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Original Article

Seal interactions and exits from fisheries: insights from the Baltic Sea cod fishery

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The number of seals in the Baltic Sea has increased dramatically in recent years. While growing seal populations are associated with a thriving marine environment, seals interact with coastal fisheries causing significant damages to catches and gears. One fishery that is severely affected is the coastal cod fishery where the negative impact of seals is believed by many to threaten the existence of the fishery. This article empirically investigates to what extent seal damages can explain the declining number of fishing vessels active in the Baltic Sea coastal cod fishery. The analysis makes use of detailed logbook data and statistical survival models to estimate the effect of seal interactions with fishing gears on the exit probability of vessels in the Swedish cod fishery. The results show that seal interactions is an important factor explaining exits, suggesting that total losses caused by seals go beyond observed costs of broken gears and damaged catches.

Keywords: Baltic Sea, coastal fisheries, seal damages, survival analysis

Introduction

In the last decades, the Baltic Sea seal populations have increased rapidly. For example, the grey seal (*Halichoerus grypus*) population has more than doubled since the early 2000s, from around 25 000 seals in year 2003 to around 60 000 in 2019 (SwAM, 2019). Growing seal populations are often regarded as a symbol of a thriving ecosystem and all three seal species present in the Baltic Sea, i.e. the grey seal, the harbour seal (*Phoca vitulina*), and the ringed seal (*Phoca hispida*), are listed as species of biological community importance in the EU's Habitats Directive (EU, 1992). According to the HELCOM (2006) management objectives for the Baltic Sea seal populations, they should (i) recover to carrying capacity levels, (ii) expand to suitable breeding distributions in all regions, and (iii) attain a good health status that secures the continued existence of the populations.

However, seals are known to cause problems for coastal fisheries by interacting with fishing gears, leading to lost catches and damaged gears. Such losses, referred to as "seal damages" in this paper, negatively affect the economic viability of fishing. In interview studies and surveys with coastal fishermen operating in the Baltic Sea, the problem of seal damages is regularly referred to as one of the most important factors why they consider leaving the sector, especially in Sweden and Finland (e.g. Svels *et al.*, 2019; Waldo *et al.*, 2020a; Arias-Schreiber and Gillette, 2021). Increasing seal damages may be seen as at odds with the Swedish management objective that the impact of seal populations on human interest should be natural or positive (SwAM, 2019). The coastal fisheries are regarded important for the cultural heritage and for preserving regional employment in many coastal communities (Bjorkvik *et al.*, 2020), and the declining number of fishermen has made community representatives and local residents deeply concerned (Wernersson *et al.*, 2017; Johansson and Waldo, 2021).

The aim of this study is to examine whether seal interactions with fishing gears increase the probability of vessels exiting the Swedish coastal cod fishery, which is a fishery that has experienced a strong increase in seal damages in recent years. The study uses logbook data from Swedish vessels between 2006 and 2016, including logbook recordings of seal interactions with fishing gears. The data makes it possible to analyze how seal interactions at the vessel level affect the probability that a vessel stop fishing. The results of the empirical analysis show that seal interactions is indeed a significant factor explaining why vessels exit the cod fishery during this period. More specifically, our results show that if the proportion of fishing trips with seal interactions increases from 50 to 100%, the probability of exiting the cod fishery in a given year increases from 10 to 35%.

The results from this study add to the large and growing literature documenting and analyzing seal-fisheries interactions in the Baltic Sea (Seal-fisheries interactions have also been studied in other areas of the world, e.g. Baraff and Loughlin, 2000; Güclüsoy, 2008; Hale *et al.*, 2011; Klenke *et al.*, 2013; Ríos *et al.*, 2017). This literature includes feeding habits of seals and competition for the fish resource (Hansson *et al.*, 2018; Scharff-Olsen *et al.*, 2019), impacts on fish stock recovery and stock assessments (e.g. MacKenzie *et al.*, 2011; Gårdmark *et al.*, 2012), increased loads of seal parasites in fish affecting fish growth (Lunneryd *et al.*, 2015), fishing gear catch losses (e.g. Königson *et al.*, 2009), costs of damaged fishing gears (Svels *et al.*, 2019; Waldo *et al.*, 2020b), bio-economic modelling of seal-fisheries interactions (Holma *et al.*, 2014), development of seal proof gear (Hemmingsson *et al.*, 2008; Königson *et al.*, 2015), socio-economic consequences of seal damages for coastal communities (e.g. Johansson and Waldo, 2021), and the effectiveness of mitigation measures such as hunting and economic compensation (Varjopuro, 2011; Olsen *et al.*, 2018; Waldo *et al.*, 2020a).

While this literature shows that the impacts of seals on fisheries vary considerably between fishing areas and target species, there is extensive evidence that seals pose significant problems to coastal fisheries using passive (static) gears in the Baltic Sea (Kauppinen *et al.*, 2005; Königson *et al.*, 2007, 2009; Lundström *et al.*, 2010; Waldo *et al.*, 2020b). Seals feed directly from the fishing gears causing increased costs (damaged gears) and foregone revenues (decreased catchability), which is the main driver of the seal-fisheries conflict in the Baltic Sea region (Bruckmeier and Höj Larsen, 2008; Varjopuro, 2011; Waldo *et al.*, 2020a). The contribution of the current study is to show that such seal damages not only affect the economic viability of *active* fishermen, but they also have a "hidden" effect in that fishers leave the sector. In addition to direct economic losses, the problems caused by seal damages may affect job satisfaction more generally by adding to frustration and a feeling of powerlessness regarding the future of the fishery, which may also contribute to the willingness to exit (Arias-Schreiber and Gillette, 2021; Johansson and Waldo, 2021). As such, the current paper confirms and complements the findings of several qualitative studies showing that fishers and local residents perceive the negative consequences of seals to threaten the survival of small-scale fisheries in the Baltic Sea (Säwe and Hultman, 2012; Svels *et al.*, 2019; Waldo *et al.*, 2020a; Arias-Schreiber and Gillette, 2021; Johansson and Waldo, 2021).

The current study is also relevant for the literature analyzing fisher behaviour and its implications for fisheries management (e.g. Fulton *et al.*, 2011; van Putten *et al.,* 2012; Wijermans *et al.*, 2020; Andrews *et al.*, 2021). Fishers are key components of marine ecosystems and knowledge of their behaviour and motivation is key to understand fleet dynamics and anticipating consequences of management decisions. The question of what factors influence exit decisions has attracted significant attention in the literature. This is especially true for fisheries managed by effort restrictions such as limited-entry programs, where participation levels can affect the sustainability of fish stocks (e.g. Bockstael and Opaluch, 1983; Smith, 2004; Crosson, 2015). Exit decisions have also been studied in the context of sustainability of coastal communities, where fisheries are regarded important for the cultural heritage and for preserving livelihood in rural areas (e.g. Cordón Lagares *et al.*, 2016). The current paper adds to this literature by showing that seal interactions with fishing gears affect the fleet dynamics of the small-scale cod fishery in the Baltic Sea. The paper also adds to the literature by showing how exit decisions can be analyzed using discrete-time survival models. While a number of previous studies have analyzed exit from fisheries using continuous-time survival models (e.g. Smith, 2004; Cordón Lagares and García Ordaz, 2015; Cordón Lagares *et al.*, 2016), the present study is the first to use a discrete-time framework.

Material and methods

The Swedish coastal cod fishery and seal damages in the Baltic Sea

The Baltic Sea cod fishery involves several countries including major fishing nations such as Denmark, Poland, and Sweden. The Baltic cod (*Gadus morhua*) has been one of the most economically important species in Swedish fisheries for many years. The fishery was booming in the 1980s with total annual landings around 400 000 tons of which 60 000 tons were Swedish landings (ICES, 2019). In 2015, the Swedish landings were significantly lower, around 6400 tons, which constituted around 10% of the total catch value of fish and seafood in Swedish fisheries (Swedish Agency of Marine and Water Management, www.havochvatten.se) (The status of the Baltic cod stocks has deteriorated since 2015 and in 2019 the EU banned demersal trawling for cod in the Baltic Sea (European Commission, 2019). However, the coastal cod fishery using passive gears was allowed to continue fishing in the southern part of the Baltic Sea.). The EU sets the quotas for the two Baltic cod stocks (eastern and western) on a yearly basis and the individual member states then allocate national quotas among their vessels. The Swedish cod quota is allocated to two different fleet segments depending on gear types. Around 75% of the Swedish quota goes to the demersal trawling fleet and the remaining 25% to the coastal fleet. The coastal fleet comprises of vessels fishing with bottom anchored nets (gillnet and trammel net) and longline (see e.g. Bergenius *et al.*, 2018). These are passive (static) gears deployed almost exclusively by vessels between 8 and 12 m relatively close to the coastline. In the Swedish context, this is the small-scale fleet. Thus, the definition of "small-scale" cod fisheries used in this study is vessels using passive gear. Ever since drift nets used for fishing Atlantic salmon were prohibited in the Baltic Sea in 2008, the small-scale cod fishery is highly specialized and few cod fishers are active in other types of fisheries (see e.g. Bergenius *et al.*, 2018; Björkvik *et al.*, 2020).

Historically, the Swedish small-scale cod fishery was an economically important fishery. Around 300 vessels, having a landing value of more than 80 million Swedish crowns (∼ €8 million), were active in the fishery in the early 2000s (Bergenius *et al.*, 2018). As a response to increasing seal damages there have been efforts to introduce seal-safe gears through baited cod pots (Königson *et al.*, 2015), but they have so far not been widely adopted in the commercial fishery (There are, however, examples of seal-safe gears that have proven successful to reduce seal damages in other fisheries in the Baltic Sea, such as the pontoon (or push-up) trap in the northern Baltic salmon (*Salmo salar*) fishery (Hemmingsson *et al.,* 2008)). Thus, the small-scale cod fishery has been identified as being severely affected by seal damages (SwAM, 2014, 2019). Seal damages for active gears used by large-scale cod vessels, such as trawls, are much less common and not discussed in this paper.

Data and descriptive statistics

This section presents the data and data sources used in the paper. It also shows some descriptive statistics of seal interactions with gears in the Swedish cod fishery. The Swedish Agency for Marine and Water Management (SwAM) provided the fisheries data, and regional labor market indicators were provided by the Swedish Public Employment Service and the Swedish Agency for Economic and Regional Growth. The fisheries data are based on information from vessel logbooks and are available from 1997 to 2016. The logbook contains detailed information about catches, fishing effort, and geographical position of fishing grounds of all commercial fishing vessels. Vessels participating in the coastal cod fishery in the Baltic Sea are required to keep daily logbook records of their fishing operations (The general rule in the EU control regulation is that vessels with a length of 10 meters or more should record their landing in daily logbooks (vessels under 10 m may keep a monthly logbook). However, the EU cod recovery plans require vessels participating in the Baltic cod fishery to keep daily logbooks (EU, 2007; EU, 2016)). In addition to information about fishing activity, from year 2006 and onwards, seal damages to catches and gears have been recorded on a regular basis in the logbook (From 2006 and onwards fishermen are required to report the presence of seal damages in their logbooks in order to be eligible for the Swedish compensation scheme for seal damages (SwAM, 2014). The compensation to the individual fishermen is, however, not based on recorded seal interactions, but rather on catches and which gears have been used. Therefore, there should be no incentive for fishermen to exaggerate the presence of seal interactions in their logbooks.). Seal interactions are recoded as an indicator variable taking a value of one if the catch and/or the gear have been damaged by seals, and zero otherwise. It is therefore possible to calculate the proportion of fishing days with seal damages for each vessel. Although this measure reveals no information about the magnitude of the seal damages, it makes it possible to capture differences in damages between vessels over time.

Between the years 2006 and 2016, gillnet, trammel net, and longline constituted between 97 and 99% of the total catches of cod caught with passive gears. Figure 1 illustrates the development of the number of vessels active in the cod fishery (Panel A) and the development of seal interactions with gears (Panel B). As can be seen in Panel A of the figure, there has been a downward trend in the number of vessels since 2006 in all gear categories. When it comes to seals, Panel B of the figure shows the proportion of fishing days with seal interactions with gears. As can be seen, the frequency of seal interactions has increased significantly for all three gear types since 2006.

While seal interactions have increased over time for all three gear types, the development has not been uniform across fishing areas in the Baltic Sea. To illustrate this, Figure 2 shows the proportion of fishing days with seal interactions calculated for each ICES statistical rectangle in the Baltic Sea where coastal cod fishing takes place (The coastal cod fishery includes ICES subdivisions 23–28. Only statistical rectangles with more than 10 fishing days in a year are shown. There is also a some cod fishing in the Åland Sea (ICES area 29) with some preliminary genetic screening suggesting that this cod may be regarded as a separate population that spawns and reproduces in the area (Bergström *et al.*, 2015). The cod fishery in the Åland Sea is very small in comparison to the cod fishery in the southern Baltic (∼ 1% of total coastal cod catches) and is not included in this paper.). Panels A and B of the figure show the geographical distribution of seal damages in 2006 and 2016, respectively.

Figure 2 shows that the geographical distribution of seal interactions has changed between 2006 and 2016. Panel A of the figure illustrates that the fishing areas around Öland and Gotland, the two large islands off the east coast of Sweden, were severely affected by seal damages already in 2006. In contrast, the fishing areas outside the south coast and southwest coast had generally low levels of seal interactions in 2006 (less than 25% of the fishing trips). Panel B of the figure shows that the proportion of fishing trips with seal interactions increased dramatically in the southern Baltic between 2006 and 2016 (more than 50% of the fishing trips), while seal interactions have been stable on the southwest coast. Panel B also shows that fishing has disappeared in some ICES rectangles, especially around Öland and Gotland.

The statistical analysis below includes several control variables created from the logbook data. In addition, data about unemployment levels at the municipal level is collected from the Swedish Public Employment Service and is included to control for labour maket opportunities outside the fishing sector (available at http://www.ams.se). An indicator variable separating rural and urban municipalities is obtained from the Swedish Agency for Economic and Regional Growth to account for rural areas far away from city centers (available at http://www.tillvaxtverket.se) (A rural municipality far away from a city center is defined by the Swedish Agency for Economic and Regional Growth as follows: (i) the municipality has less than 300 inhabitants per km^2, and (ii) more than 50% of the population have more than 45 min travel by car to a city with at least 50 000 inhabitants.). These variables are merged to the logbook dataset by the homeport municipality of the vessel. A more detailed discussion about relevant control variables are given in the methodology section below.

Empirical methodology

The aim of this study is to examine whether seal interactions with gears as defined above (proportion of fishing trips with recorded seal damages) increase the probability that a vessel exits the small-scale cod fishery. To analyze this question, we apply statistical survival analysis suitable for panel data with discrete observations, which is a novel approach to analyze exits from fisheries. This section therefore fills a methodological gap in the literature by describing how to use the discrete time survival model in fisheries applications. A more in-depth discussion of this model can be found in e.g. Jenkins (2005).

Let T_{ik} be a discrete non-negative random variable measuring the survival time in years for vessel i. The subscript k is included to account for the fact that a vessel may have multiple (k) spells of fishing during the observation period, i.e. a vessel may switch in and out of the fishery during the period. In analyzing exit decisions, the main quantity of interest is the probability that vessel i will exit its k: th fishing spell after j periods, conditional on its survival up to j and relevant explanatory variables. This conditional probability is called

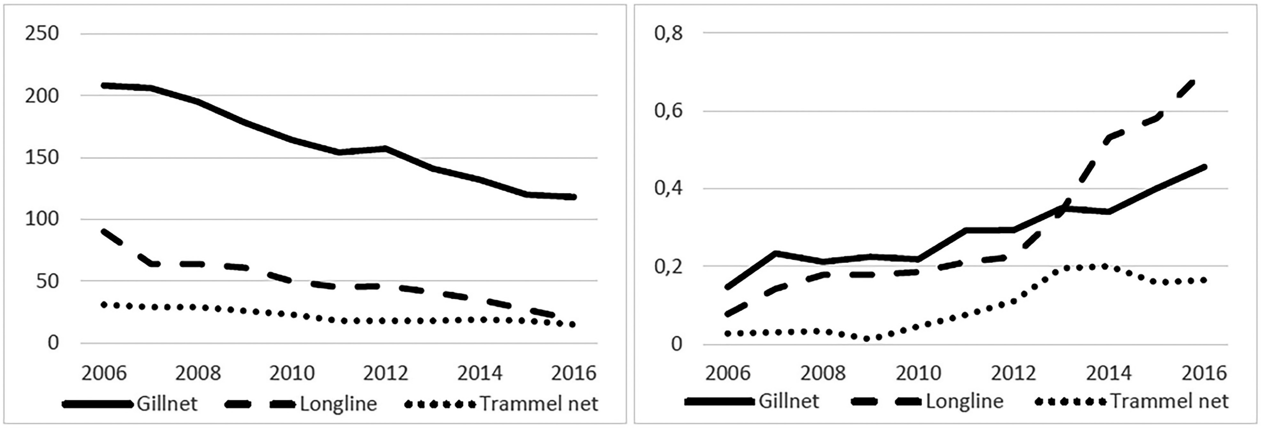

Figure 1. Number of vessels and seal interactions in the small-scale Baltic Sea cod fishery. Panel A (left), number of vessels. Panel B (right), proportion of days with seal interactions.

the discrete-time hazard and is formally defined as follows:

$$\lambda_{ijk} := P(T_{ik} = j \mid T_{ik} \geq j, x_{ijk}) = F\left(x'_{ijk}\beta + \gamma_{jk}\right), \quad (1)$$

where x_{ijk} is a vector of explanatory variables, γ_{jk} is a function of time and $F()$ is a distribution function ensuring that the hazard rate is between 0 and 1. In this paper, γ_{jk} is specified as a dummy variable that indicates the number of periods in survival, which implies that the duration dependence of the hazard function is modeled in a nonparametric fashion. The main explanatory variable is the proportion of fishing trips with seal interactions in a given year, and the corresponding β parameter to be estimated shows the impact of seals on the exit probability of vessel i in a given year. As showed in e.g. Jenkins (1995) and Willett and Singer (1995), the parameters of hazard function can be estimated by maximum likelihood routines given regularly assumptions on $F()$. Commonly encountered functional specifications include standard normal, logistic, and extreme value distribution, leading to a probit, logit and complementary log-log (cloglog) likelihood model, respectively (see Sueyoshi, 1995 for a discussion). Since the choice between them is not obvious, we report estimation results from all three models.

If seal interactions can be assumed to be independent with respect to other factors affecting the exit probability, additional explanatory variables do not need to be included when estimating the model. However, if this is not the case, estimates of β will potentially be biased as a result of confounding factors. To address this issue, we also include control variables in the regression. Since seal interactions vary by fishing areas, as evident from Figure 2, regional factors may be important to include as controls. The municipality unemployment rate and a dummy variable for rural areas are included to control for labour maket opportunities and the distance to city areas. Although seal interactions are likely to be uncorrelated with labour market opportunities, these variables are included to minimize the risk of counfounding geographical factors. At the vessel level, the length and age of the vessel are included as these have been shown in previous studies to affect the exit decision (e.g. Tidd *et al.*, 2011; van Putten *et al.*, 2012). From the logbook data, we also calculate the share of the yearly catch consisting of cod. A high degree of dependence on cod may affect the probability to exit the fishery and potentially also be related to the frequency of seal interactions with gears. In addition to vessel age, the age of the fisher (vessel license holder) is included as a control variable (The fleet register is obtained from SwAM and shows the vessel license holder as of 1 January each year.). The age variable is included as a dummy taking a value of 1 if fisher age ≥ 65 (official retirement age in Sweden) and 0 otherwise. The coefficient on this variable is expected to be positive if the vessel is not bought/transferred when the fisher retires.

It may also be important to control for time series variation. For example, we expect the status of the Baltic cod stocks to affect the probability to exit cod fisheries. Other potentially important factors include changing regulations, price fluctuations, fuel costs, and profitability of alternative fishing opportunities. Fortunately, such factors tend to be common to all fishers, which makes it possible to control for these by including yearly fixed effects in the regression model. When it comes to alternative fishing opportunities in the southern part of the Baltic Sea they are, as discussed above, limited since the ban of drift nets. However, to examine if reallocation of fishing effort to other fisheries affect the results, the empirical analysis considers two different dependent variables in the regression model: (1) the probability that vessel i exits the small-scale cod fishery as defined above, and (2) the probability that vessel i exits fisheries completely. In the latter case, an exit occurs if there is no fishing effort at all during the year (all gears considered).

In addition to observed covariates, it may be important to consider unobserved heterogeneity. For example, there may be individual-level factors, such as skills and knowledge of fishers, the desire to continue a family tradition of fishing (e.g. Pascoe *et al.*, 2015), and other non-monetary aspects of job satisfaction (e.g. Pollnac and Poggie, 2008) that are unobserved and not possible to include among the covariates. As an example, assume that more skillful fishers, having lower probability of exit, are more successful in avoiding seal interactions with gears. This may lead to confounding positive correlations caused by an unobserved individual-level factor (skill). To alleviate this potential problem, we control for unobserved heterogeneity using the correlated random effects (CRE) approach by including time averages of vessel-level variables as additional controls in the regression. This approach makes use of the panel data structure of the data to control for potential correlation

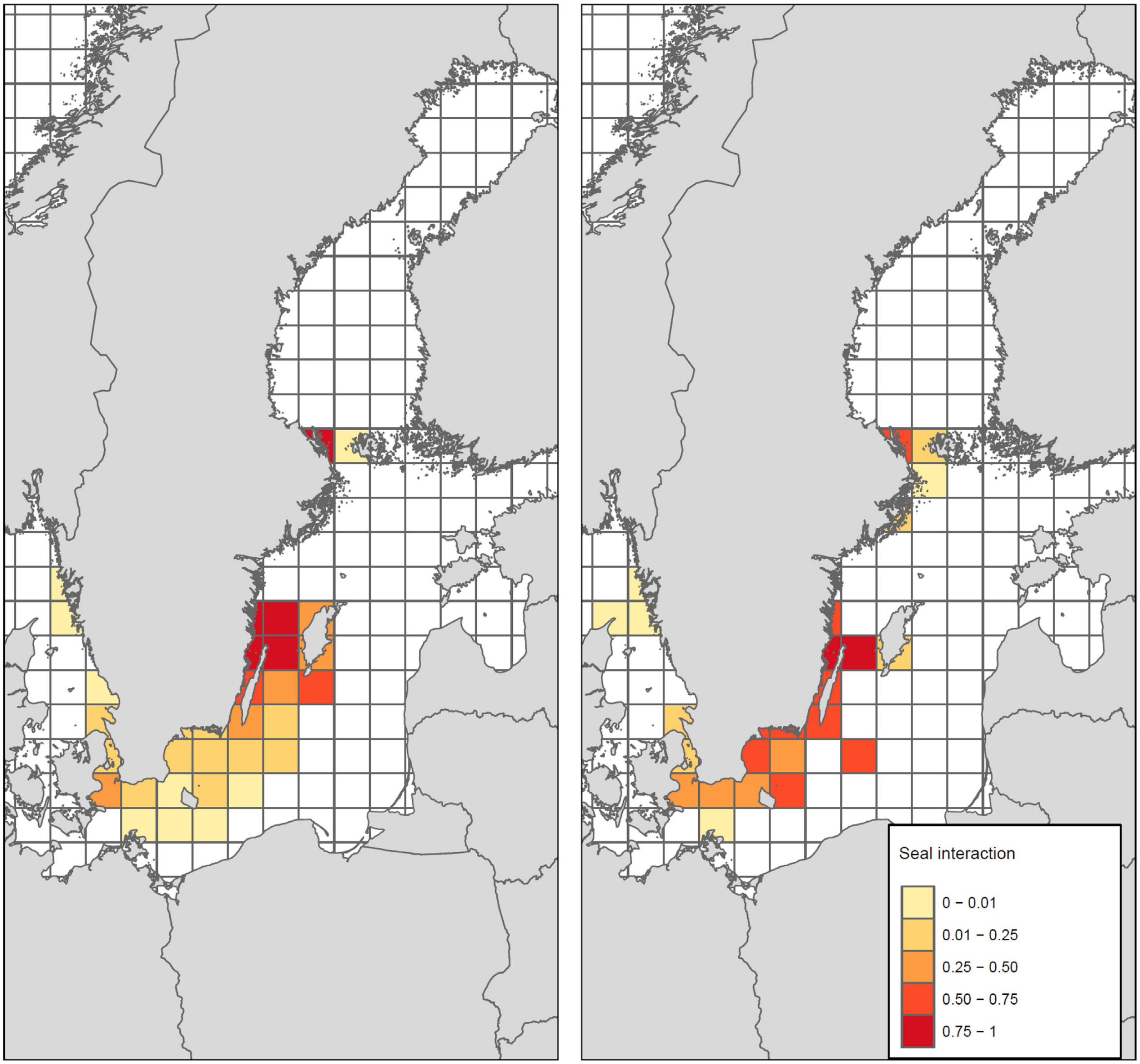

Figure 2. Geographical distribution of seal interactions in the cod fishery in 2006 and 2016. Panel A (left), 2006. Panel B (right), 2016. Source: Administrative borders are obtained from EuroGeographics and UN-FAO.

between seal interactions with gears and unobserved individual factors (see e.g. Mundlak, 1978).

Results

The estimation results from the hazard model in (1) are presented in columns 1–3 of Table 1, where standard errors are displayed in italics below each coefficient. Estimates of the time fixed effects and the duration dummies are not shown to save space. The model is specified both with and without control variables to see whether the effect of seal interactions change when covariates are included. As a further robustness check, we investigate whether our results change if vessels that switch in and out of the cod fishery are excluded from the sample. These results are presented in columns 4–6 of the table (In total, out of the 295 vessels included in the analysis, 43 vessels have multiple spells of fishing.). The main coefficient of interest, *seal*, in columns 1–3 is positive and statistically significant. Thus, a higher level of seal interactions with gears during the year increases the probability to exit the Swedish cod fishery. The seal variable is also highly significant in the model including control variables suggesting that confounding factors is not a major problem. Looking at columns 4–6 of the table it is evident that the conclusion is the same for vessels with a single fishing spell, i.e. for vessels that exit and do not return to the cod fishery.

The coefficients in Table 1 show how the hazard function changes when the explanatory variables increase with one unit. The coefficients are not easily comparable between the probit, logit, and cloglog models since different distributional assumptions are made to model the link between the dependent variable and the explanatory variables. A more interesting measure is to consider the impact of seals on the predicted probability of exit (marginal effects) (Since the models considered are non-linear, the marginal effects

Table 1. Estimation results.

Variable	All vessels Probit	All vessels Logit	All vessels Cloglog	Vessels with single spell Probit	Vessels with single spell Logit	Vessels with single spell Cloglog
No control variables						
Seal	0.619***	1.169***	1.036***	0.783***	1.518***	1.389***
	0.203	*0.387*	*0.347*	*0.240*	*0.466*	*0.423*
With control variables						
Seal	0.578***	1.065**	0.924**	0.865***	1.733***	1.567***
	0.224	*0.429*	*0.386*	*0.241*	*0.481*	*0.438*
Unemployment	− 0.015	− 0.028	− 0.027	0.006	0.017	0.014
	0.030	*0.056*	*0.051*	*0.027*	*0.052*	*0.048*
Rural	*0.013*	*0.019*	*0.009*	*− 0.057*	*− 0.120*	*− 0.099*
	0.130	*0.243*	*0.216*	*0.114*	*0.220*	*0.202*
Share cod	− 0.195	− 0.437	− 0.437	− 0.307	− 0.795	− 0.740
	0.266	*0.506*	*0.455*	*0.296*	*0.583*	*0.538*
Vessel age	0.006	0.011	0.010	0.005	0.009	0.008
	0.004	*0.007*	*0.006*	*0.003*	*0.006*	*0.005*
Vessel length	0.097***	*0.181****	*0.162****	*0.103****	*0.198****	*0.184****
	0.036	0.067	0.058	0.026	0.048	0.043
Fisher age ≥ 65	0.426***	0.803***	0.727***	0.359***	0.712***	0.669***
	0.135	*0.249*	*0.215*	*0.126*	*0.238*	*0.217*
Duration dummies	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
# obs	1805	1805	1805	1509	1509	1509

Notes: ***, **, and * indicates significance at $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively. Standard errors in italics. The estimation is carried out in STATA 16 using the xtprobit, xtlogit, and xtcloglog commands.

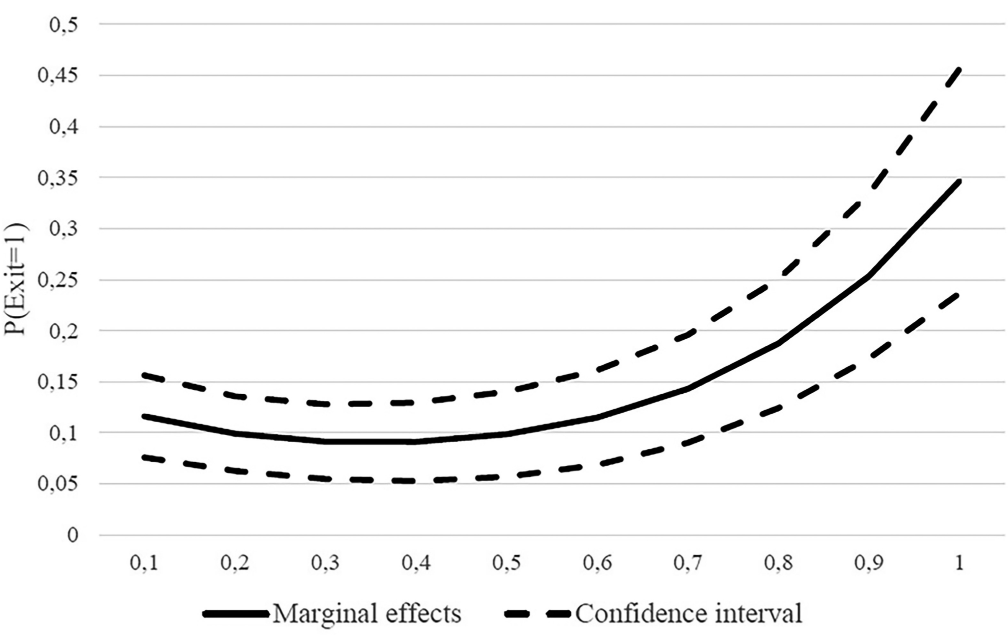

Figure 3. Effect of seal interactions with gears on the probability of exit the cod fishery.

(derivatives) will depend on the values of all explanatory variables, and in this paper we follow the conventional approach to calculate the average marginal effects as changes in predicted probability when each covariate is set to their observed values.). The effect of seal interactions with gears on the predicted probability of exit in columns 1–3 including control variables is 11.0, 11.1, and 11.0% for the probit, logit, and cloglog models, respectively. These numbers show how the probability of exit changes when the proportion of fishing trips with seal interactions increase from 0 to 1. This may be compared to the overall average predicted probability of exit of 14.6 for all three models. The corresponding marginal effects of seals in columns 4–6, i.e. for vessels with a single spell of fishing is somewhat higher: 13.6, 14.0, and 13.7 for the probit, logit, and cloglog models, respectively.

The model above specifies a linear relationship between seal interactions and the hazard rate. It is, however, possible that an

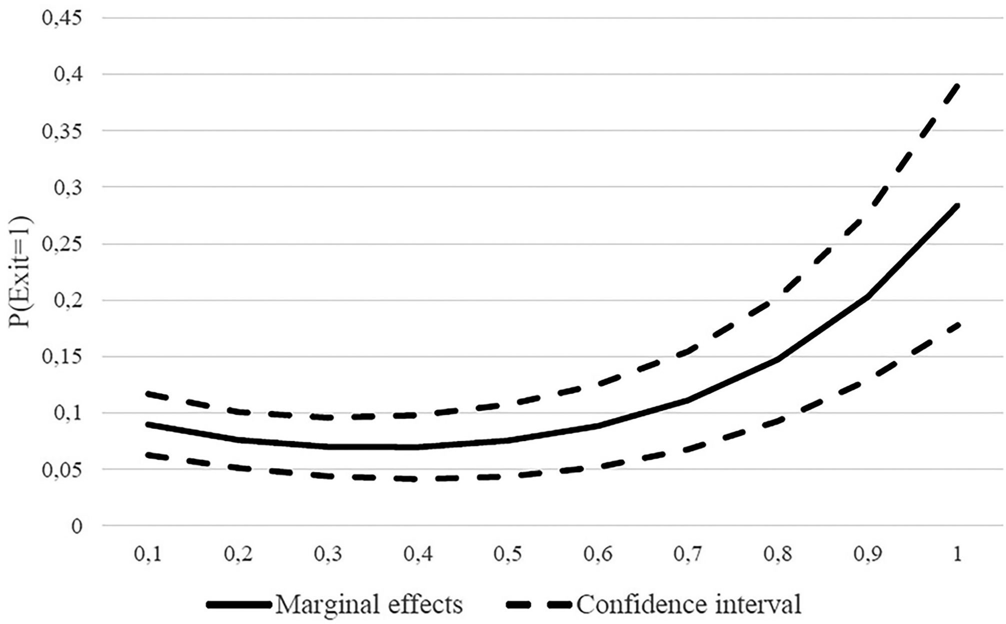

Figure 4. Effect of seal interactions with gears on the probability of exit fisheries.

increase of seal interactions from e.g. 0.1 to 0.4 does not have the same effect as an increase from 0.5 to 0.8. To capture possible non-linear effects, the square of the seal variable is included as an explanatory variable and the model is estimated using the full sample of vessels (including control variables). Likelihood ratio (LR) tests are performed to determine whether including the squared seal variable improves the fit of the model. It turns out that the LR statistics are significant at the 5% level, suggesting that the squared variable should be included. Since the effects of seals on the probability of exit is now a non-linear function, the marginal effects are plotted in Figure 3.

Figure 3 shows the effect of seal interactions on the probability of exit (solid line) together with the 95-% confidence interval (dashed lines) when the probit model is used (including control variables). The logit and cloglog models give very similar results and are omitted to save space (complete results can be found in the supplementary Appendix). As can be seen, increasing seal interactions up to 0.5 has effectively no impact on the probability to exit. However, if the proportion of trips with seal interactions increases from 0.5 to 1, the exit probability more than triples from around 10 to 35%.

The analysis above focuses on exits from the cod fishery without regarding whether or not vessels leave fisheries altogether. It turns out that few vessels exiting the cod fishery reallocate their fishing effort to other fisheries (Out of the total number of exits observed during the time period, only 11% continue fishing in the year after exiting the cod fishery. This is in line with our expectations since the small-scale cod fishery is highly specialized with few alternative target species (see e.g. Bergenius *et al.*, 2018; Björkvik *et al.*, 2020). However, to ensure that the results are not solely driven by those vessels, the hazard model in (1) is estimated using an alternate dependent variable. More specifically, we redefine the hazard λ_{ijk} to represent the probability that the vessel exit fisheries altogether. It turns out that this model produces almost identical results. Figure 4 shows the results from the non-linear probit model including control variables. Similar to above, if the proportion of trips with seal interactions with gears increases from 0.5 to 1, the exit probability more than triples from around 7 to 28%. Thus, a high level of seal interactions has a significant impact on the probability to leave fisheries.

Summary and discussion

Seals are a natural part of the fauna in Baltic coastal waters and the growing seal populations may be regarded as an example of successful marine conservation management. On the other hand, seal damages in coastal fisheries are well documented and research suggests that damages have increased significantly in recent years. Seals locate the nets and hooks and predate directly from the fishing gears, causing losses in terms of lost catches and damaged fishing gears. One fishery that has been severely affected by seal damages is the Swedish coastal cod fishery. Using logbook data between the years 2006 and 2016 the aim of this study is to examine whether seal interactions with fishing gears increase the probability of vessels exiting the cod fishery.

The results of the statistical analysis show that seal interactions have a positive and statistically significant impact on the probability of exiting the coastal cod fishery. The impact is non-linear in the sense that increases at low levels of interaction do not have the same effect as increases at high levels. For example, the results suggest that if the proportion of fishing trips with seal interactions increases from 0 to 0.5, the probability of exit is constant around 10%. However, if the proportion of trips with interactions increases from 0.5 to 1, the exit probability in a given year more than triples from 10 to 35%. Thus, seal interactions with gears constitute an important factor why vessels exit the coastal cod fishery, especially when interactions increase from an already high level.

The findings of this study are relevant for the policy discussion concerning the economic impacts of seal damages in fisheries. For example, in 2014 the Swedish management authorities made an effort to quantify the total economic losses due to seal damages in Swedish fisheries (SwAM, 2014). The calculation was based on reported seal interactions with gears in logbooks together with scientific experiments quantifying lost catches when seals were raiding the fishing gears (Fjälling, 2005). The study estimated total losses per year to be approximately 33 million Swedish crowns, or €3.5 million (SwAM, 2014). However, as shown in this paper, in addition to affecting the economic viability of active fishermen, seal damages have an unobserved cost in that fishermen leave the sector. In the extreme case where all fishermen in a region leave fisheries because of seals, there would be no observed costs related to seal damages, but large unobserved costs in terms of foregone profits. Taking this view, our paper suggests that the total societal cost of seal damages is likely to be larger than put forward in the policy debate and previous studies. This is especially relevant in fishing areas in the southern Baltic where seal interactions with gears in the coastal cod fishery have increased substantially in the recent decade. To quantify such unobserved costs is beyond the scope of this paper, and would involve in addition to a counterfactual profit calculation, a valuation of possible external effects of fisheries such as preservation of cultural heritage and promotion of tourism.

While seal damages in Baltic Sea small-scale fisheries are well documented, more research is needed to fully understand the wider socio-economic consequences of increasing seal populations. This article shows that seal damages from interactions with fishing gears is an important factor contributing to the declining number of fishing vessels in the Baltic Sea. Given the rapid growth of the grey seal population in the Baltic Sea, concerns about disappearing small-scale fisheries as a result of seals should be taken seriously and further analyzed to find management measures to mitigate the seal-fisheries conflict.

Supplementary data

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

Data availability

The data underlying this article were provided by the Swedish Agency for Marine and Water Management (individual logbook data). The data were available to the authors by a confidentiality agreement and cannot therefore be shared publicly. Please contact the corresponding author for more information about data availability.

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