Discussion paper for the Fisheries Research & Development Corporation National Workshop on Shark Depredation in Australian Fisheries

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1. Executive summary

Shark depredation is where a shark partially or completely consumes a fish caught in fishing gear before it can be retrieved to the fishing vessel (Gilman et al., 2007b; Mitchell et al., 2018b). Post-release predation is where released fish are consumed by sharks (Raby et al., 2014). There are many fisheries around Australia where shark depredation and post-release predation occurs, leading to economic (lost fishing gear and catch), social (reduced quality of fishing experience and conflict between stakeholders) and biological impacts (increased mortality of target species, injury and bycatch of sharks). Because of its widespread occurrence and impacts, there is increasing concern about shark depredation from fishers across all sectors, fishery managers, researchers and environmental stakeholders. Yet, to date, there has been relatively little research into shark depredation and its impacts, with the majority of this focused in Western Australia. Because of this, the Fisheries Research & Development Corporation (FRDC) is organising a National Workshop on Shark Depredation to bring together all affected stakeholder groups to collate the existing information on shark depredation and identify priority research gaps to address. The workshop aims to build collaboration between stakeholder groups to facilitate future research on shark depredation. To guide this workshop, a discussion paper exploring key themes around shark depredation is needed.

This paper provides information on the latest research conducted on shark depredation since the last global review of the topic in 2018 (Mitchell et al., 2018b). This particularly focuses on recent progress made in Australia, including quantification of depredation rates in commercial and recreational fisheries, which are reported to range between 1.7% and 20% of catch being lost (Mitchell et al., 2018a; Ryan et al., 2019; Carmody et al., 2021; Milburn, 2021), and use of camera-based and genetic methods, which have identified up to 12 shark species being responsible for depredation. Recent research on shark behaviour and mitigation measures for depredation are also discussed. The paper reviews where Australian research on depredation, which has mostly focused on recreational fisheries to date, fits into the wider context of shark depredation research conducted globally, which has mainly centred on large-scale tuna and swordfish fisheries. Whilst there are historical accounts of depredation occurring since the 1800s, recent anecdotal reports from around Australia indicate that depredation may be increasing in frequency in some areas. Yet, there is a lack of empirical scientific data to confirm this, apart from in the Western Australia commercial trolling fishery for mackerel, where small increases (1.1% to 3% in the Pilbara region and from 2.4% to 11.2% in the Gascoyne and West Coast region) were reported between 2006 and 2017 (Carmody et al., 2021).

Changes in depredation over time may be driven by a range of complex factors, such as shifts in patterns of fishing activity (e.g. increasing recreational fishing in remote areas, changes in spatial distribution and intensity of commercial fishing), sharks learning to take advantage of fishing catch, possible localised increases in the abundance of some shark species and environmental changes. Research has begun to document how sharks can rapidly learn to change their behaviour and movement patterns to take advantage of food from fishing vessels and that key ‘hotspots’ can occur where higher shark presence and concentrations of fishing activity overlap (Mitchell et al., 2020; Heinrich et al., 2021; Mitchell et al., 2021). Threatened, Endangered and Protected Species (TEPS) can be impacted by depredation, either through sharks depredating TEPS such as Queensland groper or potato cod, or by TEP shark species (e.g. grey nurse sharks, hammerheads or white sharks) being injured or killed during a depredation event.

Due to the lack of information about key aspects of shark depredation, this paper makes a number of recommendations for future work. Developing consistent protocols for quantifying depredation rates across all fishing sectors is a priority for assessing its impact. This will involve collecting data on the interaction rates (proportion of trips/fishing sets affected) and gross depredation rates (percentage of total fish caught that are lost to depredation) using logbook and/or app systems in commercial and charter fisheries and surveys (boat ramp/phone/online/interviews) in recreational fisheries. Continuous collection of these data over time is recommended to allow incorporation into stock assessments, following similar methodology to that trialled in the recent Queensland east coast Spanish mackerel stock assessment (Tanimoto et al., 2021). Economic and social impacts should also be investigated through fisher workshops and interviews. Identifying the shark species, and other predators (e.g. large teleosts), responsible for depredation across different fisheries and spatial areas, using recently developed underwater video and genetic techniques, should be prioritised to determine whether TEPS are involved and guide mitigation measures. More research needs to be conducted into shark abundance to assess whether population increases are occurring and leading to increased depredation. Additionally, learning more about shark behaviour and movement patterns in relation to depredation is necessary, to identity key locations where fishing activity and sharks overlap, which can guide adaptation in fishing strategies to mitigate depredation. Shark tagging, satellite monitoring of fishing vessel movements and underwater sound recorders are key tools that should be used to investigate these questions. Investigating how depredation may be leading to changes in shark diet and food web dynamics should also be pursued, using tools such as stable isotope analysis.

Developing mitigation measures for shark depredation is vital to ensure sustainable and profitable fisheries and for reducing the wide range of social and biological impacts it can have. Close collaboration and effective communication between stakeholders, scientists and fishery managers will be key to this process, ensuring common goals are identified and realistic targets for depredation reduction set. Collating information on how fishers are currently modifying fishing practices and changing fishing gear to reduce depredation will be important, so that key strategies can be identified and tested. Education will also be important to communicate strategies that fishers can use for reducing depredation. Physical devices to protect catch from sharks have been trialled in longline fisheries around the world and shark deterrents have recently been tested in Western Australia. Further scientific testing and refinement of these devices is recommended, as they offer a non-invasive means of reducing depredation that benefits fishers. Ultimately, shark depredation is a complex and widespread issue around Australia and it will require a comprehensive and collaborative effort between stakeholders, researchers and fishery managers to increase our understanding of the issue and develop tools for managing it. This national workshop represents an important first step in this process.

This discussion paper is guided by the Terms of Reference provided by FRDC, with each section heading directly following the required components provided in the Terms of Reference.

2. Review of new literature published since the last major literature review on shark depredation in 2018

2.1. Quantifying shark depredation rates

A number of new studies on shark depredation have been published since the review of Mitchell et al. (2018b), highlighting the increasing importance of this topic to a range of stakeholders (Table 1). Firstly, Rabearisoa et al. (2018) conducted a large scale study quantifying depredation across the commercial tuna and swordfish longline fisheries operating around the Seychelles and Reunion Island. This study made an important contribution to the field by demonstrating the value of four key metrics for quantifying depredation: the interaction rate, which is the proportion of longline sets where depredation occurs, the depredation rate per unit effort (e.g. number of fish depredation per 1000 hooks), the gross depredation rate, which is the proportion or percentage of the total number of fish caught that were lost to depredation and the depredation rate, which is similar to the gross depredation rate but only includes fishing sets where depredation occurred, rather than all sets (Rabearisoa et al., 2018). This study reported that depredation by toothed whales had a greater impact than from sharks, with a combined gross depredation rate of 18.3% in the Seychelles longline fishery, which was one of the highest worldwide, along with an estimated economic cost of 0.09 EUR per hook (Rabearisoa et al., 2018). In Australia, Carmody et al. (2021) used these metrics in the first study quantifying shark depredation in a commercial mackerel trolling fishery, reporting interaction rates of 18.3-37.4% and gross depredation rates of 1.7-5.7%. This study also quantified the economic losses caused by depredation, which amounted to $40,000 per year or 1.5% of annual revenue (Carmody et al., 2021). Ryan et al. (2019) also collected quantitative data to characterise the extent of shark depredation across commercial, charter and recreational fishing sectors in Western Australia, finding that 52% of fishers had experienced depredation in the last year and charter fishing operators in the Gascoyne region were the most concerned about it. A follow-up study has recently been conducted to collect further data on the impact of depredation across fishing sectors in Western Australia, including whether it has increased since 2019 (Coulson et al., in review). In Queensland, the first study of depredation in the commercial spanner crab fishery found that depredation only occurred on 3.7% of dillies, with bowmouth guitarfish and giant guitarfish identified to be the key depredating taxa, with tiger sharks consuming bait instead of crabs (Milburn, 2021).

Table 1: Research papers on shark depredation that have been published since the major review by Mitchell et al. (2018b).

Study theme	Location	Fishery type	Author(s) and year
Quantifying depredation by cetaceans and sharks using four key metrics	Seychelles and Réunion, Indian Ocean	Commercial longline fishery for tuna and swordfish	Rabearisoa et al. (2018)
Quantifying shark depredation and identifying environmental and fishing related factors influencing it	Western Australia (primarily northern regions)	Commercial trolling fishery for Spanish and other mackerel species	Carmody et al. (2021)
Quantifying shark depredation and fishing experiences across fishing sectors and regions of Western Australia	Western Australia	Commercial, charter and recreational fishers	Ryan et al. (2019)
Follow up survey from Ryan et al. (2019) to quantify changes in shark depredation over time and impacts across fishing sectors	Western Australia (primarily northern regions)	Commercial, charter and recreational fishers	Coulson et al. (in review)
Assessing the occurrence of shark depredation in the US and understanding its impacts and fisher perceptions of sharks	USA (primarily southeast)	Charter and recreational fishers	Casselberry et al. (2022)
Quantifying depredation in a spanner crab fishery and identifying predators responsible	Queensland	Commercial spanner crab fishery	Milburn (2021)
Quantifying depredation and post-release predation of permit in Florida recreational fisheries	Florida	Recreational fishers	Holder et al. (2020)
Assessing post-release predation of fish when using descender devices, as well as depredation	Gulf of Mexico	Recreational fishers	Drymon et al. (2020)

Identifying depredation of large swordfish in a harpoon fishery	Mediterranean	Commercial harpoon fishery	Malara et al. (2021)
Assessing the status and performance of the charter fishing industry	Queensland	Charter fishing	Sexton et al. (2020)
Investigating the socio-political dimensions of fisher-shark interactions in a small-boat fishery	Hawaii	Small boat commercial, charter and recreational fishers	Iwane et al. (2021)
Investigating conflict between fishers and sharks	Mariana Islands, Pacific Ocean	Small scale commercial fishers, charter and recreational fishers	Iwane and Leong (2020)
Identifying depredating shark species and understanding shark interactions with fishing gear	Ningaloo Marine Park, Western Australia	Charter fishing	Mitchell et al. (2019)
Determining predators responsible for depredation and impact on target species	Gulf of Mexico	Recreational fishing	Streich et al. (2018)
Developing a genetic technique to identify depredating shark species	Northwest Western Australia	Commercial fishing	Fotedar et al. (2019)
Using genetic samples from swabs of depredated fish to identify shark species responsible	Gulf of Mexico	Commercial and recreational fishing	Drymon et al. (2019)
Identifying depredating shark species using the genetic swab technique	Southeast Queensland	Commercial, charter and recreational fishers	Vardon et al. (2021)
Using an experimental approach to determine the response of sharks to the provision of a food source over time	Ningaloo Marine Park, Western Australia	Recreational fishing	Mitchell et al. (2020)
Using satellite vessel tracking and acoustic telemetry to assess how shark movements and fishing vessel activity overlap in time and space, to identify potential 'hotspots' of depredation and bycatch	Lord Howe Island, New South Wales	Charter fishing	Mitchell et al. (2021)
Testing the effectiveness of three shark deterrent devices for reducing shark depredation	Northwest Western Australia	Recreational fishing	Coulson et al. (in prep)
Global review of depredation across all taxa, including assessment of mitigation measures trialled to date	Global	All fishing sectors	Tixier et al. (2020)
Review of the latest research on shark depredation, identification of key knowledge gaps and best-practice methods for addressing them	Australia and USA	All fishing sectors	Mitchell et al. (in review)

Shark depredation has also become a key focus for fisheries research in the US, particularly in recreational fisheries. Casselberry et al. (2022) conducted an online survey of 541 fishers, finding that shark depredation was occurring across a wide geographical area in the US, particularly in Florida and the Gulf of Mexico, with 77% of respondents experiencing depredation in the last 5 years. Charter fishing guides reported being more affected by depredation than private boat recreational fishers, with it impacting upon their business. Fishers who completed the survey expressed concern about the impact of depredation on target species populations, particularly for trophy fish species and charter operators reported strong negative views of sharks, with some actively targeting them in an attempt to reduce depredation (Casselberry et al., 2022). This research therefore provided important insights into the scope of impacts created from shark depredation, such as the fishing sectors and regions primarily affected and fisher responses (e.g. changes to fishing practices). Understanding these variables will help to guide future management and mitigation research. In particular, the study recommends that fishery managers and advocacy groups should prioritise further research to collect data on depredation in recreational fisheries and determine how it affects fisher values, whilst testing solutions to mitigate depredation and the conflict it is causing between fishers and sharks (Casselberry et al., 2022). In another recent US study, Holder et al. (2020) investigated depredation of permit in Florida, recording a mean rate of 5.9%, although depredation was highly variable across different habitats, with zero depredation at nearshore structures and flats, compared to 35% and 90% depredation rates at reefs and shipwrecks, respectively. The study recommended that fishers should avoid these areas where depredation is higher, particularly when permit are aggregating to spawn and there are higher predator densities (Holder et al., 2020). Drymon et al. (2020) conducted a study to quantify depredation of catch on vertical longline deployments, as well as when fish were released with descender devices to mitigate barotrauma. This study recorded a depredation rate of 4.6% for fish being retrieved to the vessel, with depredation mostly committed by sharks (78%), but also dolphins (Drymon et al., 2020). No depredation occurred when releasing fish with descender devices (Drymon et al., 2020). One of the few studies of shark depredation in the Mediterranean found that a range of large shark species were depredating large swordfish caught in a harpoon fishery near Sicily (Malara et al., 2021).

2.2. Investigating socio-economic impacts of shark depredation

In an Australian context, recent surveys of fishers in Western Australia and Queensland have recorded information about the quality of their fishing experience and the impact of conflict with sharks. Ryan et al. (2019) reported that charter fishers in Western Australia were the most concerned about the loss of catch to depredation, compared to commercial and recreational fishers, although overall, 87-91% of fishers from all sectors were either ‘very satisfied’ or ‘quite satisfied’ with their fishing experience. In Queensland, 100 charter fishing operators were interviewed using telephone/email, with 74% identifying that the ‘number of sharks at fishing grounds’ was the most important factor having a ‘major impact on business performance’ (Sexton et al., 2020). Additionally, 80% of the operators interviewed thought that the charter industry was staying the same or in decline, although it must be noted that his survey was undertaken during the height of the COVID-19 pandemic, which strongly impacted tourism operators such as fishing charters (Sexton et al., 2020).

To understand the socio-political dimensions of fisher-shark interactions in Hawaii, Iwane et al. (2021) conducted a series of workshops and interviews with small-boat fishers, to collect detailed background information. This research applied a conflict and problem-solving framework and helped to characterise the broader nature of the human-wildlife conflict occurring, such as the economic costs, changes to fishing practices, perceptions of fisheries management approaches, the relationship between fishers and researchers and the socio-economic context of the fishery (Iwane et al., 2021). Fishers reported a range of interactions with sharks, including positive interactions where certain species were kept as valuable bycatch or where sharks were used as an indicator of fish presence, or where sharks had negative impacts due to scaring away target fish and/or depredating catch (Iwane et al., 2021). The study demonstrated that open and transparent communication, knowledge sharing between fishers and researchers and building trust over time are key components in developing effective strategies for managing fisher-shark conflict (Iwane et al., 2021). An earlier and smaller scale study by Iwane and Leong (2020) also investigated conflict occurring between fishers and sharks in the Mariana Islands in the Pacific Ocean, finding many similarities with the conflict investigated in

Hawaii. A number of other studies have also explored the biological and socio-economic dimensions of the broader range of human-shark conflicts that are occurring worldwide, including shark depredation, identifying important research gaps and methods for improving management (Carlson et al., 2019; Molony and Thomson, 2020; Simpfendorfer et al., 2021).

2.3. Identifying shark species responsible for depredation

There has been substantial progress in developing techniques to identify the shark species responsible for depredation. Mitchell et al. (2019) deployed underwater video cameras on fishing lines and recorded four Carcharhinid (whaler) shark species (sicklefin lemon, grey reef, blacktip and spot-tail sharks) to be responsible for depredation in the Ningaloo Marine Park (Figure 1). Streich et al. (2018) used a similar approach in the Gulf of Mexico, finding that sandbar sharks were the only shark species responsible, although large teleosts were also responsible for a large proportion of the depredation. In the Queensland commercial spanner crab fishery, the deployment of GoPro cameras on dillies revealed that bowmouth and giant guitarfish were responsible for depredating spanner crabs, as opposed to sharks, although tiger sharks were seen interacting with the bait bags (Milburn, 2021). Galapagos sharks have been identified to be responsible for depredation at Lord Howe Island, using a combination of underwater video cameras and observation (Robbins et al., 2011; Mitchell et al., 2021). Three recent studies have used a genetic approach to identify depredating shark species by swabbing the remains of depredated fish. These studies recorded similar species being responsible for depredation in the Gulf of Mexico (Drymon et al., 2019), Western Australia (Fotedar et al., 2019) and Queensland (Vardon et al., 2021), including sandbar, bull and blacktip sharks.

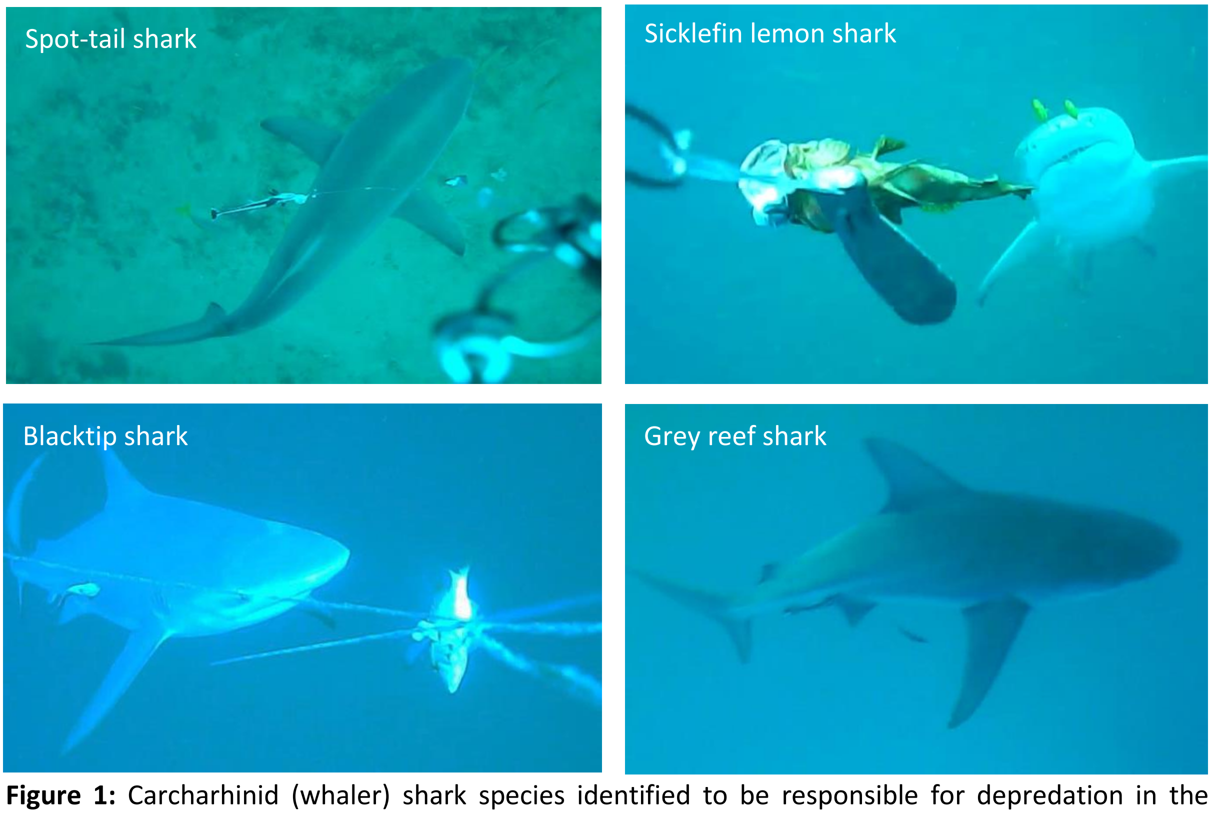

Figure 1: Carcharhinid (whaler) shark species identified to be responsible for depredation in the Ningaloo Marine Park. Credit: Jonathan Mitchell

2.4. Shark behaviour and movement patterns

Recent studies have also investigated how shark behaviour and movement patterns influences the occurrence of depredation. Mitchell et al. (2020) used an experimental approach to demonstrate that sharks can rapidly respond to the repeated presence of a vessel and the availability of food in a fished area, with their arrival times decreasing substantially in just 6 days. Conversely, when the same provision of food was conducted in a no-take zone, sharks took much longer to arrive and did not feed, possibly because they had not learned to associate the presence of vessels with food in this area (Mitchell et al., 2020). This finding is supported by Heinrich et al. (2021) who showed that lemon sharks in The Bahamas learned to anticipate the provision of food in just 11 days, and this behaviour can be retained for over 3 months. These two studies therefore provide empirical evidence supporting the many anecdotal reports of sharks learning to follow fishing vessels and associate them with food. A study by Mitchell et al. (2021) at Lord Howe Island in New South Wales used tracking data from sharks and fishing vessel activity data from Vessel Monitoring Systems (VMS) to investigate the overlap in shark and fishing vessel movement patterns. Results showed that 'hotspots' of overlap occurred at a number of locations where higher shark presence correlated with greater fishing activity, including productive shelf edges sites with complex bathymetry and an inshore site where fish waste has been regularly dumped. Sharks at the latter site, in particular, showed higher residency and smaller home ranges, further supporting the theory that regular provision of food from fishing vessels can change shark movements and behaviour over time (Mitchell et al., 2021).

2.5. Mitigation measures for shark depredation

Research has also begun to investigate mitigation measures for depredation. Mitchell et al. (2021) conducted interviews with charter and recreational fishers on Lord Howe Island to collate information about mitigation measures they are currently using to reduce depredation and Coulson et al. (in review) conducted a larger scale study in Western Australia, using both phone and online surveys to identify ways in which fishers have changed their fishing gear and/or methods with the aim of mitigating depredation. Another study by Coulson et al. (in prep) was the first to conduct experimental field testing of three shark deterrent products (the OceanGuardian Fish01, SharkBanz Sentry and SharkStopper) aimed at reducing depredation in a recreational fishing setting. These deterrents were tested at multiple locations which are considered to be depredation 'hotspots' in northwest Western Australia (Coulson et al., in prep). The results from this study will help inform fishers about the potential efficacy of shark deterrents for reducing depredation and also acts as a valuable guide for future research aiming to conduct experimental testing of new deterrents as they become available. Further details on mitigation measures are provided in sections 9 and 13 of this paper.

Building on the review by Mitchell et al. (2018b), a study by Tixier et al. (2020) reviewed depredation by a broader range of taxa, including sharks, cetaceans and pinnipeds. Depredation by these taxa occurred in 214 fisheries from 44 countries, between 1979 and 2019, involving 68 predator species, of which 20 were toothed whale species, 21 pinniped species and 27 shark species (Tixier et al., 2020). Mitigation methods that have been tested to date were reviewed, with the results indicating that deterrents were generally less effective than gear modifications or adaptations to fishing behaviour (Tixier et al., 2020). The review emphasised the need for more research into the social-ecological aspects of depredation and changing perspectives through knowledge sharing, to move towards coexistence between fisheries and marine predators (Tixier et al., 2020). To synthesise the latest research on shark depredation and provide researchers and fishery managers with best-practice methods for conducting research on depredation in future, a collaborative review paper was produced by fisheries researchers from Australia and the US, which is currently under review at the Journal of Fish Biology and Fisheries (Mitchell et al., in review).

3. Applying insights from the international experience of shark depredation to the Australian context

Shark depredation occurs in many fisheries around the world, especially those using hook and line fishing methods (including longlines, droplines and rod and reel fishing). To date, research has focused predominantly on the occurrence of shark depredation in large scale commercial longline fisheries in open ocean areas, where the rates of depredation have been quantified and the shark species responsible identified (Gilman et al., 2007b; IOTC, 2007; Mandelman et al., 2008; MacNeil et al., 2009; Mitchell et al., 2018b). There is also a large body of research focusing on depredation by cetaceans in these fisheries (Hamer et al., 2012; Tixier et al., 2020), where these predators are responsible for more substantial losses of catch than sharks in some cases (IOTC, 2007; Rabearisoa et al., 2007). Gilman et al. (2007b) quantified shark depredation in 12 commercial longline fisheries around the world, with the highest rate (20%) recorded in the Australian Eastern Tuna and Billfish Fishery. Shark depredation data was also collected by a number of countries as part of an Indian Ocean Tuna Commission (IOTC) workshop in the early 2000s, with rates ranging from 3.2 – 9.1% (IOTC, 2007). In a summary of all the shark depredation literature, Mitchell et al. (2018b) reported that depredation rates in the published literature ranged from 0.9 – 26%.

In an Australian context, most of the line fisheries (commercial, Indigenous, charter and recreational) are on a smaller scale and occur in shelf or coastal waters, and so research from large-scale commercial longline fisheries in the open ocean are less comparable. This is both because the scale of fishing operations and habitats targeted are less applicable and the shark species responsible are likely to be pelagic species such as blue and mako sharks, compared to coastal species such as bull, sicklefin lemon, sandbar and blacktip sharks. However, two new studies have quantified depredation rates in a Western Australia commercial mackerel fishery and in the Queensland spanner crab fishery, recording rates of depredation of 1.7-5.7% in WA (Carmody et al., 2021) and 3.7% in the Queensland fishery (Milburn, 2021). These rates are relatively similar to most of the other studies in commercial fisheries conducted to date. There has been very little work conducted in recreational fisheries globally, apart from a few recent studies in Australia, the US and South Africa. Depredation rates of 7.2-13.7% were reported in a recreational fishery in the Ningaloo Marine Park and Exmouth Gulf (Mitchell et al., 2018a) and 8.4% in the South African fishery (Labinjoh, 2014). These rates are at the low to medium end of the range in depredation rates (0.9-26%) found across the shark depredation literature by (Mitchell et al., 2018b). Ryan et al. (2019) also conducted a survey of commercial, charter and recreational fisher experiences with depredation in Western Australia, which has been further investigated by a more recent survey (Coulson et al., in review). Interviews of charter fishing operators in Queensland have revealed that the presence of sharks at fishing grounds are a key factor impacting their business (Sexton et al., 2020). Research has identified the shark species responsible for depredation in Western Australia and Queensland (Fotedar et al., 2019; Mitchell et al., 2019; Vardon et al., 2021), which showed that a range of Carcharhind (whaler) shark species (see section 2) were responsible. Shark depredation is known to occur in a number of other Australian commercial fisheries, such as the Queensland school and grey mackerel net fishery and Reef Line Fishery and the Northern Prawn Trawl Fishery, although no dedicated research has been conducted to date in these fisheries.

Similar to Australia, recreational fishing is widely popular in the US, and shark depredation is causing conflict between sharks and fishers, particularly in the Gulf of Mexico, Florida and Hawaii. Drymon et al. (2019) identified shark species responsible for depredation in the Gulf of Mexico, although Streich et al. (2018) reported that large teleosts (e.g. amberjack, great barracuda and Warsaw grouper) were responsible for a greater proportion of depredation than sharks. Goliath groupers and dolphins are also causing depredation in Florida recreational fisheries (Powell and Wells, 2011; Collins, 2014; Shideler et al., 2015). A recent survey by Casselberry et al. (2022) found that similar to in Australia, shark depredation occurs across a wide geographical area and is having substantial economic and social impacts on charter fishing operators and recreational fishers. Iwane et al. (2021) conducted a range of workshops and interviews with fishers to characterise the broader conflict occurring between fishers and sharks in Hawaii, which provides important insights into managing the issue in an holistic way (see section 2 of this paper).

The perspective of past research conducted in the pelagic longline fisheries has been focused on quantifying depredation and the economic impacts it causes, whereas in Australia, shark depredation has broad social implications due to the popularity of recreational fishing where fishers are motivated by a range of experiential values (Young et al., 2016) rather than solely maximising catch rate and profits. For this reason, characterising the issue of shark depredation is Australia is more complex and nuanced than solely quantifying depredation rates and the dollar value of lost fish. To understand depredation in Australia, it is therefore necessary to investigate it across a range of commercial and recreational fisheries, where different gear types and fishing methods are used to target a wide range of species. There is also a geographical consideration as sharks are mainly responsible for depredation across the northern half of Australia (e.g. from Perth in the west to northern NSW in the east) whereas depredation by other taxa (including long nosed fur seals in South Australia and sperm whales in the Heard and McDonald Islands in the Southern Ocean) dominates in the southern half of Australia.

4. Has shark depredation increased over time in Australian fisheries?

Shark depredation has been recorded in Australian waters from accounts dating back to the late 1800s (Brockman and Brockman, 1987), however, in recent years, there are many anecdotal reports of increasing depredation rates from fishers across sectors. Long term fishers have a detailed knowledge of their environment and their first-hand accounts of depredation are valuable for assessing its occurrence. A social survey of fishers in North Queensland has attempted to capture this anecdotal information and found that the majority of fishers had experienced a notable increase in depredation over the last 5-10 years (Hoel et al., 2021). During a survey of close to 1000 recreational fishers in Western Australia, many fishers expressed the view that shark depredation had increased in the last 10 years, especially for fishers who had visited the same area regularly for decades (Mitchell pers. obs.). Long term charter fishing operators on Lord Howe Island have also reported experiencing increases in shark depredation rates over recent years (Mitchell et al., 2021). Yet, it is also important to consider that depredation is an emotive topic and is regularly discussed by fishers, so there is potential for perception bias to influence fishers' perception of historical changes in depredation rates, especially since it is being more regularly discussed (especially in social media) in recent years. Additionally, some of the anecdotal reports stating that up to 70 or 80% of their catch is being lost to depredation are often referring to individual trip losses (particularly for trips where a high proportion of the catch is lost, which are more likely to stay in the mind of a fisher) rather than the overall mean rate of catch loss across the whole fishery. This was evident in the survey conducted in Mitchell et al. (2018a), where there were a number of trips with depredation rates above 50%, however there were also many trips with 0% depredation, so when averaged across a large number of trips (400+) the mean depredation rate came to approximately 7.2-13.7%.

Rigorous scientific data on depredation rates is therefore needed to reliably determine trends over time, however this does not currently exist in most Australian fisheries. Although, a new study by Carmody et al. (2021) in the WA Mackerel Managed Fishery provides clear evidence around changing depredation rates through time, with depredation rates reported to increase over a 13-year period from 2006 to 2017, from 1.1% to 3% in the Pilbara region and from 2.4% to 11.2% in the Gascoyne and West Coast region. As part of a survey of fishers across Western Australia, Ryan et al. (2019)

reported that the majority of commercial (55%) and recreational (62%) fishers experienced the same level of shark depredation as in the previous year, although 36% and 28% of fishers reported a higher level of depredation. Yet, it is important to note that this study only covered a 2-year period. For charter fishers, 50% reported similar levels of depredation and 50% reported an increase (Ryan et al., 2019). There was spatial variation in these reported changes in depredation rates, with a greater percentage of fishers in the Gascoyne region reporting increased depredation (Ryan et al., 2019). On a global level, for the few studies that had access to long term datasets, most reported a stable level of depredation over time (Gilman et al., 2007b; IOTC, 2007; MacNeil et al., 2009), apart from Muñoz-Lechuga et al. (2016) who reported an increase from 0.85% in 2011 to 4.9% in 2015 in Indian Ocean longline fisheries and Romanov et al. (2013) who showed an increase from 3% in 2011 to 9% in 2013, also in the Indian Ocean.

Overall, scientific data on long-term trends in shark depredation rates are only available for one commercial fishery in Australia – the Western Australian Mackerel Managed Fishery, where research indicates a relatively small increase in depredation rates since 2006 (Carmody et al., 2021). Therefore, this is the only fishery for which we can definitively conclude that depredation has increased. However, there are numerous anecdotal reports from other fisheries, especially in northwest Western Australia, northern and southeast Queensland and Lord Howe Island, which indicate an increase in depredation rates. However, without any scientific data for these fisheries, the extent of potential increases are unable to be verified. This highlights the clear need for development and implementation of continuous data collection protocols for generating time series data on shark depredation rates in a number of affected fisheries in future.

5. Impacts of depredation on Threatened, Endangered, and Protected Species (TEPS)

5.1. Sharks

There is potential for depredation to impact Threatened, Endangered, and Protected Species (TEPS), in the form of both the depredating taxa and the fish/animal being consumed. Up to 12 shark species have been identified to be responsible for depredation in Western Australian and Queensland fisheries, through both camera-based (Mitchell et al., 2019; 2021) and genetic methods (Fotedar et al., 2019; Vardon et al., 2021). Of these, only the grey nurse shark is listed as a protected species (Kyne et al., 2021), and this species is known to be substantially affected by recreational fishing (Robbins et al., 2013). The occurrence of depredation by this species could lead to hooking injuries or retaliatory killing by fishers, which could cause negative impacts for this species, given its small population size and 'critically endangered' status on the East Coast of Australia (DoE, 2014). White sharks (which are listed as vulnerable and migratory under the EPBC Act) and mako sharks (both shortfin and longfin, which are listed as migratory under the EPBC Act) may be responsible for depredation in some fisheries, such as the Eastern Tuna and Billfish Fishery, although the extent of this is unknown. Scalloped and great hammerhead sharks are protected under some state legislation (Kyne et al., 2021), are classed as critically endangered by the IUCN and may be negatively impacted if they become hooked in the process of depredating catch, because they are highly vulnerable to stress-induced mortality from capture in fishing gear (Ellis et al., 2017). In some fisheries around Australia, there may also be instances of sharks depredating sharks caught on fishing gear, as seen in other fisheries around the world (O'Shea et al., 2015; Mitchell et al., 2018b), and this may involve TEPS as either the depredating predator or the catch depredated (or both). Milburn (2021) documented critically endangered bowmouth guitarfish and giant guitarfish depredating spanner crabs in the Queensland commercial spanner crab fishery, which could potentially lead to negative impacts on these species if they become entangled in fishing gear. Sawfish species and speartooth sharks (*Glyphis glyphis*) could potentially be depredated by other sharks because they are sometimes bycaught in gillnet fisheries in northern Australia. The Commonwealth EPBC Act and other legislation that protects the species listed above will mean that options developed to mitigate depredation by these species must be non-harmful.

5.2. Marine mammals

Mammals are also responsible for depredation in certain parts of Australia. Long-nosed fur seals, Australian fur seals and Australian sea lions are all protected species (Environment Protection and Biodiversity Conservation Act 1999) and are known to depredate upon fisheries across Southern Australia (McLeay et al., 2015; Tixier et al., 2020). Long-nosed fur seals are the main depredating taxa in the Lakes and Coorong net fishery in South Australia and Tasmanian commercial and recreational net, pot and line fisheries (McLeay et al., 2015; Cummings et al., 2019). Frequent interactions between long-nosed fur seals and fishers are leading to conflict and possible retaliatory killing of seals in some cases, with many fishers also calling for culling (Cummings et al., 2019). Australian sea lions interact with the West Australian rock lobster fishery where they have depredated pots historically (Gales et al., 1994). This led to the seals getting trapped in pots and tangled in ropes, causing mortality, although this has been largely reduced with the introduction of sea lion excluder devices (SLEDs) in 2006 (Campbell et al., 2008). SLEDs are also in use in South Australian lobster fisheries (Mackay and Goldsworthy, 2017).

All cetaceans are protected under Australian Federal law (Environment Protection and Biodiversity Conservation Act 1999) and there are a few species which are known to depredate catch in Australian fisheries. Sperm whales are responsible for depredation in commercial longline fisheries around the Australian Heard and McDonald Islands in the Southern Ocean (Tixier et al., 2019). These whales sometimes get hooked or entangled in the longlines, leading to mortality, and they may occasionally be deliberately injured or killed by frustrated fishers (Hamer et al., 2012). Certain localised populations of these whales have changed their behaviour to take advantage of this food resource (Gilman et al., 2007a), and their habituation to vessels may make them more vulnerable to ship strikes. Orcas are known to depredate upon longline fishing operations targeting blue-eye trevalla in south-eastern Australia (Cieslak et al., 2021), where they may be impacted by hook injuries, entanglement, vessel strikes and deliberate injury/killing by fishers. Dolphins may be responsible for depredation in some fisheries around Australia, for example common bottlenose dolphins are reported to depredate catch from demersal trawl nets in Western Australia, where they can sometimes become trapped and killed when swimming inside the net (Santana-Garcon et al., 2018). Short-beaked common dolphins depredate sardines in the South Australian purse-seine fishery and can also become trapped and killed (Hamer et al., 2008).

5.3. Teleosts

Certain teleost species are classified as TEPS, especially Queensland groper and potato cod under State legislation, and may be affected as either the depredating taxa or the prey. These species reach very large sizes and are likely to be responsible for depredation in some areas, as has been reported anecdotally by fishers (Mitchell et al. pers. obs.). In the process of depredating hooked fish, they may become hooked themselves and then end up being reeled up to a vessel, causing them to be affected by barotrauma which can lead to post-release mortality. These species may also be affected by depredation as the prey, because if hooked they can take a long time to retrieve to the boat, making them vulnerable to depredation by large sharks. There is currently substantial conflict occurring in Florida recreational fisheries where goliath groupers, which are a protected species, are depredating catch (Shideler et al., 2015). This is leading to retaliatory killing by fishers and calls for the species to be removed from the protected species list (Frias-Torres, 2013). There is potential for similar conflict to develop in future for Queensland groper and potato cod in some localised areas in Australia.

6. Factors influencing potential temporal changes in shark depredation

6.1. Shark behaviour

Depredation is a complex social-ecological process which is likely driven by a range of mechanisms, such as the fishing methods used, the spatiotemporal dynamics of fishing activity, shark ecology and behaviour and fish population status. There is anecdotal information and a limited body of scientific data that indicates that shark depredation rates may be increasing in some Australian fisheries, therefore it is necessary to investigate the causal mechanisms that may be driving these changes (Table 2). Experimental studies have shown that sharks have the capability to rapidly adapt their behaviour to exploit new food sources, by responding to sensory cues and forming behavioural associations (Clark, 1959; Guttridge et al., 2009; Vila Pouca and Brown, 2018). The availability of hooked, injured fish to feed on, as well as released fish and bait, are likely to be an energy-efficient food source for sharks, so they are likely to change their behaviour to take advantage of these sources. This is supported by a growing body of literature, for example in Western Australia where the arrival and feeding time of sharks rapidly decreased over a 6 day period where sharks were provided with food at the same location (Mitchell et al., 2020), and at Lord Howe Island, where Galapagos sharks showed markedly higher residency and smaller space use areas in a location where fish waste has been dumped for a number of years (Mitchell et al., 2021). Similarly, a field experiment with juvenile lemon sharks has shown they can rapidly learn to anticipate the provision of food after 11 days and retain this knowledge for an extended period (Heinrich et al., 2021). Research in the Bahamas has also shown that sharks may migrate back to areas where they can feed on hooked fish on a predictable basis (Madigan et al., 2015).

6.2. Changing patterns of fishing

Changing fishing patterns over time may have also contributed to changes in shark depredation. For example, in some areas where the level of commercial trawling has decreased substantially due to changes in fisheries and marine park management measures, such as in Moreton Bay, sharks that would previously have fed on discards from trawlers may now have moved to other areas where they may feed on other fisheries catch. However, it is important to note that this has not been scientifically investigated to date. The level of boat ramp access and other fishing infrastructure has likely increased in recent decades, leading to greater visitation of recreational fishers to remote areas of northern Australia where shark populations are likely to be healthier, resulting in fishers and sharks coming into contact more frequently. In some areas, this may have led to fishing activity occurring frequently at the same sites, which has driven changes in behaviour of sharks as described above. Mitchell et al. (2018a) documented some of these ‘hotspot’ areas in the Ningaloo Marine Park, which were areas of intermediate depth (60 m) along the reef, which were relatively close to a boat ramp. These areas had higher visitation by recreational fishers and notably higher depredation rates (Mitchell et al., 2018a). Likewise, Carmody et al. (2021) documented higher levels of depredation in the Western Australia Mackerel Managed Fishery in areas close to population centres. The fishing methods used by recreational fishers may also be providing sharks with greater opportunities to depredate hooked fish, for example where lighter line classes are used to play the fish and create a more challenging fishing experience, which gives sharks a greater chance to depredate them. Whereas commercial fishers focused on maximising catch for economic purposes rather than the experience of fishing, may instead use electric reels, winches or handlines to retrieve the fish as fast as possible, thus suffering lower depredation rates. Charter fishing operators may experience higher depredation rates than private boat recreational fishers in some cases, because they have more customers onboard and more lines in the water and they may be more restricted in the number of sites they can visit due to the duration of their trip. A key part of developing depredation mitigation approaches in future will be generating effective education and communication tools that are specific to each fishing sector and region and take into account these complexities.

6.3. Shark abundance

Many stakeholders are anecdotally reporting increased sightings of sharks that may suggest shark populations are increasing in some areas. Reductions in commercial shark fishing quotas in Queensland since 2009 and closure of the northwest and northern shark fisheries in Western Australia in 1993 and 2005, respectively, as well as introduction of bag and maximum size limits for recreational fishers (e.g. 1 per person/2 per boat and 1.5m maximum size in Queensland), are being attributed to an increase in shark populations. Although, one of the few long-term studies on shark abundance conducted in Australia showed that populations of dusky, blacktip and spot-tail sharks (known depredating species) have been stable between 2002 and 2017 in northwest Western Australia, with a marginal increase in sandbar shark (another known depredating species) populations (Braccini et al., 2020). Catch rates of sandbar shark and dusky shark in the commercial shark fishery in the west and south of Western Australia have also remained stable since 2010 (Braccini et al., 2021). In Queensland, a stock assessment of 12 whaler and hammerhead shark species showed mixed trends over time, with stable trends in northern regions including the Gulf of Carpentaria, Far North and Lucinda, and Fraser Inshore, decreasing trends in Stanage and Whitsunday regions, but increasing trends in the Rockhampton, Sunshine Coast offshore and Moreton Bay regions (Leigh, 2015). Reasons behind these variable trends could include changes in fishing mortality, differences in species composition between regions, environmental conditions affecting recruitment and/or prey abundance, but these relationships are not well understood.

Most of the larger whaler species responsible for shark depredation have low reproductive potential, such as the dusky shark, which can take 20 years to reach maturity and only has 2-18 offspring every 2-3 years (Simpfendorfer et al., 2002; Natanson et al., 2014) and the bull shark, which has 1-15 pups, a 2 year reproductive cycle and reaches maturity at 9.5 years old (Tillett et al., 2011). As such, most of the larger species known to be responsible for depredation are unlikely to be capable of undergoing a rapid and large-scale population increase in just 10-20 years. Yet, in some cases, there is a possibility that localised populations of sharks could have increased, or that lower fishing mortality has resulted in greater numbers surviving to adulthood, meaning there are more larger sharks present which interact with fishing vessels. There may also be a perception of increased abundance of sharks due to shark behavioural factors, i.e. sharks are spending more time in areas where fishing is occurring regularly due to this artificial availability of food. So, because of these behavioural changes in sharks where they have learnt to associate fishing vessels with a source of food, it is likely fishers would see sharks around their vessel more frequently, but this does not necessarily mean that the overall population size is larger, just that the same number of sharks are concentrated in a smaller area because of greater fishing activity and possibly lower natural prey abundance. Increasing coverage of shark depredation in traditional and social media over recent years, may also have generated the perception that it is increasing in occurrence. More research is needed to reliably assess shark population status across northern Australia, as well as understanding how changes in shark behaviour are driving the occurrence of depredation.

6.4. Environmental and ecological changes

Another possibility is that depredation rates may be increasing due to certain environmental and ecological changes. Increasing water temperatures over time may be leading to changes in the distribution of certain shark species, as was predicted in two recent studies (Hammerschlag et al., 2022; Niella et al., 2022), as well as activity levels and feeding. It is also possible that changes in prey distributions and abundance in response to climate change and fishing pressure may have impacted upon the natural prey species of some shark species. The reduction in natural food sources may have led to sharks moving further to search for food and taking advantage of fishing catch as an opportunistic food source. Although, more research is needed to understand the diet of the shark species known to be responsible for depredation, including assessing what proportion of their diet is likely to be made up of key target species of fisheries, similar to Madigan et al. (2015).

Table 2: Summary of key factors likely to be influencing changes in shark depredation over time.

Factor influencing temporal change in depredation	Reason	Supporting research
Shark behaviour	Sharks learn to associate fishing vessels with food Consistent fishing activity in the same locations over time leads to sharks spending more time in these areas	Clark (1959) Guttridge et al. (2009) Vila Pouca and Brown (2018) Mitchell et al. (2020) Mitchell et al. (2021) Heinrich et al. (2021) Madigan et al. (2015)
Changing patterns of fishing	Increase in recreational fishing activity in remote areas where shark populations likely to be healthier Reduction in commercial trawl fishing may have led to sharks following line fishing vessels more Changes in recreational fishing methods have given sharks more opportunity to depredate hooked fish Recreational and commercial fishing overlapping in certain areas leading to high concentration of fishing activity influencing shark behaviour	Mitchell et al. (2018) Carmody et al. (2021) Mitchell et al. (2021)
Shark abundance	Most large whaler shark species have limited reproductive potential so are unlikely to have rapid population increases in 10-20 years Localised increases in abundance of some faster reproducing species could occur Reduced mortality due to introduction of bag limits and max. size limits may have led to more larger sharks Closure of shark fisheries in northwest and northern regions of Western Australia in 1993 and 2005 likely led to reduced mortality, although research shows stable population trends of depredating shark species Reduction in commercial shark catch quotas in Queensland have reduced mortality, although stock assessment of whaler and hammerhead species shows mixed results by region Behavioural changes in sharks and changing perceptions of fishers can affect perceptions of shark abundance	Braccini et al. (2020) Braccini et al. (2021) Leigh (2015) Simpfendorfer et al. (2002) Natanson et al. (2014) Tillett et al. (2011)
Environmental and ecological changes	Increasing water temperatures may lead to changes in distribution of some shark species and increase in activity levels and feeding Reductions in abundance of natural prey species due to climate change and fishing may have led to sharks feeding on fishing catch more frequently	Hammerschlag et al. (2022) Niella et al. (2022)

7. Effective metrics for quantifying shark depredation across Australian fisheries

Depredation occurs in a number of different fisheries around Australia, including large scale commercial longline fisheries, inshore net fisheries, invertebrate trap fisheries and single line recreational fishing. As such, the nature of depredation will be different across these fishery types. For determining the impact of depredation on commercial longline fisheries, three metrics will be useful: 1) the interaction rate, which is the proportion of sets where depredation occurs, 2) the depredation rate per unit effort, e.g. number of fish depredated per 1000 hooks and 3) the gross depredation rate, which is the proportion of the total fish hooked that were depredated (Mitchell et al., 2018b; Rabearisoa et al., 2018). For commercial pot fisheries such as the Queensland spanner crab fishery, the depredation rate per unit effort (metric 2) could instead be calculated as the number of crabs depredated per dilly or pot. For net fisheries, only the interaction rate (metric 1) and gross depredation rate (metric 3) would be possible to calculate. For recreational fisheries and commercial fisheries that use small numbers of droplines, the percentage of trips where depredation occurred (metric 1) can be calculated as in Mitchell et al. (2018a), although the gross depredation rate (metric 3) is likely to be more informative. This metric is the most explicit of the three and is widely used across a number of studies (Gilman et al., 2008; MacNeil et al., 2009; Mitchell et al., 2018a; Carmody et al., 2021), as well as being recently incorporated into the stock assessment for Queensland east coast Spanish mackerel (Tanimoto et al., 2021), whereas 1 and 2 are predominantly used in large scale longline fisheries (Gilman et al., 2007b; IOTC, 2007; Rabearisoa et al., 2018). When using metrics 1 and 2 for passive fishing gears like longlines, nets or traps, it is also important to note that some depredation may be cryptic, for example where sharks remove the whole fish from a longline hook or where spanner crabs are pulled off a dilly leaving no remains attached. Also, where branchlines or leaders are found snapped off on longlines, it could be caused by either depredation or sharks taking the bait directly and snapping off the leader. In addition to these main three metrics used, it is also possible to break down shark depredation into greater detail, such as the percentage of certain target species depredated (Kobayashi and Yamaguchi, 1978; Beerkircher et al., 2002), which would be necessary for use in stock assessments, or the proportion of fish that were totally lost, compared to those only partially damaged which may still be marketable (Gilman et al., 2007b). Where possible, metrics need to be tailored to suit the existing performance indicators used to assess a fishery. For example, where catch per unit effort is calculated based on catch per pot/set/day/trip, the depredation rate should reflect this. This information will allow the biological impacts of depredation to be directly accounted for in fisheries assessment and management.

When generating any of these depredation metrics, it is important to ensure they are representative of the whole range of the fishery, because rates of depredation are likely to be highly variable in time and space. This involves averaging the data (i.e. by calculating the mean or median) for metrics 1-3 across a suitably large sample size (which can be determined using power analysis) of trips. For example, Rabearisoa et al. (2018) calculated metrics 1-3 for shark depredation, across 2230 longline sets in the Reunion Island longline fishery, producing values of 27.1% (interaction rate), 1.42 fish depredated per 1000 hooks (depredation per unit effort) and 2% (gross depredation rate), respectively. In Western Australia, Mitchell et al. (2018a) collected data from 248 fishers interviewed at boat ramps, finding an interaction rate of 38.7% trips which experienced depredation in the Ningaloo Marine Park and a mean depredation rate of 13.7% of hooked fish being taken by sharks when averaged across all demersal fishing trips. Overall, it is important that depredation metrics are used in a consistent way across different fisheries and within the same fishery over time, to ensure that robust and comparable data that is suitable for inclusion in stock assessments, is generated.

8. Key data and knowledge gaps for shark depredation research in Australia

8.1. Quantifying shark depredation rates

A range of data and knowledge gaps exist for shark depredation research in Australia. Firstly, there is a lack of quantitative data on depredation rates across most fisheries in Australia, apart from a few studies where depredation has been quantified recently, such as the Western Australia Mackerel Managed Fishery (Carmody et al., 2021), the Eastern Tuna and Billfish longline fishery (Gilman et al., 2008), the Queensland spanner crab fishery (Milburn, 2021) and localised recreational fisheries in Western Australia (Mitchell et al., 2018a). Anecdotal reports from fishers suggest that depredation is widespread in commercial, charter and recreational fishing sectors, across Northern Australia in particular. Scientific data collection protocols therefore need to be developed to collect quantitative data on depredation rates in these fisheries where there are no existing data, such as the Queensland school and grey mackerel net fishery and the Northern Prawn Trawl Fishery, as a first step to managing the issue. Such data needs to be continuously collected over time, to allow analysis of temporal changes.

8.2. Assessing the influence of environmental factors on shark depredation

There is currently limited knowledge about how environmental factors may influence shark depredation, apart from in two studies in Western Australia. Mitchell et al. (2018a) found that depth had an important effect, with depredation increasing with depth up to a peak at 60m in the Ningaloo Marine Park, with latitude also found to be important, likely because it was acting as a proxy for habitat type. Also in Western Australia, Carmody et al. (2021) found that time of day was an important variable, with higher depredation occurring around dawn and dusk when sharks were more likely to be actively feeding. Understanding how depredation is influenced by environmental variables is important because it can help to develop targeted strategies for mitigating it. For example, fishers at Lord Howe Island report that depredation is much lower in waters deeper than 100m, as this is beyond the main depth range of the Galapagos sharks responsible for depredation (Mitchell et al., 2021). Investigating how factors such as water temperature, lunar phase and season affect shark depredation will generate greater possibility for fishers to tailor their fishing strategies to reduce it.

8.3. Understanding social and economic impacts

In addition to the biological impacts of depredation on fish stocks, there is a need to collect data on the economic and social impacts. In particular, it is necessary to understand the financial costs of depredation for commercial fishers, including the cost of lost fishing gear and catch, as well as other operational costs such as increases in fuel use due to having to travel further to avoid sharks and increased time spent on the water. For recreational and charter fisheries, financial costs should also be quantified. This would include the cost of lost fishing gear as well as the broader impacts such as whether fishers have decided to avoid certain areas due to depredation, which could be negatively impacting charter fishing businesses and tourism businesses in regional towns. In line with this, social impacts should be investigated and characterised, such as how depredation is impacting on the enjoyment of recreational fishers.

8.4. Identifying shark species responsible for depredation

Whilst recent research has begun to identify shark species responsible for depredation in some localised areas in Western Australia (Fotedar et al., 2019; Mitchell et al., 2019) and Queensland (Milburn, 2021; Vardon et al., 2021), there is a need to expand this research to more fisheries to gain a broader understanding of regional differences in the shark species responsible, and whether this includes managed or protected species. Additionally, in some cases sharks may be incorrectly associated with depredation when it is actually large teleosts (such as cods/groupers; Figure 2), rays, dolphins or other taxa responsible (Streich et al., 2018; Milburn, 2021), so research should also determine the extent to which sharks are involved, as there is likely to be substantial variation between fisheries and regions.

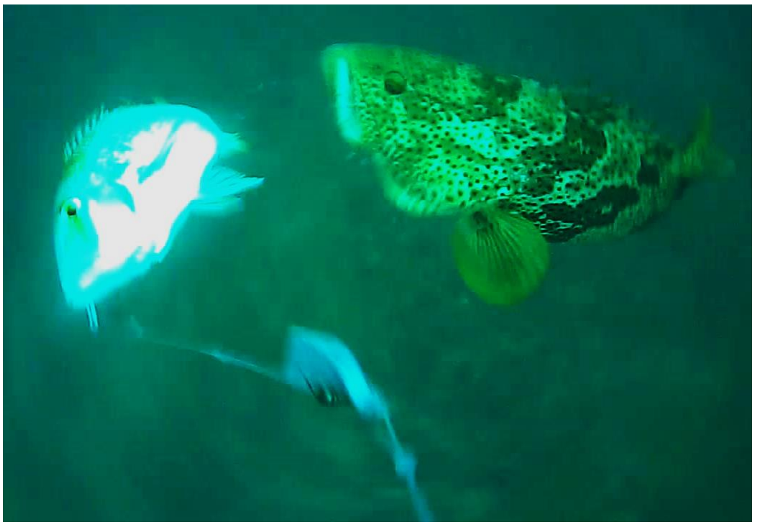

Figure 2: A large estuary cod (*Epinephelus coioides*) attempting to depredate a hooked emperor. Credit: Jonathan Mitchell.

8.5. Quantifying trends in shark abundance

Many anecdotal reports from fishers suggest that shark populations may be increasing, which could be driving increased depredation. There is a possibility that shark populations have marginally increased in northwest Western Australia and northern Queensland due to the closure of shark fisheries in 1993 and reduction in shark catch quota in 2009, respectively. Yet, as mentioned in section 6, most of the shark species responsible for depredation would not be capable of significant population increases in 10-20 years, due to their slow reproductive rate. There is currently limited scientific data on shark abundance all around Australia, although two studies conducted in Western Australia suggest that populations of some key depredating shark species have been stable for the last 10-20 years and not increasing (Braccini et al., 2020; 2021). In Queensland, the only stock assessment of Carcharhind (whaler) sharks conducted to date showed stable or decreasing trends in population over time in the northern regions of Queensland, but increases in the southern regions (Leigh, 2015). However, there were a number of data limitations in this stock assessment, including lack of discard data from commercial fisheries, gaps in effort data and issues with species identification (Leigh, 2015). Age distribution data was also not available for most of the shark species assessed. The only other recent stock assessments conducted for sharks were for smaller, commercially important species, such as school shark and gummy shark, which are not likely to be responsible for depredation. More research is therefore needed to understand the status of shark populations, particularly across northern Australia and for the key species likely responsible for depredation (listed in sections 2 and 3). As well as large scale regional or state-wide assessments, it is also necessary to conduct studies on shark abundance in localised areas where depredation is found to be more frequent, to identify if changes in shark abundance are an important influencing factor.

8.6. Investigating ecological effects of shark depredation

Shark depredation is likely to be having a range of unknown ecological impacts as well as those related to fisheries. For example, sharks that regularly feed on hooked fish in a specific area may have changed their diet compared to when they relied on natural predation only. Depredation provides sharks with opportunities to feed on fish species that they may not necessarily be able to prey on naturally, for example fish that are large, agile and fast swimming, e.g. tuna and Spanish mackerel. Because they are injured and struggling when hooked, these fish become an easy target compared to if the shark was to pursue and try to catch them naturally. Indeed, Madigan et al. (2015) reported that oceanic whitetip sharks feed predominantly on large pelagic teleosts, likely depredated from game fishers, when they are in The Bahamas, as opposed to squid in other parts of their distribution. This access to improved feeding opportunities may therefore increase the fitness, growth rate and reproductive potential of an individual shark, depending on how frequently the food source is available. However, the availability of hooked fish to feed on may also lead to more competition amongst sharks and increased aggression, leading to injuries. If depredation provides a regular enough food source to markedly change the diet of the sharks then it could also lead to knock-on effects on the food web, releasing certain prey species from predation pressure whilst leading to higher mortality for others. This concept has yet to be investigated in the case of shark depredation, however a study by Clavareau et al. (2020) was the first to attempt this for cetacean depredation, using an Ecopath trophic model. This study found that depredation of toothfish by orcas and sperm whales had cascading negative effects on other taxa in the food web but had positive effects on natural prey of these cetaceans, such as cephalopods, due to a release from predation pressure (Clavareau et al., 2020). However, this form of modelling is highly complex and there are many uncertainties associated with it, such as the extent to which depredation contributes to the daily energy requirements of the predator and how consistently this source of food is available over a seasonal basis. Nonetheless, this study highlighted the wide-ranging impacts depredation can have, beyond just the human dimensions of fisheries. It is therefore recommended that similar studies are undertaken for shark depredation, to generate a greater understanding how depredation can influence the diet of sharks and the dynamics of interrelated food webs.

8.7. Shark movement patterns and behaviour

There is growing evidence to show that sharks are able to rapidly learn to take advantage of new food sources (Heinrich et al., 2021) and associate the presence of fishing vessels with the availability of hooked fish to feed on (Mitchell et al., 2020). This may lead to changes in the movement patterns and residency of sharks, where they increase the time spent in locations where fishing is occurring regularly, as reported at Lord Howe Island (Mitchell et al., 2021) and is analogous to provisioning effects seen elsewhere, for example bull sharks fed for ecotourism in Fiji (Brunnschweiler and Baensch, 2011; Brunnschweiler et al., 2018). However, further research is needed to generate a greater understanding of how depredation may be influencing behaviour and movement patterns of different species of sharks that are responsible for depredation. In some cases, depredation may be an opportunistic behaviour and represent only an infrequent supplement to the diet of individual sharks, whereas in other circumstances where the sharks are highly resident in areas where fishing is occurring frequently, it may provide a substantial portion of their diet.

8.8. Developing mitigation approaches for shark depredation

Another key research gap is how to mitigate depredation. Recent studies have begun to investigate this question by testing devices to physically protect the catch (Goetz et al., 2011; Rabearisoa et al., 2012; Hamer et al., 2015), as well as shark deterrents (Coulson et al., in prep) and working with fishers to identify practical mitigation measures that are already being trialled, such as changing fishing gear and spatial patterns of fishing effort and diversifying target species (Mitchell et al., 2021; Coulson et al., in review). Gilman et al. (2007b) also collected detailed information on fishing method adaptations used by commercial longline fishers to reduce depredation. There is a need to expand this research to more fisheries that are suffering from shark depredation in Australia, to identify potential mitigation measures that may be suitable for use.

9. Approaches for addressing key research gaps for shark depredation in Australia

9.1. Quantifying shark depredation rates

To address the current data gap for the lack of quantitative data on shark depredation rates, a range of methods can be used. This can take the form of adding fields to logbooks for commercial and charter fishers, similar to that used in the Western Australia Mackerel Managed Fishery (Carmody et al., 2021), or having dedicated onboard observers to collect data on a subset of fishing trips. Conducting fishery independent surveys to quantify depredation, similar to the Alaska sablefish fishery (Hanselman et al., 2018a), can also provide a reliable source of data. For recreational fisheries, adding questions to boat ramp survey forms to capture depredation can be one method, as well as using other survey tools. Phone and online surveys in Western Australia have demonstrated the ability to collect data on depredation rates, although these can be affected by recall and avidity biases (Ryan et al., 2019, Coulson et al., in review). Phone apps can also be used for recreational and charter fishers to report depredation and these are currently being trialled in Queensland. The use of structured face to face interviews and workshops with fishers can also generate important historical data and background context on depredation (Hoel et al., 2021; Iwane et al., 2021), in addition to content analysis (Buckley et al., 2017), for example reviewing newspaper articles, fishing logs and other historical sources of information to provide an assessment of the prevalence of depredation over time. Social media may also provide useful information on species depredated, spatial variation and changes over time, in recent years. Once these data collection protocols are adopted, detailed analyses can be conducted to investigate the spatial and temporal occurrence of depredation across fisheries. Depredation rate data can also be incorporated into stock assessment models, similar to the approach used by Tanimoto et al. (2021) for the Queensland east coast Spanish mackerel stock assessment.

9.2. Assessing the influence of environmental factors on shark depredation

To investigate how environmental factors affect depredation rates, data needs to be collected during the fishing session, or retrospectively. Some variables such as depth and time of day may be captured in logbooks for commercial and charter fishers, but other variables such as water temperature, productivity and lunar phase may not. Data for these variables can be accessed and downloaded retrospectively from publicly accessible portals such as the Australian Ocean Data Network (AODN; portal.aodn.org.au), which has a wide array of datasets for environmental variables, which are collected from satellites, ships and buoys. These data can then be downloaded for the date ranges that match the depredation data collected. Statistical modelling approaches can then be used to conduct a detailed analysis of how these factors may influence shark depredation rates, similar to methods used by Mitchell et al. (2018a) and Carmody et al. (2021).

9.3. Understanding social and economic impacts

To assess socio-economic impacts of depredation, logbook and survey instruments could also be used, where fishers would be able to record costs attributed to different categories, such as fishing gear, target species loss/damage, fuel costs, time on the water and others. These surveys should aim to collect data from a subset of fishers over an extended period, to capture changes in financial impacts over time. Interviews and workshops that include both structured questions as well as round table discussion sessions can provide an effective forum for fishers to explain socio-economic impacts of depredation in more detail, whilst providing contextual information on their fishery more broadly. This approach was used by Iwane et al. (2021) to conduct an in-depth assessment of fisher-shark interactions in Hawaii, so this study can provide important learnings for future work in this space.

9.4. Identifying shark species responsible for depredation

Recent research has used both underwater video cameras (O'Shea et al., 2015; Mitchell et al., 2019; Drymon et al., 2020; Milburn, 2021) and genetic approaches (Drymon et al., 2019; Fotedar et al., 2019; Vardon et al., 2021) to identify shark species responsible for depredation. It is recommended that further research is undertaken using these methods in a greater range of fisheries, which will provide a broader assessment of the predators responsible for depredation in different fisheries. These methods have certain advantages and disadvantages which can limit their effectiveness. For example, underwater video relies on relatively good underwater visibility, while identification of species, especially Carcharhinid (whaler) sharks, can be difficult due to the movement of the camera mounted on the fishing line. However, video has the benefit of being able to provide a range of information on shark behaviour and other forms of interaction with fishing gear, which genetic approaches cannot. In addition to line mounted cameras, 360-degree cameras should also be utilised for observation of depredation events, as they can provide a more detailed insight into the behaviour of sharks in the vicinity of the fishing vessel. Camera based methods also enable identification of the fish depredated, which is useful when no remains of the fish are retrieved (Figure 2). Genetic identification can be costly and requires specialist laboratory protocols, and collection and storage of samples needs to be conducted carefully to achieve high identification success. Nonetheless, it can produce higher identification success than visual identification from video, as demonstrated by the 100% success rate reported by Fotedar et al. (2019). To optimise the success of sampling, swabs should be taken from depredated fish as soon as they are retrieved to the boat, particularly around the teeth marks on the fish. Additionally, primers that amplify the mitochondrial shark DNA NADH dehydrogenase two (ND2) and four (ND4) genes should be used to increase the chance of identifying closely related shark species (Vardon et al., 2021). A detailed discussion of the best practice methods for using video cameras and genetics to identify depredating sharks is provided in Mitchell et al. (in review), so this study should be referred to by researchers looking to investigate this data gap in future.

9.5. Quantifying trends in shark abundance

To generate data on shark abundance, baited camera surveys are one non-invasive approach that can be used. These surveys involve deploying a baited camera for up to 1 hour to record the species and size of sharks attracted into the field of view. A large global program of baited camera surveys known as Global FinPrint was initiated in 2015, which has now collected data on relative shark abundance from 58 countries worldwide, including 96 sites across Australia (globalfinprint.org) (MacNeil et al., 2020). This data can be used as a baseline for sites which had no shark abundance data previously. Future baited camera studies should then be conducted at the same sites and using the same methodology, to assess how abundance changes over time. This approach will be valuable for assessing abundance at localised sites and at a larger, regional level. Traditional fisheries stock assessments should also be conducted across northern Australia for key Carcharhinid species likely to be responsible for depredation, building on the approach used by Leigh (2015). To address key limitations of this past assessment in Queensland, efforts should be made to collect more detailed data on fishing effort, including net depth and technology used, as well as data on shark discards, to enable more robust catch rate analyses. Fishery observer programs (including both onboard observers and electronic monitoring) should also be expanded to collect more reliable data, particularly for shark species identification. Such data collection protocols should be implemented and maintained across long timescales to enable analysis of changes over time, in relation to fishing pressure and environmental variables. This would allow a robust, scientific assessment of whether increasing shark populations are an important factor influencing the occurrence of depredation.

9.6. Investigating ecological effects of shark depredation

To investigate potential ecological effects of depredation, research should aim to learn more about the diet of shark species responsible for depredation. In particular, it is necessary to determine the extent to which the daily energy ration of sharks is made up from fish that were naturally predated upon versus those depredated. Stable isotope analysis can provide insights into this question by identifying the food sources of sharks. Madigan et al. (2015) used stable isotope analysis to show that the diet of oceanic whitetip sharks is markedly different on a seasonal basis when they are in The Bahamas, which may be driven by their depredating teleost fish hooked by gamefishers. Once the diet of depredating shark species is known, along with the depredation rate in a particular fishery, it is then possible to create an Ecopath model similar to that generated by Clavareau et al. (2020), to explore the wider ecosystem level effects of shark depredation on natural prey species, other predators and the fishery.

9.7. Shark movement patterns and behaviour

To learn more about how depredation may be altering the behaviour and movement patterns of sharks, one approach is to use a combination of shark movement data generated from satellite or acoustic tagging and fishing vessel movement data from Vessel Monitoring Systems (VMS). This enables detailed investigation of how shark movements and fishing activity overlap in time and space. For example, it can enable identification of 'hotspot' areas where shark and fishing vessels overlap most frequently, with this information then being communicated to fishers to help them make more informed choices about where to fish to avoid these 'hotspots'. Mitchell et al. (2021) demonstrated the potential for this approach in a small-scale charter fishery at Lord Howe Island, finding that areas of higher fishing activity also had greater presence of tagged sharks, especially at a site where fish waste was regularly dumped. Another approach to investigate this overlap is by using underwater acoustic recorders to detect the presence of vessels from engine noise at a given site, and then compare this to the presence of tagged sharks. This method was used by Rider et al. (2021) to investigate whether sharks were affected by the presence of boat traffic in Florida waterways. When using either of these approaches, it can be possible to identify differences in behaviour and movement that may be related to the availability of food from depredation. For example, it would be expected that sharks that have learnt to feed on hooked fish may have higher residency in an area where fishing is happening regularly and that they would primarily reside there during the day, when fishing was occurring, then move away at night. Tagging data can also provide information about the depth of the sharks, such as whether they are moving up in the water column rapidly, which could indicate when they are pursuing a hooked fish being retrieved to a boat.

9.8. Developing mitigation approaches for shark depredation

Developing effective mitigation measures for shark depredation is a vital research goal. A key approach to doing this will be to set up face-to-face workshops between stakeholders to discuss a range of approaches that can be implemented. Collective discussions with fishers can help to collate information about potential strategies that have already been tested by fishers in the field, so that these methods can be further fine-tuned or trialled by fishers in other locations and fisheries. If certain methods are found to be successful, then educational material such as leaflets and posters can be developed to communicate these techniques to a wider audience, for example by distributing them at fishing tackle shops and on social media. This approach is already being undertaken in Western Australia and at Lord Howe Island, where fishers have been surveyed to collect information on any mitigation methods they have used in the past (Mitchell et al., 2021, Coulson et al., in review).

Likewise, in Queensland, workshops have been conducted with fishers to learn more about how depredation is affecting them and whether they currently use any methods to mitigate it (Hoel et al., 2021). A study by Iwane et al. (2021) in Hawaii provides useful detail about how these workshops can be organised and implemented to achieve successful outcomes for both fishers and managers.

Physical protection devices designed to protect a hooked fish from being taken by a shark, have been trialled in longline fisheries in an attempt to reduce loss of catch to depredation (Moreno et al., 2008; Goetz et al., 2011; Rabearisoa et al., 2012; Hamer et al., 2015). A few different forms of these devices have been tested, including 'chain' and 'cage' devices, which are triggered by the tension of a fish getting hooked on a longline and drop down to cover the fish (Hamer et al., 2015) and an 'umbrella and stones' device, which also works in a similar way (Figure 3) (Goetz et al., 2011). The 'chain' and 'cage' devices were tested in longline fisheries in Australia and Fiji and resulted in significantly lower depredation of catch compared to control lines, although the sample size of testing was relatively small (only 27 depredation events occurred, 24 of which on control lines) (Hamer et al., 2015). These devices had a net positive impact on target species catch rate, due to lower depredation, although they did reduce cost-efficiency because they required an extra crew member to deploy them (Hamer et al., 2015). The 'umbrella and stones' device restricted depredation rates and was highly effective at reducing seabird bycatch, however it also led to lower catch rates of target species (Goetz et al., 2011). Earlier research in the Chilean Patagonian toothfish fishery tested a 'net sleeve' deterrent, which was highly effective at reducing seabird bycatch and led to decreases in toothed whale depredation from 5% to 0.4% (Moreno et al., 2008). However, the 'sock' and 'spider' devices tested by Rabearisoa et al. (2012) proved to be less effective and reduced operational efficiency due to causing tangles in the lines and increasing the time required for setting and hauling the longline. Thus overall, testing of physical protection devices has produced mix results to date. Yet, the principle of such devices remains sound and further work to develop and test new devices is recommended, for a range of different fishing gears in Australia. These devices would need to be easy to deploy, cost effective and practical for fishers to use and extensive testing during real-world fishing settings needs to be conducted to assess their viability. Working closely with fishers will enable their feedback to be incorporated and the devices to be modified and optimised as necessary to ensure that they can meet fishers' needs.

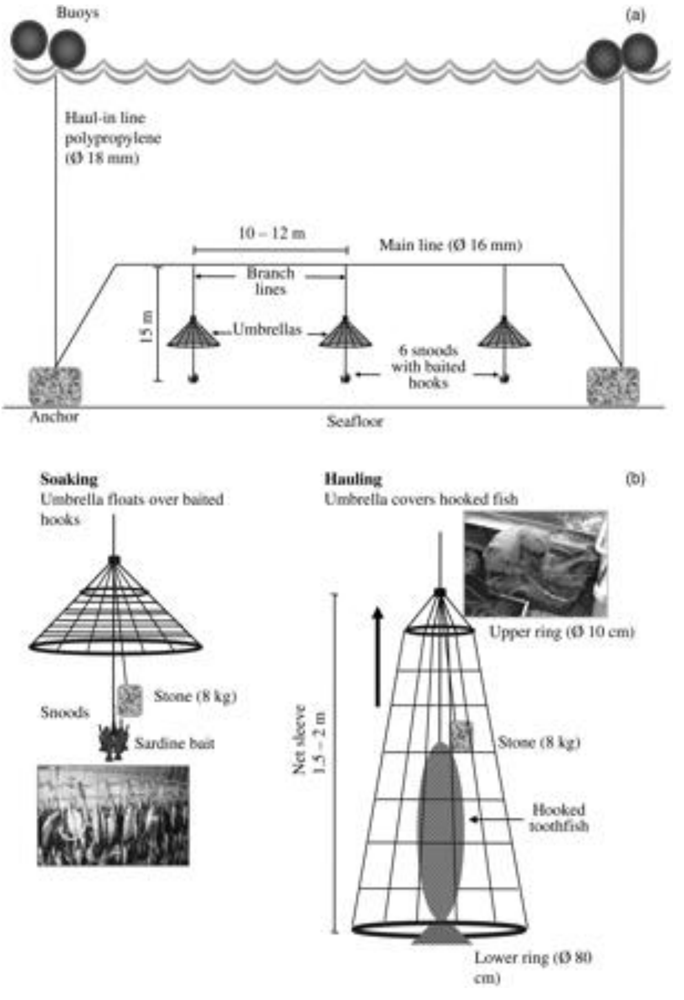

Figure 3: Diagram of the 'umbrella and stones' physical protection device developed to mitigate sperm whale depredation and seabird bycatch in bottom longline fisheries in the Southwest Atlantic. Figure taken from Goetz et al. (2011).

Testing shark deterrents is another approach that should be pursued to determine whether they can provide benefit in terms of reducing depredation rates. This includes shark deterrents, which work in a similar way to those used to protect surfers and divers (i.e. devices such as the OceanGuardian SharkShield). To objectively test deterrent products, such as the electrical OceanGuardian FISH01 (Figure 4) and the magnetic SharkBanz Sentry, both of which have been designed for reducing depredation, it is necessary to develop a robust experimental design. This will involve determining what sample size is needed to detect whether the device is effective or not, which will need to factor in the level of statistical power required, what the current level of shark depredation is and what amount of reduction in depredation would be considered a success. In addition to this, the number of sampling sites needs to be carefully considered to ensure that enough replication can be conducted, allowing for control deployments (where devices are turned off) and making sure that there is enough distance between sites to prevent the same sharks being encountered, knowing that sharks will likely follow the vessel. The fishing methods used, such as the number of lines in the water, bait used, hook and leader type, length of fishing session, should all be controlled as much as possible to remove any unwanted variation. The first testing of deterrent devices was recently conducted in Western Australia by Coulson et al. (in prep), with the results indicating that the presence of a deterrent did not significantly reduce depredation probability for a given fishing session, but they were effective at reducing the overall proportion of fish depredated by sharks and the time taken for depredation to occur. However, due to difficulties achieving the necessary sample size, it was not possible to determine the effects of each of the three deterrents tested on an individual level, only at the collective level of deterrent deployed versus no deterrent deployed (P. Coulson, pers. comm.). Generating enough data was difficult because there were many instances where not enough fish were caught at a given sampling site and/or sharks were not present or did not depredate on hooked fish (P. Coulson, pers. comm.). This highlights the difficulty in generating a large enough dataset from deterrent testing and underscores the need for careful consideration of sampling locations by researchers looking to conduct future testing.

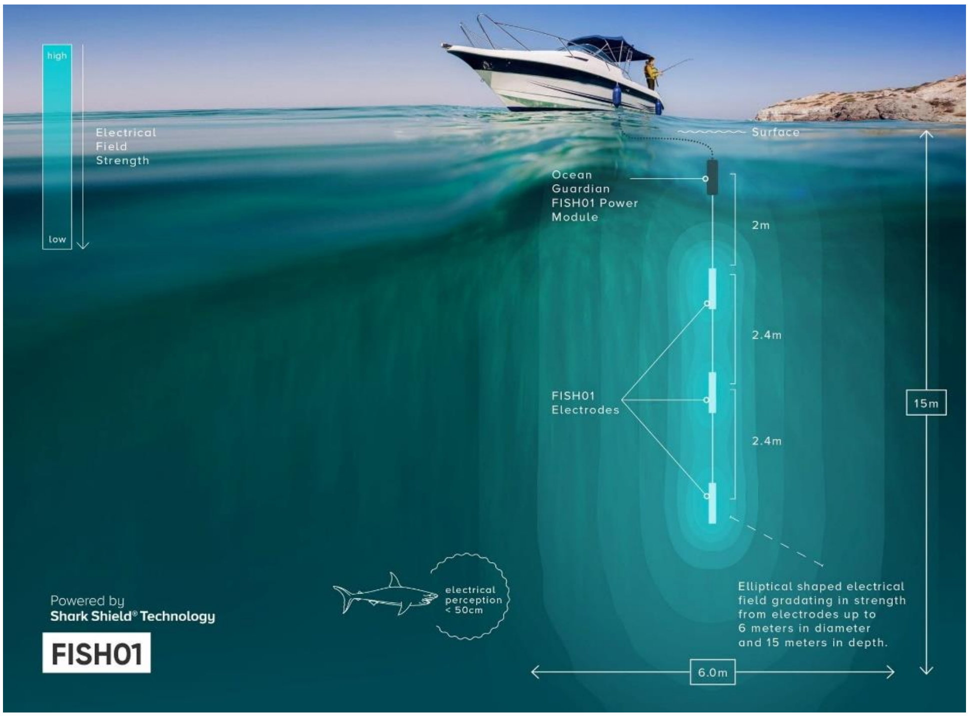

Figure 4: Diagram of the OceanGuardian FISH01 device designed to reduce shark depredation. Credit: OceanGuardian.

Table 3: Summary table of key data and knowledge gaps for shark depredation and methods for addressing them.

Data/knowledge gap	**Method of addressing gap**	**Example research from other countries**
Lack of quantitative data on shark depredation rates across Australian fisheries	Implement logbook data collection fields for commercial fisheries Use onboard observers/electronic monitoring to collect data Fishery independent surveys Survey tools for quantifying depredation in recreational fisheries Phone apps Interviews and workshops Historical content analysis Incorporate depredation into stock assessments	Carmody et al. (2021) Gilman et al. (2007) IOTC (2007) Hanselman et al. (2018a) Mitchell et al. (2018) Ryan et al. (2019) Hoel et al. (2021) Iwane et al. (2021) Buckley et al. (2017) Tanimoto et al. (2021)

Limited understanding of how environmental factors influence shark depredation	Collect data on environmental variables in logbooks Download environmental datasets from public databases e.g. AODN Use statistical modelling approaches to determine the influence of environmental variables on depredation rates	Mitchell et al. (2018a) Carmody et al. (2021)
Minimal data on socio-economic impacts of shark depredation	Record data on economic impacts in logbooks Surveys of fishers Interviews and workshops	Carmody et al. (2021) Hoel et al. (2021) Iwane et al. (2021) Sexton et al. (2020)
Shark species responsible for depredation are unknown in many fisheries	Use underwater video cameras mounted on fishing lines 360 degree cameras GoPro cameras mounted in fishing pots/traps Collect swabs from depredated fish for genetic analysis, with appropriate primers to distinguish closely related shark species	Mitchell et al. (2019) Streich et al. (2018) Milburn et al. (2021) Drymon et al. (2020) Fotedar et al. (2019) Drymon et al. (2019) Vardon et al. (2021)
Lack of reliable, long-term data on shark abundance trends	Baited camera surveys of shark abundance in localised areas, repeated over time Conduct stock assessments of key depredating shark species Fishery observer programs to collect more reliable data on shark catch in commercial fisheries	Macneil et al. (2020) Leigh (2015)
Very limited understanding of how depredation influences shark diet	Stable isotope analysis of depredating shark species	Madigan et al. (2015)
Ecological effects of depredation on food webs are unknown	Conduct food web modelling using Ecopath	Clavareau et al. (2020)
Limited data on how shark depredation influences the movement patterns and behaviour of sharks	Satellite and/or acoustic tagging of sharks to learn about movement patterns and behaviour Vessel tracking and underwater sound recorders to learn about fishing vessel activity and presence	Mitchell et al. (2021) Rider et al. (2021)
Minimal research conducted on testing of mitigation methods for depredation, e.g. changes in fishing methods, testing of shark deterrents	Stakeholder workshops to identify mitigation measures already used by fishers Dissemination of educational material about techniques for mitigating depredation Testing of physical protection devices to stop sharks accessing catch Testing of shark deterrent devices	Hoel et al. (2021) Iwane et al. (2021) Mitchell et al. (2021) Coulson et al. (in review) Moreno et al. (2008) Goetz et al. (2011) Rabearisoa et al. (2012) Hamer et al. (2015) Coulson et al. (in prep)

10. Is shark depredation causing intersectoral conflict in Australia?

Shark depredation is a topical and emotive issue in Australia and other locations around the world, because it affects a wide range of stakeholders who often have conflicting viewpoints on the issue. One of the most substantial conflicts occurs due to some fishers calling for sharks to be culled and/or commercial shark fisheries to be expanded (Mercer, 2015; Kagi, 2016), which some stakeholders supporting shark conservation are against. Awareness of shark conservation has increased substantially in recent decades due to research documenting the plight of sharks, with some species reported to have declined by as much as 95% (Robbins et al., 2006; Ferretti et al., 2010; Pacoureau et al., 2021), as well as high-profile documentaries such as 'SharkWater' exposing the global threat to sharks from international trade. This increase in shark conservation messaging has likely led to reduced marketability of sharks in Australia, as highlighted by some major supermarkets no longer selling shark products over the last 10-20 years. However, when communicating the results of shark abundance studies, such as Pacoureau et al. (2021), it is important to recognise that these trends are on a global scale, whereas shark populations in Australia may be in a healthier state, in general, due to better fisheries management and lower historical fishing pressure. Appropriate context therefore needs to be provided when disseminating these results to the wider public.

A recent example of conflict between sectors was in Western Australia, where Recfishwest made a recommendation to the Western Australia Department of Primary Industries and Regional Development to increase commercial fishing of sharks, which was met with concern from a number of environmental NGOs such as the Australian Marine Conservation Society and Sea Shepherd (Murphy, 2021). There have been numerous other media articles about fishers calling for increases in commercial shark fishing or the introduction of culling to manage shark populations (Mercer, 2015; Kagi, 2016; Daily Mercury, 2018), and this will likely continue whilst depredation impacts fisheries. For fisheries managers, managing this conflict is a difficult prospect due to the strongly polarised views of both groups. This further highlights the need for development and implementation of depredation mitigation strategies that can reduce the negative impacts of depredation on fishers whilst being non-damaging to sharks, particularly where TEPS are involved.

Another conflict that exists is between fishing sectors. Certain commercial fishing activities such as trawling are perceived by recreational fishers to exacerbate the shark depredation problem, because the sharks have learnt to follow trawlers and feed on discards. In some areas where trawling effort has now decreased from historical levels, recreational fishers now believe that the sharks have switched from following commercial trawlers to instead depredating line fishing catch. Conversely, some commercial fishers believe that recreational and charter fishers are increasing the occurrence of depredation because they keep going back to locations where depredation is worse and therefore reinforcing the behaviour of the sharks. Research by Carmody et al. (2021) showed that depredation can be higher where there is an overlap of fishing activity from both commercial and recreational fisheries, particularly near population centres. Managing this conflict between fishing sectors will require improved communication and education on the issue of depredation. Collaboration will be necessary to develop effective mitigation measures that benefit all fishing sectors, so new approaches, including non-adversarial stakeholder workshops, should be implemented to achieve this.

Exploring and understanding the complex range of factors driving intersectoral conflict will be key to developing effective collaboration on the issue of shark depredation. Hoel et al. (2021) conducted a series of workshops with fishers in North Queensland, to collate information about fisher perceptions around depredation. The study found that, in addition to their surface level frustrations caused by losing catch and gear to sharks regularly, most of the fishers expressed a distrust of fisheries managers and scientists because they felt that their views were not being heard and that recently published research on shark abundance did not match their experiences in a local context (Hoel et al., 2021). The research stressed the need to address these deeper level conflicts by rebuilding trust between fishers, managers and scientists through transparent communication and collaboration (Hoel et al., 2021). Greater incorporation of fishers' knowledge and experiences into research and management and providing locally specific information about shark populations was also recommended (Hoel et al., 2021). Holding non-adversarial stakeholder forums and conversations around scientific results and methodology, which are not connected to management change or intervention, would assist in developing a shared understanding between stakeholders and managers on shark depredation. The proposed national workshop being led by FRDC is a good positive step towards this goal.

11. Implications of shark depredation for fisheries stock assessments in Australia

Shark depredation can lead to additional mortality for target species because fishers will generally keep fishing until they have reached their allowed quota or bag limit, meaning that the fish lost to depredation are additional to those retained by fishers. If a fishery is consistently experiencing depredation rates of 10-20% each year, then this extra level of mortality could have a significant cumulative effect on a fish stock over time. This is especially the case for fisheries which are facing other threats, such as environmental changes linked to climate change, which may be reducing recruitment success. The cumulative impacts of depredation and environmental change could therefore push a stock that is otherwise sustainable towards depletion, with substantial ecological and socio-economic impacts. This has potential implications for the sustainable management of fish stocks, because it may result in catch quotas or possession limits (based on recommended biological catches) being set above sustainable levels (compared to if depredation mortality was included).

Conversely, in fisheries that heavily rely on catch per unit effort (CPUE) as a performance indicator, such as under empirical harvest control rules, or stock assessments, depredation could result in lower recommended biological catches being set. The use of CPUE in performance measurement frameworks is as an indicator of abundance, so decreases in CPUE are inferred as declines in the abundance of the target stock. However, if CPUE is reducing through time due to a proportion of the catch being taken through depredation, and therefore a lower number of harvested fish being reported, these assessment frameworks would infer that the abundance of the target stock had reduced (even though it may not have) and the level of fishing mortality would need to be decreased. Therefore, the effect of depredation on CPUE may also lead to decreases in recommended biological catches, even though biomass remained relatively stable. With a long-term data timeseries on depredation rates, these issues could be alleviated through inclusion of depredation as a term in the catch rate standardisation process. However, it should be noted that this reduction might not be completely unwarranted given the additional cryptic mortality that may be occurring on the stock (as mentioned above). Where CPUE is used as a primary indicator in a stock assessment a similar outcome could occur, or it could lead to high conflict among data inputs, such as where trends in CPUE conflict with age structures and result in poor model fits. Given these potential effects on the assessment (and management) of fisheries, the effect of changes in depredation rates on data inputs need close consideration.

Due to the lack of data on depredation rates around Australia, it is currently difficult to incorporate depredation mortality into stock assessment models, other than by assigning an arbitrary rate of depredation (in terms of the percentage of hooked fish that are lost) estimated from research in other fisheries. Due to the uncertainty in this approach, there are few stock assessments that currently incorporate depredation mortality. One exception is the recent stock assessment of Queensland east coast Spanish mackerel, where a model simulation was run which incorporated depredation

(Tanimoto et al., 2021). This model included a baseline depredation rate of 0% in 2009 and then applied an increasing rate of 1.8% per year, up to a depredation rate of 20% for the year 2020 (Tanimoto et al., 2021). The increase was set to occur from 2009 because this was when the commercial shark catch quota was substantially reduced in this region, which fishers believe has led to increasing shark populations. Also, otter trawl discards halved since 2009, which may have resulted in sharks feeding on offshore line fishing catch instead. The maximum value of 20% used in this study was based on the only depredation rate data from an Australian commercial fishery available at the time, which was from the East Coast Tuna and Billfish Fishery reported in Gilman et al. (2008). Including this level of depredation in the stock assessment model led to spawning biomass estimates being 6% higher (23%) than when it was not incorporated (17%), probably because it led to a higher catch rate used as an index of abundance (Tanimoto et al., 2021). However, recent research in the Western Australian Mackerel Managed Fishery reported lower depredation rates of between 1.7% and 5.7%, depending on the region (Carmody et al., 2021). There are also a few examples of other fisheries around the world where depredation rates have been included in stock assessment models, including for the sablefish fishery in Alaska, where cetacean depredation leads to loss of 15% of catch (Hanselman et al., 2018a; 2018b). The quota allocated to commercial fishers is adjusted based on the level of depredation recorded over time (Hanselman et al., 2018a; 2018b). This fishery has a long-term depredation dataset going back ~22 years, with data being systematically collected in annual fishery-independent surveys (Hanselman et al., 2018a; 2018b). Clavareau et al. (2020) developed an Ecopath trophic model to explicitly incorporate the impact of depredation by toothed whales on both fisheries and the wider food web. Although not a traditional stock assessment approach, this study provides important insights into the broader ecosystem level effects of depredation so it should be considered for future research in fisheries where shark depredation occurs.

Ultimately, we are only at an early stage of being able to start incorporating depredation data into stock assessment models in Australia, which underscores the need for the development of routine data collection protocols for capturing depredation data. Data on depredation should be collected in the form of a depredation rate, which represents the percentage of the total number of hooked fish that are lost to depredation. This metric is the most explicit form and is more easily incorporated into modelling datasets than other depredation metrics, such as the interaction rate. Planning and implementing long-term data collection programs for depredation is a priority, due to potential increases in depredation rates in future.

12. Quantifying post-release predation by sharks

Post-release predation, where fish/invertebrates are consumed by sharks shortly after being released, is another process causing increased mortality, in addition to those depredated when hooked. Whilst there is minimal data on the rate at which this occurs, it is possible that it could be as high as levels of depredation in some fisheries. The rate of predation would depend on many factors, such as fishing gear used, handling practices, susceptibility to barotrauma and predator density. Research in The Bahamas reported that 17% of bonefish caught in a shallow water catch and release fishery were predated upon by sharks after release (Danylchuk et al., 2007). In areas with high predator density, predation rates could be even higher, up to 40% (Cooke and Philipp, 2004). In an Australian context, Pepperell and Davis (1999) found that one out of eight black marlin tagged was predated on by a shark. A recent study in the US quantified the level of predation when descender devices (release weights) were used, finding it to be zero (Drymon et al., 2020). However, these weighted devices were able to return fish to the bottom at a relatively rapid rate, compared to their naturally ability to swim down. Nonetheless, the results highlight that such devices can provide a notable benefit in reducing post-release predation, as well as barotrauma, so they should be promoted for use in fisheries where post-release depredation may be high. Future research could aim to quantify post-release predation rates for different species using acoustic and/or satellite tags specifically designed for this purpose, e.g. INNOVASEA Predation Transmitters or Wildlife Computers Survivorship PAT tags. The latter tags are especially effective because they provide highly informative data on the fate of released fish and are capable of distinguishing death from predation versus other causes, e.g. barotrauma, using light levels, temperature and depth (Graves et al., 2016; Tracey et al., 2016). Deploying cameras underneath the boat could also provide an insight into post-release predation rates. In particular, 360 cameras could be deployed at different depths in the water column to observe fish swimming down after being released. This approach would, however, rely on relatively high water clarity. Fisheries with high rates of release would be a good target for this research, particularly in recreational fisheries where demersal species are targeted. For further detail on post-release predation, see the detailed review by Raby et al. (2014).

13. Impacts of depredation on shark populations

Shark depredation is leading to conflict between fishers and sharks, due to the impact of lost catch and fishing gear and a reduction in the fishing experience. Sharks can be negatively impacted because they often get inadvertently hooked when depredating catch, resulting in them either snapping off the line and retaining the hook in their jaw or gut, or being brought to the boat and either kept or released by fishers. Retained fishing gear can have negative long term effects on sharks, including causing internal lesions and perforation of organs, eventually leading to the death of the animal (Borucinska et al., 2001; 2002). Recent research has shown that stainless steel hooks can take up to seven years to break down and fall out of an animal (Begue et al., 2020), indicating that they can potentially have long-term impacts on feeding and fitness. The use of corrodible hooks is therefore recommended, as they broke down faster and were shed by sharks within 1-2 years (Begue et al., 2020). If depredation increases into the future then the higher frequency of shark-fisher interactions may begin to cause negative effects at the population level for some species, particularly those that are threatened and protected (e.g. great hammerheads and grey nurse sharks) and where sharks are depredating upon other sharks.

There are also numerous examples in social media of sharks being deliberately killed in retaliation for depredation. This can be compounded by the frustration of fishers towards fisheries management agencies due to a perceived lack of action on the issue. The occurrence and scale of this retaliatory killing is largely unknown, but it could potentially cause localised depletions in the populations of some species, particularly those that are highly resident or threatened. This underscores the need for fisheries managers and fishers to work together to identify and implement mitigation approaches that produce beneficial reductions in depredation rates for fishers and do not negatively impact on shark populations.

Depredation may give sharks an easy opportunity to feed in comparison to catching a fish naturally, especially in areas where fishing is occurring regularly. It is currently unknown whether this provision of food would be frequent enough to benefit sharks at a population level, in terms of increased potential for breeding and survival of offspring. The beneficial effect of feeding on hooked and released fish is likely to be fairly localised although previous research has shown that where bull sharks were hand-fed regularly over many years for ecotourism activities, this provisioning can provide a major proportion of their energy needs, although only over short timescales (days) and the effect was highly variable between individual sharks (Brunnschweiler et al., 2018).

14. Mitigation approaches for reducing shark depredation across Australian fisheries

14.1. Education and developing effective communication between stakeholders

Research on depredation in Australia is still at a relatively early stage, although significant insights have been produced in terms of characterising the issue and the impact it is having, particularly in

Western Australia. The next step is to apply this information to develop mitigation approaches that can benefit fishers. Effective communication approaches will be critical for this, to ensure that educational material reaches fishers in a form that can help them to directly apply it in their day-to-day fishing activities. A key part of this process will be breaking down barriers between scientists and the fishing community and generating realistic expectations around what is possible in terms of depredation mitigation. Whilst it is highly unlikely that depredation can be stopped altogether, it will be necessary to identify realistic goals in terms of threshold depredation rates that can be reached by using mitigation approaches.

14.2. Adaptations to fishing methods

Changes to fishing gear can provide benefits in terms of reduced depredation. Surveys of fishers in Western Australia and Lord Howe Island have begun to collate information on which approaches are being used to reduce depredation (Mitchell et al., 2021, Coulson et al., in review). In particular, switching to heavier fishing gear such as wire trace and heavier line can enable fish to be brought to the boat more quickly. Using electric reels and handlines instead of rod and reel is a strategy that many fishers are already using with some success in reducing depredation rates (Mitchell et al., 2021). Reducing the chance of attracting sharks by switching from bait to lures and jigs can also provide benefits, as well as turning off the boat engine and echosounder. In some areas, recreational fishers may be able to reduce depredation by diversifying their target species. Recent research is beginning to show that depredation 'hotspots' can occur in areas where commercial and recreational fishing occur consistently, due to sharks associating the presence of vessels with the availability of hooked fish to depredate. This has been documented in Western Australia (Mitchell et al., 2018a; Carmody et al., 2021) and at Lord Howe Island (Mitchell et al., 2021). Research can help to provide fine-scale data on the location of these depredation 'hotspots', which can then be communicated to fishers to help them make more informed choices about where to fish to reduce their likelihood of suffering depredation. Reducing the concentration and predictability of fishing activity will be key to breaking down learned behaviours in sharks. Conducting further surveys to collate information about other methods fishers have tried to reduce depredation will be necessary, combined with field testing of these techniques. For any measures that are deemed to be successful at reducing depredation, educational material promoting the best way to adopt these techniques will need to be developed and disseminated to fishers.

14.3. Physical protection devices and shark deterrents

Physical protection devices may offer a practical solution to reduce shark depredation, if they can be deployed in a way that maintains target species catch rates and operational efficiency. Some of the devices tested in longline fisheries have shown promise for reducing depredation (Moreno et al., 2008; Hamer et al., 2015), so these devices should be further tested in Australian fisheries. New devices designed for fishing gear other than longlines should also be investigated and developed in consultation with fishers and engineers, to produce products that are most likely to be effective and practical to use. At-sea trials of these devices need to be conducted using a robust experimental design, which incorporates controls and a suitably large sample size to detect any effects of the devices.

Shark deterrents also offer another possible solution to mitigate depredation. Research on shark deterrents has recently commenced in Australia, with the first testing study evaluating the effectiveness of two products on the market specifically designed to reduce depredation, namely the electrical OceanGuardian FISH01 and the magnetic SharkBanz Sentry, as well as the 'SharkStopper' acoustic deterrent. Results of this study showed that overall, the presence of a deterrent reduced the occurrence of shark depredation and increased the time taken for sharks to depredate, although they were not always effective, especially when large numbers of sharks were present (Coulson et al., in prep). However, the difficulty in creating a balanced and robust experimental design and achieving a large enough sample size to test these devices in a way that lends itself to statistical analysis was a limiting factor. In light of this, a new review paper by Mitchell et al. (in review) discusses in detail some of the main considerations around testing these devices in a rigorous way. Further testing will be required to determine whether these devices can be practically used in different fisheries to achieve reductions in shark depredation rates, which should be a priority for future research.

15. Recommendations

Based on the information provided here, it is recommended that a range of future activities are undertaken to help understand shark depredation and develop effective approaches for mitigating it:

- Consistent data collection methods should be implemented for a number of fisheries around Australia where depredation occurs. This should include logbook fields (similar to that used in the WA Mackerel Managed Fishery, see Carmody et al. (2021)), mobile applications and observer coverage in commercial and charter fisheries and survey methods (boat ramp/phone/online/interviews) for recreational fisheries. Data collection should focus on recording the interaction rate and gross depredation rate metrics defined in section 7 of this paper. The upcoming national workshop being led by FRDC will be a good opportunity to share information about best-practice approaches that should be used to collect depredation data in future.
- Gross depredation rate data should be incorporated into future stock assessments once data is available for multiple (e.g. 5+) years, following the methodology of Tanimoto et al. (2021).
- Structured interviews and workshops should be convened to investigate socio-economic impacts of depredation in local and state jurisdictions, following Hoel et al. (2021).
- Building on the methods used by Fotedar et al. (2019), Mitchell et al. (2019) and Vardon et al. (2021), genetic and underwater video techniques should be used in a greater range of fisheries to identify depredating shark (and other predator) species and learn about their behavioural interactions with fishing gear. In particular, this work should trial 360 degree cameras and use primers that amplify the mitochondrial shark DNA NADH dehydrogenase two (ND2) and four (ND4) genes, to achieve optimal success.
- Research and monitoring of the abundance of known depredating shark species should be conducted over longer timescales (5-10 years) to determine whether populations are increasing in areas where depredation is occurring. Non-invasive methods such as baited camera surveys should be used to minimise damage to the environment and to avoid negative impacts on sharks that are TEPS. Existing datasets for shark abundance from baited camera surveys (e.g. from Global FinPrint) can be used as part of this. Where possible, stock assessments similar to Leigh (2015) should be conducted or updated for key depredating shark species, incorporating improved data collection protocols for species identification, fishing effort and discard data. The upcoming national workshop will provide an important opportunity for discussing shark population trends around Australia and identifying priorities for future data collection.
- The diet of key depredating shark species should be investigated using stable isotope analysis, to determine the extent to which sharks feed on key commercial target species and whether depredation provides a substantial portion of their diet.
- Shark tagging, satellite vessel tracking and underwater sound recorders should be used in combination to learn about how shark movements overlap with fishing vessel activity. This will enable identification of overlap ‘hotspots’ where depredation is more frequent and will provide insights into how sharks may be changing their movement patterns, residency and behaviour in response to food availability from fishing vessels (i.e. hooked and released fish). By identifying ‘hotspots’ of depredation, fishers can modify their spatial fishing patterns to avoid these areas and reduce depredation.

- Workshops should be held with fishers and other stakeholders to identify methods that fishers have tested in the past, or are currently using, to reduce shark depredation, for example modification of fishing gear used, changes to spatial/temporal fishing patterns. The potential efficacy of these methods should be evaluated and those which show promise should be tested in other fisheries.
- Educational material on shark depredation should be produced to inform fishers about its causes and impacts and provide advice on which techniques can be used to reduce depredation. To maximise effectiveness, this educational material should be targeted at species fisheries and areas.
- Further development and experimental testing of physical protection devices (e.g. those trialled by Hamer et al. (2015)) and shark deterrents (Coulson et al., in prep) should be pursued, to determine which products can be practical and effective for fishers to use. This testing should follow principles of robust experimental design and ensure large enough datasets are generated to allow rigorous scientific analyses to be conducted.
- Follow up workshops should be organised in 2-5 years' time to assess future research priorities and evaluate progress made towards key goals.

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