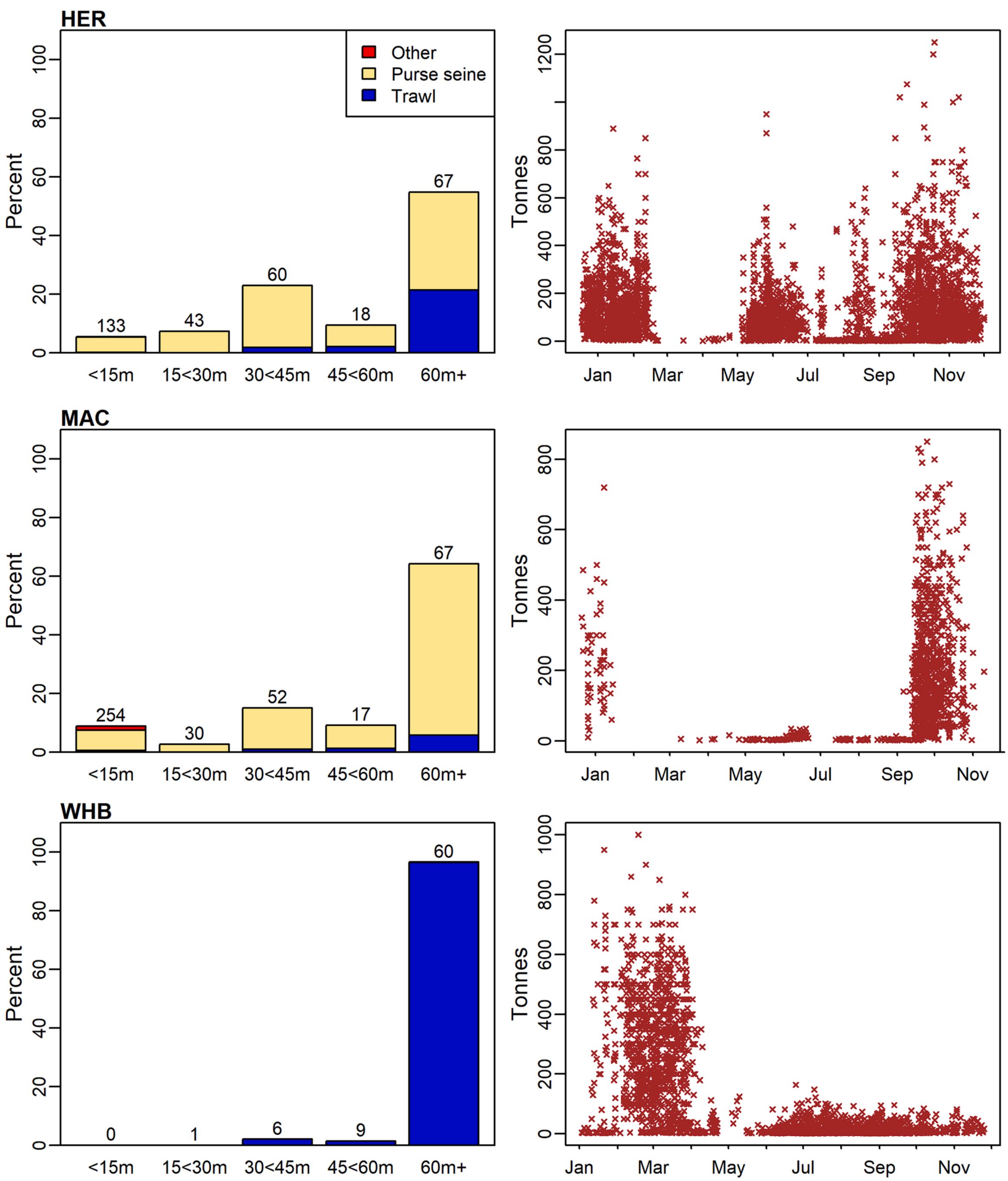

Fig. 3. Left panels; percent of the 2020 catch of herring, mackerel and blue whiting taken by different gear types and vessel sizes. Data are taken from official landing notes. The number above each bar gives number of unique vessels per length group, that fished at least 1 tonnes (t) of the respective species. Right panels show the distribution of hauls size during 2020 (ticks indicate 15th of each month). Data from electronic logbook (vessels above 15 m, hauls above 2 tons).

mackerel fishery there are about twice as many vessels in the segment < 15 m as for the herring fishery, due to a number of specialized vessels that fish with lines using automatic jigging machines. This segment contributes to a low proportion of the total catch in biomass. The blue whiting fishery, on the other hand, is a 100% trawl fishery, dominated by the oceanic fleet of combined trawlers and purse seiners.

The numbers of completed hauls and participating vessels during harvesting vary annually according to the quotas and biomass landed, and there are also clear differences between the target species, with more vessels and hauls required to land the quota for herring compared to quotas for mackerel and blue whiting (Fig. 4). The fleet below 15 m, as mentioned above is not included in these numbers, but this fleet segment only accounts for < 10% of the catch. The blue whiting fishery is here characterized as a fishery with the largest hauls, on average about 200 tonnes.

2.2. Auction system

All commercial first-hand sales of fish by Norwegian vessels are by law obliged to be arranged through certain sales-organisations. These

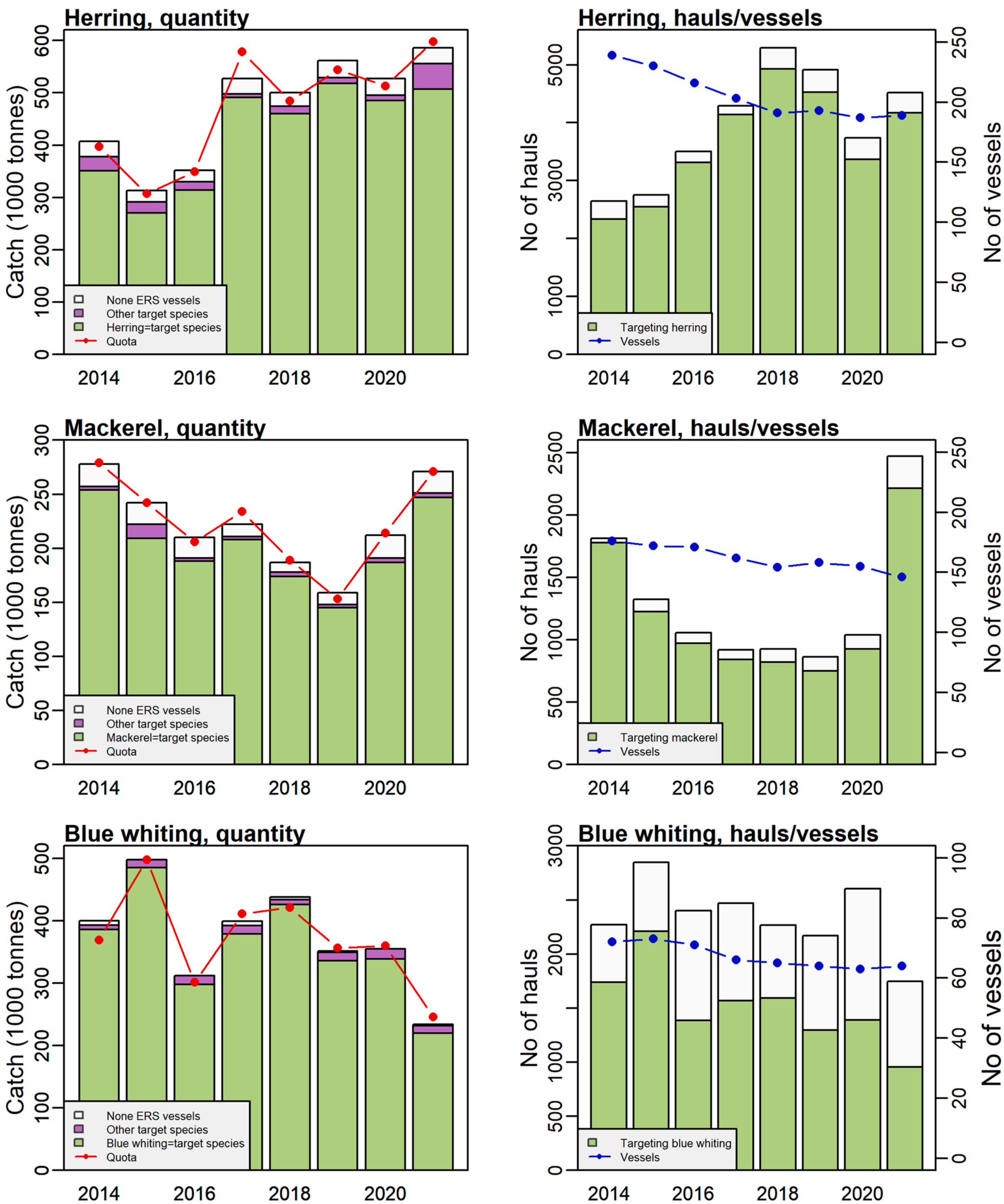

Fig. 4. Overview of catch, number of hauls and number of vessels in the period 2014–2021. Left panels show total catch (from landing notes) per year and species. This also includes vessels without ERS. The fraction of the total catch taken by vessels having ERS and the actual species as target species that trip is indicated by green colour, while those having other target species are indicated by lilac. These fractions are taken from logbook of all hauls above 2 t that year/species. Official Norwegian quota are shown as red dots. Right panels show the corresponding number of hauls (>2 t) taken from logbook, total number and fraction with actual species as target. Number of vessels targeting actual species are given as blue dots.

are cooperatives owned by the fishermen themselves, and in the pelagic sector Norwegian Fishermen's Sales Organization for Pelagic Fish (www.sildelaget.no) organises sales between vessel and buyer through an electronic auction system. Argentines are sold through other but similar sales organisations. The fishermen report their catch by species, quantity and often also by quality (e.g., size distribution, fat content etc.) by telephone to the sales organisation where potential buyers can place bids. Through this system the fishermen need to and are used to take sub-samples of fish from every haul routinely to characterize their catch – a very useful skill that we could take advantage of when implementing catch sampling for our scientific purposes.

2.3. Electronic logbook

During the last two decades the use of electronic logbook systems (ERS) has been introduced to the fishing fleet in many countries all over the world, primarily for the larger offshore vessels. As a result of more cost-effective electronic communication systems and improved onboard applications, ERS has become a valuable tool for the national governments to monitor and control that their fishing fleet is acting according to legislation. In addition, ERS provides catch data for statistics and research. ERS is often used together with vessel monitoring systems (VMS), where data from catch operations are registered in the electronic logbook while position data are registered through the VMS. Both systems use rigid data protocols to ensure the authenticity and traceability of the messages from vessel to national authorities, and failure to send the obliged reports may have legal consequences for the captain or owner of the ship.

European countries may have different requirements and communication protocols for their ERS (and VMS system), but they are all built around a common coding system and format, namely the North Atlantic Format (NAF, www.naf-format.org) organised by the Northeast Atlantic Fisheries Commission. Together with multination or bilateral agreements this format secures sharing of standardized ERS and VMS data between nations. The most important type of information relevant for the sampling system described in the present paper are listed in Table 1.

2.4. The Norwegian logbook system

In Norway, the Norwegian Directorate of Fisheries (NDF) monitors the fishing activity through the ERS and VMS systems in real time throughout the year (24/365) through their Fisheries Monitoring Centre (https://www.fiskeridir.no/English/Fisheries/Fisheries-Monitoring-Centre). Each vessel that is obliged to report by ERS has logbook software onboard. This software is provided by commercial companies that may have different user interfaces, but all fulfill the standards set by NDF and the NAF-format and uses data transfer protocols that secures the content and the integrity of the data. All messages from vessel to NDF (and vice versa) are acknowledged by the final receiver. Thus, the data flow between the vessel and NDF is two-way process. This two-way process allows the system to give feedback on each report sent by the master in an automatic way.

Table 1
Overview of the three most important message type sent from the vessel to the Norwegian fishing authority. The messages are very similar in most European countries. For a full list of message types, data elements and coding list for species, gear, etc, see www.naf-or.com.

Message name	Time sent from vessel	Content of message
DEP	Before each trip	Information about intended start of fishing, area and target species
DCA (or FAR)	At each haul or day	Information about each catch operation (or daily catch), like position, gear, effort and catch in kg per species. Information registered per operation for active gears, but report sent before midnight each day.
POR	After each trip	Information about where and when the catch is supposed to be landed, as well as the catch composition onboard

2.5. Fisheries monitoring – The catch sampling lottery

IMR is responsible for conducting the biological catch sampling from marine fisheries in Norway that combined with data from landing notes (reported to NDF, the Norwegian Directorate of Fisheries) is the basis for estimating number of individuals in each year class removed by the fishery annually. In Norway, NDF is the national authority that decides through legal regulations how the various fishing quotas are allocated between vessels and organises the collection of sales notes through the sales organisations.

The novel catch sampling program employed for the pelagic species in Norwegian fisheries that now has become the standard has been named "The Norwegian catch sampling lottery", and was first implemented in 2018 for herring, and later gradually expanded to cover blue whiting, mackerel, sprat, Norway pout, sandeels, horse mackerel, capelin and argentines. The sampling program employs probabilistic sampling of fishing operations (PSUs) in real time, using a modified ERS-system for ordering selected samples of fish to be taken by the fishermen (co-sampling). The sampling program was developed and implemented by IMR in close cooperation with NDF and involving the fishing industry.

The catch sampling lottery is based on selecting fishing operations (hauls) for sampling through a random process (see below) and where a modified ERS-system is used for communication between the fishing vessel and a computer/software at IMR (called catch "lottery machine"). If a fishing operation is selected through the lottery, the fishermen themselves upon request takes a sample of ~15 kg/30 individuals from the catch, freeze the sample, and send to IMR, where the sample is processed (fish length, age, individual weight, gonad stage etc.) and used as input data for the stock assessment. The frozen sample taken by fishermen is usually handed over to the landing site factory which ships it to IMR.

The random selection of hauls for sampling is a two-step process, where a modified departure (DEP) message (HIA) from the ship is the first step (Table 2, Fig. 5). If the captain reports that the target species of the trip is one of the species included in the catch sampling lottery, the automatic and immediate reply to the captain through the logbook will be "participate in the catch sampling lottery for this trip". This message will trigger the second step, where immediately after each haul the catch

Table 2
New messages introduced to the logbook system for the catch sampling lottery…. The HIA and HIF, respectively are involved in the selection of trip/haul for sampling, while HIL is only used for book-keeping purposes.

Message name	Purpose	Content of message	Answer to vessel
HIA	Select what trip is included in the lottery (step 1)	Information about intended start of fishing, area and target species. Copy of DEP message	Participate for this trip
HIF	Decide if sample should be taken or not (step 2)	Information about each catch operation (or daily catch), like position, gear, effort and catch in kg per species. Content is taken from DCA-elements	Take sample, or Do not take sample
HIL	Information whether ordered sample was taken or not, and where it was delivered	Sample taken (Yes or No). If sample was taken; code for port and name of landing site factory where the sample(s) was delivered, as well as date and time of delivery	No answer

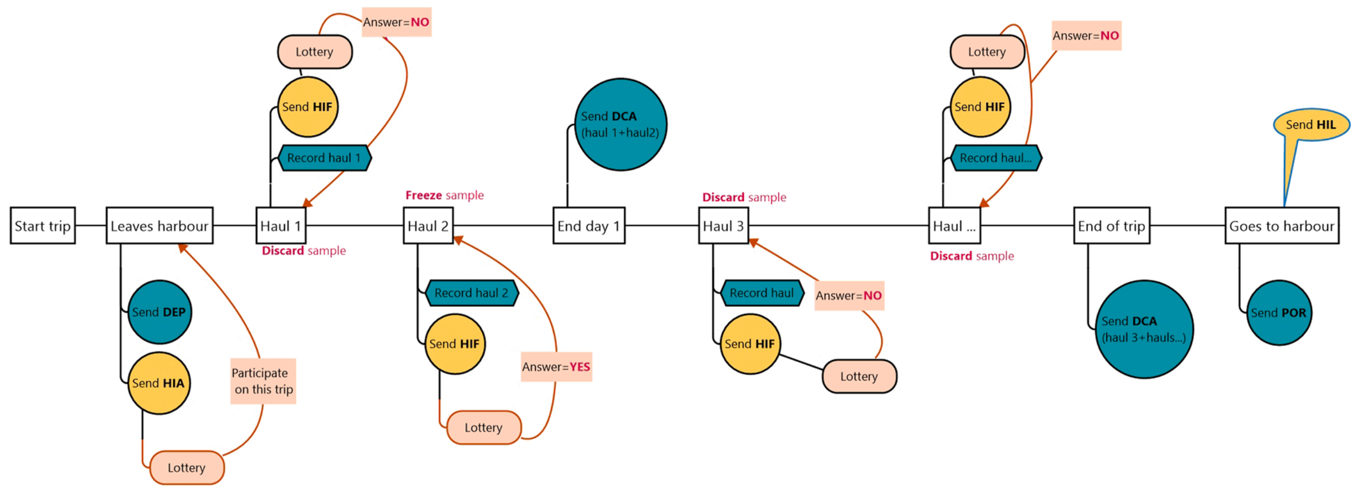

Fig. 5. Schematic figure of a vessels trip (black boxes). The official reporting to the Directorate is shown in blue-green circles, the lottery related reporting events to IMRare shown in orange circles and lottery events in pinkish colour. See text for further explanation.

composition of the haul is recorded in the logbook and a modified catch report message (HIF) is sent instantaneously to IMR's lottery computer (Table 2, Fig. 5). The computer will send a reply to the ship immediately with "yes, please take a sample" or "no, we don't need a sample this time", according to probabilistic selection procedures described in next section. If the answer is "yes" the vessel is mandated (as of 2021) to take a biological sample of fish from this haul. This stepwise procedure will be repeated for each haul for every participating vessel. Further, the vessel is obliged to report the day's catch from all hauls previously recorded that day before midnight by a DCA message. Finally, a mandatory POR message is required before the vessels end the trip and goes to harbour.

To secure that this system works as outlined above, several technical modifications of the logbook system and use of the system was implemented:

1. IMR was included in the data stream between the vessel and the NDF. This was necessary since the selection process was done at IMR and not at NDF, who is the usual receiver of logbook messages.
2. Two new message types were introduced (HIA, HIF, Table 2). These were intended only for the lottery (one for each step described above) and were routed to IMR's lottery machine. These two messages sent from the vessel to IMR generates the answer back to the vessel as described above.
3. The captain is warned by his ERS software to report the catch composition immediately after each haul, when the trip is included in the lottery. This is done through one of the new message types (HIF), while the official report sent to the Directorate at midnight usually contains all hauls that day.

A third message associated with the landing was also implemented in the ERS-system (HIL) (Table 2, Fig. 5). This is used for book-keeping purposes and is supposed to be sent to IMR to verify that the requested biological sample from a haul was taken, and after delivery inform at what port it was delivered.

The modification of the ERS-system was specified by NDF and required some programming by NDF to accommodate the new messages, as well as modifications of the software onboard each vessel conducted by the three commercial logbook providers that currently is approved for Norwegian vessels.

2.6. Selection of hauls for sampling

In principle, the decision on what hauls that should be selected for co-sampling could have been done automatically by each vessel, without any communication with the outside world. However, the modifications of the ERS system as described above makes it possible to incorporate co-sampling into a sound, transparent and flexible statistical framework where selections of hauls can be verified. The use of a central computer as "the lottery machine" ensures that selection criteria easily can be modified according to type of fishery or other parameters. The "lottery-machine" at IMR is a software-script written in R, that runs on a R-apache server, but several other applications could be used for this.

For each pelagic fishery that is covered by the catch sampling lottery we have chosen to use very simple selection rules, where the size of the catch (in kg) of the target species in a haul determine the odds of selection that haul for co-sampling. More specifically the lottery can be described as follows:

1. There is one set of lottery rules per species that is covered by the catch sample lottery, with exception for herring and sprat which in 2021 were split into two populations with different rules.
2. A vessel only participates in one lottery per trip, and this is decided by the target species in the HIA (DEP) message. So, if a vessel report that they intend to fish mackerel on a trip, but instead fishing herring, this vessel will not be included in the "herring lottery".
3. Selection is done by haul and where the catch in kg (as reported by HIF) of the target species decides the odds for being selected for sampling. This is the only variable parameter in the selection within a species-lottery. This means that a catch of 100 tonnes has twice the possibility of being selected as a 50 tonnes haul.

More specifically, we represent the size of a single haul as a fraction of the total (expected) catch that year, and where yearly Norwegian quota is used as a proxy for yearly Norwegian catch:

Haul fraction = kg of haul / kg of quota

Hence, the probability that a given haul will be selected for sampling in one draw is *Haul fraction*, and the probability for that haul being selected given that we have N draws annually will be the inclusion probability:

Inclusion probability = 1-((1 – Haul fraction) ^ N), where N is total number of draws in a year (sample size)·

E.g.; if the catch size of a single haul of herring is 100 tonnes, the annual quota is 200,000 tonnes, and we have planned for 80 biological samples (each containing ~30 individuals) to be delivered to IMR that year, then the inclusion probability for that haul will be approximately

0.04. The probabilistic sampling proportional to a relative catch makes the lottery independent of the fishing pattern and is based on the theory on unequal probability sampling, as originally described by Hansen and Hurwitz (1943) (also see Sampford, 1962, Brewer and Hanif, 1983).

We determine the desired total sample size per year (= number of draws) from historical data, as well as capacity for sample processing at IMR.

The draw by the lottery machine is equivalent to tossing a coin but where the possibility of head or tail is not 50/50 but decided by the inclusion probability described above. Since the decision to sample each fishing operation is done independently of each other, the total sample size is not strictly fixed. It is a result of a random process, with expected sample size equal to '*Number of samples per year*'. We use the "sample" function in base R.

(https://www.rdocumentation.org/packages/base/versions/3.6.0/topics/sample) for this, which give a reply YES with probability = inclusion.prob, and a NO answer = 1 – inclusion.prob.

A change in the sampling regime from a previously "expert based" sampling to a fully probabilistic sampling requires changes in the estimation procedures. In short, we now use a modified Hansen-Hurwitz estimator (Hansen and Hurwitz, 1943) in the upscaling process. A description of this is beyond the scope of the present paper, but is detailed in Fuglebakk et al., in prep.

2.7. Onboard sampling

Ideally, to maximize effective sample size and minimize bias, we would like the sample of fish to be a simple random sub-sample of individuals from the whole haul. This is clearly not possible in practice. For Norwegian spring spawning herring we ask the fishermen to take the biological sub-sample for a haul from the start of the pumping procedure (purse seine) or the top of the trawl catch to minimize handling damage of individuals. The reason is that we use the scales for age-reading for this herring-population, and scales are easily damaged or lost during handling of the fish. As mentioned earlier, the fishermen routinely take several sub-samples from each catch to provide information for auction purposes, and we encourage them to set aside one of those sub-samples for our scientific purposes to make the lottery process run in a smooth way (i.e., minimal extra work for the fishermen).

2.8. In-house processing

When a batch of frozen samples arrives IMR, usually via a transport company (see next section) they are registered and kept frozen until processing. Processing involves thawing the individual samples (10–15 kg boxes) and then recording weight, length and gonad status of each specimen or a subsample of specimen for each sample (we usually measure at least 30 individuals). In addition, otoliths or scales (for Norwegian spring spawning herring only) are collected and used for age determination under a microscope. Other biological measures and genetic samples may also be taken, depending on species (Mjanger et al., 2020).

2.9. Logistics, supporting IT-structures and information

Currently, a total of approximately 200 Norwegian vessels are targeting the pelagic species included in the catch sampling lottery and carrying electronic logbooks. Before each year we send out packaging material, instructions, and information to each of these vessels. Information about the lottery is also distributed through their organisations and through fishery newspapers and relevant webpages. It is also possible to follow the fishery and sampling at www.sildelaget.no.

When the biological samples have been processed by IMR the results (individual weights, length- and age distributions) are published on one of NDF's web-services, and each vessel can access their own samples, and see details about age- and size distribution in the sample.

IMR has also developed supporting IT systems to monitor the sampling process and handling of incoming samples from the fishing fleet.

A key factor in the logistics of the catch sampling lottery – especially the successful shipping of frozen samples to IMR, is the many fish processing plants along the Norwegian coast (~35 for pelagic sector). When a vessel has taken a sample (10–15 kg) for IMR they are supposed to freeze the sample onboard and then deliver it to a Norwegian processing plant, which collects the samples and organize transport to IMR at regular intervals.

2.10. Simulations by logbook resampling

To test the robustness of the catch sampling lottery in terms of spreading the selected hauls in time and space we simulated how the lottery would select hauls for sampling from historical logbook data. We used herring as an example, and selected all hauls catching herring, and having herring as the target species in the years 2014–2017. We then calculate the inclusion probability for each haul, having 150 samples as a target, and repeat the sampling procedure 100 times per year. Thus, we got 100 outcomes per year, each reflecting a realistic outcome of a catch sampling lottery with all vessels participating. The "simulations" were done on data prior to the start of the catch sampling lottery and were compared to the actual expert-based sampling those years.

3. Results and discussion

A major principle in the catch sampling lottery, in addition to the sampling strategy and technical parts described in material and methods is the use of co-sampling (often called self-sampling). In this case the captain and crew are responsible for taking out a sample of fish from the haul in a standardised way, packaging, freezing and delivery to a Norwegian processing plant. In addition, the captain is responsible for sending the required ERS-messages. Further, the processing plants need to have procedures to take care of the samples and make sure they are sent to IMR at regular intervals.

This division of responsibilities between industry and research institution is essential for the catch lottery sampling design to be feasible. A key advantage of the sampling approach is that we can access the fishing operations directly for sampling, through real-time catch-reports. This pretty much prohibits the use of on-board scientific observers for the selection and handling of fish from each haul. To consider application of this probabilistic sampling design to other fisheries, it is important to understand factors that make the co-sampling reliable. In this respect we would like to stress synergies with the auction system, incentives for unbiased selection, and incentives to collaborate.

For fisheries that exclusively sell their catch via an auction system that requires reliable characterization of catch composition, representative selection of fish from a catch can be considered routine for the crew, and the additional work required for sending parts of the auction-sample to IMR is therefore relatively small. Since haul selection in the lottery is a rather rare event for individual captains and crewmembers, the auction-system helps ensure that much of the process involved in providing representative sampling is familiar and easy, increasing the probability that requested samples are successfully taken and shipped. In addition, the sample of fish required by IMR is typically a very small fraction of a rather homogenous catch from selected hauls, representing a very small loss of revenue that is mostly acceptable to the fishermen. While the commercial value of the fish in the sample can in principle be compensated, this aspect is important as we can consider the incentive to provide samples from specific assortments of the catch to be negligible. Lastly, the success of the lottery sampling depends on incentives to participate in the lottery. The main incentive would ideally be that the catch lottery sampling supports improved stock assessment and advice and is recognized by the industry. Incentives are provided by IMR, NDF and providers of ERS-technology developing systems that make it easy for captains to know when samples are requested, and what exactly is expected of them. New legal requirements help ensure that technology providers implement necessary support for the lottery, and may increase nominal participation by fishing vessels, but high quality co-sampling in the fisheries requires that the involved fishermen and other in the fishing industry trust that the work they do is beneficial for them in the short or long run. In this respect it is necessary to foster a constructive dialog with the industry, allowing them to raise concerns and communicate practical challenges, and allowing research institutions to communicate the value of samples to management, and their concerns about sample quality or incomplete participation. In Norway, this extends a tradition of industry collaboration with key players in fisheries through the reference-fleet programs (Clegg and Williams, 2020; Hatlebrekke et.al, 2021).

3.1. Lottery coverage

The implementation of the technical modification of the logbook system was a gradual and voluntary process both for the logbook providers and the individual vessels. In Norway, when we started the implementation of the lottery we had three commercial logbook providers, which had to update their software and install a software update on each vessel. Such updates are performed regularly, but nevertheless requires some extra work. By 1 January 2018, when we started the lottery for the herring fishery, only one of the logbook providers had updated the software. Thus, most of the vessels did not have the possibility to participate at that time. As it was voluntary for the captain to send the new messages (HIA, HIF) it was also not all vessels or haul that did participate even though they could. The development of the participation rate (coverage) through time is shown in Fig. 6. A major reason for the increase in participation was due to the gradual implementation of the software by the two other logbook providers. Since 15 January 2021 the participation in the catch sampling lottery is not voluntary anymore, and participation rate is now close to 100%. The modifications of the ERS-system and the lottery has not caused major operational challenges during the first years, but it is important to have good routines to detect deviations in dataflow.

3.2. Lottery compliance

Coverage rate as shown in Fig. 6 only includes the first step in the process, the ordering of samples to be taken. This is mainly automated through use of computers, while the next steps (taking the sub-sample of fish, freeze and deliver it to a land facility) involves human compliance to a much higher degree. Around 200 vessels are involved in the fishery covered by the lottery. It is common to have two shifts alternating to be

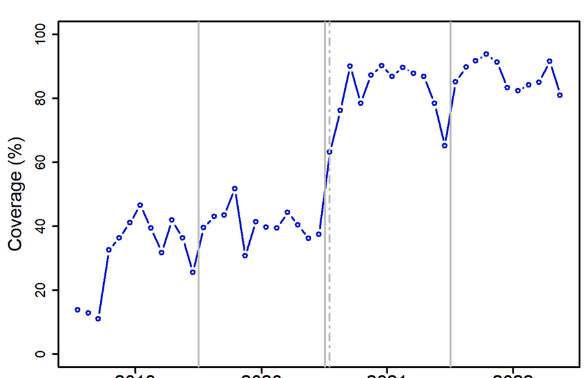

Fig. 6. Development of lottery coverage per month from January 2019 to April 2022. Lottery coverage rate is defined as the proportion of all hauls (officially reported by DCA and targeting one of the species in the lottery) that sends the required HIF message. From 15 Jan 2021 (stippled line) this was mandatory. Be aware that not all vessels had the technical possibility to send HIF before it became mandatory.

onboard over the year, so approximately 400 skippers are involved. In addition, most of the practical work related to the lottery also involves crew on deck and, hence, further several hundred people are involved in the process. It is therefore not surprising that the sampling sometimes slips. Nevertheless, a compliance rate of around 60% (Fig. 7) is lower than expected and much lower than our aim which is to have $> 80\%$ compliance. In several observer programs in the USA, with probability-based selection of trips where the vessel owners were contacted directly, they successfully obtained data from 76%–95% of the trips (Cahalan and Faunce, 2020). The numbers shown in Fig. 7 are the fraction of the samples requested through the lottery that arrives IMR. Thus, the reduced compliance is also due to several collected samples that have been frozen by the fishermen but have been misplaced or forgotten, either onboard or at the land facility ("missing samples"). The tracking of missing samples is currently time consuming and inexactly documented, and we have little reliable statistics about the magnitude of failure along each segment of the sampling and delivery process. The HIL, the message that tells whether the sample was taken or not, and to which land-facility it was delivered is of some help but not always reliable. There are many reasons for not taking a sample that is requested trough the lottery, or for not successfully delivering the sample to IMR, some of the reasons we encountered are:

- did not understand the logbook or legislation; not all captains are computer experts, and even though correct use of logbook is mandatory, errors and misunderstandings do occur
- the crew on deck did not get the message to take the sample or got it too late: a fishing operation can be very hectic, and sampling is not a prioritised task
- late reply from the lottery machine: the lottery machine only replies to a HIF, which is sent when catch quantity is recorded and the captain decides to send the HIF message to IMR. Some captains are not used to record catch quantity until they have completed the operation and know the exact quantity. This is despite that IMR only need an unofficial estimate.
- difficult to deliver the sample at the landing site: it is mandatory for the Norwegian landing facilities to accept, store and forward the samples to IMR. There are cases where this is difficult in practice due to practical constrains, lack of time or low motivation from the land side
- some vessels may have limited space for storing samples, and this in some cases even apply to the landing sites.

Overall, there are many reasons for a low compliance, but we see an improvement year by year. Many of the underlying reasons for compliance are related to motivation and information which we see as a continuous process for the whole industry.

3.3. Sampling efficiency – distribution of samples in time and space

The overall goal for developing this new sampling system is to get samples that representatively describes the commercial catch during a year. Thus, the selection of samples should reflect both the spatial and temporal distribution of the fishery. In addition, different fishing gears or vessel types may catch different components of the total catch and should also be considered in the sampling program. As an example, Fig. 8 shows all fishing operations for herring by the Norwegian fleet the first two quarters in 2021, with catches of Norwegian spring spawning herring at the northern coast of Norway in 1st quarter, and North Sea herring during the second quarter. As indicated by the maps, the lottery rules capture the dynamic in this fishery well.

The result of the simulated catch sampling lottery on herring in 2014–2017, by resampling the logbooks is presented in Fig. 9, where the fraction of each year's samples ordered within a year, quarter, and ICES statistical area (a "cell") is plotted against the fraction of yearly catch taken within the same quarter and ICES area. Thus, the reference line= 1

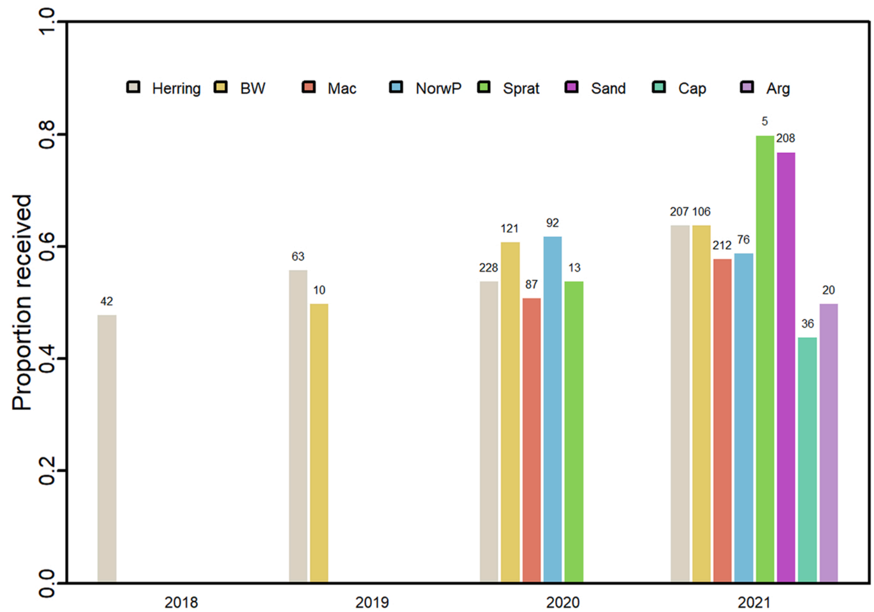

Fig. 7. Lottery compliance; fraction of the ordered samples that arrived IMR. Grouped by fishery. Numbers above each bar are the number of samples ordered per species and year. The lottery started with herring in 2018, and additional species introduced gradually (2019: blue whiting; 2020: mackerel, Norway pout, sprat; 2021: sandeels, capelin, argentines).

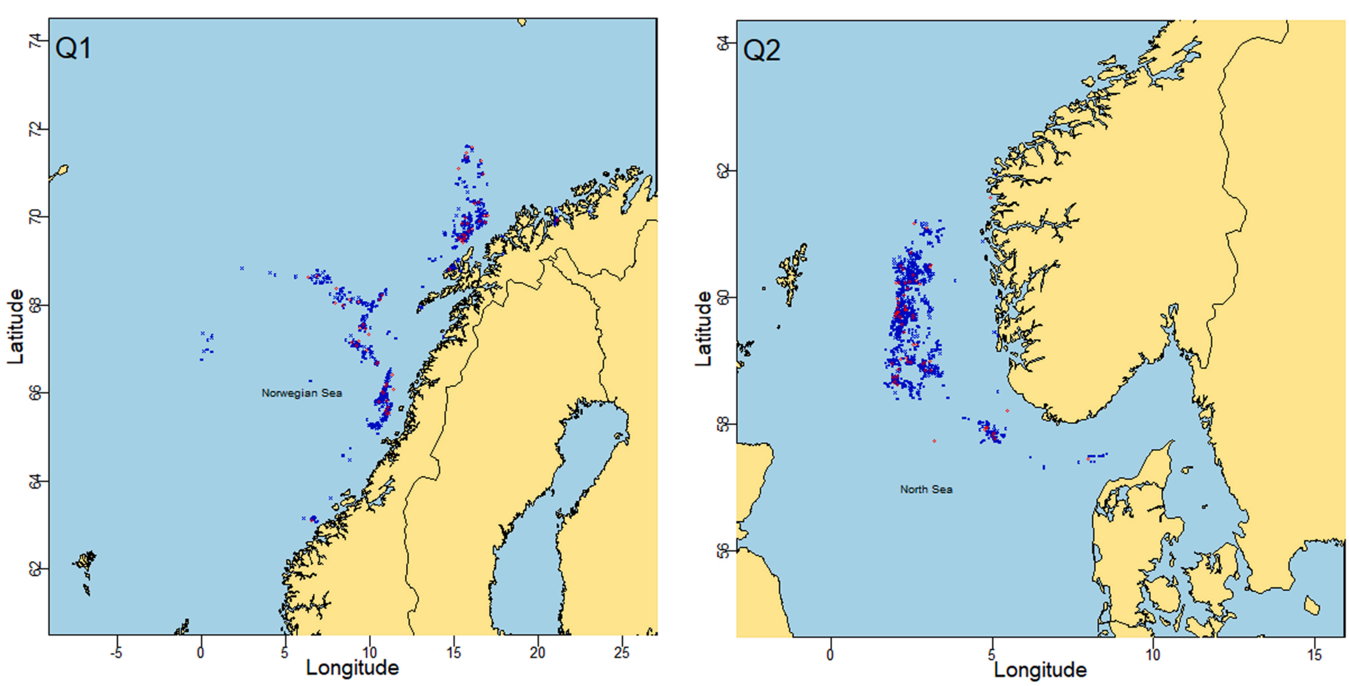

Fig. 8. Sampling of herring catches in 2021, exemplified with the catches in 1st quarter (Norwegian spring spawning herring, left panel) and 2nd quarter (North Sea herring, right panel). Single hauls of herring (>2000 kg), and where the red dots are hauls selected for sampling, and blue dots hauls not selected for sampling. Scale differs between maps.

(Fig. 9) indicates where catch in a cell and number of requested samples are proportional. Quarter and ICES areas are the major "strata" used for the sampling and upscaling in the XSAM model used in herring assessment.

Both the expert-based and lottery-based methods give reasonably good sampling coverage in time-space (Fig. 9). As an illustration, if we consider above 1.3 reference line as "oversampling" (30% more samples in cell than expected based on the total catch in this cell), and below 0.7 as "under-sampling" there are differences between actual sampling and the lottery simulation in favour of the lottery. For the actual expert-based sampling, 17% of the observations lies below the 0.7 reference line (under-sampling), and further 41% above 1.3 reference line (over-sampling), while for the simulated catch lottery sampling 16% was below 0.7% and 21% above 1.3. We also note that most of the over/under-sampling is from time-space cells with very low catch.

Further, Fig. 9 indicates that although most of the simulated values are distributed around the slope= 1 line there are exceptions. Around x-axis values of 0.12 on Fig. 9 there seem to be proportionately less samples requested than expected based on the catch proportion taken. The reason for this is that in these two "cells" (Q4 / ICES area IVa / 2014

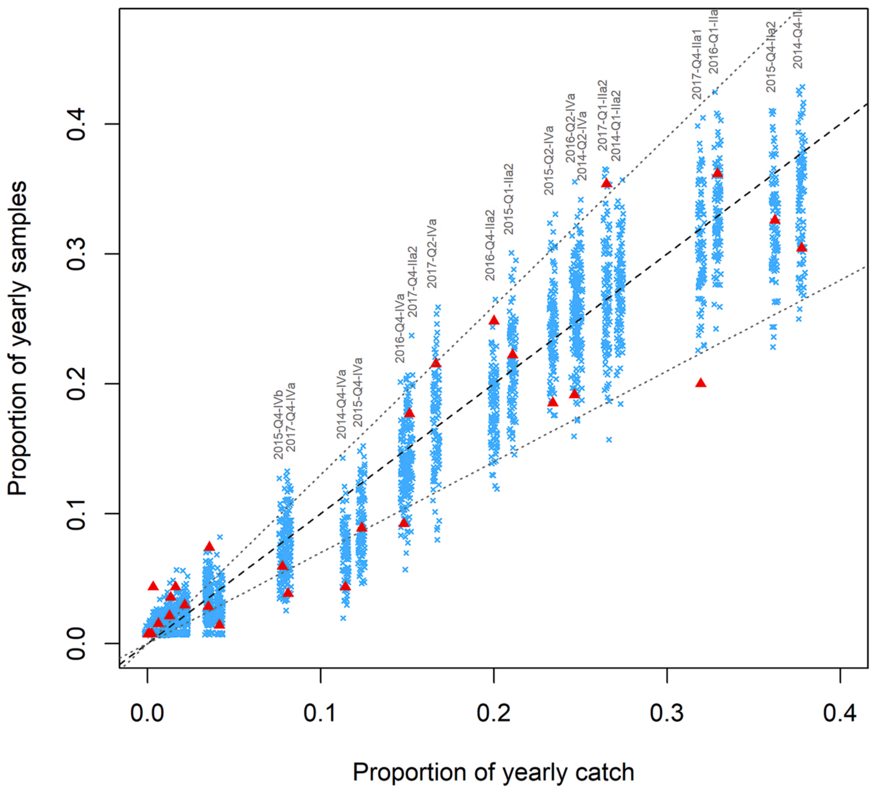

Fig. 9. Simulated catch sampling during 2014 – 2017 (blue dots) and with actual sampling those years shown by red dots. The simulation was done by resampling herring catches from official logbooks according to lottery rules. Each year was resampled 100 times to show temporal/ likely spatial spread in the sampling. Each point in the figure (both simulated and actual) gives the number of samples ordered per quarter/year and ICES area as a fraction of the total number of samples that year vs respective catch as fraction of total catch that year. Total catch is based on total catch of herring from the same logbooks. Jitter (noise) was applied to simulated values (x axis only) to increase readability. Reference lines have been included to increase readability and indicates slope = 0.7, 1 and 1.3. Each cluster of points (representing year, quarter and ICES area) are annotated, except those close to origo (due to overplotting).

and 2015) a part of the total herring catch was taken in hauls where horse mackerel was the target. Since the lottery rules for herring only includes hauls from trips with herring as the target species these hauls will not be included in the herring lottery, resulting in less samples ordered than otherwise in these “cells”. The fishermen enter the target species in the logbook at start of each trip, and this apply for the whole trip, even when their actual target may change. If such fishing behaviour is expected to be common for some fisheries, less stringent lottery rules may be used, but this must be balanced by the risk of making the lottery too complicated for the fishermen, and potentially reducing the compliance.

On average, the 100 resample simulations per year give an average of 130 (range, 94–166) samples requested per year which is lower than the 150 samples intended by the lottery rules. The reason for this is that not all hauls with herring catches enters the annual lottery, as for the example above with another target species. Further, in average, 89 unique vessels (range 64–110) are selected for sampling according to the simulations, which is a high fraction of the total number of vessels involved per year (average 208) and showing that the lottery gives high spread (low clustering) of the samples among vessels.

Nevertheless, we conclude that the lottery as expected gives a very good and robust distribution of the sampling effort in time and space relative to the catch. Moreover, the lottery provides this efficiency of sampling while ensuring that sampling probabilities are known. Known sampling probabilities are not possible with expert-based sampling, and the efficient sampling of such dynamic fisheries is not feasible with more common probabilistic techniques, such as stratification of trips or hauls by quarter and area.

3.4. Sampling bias

Low compliance in different segments of the fishery can lead to biased estimates. For instance, it could be expected that freezing capacity for collected samples can be limited among the smallest vessels and influence the compliance. On the other hand, small vessels take a smaller part of the total catch than bigger vessels, reducing the impact of potential bias. For smaller vessels it will often be impractical to request samples of fish via at-sea co-sampling since these vessels generally would lack freezer-storage capacity. If this fleet accounted for a larger portion of the total catch, this portion could be defined as a separate stratum, requiring alternative sampling strategies. A sample design that includes the whole fleet will naturally also include more crew with low motivation for cooperation, compared to a smaller group of vessels that may be selected because of their good cooperativeness, which is often the case in expert-based sampling and in observer programs, for example. It should be noted that the decision to comply with the request to take a sample – or not - has no implications for the fishermen except for the minimal extra work to take the sample and freeze it. In observer programs, compliance may be more complex, as this also may involves observation of illegal activities that potentially could bias that participation in the program. Potentially, also samples forgotten or misplaces at the landing sites (which also contribute to a lower compliance than wanted) may introduce bias. However, we expect that the loss of samples on their way to IMR for processing is mainly random and not biased. Given the gradual implementation of the catch sampling lottery and its relative short life we have little data to investigate biasing factors now and will come back to that in coming analysis.

3.5. Biological sample quality

When the samples of fish arrive frozen to IMR they will subsequently be thawed and analysed. Age, length, and weight are the most important parameters for stock assessment purposes, but also gonad status and other parameters are recorded. For Norwegian spring spawning herring we use scales for age determination, and not otoliths as for the other species. We had expected a significant improvement in scale quality from the lottery, as the samples are supposed to be taken immediately after each haul, and not from the storage tanks that would be the case for harbour sampling. The improvements in quality have so far been moderate, suggesting that some of the vessels does not take the samples early in the pumping process as prescribed, but rather take samples from the storage tank at a later stage. For other species, in contrast, like blue whiting, we have seen a significant improvement in sample quality from the lottery. When biological samples are collected from landings, which has often been the case for industrial fish, then the fish may be degraded due to handling and transport, and it can be difficult to obtain reliable data on length, weight, and gonad stadium.

3.6. Prospects

Internationally, there are several initiatives to take fisheries sampling in the direction of more rigorous probabilistic sampling designs and estimation techniques. The rigour of sampling designs has gotten increasing attention in European data-collection (STECF, 2017, section 2.2.2). Also, in the fisheries consultations between the European Union, the Faroe Islands, and Norway on the management of mackerel in the Northeast Atlantic for 2020 the parties agree that there is a need to establish a joint operational framework for regional catch data sampling. If these initiatives are brought to fruition, we will find that the sampling of different national fisheries harvesting the same stocks can be analysed in a common theoretical framework. This opens the door for internationalising the optimisation of sampling designs. That is, making sure that sampling effort is optimally distributed between different nations and fleets. For purposes of describing the total harvest across nations, this will both reduce overall cost, and increase overall precision of estimates. This has been a key motivation behind the development of the new Regional Database and Estimation System (RDBES) that is overseen by the ICES governance group WGRDBESGOV (ICES, 2021d). The RDBES may become a very important tool for this kind of international coordination, and support for probabilistic sampling has been an important design goal. The RDBES has therefore been designed to accommodate necessary design variables, such as inclusion probabilities. Data from the catch lottery have successfully been submitted with all parameters necessary for design-based estimation to the RDBES test-data calls. As a proof-of-concept, estimation of Norwegian harvest of herring has also been done from this database using catch-lottery pilot-data (ICES, 2020).

4. Conclusion

The catch sampling lottery is an automated and simple system that secures representative selection of hauls in time and space, across gear- and vessel types, given high participation from the fleet. This haul based probabilistic selection of biological samples across the fleet minimizes clustering compared to other sampling regimes based on sampling of trips, and is considered to be a the "gold standard" in surveys from a theoretical point of view. Potential criticism of the system might be that it ultimately is based on co-sampling of fish by the fishermen, and high compliance (from both fishermen and land-industry). Since fishermen report on the biological characteristics of the catches to the auction house they do have good protocols to ensure representative data by haul. The "loss" of samples due to non-compliance or loss of samples in the transport is of concern, but any bias in length- or age composition of catches due to such "non-response" is very difficult to assess, since we never will know the "truth". Nevertheless, we will continue to evaluate the catch sampling lottery in the coming years, when more data has accumulated, with particular focus on potential bias and how this may affect estimation.

CRediT authorship contribution statement

The concept is a result of a teamwork on many disciplines and all authors contributed significantly to this. The paper was mainly written by Håkon Otterå, Edvin Fuglebakk, Aril Slotte and Jon Helge Vølstad, with input from Jens Altern Wathne and Bjørn Vidar Svendsen. All authors have reviewed, commented on and finally approved the paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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