Biological Sciences

WHALE ENTANGLEMENTS IN SOUTH AFRICAN TRAP FISHERIES AND THEIR POTENTIAL MITIGATION THROUGH ROPELESS FISHING TECHNIQUES

BIO 5015W – Ocean Sciences Minor Dissertation

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Declaration

I herewith submit the following task **"Whale entanglements in South African trap fisheries and their potential mitigation through ropeless fishing techniques"** in fulfilment of the requirements of the BIO 5015W: Ocean Sciences Minor Dissertation course.

I hereby declare the following:

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- I confirm that the work submitted herewith for assessment in the above course is my own unaided work except where I have explicitly stated otherwise;
- This task has not been submitted before. either individually or jointly, for any course requirement, examination or degree at this or any other tertiary educational institution;
- I have followed the required conventions in referencing the thoughts and ideas of others;
- I understand that the University of Cape Town may take disciplinary action against me if it can be shown that this task is not my own unaided work or that I failed to acknowledge the sources of the ideas or words in my writing in this task.

Signed this 21st day January 2021

Signed by candidate

M. T. Daniel

Abstract

The increasing frequency of whale entanglements in fishing gear is a global concern. In South African waters, the west coast rock lobster (WCRL), south coast rock lobster (SCRL) and octopus fisheries are responsible for whale entanglements in trap fishing gear. To better understand the interactions between whale species and fishing gear, a study was conducted in which whale entanglement and fishing effort data were analysed. Annual whale entanglements increased since 2006, despite an overall decrease in trap fishing effort. Entanglement hotspots corresponded with fishing hotspots. The WCRL fishery was responsible for 68% of all entanglements between 2006 and 2020. Of particular concern was zone D of the WCRL fishing area, where 90% of whale entanglements in the fishery occurred; the same area where 92% of fishing effort took place. Entanglements in SCRL fishing hotspot, near the remote southern tip of the Agulhas Bank, are likely to be underreported. Humpback (*Megaptera novaeangliae)*, southern right (*Eubalaena australis)* and Bryde's (*Balaenoptera brydei*) whales accounted for 64%, 25%, and 11% of entanglements, respectively. Species and area specific GLMs showed that humpback whale entanglements increased over the whole South African coastline and in all trap fisheries. This increase was attributed to the aggregation of humpback whales in 'super-groups' off the west coast during summer months over the past decade. Consequently, a primary seasonal peak in entanglements occurred between January and March. Southern right whale entanglements decreased since 2006 over the whole South African coastline and in the WCRL fishery. This decrease was attributed to a northern shift in foraging by this species over the past decade. Bryde's whale entanglements increased since 2006 across the South African coastline, and most strongly in the octopus fishery. Since all Bryde's entanglements occurred in the past six years, a change in distribution of the species is suspected. Bryde's whale entanglements are of high concern due to their small resident population. The octopus fishery posed the greatest threat to Bryde's whales, and the WCRL fishery the least.

Along with the analyses of whale entanglements, the feasibility of ropeless fishing techniques was analysed for use in South African trap fisheries. This analysis included the testing of sinking line as ground line to reduce rope arcs between traps, the testing of three ropeless fishing release mechanisms and two rope storage systems. The results of the ground line rope tests confirmed that the use of floating rope will produce arcs between traps of sufficient height to pose threats to whales. Sinking line was effective in eliminating arcs between traps. Concerns that burial of sinking line to the extent that grappling and retrieval are affected were unfounded. Three types of releases were tested for use in ropeless fishing techniques, namely galvanic timed releases (GTRs), an electronic timed release (ETR), and an acoustic release. The electronic timed release (ETR), acoustic release, the bag rope storage system and the pipe rope storage system all demonstrated at least 85% reliability. The importance of ensuring the release is set up correctly before deployment was crucial to ensuring a successful release. The variation in release times of GTRs of the same size confirmed that their release time ranges were sufficient to reduce buoy line time in the water column by 84%. This reduction in buoy line time would reduce the probability of it entangling a whale by the same percentage. Profit estimates in the WCRL fishery suggest that locally manufactured GTRs would be a feasible option in the fishery. The simplicity of the GTR systems could also provide an opportunity for stakeholders to familiarise themselves with

ropeless fishing techniques, enabling the development of systems to better suit their needs, before moving to acoustic systems if necessary. Although the SCRL fishery can afford acoustic ropeless fishing systems, a similar approach may be beneficial to avoid costly mishaps while trialling expensive acoustic systems. GTRs and electronic timed release were determined as undesirable by the octopus fisherman due to the uncertainty of retrieval times which are based on weather conditions. Octopus fishers have subsequently started trialling 10 acoustic release ropeless fishing systems in False Bay. These trials, which implement the bag rope storage systems developed in this study, have shown that time is necessary for fishermen to familiarise themselves with these systems, with efficiencies improving with practise. These trials also showed that these systems withstand the rigors of commercial conditions. If the replacement of existing gear with ropeless fishing systems is done in stages, then cost can be spread over multiple years. A similar staged approach could be implemented in the WCRL fishery with the use of spatial management, where ropeless fishing systems are made a requirement when fishing in entanglement hotspots. The ‘user pays’ principle was suggested as a potential management strategy to incentivise fisherman to reduce whale entanglements in the WCRL, SCRL and octopus fisheries. This would be done by making fisherman liable for the costs associated with whale entanglements. However, in order to be effective, sufficient individual gear identifiers would be crucial to accurately assign liability. Therefore, a better option may be for the fishing authority to alter the rules of fishing to ensure that ropeless fishing techniques (of one form or another) become mandatory and that every reasonable step be taken to reduce the risk of entanglement. Whichever management approach or policy changes are decided upon, if stakeholders were involved in the research and development process, it is more likely that they will buy into an improved and more sustainable fishing method.

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Chapter 1: The whale entanglement problem

Introduction

Whale entanglements in fishing gear have been on the increase in South Africa and internationally (Meÿer *et al.*, 2011, Knowlton *et al.*, 2012). Entanglements in fishing gear is recognised as the greatest threat to cetacean species globally (IWC, 2010) and is the leading cause of whale mortalities in the north western Atlantic (Van Der Hoop *et al.*, 2013). The risks of entanglements do not only affect the whale populations directly through mortalities, however. The high energy demands associated with an entanglement event reduces fecundity in female whales (Van Der Hoop *et al.*, 2017). Male and female whales show emaciation after entanglement, which has the potential to affect population growth and health (Van Der Hoop *et al.*, 2017).

South Africa is legally obligated to protect marine biodiversity. The National Environmental Management Act (NEMA) promotes principles on sustainable development in chapter 1.2.4 which include “Disturbance of ecosystems and loss of biodiversity are to be avoided”, and acknowledges “that all elements of the environment are linked and interrelated.” Chapter 1.2 of the National Environmental Management: Biodiversity Act (NEMBA) states that its objectives are to “Provide for the management and conservation of biological diversity within the Republic”, “Provide for the use of indigenous biological resources in a sustainable manner”, and “give effect to ratified international agreements relating to biodiversity which are binding on the Republic.” Furthermore, South Africa’s Sea Fishery Act aims “To provide for the conservation of the marine ecology and the orderly exploitation, utilization and protection of certain marine resources”.

South Africa’s international obligations include those specified in the United Nations Sustainability Goals: Goal 14: Life Below Water, of which South Africa is a signatory. Among others, this goal aims to, i) by 2020, sustainably manage and protect marine and coastal ecosystems, ii) by 2020, effectively regulate destructive fishing practices and implement science-based management plans iii) increase scientific knowledge, develop research capacity and transfer marine technology, in particular in least developed countries, and iv) enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in UNCLOS, which provides the legal framework for the conservation and sustainable use of oceans and their resources (United Nations, 2018). Further international obligations are those set by the International Whaling Commission, of which South Africa is a founding member, whose purpose is to provide for the conservation of whale stocks worldwide (International Convention for the Regulation of Whaling, 1946).

Gear in which whales most frequently get entangled belong to those used by trap (pot) fisheries (IWC, 2010). A typical trap fishing gear setup can be seen in **Figure 1** on the following page (*IMIS Flanders Marine Institute*, 2014). It consists of a long line onto which traps are attached at regular intervals. Either end of this line will be attached to an anchor on the sea floor which will then have lines going up to surface buoys. These surface buoys serve two functions, namely (1) to identify the position of the gear, and (2) to facilitate the retrieval of the gear. Since a line connects the fishing gear to the buoy, once the buoy is retrieved, its line is used to pull the fishing gear back up and onto the ship.

This gear setup can be broken down into three components: the bottom gear, buoy lines and surface system. The surface system includes buoys and high flyers, as well as the lines that connect these components to the buoy line. Bottom gear includes ground lines and traps. Buoy lines are those which run to the surface buoys, connecting the ground gear to the surface system (Johnson *et al.*, 2005).

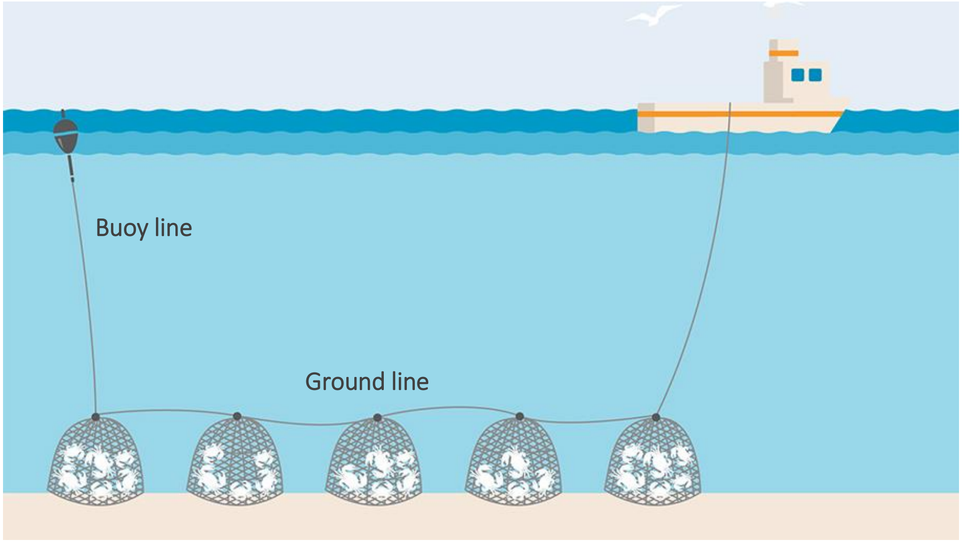

Figure 1: Trap fishing gear setup (*IMIS Flanders Marine Institute*, 2014).

All of these sections pose entanglement threats to whales. Johnson *et al.* (2005) found that buoy lines were responsible for 56% of entanglements in the north western Atlantic. This may suggest that the buoy lines present more of a risk to whales but the difficulty of distinguishing between buoy and ground line once entangled on a whale creates bias. There is an unimportant technical distinction between floating and sinking ropes, which affects the risk of entanglement. No cases of entanglements were recorded in sinking line suggesting a possible solution to reduce entanglement risk by eliminating the arcs that floating rope causes between traps (up to 6m off the ocean floor)(Johnson *et al.*, 2005). Meyer *et al.* (2011) and Mc Cue *et al.* (2016) reported highest percentages of entanglements involving ‘rope and buoy’, 50% and 41% respectively. The relatively low percentages involving ‘rope and traps’ (6% and 12% by Meyer *et al.* (2011) and Mc Cue *et al.* (2016), respectively) suggests that the buoy line does pose the highest risk as higher incidences including traps would be recorded if the whales were becoming entangled in ground line. Surface systems pose a potential risk to whales as well. Two buoys are often left at the surface with a length of rope between them so that the system can be easily grappled on retrieval. In addition, any excess rope at the surface once the traps have hit the ocean floor is often bundled up and left at the surface with the surface buoys. However, only two whales in the study done by Johnston *et al.* (2005) were documented with surface system entanglements, suggesting that most entanglements occur below the surface.

In the USA and Canada the trap fisheries most responsible for entangling whales are the American lobster fishery and the snow crab fisheries (Moore, 2019). Unfortunately it if often difficult to accurately determine exactly who was responsible for an entanglement as there are no gear identification markers and most trap fisheries use similar gear and rope types.

A 30 year retrospective study done on entanglements of Northern Atlantic Right whales off the east coasts of USA and Canada (Knowlton *et al.*, 2012) showed that of 626 individuals photographed, over 80% showed evidence of being entangled at least once and close to 60% showed evidence of being entangled more than once. Juvenile whales and calves are more likely to become entangled than adults (Knowlton *et al.*, 2012, Knowlton and Kraus, 2001) and they do not seem to learn from previous entanglements. Many mature whales show evidence of multiple entanglements.

Knowlton *et al.* (2012) found that although the number of entanglements did not seem to increase annually, the severity of the entanglements did. This could be due to a variety of reasons ranging from the use of more durable rope and changes in whale distributions, to changes in fishing gear as different species are targeted (Knowlton *et al.*, 2012).

In 2003, more than 60% and 70% of the humpback whale populations in the north Atlantic and eastern north Pacific respectively were found to have entanglement scarring. Scars were acquired at an average rate of 12% and 8% per annum respectively (Neilson *et al.*, 2009).

Due to the increasing problem of large whale entanglements in fishing gear worldwide, the International Whaling Commission held a workshop on welfare issues associated with the entanglement of large whales in 2010 (IWC, 2010). It has since held three such workshops in each of 2011, 2015 and 2018. During the 2010 workshops, national data were presented from Australia, Canada, Mexico, Norway, South Africa and the USA. Over the period of 2003 – 2008, Australia reported 91 entanglements. Canada reported 1232 entanglements on their east coast between 1979 and 2009 where 16% (197 whales) are known to have died. Mexico reported 39 entanglements between 2001 and 2010 where nine (23%) are known to have died (IWC, 2010). Data from New Zealand, Canada's west coast and Argentina were then presented in 2011. New Zealand reported an average of two large whales entangled per year since 2000. Canada reported 26 entanglements between 2008 and 2011 on their west coast. Argentina reported nine entanglements between 2009 and October 2011 (IWC, 2011). The workshop also established that it is likely that entanglement rates were underestimated by at least an order of magnitude due to the methods of reporting (IWC, 2010). Data were largely dependent on public response and large areas are not monitored, meaning that it is likely that many entanglement events go unreported.

To tackle the problem of whale entanglement and establish better response and standardized data collection, the IWC established a capacity building program to train disentanglement teams which was formalised after the 2015 workshop to the Global Whale Entanglement Response Network (GWERN)(IWC, 2015b). They have since trained and established disentanglement teams in Brazil, the United Kingdom, Argentina, Mexico, Ecuador, Panama, French Caribbean, Tonga, Dominican Republic, Japan, Oman, Chile, Guadeloupe, Martinique, Greenland, Peru, Thailand, Russian Federation, Norway and Colombia (USA, South Africa and Australia already had trained disentanglement teams) (IWC, 2015b)(IWC, 2018). It is clear that whale entanglements is a global problem.

Potential Solutions

From the outset of their workshops, the IWC have reiterated that prevention rather than disentanglement is the ultimate solution to the whale entanglement problem (IWC, 2018).

Gear modifications

The modification of fishing gear is a potential solution to reduce entanglement mortalities. The Atlantic large whale take reduction plan (ALWTRP) developed a number of measures to reduce entanglement moralities through gear modifications. These measures included the use of weak links to connect the vertical line to the buoy system for pot and gillnet gear, the use of weak links between and within gillnet panels, seasonal gillnet closures off the Florida and Georgia coast, Cape Cod Bay, and the Great South Channel, and the use of sinking ground line (versus floating ground line) between pots and for gillnet anchoring lines for most east coast US waters except for certain exempted areas nearshore. Studies done by Knowlton *et al.* (2012) and Pace *et al.* (2014) found that all these measures were unsuccessful.

As with weak links which break under the increased strain of an entanglement event, weaker rope strengths could reduce mortalities. A study done by Knowlton *et al.* (2016) suggests that the broad adoption of ropes with a breaking strength of less than 7.56kN could reduce mortalities by 72%.

With the exception of ropeless fishing modifications, gear modifications aim to reduce whale mortalities resulting from entanglements rather than decrease the risk of entanglements occurring.

Seasonal and permanent area closures

Seasonal and permanent closures of areas where the risk of entanglements are high is another potential solution. Effectiveness will vary on location but a study done by Brillant *et al.* (2017) suggests that a reduction of up to 30% in entanglements is possible through the seasonal closures of two fishing zones in Canadian waters. This suggests that through a more detailed study into the migration and distribution of whales in South African waters, seasonal closures or the implementation/revision of Marine Protected Areas (MPAs) could significantly reduce annual entanglement incidences.

Whale deterrents

Pingers and acoustic deterrents have been suggested and tested in the hopes of reducing interactions between whales and fishing gear. The intention is to use high frequency pings and noise to alert and warn whales away from fishing gear. This has proven ineffective in South Africa when tested by the KZNSB in shark nets (KZNSB, 2020) and internationally (Harcourt *et al.*, 2014;Pirotta *et al.*, 2016) and are thought to pose a threat to the hearing of nearby marine mammals (KZNSB, 2020, Lebon and Kelly, 2019).

Rope Colour

Kot *et al.* (2012) found that Minke whales reduced their speed and altered their bearing when encountering experimental rope, especially high contrast colours (black and white). This suggests that changing rope colour to high contrast colours is a potential solution to reduce whale entanglements. It is unknown whether a significant number of whale entanglements occur at night or under low light conditions where visual detection of ropes would become more difficult. Studies have suggested that nocturnal behaviour is species and area dependant. Bryde's whales rest during night hours in New Zealand (Izadi *et al.*, 2018). Humpback whales feed exclusively at night in the Antarctic and rest and socialize during the day (Nowacek *et al.*, 2011). If whales do indeed rely on sight to avoid ropes, this suggests that in waters of high nocturnal behaviour, limiting fishing to daylight hours, or illuminating rope, could be a possible solution to reduce entanglements. Limiting fishing to daylight hours, however, is unfeasible in many trap fisheries as gear is often left out for days at a time.

Potential Biological Removal (PBR)

The PBR is a biological indicator used in fisheries management in the USA. It is defined as "the maximum number of animals that can be killed by anthropogenic causes each year whilst allowing that stock to reach or maintain its optimal sustainable population level"(Moore, 2019). By implementing a PBR, stake holders are encouraged to try to reduce entanglements under the threat of fishery closures if the PBR is reached.

Seafood Certification

A less direct approach to reducing whale entanglements is through the incentivising of safer fishing practices. The Marine Stewardship Council (MSC) has one such certification program which encourages consumers to purchase products which have less harmful impacts on the environment. Through demand this encourages fishers to certify themselves with the MSC. Trap fisheries could be encouraged to implement measures to reduce entanglements and therefore become certified as "whale-safe". This is already being implemented internationally where a Canadian trap fishery recently had their certification suspended due their role in right whale mortalities (MSC, 2020).

Gear identifiers

Although not a measure to reduce entanglements or mortalities in the short term, the implementation of gear markers enables management to trace entangled gear back to specific permit holders who could then be held accountable. Gear identification allows for more accurate identification of high risk areas which could lead to the implementation of improved management plans.

Ropeless fishing

Intuitively, the most effective strategy for reducing whale entanglements is to reduce the probability of a whale encountering fishing gear. Buoy lines provide the highest risk for whales. It follows then that by getting rid of buoy lines, i.e. vertical lines in the water column, the probability of whales encountering fishing gear could be reduced significantly. This is known as ropeless fishing and such technologies are currently being developed and tested globally.

To solve the whale entanglement problem in South African trap fisheries, the underlying issues first need to be understood in detail. To this end, the following needed to be known: 1) why whales come into contact with trap fishing gear, and 2) how can gear be feasibly modified to reduce the likelihood of entanglement when encountered by a whale. To answer question 1, whale distribution data were needed to map the spatial and temporal distribution of the different whale species in South African waters throughout the year, as well as spatial and temporal fishing effort data from the rock lobster and octopus fisheries. These data would enable the identification of potential entanglement hotspots which could then be compared to entanglement data from the South African Whale Disentanglement Network (SAWDN). In order to answer question 2, gear currently used by trap fisheries and the subsequent risks they pose to whales had to be understood. A review of current gear modification solutions then had to be undertaken to determine which would be feasible. Once reviewed, a number of current technologies would be procured to test for feasibility in South African trap fisheries, where feasibility would be determined through a detailed cost-benefit analysis for all fisheries involved.

Chapter 2: Trap fishery and whale distributions in South African waters

Introduction

In South African waters the fisheries responsible for the majority of entanglements are those of the west and south coast rock lobster, and the octopus.

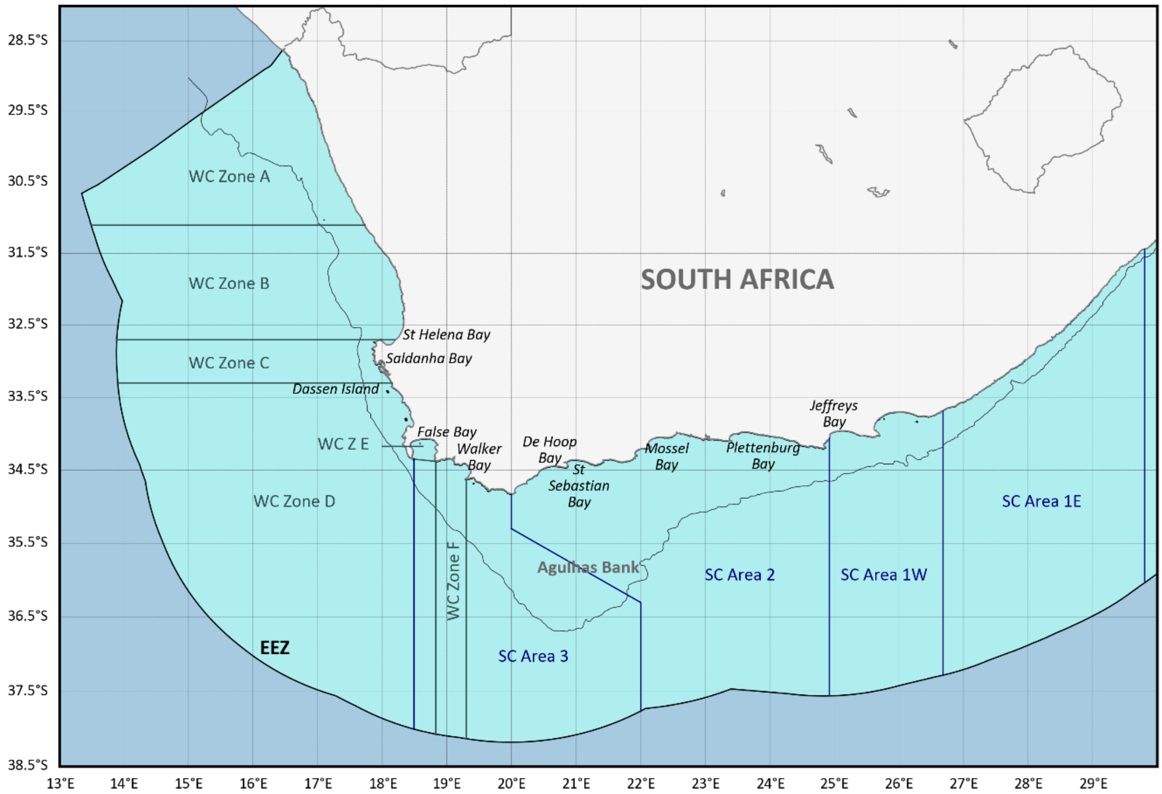

Figure 2: West coast (WC) and south coast (SC) rock lobster fishing zones and areas showing the Agulhas Bank and the exclusive economic zone (EEZ) (DAFF, 2016).

South African west coast rock lobster (WCRL) fishery

The west coast rock lobster industry is the most important lobster fishery in South Africa with a market value of over R335 million per annum in 2017/18 for the offshore and nearshore fisheries combined (South African Fisheries, 2018). The fishing grounds extend from the Orange River mouth at the border between South Africa and Namibia to Cape Point, a distance of approximately 1000km, and extends to the edge of the exclusive economic zone (EEZ) 200 nautical miles from the coast (**Figure 2**). This WCRL fishery has been commercialised since the late 1800s. After a massive fall in the lobster populations in the late 1980s, an operational management procedure (OMP) was implemented in 1997 in an effort to restore the stocks to 20% of their pre-1990 levels. An OMP is still used today with total allowable catches (TAC) allocation (DAFF, 2016). There are currently no limits on the number of traps allowed per vessel. The WCRL fishery uses a different gear setup from that shown in **Figure 1**: they use a single trap per buoy line. Vessels will typically set 25 - 50 traps at a time at depths of up to 100m. With over 100 vessels in the fishery, the possible number of traps in the water at any time is over 4000, each with its own buoy lines in the water column (Personal communication, D van Zyl, Marine Research Technician, Department of Environment, Forestry and Fisheries). Lines are usually set and retrieved in the morning, meaning that gear is typically in the water for approximately 24 hours before retrieval.

South African south coast rock lobster (SCRL) fishery

The south coast rock lobster industry is the second biggest lobster fishery in South Africa with a market value of over R311 Million in 2016 (South African Fisheries, 2016). Established as a commercial fishery in 1974, it operates over approximately 1000km of coastline between East London and Cape Point, up to 250km off shore at the edge of the Agulhas Bank (**Figure 2**). South coast rock lobster has been managed since the commencement of harvesting in 1974 and is currently managed through an OMP with the use of TAC and total allowable effort (TAE) as the basis of harvest control. Tonnage and fishing days are allocated to vessels that fish year round. Their fishing in any year stops when either the TAC or TAE limits are reached, whichever comes first (DAFF, 2016). Fishing effort shows a seasonal pattern. Minimum effort is in the months of September and October (**Figure 3**) (Norman *et al.*, 2018).

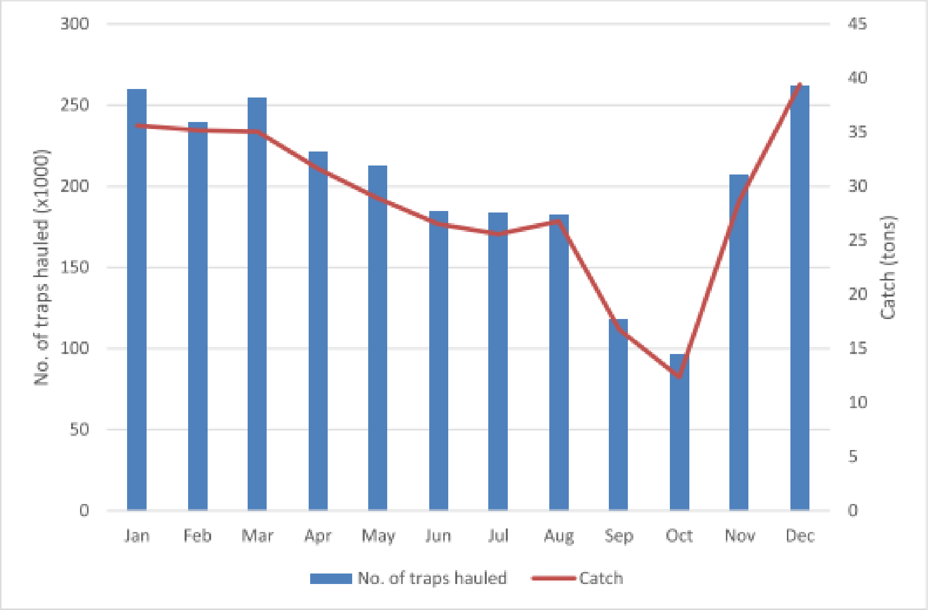

Figure 3: Catch and effort in SCRL fishery by month over the period 2006/2007.

There are currently no limits on the number of traps allowed per vessel. Between 100 and 200 “French traps” are set per line, similar to that shown in **Figure 1**. Approximately 2000 traps per vessel are set per day on approximately 16 lines. There are 8 vessels active in the fishery (South African Fisheries, 2016)(Norman *et al.*, 2018).

Octopus fishery

The octopus fishery is a relatively new fishery in South African waters. An experimental fishery was implemented in October 2004 and scheduled to run until September 2009. Due to insufficient data at the end of the five year period, the feasibility of a commercial fishery was unable to be assessed and so, in 2012, a five year exploratory fishery was launched. This exploratory fishery was extended and is scheduled to run until February 2021 when it will be reassessed. Although there were eight areas suggested as viable fishing grounds (with two permits per area)(DEA, 2003), to date there are only four operational right holders in the exploratory fishery: two in False Bay, one in Mossel Bay area, and one in the Saldanha area. False Bay is by far the most successful area and it is the only one being fished on a regular basis. Out of the 16 possible areas, only one is fished regularly. Through experimentation and gaining a better understanding of the fishing environment, gear efficiencies have improved which has resulted in more traps being hauled each year and a gradual increase in the landings from approximately 2 tons in 2013 to over 51 tons in 2018 (DAFF, 2016)(Unpublished data, Sanjay John,2019, Department of Environment, Forestry and Fisheries).

The octopus fishery uses a setup very similar to that shown in **Figure 1**. The license holder in the False Bay area has 36 lines, each holding 25-30 cradles with three pots per cradle. These cradles are typically separated by 20 – 30 m of rope meaning that a single setup is 600 – 900 m long. The license is for a total of 2000 cradles. Six thousand pots can be in the water at any one time (Personal communication, Gary Nel, octopus fishery experimental permit holder). With a buoy line running to the surface at each end of the setup the number of buoy lines in the water at any one time is 92 per area. Fishing occurs in waters 10 to 30 m depth.

Whale entanglements in South African waters

After an increase in the number of entanglement incidences in the late 1990s, South Africa's Department of Environmental Affairs together with the International Whaling Commission formed the South African Whale Disentanglement Network (SAWDN) in 2006. As a national network of partners, they are trained specifically in the disentanglement of whales. The SAWDN has captured data on whale entanglements since its inception in 2006 (Meÿer *et al.*, 2011). As with global entanglement data, that of the SAWDN is not considered comprehensive (IWC, 2010) because they are largely dependent on public response and large areas are not monitored, meaning that it is likely that many entanglement events are not recorded or attended to.

Whale entanglements which occur in shark nets off the east coast of South Africa are dealt with by the Kwazulu-Natal Sharks Board (KZNSB) which has been operating since 1964. They too have kept records of entanglements since 1981. Due to their daily monitoring of their nets, their data of entanglements in the shark nets are more comprehensive than those of the SAWDN. Their data includes 'suspected whale encounters' which refer to large holes found in the shark nets that are assumed to have been caused by whales breaking loose before they could be observed (Meÿer *et al.*, 2011).

There are 5 species of large whale which frequent the inshore waters of South Africa. These are namely the humpback whale *Megaptera novaeangliae*, southern right whale *Eubalaena* *australis,* the Bryde's whale *Balaenoptera brydei*, and occasionally the Minke whale *Balaenoptera spp* and the pygmy right whale *Caperea marginata* (Findlay *et al.*, 1992). The two species of the highest abundance are the humpback and southern right whales and are thought to be recovering at 10% and 7% per year respectively (Best, P. B., 2007). Using whale entanglement data from a number of sources including the KZN Shark Board and the Department of Environmental Affairs, Meyer *et al.* (2012) were able to show that the number of entanglement incidences has increased between the years of 1975 to 2009 in both humpback and southern right whales. Although these increases could be accounted for by the annual rate of increase of the two east coast populations (Meÿer *et al.*, 2011), of particular concern is the relatively small sub-population (approximately 500 individuals) of humpbacks that visit the west coast during the summer months (Barendse *et al.*, 2011). Barendse *et al.* (2011) suggest that this assemblage may be part of breeding stock B designated by the International Whaling Commission (IWC, 2015a). Entanglements could therefore adversely affect the population through reduced fecundity in females.

The South African inshore Bryde's whale population is another population of high conservation concern (Best, 2001). This population, resident in the region of the Agulhas Bank, has a higher risk of coming into contact with fishing gear than migrating whales due to their permanent presence in the inshore fishing zones.

All three of the species mentioned above have been given the 'Least Concern' (Red) rating by the International Union for Conservation of Nature (ICUN). Concerning the Bryde's whale, these ratings are based on global trends and are not necessarily relevant to the South African inshore population. Due to its small size (fewer than 1000 individuals) (Elwen *et al.*, 2011), the regional IUCN rating for the inshore Bryde's whale is Vulnerable D1(Penry, Findlay and Best, 2016).

The study done by Meyer *et al.* (2011) revealed that of the 90 entanglement events between 1981 and 2009 attended to by SAWDN, 23% of the whales were successfully released. In 60% of cases there was no intervention and in 5% of cases the whales managed to free themselves. In contrast, of the 80 incidences of entanglements in shark nets, the KZNSB liberated 81% of entangled whales. Their success could be due to their daily monitoring of the shark nets and their limited range whereas the SAWDN is deployed only when informed of an entanglement by a public source.

The increase in the reported whale entanglement incidences in the late 1990s can be explained by the south-eastward migration of the rock lobster fishing grounds around the South African coast. This was a result of the fall of the rock lobster populations in the late 1980s, attributed to large scale shifts in the ecosystem (Cockcroft *et al.*, 2008). At the same time, a westward expansion of the southern right whale distribution was seen due to population recovery (Best, 2000). This increased the potential for whales coming into contact with fishing gear and can explain the rise in reported entanglement incidences since the late 1990s. **Figure 4** below shows the interaction between the west coast rock lobster fishery and whale entanglements between the years of 1971 and 2009.

The monthly distribution of large whale entanglements in South Africa since 1975 show a bimodal distribution with a primary peak during the months of August to October and a secondary peak in December to February. These peaks could be explained by the annual migration routes of the southern right and humpback whales and the peak west coast rock lobster fishing seasons. During the months of July to October, the west coast rock lobster fishery moved south toward False Bay after fishing further north around St Helena Bay from November the previous year. This coincided with the migration of the whales. Whale-watching vessels reported highest sightings in the False Bay region in the months September to October. This could account for the primary peak in entanglements recorded in August to October. The secondary peak was attributed to whales that delayed their migration south to take advantage of the highly productive waters off St Helena Bay and therefore came into contact with the rock lobster gear in the months December to February (Meÿer *et al.*, 2011).

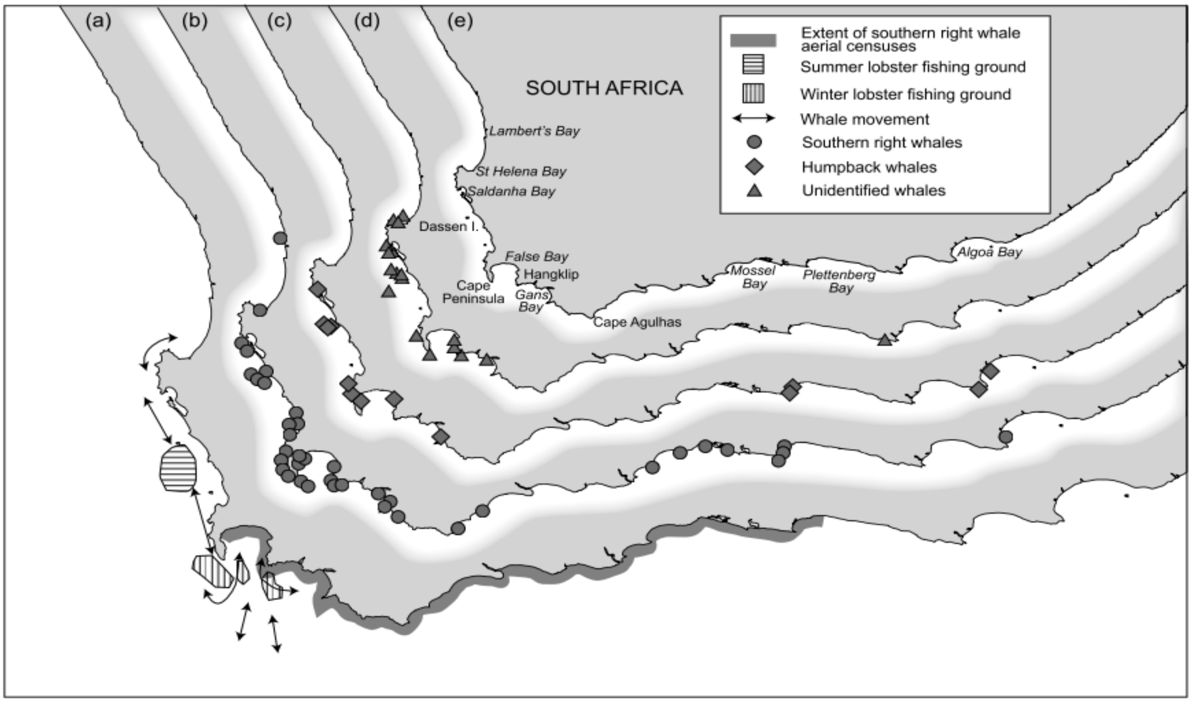

Figure 4: Map of the west and south coasts of South Africa showing (a) the West Coast rock lobster fishing grounds that pose a threat to large whales in summer (horizontal stripes) and winter (vertical stripes) in relation to movement paths (arrows) of whales on the West Coast and the False Bay area, (b) positions of southern right whale entanglements, (c) humpback whale entanglements, (d) entanglements of unidentified whales and (e) key locations. Only two entanglements (of a southern right whale and a humpback whale) were reported to the east of Algoa Bay and are not shown. The shaded area in layer (a) represents the area of coastline along which southern right whale females and calves have been censused annually since 1971 (Best, 2000, Meÿer *et al.*, 2011).

In more recent times, Mc Cue *et al.* (2016) found that over the period of 2006 to 2015, 86 incidences of entanglement were recorded with a further 24 in 2016. **Figure 5** below shows the locations and species of the most reported whale entanglements in 2016.

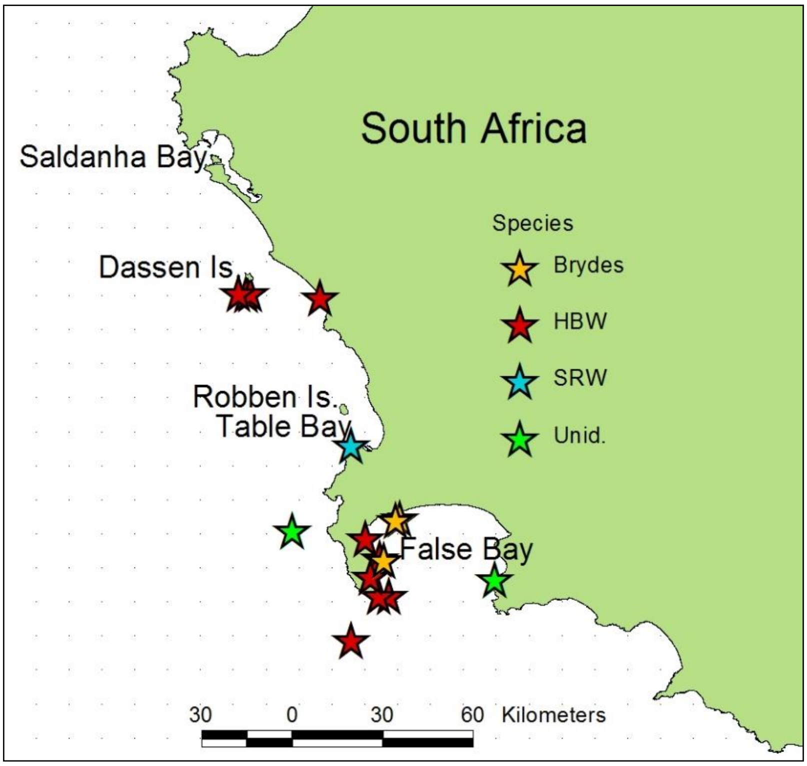

Figure 5: Locations of the most reported whale entanglements in 2016 including species Bryde's Whales, humpback whales (HBW), southern right whales (SRW) and unidentified (Unid) species (Mc Cue *et al.*, 2016).

The occurrence of whale entanglements suggests that whales move through areas frequently used as fishing grounds. **Figure 2**, **Figure 4** and **Figure 5** above suggest that gear used by the west coast rock lobster fishery is responsible for a large proportion of these entanglements. This could be explained by their larger fleet and gear setup resulting in more buoy lines in the water column. **Figure 4** and **Figure 5** show high concentrations of entanglement incidences around the Cape Peninsula where south and west coast rock lobster fisheries share a fishing zone (**Figure 2**) with that of the octopus fishery. A secondary concentration is seen further up the west coast around Dassen Island in both **Figure 4** and **Figure 5**, a region fished solely by the west coast rock lobster fishery.

Local implementation of possible solutions

Since the inception of the octopus fishery, gear has been modified and improved both to improve catch as well as mitigate entanglement risks. The Department of Environment, Forestry and Fisheries (DEFF) suggested the implementation of a number of strategies in an effort to reduce whale entanglements (SANews, 2019). These include sinking ground lines; PVC pipe sheathing over the top 1.5 to 2 m of rope to reduce the risk of wrapping, and ropeless fishing systems (including the use of timed releases and grappling). They have further threatened fishery closures should there be two or more entanglements of the southern right whale or the humpback whale, or one entanglement of the Bryde's whale within three months of the opening of the season, and threatened fishery closure should there be at least one mortality of any of these whales. Under these new threats, and estimating that the risks of entanglement were too high, the octopus fishing vessel Iingwane has been using sinking ground line with no buoy lines in False Bay as of April 2020. This vessel grapples to retrieve gear, instead of hauling from a buoy line.

Rope used in both the octopus and rock lobster industries in South Africa are 16mm diameter Polysteel ropes of breaking strength 49.1 kN when new (Southern Ropes, 2019). In order to get to a rope with a breaking strength of close to 7.56kN (as suggested by Knowlton et al., 2016 to reduce mortalities by up to 72%), 6mm Polysteel would need to be used. Although 7.56kN is more than enough to support the hanging weight of the gear, one has to take into account the inertial loads experienced while deploying and retrieving the gear. Snagging and abrasion occur regularly in fishing practise which significantly increase the loads on the rope. This significant reduction in the diameter of the rope may also not be compatible with the systems in place on the vessels. It is therefore unlikely that fishers would be willing to reduce rope size.

Throughout the decision-making process, stakeholders in the octopus fishery have been consulted in the search for possible solutions to the entanglement problem, including those tested in this study. This is in line with South Africa's commitment to the implementation of an ecosystem approach to fisheries management (DAFF, 2016, Jarre *et al.*, 2018) and imperative if a successful solution is to be found.

In this chapter I investigate the South African whale entanglement problem using data supplied by the SAWDN. I analyse the spatial and temporal distributions of major whale species in South African waters, and those of the WCRL, SCRL and octopus trap fisheries. The objective of these analyses are to identify potential entanglement hotspots which could then be compared to entanglement data. I intend this work to be useful during the implementation of management plans to reduce whale entanglements in South African waters.

Methods

Whale distribution and interaction with trap fishing gear

To better understand the interactions between whales and trap fishing gear, and therefore gain a better understanding of entanglements, information was needed on whale distribution in South African coastal waters as well as the locations of popular fishing grounds used by rock lobster and octopus fishing vessels. Along with whale entanglement data, areas of high entanglement risk were identified. These could then be used to recommend spatial or temporal management strategies such as protected areas or seasonal closures.

Entanglements

Data Source

The South African Whale Disentanglement Network (SAWDN) provided entanglement data dating back to the inception of the organisation in 2006. These data included entanglements only encountered in rock lobster or octopus fishing gear and therefore do not represent the total entanglements over the time period. The following information was included on documented entanglements: The date of the reported entanglement, the entanglement event number for the year, the fishery responsible (identified from gear), the age class of the entangled whale (calf, juvenile, sub-adult, adult), the size(m) of the entangled whale, the species of the entangled whale, the coordinates of the reported entanglement, the result of the entanglement (partly disentangled, disentangled, no intervention, freed itself, died, not found), and entanglement description. The age class was based on the estimated size which was estimated by SAWDN crew at the scene and likely to be inaccurate (Personal communication, Mike Meyer, South African Whale Disentanglement Network). Age classes did not fall into any specific size ranges, where calf, juvenile and sub-adult sizes often overlapped, and were therefore discarded. Two ring net entanglements were removed as they are used recreationally and therefore not relevant to this study. During mapping, two points were found to be over land and therefore discarded. Some data in both the fishery and species columns included questions marks, indicating uncertainty. These data were discarded from the fishery analysis and changed to unidentified in the species analysis.

Analysis

The data were analysed using Python 3.7.4 through *The Scientific Python Development Environment (Spyder) 3.3.6.*(Spyder IDE, 2021) *Matplotlib 3.1.1* (Hunter, 2007) was used for all graphing and *Basemap 1.2.0*(The matplotlib developement team, 2016)was used for mapping with the *basemap_data_hires 1.2.0* coastline. Data were read in and manipulated using *Pandas 0.25.1.*(The pandas developement team, 2020) Linear regression was performed using package *Scipy 1.3.1*(Virtanen, Pauli and Gommers, Ralf and Oliphant *et al.*, 2020) with its *linregress* attribute which calculates a linear least-squares regression for two sets of measurements.

The coastline was divided into three sections based on fishing grounds. The west coast section includes the entire WCRL fishing area, excluding False Bay; an area exclusively fished by this fishery. Although the south coast rock lobster fishing area extends to the Cape Peninsula, tracking data from their vessels indicated that little, if any, fishing is done between Walker Bay and False Bay. False Bay is an area fished by the octopus and west coast rock lobster fisheries and would therefore be its own section. Any entanglements identified as rock lobster in False Bay would be considered from the west coast rock lobster fishery as tracking data from vessels in the south coast fishery indicated they do not fish is False Bay. The south coast section would include the coast east of Walker Bay; the eastern edge of the west coast fishing zone, an area exclusively fished by the south coast rock lobster fishery. These sections can be seen in **Figure 6** below, extending to the 200m isobaths, past which no fishing occurs. Since entanglement data included only the broad "Rock Lobster" category for fishery, these zones would assist in distinguishing entanglements caused by the west coast and south coast fisheries, respectively.

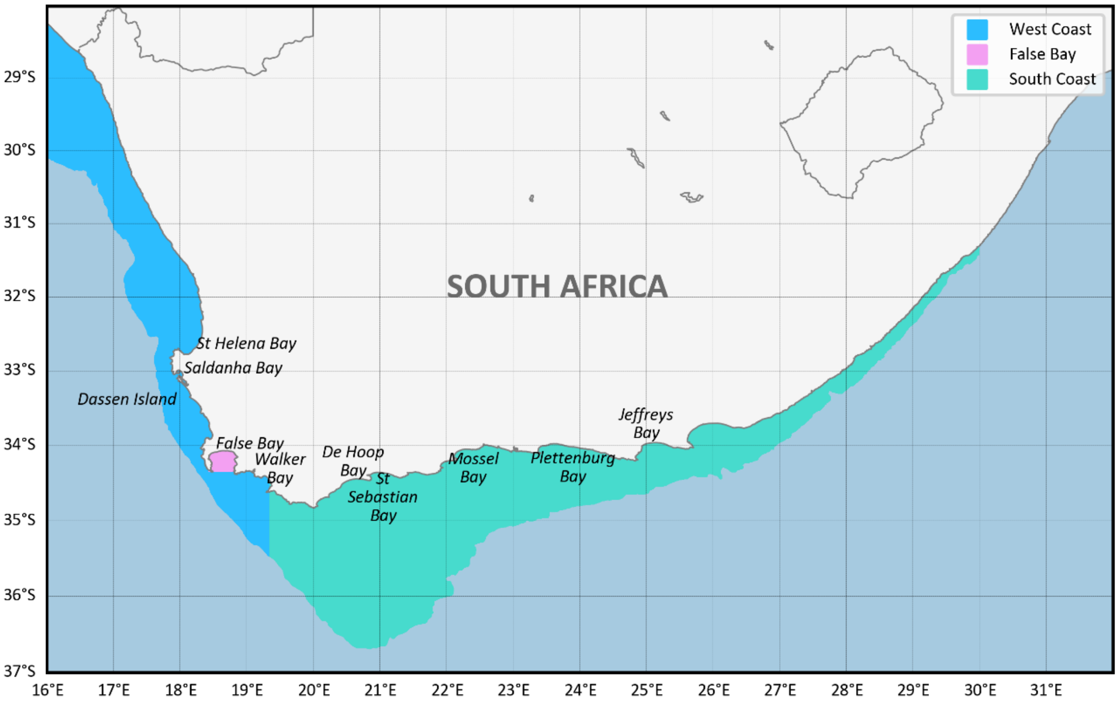

Figure 6: South Africa coast divisions for this study.

Whale Distribution

Data Source

Whale distribution data were obtained from Dr. Simon Elwen (Director of Sea Search Research & Conservation and the Namibian Dolphin Project, and Research Associate: Department of Zoology and Botany, Stellenbosch University and Mammal Research Institute, University of Pretoria). These data included communications over email, voice calls and kml files outlining various areas of interest and whale hotspots. He mentioned that the available data on whale distribution is very sparse as a result of heavy biasing from citizen sightings and limited efforts in surveying due to difficulties of accessibility. As a result, general ranges based on 'expert opinion' is what he was able to provide.

Trap Fishing Effort

Data Source

Data on fishing effort in the rock lobster and octopus fisheries were obtained through communication with the South African Department of Environment, Forestry and Fisheries (DEFF) and through the use of the Automatic Identification System (AIS) and Marine Traffic.(*MarineTraffic: Global Ship Tracking Intelligence | AIS Marine Traffic*, 2020). From the Department of Environment, Forestry and Fisheries, Danie van Zyl provided information and data on the west coast rock lobster fishery and Sanjay John provided information on the octopus fishery.

Analysis

All these data were mapped and analysed using python with the MatPlotlib Basemap package.

To analyse relationships between entanglement events and year, general linear models (GLMs) were used using statsmodels.api 0.10.1 package in Python 3.7.4 through The Scientific Python Development Environment (Spyder) 3.3.6. GLMs allow the response data to follow a distribution from the 'exponential family', which include Poisson distributions which are frequently applied to count data (McCullagh P, 1989). As done by Meyer *et al.* (2011), GLMs with a Poisson distribution and a log-link function were used to describe the relationship between the number of entanglement incidents and year. The estimated annual recovery rates of 10% and 7% for humpback and southern right whales, respectively, were incorporated into the models. The same was done for Bryde's whales where a population growth rate of 4% was used as suggested by the National Marine Fisheries Service (NMFS) (National Marine Fisheries Service (NMFS), 2016). These population growth rates were included in the models as offsets. As the offset needed to be on the same scale as the entanglements, their starting value was determined using the predicted entanglement value from the Entanglement ~ Year GLM at the first year (2006). The population proxy then increased at rates of 10%, 7% and 4% for the humpback, southern right, and Bryde's whales respectively. For an overall whale population increase, the most conservative population growth rate of 4% was used. Fishing effort was incorporated into the model using effort data provided by DEFF. Due to the differences in gear setups between the WCRL, SCRL and octopus fisheries, when combining the effort of the three fisheries, the number of buoy lines in the water column rather than number of traps was used, as this was a better indication of the risk posed to whales. The WCRL fishery use a single buoy line per trap so their effort data remained unchanged. Since the SCRL fishery set lines of 200 traps with a buoy at each end (Norman *et al.*, 2018), their effort data was divided by 200 and multiplied by 2. Similarly, the octopus fishing effort was divided by 25 and multiplied by 2. The relationship between entanglements and year were analysed for the whole South African coastline, for total entanglements and species specific entanglements. The relationship was then analysed for each of the three trap fisheries, for total entanglements and species specific entanglements.

Results

Whale distribution and interaction with trap fishing gear

Whale entanglements

A total of 141 entanglement records were provided in the data given by the SAWDN. 2020 was excluded due to being incomplete, resulting in a total of 114 entanglement events between 2006 and 2019. Annual whale entanglements in trap fishing gear have increased since 2006 (**Figure 7**), increasing at a rate of approximately 10.2% per year (**Table 5**). The exponential lay between 0.054 and 0.150 indicating that the relationship between entanglements and year was not linear.

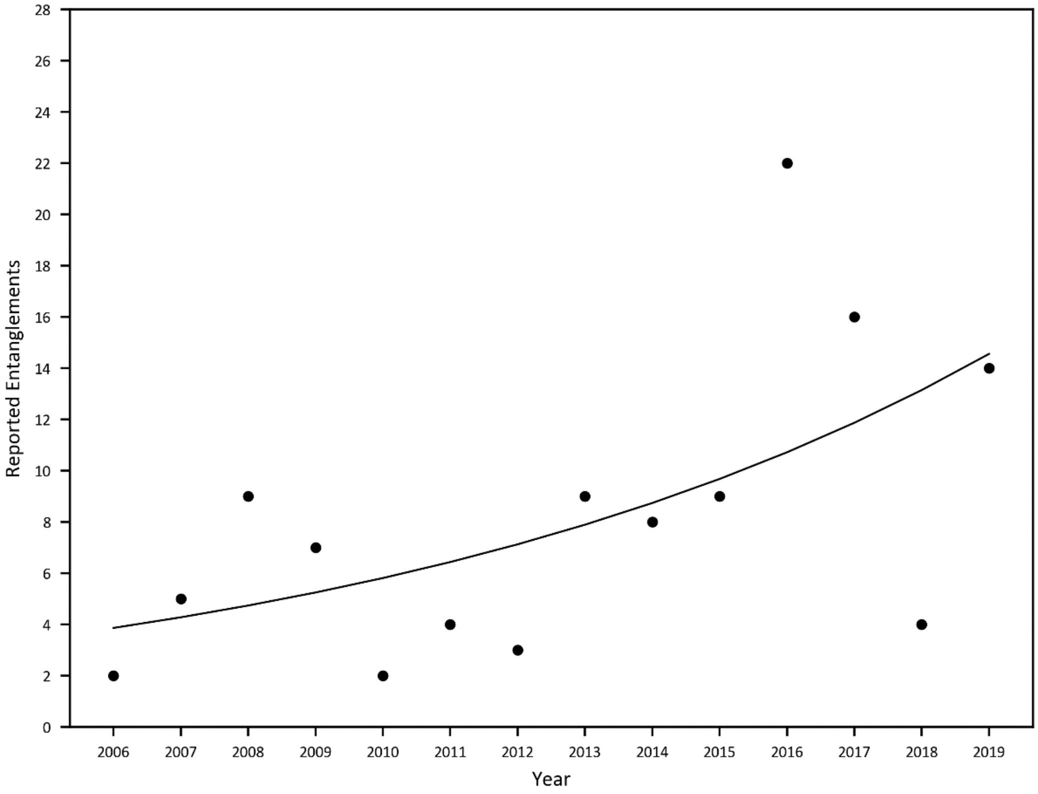

Figure 7: Scatter plot of whale entanglement events per year from 2006 - 2019. (n = 114). Regression line equation: Reported Entanglements = exp(0.102*year-203.503). The upper and lower 95% confidence intervals of the regression coefficient were 0.054 and 0.150.

Annual entanglement events have increased for both humpback and Bryde's whale species but show no significant change for southern right whale (**Figure 8** and **Table 5**). Exponentials lay between 0.089 and 0.237 for humpback whale entanglements, and between 0.145 and 0.648 for Bryde's whales, indicating that the relationship between entanglements and year was not linear for these two species.

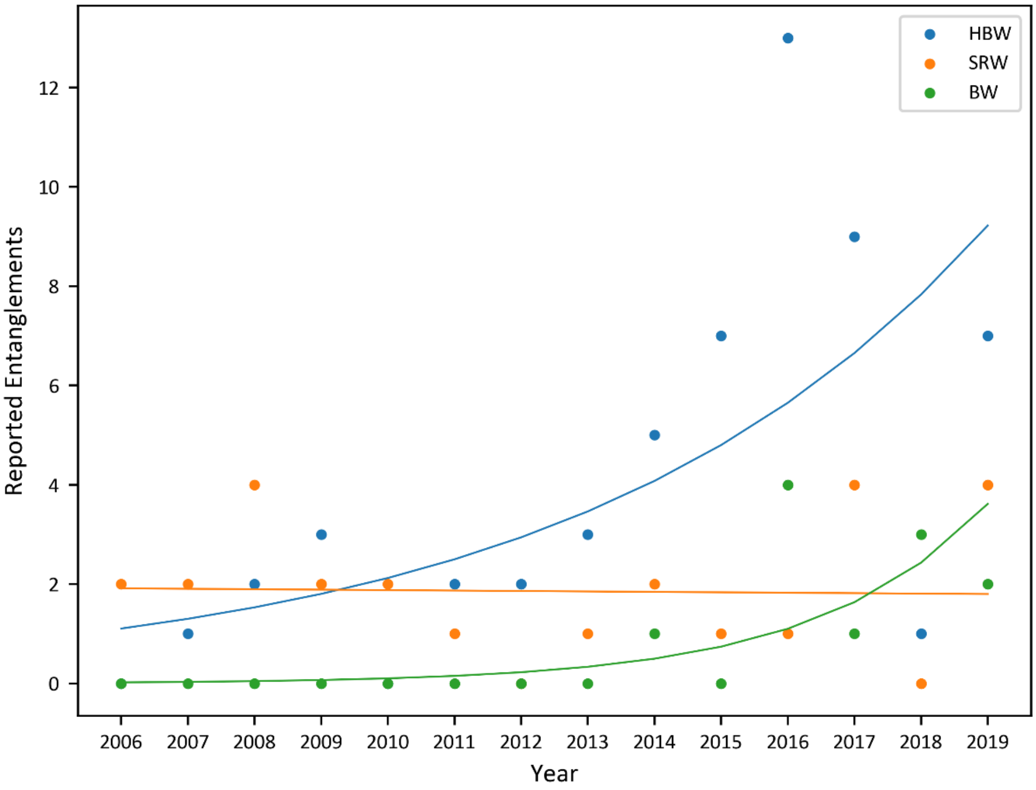

Figure 8: Scatter plot of whale entanglement events per year from 2006 – 2019 showing entanglement events for humpback whale (HBW, blue dots), southern right whale (SRW, orange dots) and Bryde's whale (BW, green dots). HBW regression line: Reported Entanglements = exp(0.163*year-327.258). SRW regression line: Reported Entanglements = exp(-0.0047*year+10.146). BW regression line: Reported Entanglements = exp(0.397*year-799.410) (n = 92).

The octopus fishery was the only fishery in which entanglements significantly increased since 2006 (**Table 8**). Entanglement trends in both the WCRL and SCRL show insignificant relationships between entanglements and year (**Figure 9**).

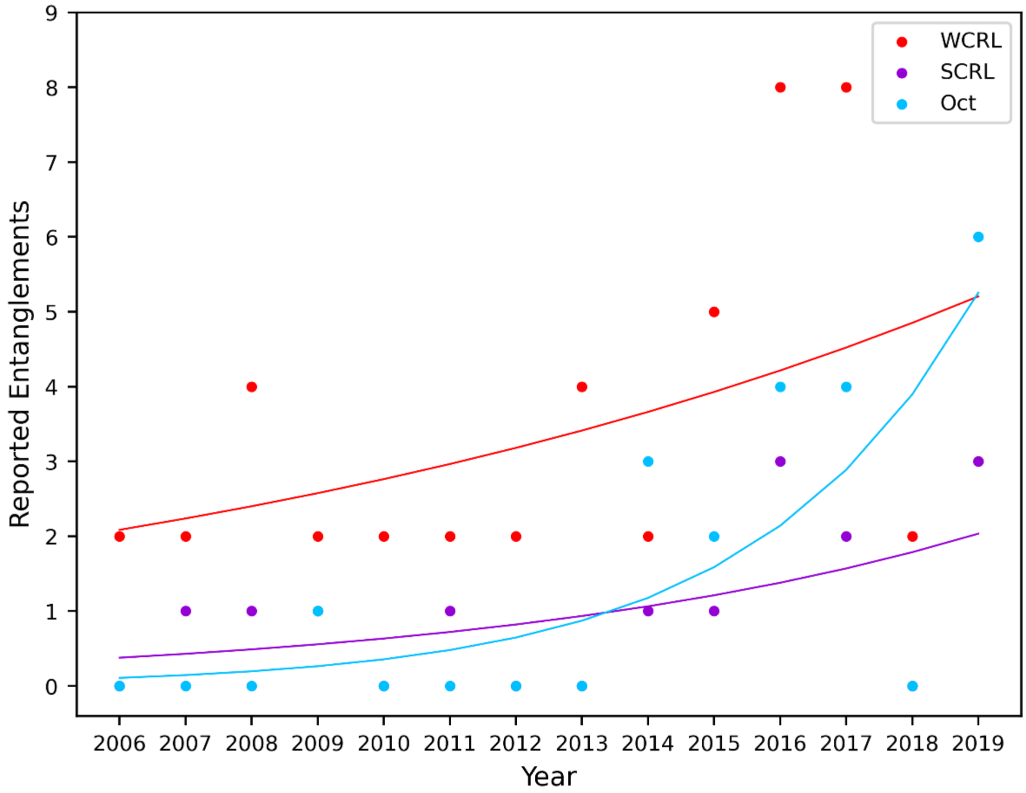

Figure 9: Scatter plot of whale entanglement events per year from 2006 – 2019 showing entanglement events in the west coast rock lobster (WCRL, red dots) fishery, south coast rock lobster (SCRL, purple dots) fishery, and octopus (Oct, blue dots) fishery. WCRL regression line: Reported Entanglements = exp(0.070*year-140.383). SCRL regression line: Reported Entanglements = exp(0.130*year-261.204). Oct regression line: Reported Entanglements = exp(0.299*year-602.821) (n = 82).

Between 2006 and 2010, entanglements were dominated by the southern right whale with a primary peak in August and a secondary peak in January to February (**Figure 10**A). These peaks then equalised between 2011 and 2015 (**Figure 10**B) and entanglements were dominated by humpback whales. Between 2016 and 2020 the peaks had reversed to a primary peak during January to March and a secondary peak during June to August, where entanglements were again dominated by humpback whales (**Figure 10**C).

The majority (60%) of whale entanglements occurred on the west coast between 2006 and 2020 (**Figure 11**). Entanglements on the west coast, south coat and False Bay peaked in January, August and June, respectively (**Figure 11**).

An increase in entanglements in the octopus fishery was seen between 2006 and 2020 (**Figure 12**) and they were responsible for the majority of entanglements in False Bay over the same period (**Figure 13**).

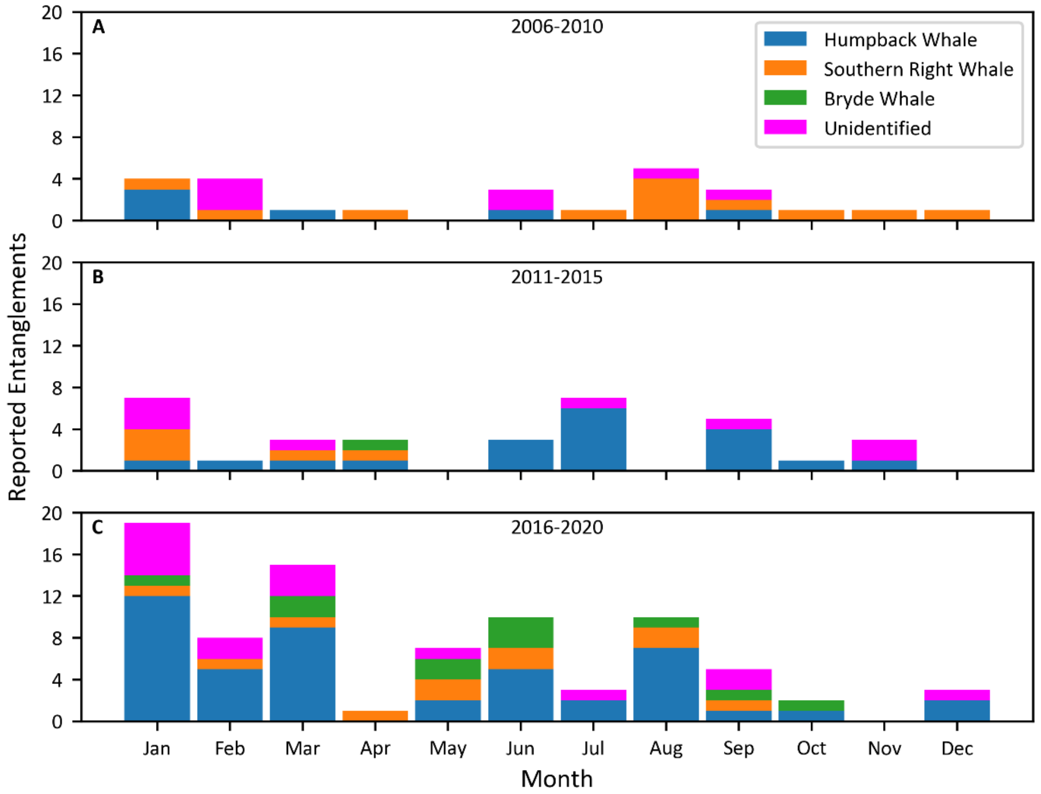

Figure 10: Five-yearly, monthly reported whale entanglements per species from January 2006 to May 2020. Plot A shows years 2006 – 2010, plot B shows years 2011 – 2015, and plot C shows years 2016 – 2020 (n = 141).

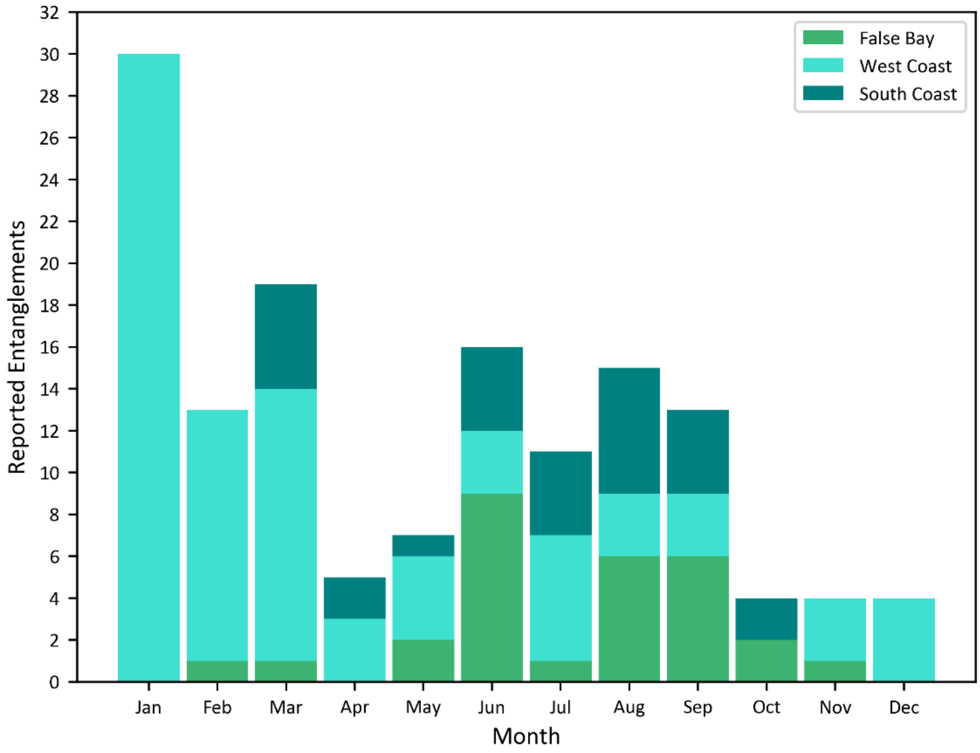

Figure 11: Monthly reported whale entanglements from January 2006 to May 2020. (n = 141; False Bay n = 29, West Coast n = 84, south coast n = 28)

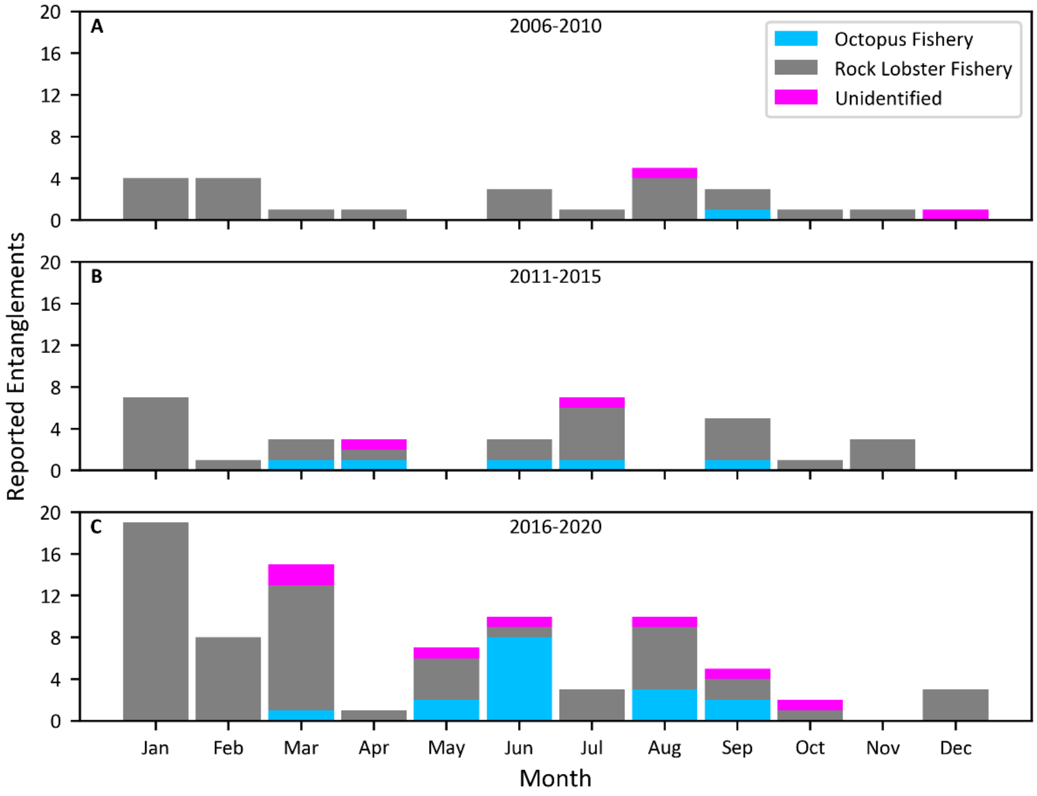

Figure 12: Five-yearly, monthly reported whale entanglements from January 2006 to May 2020 (n = 141).

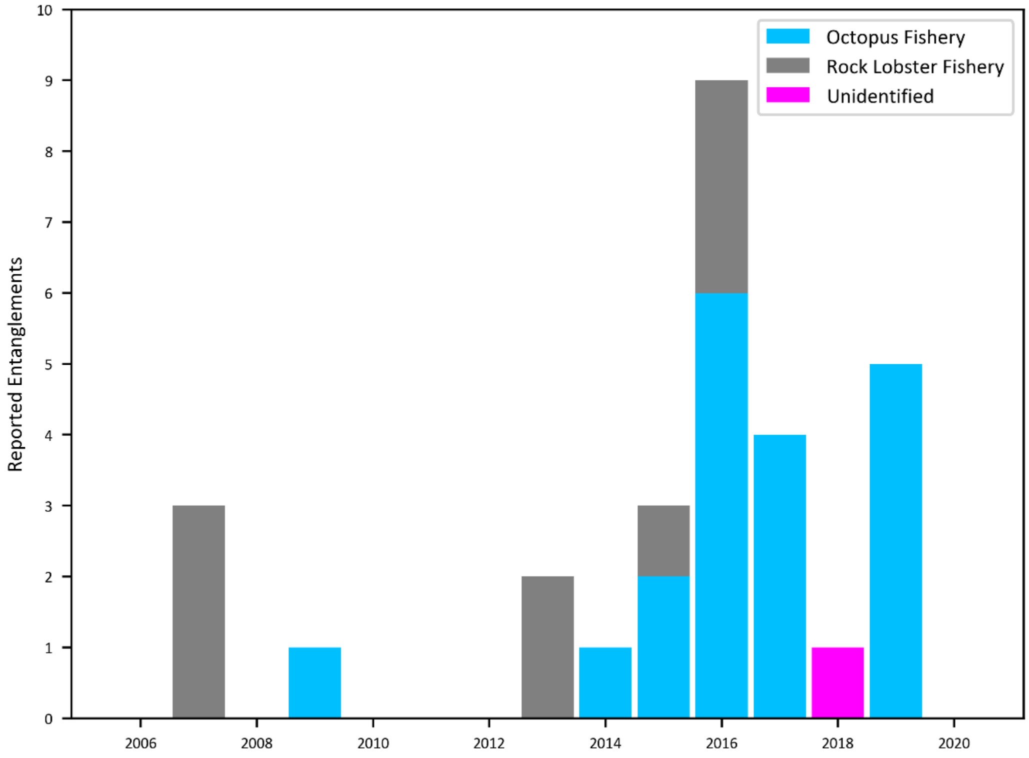

Figure 13: Yearly entanglement distribution for False Bay showing fishery responsible (n = 29, Octopus n = 19, WCRL n = 9, Unidentified n = 1).

The majority of entanglements occurred in the WCRL fishery and were dominated by the humpback whale (**Figure 14**).

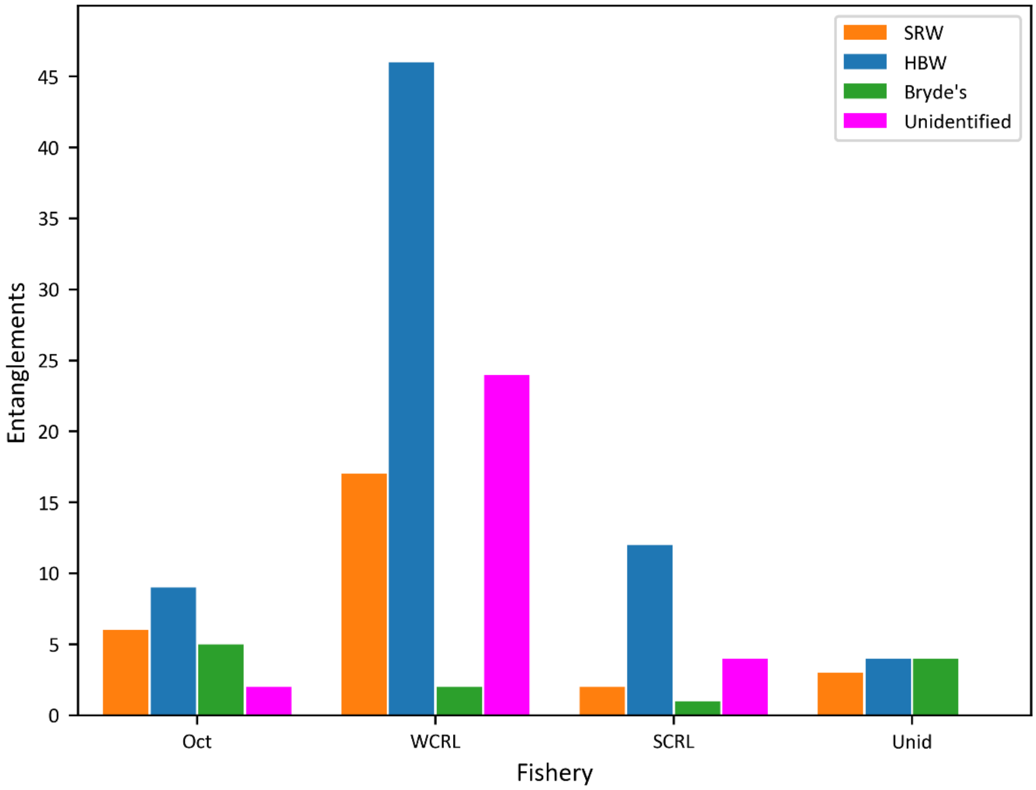

Figure 14: Species entanglements by fishery showing southern right whale (SRW), humpback whale (HBW), Bryde's whale and unidentified whale entanglements in the octopus (Oct), west coast rock lobster (WCRL), south coast rock lobster (SCRL), and unidentified fisheries (n = 141).

Entanglement hotspots were seen in St Helena and Saldanha Bay, Dassen Island, Cape Peninsula, and Jeffrey’s Bay, with the highest concentration around the Cape Peninsula and Dassen Island (**Figure 15**, **Table 2**).

The WCRL fishery has one buoy line per trap compared to the multiple traps per line for the SCRL and Octopus fisheries and therefore the combined effort (which was based off buoy lines) followed the same trend as the WCRL fishing effort (**Table 1** and **Figure 21**). Effort from the octopus fishery were only recorded from 2013 (**Table 1**).

The majority of entanglements in the SCRL fishery between 2006 and 2019 were humpback whales, where only two southern right entanglements occurred in 2007 and 2008 (**Table 3**). No entanglements of Bryde’s whales in SCRL fishing gear were recorded over the study period (**Table 3**).

The majority of entanglements in the octopus fishery from 2006 to 2019 were humpback whales (**Table 4**). The octopus fishery were responsible for the most Bryde’s whale entanglements (**Table 4**), where the first entanglement of a Bryde's whale was recorded in 2014 (**Table 1**).

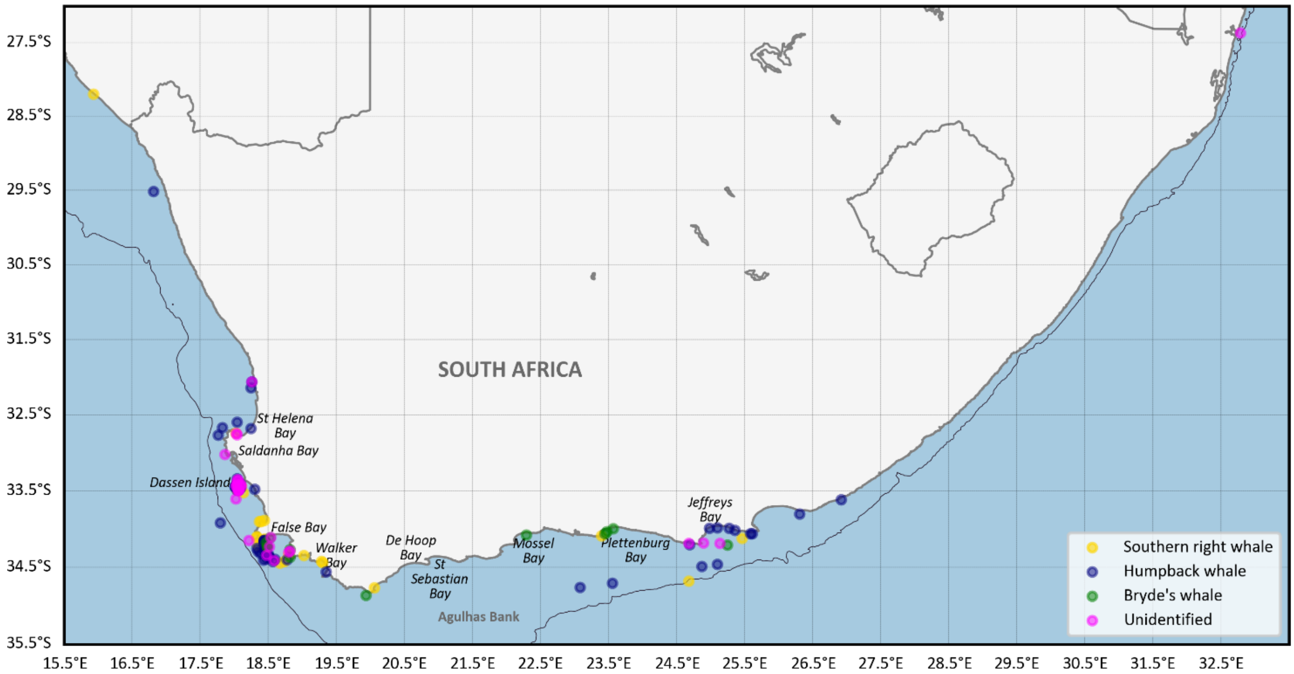

Figure 15: Reported whale entanglements in trap fishing gear from January 2006 to May 2020. Yellow dots indicate southern right whale entanglements, blue dots indicate humpback entanglements, green dots indicate Bryde's whale entanglement, and pink dots indicate unidentified species entanglements (n = 141).

Table 1: Whale entanglements per species, fishing effort per fishery (traps hauled per year) and species population growth proxy for years 2006 to 2019. Highlighted cells show interpolated values using SCRL TAE.

Year	HBW	SRW	BW	Total	WCRL Effort	SCRL Effort	Oct Effort	Combined Effort	HBW proxy	SRW proxy	BW proxy	Tot proxy
2006	0	2	0	2	201436	2664544		228081	1.105	1.915	0.021	2.508
2007	1	2	0	3	342957	3000000		372957	1.216	2.049	0.022	2.609
2008	2	4	0	6	237771	2600000		263771	1.337	2.192	0.023	2.713
2009	3	2	0	5	256280	2400000		280280	1.471	2.346	0.023	2.822
2010	0	2	0	2	164957	2600000		190957	1.618	2.510	0.024	2.935
2011	2	1	0	3	170698	2000000		190698	1.780	2.686	0.025	3.052
2012	2	0	0	2	222157	2300000		245157	1.958	2.874	0.026	3.174
2013	3	1	0	4	223721	2600000	2000	249881	2.153	3.075	0.027	3.301
2014	5	2	1	8	203982	2100000	4600	225350	2.369	3.290	0.029	3.433
2015	7	1	0	8	151283	2200000	14473	174441	2.606	3.520	0.030	3.570
2016	13	1	4	18	207497	2200000	17887	230928	2.866	3.767	0.031	3.713
2017	9	4	1	14	180625	2714063	14436	208921	3.153	4.030	0.032	3.862
2018	1	0	3	4	95963	2697325	25800	125000	3.468	4.313	0.033	4.016
2019	7	4	2	13	65932	2697325	16741	94245	3.815	4.614	0.035	4.177

Table 2: Whale entanglements in WCRL fishing gear showing species, WCRL fishing effort (traps hauled per year) and species population growth proxy for years 2006 to 2019.

Year	HBW	SRW	BW	Total	Effort	HBW proxy	SRW proxy	BW proxy	Tot proxy
2006	0	2	0	2	201436	1.073	1.174	0.004	2.085
2007	1	1	0	2	342957	1.180	1.257	0.004	2.169
2008	2	2	0	4	237771	1.298	1.345	0.004	2.256
2009	2	0	0	2	256280	1.428	1.439	0.004	2.346
2010	0	2	0	2	164957	1.571	1.539	0.004	2.440
2011	1	1	0	2	170698	1.728	1.647	0.005	2.537
2012	2	0	0	2	222157	1.900	1.762	0.005	2.639
2013	3	1	0	4	223721	2.090	1.886	0.005	2.744
2014	2	0	0	2	203982	2.299	2.018	0.005	2.854
2015	4	1	0	5	151283	2.529	2.159	0.005	2.968
2016	6	1	1	8	207497	2.782	2.310	0.006	3.087
2017	7	1	0	8	180625	3.060	2.472	0.006	3.210
2018	1	0	1	2	95963	3.367	2.645	0.006	3.339
2019	0	3	0	3	65932	3.703	2.830	0.006	3.472

Table 3: Whale entanglements in SCRL fishing gear showing species, SCRL fishing effort (traps hauled per year) and species population growth proxy for years 2006 to 2019. Highlighted cells show interpolated values using SCRL TAE.

Year	HBW	SRW	BW	Total	Effort	HBW proxy	SRW proxy	BW proxy	Tot proxy
2006	0	0	0	0	2664544.218	0.135	0.797	1.000	0.377
2007	0	1	0	1	3000000.000	0.149	0.853	1.040	0.392
2008	0	1	0	1	2600000.000	0.164	0.912	1.082	0.407
2009	1	0	0	1	2400000.000	0.180	0.976	1.125	0.424
2010	0	0	0	0	2600000.000	0.198	1.045	1.170	0.441
2011	1	0	0	1	2000000.000	0.218	1.118	1.217	0.458
2012	0	0	0	0	2300000.000	0.239	1.196	1.265	0.477
2013	0	0	0	0	2600000.000	0.263	1.280	1.316	0.496
2014	1	0	0	1	2100000.000	0.290	1.369	1.369	0.516
2015	1	0	0	1	2200000.000	0.319	1.465	1.423	0.536
2016	3	0	0	3	2200000.000	0.351	1.568	1.480	0.558
2017	2	0	0	2	2714063.436	0.386	1.678	1.539	0.580
2018	0	0	0	0	2697324.545	0.424	1.795	1.601	0.603
2019	3	0	0	3	2697324.545	0.467	1.921	1.665	0.627

Table 4: Whale entanglements in octopus fishing gear showing species, octopus fishing effort (traps hauled per year) and species population growth proxy for years 2006 to 2019.

Year	HBW	SRW	BW	Total	Effort	HBW proxy	SRW proxy	BW proxy	Tot proxy
2006	0	0	0	0		0.036	0.078	0.009	0.107
2007	0	0	0	0		0.040	0.084	0.010	0.111
2008	0	0	0	0		0.044	0.090	0.010	0.116
2009	0	1	0	1		0.048	0.096	0.011	0.121
2010	0	0	0	0		0.053	0.103	0.011	0.125
2011	0	0	0	0		0.059	0.110	0.012	0.130
2012	0	0	0	0		0.064	0.118	0.012	0.136
2013	0	0	0	0	2000	0.071	0.126	0.012	0.141
2014	1	1	1	3	4600	0.078	0.135	0.013	0.147
2015	2	0	0	2	14473	0.086	0.144	0.013	0.153
2016	3	0	1	4	17887	0.094	0.154	0.014	0.159
2017	0	3	1	4	14436	0.104	0.165	0.015	0.165
2018	0	0	0	0	25800	0.114	0.177	0.015	0.172
2019	3	1	2	6	16741	0.126	0.189	0.016	0.178

Table 5 shows the GLM results from the analysis of whale entanglement for the whole South African coastline from 2006 to 2019. The first 4 models indicate there was a significant relationship between whale entanglements and year for all species except southern right whale. This corresponds to what is seen in **Figure 8** where southern right whale entanglements show no significant relationship to year. When fishing effort was included in the models, significant positive relationships occurred between whale entanglements and year for total entanglements, humpback and Bryde's whales, but not for southern right whales. All year coefficients strengthened with the inclusion of effort due to the overall decrease in fishing effort since 2006. The inclusion of a proxy for population growth for each species as an offset resulted in significant negative and positive relationships for southern right and Bryde's whale entanglements and year, respectively.

Table 6 shows the GLM results from the analysis of the data in **Table 2**: Whale entanglements in the west coast rock lobster fishery from 2006 to 2019. The first 4 models show a significant relationship between entanglements and year for only humpback whales, although the relationship for total entanglements is marginally insignificant. However, there were 15 humpback entanglement events in WCRL fishing gear between January and May 2020. If these are included, the GLM results show a significant relationship between total entanglements and year (**Table 6**). This is due to humpbacks making up 71% of all identified entanglements in the WCRL fishery (**Table 9**). Excluding 2020 again, by including the decreasing WCRL fishing effort (**Figure 21**) into the models, significant relationships between entanglements and year are seen for total entanglements, humpback, and southern right whales. The humpback entanglements shows a positive relationship with year whereas the southern right entanglements show a negative relationship with year, showing a decrease in southern right whale entanglements in WCRL gear since 2006. The inclusion of population growth into the models as an offset, resulted in insignificant relationships between entanglements and year for both total and humpback whales, and a significant negative relationship for southern right whales.

Table 7 shows the GLM results from the analysis of the data in **Table 3**: Whale entanglements in the south coast rock lobster fishery from 2006 to 2019. The first 3 models show a significant positive relationship between entanglements and year for only humpback whales. The insignificant relationship for southern right whale entanglements is due to there having been only 2 entanglement since 2006. Bryde's whales were excluded as no entanglements were recorded since 2006. Although humpbacks dominated the entanglements in this fishery (80%,**Table 9**), the occurrence of the 2 southern right whale entanglements before any humpback entanglements in 2009 weakened the total entanglement relationship with year and resulted in an insignificant result from the model. The inclusion of fishing effort into the models resulted in a strengthening of the significant positive relationships between entanglements and year for humpback whales. With the inclusion of population growth into the models, the relationship between entanglements and year for humpbacks weakened as expected but is still significant.

Table 8 shows the GLM results from the analysis of the data in **Table 4**: Whale entanglements in the octopus fishery from 2006 to 2019. The first 4 models show that there is a significant relationship between whale entanglements and year for humpback and Bryde's whales. The inclusion of fishing effort into the models resulted in insignificant relationships for total and all species entanglements, which carried through when population proxy offsets were included. However, all models showed insignificant relationships with effort. When effort was excluded from the models and population proxy offsets included, the results showed significant relationships with year for humpback and Bryde's whale entanglements.

Table 5: Results of the GLMs showing relationships between entanglement events, year, species, effort and whale population growth proxy for the whole South African coastline from 2006 to 2019. Results were considered significant if $p < 0.05$.

South African Coastline						
Model Family	Model Formula	Coefficients	Estimate	Std. Error	z value	p value
Poisson	Total Entanglements ~ Year	Intercept	-256.170	56.287	-4.551	<0.001
		Year	0.128	0.028	4.587	<0.001
Poisson	HBW Entanglements ~ Year	Intercept	-327.258	76.142	-4.298	<0.001
		Year	0.163	0.038	4.318	<0.001
Poisson	SRW Entanglements ~ Year	Intercept	10.146	97.916	0.104	0.917
		Year	-0.005	0.049	-0.097	0.922
Poisson	BW Entanglements ~ Year	Intercept	-799.410	259.096	-3.085	0.002
		Year	0.397	0.128	3.087	0.002
Poisson	Total Entanglements ~ Year + Effort	Intercept	-435.086	94.388	-4.610	<0.001
		Year	0.216	0.047	4.637	<0.001
		Effort	0.000	0.000	2.509	0.012
Poisson	HBW Entanglements ~ Year + Effort	Intercept	-651.895	136.540	-4.774	<0.001
		Year	0.323	0.067	4.790	<0.001
		Effort	0.000	0.000	3.124	0.002
Poisson	SRW Entanglements ~ Year + Effort	Intercept	25.509	139.990	0.182	0.855
		Year	-0.012	0.069	-0.178	0.859
		Effort	0.000	0.000	-0.152	0.879
Poisson	BW Entanglements ~ Year + Effort	Intercept	-1527.847	597.436	-2.557	0.011
		Year	0.757	0.296	2.559	0.010
		Effort	0.000	0.000	1.720	0.085
Poisson	Total Entanglements ~ Year + Effort + offset(4% population growth proxy)	Intercept	-181.761	94.157	-1.930	0.054
		Year	0.089	0.047	1.908	0.056
		Effort	0.000	0.000	2.629	0.009
Poisson	HBW Entanglements ~ Year + Effort + offset(10% population growth proxy)	Intercept	-250.740	136.320	-1.839	0.066
		Year	0.123	0.067	1.821	0.069
		Effort	0.000	0.000	3.526	<0.001
Poisson	SRW Entanglements ~ Year + Effort + offset(7% population growth proxy)	Intercept	421.332	137.985	3.053	0.002
		Year	-0.211	0.068	-3.086	0.002
		Effort	0.000	0.000	-0.009	0.992
Poisson	BW Entanglements ~ Year + Effort + offset(4% population growth proxy)	Intercept	-1525.596	597.400	-2.554	0.011
		Year	0.755	0.296	2.556	0.011
		Effort	0.000	0.000	1.720	0.085

Table 6: Results of GLMs showing relationships between entanglement events, year, species, effort and whale population growth proxy in the west coast rock lobster fishery from 2006 to 2019. Results were considered significant if $p < 0.05$.

West coast rock lobster						
Model Family	Model Formula	Coefficients	Estimate	Std. Error	z value	p value
Poisson	Total Entanglements ~ Year	Intercept	-140.383	73.853	-1.901	0.057
		Year	0.070	0.037	1.918	0.055
Poisson	HBW Entanglements ~ Year	Intercept	-199.240	94.082	-2.118	0.034
		Year	0.099	0.047	2.127	0.033
Poisson	SRW Entanglements ~ Year	Intercept	28.984	129.019	0.225	0.822
		Year	-0.014	0.064	-0.224	0.823
Poisson	BW Entanglements ~ Year	Intercept	-801.115	607.634	-1.318	0.187
		Year	0.397	0.301	1.316	0.188
Poisson	Total Entanglements ~ Year + Effort	Intercept	-507.581	128.948	-3.936	<0.001
		Year	0.252	0.064	3.949	<0.001
		Effort	0.000	0.000	3.179	0.001
Poisson	HBW Entanglements ~ Year + Effort	Intercept	-777.912	171.452	-4.537	<0.001
		Year	0.385	0.085	4.546	<0.001
		Effort	0.000	0.000	3.794	<0.001
Poisson	SRW Entanglements ~ Year + Effort	Intercept	298.525	149.319	1.999	0.046
		Year	-0.147	0.074	-1.994	0.046
		Effort	0.000	0.000	-2.163	0.031
Poisson	BW Entanglements ~ Year + Effort	Intercept	-960.708	883.586	-1.087	0.277
		Year	0.475	0.437	1.086	0.278
		Effort	0.000	0.000	0.987	0.324
Poisson	Total Entanglements ~ Year + Effort + offset(4% population growth proxy)	Intercept	-91.320	120.752	-0.756	0.449
		Year	0.044	0.060	0.737	0.461
		Effort	0.000	0.000	1.829	0.067
Poisson	HBW Entanglements ~ Year + Effort + offset(10% population growth proxy)	Intercept	-267.261	179.609	-1.488	0.137
		Year	0.130	0.089	1.468	0.142
		Effort	0.000	0.000	3.436	0.001
Poisson	SRW Entanglements ~ Year + Effort + offset(7% population growth proxy)	Intercept	475.234	174.853	2.718	0.007
		Year	-0.236	0.086	-2.731	0.006
		Effort	0.000	0.000	-1.449	0.147
Poisson	BW Entanglements ~ Year + Effort + offset(4% population growth proxy)	Intercept	-1767.984	1599.990	-1.105	0.269
		Year	0.875	0.792	1.104	0.269
		Effort	0.000	0.000	0.867	0.386

Including 2020 data						
Model Family	**Model Formula**	**Coefficients**	**Estimate**	**Std. Error**	**z value**	**p value**
Poisson	Total Entanglements ~ Year + Effort + offset(4% population growth proxy)	Intercept	-278.759	114.038	-2.444	0.015
		Year	0.138	0.056	2.440	0.015
		Effort	0.000	0.000	1.964	0.049
Poisson	HBW Entanglements ~ Year + Effort + offset(10% population growth proxy)	Intercept	-547.957	167.566	-3.270	0.001
		Year	0.270	0.083	3.265	0.001
		Effort	0.000	0.000	3.531	<0.001

Table 7: Results of GLMs showing relationships between entanglement events, year, species, effort and whale population growth proxy in the south coast rock lobster fishery from 2006 to 2019. Results were considered significant if $p < 0.05$.

South coast rock lobster						
Model Family	**Model Formula**	**Coefficients**	**Estimate**	**Std. Error**	**z value**	**p value**
Poisson	Total Entanglements ~ Year	Intercept	-261.204	144.552	-1.807	0.071
		Year	0.130	0.072	1.808	0.071
Poisson	HBW Entanglements ~ Year	Intercept	-453.935	179.642	-2.527	0.012
		Year	0.225	0.089	2.528	0.011
Poisson	SRW Entanglements ~ Year	Intercept	1018.398	744.495	1.368	0.171
		Year	-0.508	0.371	-1.369	0.171
Poisson	Total Entanglements ~ Year + Effort	Intercept	-271.030	152.647	-1.776	0.076
		Year	0.135	0.076	1.777	0.076
		Effort	0.000	0.000	-0.379	0.704
Poisson	HBW Entanglements ~ Year + Effort	Intercept	-634.009	272.289	-2.328	0.020
		Year	0.317	0.136	2.331	0.020
		Effort	0.000	0.000	-1.517	0.129
Poisson	SRW Entanglements ~ Year + Effort	Intercept	670.837	777.430	0.863	0.388
		Year	-0.339	0.385	-0.880	0.379
		Effort	0.000	0.000	0.880	0.379
Poisson	Total Entanglements ~ Year + Effort + offset(4% population growth proxy)	Intercept	-231.887	152.455	-1.521	0.128
		Year	0.115	0.076	1.520	0.129
		Effort	0.000	0.000	-0.393	0.694
Poisson	HBW Entanglements ~ Year + Effort + offset(10% population growth proxy)	Intercept	-578.050	271.143	-2.132	0.033
		Year	0.289	0.135	2.135	0.033
		Effort	0.000	0.000	-1.548	0.122
Poisson	SRW Entanglements ~ Year + Effort + offset(7% population growth proxy)	Intercept	822.207	758.125	1.085	0.278
		Year	-0.415	0.376	-1.104	0.270
		Effort	0.000	0.000	0.877	0.381

Table 8: Results of GLMs showing relationships between entanglement events, year, species, effort and whale population growth proxy in the octopus fishery from 2006 to 2019. Results were considered significant if $p < 0.05$.

Octopus fishery						
Model Family	Model Formula	Coefficients	Estimate	Std. Error	z value	p value
Poisson	Total Entanglements ~ Year	Intercept	-602.821	159.235	-3.786	<0.001
		Year	0.299	0.079	3.791	<0.001
Poisson	HBW Entanglements ~ Year	Intercept	-658.029	249.981	-2.632	0.008
		Year	0.326	0.124	2.633	0.008
Poisson	SRW Entanglements ~ Year	Intercept	-423.436	247.545	-1.711	0.087
		Year	0.210	0.123	1.708	0.088
Poisson	BW Entanglements ~ Year	Intercept	-800.199	384.302	-2.082	0.037
		Year	0.397	0.191	2.081	0.037
Poisson	Total Entanglements ~ Year + Effort	Intercept	-649.603	358.226	-1.813	0.070
		Year	0.324	0.178	1.818	0.069
		Effort	0.000	0.000	-1.805	0.071
Poisson	HBW Entanglements ~ Year + Effort	Intercept	-177.384	538.825	-0.329	0.742
		Year	0.088	0.268	0.330	0.741
		Effort	0.000	0.000	-0.360	0.719
Poisson	SRW Entanglements ~ Year + Effort	Intercept	-1289.252	843.807	-1.528	0.127
		Year	0.641	0.419	1.529	0.126
		Effort	0.000	0.000	-1.513	0.130
Poisson	BW Entanglements ~ Year + Effort	Intercept	-1063.534	730.527	-1.456	0.145
		Year	0.529	0.363	1.456	0.145
		Effort	0.000	0.000	-1.272	0.203
Poisson	Total Entanglements ~ Year + Effort + offset(4% population growth proxy)	Intercept	-636.661	358.208	-1.777	0.076
		Year	0.317	0.178	1.782	0.075
		Effort	0.000	0.000	-1.804	0.071
Poisson	HBW Entanglements ~ Year + Effort + offset(10% population growth proxy)	Intercept	-157.408	538.740	-0.292	0.770
		Year	0.078	0.268	0.293	0.769
		Effort	0.000	0.000	-0.358	0.721
Poisson	SRW Entanglements ~ Year + Effort + offset(7% population growth proxy)	Intercept	-1266.426	843.592	-1.501	0.133
		Year	0.630	0.419	1.502	0.133
		Effort	0.000	0.000	-1.512	0.130
Poisson	BW Entanglements ~ Year + Effort + offset(4% population growth proxy)	Intercept	-1062.386	730.523	-1.454	0.146
		Year	0.528	0.363	1.455	0.146
		Effort	0.000	0.000	-1.272	0.203

Model Family	Model Formula	Coefficients	Estimate	Std. Error	z value	p value
Poisson	Total Entanglements ~ Year + offset(4% population growth proxy)	Intercept	-591.101	159.119	-3.715	<0.001
		Year	0.294	0.079	3.719	<0.001
Poisson	HBW Entanglements ~ Year + offset(10% population growth proxy)	Intercept	-641.673	249.403	-2.573	0.010
		Year	0.318	0.124	2.573	0.010
Poisson	SRW Entanglements ~ Year + offset(7% population growth proxy)	Intercept	-405.027	247.056	-1.639	0.101
		Year	0.201	0.123	1.637	0.102
Poisson	BW Entanglements ~ Year + offset(4% population growth proxy)	Intercept	-799.137	384.278	-2.080	0.038
		Year	0.396	0.191	2.079	0.038

Table 9: Summary of Whale Entanglements on the South African Coastline between 2006 and May 2020 showing species and fishery responsible.

	Species				
fishery	SRW	HBW	BW	Unidentified	Total
Oct	6	9	5	2	**22**
WCRL	17	46	2	24	**89**
SCRL	2	12	1	4	**19**
Unidentified	3	4	4	0	**11**
Total	**28**	**71**	**12**	**30**	**141**

Whale Distribution

Using data from Peter Best's "Whales and Dolphins of the Southern African Subregion" (2007), and complimented by kml files and written information from Dr Simon Elwen, the following distribution map was compiled. It shows the approximate distributions of the three major whale species found in South African waters, including hotspots where they are known to congregate.

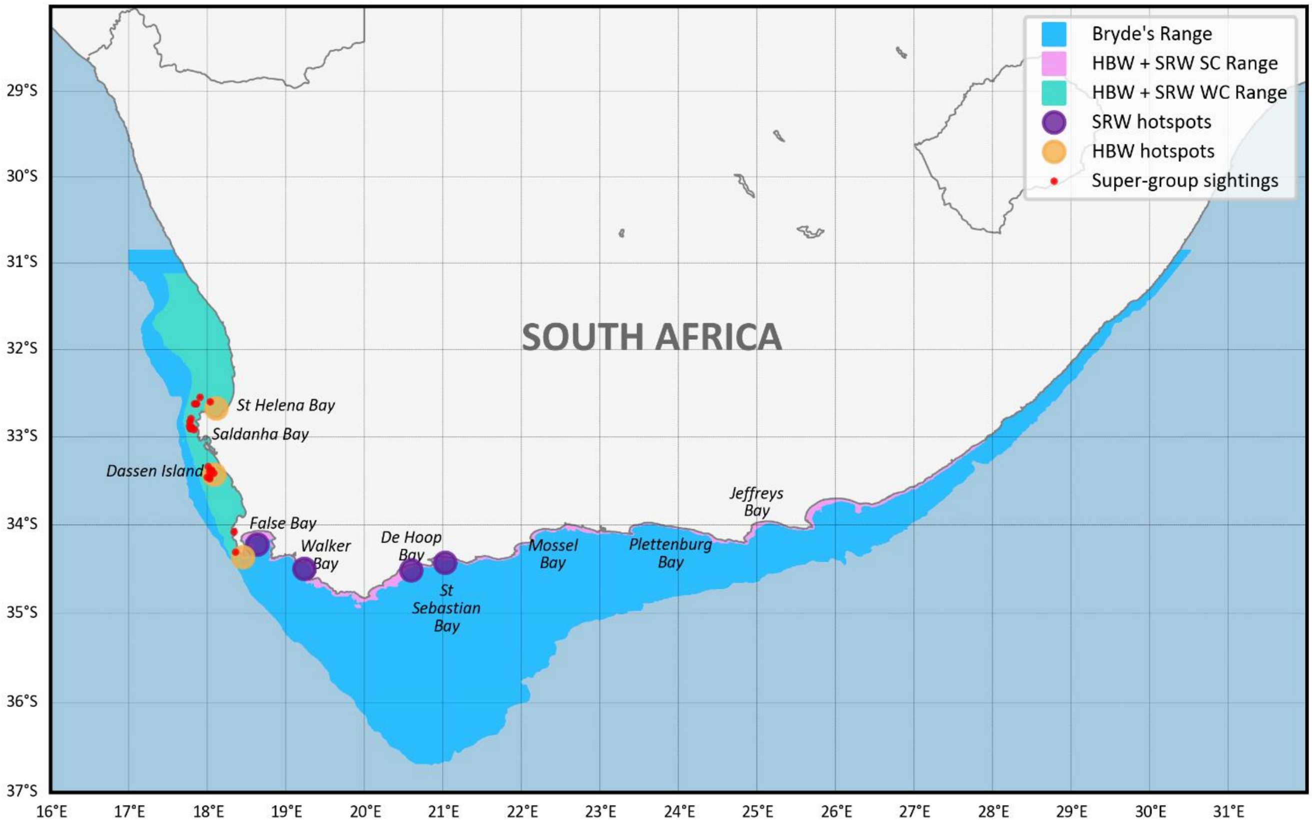

Figure 16: Whale distribution in South African waters showing the ranges of the Bryde's, humpback (HBW) and southern right whale (SRW) south coast (SC) and west coast (WC) ranges and hotspots. The Bryde's range includes the Agulhas Bank up to depths of 200m. West coast range of the HBW and SRW extend to the 100m isobath and the south coast range of the HBW and SRW extend to the 30m isobath. Super-group sightings from Findley *et al.* (2017).

Humpback whale hotspots were in St Helena Bay, Dassen Island and the Cape Peninsula while southern right whale hotspots occurred in False Bay, Walker Bay, De Hoop Bay and St Sabastian Bay. Bryde's whales occurred throughout the region of the Agulhas Bank. On the south coast, humpback and southern right whales stayed closer to the coast while migrating and their range extended further from shore on the west coast while feeding. Super-groups of humpback occurred off the west coast around St Helena Bay, Dassen Island and the Cape Peninsula (Findlay *et al.*, 2017) (**Figure 16**).

Figure 17 and **Figure 18** below show the seasonal presence of the three whale species on the west coast (including False Bay) and the south coast respectively. Bryde's whales show no seasonality, occurring year round as residents on the Agulhas Bank. Bryde's, humpback and southern right whale seasonalities overlap during the months of November to March on the west coast (**Figure 17**) and during July, September and October on the south coast (**Figure 18**).

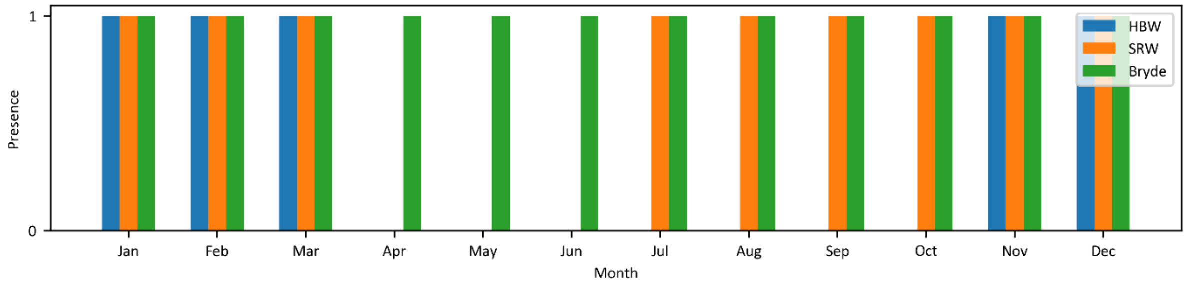

Figure 17: West Coast (including False Bay) whale seasonal presence. Blue bars show humpback whale (HBW), orange bars show southern right whale (SRW), and green bars show Bryde's whale (Bryde) presence.

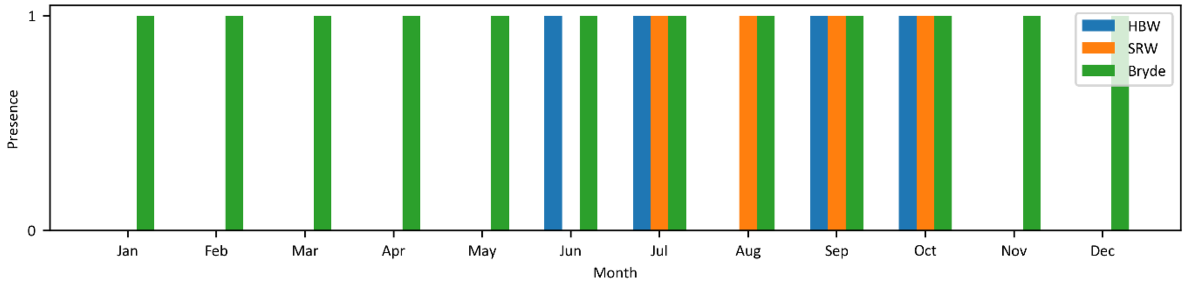

Figure 18: South coast whale seasonal presence. Blue bars show humpback whale (HBW), orange bars show southern right whale (SRW), and green bars show Bryde's whale (Bryde) presence.

WCRL fishing effort hotpots occurred around St Helena Bay, Dassen Island, Cape Peninsula, False Bay and Walker Bay (**Figure 19**).

Combined fishing effort from the three trap fisheries showed a decreasing trend between 2006 and 2019 (**Figure 20**). This was despite an increase in octopus fishing effort since 2013 (**Figure 21**). Fishing effort in the WCRL industry decreased in all but two areas (**Table 10**), with one of the areas of increase being False Bay (Zone E).

Trap Fishing Effort

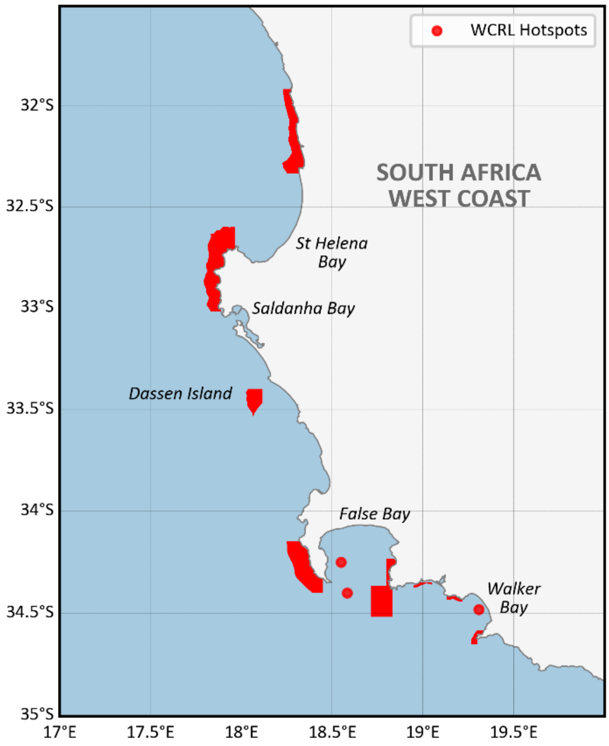

Figure 19: WCRL fishing hotspots provided by DEFF.

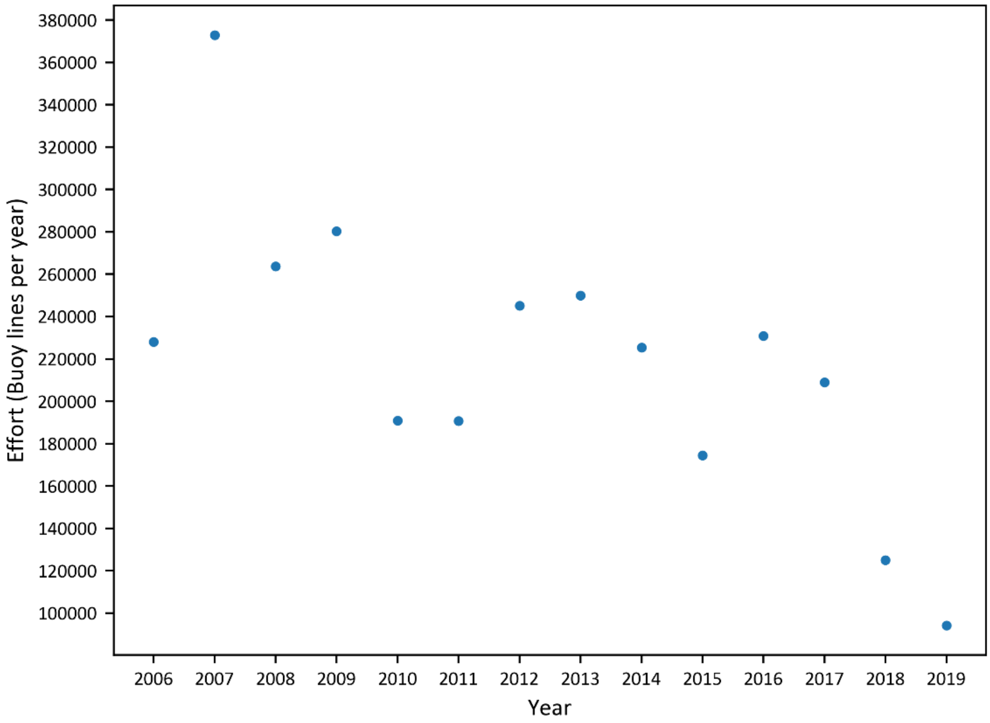

Figure 20: Total effort (buoy lines per year) from WCRL, SCRL and octopus fisheries from 2006 to 2019.

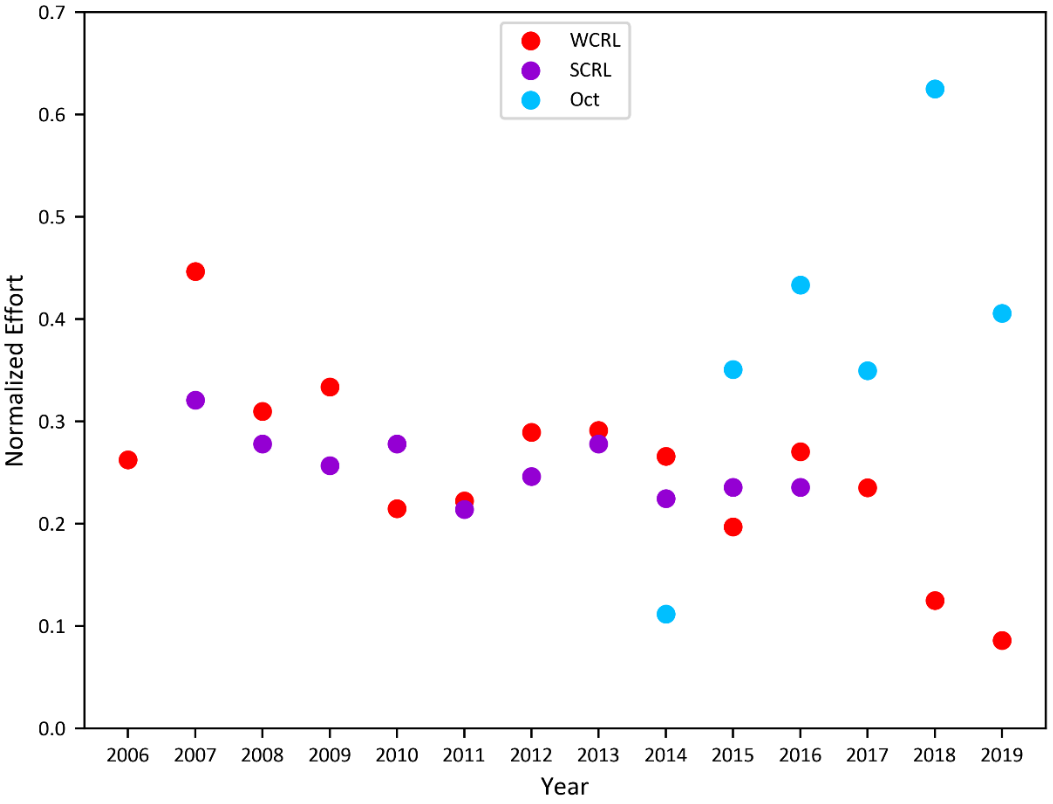

Figure 21: Normalized Fishing effort from 2006 to 2019 for the WCRL, SCRL and octopus fisheries.

Table 10: The mean effort (gear set), slope, percentage change, and r-value of WCRL fishing effort (traps hauled per year) from 2006 to 2019 for different zones and gear types.

Zone	Area	Gear Type	Mean Effort	Slope	% change	R-Value
A	1+2	Bakkie	443.214	-49.804	-84.421	-0.850
B	3	Bakkie	179.000	-34.877	-112.877	-0.657
B	4	Traps	8426.083	689.927	275.832	0.515
C	5+6	Bakkie	310.571	-21.534	-62.135	-0.841
D	7	Traps	56873.429	-7794.053	-94.223	-0.826
D	8	Traps	131116.929	-3793.022	-31.655	-0.361
E	11	Bakkie	169.571	-3.538	-23.887	-0.282
E	11	Traps	4320.308	262.659	124.422	0.850
F	12	Bakkie	627.143	-4.400	-8.723	-0.068
F	13	Bakkie	785.143	-26.330	-35.793	-0.413
F	14	Bakkie	157.429	-9.389	-55.872	-0.456

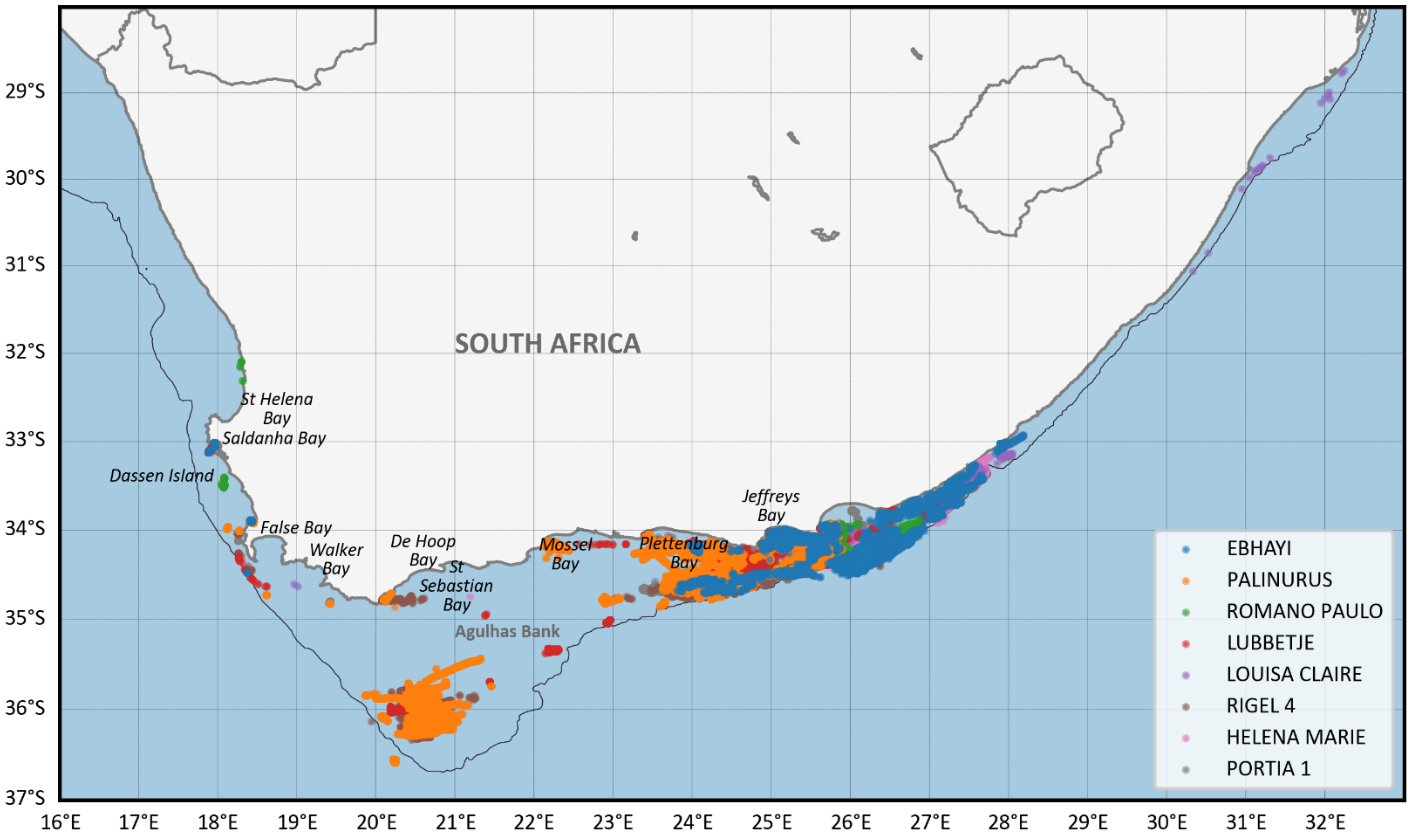

Figure 22: SCRL fishing vessel GPS tracking coordinates for 8 vessels travelling below 3 knots from 1 Jan 2018 to 31 October 2020. Obtained from AIS.

SCRL fishing hotspots occurred at the southern tip of the Agulhas Bank, Mossel Bay, and across the Agulhas bank from Plettenberg Bay at 23.5 degrees east to 28 degrees east (**Figure 22**).

Discussion

Whale entanglements in trap fishing gear have increased since 2006, increasing at a rate of 10.2% per year. This is similar to the long term trend found between 1975 and 2009 by Meyer *et al.* (2011). Two peaks were mentioned by Meyer *et al*. (2011), the primary from August to October and the secondary from December to February. They attributed the primary peak to an overlap of the peak whale season and that of the west coast rock lobster fishery's southern migration to the Cape Peninsula during those months. The secondary peak was attributed to southern right and humpback whales which delayed their migration to take advantage of zooplankton blooms associated with localised upwelling off the west coast. More recent data showed a shift of the peaks. Two peaks similar to those found by Meyer *et al.* (2011) occurred from 2006 to 2010. However, data from 2011 to 2020 showed the primary peak shifting to January to March, and the secondary peak to June to September. The secondary peak can be attributed to the octopus fishery and entanglements on the south coast (SCRL fishery). Both peaks correspond to months in which whales (particularly humpback and southern right whales since Bryde's whales are resident year round) are present on the South African coast. The low entanglements recorded in April and May can therefore be attributed to the lack of presence of humpback and southern right whales on the South African coast during those months. Entanglements occurred on the south coast from March to October, peaking in August. These months correspond with whale presence on the south coast where all three whale species are present from June to October. On the west coast, whale presence corresponds to the primary entanglement peak from January to March, and the secondary peak in June, but fails to explain the lack of entanglements from October to December. This suggests that the lack of entanglements during these months is due to a decrease in fishing effort rather than whale distribution.

Discussions with both Dr Elwen and Mike Meyer of the SAWDN confirmed that the shift in entanglement peaks is most likely due to the 'super-groups' of humpbacks which aggregate off the west coast in the summer months. This is confirmed by a paper on the subject by Findley *et al.* (2017), where super-groups were identified from 2011 in the months October and November. The increasing number of entanglements of humpback whales from January to March since 2011 support these findings by Findley *et al.* (2017). These super-groups are known to start aggregating from October, however, so we should expect to see similar entanglement data from October to December. The fact that this was not the case suggests that whales did not encounter as many fishing gear over these months. The majority of entanglements occurred on the west coast (60%), and the majority of entanglements involved gear from the west coast rock lobster industry (69%). This is despite a decrease in total (combined) fishing effort since 2006. However, this decrease in total fishing effort was due to the decrease in the WCRL fishing effort, as SCRL fishing effort stayed relatively constant and the octopus fishing effort increased. Since the WCRL has one buoy line per trap compared to the multiple traps per line for the SCRL and octopus fisheries, the overall fishing effort (which was based off buoy lines) followed the same trend as the WCRL fishing effort.

Fishing effort in the west coast rock lobster industry has decreased in all but two areas, with one of the areas of increase being False Bay (Zone E). In spite of these decreases, whale entanglements have increased. This suggests that an increase in whale abundance and/or distribution, rather than an increase in fishing effort, can account for the increases in entanglements.

Since 2016, the WCRL fishery has experienced winter seasonal fishing closures. The entanglement seasonality results suggest that although the fishing season is open over October to December, the majority of fishing is being done from January to March. The peak in January to March also suggests that more effort is being put in over these months since the winter season has been closed. Since humpback whales make up the majority of entanglements (71%), and they are known to aggregate in super-groups over the summer months, winter seasonal fishing closures seem to have increased entanglements as fishing effort is concentrated in the summer months rather than being spread over summer and winter.

The increase in WCRL fishing effort in False Bay seems at first glance to be significant, the number of traps more than doubling (124% increase) from 2006 to 2019. However, the increase in entanglements in False Bay was due to the octopus fishery rather than the rock lobster fishery. Although the data was incomplete for 2019 (the data being provided on 18 June 2019), the octopus fishery was closed (due to excessive entanglements) on 28 June 2019 and therefore will be a fairly accurate representation of the year's haul.

The majority of entanglements occurred on the west coast (60%). High concentrations of entanglements occurred around the Cape Peninsula and Dassen Island. These represent WCRL fishing zone D and it was responsible for 90% of entanglements on the west coast and 55% of all entanglements reported from 2006 to 2020 for which gear was identified. Zone D (areas 7 and 8) included 92% of all WCRL mean effort from 2006 to 2019. The two areas (7 and 8), which make up this zone, have seen 94% and 32% reductions in effort over the 13 year period, respectively, resulting in approximately 150 000 fewer buoy lines in 2019 compared to 2006. In spite of this, whale entanglements have been increasing. This is further evidence that the increase in entanglements is due to increases in whale abundance and/or distribution.

There is a significant relationship between whale entanglements and year for all species except southern right whale across the whole South African coast. The negative relationship for the southern right whale can be attributed to a change in the distribution of this species as described in a recent paper by van den Berg *et al.* (2020). They observed a dramatic northern shift in foraging strategy of southern right whales over the past 10 years. This means that although their population may be growing, they are no longer aggregating in areas of high fishing pressure. The positive relationship seen in Bryde's whale entanglements after the inclusion of fishing effort and population growth suggests that these effects are not sufficient to describe the increase in Bryde's whale entanglements. Effort shows an insignificant relationship suggesting that it does not affect the increase in Bryde's whale entanglements. This may indicate a behavioural change which has altered their distribution in the past 5 years, as all Bryde's whale entanglements have occurred since 2014. The insignificance of the relationship between total (all species) and humpback whale entanglements with year, with the significance of effort, suggests that fishing effort and population growth can account for increases in these entanglements since 2006. Since humpback whale entanglements account for 64% of the total entanglements, it is reasonable that the total entanglement relationship with year followed a similar trend. Effort played a significant role in all models except those dealing with southern right whale entanglements. Due to the negative trend in effort since 2006, it would be expected to have more of a significant relationship with positive entanglement trends than negative entanglement trends. Since the southern right whale entanglements show a negative trend with year, this explains the insignificant relationship with the negative trending effort. This insignificant relationship suggests that the decrease in southern right whale entanglements is due to the northern shift of their foraging grounds rather than the decrease in effort.

Significant relationships between entanglements and year in the WCRL fishery were found for only humpback whales, although the relationship for total entanglements is marginally insignificant. However, there were 15 humpback entanglement events in WCRL fishing gear between January and May 2020. If these were included, the GLM results showed a significant relationship between total entanglements and year. This is due to humpback whales accounting for 71% of all identified entanglements in the WCRL fishery. The insignificance in the Bryde's whale results can be attributed to the low number of Bryde's entanglements in WCRL fishing gear (2 between 2006 and 2019). The humpback and southern right whale show similar trends to those seen for the whole South African coastline discussed above. This is reasonable as the WCRL was responsible for 69% of entanglements in which gear was identified. However, I believe that the uncommonly low humpback entanglements in the WCRL fishery in 2018 and 2019 (being lower only before 2011) give a misrepresentation of the real trend. If entanglement data from 2020 were included and the fishing effort extrapolated, both the total and humpback entanglements show a significant relationship to year over the 2006 to 2020 period. This is indicative of the humpback 'super-groups' which aggregate off the west coast since 2011 as described by Findley *et al.* (2017). The super-groups overlap with the WCRL fishing hotspots. Most entanglements in the WCRL fishery occurred before May and therefore the 2020 data may be considered reasonably representative of the year.

A significant positive relationship between entanglements and year was found for only humpback whales in the SCRL fishery. The insignificant relationship for southern right whale entanglements was due to there having been only two entanglement since 2006. Bryde's whales were excluded as no entanglements were recorded since 2006. Although humpbacks again dominate the entanglements in this fishery (80%), the occurrence of the two southern right whale entanglements before any humpback entanglements in 2009 weakened the total entanglement relationship with year and resulted in an insignificant result from the model. The inclusion of fishing effort into the models resulted in a strengthening of the significant positive relationships between entanglements and year for humpback whales. This increase in strength was due to the slight downward trend in SCRL effort. However, the insignificance of the effort suggests that it does not significantly affect the relationship between entanglements and year. This was due to the weak relationship of SCRL fishing effort with year. The increase in humpback whale entanglements in the SCRL fishery since 2006 cannot be described by fishing effort and population growth alone. As with the aggregation of 'super-groups' off the west coast, this could be due to changes in humpback distribution. The standard error and p-values for the year coefficient, although significant, are relatively high, indicating a weaker certainty of this relationship. This could be due to the relatively low amount of entanglements in this fishery (19 since 2006: 15% of all entanglements recorded).

Significant relationships between whale entanglements and year were found for both humpback and Bryde's whales in the octopus fishery. The insignificant relationship for southern right whale entanglements was attributed to their northern shift in foraging strategy. All models showed insignificant relationships with effort. This is likely due to the incomplete effort data in the octopus fishery. When effort was excluded from the models and population proxy offsets included, the results showed significant relationships with year for all but the southern right whale entanglements. This suggests that the increase in total, humpback, and Bryde's whale entanglements cannot be attributed to population growth alone. The increase in humpback entanglements is likely due to the aggregation of 'super-groups' off the west coast. Similarly, a change in Bryde's whale distribution may explain the increases in the entanglements seen in this species. It is also possible that the increase in entanglements was due to increases in octopus fishing effort.

As would be expected, all entanglements were found in areas of high fishing pressure. Entanglement hotspots occurred in St Helena and Saldanha Bay, Dassen Island, Cape Peninsula, and Jeffrey's Bay. These all coincided with southern right and humpback whale hotspots, apart from Jeffrey's Bay. St Helena and Saldanha Bay, Dassen Island and the Cape Peninsula are all WCRL fishing hotspots, and Jeffrey's bay is frequented by SCRL fishing vessels. Since all other fishing hotpots corresponded to reported whale entanglement events, the SCRL fishing hotspot at the southern tip of the Agulhas Bank suggests that there should have been entanglements occurring at that location, particularly with Bryde's whales. Mike Meyer from the SAWDN confirmed that the furthest entanglement they have attended to was 50 nautical miles. The fishing hotspot at the southern tip of the Agulhas Bank is over 60nm from the closest shore. It is therefore probable that entangled whales are not reported by fisherman due to the inaccessibility of the site.

Bryde's whales were identified as the species of highest concern due to their small population size. Over the 13 year period, a total of 12 Bryde's whales were entangled, or approximately 11% off all entanglements where species were identified. The octopus fishery was responsible for 63% of Bryde's entanglements where gear was identified, the WCRL fishery responsible for 25% and the SCRL fishery responsible for 13%. However, three Bryde's whale entanglements occurred, where gear was not identified, just west of Walker Bay, in Mossel Bay, Plettenberg Bay, and Jeffrey's Bay. As none of these areas are octopus fishing areas (besides Mossel Bay but it is not fished regularly), it is likely that these entanglements were the result of SCRL fishing gear. This addition of three Bryde's whale entanglements to the SCRL fishery changed the fisheries responsible for Bryde's whale entanglements to 46%, 18% and 36% for the octopus, west coast, and south coast rock lobster fisheries, respectively. The increasing Bryde's whale entanglements over the past 5 year period suggests a possible change in distribution of Bryde's whales along with population growth.

The seasonal peaks in entanglements were dominated by humpback whales. As the WCRL fishery was responsible for the majority of humpback entanglements, and the peak was seen in January to March, a summer seasonal closure in the WCRL fishery (particularly in zone D) could potentially significantly reduce humpback entanglements. The secondary peak during June to September appears to be attributed to the octopus fishery and therefore seasonal closures over these months may reduce the secondary entanglement peak. There does not appear to be any seasonality in southern right whale entanglements and therefore seasonal closures in either fishery is unlikely to be effective in reducing entanglements of this species. A possible peak in Bryde's whale entanglements occurred in June. The winter seasonal closure in the octopus fishery discussed above may therefore reduce Bryde's whale entanglements as well.

If spatial closures are to be considered, the areas of highest concern are around Dassen Island on the west coast and around the Cape Peninsula. Both these areas fall within Zone D in the WCRL fishery and the peninsula is fished by the octopus fishery as well. However, fishing effort is unlikely to be affected by spatial or seasonal closures, so by closing one area, we may find entanglement hotspots shift to areas where new effort is concentrated.

Conclusion

Peak entanglement months corresponded with whale presence on the south coast. Similarly, on the west coast, whale presence corresponded to the primary entanglement peak from January to March, and the secondary peak in June, but failed to explain the lack of entanglements from October to December. This suggested that the lack of entanglements during these months was due to a decrease in fishing effort rather than whale distribution.

The WCRL, SCRL and octopus fisheries were responsible for 68%, 15%, and 17% of entanglements, respectively. Humpback, southern right and Bryde's whales accounted for 64%, 25%, and 11%, respectively.

Since 2006, fishing effort has decreased substantially in the WCRL fishery, remained relatively constant in the SCRL fishery, and increased in the octopus fishery.

Species specific entanglements since 2006 showed significant increases for humpback and Bryde's whales, and an insignificant relationship to year for southern right whales. Increased entanglements of humpbacks over the whole South African coast from 2006 to 2019 were attributed to fishing effort trends and whale population growth. These significant increases in entanglements seen in the WCRL and octopus fishery can be attributed to the aggregation of 'super-groups' of humpbacks off the west coast which overlap with 'hotspot' fishing areas. Similarly, increases in humpback entanglements in the SCRL fishery could be due to changes in whale distribution. Southern right whales show significant decreases in entanglements over the whole South African coastline and in the WCRL fishery, with fishing effort playing an insignificant role. This negative trend in entanglements when offset by population growth can be attributed to the dramatic northern shift in distribution seen in the species over the past 10 years. The increase in entanglements of Bryde's whales over the whole South African coastline cannot be explained by fishing effort trends or population growth alone, suggesting a possible change in distribution over the past 5 years. Entanglements in the octopus fishery showed a significant increase that cannot be explained by population growth. It is possible that the increase in Bryde's whale entanglements in the octopus fishery was due to the increase in octopus fishing effort.

As would be expected, all entanglements were found in areas of high fishing pressure. West coast fishing zone D was identified as the area of highest concern as it was responsible for 90% of entanglements in the WCRL fishery and 55% all of entanglements reported from January 2006 to May 2020. The correspondence of entanglement hotspots with fishing effort hotspots suggested that entanglements may have occurred at the SCRL fishing hotspot at the southern tip of the Agulhas Bank, particularly with Bryde's whales, but due to its inaccessibility, are not reported by fisherman.

Bryde's whales were identified as the species of highest concern due to their small population size. Over the 13 year period, a total of 12 Bryde's whales were entangled or approximately 11% off all entanglements where species were identified. The results showed that the octopus fishery was responsible for 63% of Bryde's entanglements, the WCRL fishery responsible for 25% and the SCRL fishery responsible for 13%.

If seasonal closures are to be considered to reduce whale entanglements, the results suggested that this would only be effective in reducing entanglements in humpbacks and Bryde's whales as no seasonality was seen in southern right whale entanglements. The primary and secondary peaks from January to March and June to September, respectively, suggested that summer seasonal closures in the WCRL fishery and winter closures in the octopus fishery may significantly reduce humpback and Bryde's whale entanglements. If spatial closures are to be considered, areas of highest concern are around Dassen Island on the west coast and around the Cape Peninsula. However, fishing effort is unlikely to be affected by spatial or seasonal closures, so by closing one area, we may find entanglement hotspots shift to areas where new effort is concentrated.

Chapter 3: A test of ropeless fishing techniques

Introduction

The IWC have reiterated that prevention rather than disentanglement is the ultimate solution to the whale entanglement problem (IWC, 2018). Toward this end, ropeless fishing technologies are being developed which aim to eliminate buoy lines in the water column; lines which pose the most significant threat to whales (Mc Cue *et al.*, 2016, Meÿer *et al.*, 2011, Johnson *et al.*, 2005).

Ropeless fishing solutions include three components: a submerged buoy, a rope storage system, and a release mechanism. The term ‘ropeless fishing’ is misleading as rope is still used extensively, but the ropes are not allowed to rise above the seabed. The idea is that the buoy line and buoy are held at the sea floor until retrieval where the buoy is released and comes to the surface. Submerged buoys are either solid surface buoys (foam buoys compress under pressure at depth) or inflatable bags which inflate when the release is triggered. Rope storage systems include those where the line is either coiled in a bag or cage, or spooled. The release mechanism is usually one of three devices, namely galvanic timed teleases (GTR), electronic timed releases (ETR) or acoustic releases. GTRs, the most simple and cheapest of releases, comprise of two dissimilar metals which corrode at known rates via galvanic action. The mechanisms are designed to release after a specific time, by adjusting the amount of material cast into the mechanism. Each unit, therefore, has a pre-set release time that cannot be adjusted. The range of possible time-to-release in commonly available products is anything from 1 day to 30 days. Corrosion rates are affected by ocean temperature.

ETRs release after a user specified amount of time has elapsed. The timer is electronic and the release mechanism is typically a wire which is burned to melting point by an electric current. Once broken, the wire releases a buoy. The user sets the time before deployment and cannot adjust it thereafter.

Acoustic releases are the most expensive option, but they give the greatest flexibility in timing. A deck-operated unit sends a coded acoustic signal to the submerged acoustic mechanism, which releases the buoy mechanically. Top and bottom units are independently powered.

Apart from removing hazards to whales, there are additional benefits of ropeless technologies. Some of these systems come with acoustic transponders which give real time locations of fishing gear. This decreases the risk of losing gear should it be moved by a storm or a whale. Gear loss is not only a financial loss potentially costing fisherman hundreds of thousands of dollars annually, but also contributes to ghost fishing.

Ghost fishing is a process in which marine life become entangled in abandoned fishing gear (Myers *et al.*, 2019). The Global Ghost Gear Initiative (GGGI) estimated that 640,000 tonnes of fishing gear ends up lost or discarded in our oceans each year, or 2000 tonnes a day. The true number of animals entangled each year in ghost gear is likely to be hundreds of thousands, if not millions (IWC, 2015b). The removal of the buoys from the surface reduces shipping hazards and the entanglement of propellers and rudders, which, apart from posing a safety hazard, costs the ship-owners and the fishers. A final benefit, which applies particularly to the rock lobster industry in South Africa, is the elimination of poaching of rock lobsters by fishers who raid the traps of others. By keeping the location of gear secret, fishers will not lose harvests to illegal operators. The illegal fishing, which is particularly rife in South Africa, poses a further environmental threat, by removing fish without it being recorded and accounted for in assessment models.

Ropeless fishing systems come at additional expense, the costs of which need to be weighed against the advantages listed above. These systems also present new problems. Without the surface buoy as a marker, overlaying of traps becomes a potential hazard, without communication between skippers. There are navigation software systems available which include real-time mapping software, but to access the advantage of this technology requires a level of cooperation not currently seen in the South African industry.

Lebon and Kelly (2019) compared management alternatives by scoring them according to estimated costs to fishermen, likely technical effectiveness, and anticipated reaction of fishermen in response to the change, and concluded that the use of GTRs with ropeless fishing techniques was the best option for removing surface lines. This study points to the importance of including stake holders in the decision making process of fisheries management. Its importance for success is highlighted in a paper by Jarre *et al.* (2018). Through quantitative and qualitative modelling, the paper highlights the need for adequate feedback loops between scientists and stakeholders to maintain trust in the management process. This is reiterated through all the IWC workshops on large whale entanglement issues where involvement of the fishing community is encouraged when developing mitigation measures for whale entanglements(IWC, 2018).

In this chapter I report on an evaluation of ropeless fishing solutions to the whale entanglement problem in South Africa. Several gear options were tested to determine their efficacy across a range of criteria. The gear that was tested include the use of sinking line as ground line to reduce rope arcs between traps, three ropeless fishing releases and two rope storage systems. I intend this work to be useful to the fishing industry, to assist them in a transition to ropeless fishing.

Methods

Ground Lines

To quantify the risk that floating ground lines pose to whales, the height of the rope arcs between traps above the seafloor needed to be quantified. The reason that arcs develop between traps is a result of the distance between the traps on the seafloor being less than the length of rope between them, creating slack in the line. For a fixed length of rope between traps, the closer the traps are together, the more the slack in the line and the higher the arc. On a taught line, the distance between the traps is approximately equal to the length of rope between them and therefore no arc develops. Following this reasoning, the arcs between traps will be affected by the method employed when setting the line. In the octopus fishery, lines are set off the stern while cruising at 3-5 knots. The first anchor weight (to which one end of the line is attached) is dropped and, as the line runs off the stern, a trap is clipped on every 20 m. One crew member is responsible for tensioning the line every 3-5 traps by pulling on the line for approximately 2 seconds. When the end of the line is reached, the second anchor weight is dropped and the line is set. Factors that affect the tension of a set line include the speed of the vessel while setting, the depth at which the line is being set, the elasticity of the rope, and whether or not a tensioning technique is being employed.

A solution to eliminate arcs between traps is the use of sinking rope as the ground line. When discussed with fisherman in the octopus fishery, a concern was mentioned of the potential for sinking line to become buried in sediment, thereby making retrieval more difficult. In order to test this, a section of sinking line would be set between two traps and left on the seafloor for 2 weeks. The line would be filmed after each week to determine the extent of burial in sedimentation. This footage would also be used to demonstrate the effectiveness of using sinking line to eliminate arcs.

To determine the minimum height at which an arc poses a potential threat to whales, the profiles of the three main whale species found in South African waters were analysed. Since the Bryde’s whale is the smallest of the species, it would be used to determine the minimum arc height in which it could become entangled. Bryde’s whales have also recently been recorded moving at high speeds along the seafloor while chasing prey; further evidence of the potential threat ground lines pose to Bryde’s whales (Personal communication, Dr Elwen, Sea Search Research & Conservation).

Line Setting Tests

These tests were conducted using a full 200 m roll of 16 mm, 3-core polysteel floating rope. The octopus fishery use this same rope and place traps every 20 m with two 40 kg concrete filled tyres as anchor weights. To best replicate their gear, concrete cinderblocks were used in place of traps (having a weight similar to trap setups in the fishery) and were knotted 20 m apart. Two 40 kg concrete filled tyres were also used as anchor weights and a buoy line was attached to each anchor weight for retrieval. The university boat Sargasso (11.1 m, 9 ton, 600 hp) was used to set the line from the stern. While the boat was traveling at 3 knots, the first anchor weight was dropped and each of the nine cinderblocks dropped in as it was pulled off the stern by the running line. No tensioning was applied until the last test where the running line was tensioned by hand between each trap. GPS coordinates were taken as the first and last anchor weight dropped off the stern. Once set, divers were deployed to measure the distances between each knot along the seafloor and the maximum height of the arcs between traps. **Figure 23** below shows a diagram of a set line where rope arcs and trap distances were measured.

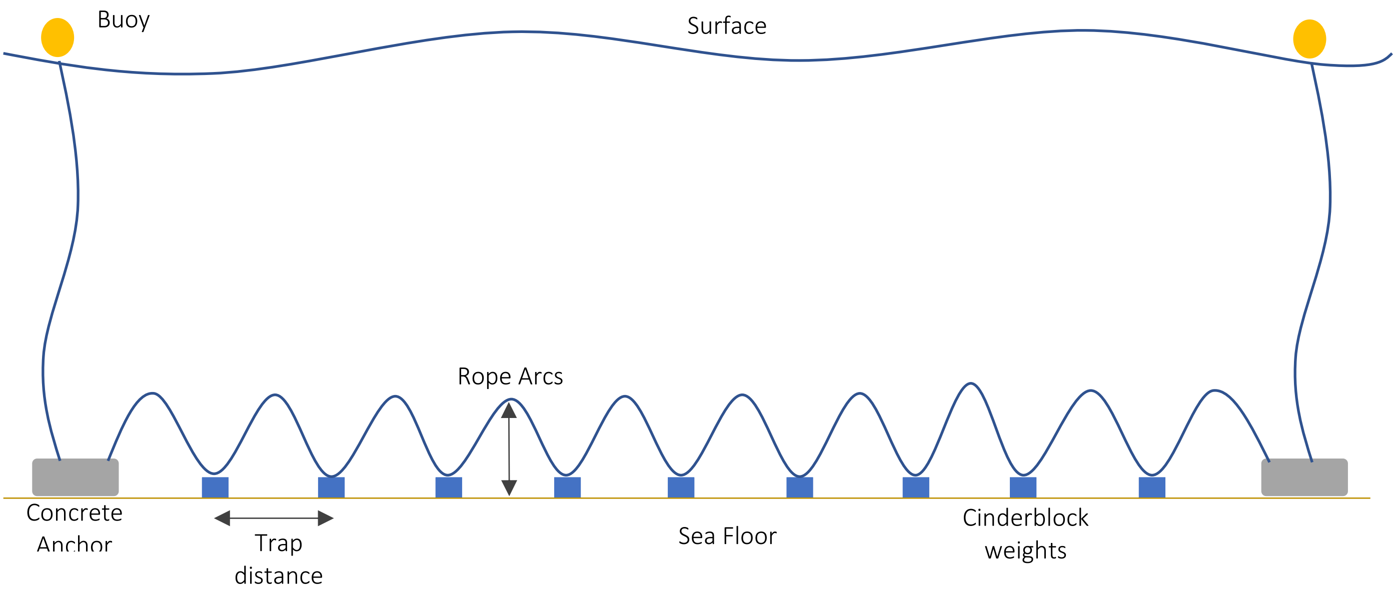

Figure 23: Rope testing setup diagram. Diagram not to scale.

Catenary

Much like the curve a chain makes when hanging between two poles, I hypothesised that rope floating between traps would follow a Catenary curve. If the floating rope did indeed follow a catenary curve, I would be able to predict the height of the rope arc between traps given the distance between them and the length of rope between the traps. Furthermore, if we assume that the tension is constant over the whole line (i.e all traps on a line are approximately the same distance apart), given the number of traps, the total length of the line and the distance between the two ends of the line, the mean arc height could be calculated. Line length and number of traps per line could be obtained from the fisherman and the distance between the two ends when set could be calculated using the GPS coordinates of the two anchor weights. I therefore set out to test first whether floating rope arcs follow a catenary curve, and secondly to determine whether arc height can be predicted within a reasonable accuracy using GPS coordinates, line length and number of traps. To test the model, measured arch heights were regressed against predicted arc heights, and the slope of the regression was compared to a value of 1.0. This was done using the OLS (ordinary least squares) attribute of the statsmodels.api 0.10.1 package in Python 3.7.4 through The Scientific Python Development Environment (Spyder) 3.3.6.

The Catenary curve equations are:

$$y(t) = -a\cosh\left(\frac{t}{a}\right) \qquad (1)$$

$$s(t) = a\sinh\left(\frac{t}{a}\right)\ for\ t > 0 \qquad (2)$$

y(t) is the parametric equation for the curve (1) and s(t) is the equation for the arc length (2). t=0 corresponds to the vertex; the midpoint between the traps where the arc height is a maximum. **a** is a parameter that determines how quickly the catenary "opens up" (Weisstein, 2020) (**Figure 24**).

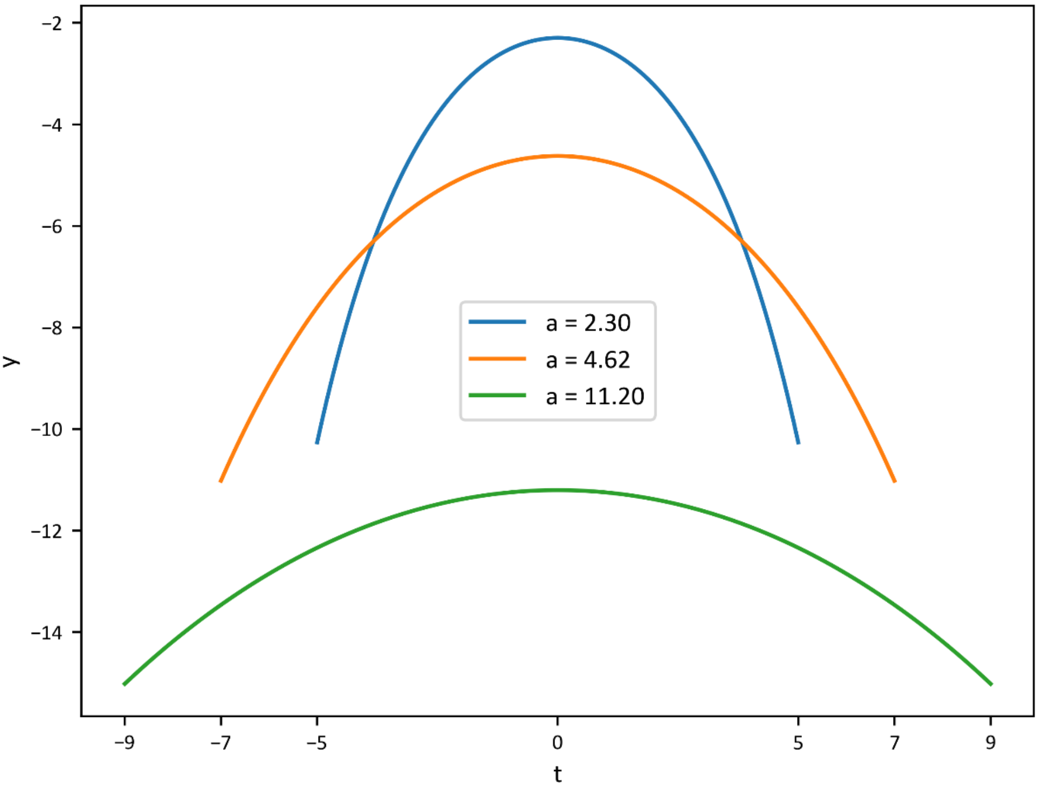

Figure 24: Catenary curves (y(t) = -a*cosh(t/a)) for varying values of a with a constant arc length of s = 20. t values represents half the distance between the traps on the seafloor. Maximum arc height occurs at t = 0.

If **d** represents the distance between the traps, t = -d/2 corresponds to the left trap and t = d/2 corresponds to the right trap). Therefore, knowing the arc length ***s*** as the length of rope between the traps, ***a*** could be solved. The arc height could then be calculated by subtracting y(t = 0) from y(t = d/2). This was done using Python 3.7.4 through The Scientific Python Development Environment (Spyder) 3.3.6 with the fsolve attribute from Scipy 1.3.1 package. The arc length was known as the length of rope between the traps and the distance between the traps was measured by divers. These measurements were then used to calculate the theoretical arc height of the catenary curve and compared to the actual arc height measured by divers. As the lower ends of the arc were not on the seafloor, but rather started at the top of the traps (concrete blocks), 30 cm was added to the catenary prediction.

Assuming my hypothesis was correct and, therefore, that a model could be developed to predict the mean arc height based on GPS coordinates of the two anchor weights, the captain of the octopus vessel Iingwane was asked to record the GPS coordinates of the anchors of four lines. This information was recorded along with the number of traps per line and the approximate distance between the traps.

Buoy Lines

The ropeless fishing technologies that I tested can be divided into two categories, namely release mechanisms and rope storage systems. Three different release mechanisms were tested: galvanic timed releases (GTRs), an electronic timed release (ETR) and an acoustic release. Two different rope storage systems were tested: a pipe storage system and a bag storage system. These two rope storage systems were chosen after consulting fisherman in the octopus fishery and the review of rope storage systems being implemented internationally.

Eliminating buoy lines entirely may not be feasible, but even a percentage reduction in the time that buoy lines hang in the water could reduce whale entanglements substantially. To determine what minimum level of reduction would be acceptable, an estimate of the Potential Biological Removal (PBR) for Bryde's whales was calculated due to it being the species of highest concern in South African waters. The PBR is a biological indicator used in fisheries management in the USA. It is defined as "the maximum number of animals that can be killed by anthropogenic causes each year whilst allowing that stock to reach or maintain its optimal sustainable population level"(Moore, 2019). The formula for PBR is given in equation 3 below. It assumes that marine mammal population growth follows a logistic model where maximum net productivity level occurs at 0.5K: half the maximum theoretical population.

$$PBR = 0.5R_{max}N_{min}F_r \qquad (3)$$

R_{max} is the maximum theoretical or estimated net productivity rate (0.04 for cetaceans) (National Marine Fisheries Service (NMFS), 2016). F_r is a recovery factor between 0.1 and 1.0 (0.1 for endangered species), the use of which "allocates a proportion of expected net production towards population growth and compensates for uncertainties that might prevent population recovery, such as biases in the estimation of N_{min} and R_{max} or errors in the determination of stock structure" (National Marine Fisheries Service (NMFS), 2016). N_{min} is the minimum population estimate (National Marine Fisheries Service (NMFS), 2016).

To get the most conservative PBR, R_{max} was set at 0.04, F_r was set at 0.1 (National Marine Fisheries Service (NMFS), 2016) and a population estimate of 800 was used (fewer than 1000 individuals) (Elwen *et al.*, 2011). This resulted in a PBR for Bryde's whales of 1.6 per year. Although not all entanglements result in death, as a conservative approach I will assume that an entanglement leads to death. The data from the SAWDN indicated that the average yearly entanglement rate of Bryde's whales was 0.8 whales per year from 2006 to 2020, which suggests that the current entanglement rate is sustainable. This ignores the ethics associated with human induced whale suffering, however, which needs to be considered in fisheries management.

Galvanic Timed Release (GTR) Tests

GTRs are the most simple and cost effective of the releases I tested. They work on the principle of galvanic corrosion of dissimilar metals and therefore come in a variety of different sizes depending on the number of days required to release, and the temperature of the water in which they will be used. Given that the rock lobster traps are typically deployed and retrieved on consecutive days, and that the octopus fishery typically leaves lines down for 5 days, 25 x 1 day, 20 x 5 day, and 15 x 7 day GTRs were tested. The objective of the tests was to determine variability in the release times among GTRs of the same size to ascertain if they are reliable enough to be utilised by fisheries. From CTD data from the test site off Glencairn in False Bay, taken in 2019, bottom (14 m) temperature ranged between 12 and 18 degrees Celsius.

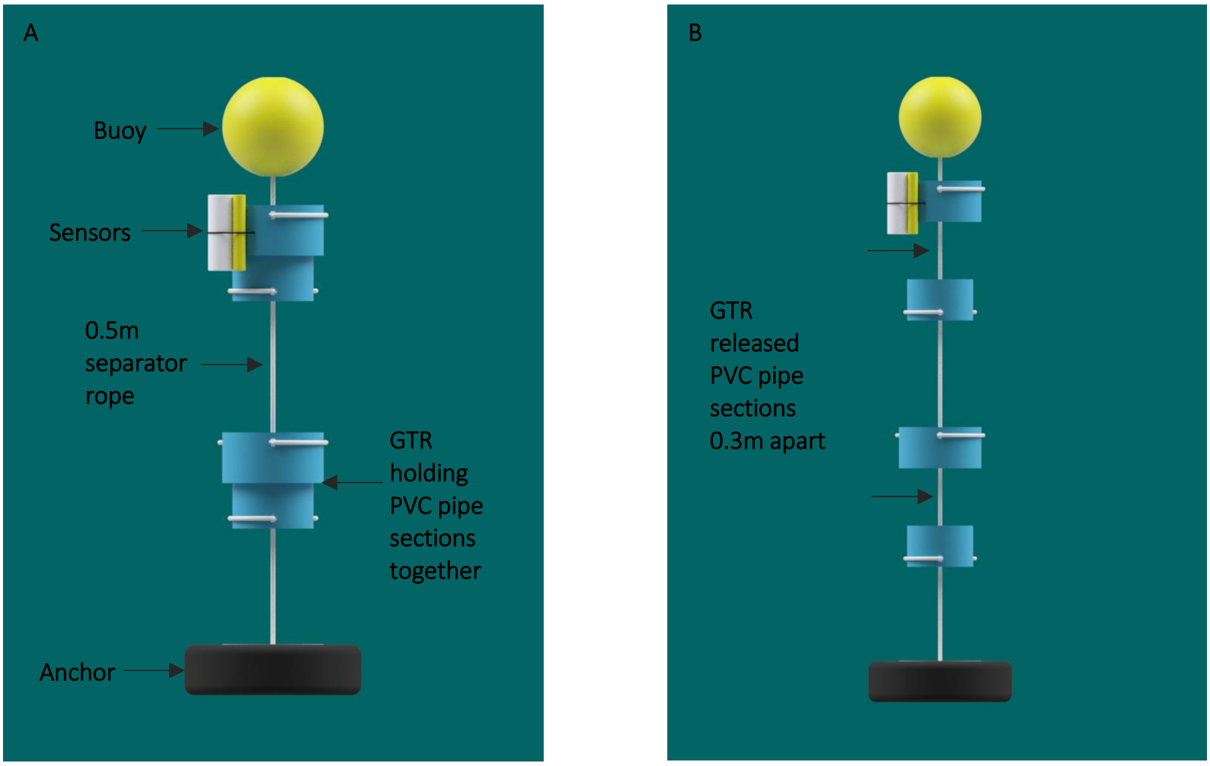

Figure 25: GTR test rig showing both set (A) at released (B) states

Based on this data, GTRs were ordered for a temperature range of 12 to 18 degrees Celsius. To test multiple GTRs at the same time, the rig shown in **Figure 25** above was designed and constructed. This modular design enabled multiple GTRs to be tested using two pressure sensors (one of each per rig) and a temperature sensors while keeping the force going through each GTR constant. A GTR held two sections of PVC pipe together as seen in **Figure 25**A. When the GTR released, the buoy rose and the sections of PVC pipe separated by 0.3 m, which resulted in a measureable pressure change picked up by the pressure sensor attached to the top most section (**Figure 25**). Each GTR was separated by 0.5 m and no metal was used in the rig to eliminate the risk of interference (Bai and Bai, 2018). Preliminary tests resulted in bungee cord being used to attach the buoy to the rig to absorb the force of a released GTR so as not to trigger the release of another. **Figure 25** shows a setup to test two GTRs but three sections were added to enable the testing of five GTRs per rig. This meant that GTRs were tested in batches of 10.

Figure 26 below shows the pressure readings from a 5 day GTR test, showing each release of the 5 GTRs.

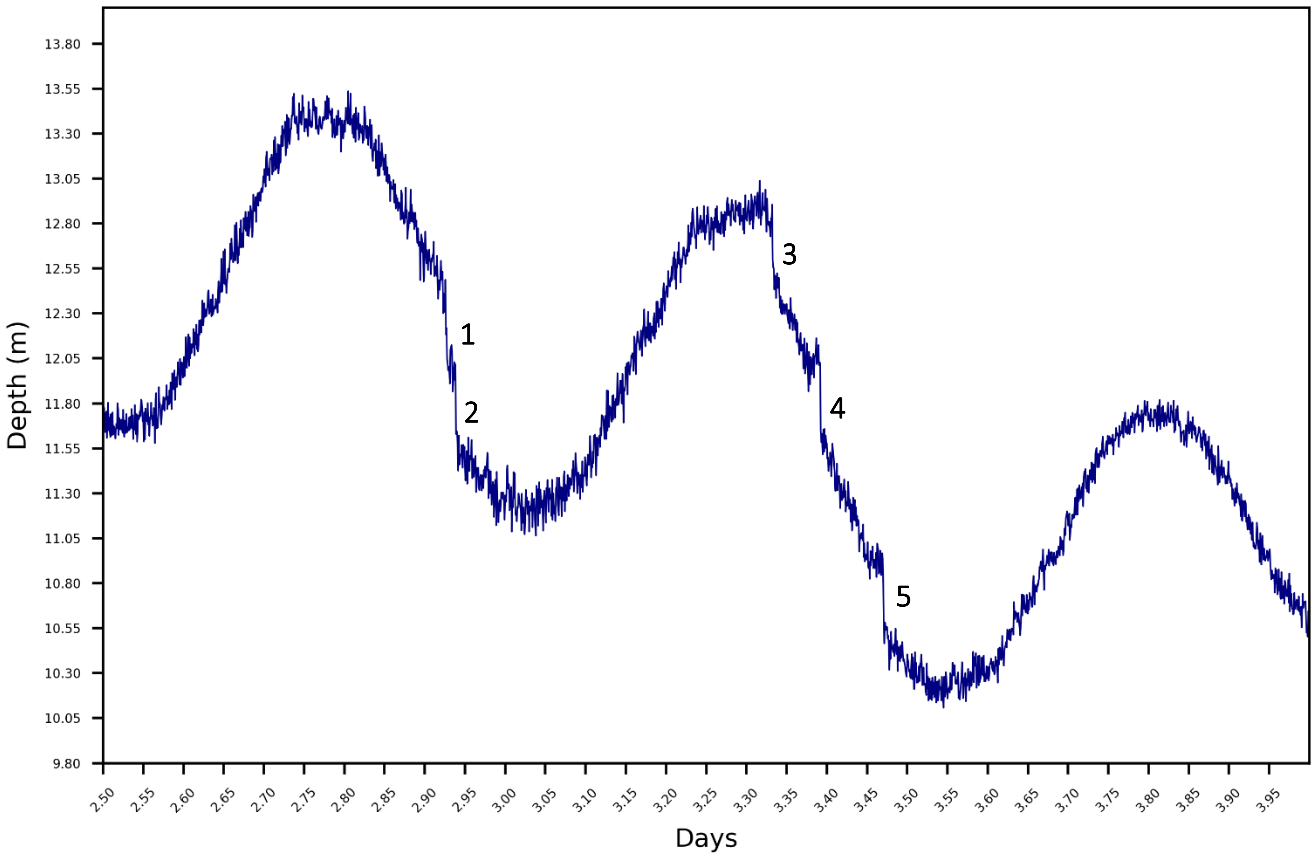

Figure 26: Pressure readings showing 5 releases of 5 day GTRs. The events 1 to 5 show the release times.

Acoustic and electronic timed release, and rope storage systems tests

To test the reliability of both the releases and the rope storage systems, a non-parametric binomial reliability demonstration test was performed. A zero failure test was designed using the equation below:

$$1 - C = \sum_{i=0}^{f} \binom{n}{i} (1 - R)^i R^{n-i} \qquad (4)$$

C is the test confidence level, R is the reliability to be demonstrated, f is the number of allowable test failures, and n is the test sample size (Gerokostopoulos *et al.*, 2015). To demonstrate a reliability of 85% with a 95% confidence interval, a sample size of 19 was required.

The reliability of the acoustic and electronic timed release were tested along with the rope storage systems (**Figure 27** and **Figure 28**).

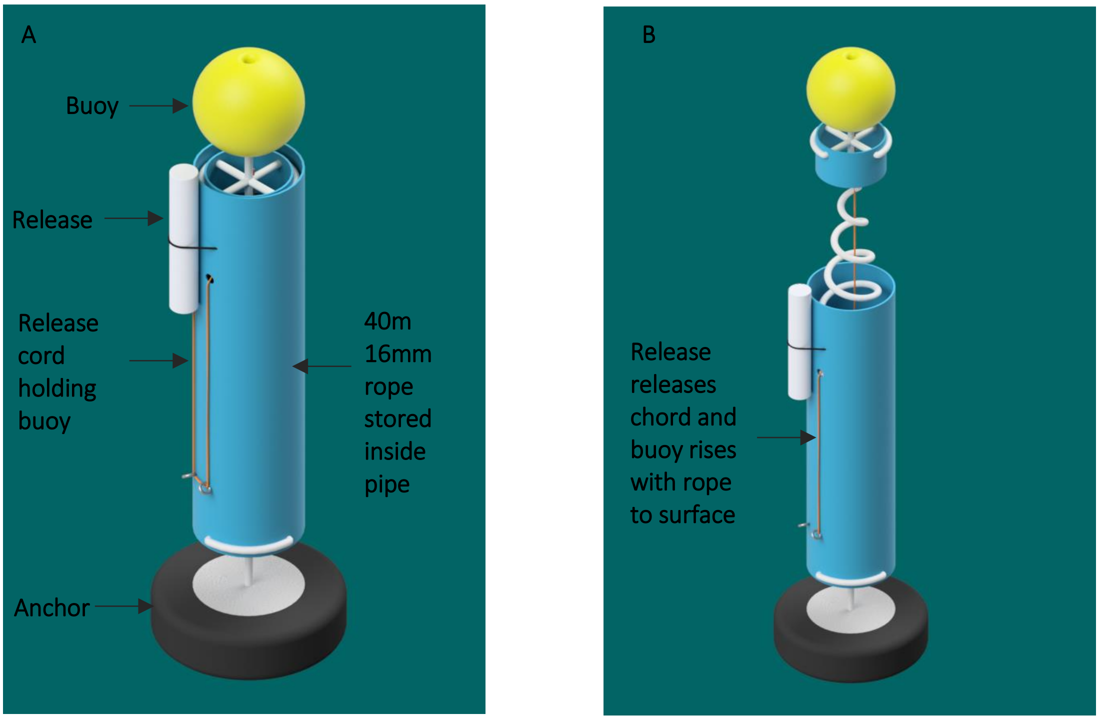

Figure 27: Pipe rope storage system. A) Stowed system. B) Buoy released and rising

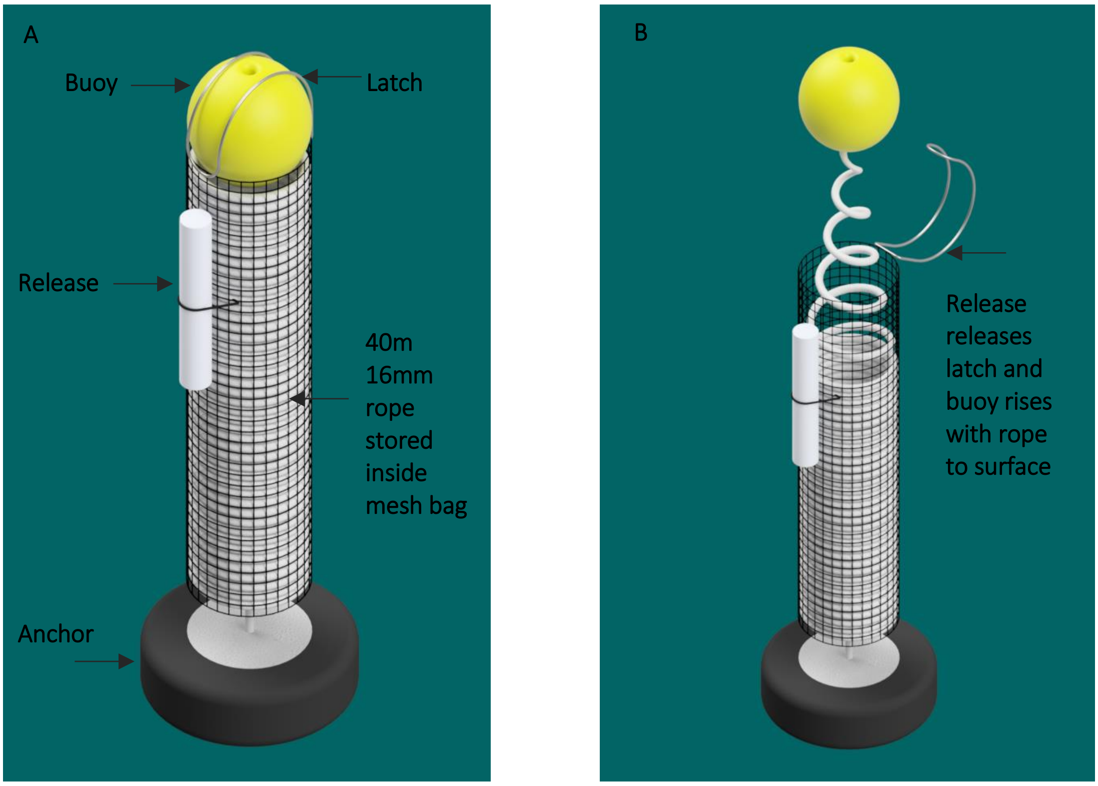

Figure 28: Bag rope storage system. A) Stowed system. B) Buoy released and rising

The rope storage systems were packed, the releases set, and the entire set-up dropped to the sea floor at a range of depths from 5 m to 35 m. A retrieval line was attached to the anchor in case of release failure. The electronic timed release had a minimum time-until-release of 8 minutes with a ±15 minute burn time once the time was reached. With a maximum working range of 300 m specified by the manufacturer, the acoustic transmitter was submerged and activated from 300 m away from the acoustic release and the distance slowly reduced until the buoy was observed to have surfaced. After each release, the gear was inspected for wear and tear before the rope storage system was repacked. Repacking of rope was timed to measure efficiencies of the different systems.

Results

Ground Lines

Un-tensioned test results

Three un-tensioned tests were conducted where 26 rope arcs were measured. **Table 11** below shows the descriptive statistics from these tests.

Table 11: Descriptive Statistics from the three un-tensioned rope tests. (n = 26)

Statistic	Arc height (m)
Mean	5.477
Max	8.8
Min	2
Standard Deviation	1.535
Median	5.3

Tensioned test results

One tensioned test was conducted where 10 arcs were measured. Using the rope tensioning technique, we were able to eliminate rope arcs between the traps. Only the rope between the final trap and the anchor weight formed an arc as the final anchor dropped off and could not be tensioned. This final arc was 2.6 m high.

Catenary

Using equation 1 and the measured distances between the traps, the arc height could be predicted using the catenary equations. These correlated very closely with the measured values (**Figure 29**). The slope lay between 0.97 and 1.13, and the confidence interval of the intercept lay between -0.74 and 0.16, indicating no difference from an intercept of zero and a slope of 1.0.

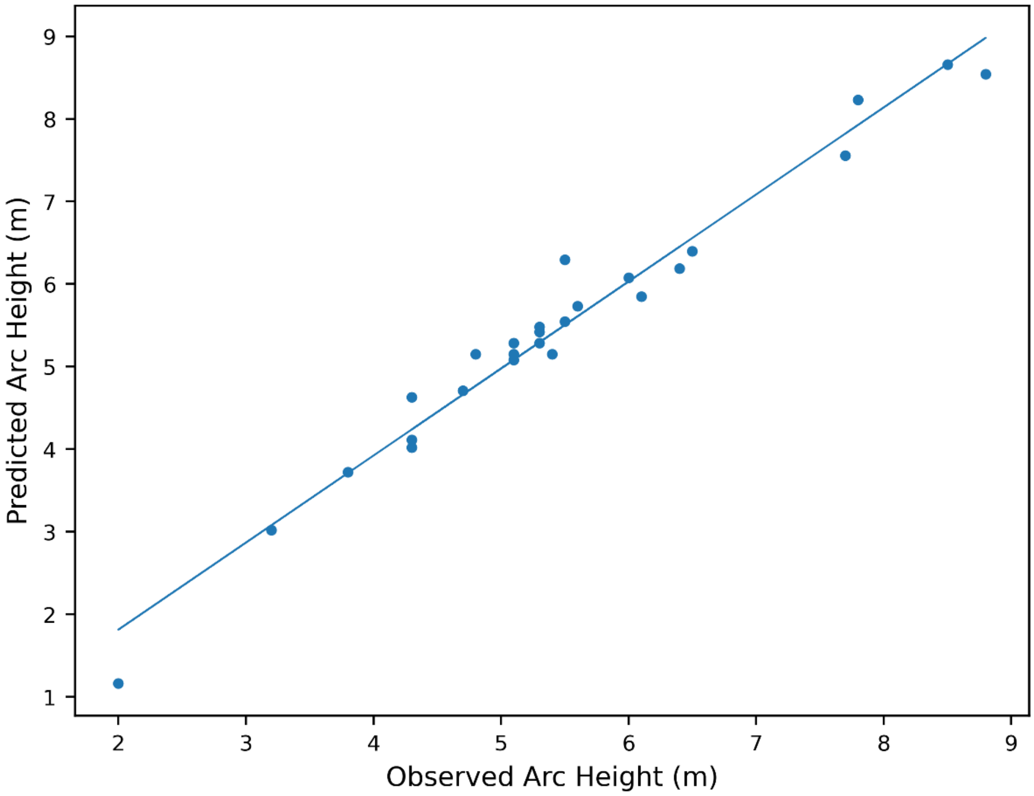

Figure 29: A scatter plot of predicted vs observed arc heights, with a regression line: Predicted = 1.05 x Observed - 0.29. The upper and lower 95% confidence intervals of the regression coefficient was 0.97 and 1.13.

Mean arc height from anchor coordinates

Knowing the length of the line, the distance between the two anchor weights when set could be used to determine the amount of slack in the line. The distance was calculated from the anchor coordinates using the package geopy 2.0.0 with its distance.distance attribute. This distance could then be divided by the number of rope arcs to get a mean arc distance (distance between the traps). Using the catenary equation, the mean arc height could then be calculated (**Table 12**).

Table 12: Results showing the predicted mean arc height using GPS coordinates of anchors compared to the mean measured arc height of each test.

Test	Actual line length (m)	Line length from Coords (m)	Predicted arc height (m)	Mean measured arc height(m)	Difference (m)
1	200	122.108	7.467	7.473	0.006
2	200	164.005	5.090	5.352	0.262
3	200	175.689	4.670	4.491	-0.179
4	200	233.249	0.540	0.300	-0.240

To test the significance of the difference between the predicted and measured arc heights, a linear regression was performed between observed arc height and predicted arc height. These correlated very closely with the measured values (**Figure 30**). The slope lay between 0.85 and 1.24, and the confidence interval of the intercept lay between -1.24 and 0.78, indicating no difference from an intercept of zero and a slope of 1.0.

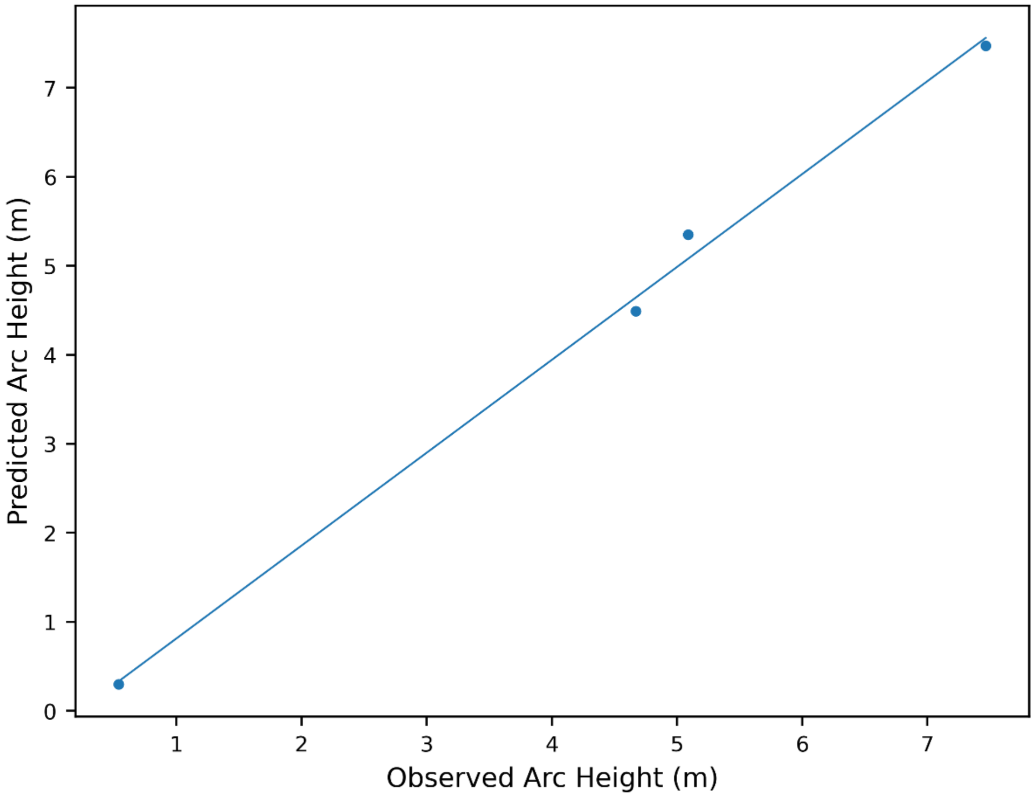

Figure 30: A scatter plot of predicted vs observed arc heights, with a regression line: Predicted = 1.04 x Observed - 0.23. The upper and lower 95% confidence intervals of the regression coefficient was 0.85 and 1.24.

Mean potential arc height from lines set by octopus vessel lingwane

According to the captain of the lingwane, each line had 25 traps, each approximately 24 m apart (measured between bollards in the harbour) (**Table 13**).

Table 13: Results of arc height prediction for different anchor separations for 4 lines set by octopus vessel lingwane.

Line	Line Length (m)	Anchor Distance (m)	Mean arc height (m)
1	624	665.300	<0.001
2	624	562.603	4.541
3	624	591.087	3.349
4	624	553.385	4.849

Minimum threatening arc height

Since the Bryde's whale is the smallest of the significant species, it would be used to determine the minimum arc height in which it could become entangled. Judging from its profile (**Figure 31**), the ratio of maximum breadth to length is approximately 0.13. Therefore an 8 m juvenile Bryde's whale's back would be approximately 1 m from the sea floor when swimming along the bottom. The backs of Adults 15 m long would be approximately 2 m off the seafloor. This suggests that a juvenile could get under any rope over 1m off the seafloor while anything over 2 m could pose a threat to adults. Floating rope trap lines almost always exceed the critical height of 1m (**Figure 32**).

Figure 31: Bryde's whale profile (NOAA, 2018), showing height of 8 m juvenile when swimming along the seafloor.

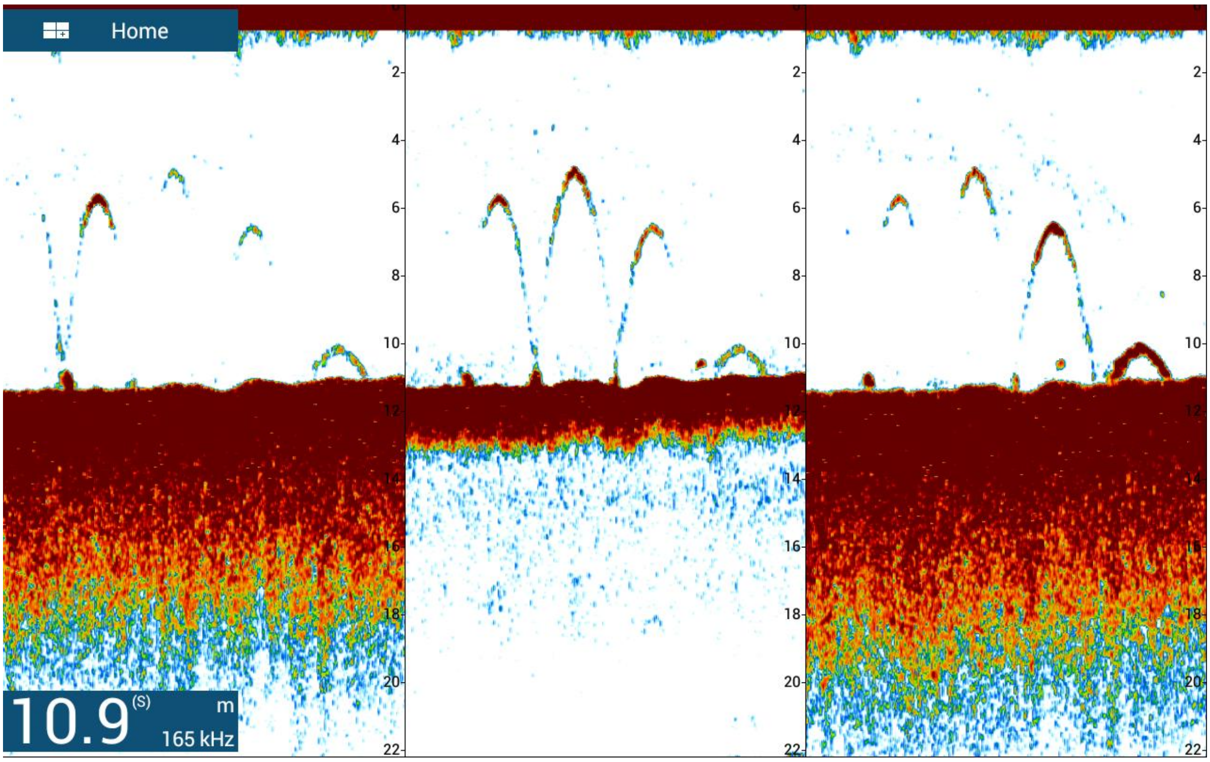

Figure 32: A multibeam sounder trace of a floating rope trap line. The images are vertically exaggerated, but the scale indicates the height of arcs (m). The three panels show the same arcs captured by tranducers on the port side, centreline and starboard side.

Sinking ground line

The sinking line tethered between traps does not bury in the sand after 15 days (**Figure 33** and **Figure 35**).

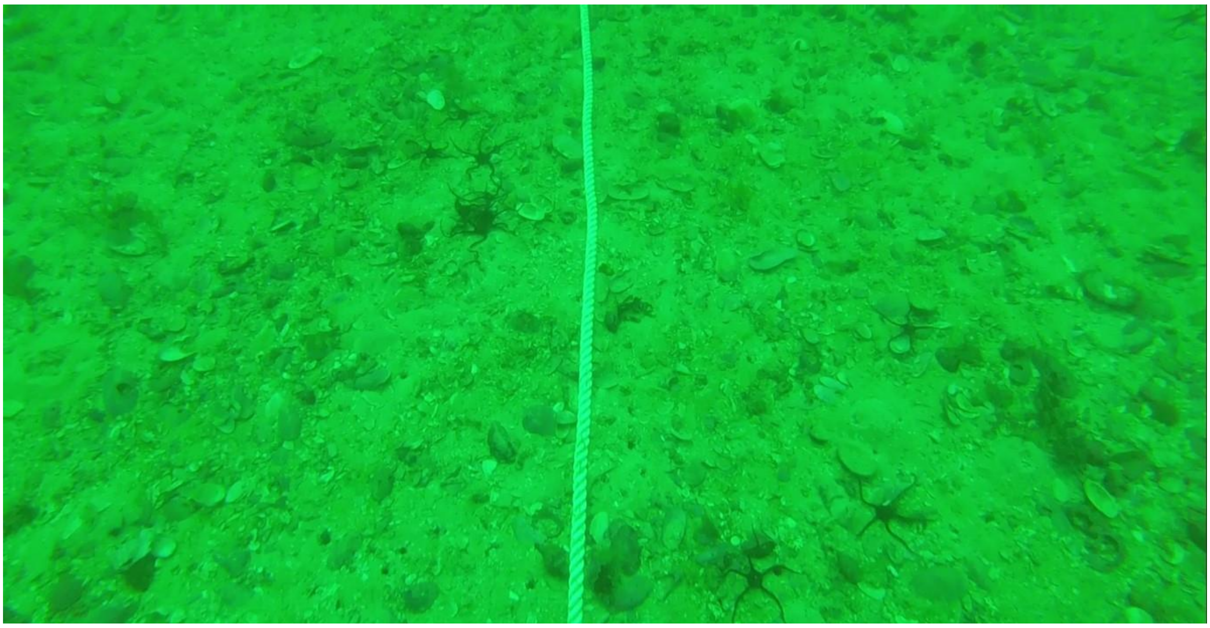

Figure 33: Image of sinking line after spending 5 days on the seafloor at 15m depth in False Bay.

Figure 34 shows an image of a section of a line set by the octopus vessel Iingwane. It shows no tendency to bury.

Figure 34: Image of a section of a line set by the octopus fishery

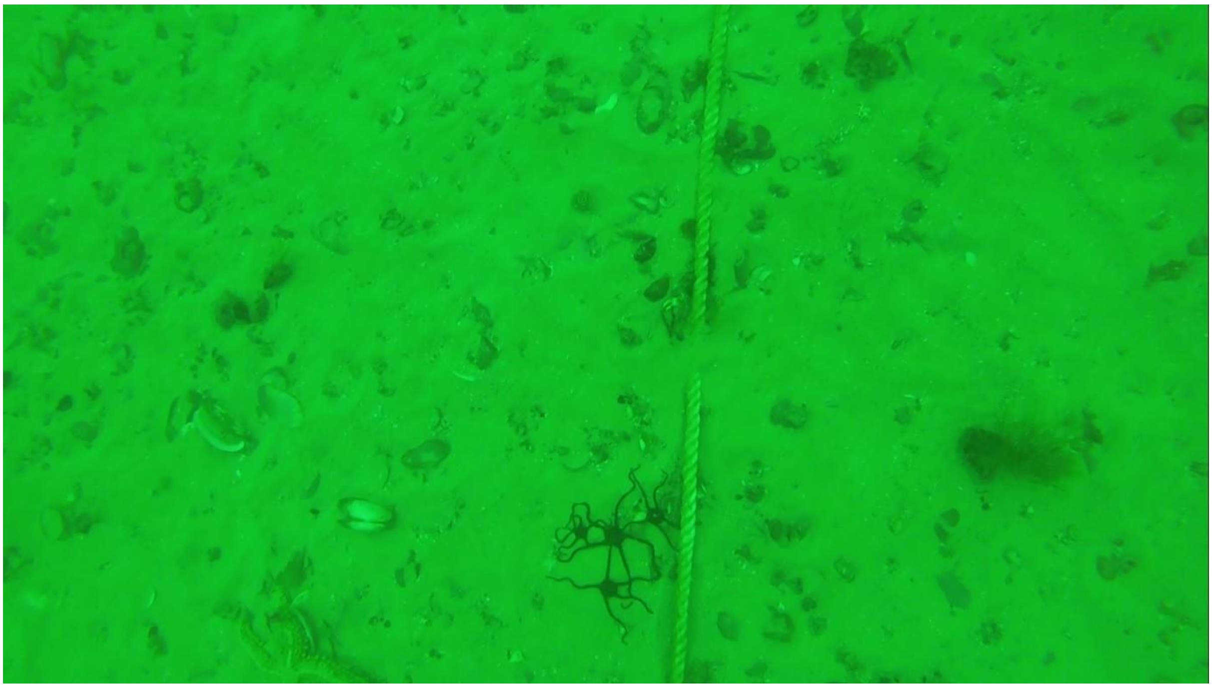

Figure 35: Image of sinking line after spending 15 days on the seafloor at 15m depth in False Bay.

Buoy Lines

Galvanic timed releases (GTRs)

A total of 60 GTRs of varying sizes were tested in batches of 10 at a time, five on each rig. The release times were always less than the rated release times, by a large margin. Temperature will affect release time, which is important because the mean ambient temperature exceeded the rated temperature by a fraction of a degree in four out of the seven cases (**Table 14**). Nevertheless, even the three for which the mean temperature fell within the rated range fell short of the rated release time. The CV of the release times averaged 5.7% (**Table 14**).

Table 14: Results of galvanic timed release tests. Shortfall is the mean hours below the rated release time that the GTRs released, and Release range is the difference in hours between the first and last release in each batch.

GTR	Rated temp Range (°C)	No. Tested	Mean release time (h)	Shortfall (h)	Release range (h)	Mean temp (°C)	CV release time	CV temp
1 Day – A4	11–15	10	13.417	10.583	1.467	15.278	0.036	0.020
1 Day – A4	11–15	10	13.338	10.662	2.483	15.744	0.055	0.035
1 Day – A5	15–21	5	18.247	5.753	2.000	15.095	0.048	0.007
5 Day – E5	12–15	10	76.392	43.608	10.350	15.639	0.054	0.011
5 Day – E5	12–15	10	78.132	41.868	19.717	15.609	0.078	0.021
7 Day – G7	16–20	10	127.883	40.117	25.233	16.757	0.057	0.016
7 Day – G7	16–20	5	126.377	41.623	17.250	16.565	0.071	0.023

Temperature variation positively affected release time variation. An increase in the CV of temperature resulted in an approximately doubling of the CV of the release time (**Figure 36**).

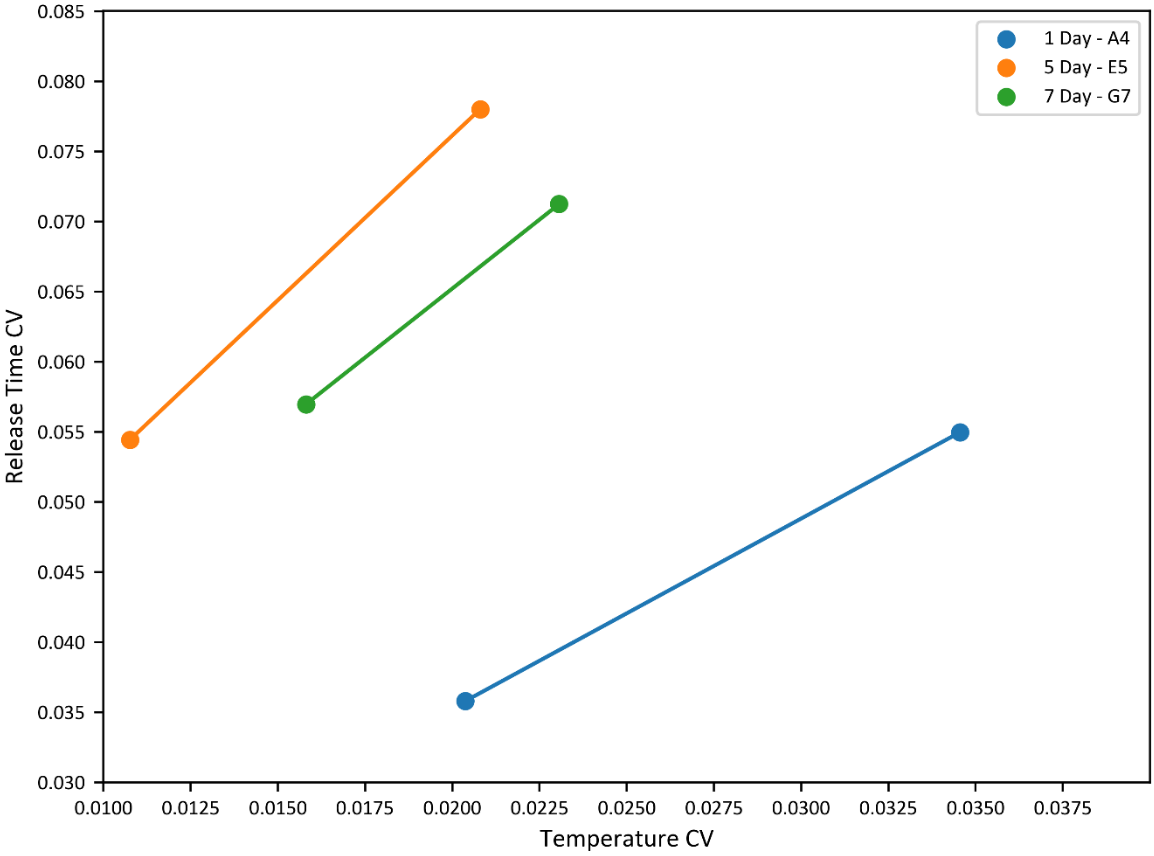

Figure 36: A plot of coefficient of variation of GTR release time against the coefficient of variation of temperature. Each instrument's data are identified by colours.

Acoustic and electronic timed releases, and rope storage systems

A total of 20 tests were done for both storage systems with the ETR and acoustic release. The electronic timed release coupled with bag storage never failed (**Table 15**). The acoustic release failed on three occasions, but the pipe storage never failed (**Table 16**).

Table 15: Electronic timed release and bag storage systems reliability results (1 indicates successful release, 0 indicates failure). Reset times were not measured for all releases.

	Electronic Timed Release				
	Depth (m)	**Release**	**Bag Release**	**Reset Time**	**Location**
1	5	1	1		Harbour
2	15	1	1		False Bay
3	15	1	1		False Bay
4	15	1	1	7:03	False Bay
5	15	1	1	7:40	False Bay
6	16	1	1	8:32	False Bay
7	16	1	1	8:10	False Bay
8	16	1	1	6:15	False Bay
9	25	1	1	7:43	False Bay
10	25	1	1		False Bay
11	5	1	1	7:12	Harbour
12	5	1	1	9:54	Harbour
13	5	1	1	6:51	Harbour
14	5	1	1		Harbour
15	5	1	1		Harbour
16	5	1	1		Harbour
17	5	1	1		Harbour
18	5	1	1		Harbour
19	5	1	1		Harbour
20	5	1	1		Harbour

Table 16: Acoustic release and pipe storage system reliability results. (1 indicates successful release, 0 indicates failure). Reset times were not measured for all releases.

	Acoustic Release					
	Depth (m)	**Release**	**Pipe Release**	**Trigger Distance (m)**	**Reset Time**	**Location**
1	5	1	1	5		Harbour
2	5	1	1	5		Harbour
3	5	1	1	5		Harbour
4	15	1	1	50		False Bay
5	15	0				False Bay
6	15	1	1	227	5:12	False Bay
7	15	1	1	370	8:00	False Bay
8	15	1	1	380	8:15	False Bay
9	35	1	1			False Bay
10	20	0				False Bay
11	20	0				False Bay
12	5	1	1	10	6:34	Harbour
13	5	1	1	10	6:03	Harbour
14	5	1	1	10	4:41	Harbour
15	5	1	1	10	4:38	Harbour
16	5	1	1	10	4:21	Harbour
17	5	1	1	10		Harbour
18	5	1	1	10	4:48	Harbour
19	5	1	1	10	5:15	Harbour
20	5	1	1	10	4:31	Harbour
21	5	1	1	10	4:20	Harbour
22	5	1	1	10	4:25	Harbour
23	5	1	1	10		Harbour

Discussion

Ground Lines

Based on the analysis of the profile of the Bryde's whale, a conservative minimum threatening arc height of 1 m was determined. Therefore, any arc above 1 m high should be considered a threat to whales.

The un-tensioned rope tests showed the worst case scenario when it comes to setting lines. Arcs have a mean height of 5.6 m, with some reaching as high as 8.8 m above the seabed. The minimum measured arc height of 3.2 m is still well above the 1 m threat limit and therefore setting floating line without tensioning would produce arcs between the traps in which whales could become entangled.

The tensioned test showed that tensioning the rope while deploying can eliminate arcs in floating ropes. This only applies when the rope is tensioned to such an extent that the anchor is dragged (as was observed during the test), and does not include the potential arc between the last trap and the second anchor, which cannot be tensioned as it is dropped off the vessel. As seen in the last arc of the tensioned test, this could be up to 2.6 m in height. This suggests that although tensioning reduces the number of potentially threatening arcs, there is still a potential for a sufficiently high arc between the last trap and the anchor to pose a threat to whales.

The purpose of determining the accuracy with which the catenary equations could predict the mean arc height was to determine the mean arc height in lines set in the octopus industry without having to dive and measure them ourselves. This would be done using GPS coordinates of the anchors at the ends of the line, trap separation distances and the number of traps per line, all supplied by the fisherman. Using the un-tensioned rope tests, the catenary equations were found to be able to predict the arc height.

Having been given the number of traps per line, the distance between each trap, and the GPS coordinates of the drop points of the anchors at the ends of 4 lines by the captain of the octopus vessel Iingwane, I was able to run the numbers through the model to predict potential mean arc height for each of the lines. One line was sufficiently tensioned that arcs would have been eliminated in all but the final arc between the last trap and the anchor. The other three lines show potential mean arc heights of 4.5 m, 3.5 m and 4.9 m respectively, all high enough to pose threats to whales. This suggests that the tensioning technique they deploy is insufficient. This could be due to the length of the line; as more line runs out, the weight increases and it becomes more and more difficult to drag the anchor, until it becomes impossible. Their lines are more than triple the length of my test line, so this is very likely the case. Longer lines also stretch further than shorter lines, further reducing tensioning effects as it pulls back when the last anchor is released. Another explanation for the high mean arc heights could be inaccuracies in the total line length, as this was based off the number of traps and the distances between them. This too is plausible as trap distances were measured between bollards in the harbour. However, for the model to predict arc heights of zero, the distance between the traps would have to be reduced from 24 m (the measured distance between the bollards) to 21 m, a measurement error of 3 m, which is too high to be likely.

The mean arc height prediction from the model is conservative as it is calculated over the whole length of the line. In practice the arcs will increase in size as tensioning becomes more difficult, resulting in increasingly bigger arcs approaching the last anchor. Over time the line between the anchors will reach an equilibrium, the tension in the first section pulling back some of the slack in the last. Even so, the minimum mean arc height it could reach would be that predicted by the model.

In cases where a line is set perpendicularly to a current, no amount of tensioning will prevent the force of the current from pulling the traps together, and thereby creating slack in the line; a situation where the rope between the traps is longer than the distance between them.

Due to the threat of fishery closure should whales become entangled in their gear, the octopus fishery in False Bay have changed to sinking line between all traps and have eliminated buoy lines since the beginning of 2020, relying on grappling to retrieve their gear. This means that even though their lines do not seem to be sufficiently tensioned, there will be no arcs between the traps, therefore eliminating the threat posed to whales. The concern of sinking rope becoming sufficiently buried in sediment seems unfounded. The image of the line after 5 days on the seafloor shows no covering whatever. After 15 days, small sections are seen to be covered in a thin layer of sediment but these would not be sufficient to effect grappling or provide any significant hold on the rope. Since the lines are typically pulled every 7 days, the evidence suggests that burial in sediment would not occur. It is possible that higher levels of sedimentation could occur in rougher weather but not to the extent to affect grappling or line retrieval, or that it would cause unacceptable damage to benthic macro fauna.

Removal of Buoy Lines

Galvanic timed releases (GTRs)

Two factors of importance are the accuracy of the release times when compared to their rated release times, and the variability in release times of GTRs of the same size. The concern here is that the vessel will have to be in position to receive the popped up buoy at the advertised time, but if that time is either biased or variable, then the vessel will waste valuable time.

As it turned out, all GTRs tested released prior to their rated release times. The 1 day – A4 GTRs released on average after 0.56 days, 56% of the way through their rated release time. The 1 day – A5 GTRs released on average after 0.76 days, 76% of the way through their rated release time. The 5 Day – E5 GTRs released on average after 3.22 days, 64% of the way through their rated release time, and the 7 day - E7 GTRs released on average after 5.30 days, 76% of the way through their rated release time. Differences in mean release times between each batch of the 1-day, 5-day and 7-day GTRs were 0.59%, 2.23% and 1.18%, respectively.

The high inaccuracies in the mean release time compared to the rated release time can be attributed to the nature of these devices. Although some were tested marginally outside their rate temperature range, all showed a bias, regardless of temperature. The fact that the two GTR sizes with the highest accuracies were the two which experienced mean temperatures within their rated ranges, suggests that, with further trialling, mean release times could be achieved to the desired accuracy. Discussions with the manufacturer revealed that the GTR sizing chart is used rather for guidelines than guaranteed release times. Since galvanic corrosion rate is affected by the chemical composition of the electrolyte (sea water), and different environmental conditions create different chemical compositions of sea water, a ‘trial and error’ based approach is needed to determine which size GTRs are suitable in specific regions. In one area, different sizes are often needed in different seasons. It is therefore not uncommon that I did not get good accuracy.

These data also suggest that it is unlikely that a ‘one-size-fits-all’ solution will be obtained for the rock lobster industry, as each fishing zone and each depth will have different conditions, which will affect release times. This is especially evident in the difference between the west coast and south coast rock lobster industries where the west coast fishery is dominated by the cold Benguela current and the south coast by the warm Agulhas current. Within the octopus fishery in False Bay, they are likely to need different sizes for different seasons and different sites as temperature can vary significantly between their fishing depths of 10 to 30 m.

Coefficients of variation of mean release times within batches of same size GTRs were also in the order of 0.057. Being in an upwelling zone, all the fisheries considered in our study will experience large fluctuations in temperature, between 9° and 18° C, which will reduce precision in release time to several hours, which I expect is unacceptable in terms of waiting time and conversely, entanglement risk.

The variability in release times of GTRs of the same size is of high importance when considering their utility to fisherman. For practical purposes, the fisherman needs to be certain that the GTRs have released before embarking to retrieve gear. Unreleased GTRs will waste valuable time and money making a second retrieval trip necessary, and early releases increase the risk of whale entanglements. It is therefore important that GTRs of the same size, operating in similar conditions, release within an acceptable range.

Entanglement risk will still be substantially reduced in the presence of release-time variation, but not by 100%. A reduction in the time a buoy line is in the water column would result in the same reduction in the probability of that buoy line entangling a whale. Using a 1-day release mechanism with no bias in release-time but a measured release-time CV of 6%, a skipper would need to delay retrieval for 4.3 hours after the 24 h interval has elapsed, to be 99% sure that the release has occurred. They would almost certainly delay recovery by that extent, because ship’s time is expensive. This means that for a 28.3 h period, the average time the buoy spends in the water is 24 h. The entanglement risk is therefore reduced by 84%, with a CV of 6%.

Therefore, correctly sized GTRs have the potential to reduce the time buoy lines spend in the water column by 84% at best, but if greater precision in release time is desired, the electronic methods will need to be used.

Electronic timed release (ETR) and bag rope storage system

The results of the reliability tests of the ETR and bag storage system tests showed that every one of the 20 tests were successful; both the ETR and the bag rope storage system released the buoy. The non-parametric binomial reliability demonstration test revealed that a sample size of 19 would demonstrate an 85% reliability if no failures were encountered. Since this was the case for both the ETR and the bag rope storage system, they can both be assumed to be at least 85% reliable.

Nine of the 20 tests were conducted in locations in False Bay identical to those fished by the octopus fishery, at varying depths from 15 m to a maximum of 25 m. On observation of a video of the ETR releasing, a potential snagging point was identified on the release zip-tie if the zip-tie is not set correctly. This emphasised the importance of ensuring the release was setup correctly before deployment, thereby ensuring that negligence does not result in a failure to release. As was expected, the depth had no effect on the ETR or the rope storage mechanism. Unlike the acoustic release, once set, the ETR is not reliant on a signal from the boat, being self-contained and therefore less likely to be affected by environmental conditions when releasing.

A total of nine reset times were recorded, showing a mean of 7 min 42 sec. Although the bag could be repacked in approximately 2 min 30 sec, the resetting of the ETR took the most time. This was due to the setup of our particular ETR which demanded it be taken off the bag to be reset. Resetting involved removing the ETR from the bag, unscrewing the burnt release link, replacing it with a new one, and screwing the link back on. Occasional difficulty would be encountered while trying to get the new release link into place and this resulted in the higher rest times seen.

The only visible wear on the ETR device was salt encrusting on one of the electrode wires. This occasionally resulted in a failed reset when setting the release time, but this could be solved with a small rub of the connection wires and wasted no more than 20 seconds.

Acoustic release and pipe rope storage system.

Three of the acoustic release tests failed. The acoustic release was designed to have a 1 hour sleep period after releasing in which it will not trigger if it receives the acoustic signal. This was not known at the time of the first failure and this was the reason the failure occurred; the acoustic release was triggered before 1 hour had elapsed since its last release. Failures 2 and 3 were determined to be related to the alternating current (via a 400W inverter) supplied to the on board acoustic transmitter which resulted in the transmitter failing to transmit the acoustic signal. Once rectified, no further failures were encountered, and since they were not failures of the devices, but rather operator error, they were discarded from the reliability test. The results show that every one of the 20 tests were successful; the acoustic release and the pipe rope storage system released the buoy. Since no failures were encountered, they can both be assumed to be at least 85% reliable.

Eight of the 20 tests were conducted in locations in False Bay identical to those fished by the octopus fishery, at depths varying from 15 m to a maximum of 35 m. Although the manufacturer specified range was 300 m, we did trigger a release from 380 m. As fisherman capture the GPS coordinates of both ends of their lines, and modern GPS systems usually have accuracies of approximately 5 m, it is reasonable to assume that they would be able to get within 300 m of the device to trigger the release. This same logic applies to the potential of a reduced acoustic range in rough seas; the vessel should always be able to get close enough to trigger the release.

A total of 10 reset times were recorded, showing a mean of 5 min 27 sec. Although the pipe, as with the bag, could be repacked in approximately 2 min 30 sec, the resetting of the release took the remaining time. The reset time decreased with practise and when plotted, a linear regression showed a negative gradient (n = 13, r = 0.705). This suggests that with practise, this reset time could be further reduced. Having observed the fishing process on board an octopus vessel, there would be ample time for a crew member dedicated to the resetting of the rope storage system and release to complete this task while the traps are being emptied and rinsed before redeployment.

No visible wear and tear were noticed on inspection of the acoustic release or the pipe storage system. However, due to the design of the pipe storage system, the full buoyancy force of the buoy was held by the release mechanism of the acoustic release. This was observed to bend the burn wire, in one instance pulling it out when it was not secured in place properly. Although it held during all deployments, this puts unnecessary strain on the device and needs to be considered when choosing a design to be used in industry. This again emphasises the importance of ensuring the release is setup correctly before deployment.

Due to the threat of fishery closure should whales become entangled in their gear, as of 8 December 2020 the Octopus fishery in False Bay are trialling 10 ropeless fishing systems using acoustic release mechanisms with the bag rope storage system developed in this study. Five deployments and retrievals have taken place so far. Of nine systems set, only five released on the first retrieval, approximately two weeks after deployment. Seven out of nine released after the second deployment, and seven out of eight released on the third. Six out of 10 released on the forth retrieval and nine out of 10 released on the fifth. These data show that time is necessary for the fishermen to familiarise themselves with these ropeless fishing systems, and that efficiencies will increase with practise. As with my tests, the failures seem to be operating error (such as uncharged releases or triggering the releases out of range) rather than component failure. Of the unreleased systems, all were fully intact when retrieved suggesting that the rope storage systems hold up in commercial conditions. The unburnt release wires on the acoustic releases also confirm that the releases were not triggered rather than a snag in the rope storage system. An unforeseen issue is the difficulty in finding the released buoy at the surface in rough seas. This should be considered when developing future designs.

Conclusion

The results of the ground line rope tests confirmed that the use of floating rope as ground line will produce arcs between traps of sufficient height to pose threats to whales. Although rope tensioning techniques may reduce the number and height of arcs between traps, the increased weight and drag of a longline reduces the effectiveness of tensioning. A model was developed using catenary curves to predict the mean arc height from the GPS coordinates of the ends of each line, effectively comparing this separation distance with the actual length of the rope to determine the amount of slack in the line. The model was found to be able to predict mean arc height accurately. Coordinates of anchor points from four lines set by the octopus fishing vessel lingwane were then run through the model which showed that only one line was sufficiently tensioned to eliminate arcs between traps. The remaining three showed potential mean arc heights of 4.5 m, 3.5 m and 4.9 m, respectively, all well above the 1 m potential threat limit. This confirmed that their line tensioning techniques are insufficient, most likely due to the length of the line.

Sinking line was shown to be effective in eliminating arcs between traps and tests revealed that concerns of burial of sinking line to the extent that grappling and retrieval is effected is unfounded. Under the threat of fishery closure in the event of whale entanglements, the octopus fishery have been using sinking ground line since the beginning of 2020 and have eliminated buoy lines, using grappling to retrieve their lines. This resulted in the elimination of arcs between traps, as seen by divers when one of their lines was found running across one of my test sights.

Three types of releases were tested for use in ropeless fishing systems, namely Galvanic timed releases (GTRs), an electronic timed release (ETR), and an acoustic release. The objectives of the tests were to determine whether they are reliable enough to be utilised by fisheries. The GTR test results of 1-day, 5-day and 7-day releases revealed that all sizes released earlier than their ratings. However, due to the regional variation of the chemical composition of seawater, it is typical that a ‘trial and error’ approach be necessary to obtain mean release times that fall within the desired window. Since a reduction in the time buoy lines spend in the water column would reduce the probability of it entangling a whale, the variation in release times of GTRs of the same size confirmed that their release time ranges were sufficient to reduce buoy line time, and therefore entanglements, by 84%.

The electronic timed release (ETR) and acoustic release, and the bag rope storage system and pipe rope storage system all demonstrated 85% reliability, as revealed by the non-parametric binomial reliability demonstration test. No wear and tear was visible on either of the devices apart from some salt build up on one of the electrodes on the ETR which was easily removed. It was noted that the full force of the buoy should not be held directly by the release device as this puts unnecessary load on its release mechanism. The importance of ensuring the release is setup correctly before deployment is crucial to ensuring a successful release.

Trialling of the bag rope storage systems with the acoustic release by the octopus fishery has shown that time is necessary for fishermen to familiarise themselves with these systems. As with this study, failures seemed to be the result of operator error rather than components failure and success rates are improving with every trial. The deployments of the systems have demonstrated the ability of the bag rope storage system to withstand commercial conditions.

When considering the massive cost disparity among the release mechanisms, the industry will need to consider the advantages and disadvantages of each system. GTRs cannot offer the release time precision of the electronic devices. The timing is pre-set in the mechanism. The electronic release gives the skipper the choice of selecting the release time, but once deployed, it can no longer be changed.   Only the acoustic release can offer release on demand. Concerns about reliability, and technical failure are likely to follow the reverse trend. Electronic devices will require a level of training that might presently not be found among the crew of South Africa’s trap fishing boats.

Chapter 4: Fishery economics

Introduction

Whale entanglement by trap fisheries can largely be averted by the use of ropeless fishing techniques. Ropeless fishing will require new hardware and a change in the way fishing gear is set and retrieved, with a greater reliance on electronic technology than before. These reforms will cost the industry. In this report I examine the costs of ropeless fishing in relation to estimates of cost and revenue in South Africa's three trap fisheries, to gauge the financial impact, and with it, the likely resistance to such reforms. I also consider the value of a whale and the costs of entanglement, in relation to the costs of ropeless gear.

The most lucrative of the South African trap fisheries is the west coast rock lobster fishery (WCRL). It has an estimated market value of over R335 million per annum in 2017/18 for the offshore and nearshore fisheries combined (South African Fisheries, 2018). The embattled fishery has suffered massive stock losses of the last 100 years, and the mature stock is now only 2% of its pre-exploitation value. The current TAC of 837 tons is the lowest on record. Among the difficulties in managing the fishery is the fact that poaching in this sector is rife.

The south coast rock lobster fishery (SCRL) employs larger vessels, and operates further offshore than WCRL. The SCRL TAC has averaged around 360 tons over the last decade. SCRL had a market value of R311 million in 2016. The industry supports about 300 jobs (South African Fisheries, 2016). Being offshore, poaching is less of a concern in this fishery, but ghost fishing is problematic.

The octopus fishery is an emerging fishery in South Africa. With the price per kg of octopus being approximately 8.5 Euros, the earnings for 2018 based on landings of 34 tons would be 289 000 Euros (or R5.08 million at current exchange rates).

Whales have value too, even when they are not harvested. The conservative estimate is $2 million (Chami *et al.*, 2019), or R28 million at current exchange rates. Presently, the three trap fisheries pose a threat to whales, by way of entanglement with gear. Losses of whales to trap gear have been estimated. Estimates of the cost of removing stranded carcasses are also available. Presently, the state pays these costs and the economies of the world absorb the cost of lost whales. We will consider the application of the user-pays principle and suggest that the cost of the fishing, which includes the damage it causes, should be absorbed by the industry. When viewed in this way, we will compare the cost of the ropeless gear to the cost of entanglement.

Cost estimates

To determine feasibility of ropeless fishing techniques in South African Trap fisheries, the fishing costs needed to be determined. Costs incurred by fisherman include permit costs, port fees, crew wages, gear costs and maintenance, vessel costs and maintenance, and marketing costs of catch. Permit costs were obtained from the Department of Environment, Forestry and Fisheries(DEFF, 2019). Port fees were obtained from the Transnet Tariff Book (TRANSNET NATIONAL PORTS AUTHORITY, 2020).

Fishing equipment is assumed to have a life span of 5 years and the vessels 20 years. **Table 17**, **Table 18**, and **Table 19** show the vessel specifications that were used for the octopus, WCRL and SCRL fisheries respectively.

Table 17: Octopus fishing vessel specifications.

Octopus fishing vessel		
Vessel length	15	m
Vessel Weight	25	ton
Engine size	300	hp
Fuel consumption	800	l/trip
Fuel price	15	R/l
Average haul	40000	kg
Trips	30	per year
Crew	7	people
Number of lines	36	
Number of traps	2700	
Equipment lifespan	5	years

Vessel specifications for the octopus fishery were obtained from the vessel owner Garry Nel (**Table 17**). Average haul was the approximate catch of 2018 as the 2019 season was not completed due to fishery closure. Each of the 36 lines comprised of 25 cradles of 3 traps per cradle. Crew wage estimates were made after consulting vessel owner Garry Nel of the octopus fishery. Gear costs were estimated based on current market prices of various gear types. Vessel running costs were estimated using the FAO's Fisherman's Workbook(Prado, 1990) and confirmed through communication with Garry Nel. The market value per kg was set at 8.5 Euros per kg for octopus after communication with Garry Nel.

Table 18: WCRL trap fishing vessel specifications

WCRL fishing vessel		
Vessel length	15	m
Vessel Weight	25	ton
Engine size	300	hp
Fuel consumption	800	l/trip
Fuel price	15	R/l
Average haul	15880	kg
Trips	30	per year
Crew	7	people
Number of lines per vessel	36	
Number vessels in fishery	100	
Equipment lifespan	5	years

Information on costs in the WCRL fishery were obtained through communication with a fishing vessel operations manager, Michael Stowe (**Table 18**). The average haul was calculated by dividing the average TAC over the past 5 years with the number of vessel operating in the fishery, given as approximately 100 vessels for the WCRL fishery (Personal communication, Danie van Zyl, Department of Environment, Forestry and Fisheries). The market value per kg was then used to estimate annual income based on annual catch estimates for each fishery. This was set at R454 per kg for rock lobster based on TAC and value of catch figures from 2018 (South African Fisheries, 2018).

Table 19: SCRL fishing vessel specifications

SCRL fishing vessel		
Vessel length	30	m
Vessel Weight	50	ton
Engine size	800	hp
Fuel consumption	121.429	l/h
Fuel price	15	R/l
Average haul	41250	kg
Operating hours	4296	per year
Crew	16	people
Number of lines per vessel	16	
Number vessels in fishery	8	
Equipment lifespan	5	years

Information on costs in the SCRL fishery were obtained from Norman *et al.*, 2018 (**Table 19**). Average haul was calculated by dividing the average TAC over the past 5 years with the number of vessel operating in the fishery. Marketing costs were estimated after personal communication with the owner of a rock lobster processing plant who is involved in the processing and exporting of rock lobsters. The market value per kg was set at R866 per kg for rock lobster based on TAC and value of catch figures from 2016 (South African Fisheries, 2016).

Costs (negative) and revenue were summed to calculate the profitability of each industry.

Results

Depending on the gear options, ropeless fishing systems would cost between R 40 000 and R150 000 to implement (Table 20). Although the acoustic release was the most expensive once off, the electronic timed release would result in a more expensive option due to the type of release link it uses and the high price of these links. However, since the commencement of this project, Sub Sea Sonics have developed a low cost electronic timed release specifically for ropeless fishing systems (TR4RT) which does not require links or a programming unit. It is far cheaper than the TR-45 I tested, costing just 300 USD (±R4300) each. Thirty six of these would work out to approximately R33 000 per year with a five year life span, which makes them the cheapest option of all. However, if GTRs were chosen to be implemented, they could easily be manufactured locally for a fraction of the price and the expense of shipping would be eliminated. A local foundry gave an approximate price of R15 per GTR (excluding drilling and tapping which adds considerable cost but could be done by fisherman), resulting in a total cost of R18 000 per year (Personal communication, Protea Foundry and Engineers).

For each of the three fisheries I took the view that the economic entity was the fishing vessel rather than the right holder or vessel owner. Fishing operations are complex economic entities. A company might own a fishing right and a vessel in the simplest scenario, but other scenarios include multiple vessels per right holder, or multiple right holders fishing off one vessel. The vessel owners and right holders might not be the same company. I have simply viewed the vessel as the heart of the operation, regardless of the complexities of ownership, as all the costs are covered by the value of the catch and the vessel operations are essential for producing the catch. How the excess revenue (‘profit’) is dissipated from that point is not included in this analysis, but I accept that further losses may be important. For example, some land-based operational costs (including administrative staff) have not been included, but these costs will depend on the size of the right holder company and associated economies of scale. I am therefore not suggesting that the value I term ‘profit’, the difference between total cost and revenue generated by a typical vessel in the fleet, in any way reflects real profits by the industry. I have obtained cost estimates of vessel operations, and I have estimated the value of the catch landed by an average vessel in the fishery. My intention rather was to scale the costs of the new gear in relation to total costs and revenue, to get an idea of the financial burden that will be imposed by a transition to ropeless fishing. I listed our estimates knowing that adjustments might need to be made if either my estimates are incorrect or the current scenarios change.

Table 20: Ropeless fishing system costs per year.

Ropeless Fishing Costs				
Technology	Cost	unit	Quantity	Cost/yr
Releases				
Galvanic Timed Releases - International Fishing Devices				
Galvanic Timed Release	R43.17	per unit	1080	R46 623.60
Shipping	R2 000.00	per shipment	1	R2 000.00
				R48 623.60
Acoustic Release - Desert Star Systems				
ARC-2 Release	R18 050.00	per unit	36	R649 800.00
STM-4 Deck Unit	R76 000.00	per unit	1	R76 000.00
Shipping	R10 450.00	per shipment	1	R10 450.00
				R147 250.00
Electronic Timed Release - Sub Sea Sonics				
Release	R3 021.90	per unit	36	R21 757.68
Deck Unit	R9 353.50	per unit	1	R1 870.70
Release link	R215.85	per unit	1080	R233 118.00
Shipping	R10 000.00	per order	1	R2 000.00
				R258 746.38
NEW Sub Sea Sonics ETR				
Release: TR4RT	R4 317.00	per unit	36	R31 082.40
Shipping	R10 000.00	per shipment	1	R2 000.00
				R33 082.40
Locally manufactured GTRs				
Galvanic Timed Release	R15.00	per unit	1080	**R16 200.00**
Rope Storage				
Mesh	R574.70	per item	36	R4 137.84
Pipe	R548.10	per item	36	R3 946.32
Sinking rope	R4 232.00	per 220 m coil	100	**R84 640.00**

The octopus vessels generates approximately R2 million in profits (**Table 21**). The most expensive option of electronic timed releases paired with a mesh bag rope storage system would reduce this profit by approximately 15% per year. The least expensive option of the GTRs would reduce profits by approximately 3% per year. Looking at these figures alone, ropeless fishing seems feasible in the South African octopus fishery. Ropeless fishing will increase costs by 4.2%, for the acoustic release option.

Table 21: Octopus fishery yearly expenses and income.

Expenses			
Description	**Cost**	**unit**	**Cost/year**
Port Fees	R600.00	per month	R7 200.00
Permits			
Commercial fishing permit	R3 300.00	per year	R3 300.00
SAMSA certifications	R3 000.00	per 2 years	R1 500.00
	R5 000.00	per year	R5 000.00
Labour			
Crew commission	R2.00	per kg	R480 000.00
Captain salary	R12 000.00	per month	R144 000.00
Captain commission	R5.50	per kg	R220 000.00
Deck Boss	R3.00	per kg	R120 000.00
Marketing			
Catch processing	R10.00	per kg	R400 000.00
Freeze and storage			
Ship container freight			
NRC Health Certificate	R737.00	per shipment	R1 474.00
Certificate of Origin	R200.00	per shipment	R400.00
Boat running cost			
Boat Value incl. equipment	R6 000 000.00	per vessel	R300 000.00
Fuel	R7 500.00	per trip	R225 000.00
Insurance	R10 000.00	per month	R120 000.00
Maintenance	R400 000.00	per year	R400 000.00
Gear			
Sinking rope	R4 232.00	per 220m coil	R83 101.09
octopus trap	R1 960.00		R1 058 400.00
Buoy	R250.00	per buoy	R18 000.00
Total			**R3 587 375.09**
Income			
Catch	R149.26	per kg	R5 970 400.00
Profit per vessel			**R2 383 024.91**

Although the market price per kg for west coast rock lobster is higher than octopus (R450 per kg compared to R150 per kg), this market value is not seen by the vessel owners as permit holders pay vessel owners a fraction of the market price for their haul (**Table 22**). The permit holders are then responsible for packaging and shipping the catch. Since the vessel owners would be responsible for gear costs, it is their expenses that are of concern. With annual profits of approximately R240 000, the inclusion of ropeless fishing techniques would cut their profits by more than 50% for the acoustic option, or 20% for the least expensive GTR option. With the declining WCRL stock and the uncertainty of the future of the fishery, ropeless fishing does not seem feasible in the WCRL fishery. However, with the reductions in price of locally manufactured GTRs, ropeless fishing techniques become feasible, costing 7% of annual profits, or increasing costs by 1.3% for the local manufactured GTR option.

Table 22: WCRL vessel owner yearly expenses and income.

Expenses: Vessel Owner			
Description	**Cost**	**unit**	**Cost/year**
Port Fees	R600.00	per month	R7 200.00
Labour			
Crew commission	R17.00	per kg	R269 960.00
Captain salary	R12 000.00	per month	
Captain commission	R8.00	per kg	R127 040.00
Boat running cost			
Boat value incl. equipment	R3 000 000.00	per vessel	R150 000.00
Fuel	R12 000.00	per trip	R360 000.00
Insurance	R5 000.00	per month	R60 000.00
Maintenance	R400 000.00	per year	R400 000.00
Gear			
Floating rope	R1 584.70	per 220m coil	R28 524.60
Lobster trap	R200.00	per trap	R1 440.00
Buoy	R150.00	per buoy (Alibaba)	R1 080.00
Total			**R1 405 244.60**
Income			
Catch	R103.50	per kg	R1 643 580.00
Profit per vessel			**R238 335.40**

As a well-managed fishery with stable stocks, very limited entry and few vessels, the south coast rock lobster (SCRL) fishery is more profitable than the other two fisheries. These profits would be affected by as little as 2% with the implementation of the most expensive ropeless fishing technique (**Table 23**). The fishery costs will increase by 0.4% for the acoustic release option. Ropeless fishing techniques are therefore economically feasible in the SCRL fishery.

Table 23: SCRL vessel owner yearly expenses and income.

Expenses			
Description	Cost	unit	Cost/year
Port Fees	R1 200.00	per month	R14 400.00
Permits			
Commercial fishing permit	R3 300.00	per year	R3 300.00
SAMSA certifications	R3 000.00	per 2 years	R1 500.00
	R5 000.00	per year	R5 000.00
Labour			
Crew commission	R3.00	per kg	R3 712 500.00
Captain salary	R20 000.00	per month	R240 000.00
Captain Commission	R15.00	per kg	R618 750.00
Marketing			
Packaging to airport	R54.00	per kg	R2 227 500.00
Airport Freight	R66.00	per kg	R2 722 500.00
NRC Health Certificate	R737.00	per shipment	R22 110.00
Certificate of Origin	R200.00	per shipment	R6 000.00
Boat running cost			
Boat Value incl. equipment	R12 000 000.00	per vessel	R600 000.00
Fuel	R1 821.43	per hour	R7 824 857.14
Insurance	R20 000.00	per month	R240 000.00
Maintenance	R800 000.00	per year	R800 000.00
Gear			
Floating rope	R1 584.70	per 220m coil	R50 710.40
Lobster trap	R200.00	per trap	R128 000.00
Buoy	R150.00	per buoy	R480.00
Total			**R19 217 607.54**
Income			
Catch	R866.00	per kg	R35 722 500.00
Profit per vessel			**R16 504 892.46**

An entanglement that results in the death of a whale not only results in the loss of the whale's financial value but also a cost to the local government as waste management services are needed to clear the carcass from coastal areas. These operations usually include the use of heavy earth moving equipment such as front end loaders, as well as a 30 ton flatbed truck to transport the carcass. Based off estimates from daily hiring rates, this amounts to approximately R10 000 per entanglement death. According to the data supplied by the SAWDN, there has been an average of 1 entanglement death per year since 2006.

There are also costs of disentanglements carried by the SAWDN. In response to entanglements, the SAWDN send out a 6.5 m Rhib accompanied by a bigger safety vessel, both of which use duel engines, using approximately 150 l of fuel during a 5 hour disentanglement (Personal communication, Mike Meyer, South African Whale Disentanglement Network). This is R4500 per entanglement at R15/l fuel. With an average of 14 entanglements per year for the past 5 years, that equates to an approximate R63 000 per year.

Although great whales have been valued at 2 million USD (R28 million), this value would not be to one country alone but rather to all countries who benefit from the ecosystem in which it lives. According to the International Whaling Commission, the primary range of African humpback populations extend from Morocco in the north west to Tanzania on the east coast (International Whaling Commision, 2021). Since humpbacks are the most numerous and have the biggest range, a conservative estimate of the value per country can be obtained from their range. Twenty eight countries (including islands) occur between Morocco and Tanzania. Dividing the whale value by 28 countries results in a value of approximately 71 000 USD per country, or approximately R1 million. Regardless of how the cost is treated, the costs of an entanglement are greatly dominated by the estimated value of a whale (**Table 24**).

The estimated annual costs due to entanglements in each of the three fisheries' gear, based on entanglement frequencies and frequencies of mortality recorded by the SAWDN, are R352 700, R85 033 and R487 933, for the WCRL, SCRL, and octopus fishery, respectively (**Table 25**). These estimates depend on the likelihood of discovering entangled whales, which is naturally highest for the inshore fisheries (octopus) and lowest for the offshore fisheries (SCRL).

Table 24: Summary of cost estimates resulting from whale entanglements.

Incident	Cost
Whale disentanglement	R4500
Whale death due to entanglement	R1 000 000
Whale carcass removal	R10 000

Table 25: Annual frequency of whale entanglements and deaths (2006 – 2020) and estimated cost to South Africa.

Fishery	Entanglements	Deaths	Cost
WCRL	5.933	0.267	R352 700.00
SCRL	1.267	0.067	R85 033.33
Octopus	1.467	0.467	R487 933.33

Discussion

My preliminary cost analysis suggests that in none of the three fisheries will the preferred ropeless fishing solution push up costs by more than 4.2%. Many of the costs and the revenue earned on exports are highly variable due to the volatility of South Africa's currency, and due to fluctuations in demand for specific seafood products, which means that fairly wide confidence intervals should be placed on these estimates.

Fishing companies, like any other business, will naturally try to keep costs down, and would also not readily change a practice that has been successful over many decades. Resistance to ropeless fishing is to be expected. A policy change will be needed to remove the hazards to whales.

I recognise two broad possible policy options that the fishery management authority can adopt and impose on fishers, in the light of evidence that whale entanglements are caused by fishing operations. The first is that the rules of fishing are altered to ensure that ropeless fishing techniques (of one form or another) become mandatory and that every step be taken to reduce the risk of entanglement. The second is that the fishers use gear that are well marked with the name of the vessel, and that each right holder is fined an amount equivalent to the cost of a whale for each proven entanglement in its gear.

In the first option we are expecting the industry to take reasonable steps to avoid entanglement, but the state will continue to absorb the cost of entangled whales. In the second, the costs of entangled whales are passed to the industry. In each of the three fisheries, the cost of ropeless fishing is less than the cost of whales that become entangled in the gear of that fishery.

A potential management strategy to incentivise fisherman to reduce whale entanglements would be the implementation of the 'user pays' principle into the WCRL, SCRL and octopus fisheries. This principle states that "all resource users should pay for the full long-term marginal social cost of the use of resources and related services including any associated treatment cost"(Dommen, 1993). What this means is that fisherman would be liable for the costs associated with entanglements, i.e. disentanglement costs from the SAWDN, costs associated with clearing of whale carcasses when necessary, and the value of a lost whale.

A successfully implemented user-pays principle will surely result in ropeless fishing becoming widely adopted in the trap fisheries, without further rule-making, but for the reasons we offer below I believe that option 1 might be preferable.

The first reason is that all fisheries cause damage, and that there is no precedent for passing these costs on to the fishers. Common accusations are that purse-seiners remove forage fish from seabirds, trawlers damage the seabed, gill-nets entangle birds and turtles, recreational anglers pollute reefs with their lost terminal tackle, etc., but in no case are the fishers expected to make good for their damages. It would also be very difficult to place a fair value of any of the impacts listed above. The costing of a whale might prove to be an exception, but to apply a policy to one fishing sector and not all is likely to invite a challenge.

The second reason is that not all entangled whales will be found and where they are found, the guilty vessel might not be easily identified. In other words, the allocation of costs will not be done fairly.

The third reason is that fishers will more likely ensure that their gear is unidentifiable, rather than invest in expensive mitigation.

Finally, a fine equivalent to the loss of a whale might be a deterrent, but the money will not compensate for the loss. Such money could be channelled to the SAWDN, for example, and so help future entangled whales, but it is unlikely to compensate the real victims (not the whale, nor those people who suffer from their loss).

I therefore contend that ropeless fishing should become a mandatory method of fishing in all trap fisheries, and this is indeed the path that has been followed by DEFF in the octopus fishery. After a temporary suspension of fishing in 2019, fishers were expected to adjust their gear to remove hazards posed by that fishery. At least one right holder responded immediately, judging that cost was outweighed by the right to continue fishing.

A right holder in the octopus fishery in False Bay is trialling 10 ropeless fishing systems using acoustic releases with the bag rope storage system developed in this study. As a single entanglement of Bryde's whale will result in fishery closure, the fisherman is unwilling to take any risks. The use of GTRs or electronic timed releases were deemed unacceptable due to the uncertainty in retrieval times as a result of weather. Fishing with sinking ground line and using grappling to retrieve gear have limited their fishing grounds to sandy bottom locations for the past year. With the use of the ropeless fishing systems, they hope to get back to the rocky/reef locations that have been inaccessible until now. By implementing ropeless fishing in stages, they will be able to spread the cost over a number of years until they are fully ropeless. Alternatively, they may deem grappling adequate for sandy bottom sites and invest only in a few ropeless fishing systems for the rocky/reef locations. Either way, the octopus fishery seem to have made ropeless fishing with acoustic releases feasible.

The WCRL industry do not have the option of grappling as each trap is on a single buoy line, and typically deployed on reef. This means that if ropeless fishing became a legal requirement, they would have to modify all of their traps, a large capital investment that could strain the industry.

Most commercial fisheries overseas use ropeless fishing systems with timed releases (GTRs and ETRs) for years before moving to the more complicated acoustic option. This enables fisherman to become familiar with the systems and develop them to best suit their needs. It would therefore be more practical to gradually implement ropeless fishing systems with the use of GTRs. The time between setting and retrieval being only 24 hours in the fishery, 1-Day GTRs would suffice and, as demonstrated, would be able to reduce buoy line times by 84%, potentially reducing entanglements by the same percentage. It is unknown whether more entanglements occur during the day or during the night, but if whales are able to detect lines visually (as shown by Kot *et al.*, 2012) and therefore at greater risk during night, the use of GTRs could further reduce entanglements by eliminating buoy lines during hours of darkness.

The absence of buoy lines has a further advantage of discouraging poachers. The WCRL scientific working group (SWG) estimates the total exported poached rock lobster to be between 718 and 1018 tons (Oceana Group Limited, 2019). This is very close to the 2019 TAC of 1084 tons for the legal fishery. This suggests that by reducing poaching potential, commercial fisheries could significantly improve their profits.

I see no economic impediment to the adoption of ropeless fishing in the SCRL fishery.

Conclusion

Data on the expenses and income of South African trap fisheries suggest that ropeless fishing techniques are economically feasible in all trap fisheries. Each fishery will need a different set of gear types, but they should be affordable in each case. Estimates suggest that the appropriate ropeless fishing systems should push up costs by less than 5%. The cost increase is lowest for the SCRL fishery. The octopus fishers could, and have, started implementing acoustic release ropeless fishing systems. By implementing in stages, costs can be spread over multiple years, thereby avoiding cash flow issues that would make full scale implementation impossible.

Due to the structure of the WCRL, vessel owners do not benefit from the high market value of the lobsters, being paid 20% of the market value for their catch. This results in far lower profits for vessel owners in this fishery and might make the implementation of acoustic releases less feasible than in the other two fisheries. However, with the release of new electronic timed releases specifically designed for use in ropeless fishing systems, Sub Sea Sonics have made a feasible option which would cost just 3% of annual profits. The initial investment of 18% of annual profits should also be feasible by vessel owners. Should this prove too high, locally manufactured GTRs would prove a cheaper alternative that could reduce buoy line time by 84%, potentially reducing entanglements by the same percentage.

The simplicity of the GTR systems would also provide an opportunity for stakeholders to familiarise themselves with ropeless fishing techniques, enabling the development of systems to better suit their needs, before moving to acoustic systems if necessary. A similar approach may be beneficial in the SCRL fishery to avoid costly mishaps while trialling acoustic systems. The implementation of ropeless systems in the WCRL fishery could also benefit the fisherman by reducing poaching potential.

Due to the complexities of managing the implementation if the ‘user pays’ principle, I suggest a better option may be for the fishing authority to alter the rules of fishing to ensure that ropeless fishing techniques (of one form or another) become mandatory and that every step be taken to reduce the risk of entanglement.

Importantly, I find that the cost of ropeless fishing is less than the cost of entangling a whale. I recognise that all three trap fisheries are significant exporters that earn much needed forex. Their productivity should be supported. The unresolved problem is who should be expected to pay for the reforms?

Chapter 5: Conclusion

Whale entanglements in trap fishing gear in South Africa increased since 2006, despite an overall decrease in trap fishing effort. For entanglements in which the gear was identified, the WCRL, SCRL and octopus fisheries were responsible for 68%, 15%, and 17%, respectively. Among entanglements in which species were identified, humpback whale *Megaptera novaeangliae*, southern right whale *Eubalaena australis,* the Bryde's whale *Balaenoptera brydei* accounted for 64%, 25%, and 11%, respectively. Humpback whale entanglements increased over the whole South African coastline and in all trap fisheries. This increase was attributed to the aggregation of humpback whales in 'super-groups' off the west coast during summer months over the past decade. Southern right whale entanglements decreased since 2006 over the whole South African coastline and in the WCRL fishery. This decrease was attributed to the northern shift in foraging in the species over the past decade. Bryde's whale entanglements increased since 2006 over the whole South African coastline and in the octopus fishery. All Bryde's whale entanglements occurred in the past 6 years, which suggests a change in distribution of the species, and possible population growth. The octopus fishery posed the greatest threat to Bryde's whales.

All entanglements were found in areas of high fishing pressure. West coast fishing zone D was the area of highest concern as it was responsible for 90% of entanglements in the WCRL fishery and 55% all of entanglements reported from 2006 to 2020. The correspondence of entanglement hotspots with fishing effort hotspots suggest that entanglements may have occurred at the SCRL fishing hotspot at the southern tip of the Agulhas Bank, particularly with Bryde's whales, but due to its inaccessibility, were not reported by fisherman.

If seasonal or spatial closures are to be considered to reduce whale entanglements, the areas of highest concern are around Dassen Island and the Cape Peninsula on the west coast. However, fishing effort is unlikely to be affected by spatial or seasonal closures. However, since the temporary closure of the octopus fishing season in 2019, and the subsequent use of sinking line with no surface buoys, there have been no entanglements in octopus fishing gear up until the time of this report. These recent gear modifications might make the need for seasonal closures in the octopus fishery obsolete. The absence of recent entanglements in the octopus fishery is further evidence that buoy lines and floating rope pose the risk to whales.

The use of floating rope as ground line will produce arcs between traps of sufficient height to pose threats to whales. The drag of a longline with multiple traps reduces the effectiveness of tensioning. Sinking line was effective in eliminating arcs between traps. Concerns that the burial of sinking line to the extent that grappling and retrieval is affected are unfounded.

Three types of release mechanism were tested for use in ropeless fishing techniques, namely galvanic timed releases (GTRs), an electronic timed release (ETR), and an acoustic release. The electronic timed release (ETR) and acoustic release, and the bag rope storage system and pipe rope storage system, all demonstrated 85% reliability, where the importance of ensuring the release is setup correctly before deployment was found to be crucial to ensuring a successful release. The variation in release times of GTRs of the same size confirmed that their release time ranges were sufficient to reduce buoy line time in the water column by 84%.

Trials involving acoustic releases coupled with bag rope storage systems in the octopus fishery showed that time is necessary for fishermen to familiarise themselves with these systems, with deployment efficiencies improving with practise.

The expenses and income of South African trap fisheries suggest that ropeless fishing techniques are economically feasible in all trap fisheries. Estimates suggest that the appropriate ropeless fishing systems should push up costs by less than 5%.

Importantly I find that the cost of ropeless fishing is less than the cost of entangling a whale.

Whichever management approached or policy changes are decided upon, if stakeholders were involved in the research and development process, it is more likely that they will buy into an improved and more sustainable fishing method.

Future work should include the testing of a larger variety of ropeless fishing techniques in locations more representative of all relevant fisheries. A global standardized method of testing ropless fishing systems needs to be established.

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