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# Latent Gaussian models to predict historical bycatch in commercial fishery

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ABSTRACT

Knowledge about how many fish that have been killed due to bycatch is an important aspect of ensuring a sustainable ecosystem and fishery. We introduce a Bayesian spatio-temporal prediction method for historical bycatch that incorporates two sources of available data sets, fishery data and survey data. The model used assumes that occurrence of bycatch can be described as a log-linear combination of covariates and random effects modeled as Gaussian fields. Integrated Nested Laplace Approximations (INLA) is used for fast calculations. The method introduced is general, and is applied on bycatch of juvenile cod (*Gadus morhua*) in the Barents Sea shrimp (*Pandalus borealis*) fishery. In this fishery we compare our prediction method with the well known ratio and effort methods, and make a strong case that the Bayesian spatio-temporal method produces more reliable historical bycatch predictions compared to existing methods.



## 1. Introduction

Bycatch in commercial fisheries may potentially threaten a sustainable ecosystem and fishery, and knowledge about historical bycatch is therefore important. If bycatch is not recorded in the fishermen catch logbooks, which is the main source of information within commercial fisheries, historical bycatch needs to be estimated. In this research, we introduce a prediction procedure based on the newly constructed Bayesian hierarchical spatio-temporal bycatch model in Breivik et al. (2016). We further compare our method with the frequently used ratio method (Scheaffer et al., 1996, p. 204) and effort method (e.g. Walmsley et al., 2007; Hall, 1996) for a specific fishery.

Typically two sources of data are available for predicting bycatch; the commercial catch logbooks the fishermen are obliged to report, and observations taken for monitoring purposes. The first source, referred to as fishery data, contains only target catch, whiles the latter, referred to as survey data, contains both target catch and bycatch. To predict historical bycatch in the commercial fishery, we combine the fishery data with the survey data.

The ratio method and the effort based method are widely used to predict historical bycatch (Davies et al., 2009; Vinther, 1999; Ye et al., 2000; Amandè et al., 2010; Ye, 2002; Walmsley et al., 2007). The ratio method scales the commercial target catch with the observed bycatch ratio in the survey data, while the effort based method scales the observed bycatch with the commercial trawl effort.

The model proposed to predict historical bycatch takes a regression approach and utilizes possible important explanatory variables (such as seasonal effects and the size of target catch). It also includes an underlying stochastic structure that partly explains the processes that the explanatory variables fail to capture and simultaneously takes dependence structures into account. By using our bycatch model we can utilize observations taken over several years to describe global structures of bycatch. Our model-based approach is thereby able to provide good realistic bycatch predictions (with uncertainty) even in areas and time periods with few or no inspected trawl hauls.

The prediction method introduced in this research is general and is applied to bycatch of juvenile cod in the Barents Sea shrimp fishery. A sorting grid, which sorts out the larger cod and reduces bycatch, was imposed in this fishery in 1992/1993 (ICES, 1994). Because of the grid, the bycatch is of no commercial value, and is discarded. There is a real time regulation of this fishery with respect to bycatch of juvenile cod, haddock (*Melanogrammus aeglefinus*), red-

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**Table 1**
Summary of fishery data, intervals in parentheses are 90% coverage intervals.

| Data | Description |
|---|---|
| Time | Date of catch (day, month and year) |
| Location | Which region the catch was taken (see small areas in Fig. 1a) |
| Target catch | Total shrimp catch by one boat in a given area and day (770 kg, 13,750 kg) |
| Duration | Hours used to trawl by a boat in a given area and day (7 hours, 22.9 hours) |
| Number of trawls | The number of trawls varies between (76%), two (23%) or three (1.7%) |
| Quarter of the year | 1st (9.2%), 2nd (42%), 3rd (38%) and 4th (11%) |

**Table 2**
Summary of data collected by the MSS, intervals in parentheses are 90% coverage intervals.

| Data | Description |
|---|---|
| Target catch | Shrimp catch varied between 2.4 kilogram and 17.7 tons (20, 3190) |
| Bycatch cod | The number of cod varied between 0 and 35,775 cod (0, 1008) |
| Time | Time of catch down to minutes scale |
| Location | Catch location (single point) given in longitude and latitude |
| Open/Closed | Describes if the location was open for commercial fishery or not (83% open) |
| Duration trawled | The hours used to trawl (1.6 h, 6 h) |
| Number of trawls | The number of trawls varies between one (74%), two (23%) or three (3.0%) |
| Temperature | Bottom sea temperature (0.17, 9.3) |
| Depth | Ocean depth at catch location (227, 410) |
| Quarter of the year | 1st (21%), 2nd (35%), 3rd (20%) and 4th (23%) |

fish (*Sebastes norvegicus* and *Sebastes mentella*), Greenland halibut (*Reinhardtius hippoglossoides*) and undersized shrimp. If the Norwegian Directorate of Fisheries Monitoring and Surveillance Service (MSS) believes that an area has a higher bycatch ratio than allowed, that is e.g. 8 cod per 10 kilogram of shrimps (Fiskeridirektoratet, 2005), the area is temporarily closed. The survey data used in this research have previously been used by MSS to regulate the shrimp fishery (Breivik et al., 2016). See Little et al. (2015) for a summary of management methods with respect to bycatch in several other large fisheries.

Bycatch was also predicted in Breivik et al. (2016) for regulation purposes. Our research differs mainly because we utilize huge amounts of fishery data, resulting in new computational difficulties, and that the data distribution is changed from log-Gaussian to zero-inflated negative binomial. Furthermore, the target catch is in this research a given covariate since it is included in both the fishery data and the survey data, while in Breivik et al. (2016) where future predictions was the focus, the shrimp catch was stochastic. To adapt to the information given in the fishery data, the response variable for bycatch in Breivik et al. (2016) is changed from *bycatch per nautical mile* to *total bycatch*, and with duration trawled included as an offset.

The paper is organized as follows. Section 2 presents the data used for historical bycatch prediction. Section 3 provides a brief overview of historical bycatch prediction methods. Section 4 presents the model and Section 5 illustrates the inference and prediction procedure. Section 6 presents the estimated model and predictions of historical bycatch. Section 7 validates the predictions and compares them with the ratio and effort method. Finally, Sections 8 and 9 present discussion and conclusions.

## 2. Data

Fig. 1 shows the spatial distribution of the data. The left panel shows the spatial resolution of the fishery data (specific locations are not recorded), while the right panel shows the spatial locations of the survey data.

There were reported in total 81,809 commercial shrimp catches during the period 1994–2006. Table 1 gives a short summary of possible covariates in the fishery data. Notice that the fishery data consists of daily catches, meaning that if a vessel has made several trawl hauls in the same small-scale spatial unit (see Fig. 1) in a single day, this counts as one record.

We used 7363 observations of shrimp and bycatch of cod from 1994 to 2006 taken by the MSS (the survey data), and provided by the Institute of Marine Research (IMR) in Bergen, Norway, see Table 2 for a short summary of the survey data. There were 18.5% zero-observations of bycatch. The survey observations are collected for regulation purposes and the trawl hauls are conducted using the same equipment as in the commercial fishery. These observations may either have been taken on board at vessels active in the commercial fishery (23%), or by vessels hired by the MSS (77%) for collecting a sufficient amount of observations at selected areas where commercial shrimp trawling occurs.

In addition to the variables in Table 1 we also use total abundance estimates of 0-group cod (juvenile cod less than one year old) in the whole Barents Sea to predict the historical bycatch. These estimates can be found in Jakobsen and Ozhigin (2011, pp. 565–567).

## 3. Methods to estimate historical bycatch

This section gives a brief overview of methods to estimate historical bycatch. Our research focuses on the third method (the model based method).

### 3.1. The ratio method

The ratio method (Scheaffer et al., 1996, p. 204) has been widely used to estimate historical bycatch. The ratio method uses the reported bycatch ratio in the survey data to scale the commercial target catch (here shrimp) to achieve estimates of bycatch, and is defined as

$$\hat{B}_{A,t}^{\text{ratio}} = \frac{\sum_{i=1}^{n} b_{i,A,t}}{\sum_{i=1}^{n} z_{i,A,t}} Z_{A,t} = \text{R}_{A,t} Z_{A,t}. \tag{1}$$

Here $(z_{i,A,t}, b_{i,A,t})$ are the $i$th observed target catch and bycatch in the survey data in area $A$ and time interval $t$, $Z_{A,t}$ is the total commercial target catch in area $A$ and time interval $t$, and $\text{R}_{A,t}$ is the observed bycatch ratio in area $A$ and time interval $t$. The historical bycatch in several time intervals can then be estimated in the whole Barents Sea as $\sum_A \sum_t \text{R}_{A,t} Z_{A,t}$. We let the areas, $A$, be the small green rectangles in Fig. 1a and each time intervals, $t$, be quarters of years. The ratio method with these areas and time intervals is currently used as a standard for providing official historical bycatch estimates in the Barents Sea shrimp fishery (Ajiad et al., 2007; Hylen and Jacobsen, 1987).

Eq. (1) assumes there exists survey data in each area and time interval where commercial catches occurred. This is not always fulfilled, and in such situations it is a common procedure to expand the area on which the ratio, $\text{R}_{A,t}$, is calculated. In our experiments, we expand the area in the following order: First we use all observations in the larger red area containing the area of interest (Fig. 1a) within the given time interval. If there are no observations in this larger area, we use all the observations in the Barents Sea within the given time interval. If there are no observations in the Barents Sea, we use all observations collected one time interval before and after. We also experimented with expanding the time interval before increasing the spatial areas, but this had little effect on the