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*Marine Mammal Science*

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# Evidence of Pinniped Depredation Activity in South Georgia's Patagonian Toothfish Fishery

Huw W. James[1,2,3] | Jamie Coleman[2] | Martin A. Collins[2] | Jaume Forcada[2] | Philip R. Hollyman[2,4]

[1]School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, UK | [2]British Antarctic Survey, Natural Environment Research Council, Cambridge, UK | [3]MRAG Ltd., London, UK | [4]School of Ocean Sciences, Bangor University, Menai Bridge, UK

**Correspondence:** Huw W. James (h.james9@newcastle.ac.uk)

**Received:** 3 July 2026 | **Revised:** 5 November 2026 | **Accepted:** 10 November 2026

**Keywords:** Antarctic fur seal | depredation | fisheries | human–wildlife conflict | leopard seal | marine mammals

## ABSTRACT

Marine mammal depredation is an important consideration within sustainable management. Studies on depredation activity in South Georgia's Patagonian toothfish (*Dissostichus eleginoides*) fishery have focused on odontocetes, with little attention directed toward pinnipeds. This study provides the first detailed description of fishery-leopard seal (*Hydrurga leptonyx*) interactions and explores multiyear spatial and temporal trends in the depredation behavior of both leopard seals and Antarctic fur seals (*Arctocephalus gazella*) in the toothfish fishery. Although less frequent than odontocete depredation, pinnipeds repeatedly depredated the Patagonian toothfish longline fishery. The likelihood of pinniped depredation increased through the fishing season (April–August) and differed between continental shelves in both species. Interannual variation in depredation rates was apparent, with no recorded depredation events post-2021, coinciding with a fleet-wide alteration in the hauling configuration of the fishing vessels. It remains unclear whether the updated configuration prevents depredation activity or obstructs observers' ability to accurately record this behavior. Based on the limitations of the current data, we outline recommendations to enhance the data-collection process, which will support future investigations into the drivers of this behavior and potential mitigation measures. Addressing these knowledge gaps will guide effective sustainable fisheries management and reduce fisheries–wildlife conflict.

## 1 | Introduction

The expansion of environmentally exploitative industries is increasing the overlap and conflict between humans and animals (Schell et al. 2021). An example of this interaction is depredation in the fisheries sector, where wild animals interact with fishing gear and consume catch (Earl et al. 2021). A number of different taxa have been observed depredating fisheries, such as invertebrates (Brock et al. 2006; Remeslo et al. 2019), elasmobranchs (Mitchell et al. 2018), cetaceans (Earl et al. 2021), and pinnipeds (Collins et al. 1993; Meÿer et al. 1992). Depredation behavior is a widespread issue, with losses being recorded from fisheries in Alaska (Peterson et al. 2014) to the sub-Antarctic region (Earl et al. 2021; Guinet et al. 2015), and its occurrence appears to be increasing on a global scale (Purves et al. 2004; Tixier et al. 2021).

South Georgia's Patagonian toothfish (*Dissostichus eleginoides* Smitt 1898) longline fishery began in the late 1980s and underwent rapid expansion in the 1990s. Marine mammal depredation was first recorded in the fishery in 1994 and has largely been attributed to odontocetes (Purves et al. 2004), specifically orcas (*Orcinus orca* (L. 1758)) and sperm whales (*Physeter macrocephalus* L. 1758), with rarer reports of Antarctic fur seals (*Arctocephalus gazella* Peters 1875) exhibiting this behavior (Söffker et al. 2015). Depredation activity reduces the financial viability of the Patagonian toothfish fishery, as an estimated 5% of the total catch is lost each year to marine mammal depredation

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(Earl et al. 2021; Söffker et al. 2015). The sustainability of the fishery is also impacted, as mortality associated with depredation is a crucial metric to account for in fisheries management (Earl et al. 2021; Tixier et al. 2021). Furthermore, the inherent risk of injuries caused by interactions with the fishing gear increases with depredation behavior (Hamer et al. 2012; Passadore et al. 2015; Tixier et al. 2021). Depredation associated with odontocetes is well documented in the South Georgia longline fishery (Earl et al. 2021; Söffker et al. 2015). However, few studies have explored the characteristics of depredation attributed to pinnipeds. As the characteristics, risks, and potential mitigation measures of pinniped depredation are likely to differ from those of odontocetes, it is crucial to improve the current understanding of this behavior.

Leopard seals (*Hydrurga leptonyx* (Blainville 1820)) and Antarctic fur seals both occupy high trophic positions in the Southern Ocean, possess circumpolar distributions, and are present year-round at South Georgia (Arthur et al. 2017; Boveng et al. 1998; Staniland et al. 2018). Antarctic fur seals predominantly depend on crustaceans, mesopelagic fish, and cephalopods as prey (Lea et al. 2002; Waluda et al. 2010), whereas leopard seals are considered top predators with a generalist diet, mainly predating seals, birds, fish, and krill (Ainley et al. 2005; Boveng et al. 1998; Casaux et al. 2009; Edwards et al. 2010; Robbins et al. 2019; Schwarz et al. 2013; Walker et al. 1998). Adult Patagonian toothfish are demersal and generally occupy depths > 500 m (Bamford et al. 2024), outside of the normal foraging range of both species (Boyd et al. 1994; Krause et al. 2015; Staniland and Robinson 2008). Therefore, it is unlikely that adult toothfish naturally feature in each seal's diet, and their consumption is only possible due to depredation. Although both species have been recorded depredating toothfish fisheries (Devine 2022; Söffker et al. 2015; Tixier et al. 2021), the exact method and behavior, as well as the temporal and spatial trends, have not been described in depth in the literature. Improving the current understanding of this behavior and its frequency throughout the fishery is key to managing this conflict (Purves et al. 2004; Tixier et al. 2021).

Using marine mammal observation (MMO) data collected during longline hauling events (1998–2024) by observers (Figure 1), we aimed to provide detailed information on the characteristics of depredation behavior attributed to leopard seals and Antarctic fur seals in South Georgia's Patagonian toothfish fishery. The following objectives were explored: (1) describe the observed behavior of both species during interactions with longline fishing gear, (2) identify the temporal trends of pinniped depredation, (3) assess the spatial preferences of depredation activity in pinnipeds, and (4) suggest recommendations to enhance the data-collection process for pinniped depredation events.

## 2 | Methods

### 2.1 | Study Site

The study site encompassed the CCAMLR Subarea of 48.3, which is subdivided into three Management Areas (Figure 1). Longline fishing activity targeting Patagonian toothfish is generally restricted to the continental shelves of South Georgia (Management Area C—$n = 29{,}766$) and Shag Rocks (Management Area B—$n = 14{,}827$) (Figure 1). Management Area A was closed to fishing activity after 2005 ($n = 725$). The spatial references for the hauls included within this study (1998–2024) are displayed in Figure 1 ($n = 45{,}318$).

### 2.2 | Ethical Statement

Observations were conducted following the best practice guidelines (CCAMLR 2026), and no animals were harmed, handled, or disturbed during this study.

### 2.3 | Data Collection

All data were supplied by CCAMLR (Data Request 745) and were sourced from the scientific fisheries observer program associated with South Georgia's Patagonian toothfish fishery, spanning the designated region of normal fishing practices (Figure 1) between 1998 and 2024 (Söffker et al. 2015). Before 2003, MMOs were not collected on all vessels operating in the fishery (Purves et al. 2004). All observers operated under the Scheme of International Scientific Observation (SISO), and standardized CCAMLR protocols were followed throughout, ensuring consistency in data collection. Observations were made following the line-hauling observation methods (CCAMLR 2006, 2026), summarized as follows: MMOs were generally conducted for 50% of the hauling period per line. Observers were required to describe marine mammal interactions with the fishing gear during this time. The observation recording process has altered

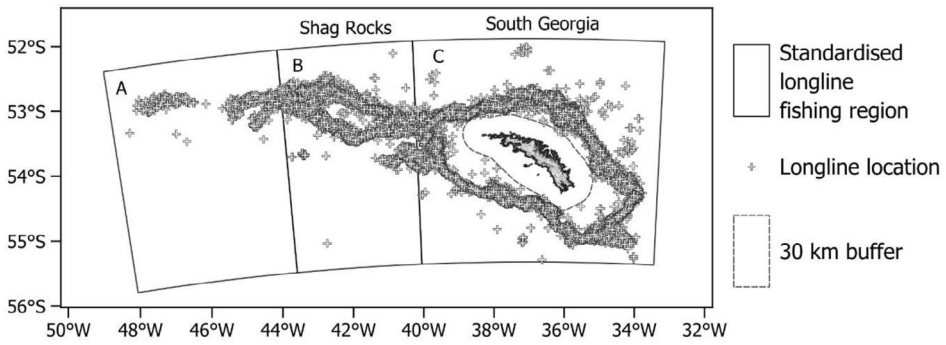


**FIGURE 1** | The haul locations ($n = 45{,}318$) conducted between 1998 and 2024 in the standard fished area within CCAMLR Subarea 48.3 (Management Areas A–C), which includes the Shag Rocks and the South Georgia continental shelves (South Georgia GIS 2019).



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slightly across the study period, with MMOs from 1998 to 2016 exclusively listing when a marine mammal was sighted, the species, an estimated number of individuals, and whether they were observed depredating the line. From 2016 to 2024, additional information was also recorded, including whether an MMO was undertaken for a given haul, as well as additional comments on noteworthy behavior. Both data-collection periods were incorporated in this analysis.

All photos and videos were taken by the allocated fisheries observer during the 2019 and 2021 Patagonian toothfish fishing seasons. During both events, the observer made detailed notes of the depredation behavior of leopard seals and Antarctic fur seals, which were summarized for this study. To accompany the observer data, the vessel also recorded the date and spatial position of the sets and hauls.

### 2.4 | Data Analysis

If one or more pinniped depredation events were recorded during a haul, depredation was considered present. As absences were not specifically recorded before 2016, any haul with no depredation activity attributed to it was treated as an absence. For post-2016 data, hauls were removed if the observer deemed it was not possible to conduct an MMO (generally due to obstructed viewpoints or poor visibility attributed to the weather conditions). If an observation was deemed possible but no depredation activity attributed to pinnipeds was recorded, these were treated as absences. Accordingly, the resulting depredation rates represent conservative estimates, reflecting the potential for unrecorded events in years where MMOs were not standardized across all vessels and where absence data were not systematically collected.

For spatial references, the haul start position was the primary choice, but for hauls when this was not recorded ($n = 2623$), the set-start position was used. Hauls that were recorded within the 30-km buffer around the South Georgia landmass or outside the standardized longline fishing region (Figure 1) were removed from the dataset to ensure that the data represented normal fishing practices for the fishery. For standardization, the number of hauls with depredation events recorded per species was divided by the total number of hauls conducted in the year or month.

The timings of South Georgia's toothfish fishery have been constrained to the austral winter since 1995 (Söffker et al. 2015). To ensure comparability across fishing seasons, we restricted the data to hauls completed between April and August, as in Abreu et al. (2024). To assess trends in the probability of depredation events during the fishing season, we fitted separate binomial generalized linear models to both leopard seal and Antarctic fur seal depredation data grouped by month, which acted as the fixed effect. We also assessed whether depredation rates varied between the continental shelves (Shag Rocks vs. South Georgia) for each species by fitting separate generalized linear models, using a logit function, to each seal species depredation activity, with the shelf affiliated with the behavior as the fixed effect. Hauls affiliated with Management Area C were categorized as South Georgia and those with Management Area B as Shag Rocks (Figure 1). As no depredation behavior was recorded in Management Area A, these hauls were not included in the spatial analysis. The sum of depredation events for each species was plotted in 5 × 5-km grid cells across both continental shelves. All analyses were conducted using R v4.5.0 (R Core Team 2025). The figures were produced with the packages *ggpubr* (Kassambara 2023), *ggplot2* (Wickham 2016), and *QGIS 3.40.10-Bratislava* (QGIS Development Team 2024). Silhouettes of each species were extracted from PhyloPic with the package *rphylopic* (Gearty et al. 2018).

## 3 | Results

### 3.1 | Description of Pinniped Depredation Behavior

Although pinniped depredation has been widely recorded throughout the fishery, detailed descriptions of the associated behaviors are limited. We therefore summarize behavioral observations of depredation activity for both Antarctic fur seals and leopard seals during hauling operations on vessels using a side-haul configuration. On July 24, 2021, an Antarctic fur seal was repeatedly seen approaching the line that was being hauled. After several forays into the area covered by the bird exclusion device, the seal captured a blue antimora (*Antimora rostrata* (Günther 1878)) from the fishing hooks. It was then seen to repeatedly shake and throw the fish and eventually consume it (Figure 2). The behavior was also documented with video footage and was observed for approximately 10 min before the observer lost sight of the individual (Supplementary Material 1). There are records of Antarctic fur seals depredating other bycatch species, such as grenadier (*Macrourus* spp.), but no observer records specifically described Antarctic fur seals consuming Patagonian toothfish.

On June 6, 2019, video footage of a single leopard seal removing a Patagonian toothfish from the line was obtained as the fish (~100-cm total length [TL]) broke the surface during the hauling process (Supplementary Material 2). It was noted by the observer that the seal had unsuccessfully attempted to remove two other fish in the same haul. Due to the low light levels, it was



**FIGURE 2** | An Antarctic fur seal (*Arctocephalus gazella*) feeding on a blue antimora (*Antimora rostrata*) after dislodging it from the line during the hauling process.



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not possible to record further information regarding the leopard seal's behavior before or after the depredation event. On August 28, 2021, a leopard seal was photographed unsuccessfully attempting to remove a Patagonian toothfish, approximately 80-cm TL, that had been captured during daylight hours. The same individual then returned and successfully acquired another similarly sized toothfish from the hooks before it reached the surface. The leopard seal was then observed swimming away with the Patagonian toothfish, vigorously shaking the individual, and then consuming it incrementally (Figure 3). The feeding process was observed for approximately 15 min before the observer lost sight of the leopard seal. In both 2019 and 2021, seals were observed inspecting the region surrounding the hauling area multiple times before approaching the line and making close passes to the toothfish as they were being hauled on board the fishing vessel. After several passes, the seals were eventually seen pulling the toothfish off the hooks in the upper 10 m of the water column. From July 7 to August 31, 2021, successful leopard seal depredation was recorded on seven different occasions by the fisheries observer, with a single individual removing and consuming one to four Patagonian toothfish in a single depredation event.

### 3.2 | Temporal Variation in Depredation Events

Although detailed accounts of pinniped depredation were rare, the behavior was widespread throughout the fishery. Antarctic fur seal depredation was recorded on 2% of the hauls, whereas leopard seal depredation rates were 0.2%, which was lower in comparison to sperm whale (17.7%–25.4% of hauls) and orca depredation rates (3.8%–4.7%) reported in the literature (Clark and Agnew 2010; Söffker et al. 2015). Two distinct peaks were observed in leopard seal depredation rates in 2003 (28 events) and 2021 (8 events). A peak was also observed in 2009 for Antarctic fur seals, where 286 depredation events were recorded. No depredation events were recorded post-2021 for either pinniped species (Figure 4).

Depredation rates increased during the standard fishing season (April–August), with the highest rate observed in August for both seal species (Figure 5). The results from binomial GLMs indicated that the probability of depredation increased significantly throughout the fishing season for both leopard seals ($\beta = 0.50 \pm 0.11$ SE, $z = 4.51$, $p < 0.001$) and Antarctic fur seals ($\beta = 0.57 \pm 0.03$ SE, $z = 17.6$, $p < 0.001$).

### 3.3 | Spatial Distribution in Depredation Events

Spatial separation was observed between depredation events attributed to each pinniped species across South Georgia ($n = 29{,}766$) and Shag Rocks ($n = 14{,}827$) continental shelves (Figure 6). Leopard seal depredation incidents were more frequent at Shag Rocks (54 events) than at South Georgia (18 events), and the binomial GLM confirmed that the likelihood of depredation incidents was significantly lower at South Georgia ($\beta = -1.80$, SE = 0.27, $z = -6.60$, $p < 0.001$). The opposite was observed for Antarctic fur seals, where depredation incidents were significantly more frequent at South Georgia (873 events) than at Shag Rocks (32 events) ($\beta = 2.64$, SE = 0.18, $z = 14.63$, $p < 0.001$). Antarctic fur seal depredation events were primarily clustered to the south of South Georgia's landmass, with the majority of depredation events located to the south of −54°S latitude and between −38°W and −36°W longitude. Zero depredation events were recorded in Management Zone A. Therefore, these hauls ($n = 725$) were not included in the GLMs.

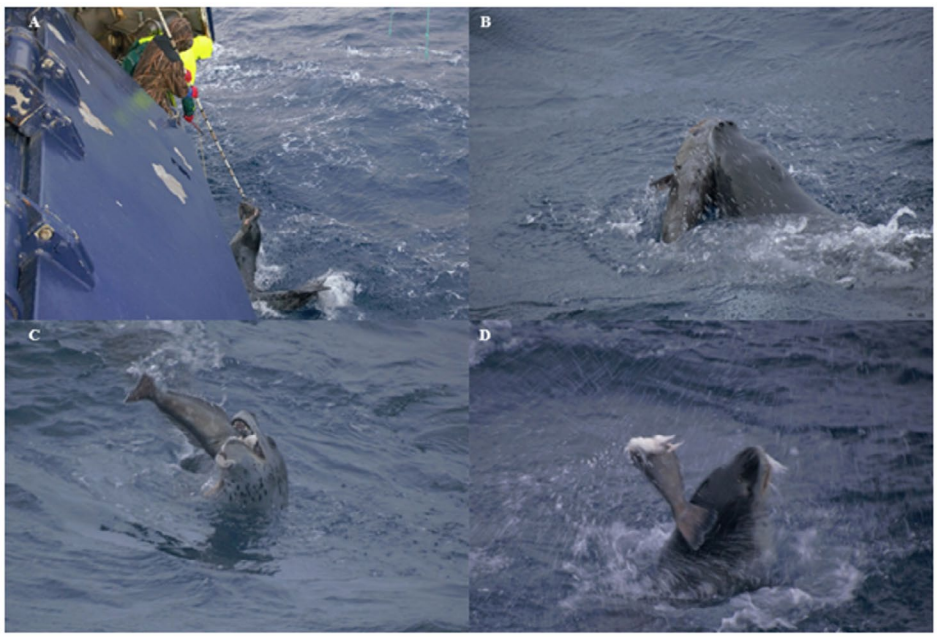


**FIGURE 3** | Leopard seal (*Hydrurga leptonyx*) depredation behavior. (a) Attempting to dislodge a Patagonian toothfish (*Dissostichus eleginoides*) that had been captured. (b) Carrying away a dislodged Patagonian toothfish. (c) Attempting to consume large portions of a Patagonian toothfish. (d) Vigorously shaking the body of a Patagonian toothfish dislodged from the fishing line.



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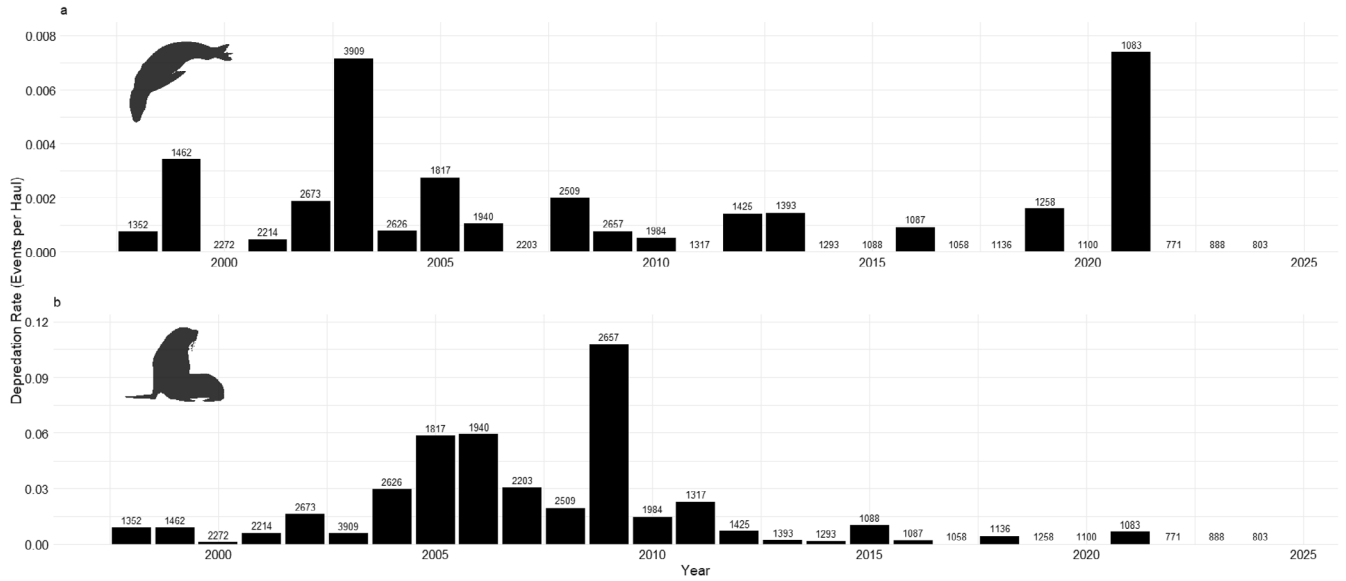


**FIGURE 4** | The number of hauls where leopard seal (*Hydrurga leptonyx*) (a) and Antarctic fur seal (*Arctocephalus gazella*) (b) depredation events were recorded as present, divided by the total number of hauls (1998–2024) conducted per annum (displayed above each column) ($n = 45{,}318$).

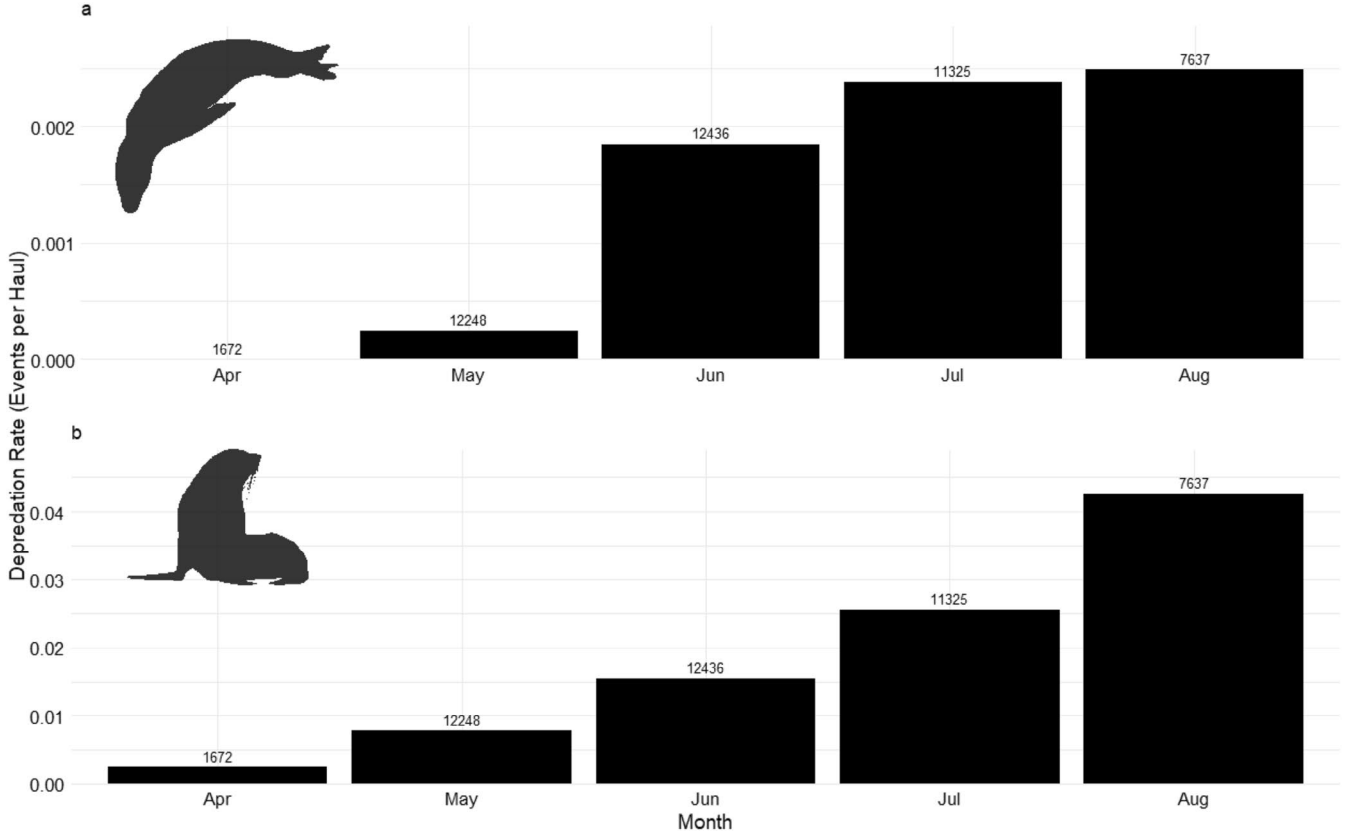


**FIGURE 5** | Monthly depredation rates for leopard seals (*Hydrurga leptonyx*) (a) and Antarctic fur seals (*Arctocephalus gazella*) (b) across the standard Patagonian toothfish fishing season (April–August). Rates were calculated by dividing the number of hauls in which depredation was recorded by the total number of observed hauls in each month, pooled across all fishing seasons. The number of hauls conducted per month is shown above each column ($n = 45{,}318$).

## 4 | Discussion

This study details behaviors and trends linked with leopard seal and Antarctic fur seal depredation in South Georgia's Patagonian toothfish fishery. Spatial partitioning was identified in depredation activity, with both species displaying a preference for a specific continental shelf. Depredation rates significantly increased during the course of the fishing season, and interannual variation was also observed in both species, with over a quarter of all Antarctic fur seal depredation events being



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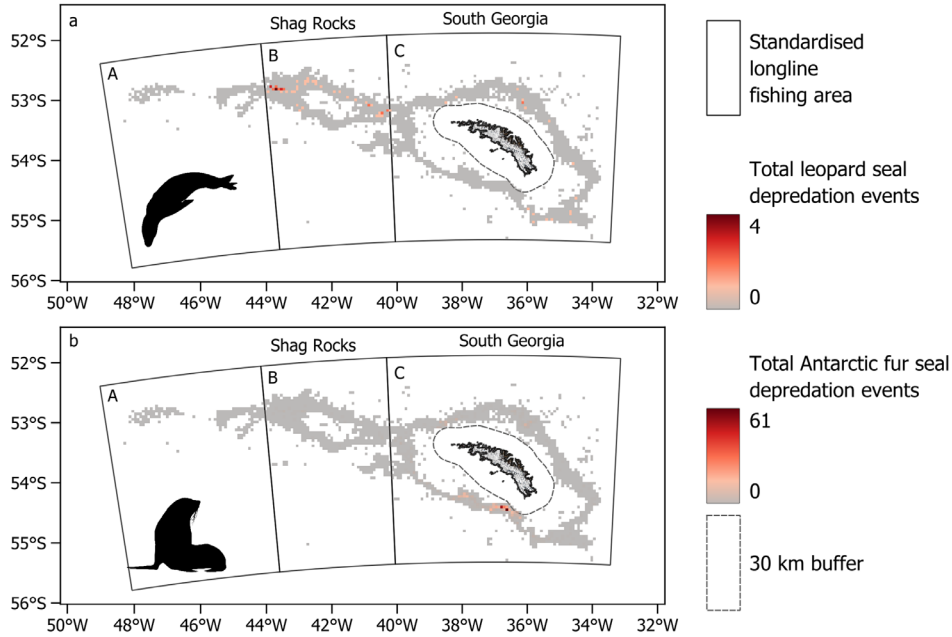


**FIGURE 6** | The spatial distribution of the sum of depredation events attributed to leopard seals (*Hydrurga leptonyx*) (a) and Antarctic fur seals (*Arctocephalus gazella*) (b) within a 5 × 5-km grid cell. The extent of the study area and the 30-km buffer region surrounding South Georgia's landmass is also displayed (South Georgia GIS 2019).

recorded in 2009. No pinniped depredation activity was recorded in years post-2021. Although we hypothesize potential causes of these trends, it is currently unclear which variables drive temporal and spatial variation in seal depredation rates in the fishery. We therefore set out a series of recommendations to enhance the data-collection process to improve the ability of the data to quantify the rate and specific drivers of pinniped depredation in South Georgia's Patagonian toothfish fishery.

### 4.1 | Temporal Variation

Although there were alterations in the data-collection technique across the 26-year dataset, depredation rates fluctuated over time for both species. In the case of leopard seals, there is potential that this variability may be linked to interannual variation in their abundance across South Georgia (Walker et al. 1998). The increase in leopard seal abundance may enhance competition for resources and subsequent depredation incidences. Similarly, years with low prey availability may also increase trophic competition, causing pinnipeds to become more reliant on depredation for resources, as has been hypothesized as a driver in other marine mammals (Luck et al. 2025). It was noted that the highest recorded number of Antarctic fur seal depredation events was recorded in 2009, coinciding with a year of high sea surface temperature, low Antarctic krill densities, and poor breeding success in krill-dependent predators (Fielding et al. 2014; Söffker et al. 2015; Trathan et al. 2021). Current predictions suggest densities of Antarctic krill may continue to vary in the coming decades (Atkinson et al. 2019; Flores et al. 2004; Forcada et al. 2023). Any reductions in prey availability may increase the likelihood of marine mammals undertaking depredation and for dependencies to develop among individuals for this resource (Esteban et al. 2016; Hobday et al. 2015).

In contrast, no depredation events were recorded in either species post-2021. This period coincides with the final season where side-hauling vessels were utilized in South Georgia's Patagonian toothfish fishery, as the present fleet exclusively employs moon pool configurations. This configuration, in which the line is hauled directly through the hull, is expected to reduce interactions with wildlife during the hauling procedure (Pierre 2018). Although several MMOs recorded both cetaceans and pinnipeds accessing moon pools (with a single unidentified seal species depredating within a moon pool in 2021), this hauling configuration may act as a barrier to pinniped depredation, as there are additional obstacles to accessing the hauling point. Conversely, the moon pool configuration may limit observers' ability to conduct MMOs, resulting in depredation events being underreported.

### 4.2 | Spatial Distribution

Leopard seals exhibited a preference for conducting depredation activity at Shag Rocks, whereas Antarctic fur seals favored South Georgia. Although the underlying drivers of these spatial preferences remain unclear, several mechanisms may contribute. Environmental variables, such as rates of productivity and prey availability, may influence the distribution of leopard seals and the subsequent likelihood of encountering fishing gear (Janc et al. 2021; Staniland et al. 2018). Preferred haul-out locations could also contribute, as leopard seals have been regularly recorded to the northwest of South Georgia (Forcada and Robinson 2006), an area in close proximity to Shag Rocks. In addition, fishing strategy, including the timing and density of fishing operations, has been shown to influence depredation rates in other species (Tixier, Vacquie Garcia, et al. 2015; Tixier et al. 2021). However, the mechanisms driving marine mammal



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aggregations around Shag Rocks and subsequent depredation activity remain poorly understood (Söffker et al. 2015).

Heightened rates of Antarctic fur seal depredation activity were identified to the south of South Georgia. Previous studies have identified concentrations of Antarctic fur seals in this area, which are likely following the krill swarms that are at their highest density in the south during August (Atkinson et al. 2001; Söffker et al. 2015). Therefore, the distribution of Antarctic fur seal depredation events may reflect the natural seasonal distribution of their foraging behavior, and interactions with fishing gear are opportunistic.

### 4.3 | Depredation Changes During the Fishing Season

Depredation rates increased during the fishing season and were highest for both species during August. The timings of the increases in depredation rates coincide with leopard seals' northward migration from the pack ice (Forcada and Robinson 2006; Jessopp et al. 2004) and with Antarctic fur seals dispersing post-breeding during the Austral winter (Staniland et al. 2012). In other regions, marine mammal depredation rates also increased in the winter months, which were hypothesized to be driven by reductions or seasonal changes in distributions in prey availability and the subsequent increased efficiency in depredation (Brotons et al. 2008). Thermoregulatory costs also increase during the winter months, suggesting that pinnipeds may undertake foraging behavior that includes a heightened risk, such as depredation. Finally, social learning may occur across the season, where individuals associate fishing vessels as a resource and will repeatedly undertake depredation and possibly transfer this behavior to other individuals (Schakner et al. 2014). However, there is uncertainty as to whether a few solitary individuals are responsible or whether this behavior is widespread throughout each species population.

### 4.4 | Recommendations

Although we have developed a series of hypotheses regarding the causation of the observed spatial and temporal variation in pinniped depredation behavior, further efforts are required to identify the drivers of this phenomenon. Furthermore, as climate change has the potential to alter food availability in the region surrounding South Georgia (Hill et al. 2013), there is a likelihood that human–wildlife conflict will increase in the region in the future (Purves et al. 2004; Tixier et al. 2021). With potential increases in depredation rates, further efforts should be made to quantify their frequency by enhancing aspects of the marine mammal interaction data-collection process using the following recommendations.

The rate of reporting of depredation activity is likely to be observer-specific. Observer training materials and MMOs are generally focused on depredation activity attributed to cetaceans with comparatively little emphasis placed on pinnipeds (CCAMLR 2026). Consequently, the observer training process may contribute to biases and subsequent underreporting of pinniped depredation behavior relative to events attributed to cetaceans. During the observer training phase, a greater emphasis should be placed on reporting depredation activity regardless of which species is responsible.

Data collection on marine mammal interactions should not rely exclusively on visual MMOs, as depredation activity is often inconspicuous and difficult to record. This is crucial on vessels that implement a moon pool hauling configuration, as the ability for observers to conduct observations is likely to be restricted. Vessels with moon pool configurations often implement camera systems below the hauling point, which are likely to capture depredation activity. This technology should be utilized to both ensure that all pinniped depredation activity is detected and accurately recorded, and to help estimate losses of catch, both for target and bycatch species.

It is currently unclear how widespread depredation behavior is throughout the populations of each pinniped species. Previous studies have identified intrapopulation heterogeneity of depredation rates in other marine mammal species (Tixier, Authier, et al. 2015). As leopard seals exhibit high rates of specialization in their natural diet, this may also extend to the depredation of the fishery, where a small number of individuals account for a disproportionate amount of this activity (Sperou et al. 2025). It is therefore advisable to attempt to identify individuals that undertake depredation behavior. This could be facilitated via photographic identification of leopard seals (Forcada and Robinson 2006; Grabham et al. 2024; Walker et al. 1998), which could aid in comprehending how widespread this behavior is. To achieve this, observers would require sufficient photographic equipment to capture images of individuals conducting depredation.

In summary, although we have identified variation in pinniped depredation rates across space and time, uncertainties remain regarding the drivers of this behavior and how management bodies can help reduce human–wildlife conflict. We advocate for the inclusion of additional protocols, which will aid in identifying what drives variation in depredation rates between these species. A further important consideration is to ascertain whether altered vessel configurations have reduced pinniped depredation or whether this has reduced the observer's ability to accurately record rates. Confirming key drivers and possible mitigation measures will aid management bodies in designing and implementing management measures to reduce this conflict (Söffker et al. 2015). Aside from enhanced data-collection protocols, management bodies should also encourage continued exploration of methods to dissuade depredation in line with conservation goals, promoting sustainable fisheries management and resilient fisheries moving forward.

#### Author Contributions

**Huw W. James:** conceptualization, data curation, formal analysis, writing – review and editing. **Jamie Coleman:** conceptualization, writing – review and editing. **Martin A. Collins:** writing – review and editing, supervision. **Jaume Forcada:** writing – review and editing. **Philip R. Hollyman:** conceptualization, writing – review and editing, supervision.



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## Acknowledgments

We would like to thank the fisheries observers and members of the fishing industry who collected this data and CCAMLR for supplying the data. Thanks also to Dr. Lukas H. A. Edwards and Dr. Ben W. Rowland for their insights.


## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

The data that support the findings of this study are available on request from CCAMLR.

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** An Antarctic fur seal (*Arctocephalus gazella*) consuming a blue antimora (*Antimora rostrata*) that was depredated from South Georgia's Patagonian toothfish (*Dissostichus eleginoides*) longline fishery. **Figure S2:** A leopard seal (*Hydrurga leptonyx*) obtaining a Patagonian toothfish (*Dissostichus eleginoides*) during a depredation event in South Georgia's Patagonian toothfish fishery.



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