The extent and the influencing factors of grey seal depredation on the monkfish static net fishery in northern Brittany, France

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Abstract

Grey seals (*Halichoerus grypus*) feeding on fishery catches, a behavior termed “depredation”, is a major socio-economic and environmental issue in many regions of the north Atlantic. In northern Brittany, seals depredating on monkfish in static nets (gillnet and trammel net) is increasingly reported as problematic, but the issue has yet to be assessed and understood. In this study, we monitored 795 net sets between 2016 and 2018 to i) quantify the frequency of depredation events and the amount of depredated fish and ii) identify the drivers influencing variation in these two metrics. We found that during this period, seal depredation occurred on 18.5% of the net sets and resulted in the removal of 5.3% of the total number of monkfish catches. From statistical models, our results suggested that the probability of seal depredation to occur was higher near haulout sites, in shallower water. However, when depredation occurred, the amount of fish depredated was higher in gillnets than in trammel nets, in longer nets, and nets set further from haulout sites. As seal depredation is likely to escalate with the increase of local grey seal populations, our results provide insights on how fishers may adjust their practices to reduce depredation in northern Britanny and other fisheries facing a similar issue.

Highlights

- We assessed grey seal depredation in the static net fishery in northern Brittany between 2016 and 2018
- Grey seal depredation occurred on 18.5% of the net sets and resulted in the removal of 5.3% of the total number of monkfish catches.
- Depredation levels were influenced by spatio-temporal and operational variables including fishing area, soaking time, depth, net type and length.
- The study highlights the needs for a closer monitoring of seal depredation and for research on seal foraging to identify effective mitigation solutions.

Keywords: Depredation, Net fishery, Monkfish, Mitigation, Co-management

1. Introduction

The accelerated expansion of human activities has led to increased interactions with wildlife (Nyhus, 2016; Treves et al., 2006). In the oceans, the spatial and trophic overlaps between marine megafauna and fisheries often result in negative interactions such as competition for fish resources, bycatch and or depredation (Bonizzoni et al., 2022; Hamer et al., 2012; Northridge, 1991; Wickens, 1995). Depredation is a behaviour developed by predators such as sharks and marine mammals when feeding on fish caught on fishing gear. It has been reported in an increasing number of fisheries since the 2000s, primarily in fisheries using nets and longlines (lines with series of baited hooks) as fishing techniques (Mitchell et al., 2018; Tixier et al., 2021). By causing catches removals and/or gear damage for the fishers, and by exposing the depredating individuals to risks of injuries or death from direct interactions with the gear or from lethal retaliation practices used by fishers, depredation on fishery catches can lead to conflicts involving both socio-economic and conservation stakes (Tixier et al., 2021).

The grey seal *Halichoerus grypus* is among the species most frequently documented feeding on fishery catches (Tixier et al., 2021). Grey seal depredation has been reported in lobster trap fisheries of the western Atlantic Ocean (Gruber, 2014), in Scottish salmon farms (Northridge et al., 2013) and in gillnet fisheries of Ireland, Scotland and the Baltic Sea (Cronin et al., 2014; Königson et al., 2007, 2005; Northridge et al., 2013). Along the west and south coasts of Ireland, grey seals were estimated removing nearly 60% of the monkfish (*Lophius spp.*) caught in nets (Cosgrove et al., 2015). Together with undetected depredation events (seals removing fish from the fishing gear without leaving any evidence) and the potential deterring effect towards fish because of the presence of seals in the vicinity of the gear, seal depredation can considerably reduce fisher's income (Fjälling, 2005; Königson et al., 2007; Waldo et al., 2020). These interactions are also a substantial cause of seal bycatch in gillnet fisheries (Cosgrove et al., 2016; Luck et al., 2020; Moan, 2016) and potential killing (Butler et al., 2008; Cronin et al., 2014; Harris et al., 2014; Olsen et al., 2018; Varjopuro, 2011). They can also lead to changes in grey seal diet (Cronin et al., 2014; Gosch, 2017), subsequently altering the food chain and predated fish stocks (Benoît et al., 2011; Cook et al., 2015; Vincent et al., 2016).

In the north-east Atlantic, the severity of grey seal depredation on fisheries catches may have increased with the recovery of seal populations over the past decades (Härkönen et al., 2007), following legal protection provided under the 1979 Berne Convention and the 1992 Council Directive 92/43/EEC (the "Habitats Directive"). While the size of grey seal populations greatly varies between regions (152,800 seals in the UK and 1,000 seals in France in 2018 - (INPN, 2023; Poncet et al., 2022; Special Committee on Seals, 2019)), most of the colonies monitored have been increasing since the 1960s (Russell et al., 2019; Vincent et al., 2017). Grey seal depredation has become a major issue confronting the socio-economic viability of the activity with conservation objectives in many fisheries of the region, especially in inshore pollack (*Pollachius virens*), monkfish (*Lophius piscatorius*), cod (*Gadus morhua*) and turbot (*Scophthalmus maximus*) fisheries using passive gear such as static nets, fish traps and salmon farms (Cronin et al., 2014; Olsen et al., 2018; Tixier et al., 2021). However, the spatio-temporal dynamics of the occurrence of seal depredation and how these are influenced by local fishing practices and grey seal haulout sites, are often poorly understood. Together with the depredation behaviour of grey seals being difficult to assess at the individual-level, these barriers make it difficult to develop appropriate mitigation measures.

Off the north coast of Brittany (France), grey seal depredation has recently emerged as problematic in the static net fishery, with fishers reporting an increase in the frequency of such depredation events since the early 2010s (Savelli, 2013). This appears to be especially the case in waters surrounding the Sept-Îles National Natural Reserve (NNR) included in the marine protected area of the Côtes- d'Armor region, which hosts a grey seal breeding colony which size has increased by 8% between 2009 and 2019 (Provost et al., 2021). In 2019, the colony size was estimated at 42 individuals with an annual pup production contributing to 70% of all births recorded in France (Provost et al., 2021). However, despite a growing conflict between small-scale fishing activities, which are socio-economically preponderant in the region (CRPMEM de Bretagne, 2015), and the conservation of grey seals, which are threatened by extinction and protected by the law since 1999, the extent of seal depredation has yet to be quantified and its drivers to be identified before implementing any mitigation actions.

Therefore, in this study, we used data dedicatedly collected between 2016 – 2018 to assess grey seal depredation in the static net monkfish fishery of around the Sept-Îles NNR. The specific objectives of our study were to i) quantify the frequency of depredation events and the amount of depredated fish and

ii) identify the spatio-temporal, environmental and operational factors influencing variation in these two metrics.

2. Material and methods

2.1. Study fishery

We monitored grey seal depredation in the small-scale fishery operating in the French waters off the northern coast of Brittany, between 48.73 – 49.05°N and 3.34 – 3.60°W (Figure 1), between 2016 and 2018. This area, hereafter ”CGR-SI” (Côte de Granit Rose – Sept-Îles), includes three protected areas with the Natura 2000 site “Côte de Granit Rose – Sept-Îles” overlapping with a marine protected area and the NNR “Sept-îles”, where the main grey seal colony and haulout sites are located (Figure 1). The Triagoz and Méloine sites are also resting places for the seals of the colony (Figure 1), and some individuals are also observed along the coast. The fishery includes 19 boats of 6 – 13.5 m in length that depart from 8 ports (from Batz to the west to Port Blanc to the east) (CRPMEM de Bretagne, 2015). The fishers primarily target monkfish, mainly between April and August, with static nets (gillnets and trammel nets). However, they also catch high value species such as flatfish (*Scophthalmus rhombus, Scophthalmus maximus*), bass (*Dicentrarchus labrax*), and lobsters (*Homarus gammarus, Palinurus elephas*). Fishers use 1 km long units of nets that they tie together to form a set of 1 to 20 km long. Gillnets are composed of a single net with a mesh size ranging from 110 to 160 mm. Trammel nets consist of two parallel outer nets with a 220 mm large mesh and an inner net with a mesh size of 135 or 154 mm. Fishers often deploy several sets during a trip (one trip per day), usually parallel to each other, at the beginning of neap-tides when the tidal coefficient is below 75 in order to avoid strong current forcing nets onto the bottom. They retrieve the nets two to three days after setting.

2.2 Data collection

We collected data on fishing operations, catches and the occurrence of seal depredation from June 2016 to August 2018 in two ways: through surveys across the fishers and through observers on boats. We conducted the surveys every two weeks following each neap-tide. For sets they had deployed over the last two weeks, we asked fishers to indicate the location of the gear (as an approximate point on a map), its type (gillnet or trammel net), its length (in km), its mesh size (stretched in mm), its soaking time, and the number of monkfish catches landed and depredated by seals. Fishers provided these data aggregated per fishing trip in 2016, and for each individual set in 2017 and 2018. Observers collected data during one fishing trip per neap-tide. These data included, for each set, the coordinates of the start and the end of the set, its type, its length, its mesh size, the time it was left soaking and the number of monkfish catches landed and depredated by seals. Both fishers and observers identified monkfish depredated by seals when the fish was damaged with large pieces or only the liver having been removed and with visible typical V-shaped bite marks (Cosgrove et al., 2015 - Figure 2).

2.3. Assessing depredation

We assessed the extent of grey seal depredation through four metrics: the interaction rate (IR), the number of depredated fish (DF), the depredation rate (DR), the mean depredation per unit effort (DPUE) (Rabearisoa et al., 2018). The IR was calculated as the proportion of sets depredated by grey seals (I, with a set considered as depredated when at least one monkfish was depredated) out of all sets monitored (MS), as follows:

The IR is the proportion of sets depredated by grey seals.

$$IR = \frac{Number\ of\ sets\ with\ depredation}{Total\ number\ of\ sets}$$

The DF was used to estimate the depredation rate (DR), as the proportion of monkfish depredated out of the total number of monkfish caught for a given period

$$DR = \frac{DF}{TC}$$

With TC being the total catch (number of monkfish caught whether landed or depredated).

The DPUE was defined as the number of monkfish depredated per km of net per set (Effort) as follows:

$$DPUE = \frac{DF}{Effort}$$

Means and standard deviations (SD) of these indices were calculated for the sets monitored overall, per year and per month.

Additionally, we estimated the loss of earnings associated with the amount of fish depredated by seals in the fishery using a range of 6-10 kg for the weight of individual monkfish and the mean market value of monkfish (P_4;8i for fish >4 kg and <8 kg, P_8i for fish >8 kg) per month i as provided by the Chambre de Commerce et d'Industrie des Côtes d'Armor (CCI Côtes d'Armor, unpublished data).

2.4. Identifying the drivers of depredation

We developed two models to examine the environmental and operational factors influencing the extent of seal depredation. First, we modelled the occurrence of seal depredation on sets (0 for sets with no depredation, 1 for depredated sets) using a generalized linear model (GLM) fitted with a binomial distribution (Zuur et al., 2007). Second, we modelled the number of depredated fish for sets on which seal depredation occurred using a GLM fitted with a Poisson distribution.

Fixed terms associated with the fishing practice we included in the two models were the depth at which sets were deployed (i.e., the depth at the centroid of each set retrieved from EMODnet, 2022), the distance between the centroid of each set and the nearest haul out site of seals (the minimum distance between the centroid of each set and the centroids of the main grey seal haul out sites), the fishing area (4 main distinct fishing areas identified by fishers during surveys – Figure 3), the soaking time, the net type, the length of the net and the time of the year (Table 1). We also included to the models fixed terms associated with environmental conditions and the local grey seal population. These were the abundance of monkfish (CPUE of depredated and landed monkfish), the tidal coefficient (retrieved from the Official Hydrographic Service of the World as a mean per neap-tide) and the number of grey seals in the Sept-Îles NNR (retrieved for each neap-tide from direct counts of individuals conducted during the spring tide preceding the neap-tide at the NNR haulout site).

For the two models, we selected the best model according to the lowest AICc (corrected Akaike Information Criterion) using "drop1" function from the "lme4" R library. Influence of collinearity between terms was verified through the Variance Inflation Factors (VIF). All statistical analyses were performed in R version 4.1.2 (R Core Team, 2021).

3. Results

3.1. Assessing depredation

We monitored 41 trips from June to September 2016 and 754 sets from October 2016 to August 2018, for a total of 795 sets (502 gillnets, 187 trammel nets and 106 combined) monitored over the whole study period with an observer coverage of 5% (43 sets).

In total, 15 fishers were surveyed between 2016 and 2018 (80% of all fishers that used static nets to target monkfish during that period), ranging from 8 to 10 per year (Table 2). The fishing effort of these surveyed fishers was the highest between 10 and 30 km off the northwest coasts of the Sept-Îles NNR (Figure 5). The fishing effort was the highest in spring and summer, with a maximum of 900 km in July, and the lowest in autumn and winter, with a minimum of 12 km in December and no static net effort in November (Figure 4). The monkfish CPUE of the sets monitored varied from 2.5 to 3 catches per km per year.

Total depredated biomass was estimated between 8,208 and 13,680 kg, which was equivalent to an estimated financial loss ranging from EUR 44,241 to 73,736 for the 15 surveyed fishers between 2016 and 2018 (Table 4). It represented a loss of EUR 983-1,639 per year per fisher, and EUR 1,660-2,770 per year per fisher when considering the 8 fishers that lost 90% of the total depredated monkfish throughout the whole study (Appendix). This loss was the highest in 2017 with EUR 23,696 – 39,494 (equivalent to EUR 2,370 – 3,949 per fisher, with 10 fishers surveyed in 2017).

During the study period, grey seal depredation occurred on 147 sets (IR = 18.5% of all 795 sets monitored). The number of depredated sets was the highest in the fishing area located to the north/northwest of the Sept-Îles NNR, that is <30 km away from the nearest grey seal haulout sites (Figure 5). No depredation was recorded in winter months except in February. February was the month for which the IR was the highest, with a maximum of 64% of 11 sets monitored in February 2017. The IR varied between 17% and 28% during the rest of the year (Figure 4). Depredation rate (DR) was 5.3% during the study period, four times higher in 2017 (8.3%) than in 2016 (2%) (Table 3). The Depredation Per Unit Effort (DPUE) on depredated set only varied between 0.2 and 1.1 catches per km per year (Table 3). The DR was the lowest (< 1% of the total monkfish catches) between September and January, and increased to > 4% between February and August, with maxima of 16% and 11% in March and May, respectively (Figure 4). The number of grey seals at the haulout sites of the Sept-Îles NNR was the highest between January and March with means >75 individuals (Figure 4).

3.2. Identifying the drivers depredation

The model best fitted to the occurrence of depredation included the fishing area, the soaking time, the tidal coefficient and the depth as fixed terms (AIC = 541 against AIC = 704 for the null model – Table 5). The model best fitted to the number of fish depredated on sets with depredation included the fishing area, CPUE, type of net, length of net, minimum distance between net and haulout site and number of seals on haulout sites as fixed terms (AIC = 906 against AIC = 1319 for the null model – Table 6). Depredation was significantly less likely to occur in zones 3 and 4 ($P < 0.001$ – Table 5) but when it occurred, the number of fish depredated was greater in zones 3 than in zone 2 ($P < 0.001$ – Table 6). The effect of the depth at which the nets were set and the tidal coefficient was significantly negative, and that of the soaking time was significantly positive on the probability of depredation to occur ($P < 0.001$ – Table 5).

When depredation occurred, the number of depredated fish was significantly lower in trammel nets than in gillnets ($P = 0.002$ – Table 6). It was positively and significantly correlated to the CPUE, the length of the set and the distance to the nearest seal haulout ($P < 0.001$). However, the number of depredated fish on sets with depredation was negatively and significantly correlated to the number of seals counted on the haulouts ($P < 0.001$ - Table 6).

4. Discussion

With 18.5% of the sets with monkfish depredated by grey seals and 5.3% of the total monkfish catches depredated between 2016 and 2018, the impact of grey seal depredation on the RGC-SI net fishery is not negligible although lower than that estimated in the Irish and Swedish static net fisheries (50-85% of the sets, 20-60% of the catches - (Cosgrove et al., 2015; Cronin et al., 2014; Königson et al., 2009, 2007, 2005)). Grey seal depredation affected 50% of the gillnets targeting cod in the central Baltic Sea in 2005 and 2006 (reaching 85% in the northern area) (Königson et al., 2009), i.e. more than 2.5 times higher than in our study. These differences may be explained by the size of the grey seal populations being larger in Ireland (7,284 – 9,365 seals in 2013 - (Ó Cadhla et al., 2013)) and in the Baltic Sea (19,400 seals in 2003 - (Harding et al., 2007)) than the size of the population in Brittany (633 seals in 2021 - Poncet et al., 2022). However, this population has been increasing by 14.1% since the 1990s, with for the Sept-Îles, the number of seals going from 22 in 1999 to 241 in 2021 (Poncet et al., 2022). Although we could not assess temporal trends in our estimates of grey seal depredation in the CGR-SI fishery due to the short times series, these are likely to increase in the future if the local seal population continues to grow.

We showed that the amount of monkfish taken by grey seals from fishing nets in the CGR-SI fishery was equivalent to EUR 1,660-2,770 per year per fisher when considering the 8 fishers that lost 90% of total depredated monkfish during the study. As a comparison, these losses are similar to those due to monk seal *Monachus monachus* depredation in small-scale fisheries in Greece (EUR 1,670 per fisher per year - Ríos et al., 2017). Fish losses due to seal depredation are associated with indirect socio-economic costs that have yet to be quantified for the CGR-SI fishery. Among these costs, although no damages to fishing gear in the form of nets being torn by seals were observed during our study, there may be additional fuel expenditures and working-time for when fishers have to increase their effort to recoup fish lost to depredation as well as a decreased CPUE due to seals scarring off the fish when coming into the vicinity of nets. In the Baltic Sea, early studies showed that 46% of these indirect costs associated with grey seal depredation were not quantified (Fjälling, 2005) and more recently, Waldo et al. (2020) estimated that grey seal depredation caused an 8% increase in the working time of fishers in this region.

The factors that we identified as influencing the extent of seal depredation in RGC-SI area can help initiate the development of potential mitigation solutions based on adjustments in the fishing practice. Specifically, we found that depredation was more likely to occur in the vicinity of seal haulout sites and between March and May. This is mainly due to the overlap between the spatio-temporal characteristics of the fishery targeting monkfish in this area and the ecology of grey seals. As shown in other regions, including in the Iroise Sea (100 km to the west of our study area), the bathymetry and the distance to haulout sites are key drivers of grey seal foraging activity, with most of this activity occurring within 30 km of the haulout sites (Huon et al., 2015; Vincent et al., 2016). High probabilities of depredation to occur between March and May may be explained by the fact that seals increase their foraging activity as they have greater energy requirements during this post-moulting period (Boily, 1995; Bowen et al., 1993). However, this assumption needs to be further examined as little seasonal variation in the foraging activity was reported for the species, for instance in Canada (Nowak et al., 2020).

In addition to avoiding areas and times of the year with high probability of seal depredation, our results suggest that fishers may reduce the amount of fish removals by adjusting the way they use their fishing gear. Firstly, we found that the depredation rate was lower in trammel nets than in gillnets. In trammel nets, it may be more difficult for seals to access and remove monkfish when it is entangled than in gillnets. Secondly, we found that depredation decreased with the length of the set. This may be explained by the fact that when a seal finds a net, it likely swims along and inspect the whole set, resulting in greater numbers of monkfish removed. Using multiple short sets instead of a single long one (the average length of the sets in the RGC-SI fishery was 12 km during the study) may involve a greater searching effort from the seals to find all the gear. Dividing the gear into small units, although potentially increasing travel and handling costs, was for instance shown as reducing the extent of killer whale *Orcinus orca* and pilot whales *Globicephala macrorhynchus* depredation on longlines (Garrison, 2007; Tixier et al., 2015). Lastly, we found that the probability of seal depredation to occur decreased with the soaking time of the gear. As leaving the nets for longer in the water increases the number of fish retrieved dead, we interpret this result as seals being more attracted to, and/or being able to find more easily, nets with greater proportions of live fish. Although fish are more likely to be hauled alive as soaking time decreases, fishers that participated in the study never spotted seals around the vessel or in the vicinity of the gear during hauling. As such, reducing the soaking time and hauling the gear faster or even using deterrent devices during hauling, as measures used in other fisheries to reduce depredation (Cosgrove et al., 2013, Gosch et al., 2017), although they may not be as effective in that fishery, require further research along with a better understanding of seal foraging behaviour around nets.

Together, the spatio-temporal and operational factors that we found as influencing grey seal depredation in the RGC-SI fishery can already help the fishers in their efforts to adjust their practices to reduce the issue. However, these adjustments should be discussed and implemented in a voluntary and adaptive manner through a stronger collaboration between fishers, managers and scientists to find a socio-economically and ecologically sustainable way of managing grey seal depredation in the region. Typically, while closing fishing areas near the seals haulout sites and during periods of high probability of seal depredation would be difficult given the small size of the total fishing area and the fact that fishers economically rely of the activity year-round, such measures should be first tested and assessed through collaborative projects. Such adaptive co-management was suggested as particularly suited to find long-term solutions to depredation, a type of human-wildlife interaction often involving conflicts between socio-economic and conservation stakes (Butler et al., 2015; Tixier, 2023; Tixier et al., 2021). In northern Brittany, the recovery of grey seal populations is considered as a conservation success. Except for perhaps a complete change in fishing techniques, which may involve some loss of local fishing knowledge, there is no solution suppressing completely grey seal depredation while meeting all other requirements for a sustainable socio-ecosystem (i.e., solutions being affordable, not affecting fish catch rates or income for fishers, not impacting the seals, fish stocks and the environment). For example, in several other fisheries, the use of acoustic deterrents has proved unsuccessful at meeting these requirements, including a loss of effectiveness towards depredation in time and potential impacts on the environment through acoustic disturbance (Götz and Janik, 2013).

5. Conclusions

From our study, and in a context of depredation likely to further escalate as grey seal populations continue to increase in the CGR-SI area, we recommend the short-term priority for the fishery being to improve the knowledge on the extent and on the mechanisms of the issue by i) implementing a consistent monitoring of fishing activities and occurrences of seal depredation, and ii) elucidating aspects of the seals foraging behaviour that can help predicting and thus anticipating depredation. On the long term, and through an adaptive co-management approach and transdisciplinary projects, we also suggest research efforts to be directed towards i) pairing mitigation measures based on adjustments in fishing practices with full socio-economic costs/benefits assessments, ii) exploring possibilities of implementing compensation or incentive schemes fostering the contribution of fishers to research efforts, iii) developing collaborations with engineering and fishing gear companies to investigate the technological tools that can help minimizing depredation, and iv) examining the role of perceptions and attitudes in the extent of the seals-fishers conflicts in the region, and how a change in these may help to increase acceptability levels towards a situation of coexistence.

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8. References

Benoît, H.P., Swain, D.P., Bowen, W.D., Breed, G.A., Hammill, M.O., Harvey, V., 2011. Evaluating the potential for grey seal predation to explain elevated natural mortality in three fish species in the southern Gulf of St. Lawrence. Mar. Ecol. Prog. Ser. 442, 149–167. https://doi.org/10.3354/meps09454

Boily, P., 1995. Theoretical heat flux in water and habitat selection of phocid seals and beluga whales during the annual molt. J. Theor. Biol. 172, 235–244. https://doi.org/10.1006/jtbi.1995.0020

Bonizzoni, S., Hamilton, S., Reeves, R.R., Genov, T., Bearzi, G., 2022. Odontocete cetaceans foraging behind trawlers, worldwide. Rev. Fish Biol. Fish. 32, 827–877. https://doi.org/10.1007/s11160-022-09712-z

Bowen, W.D., Lawson, J.W., Beck, B., 1993. Seasonal and Geographic Variation in the Species Composition and Size of Prey Consumed by Grey Seals (*Halichoerus grypus*) on the Scotian Shelf. Can. J. Fish. Aquat. Sci. 50, 1768–1778. https://doi.org/10.1139/f93-198

Butler, J.R.A., Middlemas, S.J., McKelvey, S.A., McMyn, I., Leyshon, B., Walker, I., Thompson, P.M., Boyd, I.L., Duck, C., Armstrong, J.D., Graham, I.M., Baxter, J.M., 2008. The Moray Firth Seal Management Plan: an adaptive framework for balancing the conservation of seals, salmon, fisheries and wildlife tourism in the UK. Aquat. Conserv. Mar. Freshw. Ecosyst. 18, 1025–1038. https://doi.org/10.1002/aqc.923

Butler, J.R.A., Young, J.C., McMyn, I.A.G., Leyshon, B., Graham, I.M., Walker, I., Baxter, J.M., Dodd, J., Warburton, C., 2015. Evaluating adaptive co-management as conservation conflict resolution: Learning from seals and salmon. J. Environ. Manage. 160, 212–225. https://doi.org/10.1016/j.jenvman.2015.06.019

Cook, R.M., Holmes, S.J., Fryer, R.J., 2015. Grey seal predation impairs recovery of an over-exploited fish stock. J. Appl. Ecol. 52, 969–979. https://doi.org/10.1111/1365-2664.12439

Cosgrove, R., Cronin, M., Reid, D., Gosch, M., Sheridan, M., Chopin, N., Jessopp, M., 2013. Seal depredation and bycatch in set net fisheries in Irish waters. Fish. Resour. Ser. 10, 1–44.

Cosgrove, R., Gosch, M., Reid, D., Sheridan, M., Chopin, N., Jessopp, M., Cronin, M., 2016. Seal bycatch in gillnet and entangling net fisheries in Irish waters. Fish. Res. 183, 192–199. https://doi.org/10.1016/j.fishres.2016.06.007

Cosgrove, R., Gosch, M., Reid, D., Sheridan, M., Chopin, N., Jessopp, M., Cronin, M., 2015. Seal depredation in bottom-set gillnet and entangling net fisheries in Irish waters. Fish. Res. 172, 335–344. https://doi.org/10.1016/j.fishres.2015.08.002

Cronin, M., Jessopp, M., Houle, J., Reid, D., 2014. Fishery-seal interactions in Irish waters: Current perspectives and future research priorities. Mar. Policy 44, 120–130. https://doi.org/10.1016/j.marpol.2013.08.015

CRPMEM de Bretagne, 2015. Diagnostic socio-économique des activités de pêche professionnelle. Site Natura 2000 Côte de Granit Rose – Sept Îles (ZSC FR 300009 et ZPS FR 5310011).

EMODnet, 2022. Bathymetry [WWW Document]. Eur. Mar. Obs. Data Netw. EMODnet. URL https://emodnet.ec.europa.eu/en/bathymetry (accessed 12.5.23).

Fjälling, A., 2005. The estimation of hidden seal-inflicted losses in the Baltic Sea set-trap salmon fisheries. ICES J. Mar. Sci. 62, 1630–1635. https://doi.org/10.1016/j.icesjms.2005.02.015

Garrison, L.P., 2007. Interactions between marine mammals and pelagic longline fishing gear in the U.S. Atlantic Ocean between 1992 and 2004. Fish. Bull. 105, 408–417.

Gosch, M., 2017. The diet of the grey seal [Halichoerus grypus (Fabricius, 1791)] in Ireland and potential interactions with commercial fisheries. Dr. Diss. Univ. Coll. Cork 195.

Gosch, M., Luck, C., Cosgrove, R., Goetz, T., Tyndall, P., Cronin, M., 2017. Development of acoustic deterrent device to mitigate seal fisheries interactions interim report January 2017.

Götz, T., Janik, V.M., 2013. Acoustic deterrent devices to prevent pinniped depredation: efficiency, conservation concerns and possible solutions. Mar. Ecol. Prog. Ser. 492, 285–302. https://doi.org/10.3354/meps10482

Gruber, C., 2014. Social, Economic, and Spatial Perceptions of Gray Seal (Halichoerus grypus) Interactions with Commercial Fisheries in Cape Cod, MA 68.

Hamer, D.J., Childerhouse, S.J., Gales, N.J., 2012. Odontocete bycatch and depredation in longline fisheries: A review of available literature and of potential solutions. Mar. Mammal Sci. 28, E345–E374. https://doi.org/10.1111/j.1748-7692.2011.00544.x

Harding, K.C., Härkönen, T., Helander, B., Karlsson, O., 2007. Status of Baltic grey seals: Population assessment and extinction risk. NAMMCO Sci. Publ. 6, 33–56. https://doi.org/10.7557/3.2720

Härkönen, T., Brasseur, S., Teilmann, J., Vincent, C., Dietz, R., Abt, K., Reijnders, P., 2007. Status of grey seals along mainland Europe from the Southwestern Baltic to France. NAMMCO Sci. Publ. 6, 57. https://doi.org/10.7557/3.2721

Harris, R.N., Harris, C.M., Duck, C.D., Boyd, I.L., 2014. The effectiveness of a seal scarer at a wild salmon net fishery. ICES J. Mar. Sci. 71, 1913–1920. https://doi.org/10.1093/icesjms/fst216

Huon, M., Jones, E.L., Matthiopoulos, J., McConnell, B., Caurant, F., Vincent, C., 2015. Habitat selection of gray seals (Halichoerus grypus) in a marine protected area in France. J. Wildl. Manag. 79, 1091–1100. https://doi.org/10.1002/jwmg.929

INPN, 2023. Halichoerus grypus (Fabricius, 1791) - Phoque gris [WWW Document]. Inventaire Natl. Patrim. Nat. URL https://inpn.mnhn.fr/espece/cd_nom/60776 (accessed 8.8.22).

Königson, S., Fjälling, A., Lunneryd, S.-G., 2007. Grey seal induced catch losses in the herring gillnet fisheries in the northern Baltic. NAMMCO Sci. Publ. 6, 203–213. https://doi.org/10.7557/3.2735

Königson, S., Fjälling, A., Lunneryd, S.-G., 2005. Impact of grey seals in the herring gillnet fishery along the Swedish Baltic coast. Inst. Coast. Res. Swed. Board Fish. ICES CM 10, 6.

Königson, S., Lunneryd, S., Stridh, H., Sundqvist, F., 2009. Grey Seal Predation in Cod Gillnet Fisheries in the Central Baltic Sea. Fish Sci J Northw Atl Fish Sci 42, 41–47. https://doi.org/10.2960/J.v42.m654

Luck, C., Jessopp, M., Tully, O., Cosgrove, R., Rogan, E., Cronin, M., 2020. Estimating protected species bycatch from limited observer coverage: A case study of seal bycatch in static net fisheries. Glob. Ecol. Conserv. 24, e01213. https://doi.org/10.1016/j.gecco.2020.e01213

Mitchell, J.D., McLean, D.L., Collin, S.P., Langlois, T.J., 2018. Shark depredation in commercial and recreational fisheries. Rev. Fish Biol. Fish. 28, 715–748. https://doi.org/10.1007/s11160-018-9528-z

Moan, A., 2016. Bycatch of harbour porpoise, harbour seal and grey seal in Norwegian gillnet fisheries 73.

Northridge, S., Coram, A., Gordon, J., 2013. Investigations on Seal Depredation at Scottish Fish Farms. Rep. Mar. Scotl. Scott. Gov.

Northridge, S.P., 1991. An updated world review of interactions between marine mammals and fisheries. FAO Fisheries Technical Paper, 58.

Nowak, B.V.R., Bowen, W.D., Whoriskey, K., Lidgard, D.C., Mills Flemming, J.E., Iverson, S.J., 2020. Foraging behaviour of a continental shelf marine predator, the grey seal (Halichoerus grypus), is associated with in situ, subsurface oceanographic conditions. Mov. Ecol. 8, 41. https://doi.org/10.1186/s40462-020-00225-7

Nyhus, P.J., 2016. Human–Wildlife Conflict and Coexistence. Annu. Rev. Environ. Resour. 41, 143–171. https://doi.org/10.1146/annurev-environ-110615-085634

Ó Cadhla, O., Keena, T., Strong, D., Duck, C., Hiby, L., 2013. Monitoring of the breeding population of grey seals in Ireland, 2009 - 2012. Irish Wildlife Manuals.

Olsen, M.T., Galatius, A., Härkönen, T., 2018. The history and effects of seal-fishery conflicts in Denmark. Mar. Ecol. Prog. Ser. 595, 233–243. https://doi.org/10.3354/meps12510

Poncet, S., Mercereau, I., Couvrat, C., Le Baron, M., Francou, M., Hemon, A., Fremau, M.-H., Lecarpentier, T., Elder, J.-F., Gicquel, C., Monnet, S., Rault, C., Karpouzopoulos, J., Lefebvre, J., Everard, A., Colomb, F., Diard Combo, M., Provost, P., Deniau, A., Urtizberea, F., Koelsch, D., Letournel, B., Vincent, C., 2022. Recensement des colonies et reposoirs de phoques en France en 2020 et 2021. Rapp. Collect. Réseau Natl. Phoques 45.

Provost, P., Morinière, R., Deniau, A., 2021. Réserve Naturelle Nationale des Sept-Îles Rapport d’activités 2020. Ligue pour la Protection des Oiseaux.

R Core Team, 2021. R: A language and environment for statistical computing.

Rabearisoa, N., Sabarros, P.S., Romanov, E.V., Lucas, V., Bach, P., 2018. Toothed whale and shark depredation indicators: A case study from the Reunion Island and Seychelles pelagic longline fisheries. PLOS ONE 13, e0202037. https://doi.org/10.1371/journal.pone.0202037

Ríos, N., Drakulic, M., Paradinas, I., Milliou, A., Cox, R., 2017. Occurrence and impact of interactions between small-scale fisheries and predators, with focus on Mediterranean monk seals (Monachus monachus Hermann 1779), around Lipsi Island complex, Aegean Sea, Greece. Fish. Res. 187, 1–10. https://doi.org/10.1016/j.fishres.2016.10.013

Russell, D.J.F., Morris, C.D., Duck, C.D., Thompson, D., Hiby, L., 2019. Monitoring long-term changes in UK grey seal pup production. Aquat. Conserv. Mar. Freshw. Ecosyst. 29, 24–39. https://doi.org/10.1002/aqc.3100

Savelli, R., 2013. La déprédation des phoques dans les espaces protégés en France: revue bibliographique, enquête et préconisations. https://doi.org/10.13140/RG.2.1.3822.6006

Special Committee on Seals, 2019. Scientific advice on matters related to the management of seal populations: 2019.

Tixier, P., 2023. Tixier, Paul, UMR IRD, and France Sète. "Sustainable solutions to fishing-marine megafauna conflicts. Sustain. Sci. Understand Co-Constr. Transform Collect. Think. 24–27.

Tixier, P., Lea, M.-A., Hindell, M.A., Welsford, D., Mazé, C., Gourguet, S., Arnould, J.P.Y., 2021. When large marine predators feed on fisheries catches: Global patterns of the depredation conflict and directions for coexistence. Fish Fish. 22, 31–53. https://doi.org/10.1111/faf.12504

Tixier, P., Vacquie Garcia, J., Gasco, N., Duhamel, G., Guinet, C., 2015. Mitigating killer whale depredation on demersal longline fisheries by changing fishing practices. ICES J. Mar. Sci. 72, 1610–1620. https://doi.org/10.1093/icesjms/fsu137

Treves, A., Wallace, R.B., Naughton-Treves, L., Morales, A., 2006. Co-Managing Human–Wildlife Conflicts: A Review. Hum. Dimens. Wildl. 11, 383–396. https://doi.org/10.1080/10871200600984265

Varjopuro, R., 2011. Co-existence of seals and fisheries? Adaptation of a coastal fishery for recovery of the Baltic grey seal. Mar. Policy, The Human Dimensions of Northern Marine Mammal

Management In A Time Of Rapid Change 35, 450–456. https://doi.org/10.1016/j.marpol.2010.10.023

Vincent, C., Huon, M., Caurant, F., Dabin, W., Deniau, A., Dixneuf, S., Dupuis, L., Elder, J.-F., Fremau, M.-H., Hassani, S., Hemon, A., Karpouzopoulos, J., Lefeuvre, C., McConnell, B.J., Moss, S.E.W., Provost, P., Spitz, J., Turpin, Y., Ridoux, V., 2017. Grey and harbour seals in France: Distribution at sea, connectivity and trends in abundance at haulout sites. Deep Sea Res. Part II Top. Stud. Oceanogr., Abundance, distribution and habitats of Atlantic and Mediterranean marine megafauna 141, 294–305. https://doi.org/10.1016/j.dsr2.2017.04.004

Vincent, C., Ridoux, V., Fedak, M.A., McConnell, B.J., Sparling, C.E., Leaute, J.-P., Jouma'a, J., Spitz, J., 2016. Foraging behaviour and prey consumption by grey seals (*Halichoerus grypus*) spatial and trophic overlaps with fisheries in a marine protected area. ICES J. Mar. Sci. J. Cons. 73, 2653–2665. https://doi.org/10.1093/icesjms/fsw102

Waldo, S., Paulrud, A., Blomquist, J., 2020. The economic costs of seal presence in Swedish small-scale fisheries. ICES J. Mar. Sci. 77, 815–825. https://doi.org/10.1093/icesjms/fsz221

Wickens, P.A., 1995. A review of operational interactions between pinnipeds and fisheries, FAO fisheries technical paper. Food and Agriculture Organization of the United Nations, Rome.

Zuur, A., Ieno, E.N., Smith, G.M., 2007. Analyzing Ecological Data. Springer.

Tables

Table 1. Description of the spatio-temporal, environmental and operational covariates included in the models fitted to the occurrence of seal depredation and to the amount of depredated fish.

Covariate	Type	Name	Unit
Fishing set depth	Numerical	Depth	m
Minimum distance between fishing set and grey seal haulout site	Numerical	Minimum distance	m
Area (Figure 3)	Categorical	Area	
Soaking time	Categorical	Soaking time	days
Fishing net type	Categorical	Net type	
Capture Per Unit of Effort	Numerical	CPUE	n/km
Fishing set length	Numerical	Length	km
Season	Categorical	Season	
Tidal coefficient	Numerical	Tidal coefficient	
Grey seal population on haulout sites	Numerical	Seals	n

Table 2. Summary of the data used for the study with, for the 2016-2018 period, the number of fishers surveyed, the number of fishing sets monitored and their length (fishing effort), the number of monkfish captured and landed, and the mean and standard deviation of the CPUE (total number of monkfish individuals captured, including monkfish both landed and depredated, per km of net per set). * indicates that the number of sets monitored was considered as equivalent to the number of trips (year 2016 only).

	Number of fishers	Number of fishing sets	Fishing effort (km of net)	Number of monkfish landed	Capture Per Unit Effort (Mean ± sd)
2016	9	42*	2136	8091	3.4 ± 1.5
2017	10	411	3438	7938	2.5 ± 1.8

2018	8	342	3453	8711	2.8 ± 2.0
Total	15	795	9027	24730	2.7 ± 1.8

Table 3. Seal depredation level estimates for the 2016-2018 study period with the interaction rate (% of sets depredated out of all sets), the depredation rate (% of depredated monkfish out of all monkfish captured on sets), the mean number of depredated monkfish per unit effort (in number of depredated monkfish per km of net, including both non-depredated and depredated sets, and for depredated sets only), the mean number of depredated monkfish per set (including depredated sets only). * indicates that the number of sets monitored was considered as equivalent to the number of trips (year 2016 only).

	Interaction rate	Depredation rate	Depredation Per Unit Effort (Mean ± sd)	Depredation Per Unit Effort on depredated set (Mean ± sd)	Depredation on depredated set (Mean ± sd)
2016	33%	2%	0.1 ± 0.1	0.2 ± 0.1	12.1 ± 10.8
2017	16%	8.3%	0.2 ± 0.6	1.1 ± 1.0	10.9 ± 9.6
2018	19.6%	5.3%	0.2 ± 0.6	1.1 ± 1.0	7.3 ± 6.2
Total	18.5%	5.3%	0.2 ± 0.6	1.0 ± 1.0	9.3 ± 8.5

Table 4. Number of depredated monkfish during the 2016-2918 study period and the estimated depredated biomass and loss of earnings associated with depredation. The estimation of the depredated biomass and loss of earnings were made using a range of 6-10 kg for the weight of individual monkfish and the mean market value of monkfish (P_20i for fish >4 kg and <8 kg, P_10i for fish >8 kg) per month i as provided by the Chambre de Commerce et d'Industrie des Côtes d'Armor (CCI Côtes d'Armor, unpublished data).

	Number of depredated monkfish	Estimated depredated biomass (kg)	Loss of earnings (EUR)
2016	169	1,014 – 1,690	5,724 - 9,540
2017	713	4,278 – 7,130	23,696 - 39,494
2018	486	2,916 – 4,860	14,821 - 24,702

total	1,368	8,208 – 13,680	44,241 - 73,736

Table 5. Outputs of the model fitted to the occurrence of seal depredation on sets.

Model	Covariates	Estimates	Odds-Ratio	Wald statistic (p-value)	$R^{2\ MacFadden}$
GLM Binomial	Area 3 (Compared to area 2)	-0.55	0.58	1.81e-02	0.14
	Area 4 (Compared to area 2)	-2.28	0.10	7.64e-06	
	Soaking time 4 days (compared to 3 days)	-0.91	0.4	2.34e-02	
	Tidal coefficient	-0.1	0.91	2.89e-05	
	Depth	-0.04	0.96	5.30e-04	

Table 6. Outputs from the model fitted to the number of fish depredated by seals.

Model	Covariates	Estimates	Wald statistic (p-value)	$R^{2\ MacFadden}$
GLM Poisson	Area 3 (Compared to area 2)	0.27	4.77e-06	0.29
	CPUE	0.03	< 2e-16	
	Seals	-0.02	9.65e-13	
	Net type (Compared to gillnet)	-0.37	9.37e-05	
	Minimum distance	2.10^{-5}	3.04e-04	
	Length	0.07	1.28e-07	

Figure captions

Figure 1. Map of the study area with in the black polygon: the area in which fishing activities and depredation were monitored for the study, and grey polygon with shaded lines: the Natura 2000 “Côte de Granit Rose – Sept_Îles” protected area. Green dots are fishing harbours. Yellow triangles are grey seals haulout sites.

Figure 2. Examples of a non-depredated monkfish (a) and monkfish depredated by seals (b-c)

Figure 3. Delineation of the four fishing areas included in the models fitted to the occurrence of grey seal depredation and to the amount of depredated fish as a spatial covariate

Figure 4. Monthly variation of the fishing effort, the depredation levels and the number of seals in adjacent haul-out sites. Values were calculated as means (+/- SD – error bars) for each month over the number of years of study for which data were available (in brackets on the x-axis) and included: (A) the mean fishing effort (in km of net), (B) the mean interaction rate (IR, % of sets with depredation out of all sets), (C) the mean depredation rate (% of the monkfish depredated out of all monkfish captured), and (D) the mean number of seals in haul out sites. No fishing effort was monitored during November no counting of seals were conducted in December.

Figure 5. Spatial variation of (A) the fishing effort (in km of net) and (B) the number of sets depredated by seals over the CGR-SI area between 2016 and 2018. Values were calculated for squares of 0.1° side.