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Discards of cod (*Gadus morhua*) in the Norwegian coastal fisheries: improving past and future estimates

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Discarding can be an unknown source of biases and uncertainties in stock assessments. Discarding patterns and quantities vary so a routine methodology for estimating discards is important to give a better picture of total catches, and potentially mortality, in fisheries. Using data from the Norwegian Reference Fleet between 2012 and 2018, this study presents a revised methodology for estimating discards of cod (*Gadus morhua*) in the Norwegian coastal gillnet fisheries, which accounts for variations in discarding between vessels and uncertainties in the conversion of numbers to weight discarded. The estimated average discard rate of cod (weight of cod discarded as percentage of total weight caught) is 0.55% (95% confidence interval: 0.45–0.70%), although discard rates in southern areas were an order of magnitude higher than in northern areas. We also present an exploratory analysis of the drivers behind discarding using a random forest regression model. Spatial variations and fishing intensity were identified as the most important drivers of discarding. Results from this study suggest ways in which self-sampled data can be used to estimate discards in Norwegian coastal fisheries, and where the accuracy of future estimates can be improved when a higher resolution data collection programme is established.

Keywords: design-based estimator, discards, *Gadus morhua*, Norwegian Reference Fleet.

Introduction

Discarding of fish at sea is widely perceived as an unethical waste of resources and discarding can be a major unknown factor in stock assessments. Discarding patterns can vary greatly between different fisheries, areas, gears, and target species, but an estimation of these variations is sometimes complicated by limited data availability. Simulation studies have explored the consequences of ignoring discards in stock assessments (Dickey-Collas *et al.*, 2007; Perretti *et al.*, 2020), as well as accounting for trends in discarding over time to ensure accurate estimates of the fishery status (Rudd and Branch, 2017; Cook, 2019).

Incentives to discarding are often based on conflicting regulatory and economic factors. Examples include catch of unmarketable or undersized fish, "choke species" when a vessel has exceeded the quota of targeted marketable catch, "high-grading" when fish of lower value are discarded so that fishing for more valuable catch can continue (Rochet and Trenkel, 2005; Batsleer *et al.*, 2015; Karp *et al.*, 2019), or catch of fish that are unfit for human consumption (e.g. disease, gear damage, or scavenging). Discarding is illegal in Norway, but with some exemptions (e.g. viable fish can be released back to the sea) (Gullestad *et al.*, 2015). The scale of discarding has largely been unknown in Norwegian fisheries since the discard ban was implemented in 1987 (Gullestad *et al.*, 2015; Karp *et al.*, 2019). As a result, Norway does not currently provide discard information for cod (*Gadus morhua*) stock assessments in either northeast Arctic, Norwegian coastal (ICES, 2020a), or North Sea (ICES, 2021) stocks and therefore discards are currently assumed to be negligible.

Independent scientific observers are widely seen as the most reliable data collection method for discarding (Pérez-Roda *et al.*, 2019). However, this approach becomes unreliable under a discard ban where the presence of an observer may deter fishers from discarding (Benoît and Allard, 2009), especially if the observer must report illegal activities or if there is less than 100% observer coverage (Ewell *et al.*, 2020). To address this issue, countries are increasingly moving towards self-reported data to support or replace observer programmes (Mangi *et al.*, 2013). The Norwegian Institute of Marine Research (IMR) monitors discarding using the Norwegian Reference Fleet, an enhanced self-sampling programme in which participating vessels are paid to provide detailed information on catches and fishing activity regularly and confidentially. Data from the Norwegian Reference Fleet have previously been used to estimate bycatches of fish (Berg and Nedreaas, 2020), seabirds (Fangel *et al.*, 2015; Bærum *et al.*, 2019), and harbour porpoises (Moan *et al.*, 2020) in the coastal gillnet fisheries.

In coastal fisheries, the Norwegian Reference Fleet records a wide range of variables, which cannot be incorporated into current estimators due to the limited comparable data submitted by the rest of the vessels in the fishery. However, the Norwegian authorities have approved an extension of requirements for a daily electronic reporting system for coastal vessels, which will be gradually implemented between 2022 and

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2024, providing higher resolution data on catches and fishing activity. This creates the opportunity to explore the complex drivers of discarding in more detail, based on information recorded by the Norwegian Reference Fleet, and evaluate whether the electronic reporting system dataset can be useful for improving estimations of discarding in the future.

In this study, we present a development in the methodology for estimating discards in the Norwegian coastal gillnet fisheries between 2012 and 2018, which accounts for variations in discarding behaviour between vessels. Of particular importance to these estimations is the clustering of samples in the Norwegian Reference Fleet sampling design. The importance of clustering has been discussed in many previous studies (Aanes and Pennington, 2003; Helle and Pennington, 2004; Pennington and Helle, 2011; Clegg *et al.*, 2021), and is currently accounted for when using generalized linear models to estimate discards (Bærum *et al.*, 2019; Moan *et al.*, 2020). However, traditional applications of a design-based estimator in Norwegian fisheries do not account for variability in discarding between vessels, which may be resulting in an overestimation of precision (Lohr, 2010; Nelson, 2014). Importantly, the scale of this impact is unknown until a clustered estimator is applied. The study also presents an exploratory analysis of the drivers behind the discarding of the Norwegian Reference Fleet using a random forest regression model, and in preparation for improvements in the mandatory catch reporting system. This aims to identify important potential drivers behind discarding behaviour in the coastal fisheries and suggests a framework for a model-based approach to estimating discards once the more detailed electronic reporting system is fully operational.

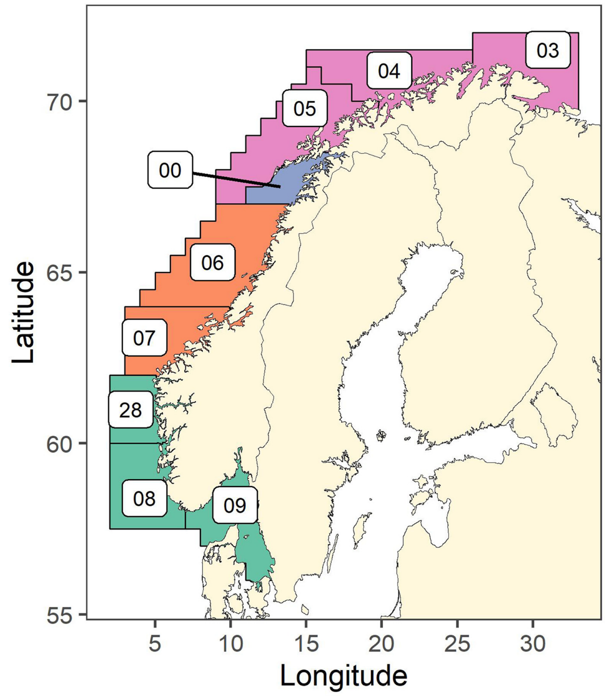

Figure 1. Map of a study area, including statistical areas defined by the Norwegian Directorate of Fisheries. Shading indicates regions used in an estimation procedure. The division between north and south management systems is at 62°N (the boundary between statistical areas 07 and 28). There was a small change in the geographic extent of areas 08 and 09 from 2018. This is accounted for in the analyses, but not shown in the maps presented.

Case study fishery

Our study focuses on Norwegian coastal gillnet fisheries, which we define as vessels under 15 m LOA (overall length) using gillnets within 12 nautical miles of the coast (Figure 1). There is an important division in ecosystems and stock distributions at 62°N, and this line subsequently represents a division in Norwegian fisheries management and regulations. Between 2012 and 2018, commercial vessels under 15 m LOA accounted for 33% of total reported cod catches by Norwegian vessels. Within the coastal fisheries, gillnets accounted for 59% of reported cod catches by commercial vessels under 15 m LOA in coastal statistical areas. Hook (longline and jigging) and Danish seine fisheries accounted for 34% and 8% of cod catches, respectively. However, the latter fisheries were excluded from the study as the Norwegian Reference Fleet programme prioritizes these fishing gears only for specific areas and target species (Clegg and Williams, 2020).

Catch of cod in the Norwegian coastal areas is a combination of northeast Arctic cod, Norwegian coastal cod, and North Sea cod. Between January and April, northeast Arctic cod migrate for annual spawning from the Barents Sea to the Norwegian coast, mainly areas 00, 05, and 06. The Norwegian coastal cod spends its whole life along the Norwegian coast, in fjords and coastal sea banks. In southern parts of Norway, North Sea cod occasionally migrate to coastal areas. The three stocks overlap to varying degrees between both seasons and areas (ICES, 2020a).

In the coastal areas of Norway, cod is for the most part caught in three gillnet fisheries: the targeted cod fishery, the mixed gadoid fishery, and the anglerfish (*Lophius piscatorius*) fishery. The targeted cod fishery targets the northeast Arctic cod on their spawning migration and concentration in the Lofoten area in the first quarter of the year. The mixed gadoid fishery operates throughout the year, and in addition to cod it targets species like saithe (*Pollachius virens*), haddock (*Melanogrammus aeglefinus*), pollack (*Pollachius pollachius*), and ling (*Molva molva*). The targeted cod and mixed gadoid fisheries use similar mesh sizes, from a minimum of 156 mm to approximately 210 mm stretched mesh. It is therefore difficult to differentiate between these two fisheries besides assumptions based on area and season, even if mesh sizes are known. The targeted anglerfish fishery, which operates throughout the year except between 1 March and 20 May between 62 and 64°N and except between 20th December and 20th May north of 64°N, uses gillnets with mesh sizes >360 mm stretched mesh. The anglerfish fishery overlaps with the mixed gadoid fishery in both space and time. The catches of cod are generally lower in the south than in the north for all gillnet fisheries. The three cod stocks have separate assessments and management plans, and the quotas are determined in annual negotiations between the relevant countries. There is insufficient information available in data collected by the Norwegian Reference Fleet to determine the stock origin of individual discards, and we therefore do not differentiate between individual stocks in this study.

Under the Marine Resources Act 2008, discarding of all species is in principle illegal, and all catches must be landed and reported. However, the "Discard Ban Package" (see Gullestad *et al.*, 2015 for detailed description) contains several exemptions and measures to ease the discard ban with aims of making it more practical to follow. First, this includes formal exemptions from the ban for fish that are alive when released, and informal exemptions for damaged fish unfit for human consumption. Second, other measures include compensation for landing of some unwanted catches, which could otherwise end up as discards; an obligation to move away from areas with high levels of illegal catches, such as undersized fish; requirements for selectivity devices in certain fishing gear; and adjustments to the quota system to include a certain amount of bycatch to reduce discarding incentives. Despite these additional measures to avoid unwanted catches and incentivize their landing if incurred, the risk of illegal discarding should still be acknowledged. The Norwegian Coast Guard enforce fishing regulations, including the discard ban, through at-sea surveillance, and inspections (on all vessels from all nations), whilst the Fisheries Directorate run both at-sea surveillance (only on Norwegian vessels) and shore-based inspections of landings and sales.

Data

The sales note database

The reporting system in the coastal gillnet fishery is centred around the landing and sale of catches. All Norwegian catches are sold through registered sales organizations, for which there were six in the study period (reduced to five since 2020). The sales organizations are responsible for correct landing statistics, deducting quota, compensating the landing of unintended catches, and reporting any suspected illegal activity. Skippers are required by law to report first-hand sale of catches (Norwegian Ministry of Trade, Industry and Fisheries, 2014), which are signed by both the seller and buyer. This sales note database therefore creates a census of all landed catches by species and weight in Norwegian waters. When a vessel returns to the port to land catches, they must submit a landing note, which includes the total catch weight of each species, statistical area of catch, and date it was landed. For each sale of fish, a sales note is generated, which reports the quantity sold.This quantity is then deducted from the associated landing note and from the vessels quota. Sales notes are not a reliable metric of fishing effort because multiple sales notes can be generated for one catch depending on the number of buyers. Sales notes therefore need to be back traced and aggregated to individual trips based on the landing date reported on the sales notes. Coastal vessels operate on day trips, meaning that one reported landing date should generally represent one day of fishing. However, we expect some variability in this assumption due to complex sales of fish from multiple trips, delayed reporting, or due to reporting errors. To evaluate whether landing date is a suitable identifier of trips, we linked the daily observations from vessels in the Norwegian Reference Fleet to the most recent landing date following each observation. This linkage determined that 75% of trips comprised one fishing day and 98% of trips comprised three fishing days or less. Comparing this to the larger variabilities in trip duration and associated catches in offshore fisheries, we concluded that landing dates are a suitable identifier of fishing trips.

The Norwegian Reference Fleet data

The participating vessels in the Norwegian Reference Fleet are selected through an open tender process and are paid for high-resolution self-sampling and recording of catches. The tender specifications (see Clegg and Williams, 2020) aim to select vessels that are representative of the wider fleet in each statistical area. If multiple vessels meet the required specifications, then the contract is awarded randomly. Each vessel has a contact person employed at IMR who follows up and regularly visits the vessels to guide methods and procedures for correct sampling protocols. The accuracy and reliability of self-sampled discard data is a recognized concern (Kraan *et al.*, 2013), given that data could be used for prosecution, and results could affect fishery access. There is an agreement between fishers, scientists, and the Norwegian authorities that data shall not be used for prosecution. To date, this agreement has not been compromised, which provides fishers with the trust to record discards with the assurance that the data shall only be used for scientific purposes. Lastly, misreporting is mitigated by a willingness to participate and honest communication between fisheries and scientists. Furthermore, a lot of effort and emphasis is invested in the Norwegian Reference Fleet programme to ensure true and correct sampling and reporting.

This study uses data from the Coastal Reference Fleet, a subdivision of the Norwegian Reference Fleet for vessels under 15 m LOA. Coastal vessels record catches and fishing activity for every calendar day they are active, which we refer to in this study as a fishing operation. This includes retained catches (recorded as weight) and discards (recorded as numbers) by species. Fishers do not record whether discards are legal (e.g. viable or damaged) or illegal. To target a wider range of species, skippers often have gillnets with different specifications (e.g. mesh size, material) set in different locations. To account for this behaviour, the sampling guidelines specify that if groups of gillnets differ significantly in specifications and geographic locations, then these should be recorded as separate fishing operations. In addition to daily reporting of catches and discards, a representative sample of 20 fish per species are taken each week from each of the retained and discarded portions of the catches for length measurements.

Statistical analyses

Data handling and statistical analyses were done in R (version 4.1.0; R Core Team, 2021).

Defining the study fisheries in datasets

The sales note database only classifies fishing gears by broad groups. This makes it possible to distinguish between fisheries using different gear types, such as gillnets, hooks, or trawls, but there is no detailed information on the specifications of these gears, which for gillnet fisheries would be mesh size, materials, soaking time, and number of nets used. Therefore, excluding non-gillnet fisheries from this study must be based on the limited information available.

The pelagic gillnet fisheries have a low bycatch rate for cod relative to the demersal gillnet fisheries, where cod is more likely to encounter the fishing gear. We therefore excluded pelagic fisheries from the study by removing trips in which a pelagic species contributed the largest proportion to reported catch weight.

Recreational fishing with gillnets is popular along the Norwegian coast. Whilst there is no obligation to report recreational catches, any catches that are sold (limited to

Table 1. Number of sampled vessels and trips with detailed information on fishing activity from the Norwegian Reference Fleet (NRF) compared to the whole Norwegian fleet within coastal gillnet fisheries (vessels < 15 m LOA) in the period 2012–2018.

Year	Number of vessels			Number of trips		
	NRF	Whole fleet	% Sampled	NRF	Whole fleet	% Sampled
2012	20	2 273	0.9	729	62 917	1.2
2013	16	2 054	0.8	939	57 458	1.6
2014	16	1 942	0.8	908	58 217	1.6
2015	20	1 943	1.0	857	51 901	1.7
2016	22	1 965	1.1	1 156	53 465	2.2
2017	20	1 992	1.0	1 028	52 601	2.0
2018	20	2 081	1.0	1 045	56 903	1.8
All years	43	3 497	1.2	6 662	393 462	1.7

Number of vessels across all years (last row) is not the sum of individual years because vessels are active across multiple years.

50000 NOK per year) must be reported using a sales note. As this study is limited to commercial fisheries, we excluded recreational catches from the study by removing sales notes without a documented vessel length, which was deemed the best identifier of recreational vessels.

Estimating total discards

To estimate total discards in the coastal gillnet fisheries, we first needed to standardize the sample (Norwegian Reference Fleet) and the population (sales note database) datasets. We therefore aggregated all fishing operations by Norwegian Reference Fleet vessels within the study to summarize total discards per trip. Fourteen fishing days could not be associated with a landing date, due to data recording errors, so we assumed these were 1-d trips. For the same reason, we also assumed that trips comprising more than 5 fishing days were erroneous, resulting in the removal of 31 trips consisting of 273 fishing days. After this initial cleaning step, we had a dataset containing 6662 trips from 43 Norwegian Reference Fleet vessels over the study period (Table 1).

The estimation methodology is based on Berg and Nedreaas (2020), who used a stratified unit estimator (Lohr, 2010). However, the estimator was redefined to reflect the clustered sampling routine of the Norwegian Reference Fleet, which defines vessels as the primary sampling unit from which fishing operations are repeatedly sampled and provide a more accurate estimate of variance. This was defined as a ratio estimator based on the assumption that total discards are positively correlated with the number of trips for individual vessels (Lohr, 2010; $r\ (41) = 0.78$, $p < 0.001$). For each sample stratum [defined as a combination of statistical area (Figure 1), annual quarter, and year; $n = 258$], the total number of discarded cod $\hat{Y}$ was estimated by

$$\hat{Y} = M_0\, \frac{\sum_{i=1}^{n} \sum_{j=1}^{m_i} M_i \frac{y_{ij}}{m_i}}{\sum_{i=1}^{n} M_i}, \tag{1}$$

where for trip j by vessel i, y is the number of cod discarded; m is the number of trips sampled; n is the number of vessels sampled; M_i is the total number of trips by sampled vessel i; and M_0 is the total number of trips in the population. This estimator assumes that sampled vessels are a simple random selection from the wider fishing fleet. Note that because coastal vessels record discards for all trips (i.e. $m_i = M_i$), Equation (1) simplifies down to the stratified unit estimator used by Berg and Nedreaas (2020).

Strata with fewer than two sampled trips were defined as unsampled ($n = 51$). To estimate discards in unsampled strata, observations were borrowed from adjacent statistical areas in the same period, by assuming that discarding behaviour is more similar across statistical areas in the study than across quarters and years. For each unsampled stratum, the areas included were incrementally expanded for imputation, whilst keeping fixed the annual quarter and year, until there were sufficient samples for estimating discards. This meant imputing based on the mean across all areas in (1) the region (Figure 1), then (2) management system (north or south of 62°N latitude), and, finally, (3) all areas in the study.

Estimating the discard rate

The discard rate of cod, as the percentage of total catch of cod in weight, is defined as

$$Discard\ rate\ (\%) = 100 \times \left(\frac{discards}{landings + discards}\right). \tag{2}$$

Because information on total landed cod is only available in weight, the total weight of discarded cod needed to be estimated. This is only possible by conversion, as the Norwegian Reference Fleet do not record weights of individual fish. For each year, annual quarter, and management system (north or south of 62°N), we produced a length–weight relationship (Equation 3) by using data from all fisheries-dependent and fisheries-independent sampling programmes in the study fishery for which IMR has access (summary of data sources available in Appendix A). Parameters a and b in the length–weight relationship were estimated using non-linear least-squares.

$$W = aL^b, \tag{3}$$

where W and L are weight (kg), and length (cm), respectively. We averaged these estimated weights per stratum then multiplied values by the estimated number (Equation 1) to produce an estimate of total weight of cod discarded and subsequently estimated discard rate using Equation (2).

Variance in discard estimates

We estimated the 95% confidence interval (CI) of discard estimates using the bootstrapping method (Efron and Tibshirani, 1994). We present a refined procedure for estimating variance in total catches, which reflects the clustered sampling design of the Norwegian Reference Fleet by accounting for the variation between vessels. For each bootstrap replicate, vessels were resampled in each year, then estimated discards using Equation (1) and the defined imputation procedure. As sampling of coastal vessels follows a one-stage cluster sampling design (i.e. all trips are sampled for each vessel), total discards per vessel were known, so trips were not resampled.

Table 2. Explanatory variables included in the random forest model to predict variations in discarding of cod in the Norwegian coastal gillnet fisheries.

Variable	Type	Description
Year (abc)	Factor	2012–2018
Month (abc)	Factor	Calendar month
Quarter (abc)	Factor	Calendar quarter
Vessel (b)	Factor	Unique vessel identifier (call signal)
Latitude (abc)	Continuous	Decimal degrees north
Longitude (abc)	Continuous	Decimal degrees east
Depth (ab)	Integer	Maximum fishing depth (nearest metre)
Number of nets (bc)	Integer	Total number of nets
Mesh size (bc)	Factor	Five categories: <140, 140–180, 181–260, >260 mm, and mixed
Soak time (b)	Integer	Soak time of nets (hours)
Statistical area (c)	Factor	Management area defined by the Norwegian Directorate of Fisheries (Figure 1)
Management system (c)	Factor	Division between two fisheries management systems (north or south of 62°N latitude)
Landed weight of cod (b)	Continuous	Total weight of retained cod (tonnes)
Target species (b)	Factor	Species contributing most to total retained catch weight: cod, anglerfish, other
Cod price (b)	Continuous	Average weekly prices of cod (NOK/kg) in each statistical area; prices included sales of fresh fish sold either whole, gutted, or headed and gutted; all prices standardized to the 2018 consumer price index
Random variable 1	Continuous	Random values from a normal distribution with mean = 0 and standard deviation = 1
Random variable 2	Continuous	Random values from a uniform distribution between 0 and 1
Random variable 3	Factor	Random factor with five levels
Random variable 4	Factor	Random factor with 50 levels

Random variables are included to detect bias in importance in the random forest model. Letters in parentheses refer to grouping of explanatory variables: a = species distribution, b = fishing behaviour, and c = management.

We accounted for uncertainty in the conversion of numbers discarded to biomass in the selection of fishing operations for both length measurements and the length–weight relationship. First, we resampled with replacement the discarded fish sampled weekly for length measurements by each vessel. Second, to account for the variation in the length–weight relationship, we performed a parametric bootstrap of model parameters using the fitted model.

To evaluate the importance of accounting for additional variance in the conversion from number to weight, we compared the coefficient of variation of estimated discard rates for individual strata before and after including the additional sources of variation.

Modelling important drivers of discards

To identify important potential drivers of discarding in the coastal cod fishery, we fitted a random forest regression model (Breiman, 2001). We chose a random forest model over a generalized linear or additive modelling (GLM/GAM) framework due to the minimal assumptions needed to understand the complex reasons for discarding, allowing for a more explorative analysis. Random forests require no assumption of relationships between discarding and the explanatory variables, nor interactions between explanatory variables. Furthermore, the inclusion of multiple potentially uninfluential and collinear variables has little impact on model fit (Cutler *et al.*, 2007).

Relationships between the response and the explanatory variables in a GLM or GAM are typically evaluated using the strength and statistical significance of the relationship, which are strongly influenced by prior assumptions and decisions made in the model selection procedure (Burnham and Anderson, 2002). Contrastingly, random forests produce a useful measure of variable importance, which helps to identify the most important explanatory variables. We calculated variable importance using the permutation method (Breiman, 2001). After calculating the prediction accuracy of the fitted model, each variable is randomly permuted in turn and the predictions re-calculated. The importance is calculated as the mean decrease in model accuracy, scaled by the standard error. If an explanatory variable is strongly associated with discards of cod, then model accuracy will decrease when the values are permuted.

For the modelling of important drivers of discards, we used observations of total number of discarded cod for individual fishing operations by the Norwegian Reference Fleet, which allows us to include more detailed information on gear specifications and geographic location. The full list of explanatory variables used in the model is shown in Table 2. These variables were selected from the available data to capture the complex interaction of factors affecting discarding behaviour based on species distribution, fishing behaviour, and management regulations. Some studies have noted possible downsizing of importance for strongly correlated variables (Boulesteix *et al.*, 2012). In this study, only latitude and longitude had a correlation > 0.7 amongst the continuous variables (Supplementary Figure S2). Correlation is also expected between categorical descriptions of spatial and temporal variations in the model (e.g. month and quarter; statistical area and management system). We decided to keep these variables in the model as relative importance will still be interpretable and inform future predictive models. Where two spatial or temporal variables are important, then devoted methods are available (Yan *et al.*, 2021), and the decision of which variable to use will also be driven by data availability. Geographic coordinates were missing for 35 observations, which were imputed with the centroid of the reported statistical location (a subdivision of statistical area typically spanning one degree of longitude and half a degree of latitude). Fourteen observations with missing soak time values were removed from the study as soak times vary too much to assume an imputed value. Fishing depth was imputed for 137 observations with the recorded depth from the geographically nearest observation.

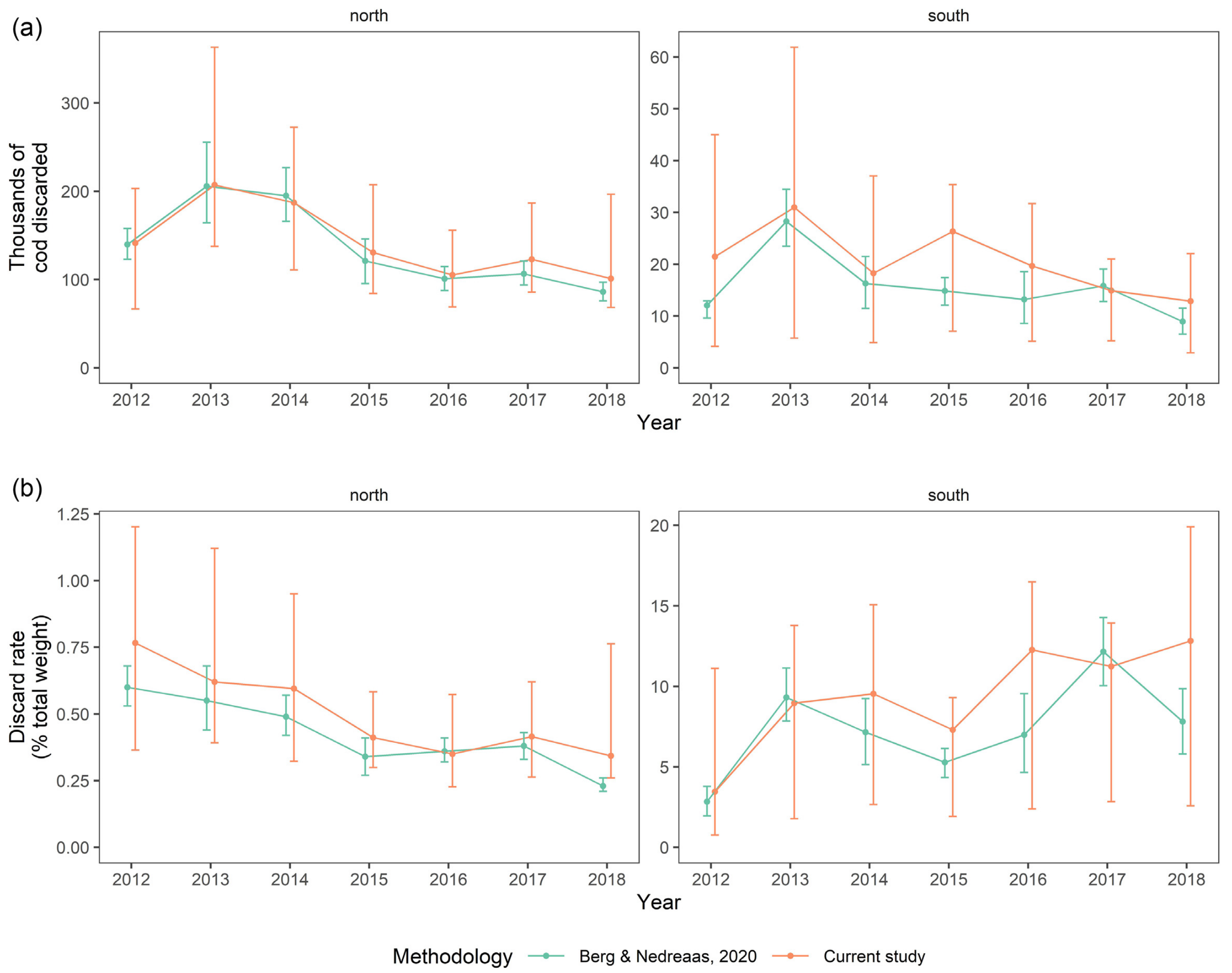

Figure 2. Annual estimated discards of cod in Norwegian coastal gillnet fisheries expressed as (a) total number discarded and (b) discard rate. Panels separate discards north and south of 62°N (note different y-axes). Previous estimates by Berg & Nedreaas (2020) are included for comparison.

All imputed values were from within 4 km, and 23 were from an observation with the same geographical coordinates. Weekly prices per statistical area were deemed erroneous if they were outside 1.5 times the interquartile range of all prices and were imputed with the most recent price prior to it in that statistical area. Of the 2938 weekly price values, 29 were imputed from the previous week and 8 were imputed from between 2–4 weeks prior. This data cleaning procedure resulted in a dataset containing 10090 fishing operations.

Subsamples of fish length measurements are available in the dataset, but this information could not be included in the random forest model because length sampling of catches is only done on a subset of fishing days with a maximum of 20 discarded and 20 landed individuals each week, meaning that data are only available for a small fraction of fishing operations. Including length as an additional variable must be done separately on the limited dataset and was therefore out of the scope of this study.

To mitigate bias in the random forest model arising from numeric variables on different scales, we standardized all numeric variables by subtracting the mean and dividing by 2 *SD* (Gelman, 2008). We also included two continuous variables with randomly generated values from a normal distribution with mean = 0 and *SD* = 1, and two random categorical variables with 5 and 50 levels, respectively. These four random variables will help to identify if the permutation method of evaluating variable importance is biased towards numeric variables, or categorical variables with a differing number of levels (Ono *et al.*, 2016).

Random forests were fitted using the *ranger* package (Wright and Ziegler, 2017). The optimal random forest model was defined by the lowest number of variables randomly sampled at each node (*mtry*) and lowest number of trees *(ntree)* needed to minimize the mean square error of predictions. The tuning procedure resulted in the final model using parameters *mtry* = 4 and *ntree* = 5000 (Supplementary Figure S1). To understand the uncertainty in variable importance, we estimated importance from 50 replicate random forest models fitted to the original dataset but with different random seeds. We explored the relationship between numbers of discarded and explanatory variables using partial dependence plots (R package: *pdp* version 0.7.0; Greenwell, 2017), selecting specific interactions for visualization depending on the outcome of the importance estimation.

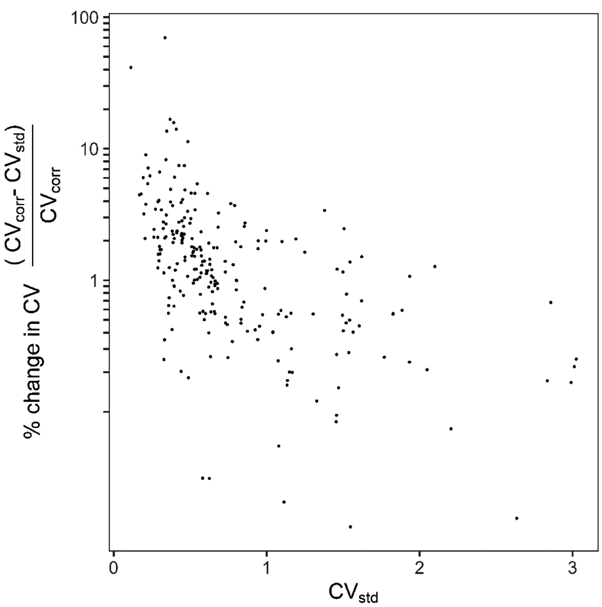

Figure 3. Percent change in coefficient of variation (*C.V.*) of discard rate estimates in individual strata ($n = 252$) when uncertainties in the numbers-to-weight conversion are included ($C.V._{corr}$), compared to when they are ignored ($C.V._{std}$). Strata are defined as year, statistical area (Figure 1), and calendar quarter.

Results

Discard estimates

In the coastal gillnet fisheries during the period 2012–2018, cod were discarded in half (49%) of the observed fishing trips. Of those trips in which discarding occurred, 99% of discarding events involved 20 individuals or fewer. An estimated number of 1139198 (95% *CI*: 975529–1373548) cod were discarded in the study period across the entire Norwegian coast with an average discard rate (Equation 2) of 0.55% (95% *CI*: 0.45–0.70%). Whilst this discard rate is low, there are still important spatial and temporal variabilities to consider.

There was an overall weak decreasing trend in total numbers of discarded cod throughout the study period in both north and south management systems (Figure 2a). Trends in discard rates between north and south were dissimilar. North of 62°N, where 88% of all fishing activity occurred, discard rates averaged less than one cod per trip for most years (Figure 2b). On the other hand, estimated discard rates were an order of magnitude higher in southern areas and showed an overall increasing trend across years.

The revised methodology produces estimates with lower precision than previously reported by Berg & Nedreaas (2020). This increased uncertainty arises from accounting for variations in discarding across vessels and the conversion from total number of cod discarded (Figure 2a) to total weight to describe the discard rate (Figure 2b). The redefined assumptions for excluding fisheries and defining a fishing trip affected estimates in areas south of 62°N much more than in the north. However, the trends remain very similar and previous estimates fall almost entirely into the range of uncertainty described in the revised methodology.

Accounting for additional sources of variance in the conversion from numbers to weight can result in large losses in precision [i.e. increase in coefficient of variation (C.V.); Figure 3]. There are many strata for which ignoring the additional sources of variance results in an over-optimistic picture of precision. In these strata, including the additional variance causes *C.V.* to increase by as much as 70%. However, if *C.V.* was already high before accounting for the additional variance, then their inclusion has negligible impacts on precision (increase in *C.V.* < 1%).

The largest numbers of estimated discards were in the seasonal targeted spawning migration fishery on cod, which is confined to the Lofoten area of Norway (statistical areas 00, 04, and 05) in the first annual quarter (Figure 4a). However, when expressed as a discard rate (Equation 3; Figure 4b), values are low in these areas. In southern areas, particularly in Skagerrak and Kattegat (statistical area 09), and adjacent North Sea (statistical area 08), discard rates are higher.

Drivers of discarding

The random forest model explained about half (44%) of the variance in discarding of cod in the coastal gillnet fisheries using the 16 explanatory variables available. Of highest importance was the retained weight of cod in each fishing operation (Figure 5), alongside the soak time of nets. Fine-scale spatial variations were of higher importance than statistical area and management systems which are on coarser scales. Of the variables explaining temporal variations, the random forest model found that price and month were most important, with annual and quarterly variations being relatively less important. However, some temporal trends may also be related to the landed weight of cod, which describes the large increases in catches of cod in the seasonal targeted cod fishery. Negligible importance of random variables suggested that these results can be interpreted without the risk of confounding biases from the permutation method.

When no cod were landed, an average of 1.2 (95% *CI*: 0.0–4.6) cod were discarded per trip. As landed and reported catches of cod increased, discards increased proportionally, until reaching a saturation point at approximately 12000 kg of landed cod, above which discards did not increase (Figure 6). A similar trend occurred with soak time of nets, where discarding did not increase above a soak time of ~100 h. However, these interpretations should consider the reduced number of data points at the extreme values, particularly for soak time.

Discarding increased as the price of cod decreased and quantities landed increased (Figure 7a). However, there are fewer observations with large quantities of landed cod, so caution is advised when interpreting trends. When there were no cod landed, discarding was not dependent on price, but was highly variable (Figure 7b). This variability can be explained by the variations in cod catches that were discarded and may indicate either over-quota discarding or unwanted catches in the non-target fisheries.

Plotting fine-scale spatial variations (Figure 8) reveals that discarding is relatively homogeneous within statistical areas, except for the Lofoten area (statistical areas 00, 04, and 05), where discarding is more variable (Figure 8a) and uncertain (Figure 8b). However, uncertainty is highest in mid Norway in statistical areas 06 and 07.

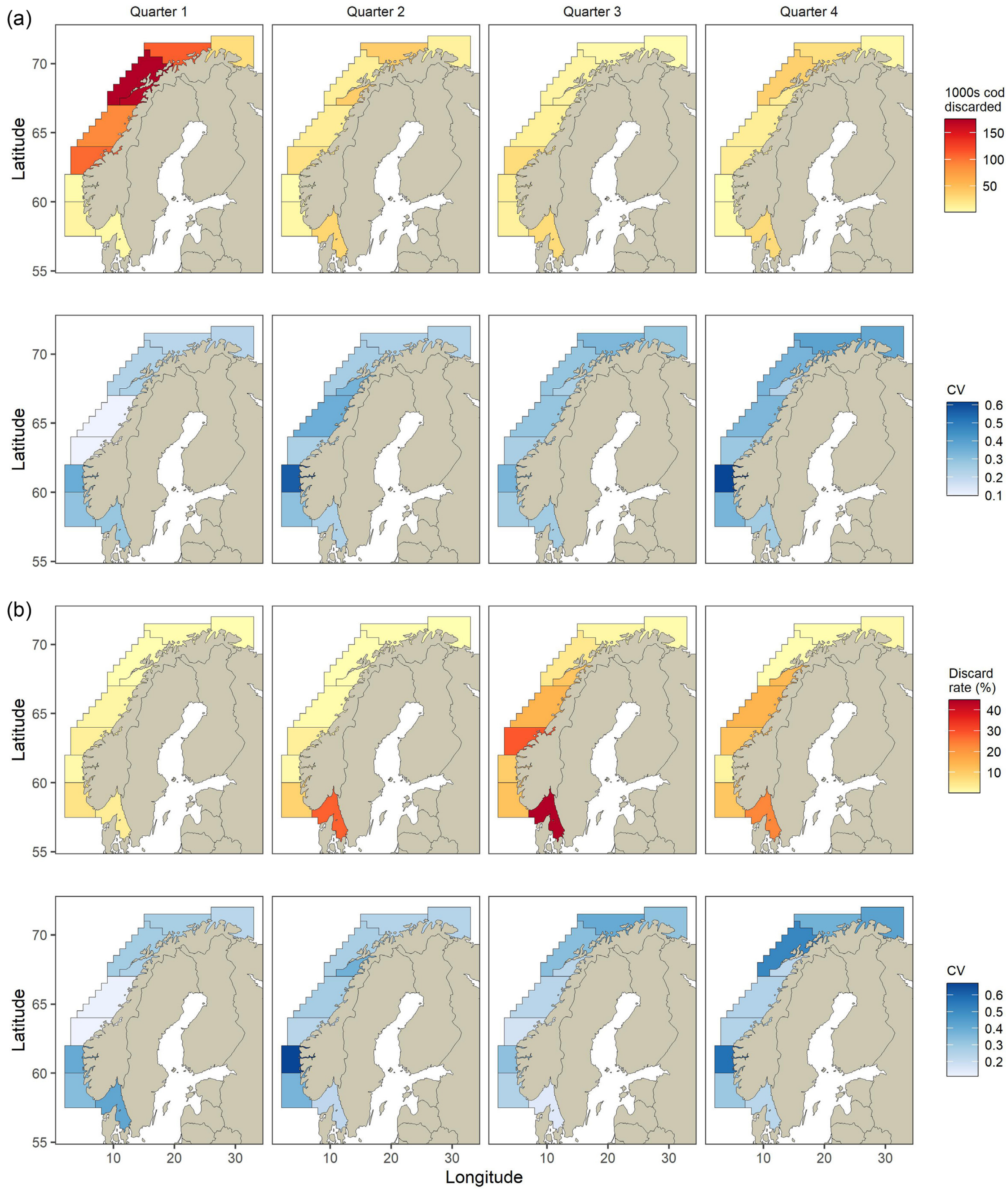

Figure 4. Spatial and temporal variations in discards of cod in Norwegian coastal gillnet fisheries expressed as (a) total numbers discarded and (b) discard rate, with associated uncertainty (coefficient of variation).

Discussion

Earlier estimates of discards in Norwegian fisheries (McBride and Fotland, 1996; Dingsør, 2001; Valdemarsen and Nakken, 2002; Nedreaas *et al.*, 2015) were based on inference or assumptions due to a lack of direct scientific sampling of discards. Berg and Nedreaas (2020) presented a generalized approach to estimating discards in the coastal gillnet fisheries using direct observations by the Norwegian Reference Fleet. This study developed the methodology further by accounting for both the clustered nature of sampling by the Norwegian Reference Fleet and additional uncertainties in the conversion from estimated numbers to weights. The stratifi-

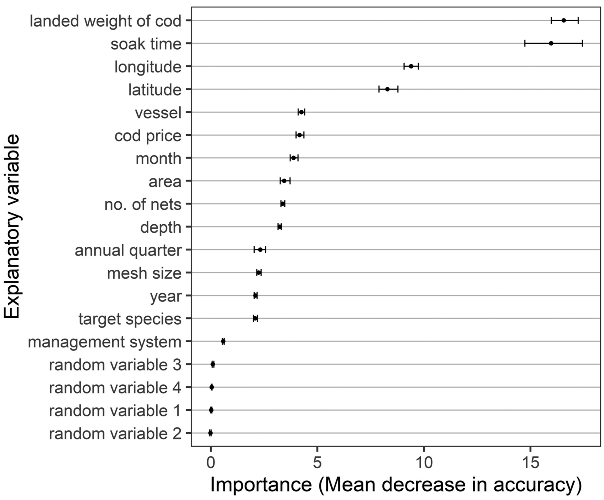

Figure 5. Importance of explanatory variables from a random forest model predicting discarded cod in the Norwegian coastal gillnet fisheries between 2012 and 2018. Importance is defined as the mean decrease in model accuracy when the values of each variable are randomly permuted. If a variable is important, then model accuracy will decrease when values are randomly permuted because the association with discarding is destroyed. Estimates are mean and range of importance measures from 50 replicate random forests fitted to the original dataset with different random seeds.

cation system is limited by the spatial information in sales notes, and the sampling effort limits a finer temporal scale of stratification. A ratio estimator based on soaking time of nets is unavailable, again due to a lack of information in sales notes, and using the landed weight of cod is unsuitable due to a non-linear relationship between landed and discarded cod (Figure 6; see also Rochet and Trenkel, 2005; Lohr, 2010). Using a different assumption to remove recreational and pelagic fisheries from the sampling frame has also resulted in a slight change in the annual trend. Whilst this change is quantifiable, any interpretations are masked by large, overlapping uncertainties. The exploratory modelling presented here has improved our understanding of the potential drivers of discarding. Strong fine-scale spatial variations and a dependence on fishing intensity (total catches of cod and soaking time) are the most important drivers of discarding, but we found that discarding was also explained by a complex combination of all other variables included in the model.

We included simple descriptors of fisheries (e.g. mesh size, target species) in the random forest model to suggest future improvements to the stratification of the design-based estimator. However, the model suggests that discarding variations across fisheries cannot be described by a simple categorization. Instead, the model suggests that different variables may be characterizing each fishery. For example, the landed weight of cod explains the degree to which cod is targeted in the mixed gadoid fishery, soak time helps to identify anglerfish nets that have longer soaking times, and an interaction of fine-scale spatial and temporal variables may pinpoint the targeted cod fishery that is isolated to the Lofoten area (statistical areas 00, 04, and 05) between January and April. These complex interactions should be an important consideration for future model-based estimators to ensure that all fisheries are well-described in the model.

Under the Norwegian discard ban, fishers are legally allowed to discard viable fish. It has also become a practice for the enforcement agencies not to prosecute discarding of damaged fish that are unfit for human consumption (Gullestad *et al.*, 2015). These exemptions must be considered when interpreting results, as discarding is used to correct catch data in stock assessments, which assumes 100% mortality. However, the survivability of discards in gillnet fisheries is dependent on a complex interaction of factors, including species, gear specifications, soaking time, catch size and composition, air exposure, and handling (Davis, 2002; Veldhuizen *et al.*, 2018; Sogn-Grundvåg *et al.*, 2022). Considering that coastal fisheries can have shorter soaking and handling times, the assumption of 100% mortality is uncertain. Nevertheless, there are no survival studies to date that can be applied to discarded cod in coastal gillnet fisheries (ICES, 2020b), and the Norwegian Reference Fleet do not record the viability of discarded fish, or even the reason for discarding. However, even if 100% discard mortality is assumed, the small estimated average

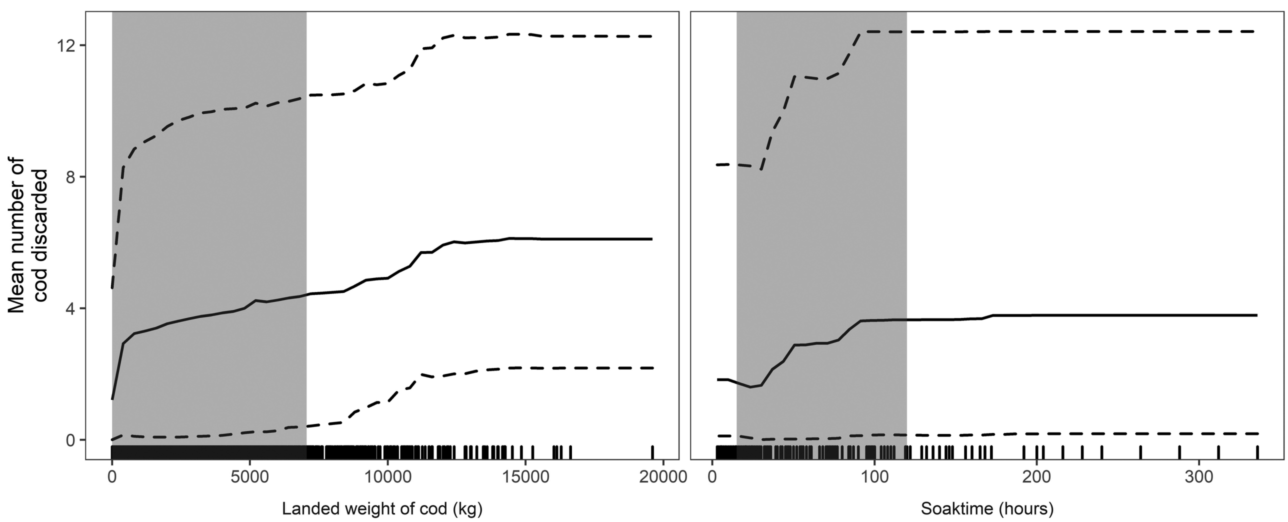

Figure 6. Partial dependence plots of selected important variables for predicting discards of cod in the Norwegian coastal gillnet fisheries between 2012 and 2018. Plots show the marginal effect of each variable on cod discards (solid line = mean; dashed lines = 95% confidence interval). Tick marks along *x*-axes show the distribution of observations and the grey-shaded area shows where 95% of all observations lie.

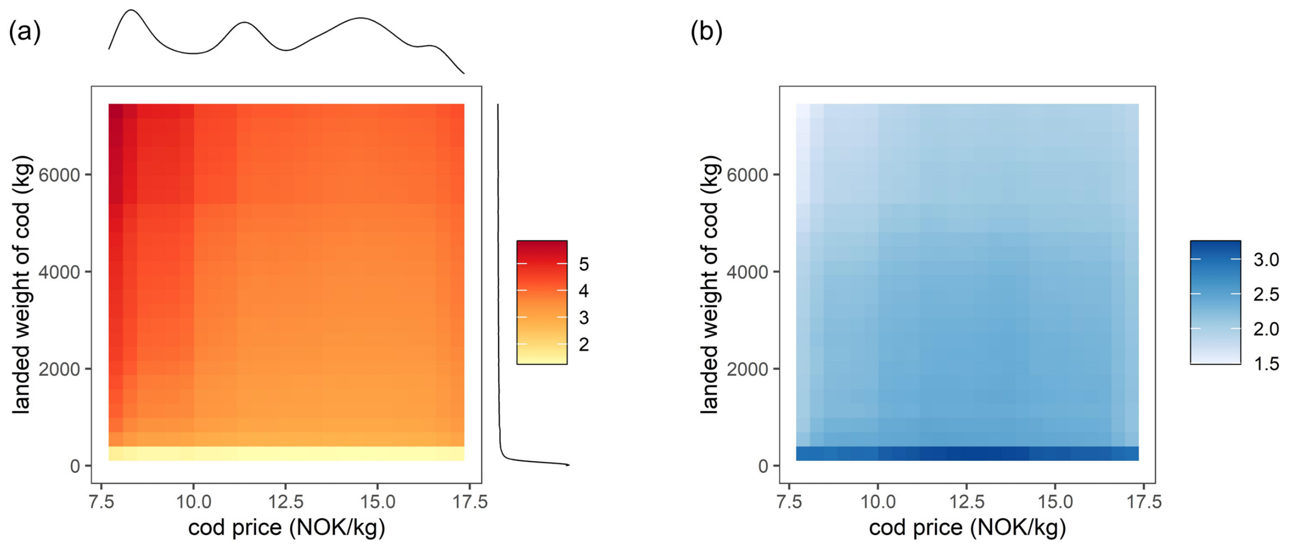

Figure 7. Interaction between cod price and landed weight of cod on estimated mean number of cod discarded per fishing day between 2012 and 2018. Data limited to 95% range of observations. (a) Estimated number of discarded cod, and (b) uncertainty (standardized 95% confidence interval). Marginal density plots in (a) show the distribution of data for each of the explanatory variables.

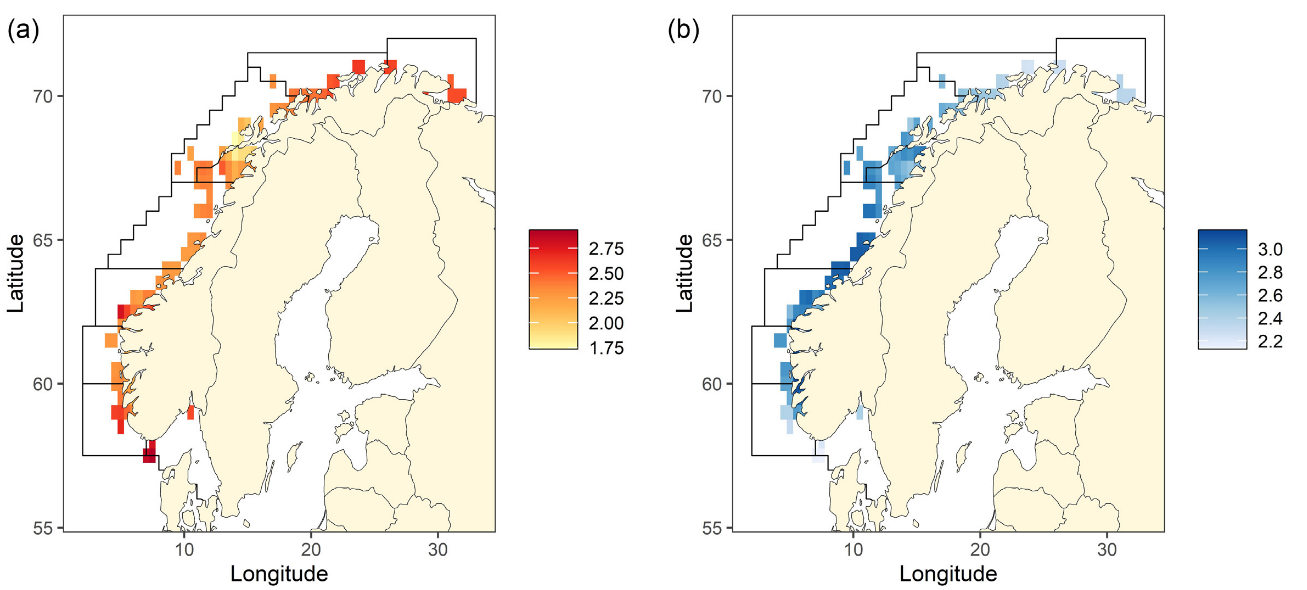

Figure 8. Influence of spatial variation on estimated mean number of cod discarded per fishing day between 2012 and 2018. (a) Estimated number; (b) uncertainty (standardized 95% confidence interval). Partial dependence of latitude and longitude estimated for a 0.5 × 0.5° grid of observed fishing activity.

discard rate of 0.55% (95% *CI*: 0.45–0.70%) throughout the study period for this fishery will fall within the general uncertainties in stock assessments for cod and are likely negligible.

There were large differences in estimated discard rates between the areas north and south of 62°N. These differences can likely be explained by the differences in regulations, fishing pattern, and behaviour between the northern and southern parts of the Norwegian coast. In northern areas, there is a much larger fishery for cod in general (88% of landed cod). This results in large total catches and in the targeted fishery for spawning northeast Arctic cod, catches almost exclusively consisting of larger, mature cod. This large targeting might explain why the estimated numbers of discarded cod are the highest in these areas, but with correspondingly low discard rates. In southern areas, the cod stocks are smaller, which results in cod being targeted to a lesser extent, and probably also consists of smaller individuals on average (Berg and Nedreaas, 2020). This results in higher estimated discard rates for cod, even if the estimated numbers of discarded cod are lower. Interpreting the results of discards in terms of consequences for the three cod stocks being caught in the coastal gillnet fishery is complex, and due to data limitations, it has not been investigated further in this study.

This study found that discarding was driven by a complex combination of factors, most important of which were total catches of cod, soak time, and fine-scale spatial variations. However, all other variables included, such as sampling units (vessels) and prices, were of importance to some degree.

Whilst we have demonstrated the effectiveness of these data for describing variations in discarding, their usefulness for predicting discards in the wider fishery is limited by the lack of complementary data in the mandatory reporting system for all vessels. Historical estimates are limited in their stratification by the available data. For example, monthly variations in discarding were important (Figure 5), but there are too few observations to estimate monthly discard rates using a design-based approach. A similar issue occurs with fine-scale spatial information, as the large scale of statistical areas was not very important for explaining variations if latitude and longitude were included in the model. The Norwegian Reference Fleet report the latitude and longitude of fishing operations, which allows for spatial modelling (Yan *et al.*, 2021), as well as attaching additional information that may explain discarding such as depth or habitat. However, the predictive capability of spatial modelling is limited if comparable data are not available for all fishing operations in the fishery.

Fish length is recognized as an important driver of discarding where minimum landing sizes are enforced (Batsleer *et al.*, 2015; Rochet and Trenkel, 2005; Borges *et al.*, 2006). Even though discarding in coastal gillnet fisheries is very low on average, there is still a risk that discarding is size-based in terms of high-grading or undersized catches, as an inverse relationship between price and discards was found in this study (Figure 7). Ignoring the disproportionate impact of discarding on smaller fish could mask estimated recruitment trends in stock assessments (Punt *et al.*, 2006; Batsleer *et al.,* 2015). Our study could not address size-based discarding due to both the limited biological sampling of discards by the Norwegian Reference Fleet and the added complications of the clustered structure of sampling (Nelson, 2014) that could not be accounted for sufficiently in our random forest model. However, graphical comparisons of length distributions of the discarded and retained catches of cod by Berg and Nedreaas (2020) have found variations in size-based discarding in both space and time. For example, size-based discarding was detected in the northernmost areas in the first two quarters when fishing intensity is highest, whilst in southern areas, discarding was relatively similar over all sizes. We therefore suggest a further study on size-based discarding of cod in the coastal gillnet fisheries, using the subset of discards data where length measurements were taken.

A new reporting system is gradually being rolled out in Norwegian coastal fisheries, requiring all vessels to report catches and fishing activity after every trip through an electronic reporting system alongside a mandatory vessel monitoring system for spatial tracking (Norwegian Ministry of Trade, Industry and Fisheries, 2009). Based on results from this study, this new reporting system will provide a wealth of data for improving fishery-scale predictions of total discards in coastal fisheries. We therefore suggest that model-based estimators can make use of these data to hopefully improve the precision and bias of estimates. However, we highlight that this study did not assess the predictive performance of the random forest model, which is important if this model will be used to estimate total discards in the fishery once the new reporting system is in full operation. The most important variables identified by the random forest model (Figure 5) can inform an information-theoretic approach to generalized linear model fitting (Burnham and Anderson, 2002), although correlated variables would need to be accounted for in this context (Supplementary Figure S2).

Estimates presented here are based on data from a fishery self-sampling programme, and although the reference fleet is protected from prosecution and operating under a contractual agreement of accuracy, we must acknowledge the potential sources of bias. Participation in the Norwegian Reference Fleet is voluntary, and there is a possibility that the behaviour of the fishers on the participating vessels behave differently from the rest of the fishing fleet. Participation is paid, but the structure of this payment might influence the fishing behaviour of the participants. Reliability of self-sampled data must also be acknowledged. As discarding of viable fish is legal and data are not available to enforcement and control authorities, the risk that data are intentionally manipulated to avoid prosecution is negligible. This is supported by the fact that fishers are willing to report discards in the first place. However, there is also the risk of under-reporting discards if undesirable results could lead to a reduction in quotas or loss of fishing rights (Roman *et al.*, 2011). There is evidence that suggests the Norwegian Reference Fleet are equally willing to record discards as the wider fleet based on a study by Fangel *et al.* (2015), who found similar estimates of seabird bycatches in the coastal gillnet fisheries based on the Norwegian Reference Fleet and a questionnaire survey. We argue based on values that fishers willing to participate in the Norwegian Reference Fleet have an interest in the long-term sustainability of their fisheries and understand the impacts of data manipulation. There is always a risk that individual data collectors could manipulate data, even in independent observer programmes (Ewell *et al.*, 2020), but we believe that the issue is not systemic enough to incur substantial biases. Nevertheless, quantitative studies on reliability are needed, which would provide statistical evidence for these claims.

In conclusion, we have improved estimations of discards in the coastal gillnet fisheries for both past and future years, placing emphasis on the importance of accounting for uncertainties in each step of the analysis, and suggesting ways in which both the accuracy and precision of future estimates can be improved when a higher resolution data collection programme is established. The methods are applicable to all other species in the gillnet fisheries and are robust in terms of precision, given that uncertainty is accounted for at every stage of sampling. The results presented here suggest that discarding is negligible. However, this cannot be concluded without determining how the corrected catch statistics will impact the stock assessment (Perretti *et al.*, 2020). Simulation studies have found that the impact of additionally fishing mortality incurred by discarding is also dependent on the trend in fishing effort (Dickey-Collas *et al.*, 2007) and produce “unintuitive” biases in estimates of stock status (Rudd and Branch, 2017). Furthermore, Berg and Nedreaas (2020) identified that discarding of cod in the coastal fisheries may be size-based, suggesting that some stock assessment parameters such as recruitment may be disproportionally affected by unknown levels of discarding.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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Data availability statement

The data underlying this article cannot be shared publicly due to the sensitivity of the contents and the privacy of fishers involved in data collection. The data will be shared on reasonable request to the corresponding author.

Author contributions

HSFB and TLC contributed equally to all aspects of the study. All other authors contributed to developing the methodology, interpretation of results, and editing of the manuscript.

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