Patterns in the landed catches and determinants of catch composition in the South African inshore trawl fishery

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ABSTRACT

The inshore trawl fishery, which nominally targets *Merluccius capensis* (shallow water hake) and *Austroglossus pectoralis* (east coast sole), has the second highest bycatch rate of all South African fisheries. For over one hundred years there has been concern about the sustainability of the harvests in this fishery. To enable effective management of the many species harvested, I aim to describe patterns in the effort, landed catches, catch composition, and bycatch rate in the inshore trawl fishery from 1990 to 2019. In a second analysis, I aim to determine the driving factors that influence landed catch composition in the fishery, with a specific focus on area and vessel effects, which can be used to improve management strategies.

The total size of the fishery has decreased from 40 vessels in 1990 to 15 vessels in 2019 and has a total bycatch rate of 36%. A total of 48 nominal species were recorded among the landings, but only thirteen made up 99% of the total landed catch composition by weight. Total effort and landed catch decreased by 70% and 62% respectively from 1990 to 2019, but bycatch rate increased by 22.7%. The landed catch per unit effort (cpue) of the landed target and bycatch species showed a cycle of increasing periodicity of five, six, eight, and nine years. Bycatch rates were 3% higher in trawls targeting *A. pectoralis* than those targeting *M. capensis* (t(df=284077) = 26.5, p <0.001). Bycatch rates were 3% higher during the day than at night (t(df= 86239) = 30.33, p <0.001). Bycatch rates were 12% higher in the depth group with the highest bycatch rates (90 to 100 m) than in the group with the lowest bycatch rates (110 to 120 m) (H = 4955.2, DF_{groups}= 5, P<0.001).

I tested whether the variation in landed catch composition among trips was due to the vessel or environmental influences, including year and season, using PERMANOVA models. Based on landed catch compositions, the years clustered into three groups at an 85% similarity (1990 to 1999, 2012 to 2015, and the remaining years in the period 2000 to 2019). The months clustered into three groups at a 94% similarity splitting the year into two almost equal halves, and then splitting the second half of the year into winter and spring. The vessels clustered into five groups at a 78% similarity. The inshore trawl grounds were divided into 20’ by 20’ grid cells, which were used to aggregate the trawls and clustered into six groups at an 87% similarity.

The landed catch composition per trip was influenced by the *vessel* (F(1, 21) = 32.7, $p < 0.001$, $R^2 = 0.31$), *year* (F(1, 29) = 16.0, $p < 0.001$, $R^2 = 0.21$), and *season* (F(1, 3) = 30.0, $p < 0.001$, $R^2 = 0.04$).

To test whether the variation in landed catch composition that was explained by the *vessel* was due to differences in vessels or differences in the areas trawled by the vessels, direct comparisons were made between landed catches of vessels fishing in the same area and the same year and season. The landed catch composition of five vessels was compared for two years, while 'simultaneously' operating in ten grid cells. The landed catch composition per trawl was influenced by the *grid cell* (F(1, 9) = 15.5623, $p < 0.001$, $R^2 = 0.12$), *vessel* (F(1, 4) = 25.2, $p < 0.001$, $R^2 = 0.08$) and *year* (F(1, 1) = 22.9, $p < 0.001$, $R^2 = 0.02$).

The *grid cell* has the largest measured impact on the landed catch composition. The grid cells in all clusters were grouped spatially, except for one grid cell in group four. Each group showed distinct species assemblages that could be used to tailor management strategies for bycatch in the fishery.

Vessel is an important factor in determining the landed catch composition of a trawl and has a greater effect than *year*. The ability to control the catch composition is posited to be a function of the fishers' skill level, the fishing strategy employed, the vessel specifications, and decisions regarding discarding and retention of bycatch species. Knowledge of the effect of the vessel on the landed catch composition implies that there is scope for targeting fisher behaviour when designing new mechanisms to control bycatch.

CHAPTER 1: LITERATURE REVIEW AND INTRODUCTION

Global catch

The global consumption of fish is increasing, outpacing both the rate of human population growth and red-meat consumption, and peaked at around 214 million tons in 2020 (FAO, 2022). Fisheries are therefore essential to global food security. However, as fisheries production has increased, the health of fish stocks has decreased (FAO, 2022). Since 1974 the proportion of fish stocks fished within biologically sustainable rates has decreased while the proportion of stocks that are overfished has increased (FAO, 2022).

Fish stocks fished within biologically sustainable rates have been linked to fisheries with robust management, highlighting the importance of effective management for a sustainable fishery (FAO, 2022). Where fisheries management is most often lacking is in the regulation of bycatch within a fishery (Alverson & Hughes, 1996). The bycatch of a fishery refers to that part of the catch that is not targeted or not managed (Davis, et al., 2009). That part of the bycatch that is dumped at sea is referred to as discards and the remainder is referred to as the landed bycatch.

Bycatch species are vulnerable to overfishing because target species are normally the most productive species caught by a fishery (Scheffer, et al., 2005). As the less productive bycatch species struggle to cope with the optimal fishing pressure set for the target species, their populations become depleted. Management of target species has been successful in increasing the number of maximally sustainably fished stocks (FAO, 2022). However, the management of bycatch species requires further improvement to decrease the proportion of global stocks that are overfished.

Bycatch is not in itself a problem. However, unmanaged bycatch can cause several issues depending on the species and fishery, including overfishing, degradation of the ecosystem, and conflict between fisheries (Crowder & Murawski, 1998; Kennelly, 1995; Scheffer, et al., 2005). When a bycatch species of one fishery is targeted by another, conflict around resource management and allocations can occur between the two fisheries. Discards are often extremely detrimental to the marine ecosystem (Bellido, et al., 2011) as species do not typically survive the fishing and discarding process. However, the landed bycatch that is marketed creates an incentive to target the bycatch, increasing the fishing pressure on these species and increasing the likelihood of overfishing (Bellido, et al., 2011).

Bycatch is one of the most pressing problems facing fisheries management (Beddington, et al., 2007). As all commercial fishing gear is unselective to some degree bycatch is an unavoidable component of all fisheries (Hall, 1996). Bycatch, therefore, represents a significant threat to the sustainability of the fisheries and the health of their ecosystems but is extremely hard to manage and avoid (Crowder & Murawski, 1998; Hall, et al., 2000).

Of all commercial fishing techniques, bottom trawling results in the highest proportion of bycatch (Pérez Roda, et al., 2019). Due to the highly unselective nature of trawl gear incidental catches of non-target species are common and the average bycatch rate for trawl fisheries globally was estimated at 40.4% (Davis, et al., 2009). However, bycatch rate is highly variable within trawl fisheries, and is dependent on a number of factors such as gear type, bycatch mitigation devices, location, and skipper behaviour (Roberson & Wilcox, 2021). With the bycatch rate ranging between more than 90% in some prawn trawl fisheries (Mendo, et al., 2022) and less than 5% in some krill trawl fisheries (Krafft, et al., 2023), it is important to understand the factors that determine both the bycatch rate, and composition within trawl fisheries.

The level of control that skippers have over the catch composition is hard to gauge, however many studies have suggested that the ‘skipper effect’ plays a large role in determining bycatch composition in many fisheries (Hilborn, 1985; Gaertner, et al., 1999; Marchal, et al., 2006). The ‘skipper effect’ refers to the ability of skippers to target or avoid certain species and control their catch composition through fishing behaviours (Costa, et al., 2008). Studies have shown that even within fisheries with highly unselective gears such as otter trawls, skippers were able to have a significant effect on their landings (Gaertner, et al., 1999; Roberson & Wilcox, 2021). Therefore, even in fisheries with unselective fishing gear, if the influence of the skipper on the bycatch can be understood then management can improve the sustainability of the bycatch landed by the fishery.

South Africa has a robust fishing industry with highly effective management (Cochrane, et al., 2007), however, there is still concern over the bycatch in some fisheries (Andrews, et al., 2015). Of the 22 fisheries sectors, the inshore trawl fishery has the second-highest bycatch rate of any South African fishery (Attwood, et al., 2011). There have been concerns over the bycatch in the inshore trawl fishery for over one hundred years due to the number of bycatch species landed in the fishery that are vulnerable and commercially valuable (Marchand, 1933).

History of the inshore trawl fishery

South Africa has twenty-two fishery sectors that are worth an estimated R6 billion annually (DEFF, 2020). The most valuable sector is the hake-directed demersal trawl fishery, made up of the inshore and offshore trawl fisheries (DEFF, 2020). The demersal trawl fishery in South Africa began with the arrival of the first survey trawl ship in 1897 (Payne, 1989). The fishery initially only targeted east coast sole (*Austroglossus pectoralis*) but following the end of World War One began targeting the more abundant Cape hakes (*Merluccius paradoxus* and *Merluccius capensis*) in addition to *A. pectoralis* (Payne, 1989).

The hake-directed trawl fishery expanded quickly, with the annual *Merluccius* catch increasing from 1000 t during World War One to 50 000 t by the 1950s (Payne, 1989). As news of the abundance of *Merluccius* around Southern Africa spread, many foreign trawling vessels arrived and in 1972 catches of *Merluccius* in the South-East Atlantic peaked at 1.115 million tonnes (Payne, 1989). Overfishing led to a collapse of the *Merluccius* stocks and a subsequent drop in catch rates (Payne, 1989).

In 1977 South Africa established its exclusive economic zone (EEZ), preventing foreign vessels from fishing within 200 nautical miles of the South African coast (Payne, 1989). The removal of foreign vessels resulted in an almost immediate 25% decrease in effort in the *Merluccius* fishery, which, coupled with TAC control, resulted in increased catch rates for *Merluccius* by the 1980s (Payne, 1989; DEFF, 2020).

In 1978 the hake demersal trawl fishery was split into two management components: the offshore trawl fishery, which targets deep-water hake (*M. paradoxus*), and the inshore trawl fishery which targets shallow-water hake (*M. capensis*) and *A.*

pectoralis (Payne, 1989; DEFF, 2020). The inshore trawl fishery is assigned 6.2% of the annual hake total allowable catch (TAC) and the total TAC for *A. pectoralis* (Stewart & Japp, 2019).

The inshore trawl fishery is based out of Mossel Bay and Port Elizabeth, operating between the Great Kei River on the east coast and Cape Agulhas on the south coast. Trawls for *M. capensis* occur throughout the inshore trawl grounds, while trawls for *A. pectoralis* generally take place between 20 and 22 degrees east, known as the sole grounds (Japp, et al., 1994).

Bycatch in the inshore trawl fishery

The inshore trawl fisheries bycatch rate is estimated at 42% using observer records of total catch and consists of an estimated 137 species (Attwood, 2011). The main concerns with the bycatch in the inshore trawl fishery are the large catches of vulnerable and commercially important species, and conflicts with the other fisheries in which these species are targets (Attwood, 2011; Visser, 2015). The inshore trawl fishery's catch composition is impacted by both its gear and the area over which it operates. The fishery uses otter trawls, which are unselective fishing gear, known to result in high levels of bycatch and operates over the highly biologically diverse Agulhas Bank (Davis, et al., 2009). The Agulhas Bank has many distinct habitats that support a large diversity of species and fisheries (Japp, et al., 1994).

Bycatch in the inshore trawl fishery is made up of many commercially important species, primarily teleosts (Attwood, et al., 2011; Walmsley, et al., 2007; Booth & Hecht, 1998). Many of the bycatch species are themselves targets of other fisheries and may experience high combined fishing pressure (DEFF, 2020). As a result, eight of the twenty bycatch species that make up 98% of the inshore trawls catch by weight are listed between vulnerable and critically threatened (Griffiths, 2000; Brandao, 2021). However, the lack of accurate stock assessments for many bycatch species suggests that this number could well be higher (IUCN, 2020).

Species such as *Argyrozona argyrozona* (carpenter), *Argyrosomus inodorus (S*ilver kob*)*, *Pterogymnus laniarius* (Panga), and *Rhabdosargus globiceps* (White stumpnose) are target species in the linefishery but are also caught in similar or greater proportions in the inshore trawl fishery as bycatch (Attwood, et al., 2011). The inshore trawl fishery also operates over the nursery grounds of *A. inodorus,* and the resulting bycatch often contains juveniles below the legal-size limit in the linefishery (Japp, et al., 1994; Attwood, et al., 2011). The high bycatch in the inshore trawl fishery, often of individuals below the minimum size and age limits in the adjacent handline fishery, has created conflict between the two fisheries and could be a factor in the slow recovery in many of the stocks (Visser, 2015).

The hake trawl fishery is one of only two fisheries in Africa to be certified by the Marine Stewardship Council (MSC, 2022). As most of the European markets will only accept fish from MSC-certified fisheries, it has become especially important for fisheries that wish to export their catches to these markets to maintain certification (Lallemand, et al., 2016). As the hake trawl fishery exports around 80% of its catches to European markets and would lose as much as 36% of its value without the MSC certification, maintaining the certification has become an important consideration in its management (Lallemand, et al., 2016). Bycatch in the inshore trawl fishery has been identified as an area of concern, and improvements in bycatch management are a pre-requisite for future accreditation of the fishery by the MSC (MSC, 2022).

Bycatch management poses a challenge in the inshore trawl fishery as the catches are diverse and the determinants of the bycatch are as yet not well studied (Walmsley, et al., 2007; Attwood, et al., 2011; Attwood, 2012). Successful bycatch management requires an understanding of the bycatch in a fishery and the determinants of the bycatch (Beddington, et al., 2007). Understanding the determinants of bycatch, management can regulate catches of bycatch species that are over fished or experiencing excessive fishing pressure, without negatively impacting the target catches and therefore the profit and sustainability of the fishery.

Management of the inshore trawl fishery

The inshore trawl fishery is managed by catch and effort limits (Stewart & Japp, 2019). Catch limits include total allowable catch (TAC) and individual company quotas for the two target species *M. capensis* and *A. pectoralis* and precautionary catch limit (PCL) restrictions for several bycatch species (DAFF, 2010). Due to the difficulty in distinguishing between the two *Merluccius* species they are managed as one stock (DEFF, 2020), although the deep-sea hake *M. paradoxus* is not caught on the inshore grounds.

The TAC for *Merluccius* is calculated using the operational management plan (OMP), developed in 1991 and regularly updated and revised (de Moor, et al., 2022). The OMP is a set of guidelines requiring the yearly assessment of the *Merluccius* stocks which is then used to set an annual TAC (Rademeyer, et al., 2008). There is one combined TAC for both species which is then split between the four fisheries that target *Merluccius* in South Africa: offshore trawl, inshore trawl, hake longline and hake handline (DEFF, 2020). Within each fishery, the subdivided TAC is then further split into individual quotas and distributed amongst rights holders.

For *A. pectoralis* the TAC was unchanged at 872 t from 1991 to 2016 (DEFF, 2020). After 2016, due to a decline in *A. pectoralis* catch per unit effort (CPUE), the TAC was reduced to 600 t and effort restrictions were put in place (DEFF, 2020). The stock subsequently showed signs of recovery, allowing the TAC to be increased to 627 t in 2019 (Stewart & Japp, 2019). All vessels in the inshore trawl fishery are awarded quotas for *Merluccius* and *A. pectoralis* (DAFF, 2010).

Catch regulations for bycatch species in the fishery include fishery-wide PCLs, bycatch reserves, per trip catch limits and a ‘move-on’ rule for some of the most important bycatch species (Attwood, 2012). *Genypterus capensis* (kingklip) and *Lophius vomerinus* (monk) have PCLs of 3905 t and 7972 t respectively (DFFE 2021). When setting the *Trachurus capensis* (horse mackerel) quota for the midwater trawl, a 12500 t bycatch reserve is kept for bycatch in the demersal trawl fisheries (DFFE 2021)(DAFF, 2010). Neither the PCLs nor the bycatch reserve has been exceeded since their implementation (DFFE 2022)(DAFF, 2010; Attwood, 2012).

A vessel’s catches of *Argyrosomus inodorus* (silver kob), *G. capensis* and *L. vomerinus* are restricted to its average catch of the species over the period 1998 to 2002, or 80% of historical catches in the case of *A. inodorus* (DFFE 2021). However, the lack of concrete historical catch values makes comparisons difficult and increases the difficulty of applying and enforcing these regulations to new entrants to the fishery (Attwood, 2012).

A. inodorus, G. capensis, and *Thyrsites atun* (snoek) are managed through a 'move-on' rule (DAFF, 2010). A move-on rule requires vessels to move five nautical miles from a fishing area if more than a pre-determined amount of the species is caught. However, whether the vessel must vacate from the start or end position of the trawl is unclear (Attwood, 2012).

Effort control in the fishery includes a limit on sea days for each rights holder, gear restrictions, and closed areas (DEFF, 2020). Effort restrictions are used to increase compliance with catch restrictions and to reduce targeting of bycatch species once quotas for target species have been exhausted (Attwood, 2012). The number of days a rights holder is permitted to fish is calculated based on their *Merluccius* and *A. pectoralis* quotas (Attwood, 2012).

Gear restrictions include limiting inshore trawl vessels to a maximum length of 35 m and a maximum engine power of 1000 bhp, which effectively limits them to depths less than 120 m, although there is no official limit to the depth a vessel is permitted to trawl (Stewart & Japp, 2019). The mesh size is limited to 90 mm for hake-directed trawls and 75 mm for *A. pectoralis* directed trawls (DAFF, 2010). Mesh size is limited to reduce the bycatch of non-target species and juvenile target species.

Area restrictions limit vessels to the area between the Great Kei River and Cape Agulhas (DAFF, 2010). There are also several marine protected areas (MPAs) and closed bays that reduce the size of the inshore grounds. The main MPAs which affect the fishery are Bird Island, De Hoop, Tsitsikamma, and one seasonal closure off Port Elizabeth during the spawning season of *Genypterus capensis* (kingklip) (Attwood, 2012; DEFF, 2020).

The inshore trawl fishing industry has also committed to limiting their trawl footprint by creating a ring fence initiative whereby they only trawl in areas that had been trawled historically to limit the damage to the benthic environment. (DEFF, 2020). The 'trawl ring fence' initiative was initiated in 2015 and further reduces the size of the inshore grounds (DAFF, 2010; DEFF, 2020).

The present system used to allocate fishing rights in the inshore trawl fishery is the Long-Term Rights Allocation Management Process (LTRAMP) (DAFF, 2010). Rights are assigned to companies on a competitive basis, allowing them the right to catch a quota or a 'base percentage' of *Merluccius* and *A. pectoralis* each year. The base percentage is then applied to the TAC for the target species to calculate the mass each rights holder is permitted to harvest. The rights holders are split into three groups.Of the hake quota 70% is shared between rights holders in the first group, and the remaining 30% is divided between the other two groups (Greenston & Attwood, 2013). Rights are valid for ten years and were re-allocated in 2015 for a further ten years (Stewart & Japp, 2019).

Although the rights allocation process is meant to be settled in one year, the 2015 rights allocation process lasted close to three years due to legal challenges surrounding the original allocation. In 2015 the number of rights holders in the fishery was increased to 37 but after an appeal process in 2019, it was brought down to the current 27 rights holders (Feike, 2020). There are currently fifteen group A, six group B, and six group C rights holders in the inshore trawl.

Previous studies have shown that the inshore trawl fishery has a relatively low discard rate of 10% when compared with similar fisheries globally (Walmsley, et al., 2007; Davis, et al., 2009). The low discard rate has been attributed to the high marketability of the bycatch (Attwood, et al., 2011; SADSTIA, 2019). Fisheries management traditionally strives for the lowest possible discards (Bellido, et al., 2011). However, in multi-species fisheries such as the inshore trawl fishery, it is always difficult to manage the catches of multiple, diverse species to ensure their sustainability, while also ensuring regulations do not encourage an increase in discards (Bellido, et al., 2011; Attwood, 2012).

Previously bycatch management has attempted to reduce the bycatch rate in a fishery and increase the selectivity of catches (Alverson, 1999). However, increasing the selectivity of catches can be more detrimental to the ecosystem than a well-managed and controlled harvest of all components of the ecosystem (Bellido, et al., 2011). Removal of only select species and size classes can cause imbalances in the ecosystem which harms all species and ultimately the fisheries (Hall, et al., 2000). Therefore, balanced harvests have become a more common management strategy in, thereby minimizing the effects on the ecosystem as well as any one species (Cochrane, et al., 2007; Zhou, et al., 2019).

However, while a more diverse catch is encouraged, a lack of regulations for all species can create incentives to maximize bycatch for profit, especially if the bycatch includes commercially valuable species (Leslie, 2004). Targeting unmanaged bycatch can lead to a large amount of undocumented biomass being intentionally removed from the marine environment with unknown consequences for the ecosystem (Davis, et al., 2009). Therefore, ecosystem-based management encourages fisheries to switch from only regulating nominally targeted species catches, to sustainably utilizing all marine resources by incorporating ecosystem considerations into the management strategy(Cochrane, et al., 2007; Trochta, et al., 2018).

To effectively manage all species landed by a fishery, management needs to know what is determining the landed catch composition of the fishery so that they can create regulations that will be effective in manipulating the landed catch composition to that which will be the most sustainable for all species. The factors that have the most effect on the bycatch of a fishery are the yearly and seasonal changes in species abundances, the gear used, the areas fished, and the ‘skipper effect’ (Roberson & Wilcox, 2021).

The aims and objectives

This study aims to determine the causes of variation in landed bycatch volume and composition in the inshore trawl fishery. Interannual and seasonal effects will be quantified, as these may reflect natural variations in fish abundance and availability. Yearly changes might also reflect market forces and seasonal effects might also reflect changes in fisher behaviour during the year as quotas in the multi-species fishery are progressively filled.

Another focus is the effect of where the vessels fish compared to the effects of the vessels themselves. Vessel effects could be ascribed to the physical characteristics of the vessel and gear and the decisions of the skipper. The decisions of the skipper can influence targeting (how the gear is used) and discarding (or what is retained), both of which will influence the landed catch composition. I will apply models to quantify the influence of *year*, *season*, *area* and *vessel effects* on the landed catch composition. The extent of these influences will be critically important for the management of the bycatch. For this study, I will use three decades of fishery-dependent landing records supplied by the Department of Forestry, Fisheries and the Environment (DFFE).

In chapter two I will describe the yearly and seasonal changes in the effort, landed catch, cpue, and bycatch rate in the fishery. I will then test the hypotheses that the bycatch rate differs between trawls targeting *A. pectoralis* and trawls targeting *M. capensis*, trawls made during the day and trawls made at night, and trawls made at different depths.

In chapter three I will describe the landed catch composition. I will analyse the interannual, seasonal, and spatial variability in landed catch composition, and the variability in landed catch composition among vessels. I will find the factors that determine the landed catch composition by modelling the landed catch composition with the factors: *year*, *season*, and *vessel*. If vessels are landing significantly different catch compositions, even when fishing at the same time, I will determine if the differences are due to the area the vessels trawled, or the fishing behaviour of the vessel by modelling the landed catch composition of a subset of vessels that fished at the same time, in the same area.

In chapter four I will use my results to evaluate possible management strategies for reducing bycatch in the inshore trawl fishery. The two main management systems recommended for the fishery so far have been individual quota systems (ITQs) and cooperative management (Greenston & Attwood, 2013). Therefore, I will focus on these two management systems.

Catch and effort records

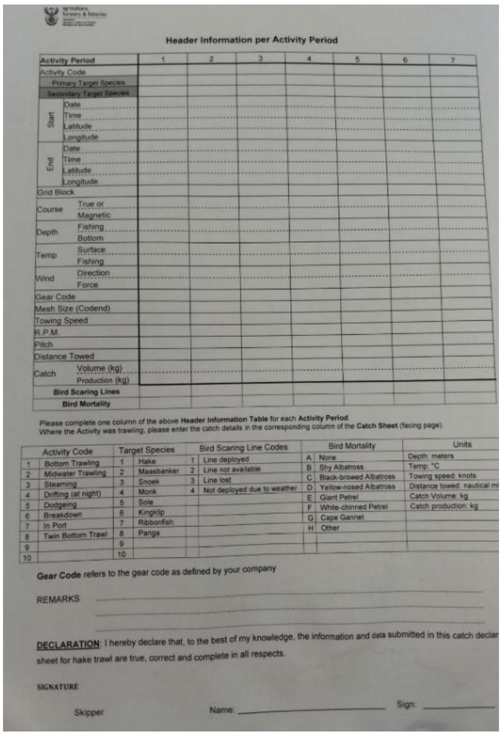
Catch and effort records for the inshore trawl fishery for the years 1990 to 2019 were made available by DFFE. The records came in two datasets, (1) catch and effort records of each trip, and (2) catch and effort records of each trawl made during the trips. These records were compiled from fishing logs completed by the skippers. The skipper was required to complete a logbook during the trip to record the catch and effort information for each trawl performed during the trip (figures 1, 2, and 3). The fishing log entries were handwritten into proforma logbooks.

When a trip was completed, the skipper was required to fill out the last page of the logbook with the names of all species caught during the trip, their landed or cleaned weights, and any cleaning or processing that was performed on them, as well as the start and end date of the trip and the number of trawls made during the trip.

For the trawl catch information an estimate of the amount of ‘bins’ that were caught of each species, and information on any processing performed on the species was required. For the effort information, the start and end date and time of the trawl, the species targeted, and the grid cell the trawl began in, among other variables, were required. The grid cell refers to the 20’ x 20’ commercial grid system used along the South African coast. Each grid cell is allocated a unique number, which is used to identify the location of the trawl, and aggregate trawl catch and effort data.

hese logbooks were then sent to DFFE, where they were transcribed into a digital database. The species landed weights, processing information, and ‘bin’ estimates were used to back-calculate the nominal mass caught per trawl. Vessels and companies were identified by codes, as the identity of the vessels and companies are withheld by DFFE. A trip identification code was added, made using a combination of the acronym RSA (Republic of South Africa), the company code, the vessel code, and the date and time the trip ended.

The fishing logs restrict the number of species that can be recorded in a single trawl to 25 (21 species names, one offal category, and three empty fields), and a single trip to 29 (21 species names, one offal category, and seven empty fields) (figure 2 and 3). The species weight (kg) was reported to two decimal places and the species names were recorded using abbreviated species codes.



Header Information per Activity Period

Activity Period		1	2	3	4	5	6	7
Activity Code								
Primary Target Species								
Secondary Target Species								
Start	Date							
	Time							
	Latitude							
	Longitude							
End	Date							
	Time							
	Latitude							
	Longitude							
Grid Block								
Course	True or							
	Magnetic							
Depth	Fishing							
	Bottom							
Temp	Surface							
	Fishing							
Wind	Direction							
	Force							
Gear Code								
Mesh Size (Codend)								
Towing Speed								
R.P.M.								
Pitch								
Distance Towed								
Catch	Volume (kg)							
	Production (kg)							
Bird Scaring Lines								
Bird Mortality								

Please complete one column of the above **Header Information Table** for each **Activity Period**.
Where the Activity was trawling, please enter the catch details in the corresponding column of the **Catch Sheet** (facing page).

	Activity Code		Target Species		Bird Scaring Line Codes		Bird Mortality	Units
1	Bottom Trawling	1	Hake	1	Line deployed	A	None	Depth: meters
2	Midwater Trawling	2	Maasbanker	2	Line not available	B	Shy Albatross	Temp: °C
3	Steaming	3	Snoek	3	Line lost	C	Black-browed Albatross	Towing speed: knots
4	Drifting (at night)	4	Monk	4	Not deployed due to weather	D	Yellow-nosed Albatross	Distance towed: nautical mi
5	Dodgeing	5	Sole			E	Giant Petrel	Catch Volume: kg
6	Breakdown	6	Kingklip			F	White-chinned Petrel	Catch production: kg
7	In Port	7	Ribbonfish			G	Cape Gannet	
8	Twin Bottom Trawl	8	Panga			H	Other	
9		9						
10		10						

Gear Code refers to the gear code as defined by your company

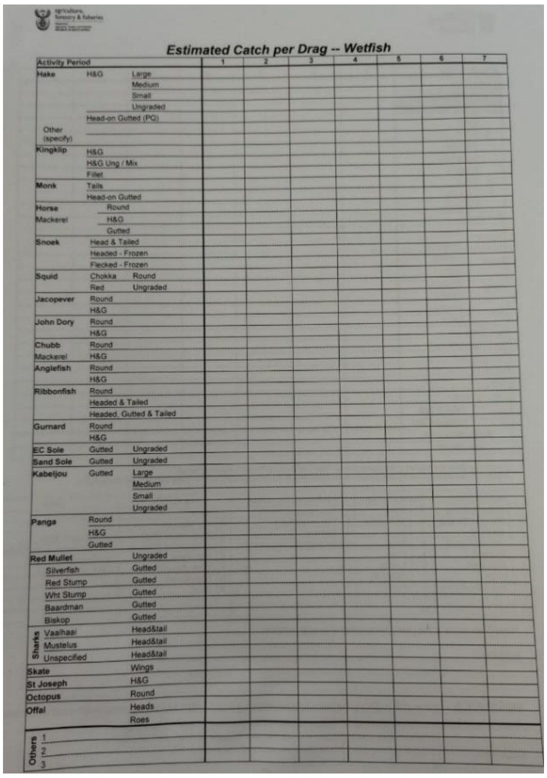
REMARKS ....

DECLARATION: I hereby declare that, to the best of my knowledge, the information and data submitted in this catch declar sheet for hake trawl are true, correct and complete in all respects.

SIGNATURE

Skipper Name: ____________________ Sign: ____________

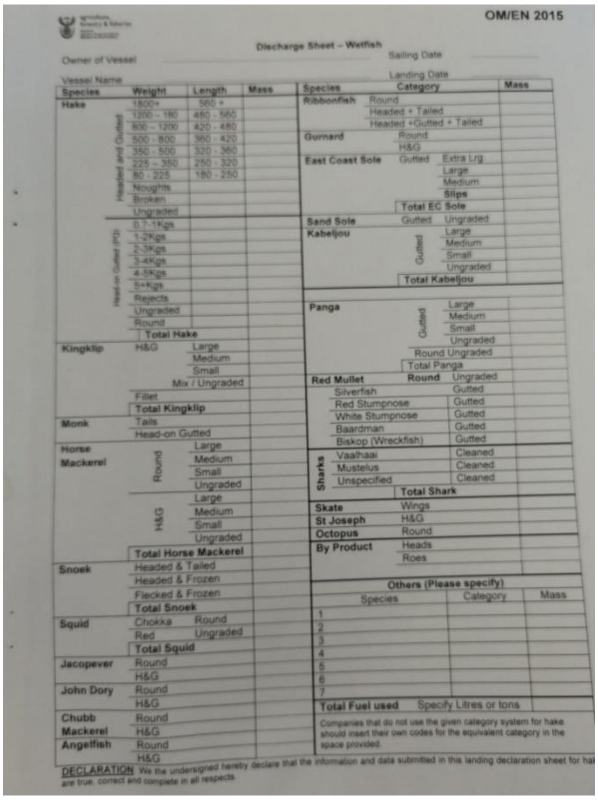
Figure 1. The sheet for effort information for each trawl.



Estimated Catch per Drag -- Wetfish

Activity Period			1	2	3	4	5	6	7
Hake	H&G	Large							
		Medium							
		Small							
		Ungraded							
	Head-on Gutted (PQ)								
Other (specify)									
Kingklip	H&G								
	H&G Ung / Mix								
	Fillet								
Monk	Tails								
	Head-on Gutted								
Horse Mackerel	Round								
	H&G								
	Gutted								
Snoek	Head & Tailed								
	Headed - Frozen								
	Flecked - Frozen								
Squid	Chokka	Round							
	Red	Ungraded							
Jacopever	Round								
	H&G								
John Dory	Round								
	H&G								
Chubb Mackerel	Round								
	H&G								
Anglefish	Round								
	H&G								
Ribbonfish	Round								
	Headed & Tailed								
	Headed, Gutted & Tailed								
Gurnard	Round								
	H&G								
EC Sole	Gutted	Ungraded							
Sand Sole	Gutted	Ungraded							
Kabeljou	Gutted	Large							
		Medium							
		Small							
		Ungraded							
Panga	Round								
	H&G								
	Gutted								
Red Mullet		Ungraded							
Silverfish		Gutted							
Red Stump		Gutted							
Wht Stump		Gutted							
Baardman		Gutted							
Biskop		Gutted							
Sharks Vaalhaai		Head&tail							
Mustelus		Head&tail							
Unspecified		Head&tail							
Skate		Wings							
St Joseph		H&G							
Octopus		Round							
Offal		Heads							
		Roes							
Others 1									
2									
3									

Figure 2. The proforma sheet for catches for each trawl made.



OM/EN 2015

Discharge Sheet – Wetfish

Owner of Vessel
Sailing Date
Vessel Name
Landing Date

Species		Weight	Length	Mass
Hake	Headed and Gutted	1800+	560 +	
		1200 – 180	480 - 560	
		800 – 1200	420 - 480	
		500 - 800	360 - 420	
		350 - 500	320 - 360	
		225 – 350	250 - 320	
		80 - 225	180 - 250	
		Noughts		
		Broken		
		Ungraded		
	Head-on Gutted (PG)	0.7-1Kgs		
		1-2Kgs		
		2-3Kgs		
		3-4Kgs		
		4-5Kgs		
		5+Kgs		
		Rejects		
		Ungraded		
		Round		
		Total Hake		
Kingklip	H&G		Large	
			Medium	
			Small	
			Mix / Ungraded	
		Fillet		
		Total Kingklip		
Monk		Tails		
		Head-on Gutted		
Horse Mackerel	Round		Large	
			Medium	
			Small	
			Ungraded	
	H&G		Large	
			Medium	
			Small	
			Ungraded	
		Total Horse Mackerel		
Snoek		Headed & Tailed		
		Headed & Frozen		
		Flecked & Frozen		
		Total Snoek		
Squid		Chokka	Round	
		Red	Ungraded	
		Total Squid		
Jacopever		Round		
		H&G		
John Dory		Round		
		H&G		
Chubb Mackerel		Round		
		H&G		
Angelfish		Round		
		H&G		

Species	Category		Mass
Ribbonfish	Round		
	Headed + Tailed		
	Headed +Gutted + Tailed		
Gurnard	Round		
	H&G		
East Coast Sole	Gutted	Extra Lrg	
		Large	
		Medium	
		Slips	
	Total EC Sole		
Sand Sole	Gutted	Ungraded	
Kabeljou	Gutted	Large	
		Medium	
		Small	
		Ungraded	
	Total Kabeljou		
Panga	Gutted	Large	
		Medium	
		Small	
		Ungraded	
	Round Ungraded		
	Total Panga		
Red Mullet	**Round**	Ungraded	
Silverfish		Gutted	
Red Stumpnose		Gutted	
White Stumpnose		Gutted	
Baardman		Gutted	
Biskop (Wreckfish)		Gutted	
Sharks Vaalhaai		Cleaned	
Mustelus		Cleaned	
Unspecified		Cleaned	
	Total Shark		
Skate	Wings		
St Joseph	H&G		
Octopus	Round		
By Product	Heads		
	Roes		

Others (Please specify)

	Species	Category	Mass
1			
2			
3			
4			
5			
6			
7			

Total Fuel used	Specify Litres or tons	

Companies that do not use the given category system for hake should insert their own codes for the equivalent category in the space provided.

DECLARATION We the undersigned hereby declare that the information and data submitted in this landing declaration sheet for ha are true, correct and complete in all respects.

Figure 3. The proforma sheet for catch and effort data for the trip.

Study area

The inshore trawl grounds lie between a line due south of Cape Agulhas (34°49′59.6″S and 20° E) and another due south of the Great Kei River (32° 40’6” S and 28° 23’1” E) (figure 4). Trawling typically takes place between 60 and 120 m depths. The area is divided into a 20’ by 20’ grid system, which is used in this study to spatially aggregate the effort and catches. Not all of the grid cells in the inshore trawl grounds present equally sized areas for trawling, and there is a large disparity in the effort applied to each cell.

Within the inshore trawl grounds, several factors limit trawl locations. These include physical restraints such as the seafloor geology and the targeted species population ranges as well as human-instigated restrictions such as MPAs, areas around well heads used in the exploitation of natural gas that have been removed from the inshore trawl ground as they present a physical hazard, and the trawl footprint that has been frozen in an attempt to prevent trawlers from breaking new ground and further damaging habitat. (Japp, et al., 1994).

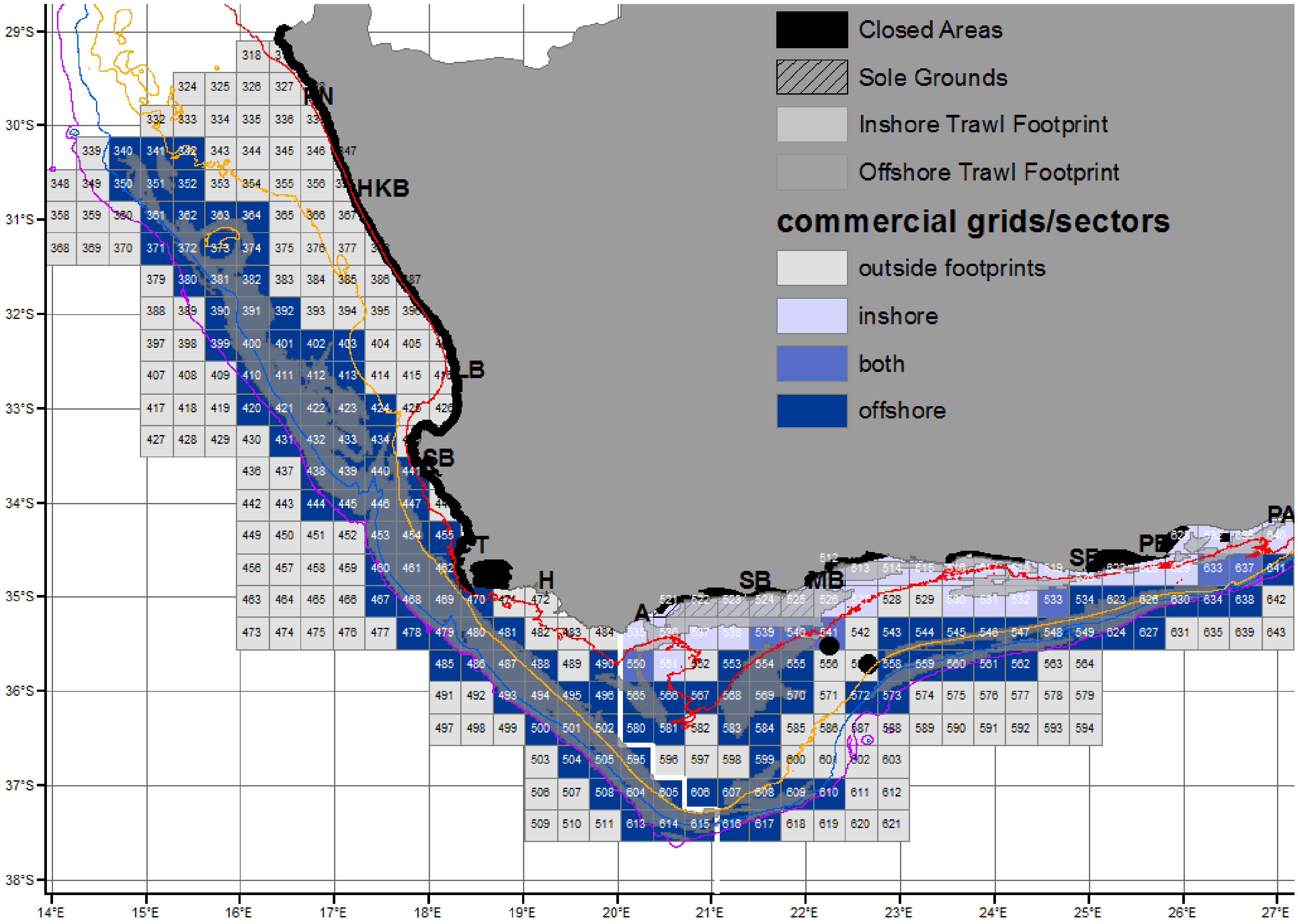


Figure 4. A map of the South African coast between 24 and 38 degrees south and 14 and 34 degrees east. The 20' by 20' grid is mapped, showing the codes for the grid cells. The map was provided by the Department of Environment, Forestry, and Fisheries (pers comm).

CHAPTER 2: PATTERNS IN THE SOUTH AFRICAN INSHORE TRAWL LANDED CATCHES

Abstract

The inshore trawl fishery nominally targets *M. capensis* and *A. pectoralis*. The fishery has the second-highest bycatch rate of any South African fishery and there has been concern over the bycatch in the fishery for over one hundred years. In this chapter, I describe the effort, landed catches, landed catch per unit effort (cpue), and bycatch rate in the fishery from 1990 to 2019. I then assess how target species, time-of-day, and depth affect the bycatch rate in the fishery. The effort and landed catch decreased by 70% and 62% respectively from 1990 to 2019. The cpue of the landed target and bycatch species showed a cycle with increasing periodicity from five to nine years. The bycatch rate increased by 22.7% from 1990 to 2019. Target and bycatch landings and cpue showed opposite seasonal patterns, but no seasonal pattern in the effort. Bycatch rates were 3% higher in trawls targeting *A. pectoralis* than those targeting *M. capensis* (t(df=284077) = 26.5, p <0.001). Bycatch rates were 3% higher during the day than at night (t(df= 86239) = 30.33, p <0.001). Bycatch rates were 12% higher in the depth group with the highest bycatch rates (90 to 100 m) than in the group with the lowest bycatch rates (110 to 120 m) (H = 4955.2, DF_{groups}= 5, P<0.001). While total bycatch landings in the fishery are decreasing the problem of bycatch and bycatch targeting within the fishery is getting worse. The low differences in bycatch rates when compared with previous studies suggest that selective retention and dumping are prevalent in the fishery. As the fishery is dominated by trawls for *M. capensis*, analysis of bycatch rates is dominated by *M. capensis* trawls, despite trawls for *A. pectoralis* resulting in higher bycatch rates.

Introduction

The inshore trawl fishery

The inshore trawl fishery is a dual-target fishery nominally targeting *M. capensis* and *A. pectoralis*. However, as many as 130 different species have been recorded in the catches (Attwood, et al., 2011). These species are not currently managed by catch or effort limits in the fishery but are marketed and sold by the fishery (DAFF, 2010; SADSTIA, 2019). The unmanaged species landed by the fishery have been termed bycatch in previous studies, but 'joint product' or 'semi-targets' by the fishery. The problem with bycatch in the inshore trawl fishery is that because these species are unmanaged many of them are experiencing unsustainable fishing pressure which is leading to or has already led to declines in their populations (Griffiths, 2000; DEFF, 2020).

Bycatch in the inshore trawl fishery

There have been limited studies made on the bycatch in the inshore trawl fishery as most studies have focused on the discarded portion of the catch. In 1949 bycatch was estimated at 16%, with six species making up 97% of the catch by weight (Scott, 1949). By 1998 this estimate increased to around 50%, with eight species making up 98% of the catch by weight and by 2011 decreased to 42% with twenty species making up 98% of the catch by weight (Booth & Hecht, 1998; Attwood, et al., 2011).

The catch composition consists mainly of teleost species, with a few Chondrichthyes and even fewer cephalopods (Booth & Hecht, 1998; Attwood, et al., 2011). This is consistent with the species composition found on the Agulhas Bank (Smale, et al., 1993; Japp, et al., 1994). The main bycatch species in the fishery is *Trachurus capensis* (horse mackerel) (Attwood, et al., 2011). While the fishery catches many species, only a few of these makeup majority of the catches by mass (Attwood, et al., 2011).

Causes of bycatch in the inshore trawl fishery

The inshore trawl fishery's high bycatch rate has been linked to the area over which the fishery operates, the species that are targeted during a trawl, the time of day that the trawl was made (Booth & Hecht, 1998; Walmsley, et al., 2007; Attwood, et al., 2011). The inshore trawl fishery operates over the Agulhas Bank, an area known for its highly diverse and endemic fish assemblage (Japp, et al., 1994; Currie, 2017). One way of assessing the relationship between the bycatch rate and the area is to look at how the bycatch rate differs by depth.

In 2007 a study using observer records estimated that *M. capensis* directed trawls in the inshore trawl fishery had a bycatch rate of 47%, and *A. pectoralis* directed trawls had a bycatch rate of 22% (Walmsley, et al., 2007). In 2011 a study using the updated observer records estimated a bycatch rate of 42% for the whole fishery (Attwood, et al., 2011). The similar bycatch rate of *M. capensis* directed trawls, and the whole fishery is a result of *M. capensis* making up most trawls in the fishery. The *A. pectoralis* directed trawls resulted in lower bycatch rates because they had similar proportions of *M. capensis* as the *M. capensis* directed trawls, but greater proportions of *A. pectoralis*, thereby increasing the total proportion of target species in the catches (Walmsley, et al., 2007).

In 2011 a study also using observer records found that there was a significant difference in the catch rates of *M. capensis* between day and night trawls (Attwood, et al., 2011). The difference in catch rates of *M. capensis* is due to its vertical diurnal migration (Payne, 1989). As *M. capensis* moves up the water column at night, its proportion in the catch decreases and the bycatch rate increases.

Aims

In this chapter, the trends in the effort and catch in the fishery during the period 1990 to 2019 will be described and the difference in bycatch rate between various factors will be tested for significance. I will start by describing the yearly and seasonal variation in effort, landed catches, cpue, and bycatch rate in the fishery. I will then test if there is a difference between the bycatch rate of trawls at different depth zones, trawls that nominally target *M. capensis* and trawls that target *A. pectoralis*, and trawls undertaken during the day (5:00 to 17:00) and trawls undertaken during the night.

Methods

Cleaning, filtering, and deriving of records

Records of trips completed by vessels in the inshore trawl fishery were available in two formats namely trawl-level data and trip-level data. The records were checked for outliers, which I typically defined as values greater than four standard deviations from the mean. Typographic errors were identified by comparing data with previous or later trawls and by reconciling data between trawl and trip totals. The variables that typically presented with errors were the trip and trawl dates and times, the species codes, and the trawl nominal masses (the reconstructed whole mass-see chapter 1). Identified errors were corrected, but all remaining records for which there were irreconcilable discrepancies between trawl level and trip level data were removed. Removed records accounted for less than 1% of the original data.

As some inshore trawl vessels operated in the offshore fishery too, not all trips were completed entirely within the inshore trawl grounds. To limit the data to trips that were made within the inshore trawl fishery grounds, trips with trawls made in waters deeper than 200 m or west of 20° E were excluded. All trips lasting less than two days, or with less than two trawls were deemed incomplete trips and were also removed. All trawls lasting less than 30 minutes, or more than nine hours, were removed. All depths recorded as less than 60 meters were removed.

Three new categorical variables were derived from existing information: *Season* (Summer, Autumn, Winter, and Spring), *Trip duration* (in days), and *Trawl duration* (in hours). The *Season* variable was derived from the end date of each trip. The months were grouped into four seasons such that January, February, and March fell into *Summer*, and so forth. The *Trip duration* and *Trawl duration* variables were calculated by subtracting the start date and time from the end date and time. The nominal (whole) weight of the species was calculated for each trip by multiplying the landed mass by the appropriate conversion factor for the processing method used (Chalmers, 1976; Tracey Fairweather pres. comm).

Trip and trawl records were used to describe the effort. Trip records (total effort and landed catches for the trip) were used to describe the yearly and seasonal landings, from which the catch per unit effort (cpue) and the bycatch rate were calculated. Trawl records (effort and landed catches per trawl) were used to compare the bycatch rates between the *M. capensis* and *A. pectoralis* directed trawls, between day and night trawls, and among trawling depths.

Description of effort

To visualize trends in fishing behaviour, the number of hours trawled was graphed against year. Total effort is a function of the number of vessels in the fishery, the number of trips a vessel makes, the duration of the trips, and the number of trawls per trip. Therefore, the number of vessels in the fishery, the average number of trips per vessel, trip duration, number of trawls per day, and trawl duration were calculated for each year and graphed.

The average number of hours trawled, number of trips per vessel, trip duration, number of trawls per day, and trawl duration in a season across the years was graphed and an ANOVA test was used to determine if there is a significant difference in any variable among the seasons. If a significant result was found a Tukey test was used to determine which seasons differed.

Description of landed catch, cpue, and bycatch rate

The total landed bycatch and target catch from 1990 to 2019 were described and graphed against year. A linear regression was used to model the yearly landed catch from 1990 to 2019 using the number of vessels. The average landed bycatch and target catch per season across the years were calculated and graphed. An ANOVA test was used to determine if the landed bycatch or target catch differed among the seasons and if a significant result was found a Tukey test was used to determine which seasons differed.

Average cpue of bycatch and target catch was described by year and season. The cpue was calculated by dividing the landed catch in trip (tons) *i* by the total number of hours trawled in trip *i*.

$$cpue_{ib} = C_{ib}/E_i \qquad 1.0$$

and

$$cpue_{it} = C_{it}/E_{i}, \qquad 1.1$$

where $cpue_{ib}$ is the bycatch cpue in trip *i,* C_{ib} is the bycatch landed in trip *i,* $cpue_{it}$ is the target catch cpue in trip *i,* C_{it} is the target catch landed in trip *i,* and E_i is the number of hours trawled in trip *i.* The average bycatch and target catch cpue was calculated for each year (across all vessels) and season (across all vessels and years). An ANOVA was used to test if target and bycatch cpue differed among the seasons, and if a significant result was found a Tukey test was used to determine which seasons differed.

The bycatch rate is the proportion of the total landed catch that is made up of bycatch. To calculate the bycatch rate, the landed bycatch mass *b* in trip *i* was divided by the landed total mass in trip *i*.

$$B_i = M_{bi}/M_{i}, \qquad 1.2$$

where B_i is the bycatch rate in trip *i*, M_{bi} is the mass of bycatch landed in trip *i*, and M_i is the total mass landed in trip *i*. The average bycatch rate for each year (across all vessels) and season (across all vessels and years) was calculated and graphed. An ANOVA was used to test if bycatch rate differed among the seasons and if a significant result was found a Tukey test was used to determine which seasons differed.

Bycatch rate as functions of target species, time of day, and depth

To calculate the bycatch rate per trawl, the landed bycatch mass *b* in trawl *j* was divided by the landed total mass in trawl *j*.

$B_j = M_{bj}/M_j,$ 1.3

where B_j is the bycatch rate in trawl *j*, M_{bj} is the mass of bycatch landed in trawl *j*, and M_j is the total mass landed in trawl *j*.

Bycatch rates of *M. capensis* and *A. pectoralis* directed trawls were graphed using a box and whisker plot. The hypothesis that there is a difference in bycatch rate between *M. capensis* and *A. pectoralis* directed trawls was tested using a Welch t-test, as the samples were not homoscedastic.

All trawls starting after 05:00 and before 17:00 were categorized as day trawls and all remaining trawls were categorized as night trawls. Bycatch rates of day and night trawls were graphed using a box and whisker plot. The hypothesis that there is a difference in bycatch rate between day and night trawls was tested using a welch t-test, as the samples were not homoscedastic.

Trawling depths were grouped into six groups of 10 m each starting at 60 m, such that group one included all trawls starting at depths between 60 and 70 m and so on. The bycatch rates of the depth groups were graphed using a box and whisker plot. The hypothesis of a difference in bycatch rate among the depth groups was tested using a Kruskal-Wallis test as the data were non-normal. Wilcox pairwise tests were then used to determine which groups differed.

Rstudio (2020) was used to undertake all analyses.

Results

Yearly trends in the effort, landed catch, cpue, and bycatch

Effort

Effort in the inshore trawl fishery decreased from 68 558 hours in 1990 to 20 367 hours in 2019, a decrease of 70% (figure 1).

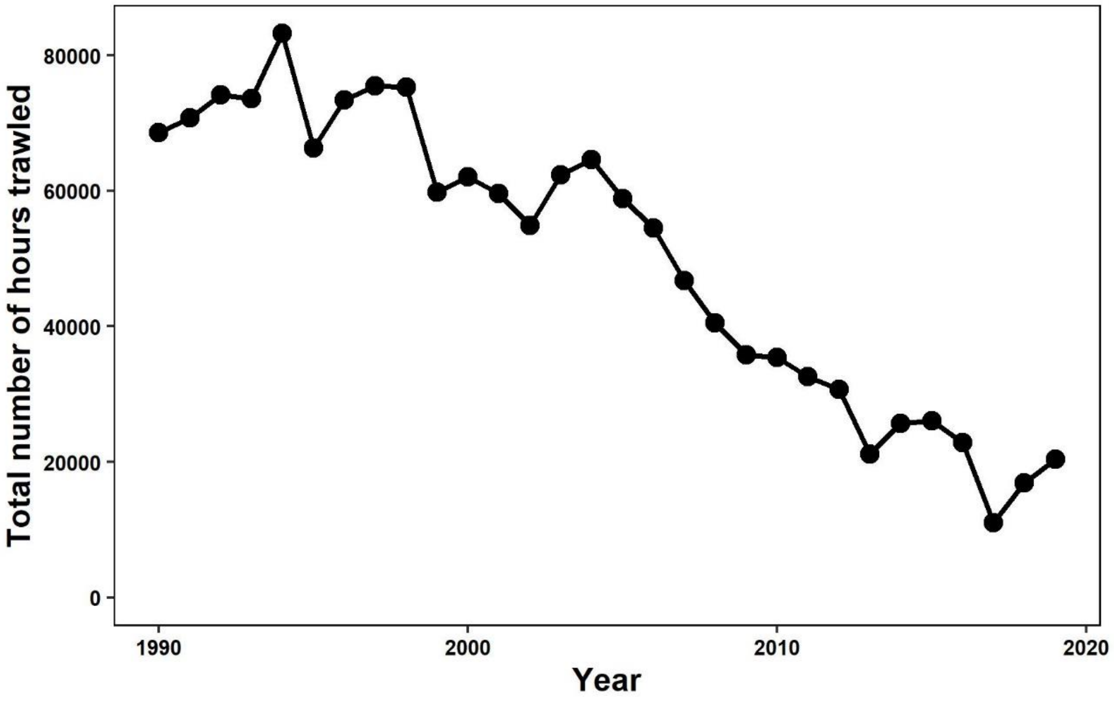


Figure 1. A time-series of the total number of hours trawled per year

The number of vessels in the fishery decreased from 40 in 1990 to 15 in 2019 (figure 2a). Vessels made an average of 24.9 (sd = 12.63) trips a year. The average number of trips per vessel per year increased from 19 in 1990 to 30 in 2003 and then decreased from 30 in 2003 to 25 in 2019. The sharp drop in 2017 is due to a legal challenge in the administration of the fishery, causing the fleet to be tied up for much of 2017 and 2018 (figure 2b). Trips lasted for a minimum of two and a maximum of fifteen days, with an average of 6.9 (sd = 2.15) days. The average trip duration decreased from eight days in 1990 to five days in 2019 (figure 2c).

There was a minimum of one trawl per day during a trip, and a maximum of nine, with an average of 3.7 (sd = 1.29). The average number of trawls made per day during a trip increased from 3.3 in 1990 to 4.0 in 2010 and then decreased to 3.3 in 2019 (figure 2d). Trawls lasted a minimum of half an hour, and a maximum of nine hours, with an average of 3.5 (sd = 1.05) hours. The average trawl duration decreased from 3.8 hours in 1990 to 3 hours in 2002 and then increased to 3.5 hours in 2019, with a peak of 3.8 hours in 2013 (figure 2e).

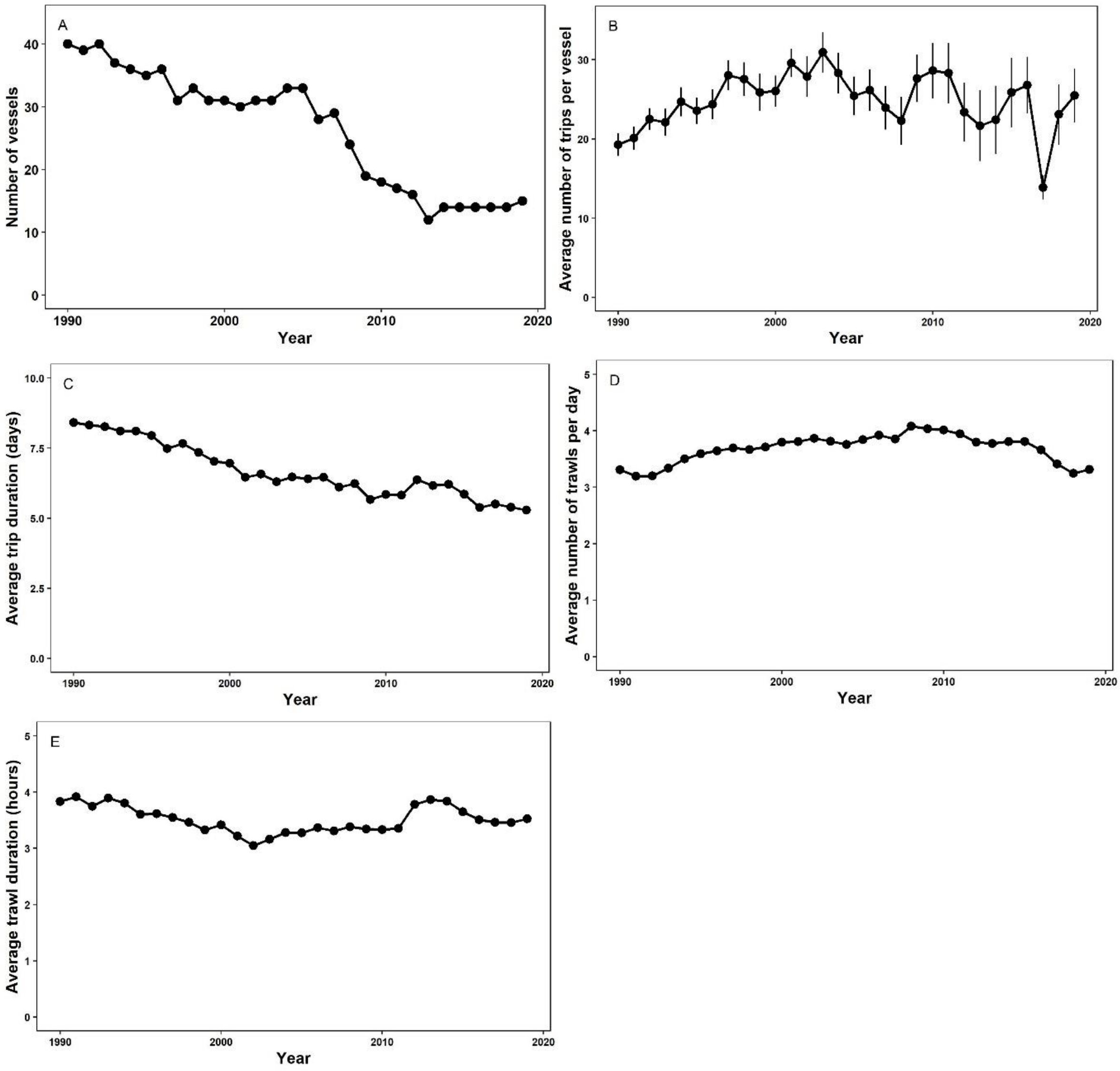


Figure 2. Time-series plots of (A) the number of vessels in the fishery, (B) the average number of trips made per vessel, (C) the average trip duration, (D) the average number of trawls made a day, and (E) the average trawl duration, over the period 1990 to 2019. Error bars represent the standard error of the mean, but are only large enough to be visible in graph B.

Landed catch

From 1990 to 2019 a total of 295477 t was landed by the inshore trawl fishery, of which 107396 t was bycatch, making up 35.3% of the total landed catch. The yearly landed mass decreased by 62% from 14688 t in 1990 to 5585 t in 2019. The year with the lowest landings was 2013 at 2076 t and the year with the highest landings was 2001 at 17002 t.

A linear regression was calculated to predict the total nominal mass landed each year using the number of vessels active. A significant regression equation was found (F(1, 28) = 157.7, $p < 0.001$, $R^2 = 0.85$). The predicted nominal landed catch in tons is:

Catch (tons) = (447.02 x number of vessels) - 1900.37.

The target and bycatch landings showed similar trends, except for the years 1990 to 2001. The target landings showed a generally increasing trend from 1990 to 2001, while bycatch landings showed a steadier trend. Both target and bycatch landings showed a decreasing trend from 2001 to 2013, followed by an increase from 2013 to 2019. The only years when bycatch landings exceeded target landings are 2012, 2013, and 2014 (figure 3).

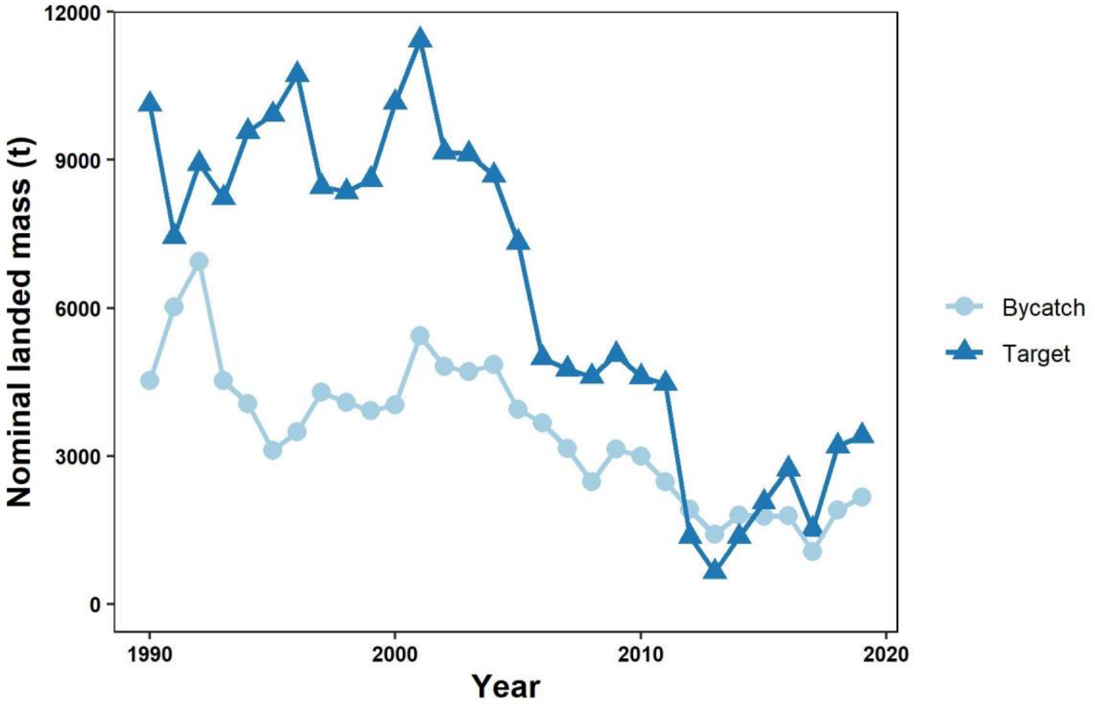


Figure 3. A time-series of the total landed target catch and bycatch each year in tons

Cpue

The landed target cpue shows four cycles with wave lengths of 6, 5, 8, and 9 years. In the four cycles, the amplitudes were 59.2%, 82.8%, 75.4%, and 142.7% of the average cpue respectively. Landed bycatch cpue shows less variation than target cpue and has less pronounced cycles. In the same four cycles, the bycatch amplitudes were 30.3%, 48.1%, 23.0%, and 40.7% of the average cpue respectively (figure 4).

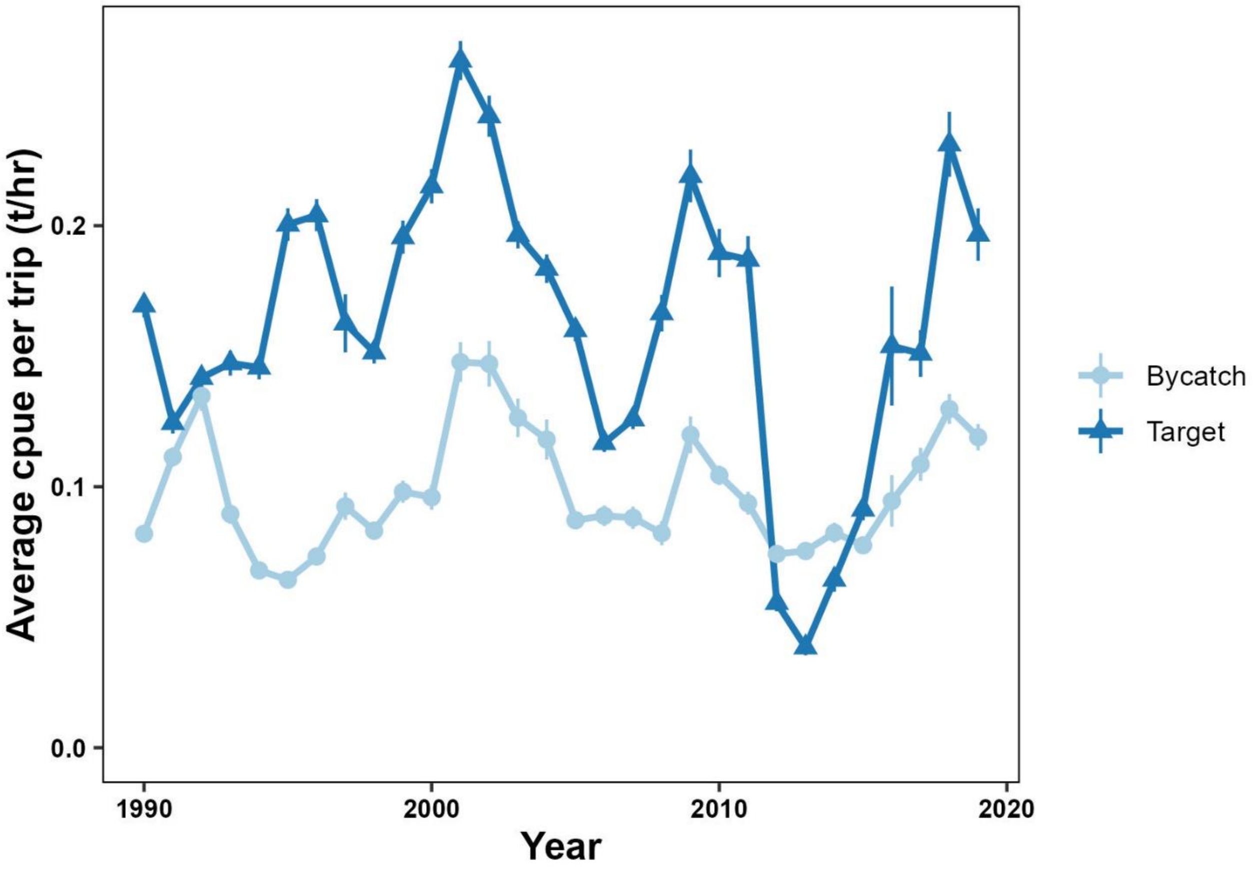


Figure 4. A time-series of the average cpue per year for bycatch and target species. Error bars represent one standard error from the mean. Standard errors are too small for representation on this scale.

Bycatch rate

The average bycatch rate per trip increased by 22.7% from 0.34 in 1990 to 0.44 in 2019. There were two spikes in average bycatch rate, which occurred in the years 1991 to 1992 and 2012 to 2014 (figure 5).

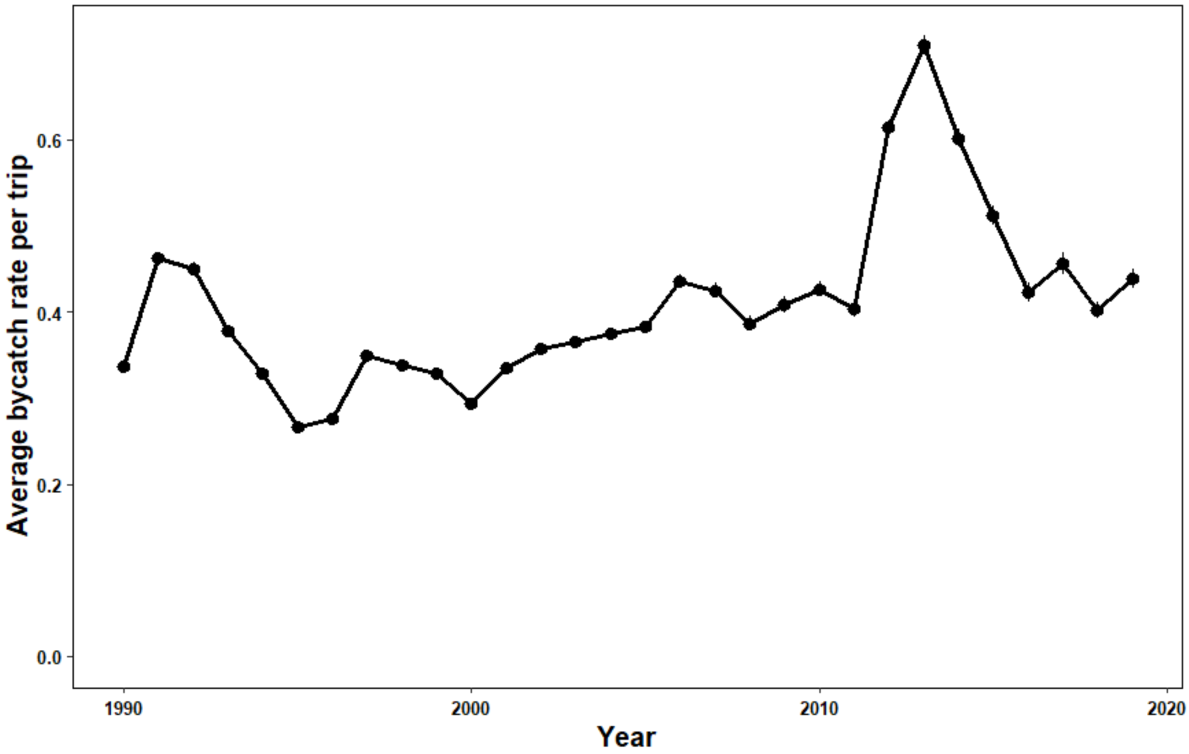


Figure 5. A time-series of the average bycatch rate per trip. Standard errors are too small for representation on this scale.

Seasonal patterns in the effort, landed catch, cpue, and bycatch

Effort

Effort does not vary significantly among the seasons (F= 0.107, DF_{groups} = 3, P = 0.96) (Figure 6).

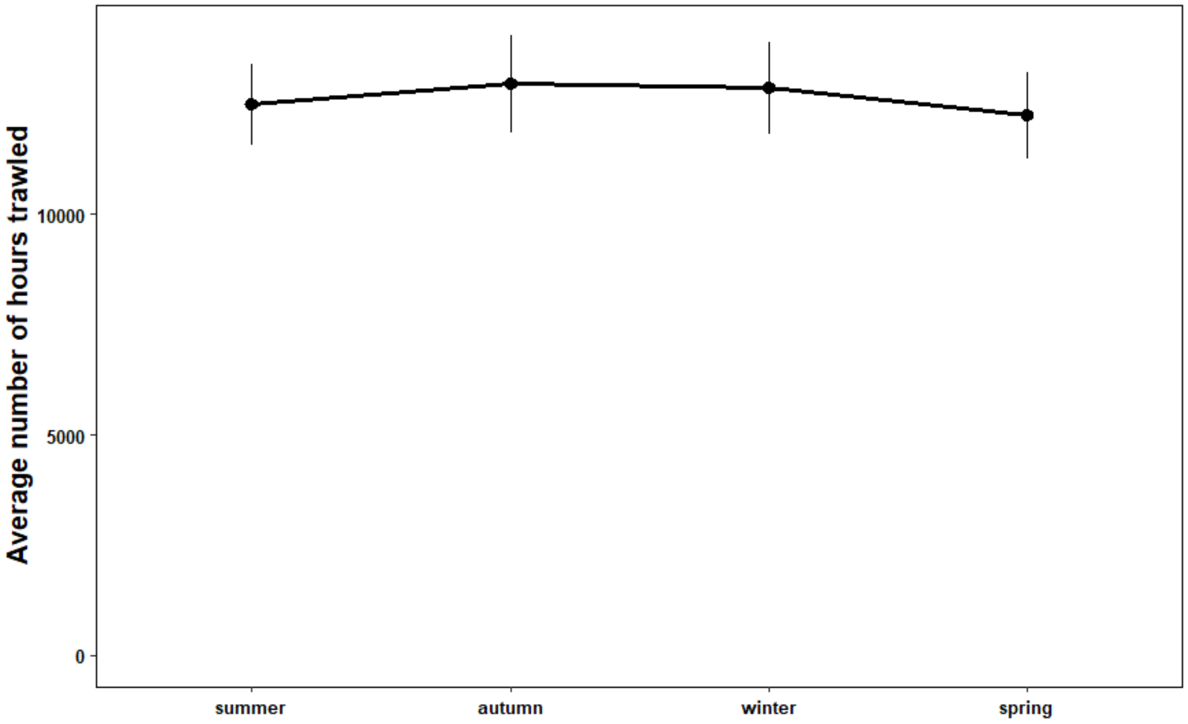


Figure 6. The average number of hours trawls per season across the years. Error bars represent the standard error of the mean.

The number of trips made by a vessel, the duration of a trip, the number of trawls made a day, and the duration of a trawl all differed significantly among the seasons. However, there was only a small variation among the seasons for all variables. The greatest variation is in the average number of trips, which increased by 8.1% from 6.8 in summer to 7.4 in winter (figure 7a). The trip duration increased by 1.4% from summer to winter (figure 7b), the number of trawls per day decreased by 6.1% from summer to winter (figure 7c), and the trawl duration increased by 3.1% from summer to winter (figure7d).

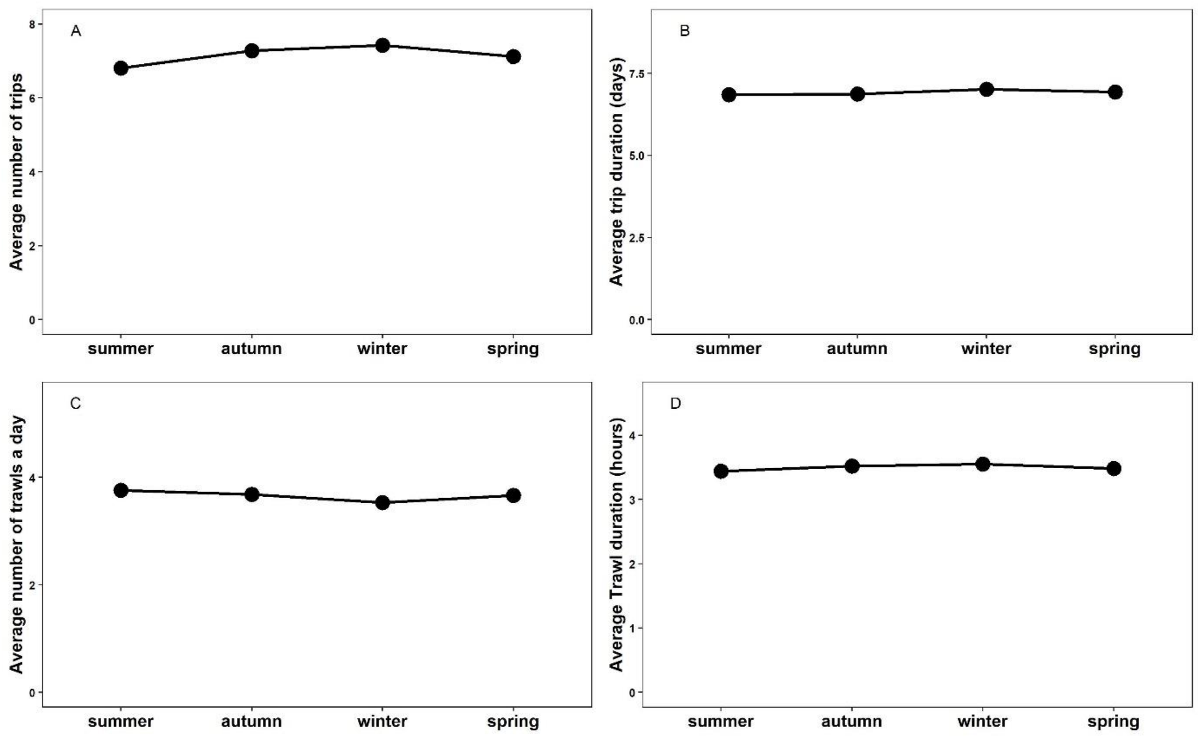


Figure 7. Plots of (A) the average number of, (B) the average trip duration, (C) the average number of trawls made a day, (D) the average trawl duration, over the period 1990 to 2019. Standard errors are too small for representation on this scale.

Landed catch

There is no significant difference in target landings among seasons (F = 1.69, DF_{Groups}= 3, P = 0.173). Bycatch landings in summer are significantly lower than those in winter (f(3) = 3.428, p = 0.019). Average seasonal bycatch landings increased by 30.6% from 717 t in summer to 1034 t in winter (figure 8).

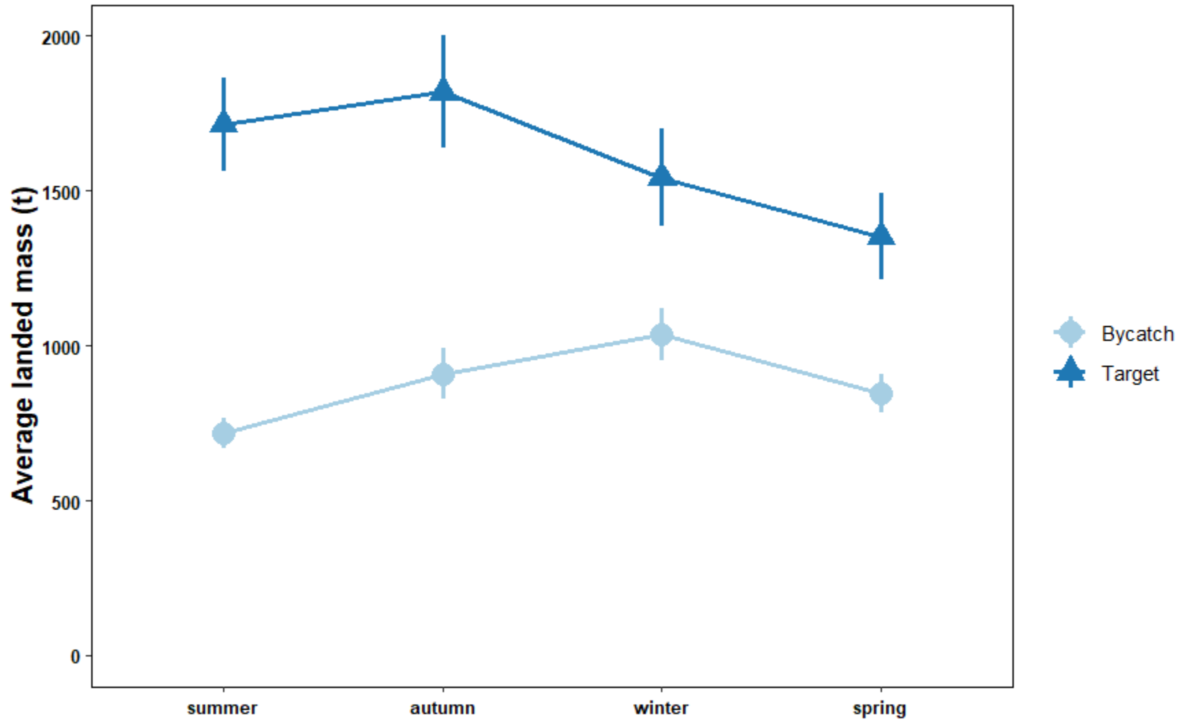


Figure 8. A plot of the average landed bycatch and target catch, with error bars representing the standard error from the mean.

Cpue

Target cpue differed significantly among the seasons ($F = 161.8$, $DF_{groups} = 3$, $P < 0.001$). The Tukey test showed no difference between summer and autumn, but for the reminder of the year cpue dropped by 11.1% in winter and a further 6.3% in spring. Bycatch cpue differed significantly among the seasons ($F = 128.7$, $DF_{groups} = 3$, $P < 0.001$). The Tukey test showed no difference between autumn and spring, but from autumn to winter the cpue increased by 9% and from spring to summer decreased by 20% (figure 9).

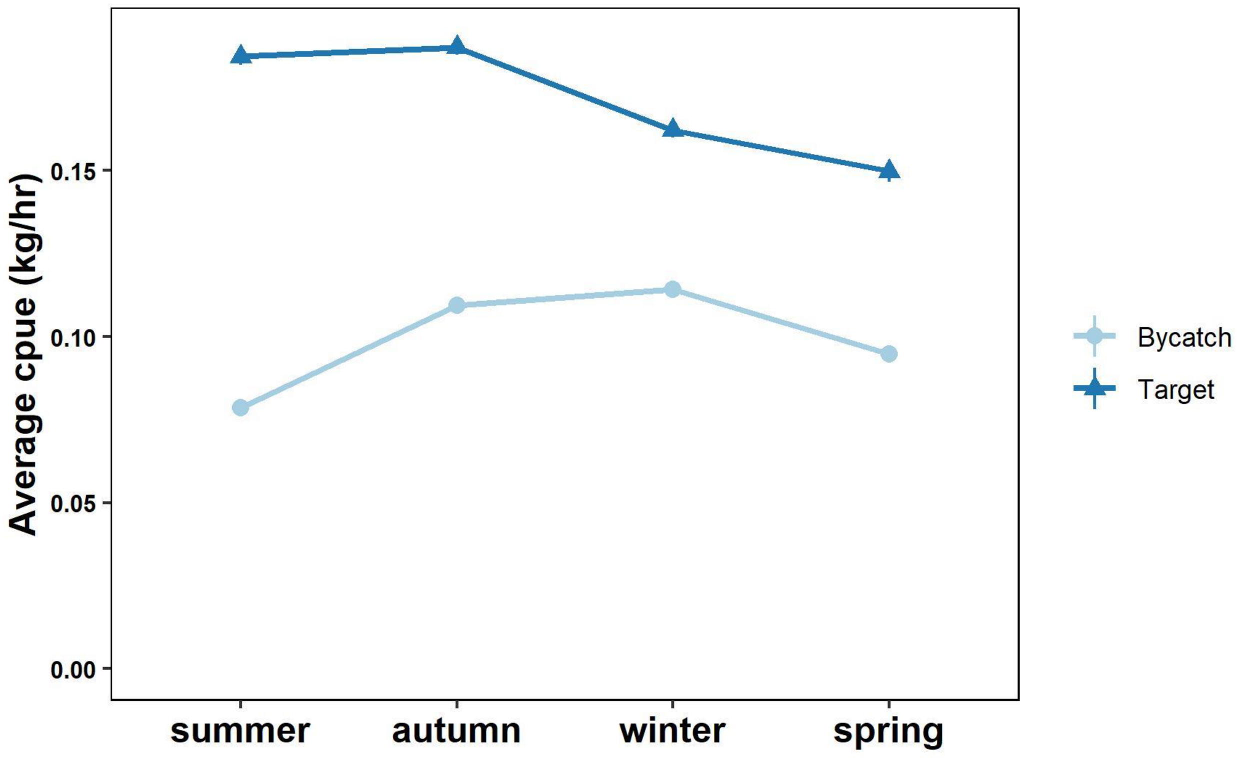


Figure 9. A plot of the average landed cpue per season. Error bars represent one standard error from the mean. Standard errors are too small for representation on this scale.

Bycatch rate

Landed bycatch rate per trip was significantly different among the seasons (F =312.9, DF_{groups}=3, P<0.001). The Tukey test showed that there was no difference between winter and spring, but that the bycatch rate significantly increased by 6.8% from summer to autumn and 17.2% from autumn to winter (figure 10).

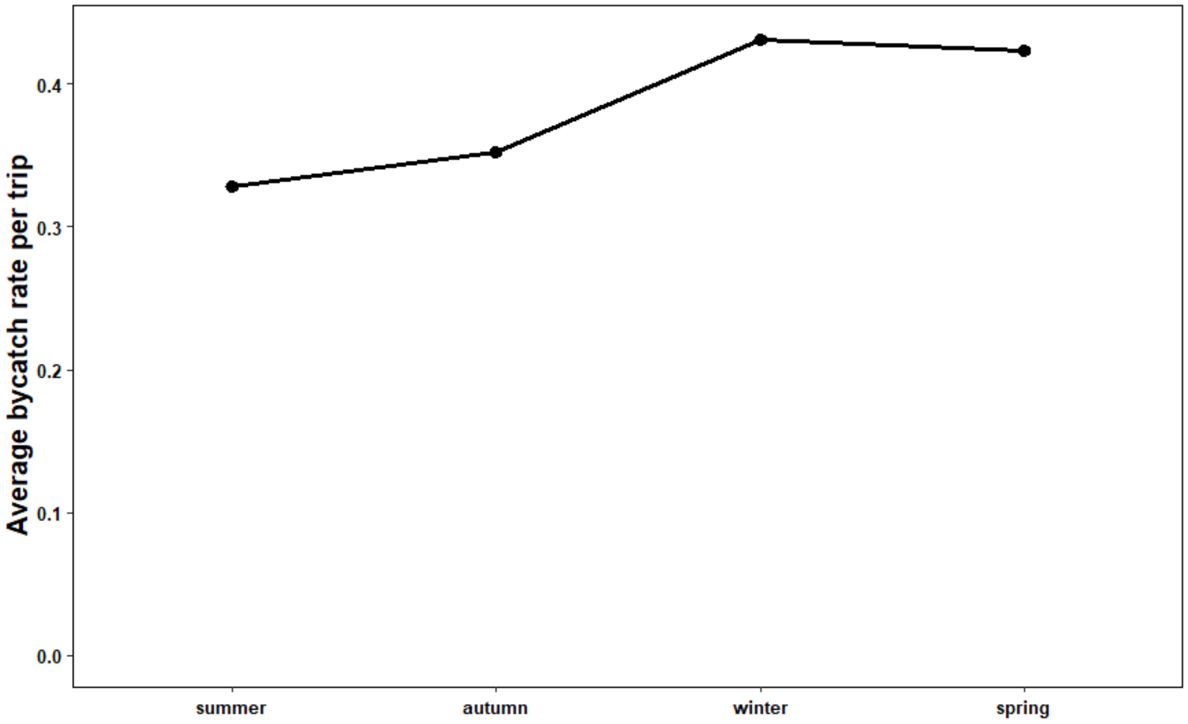


Figure 10. A plot of the average bycatch rate per trip. Standard errors are too small for representation on this scale.

Hypothesis testing

M. capensis was targeted in 62% of trawls and accounted for 80% of the total landed catch. *A. pectoralis* was targeted in 38% of trawls and accounted for 20% of the total landed catch. *M. capensis* directed trawls (mean = 0.38, sd = 0.257) had significantly lower landed bycatch rates than *A. pectoralis* directed trawls (mean = 0.41, sd = 0.274), t(df=284077) = 26.5, p <0.001 (figure 11).

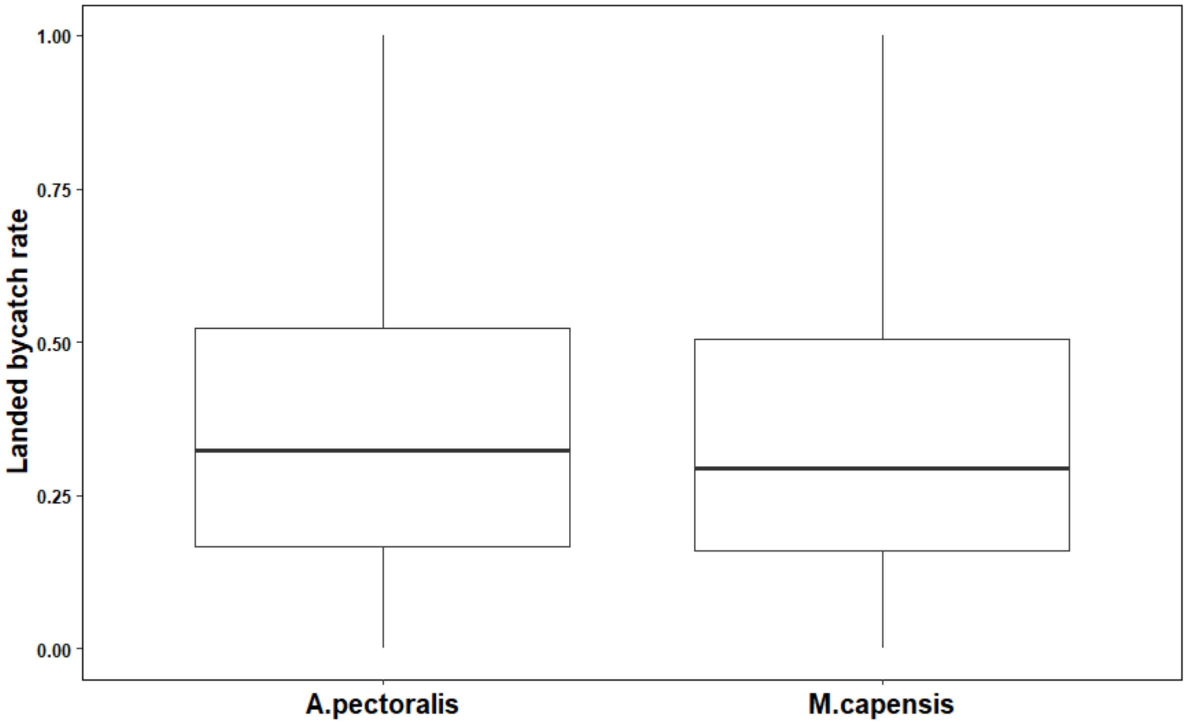


*Figure 11. A boxplot of the landed bycatch rate in A. pectoralis directed trawls and M. capensis directed trawls. Five summary statistics are visualized, the median, the first and third quartiles and two whiskers. The upper and lower whisker extends from the edge of the box to the largest and smallest value, but no further than 1.5 * IQR (inter-quartile range). Data beyond the end of the whiskers are called "outlying" points and are plotted individually.*

Day trawls made up 79% of all trawls made from 1990 to 2019 and accounted for 89% of the landed mass. The day trawls (mean = 0.36, sd = 0.253) had significantly higher landed bycatch rates than night trawls (mean = 0.33, sd = 0.255), t(df= 86239) = 30.33, p <0.001 (figure 12).

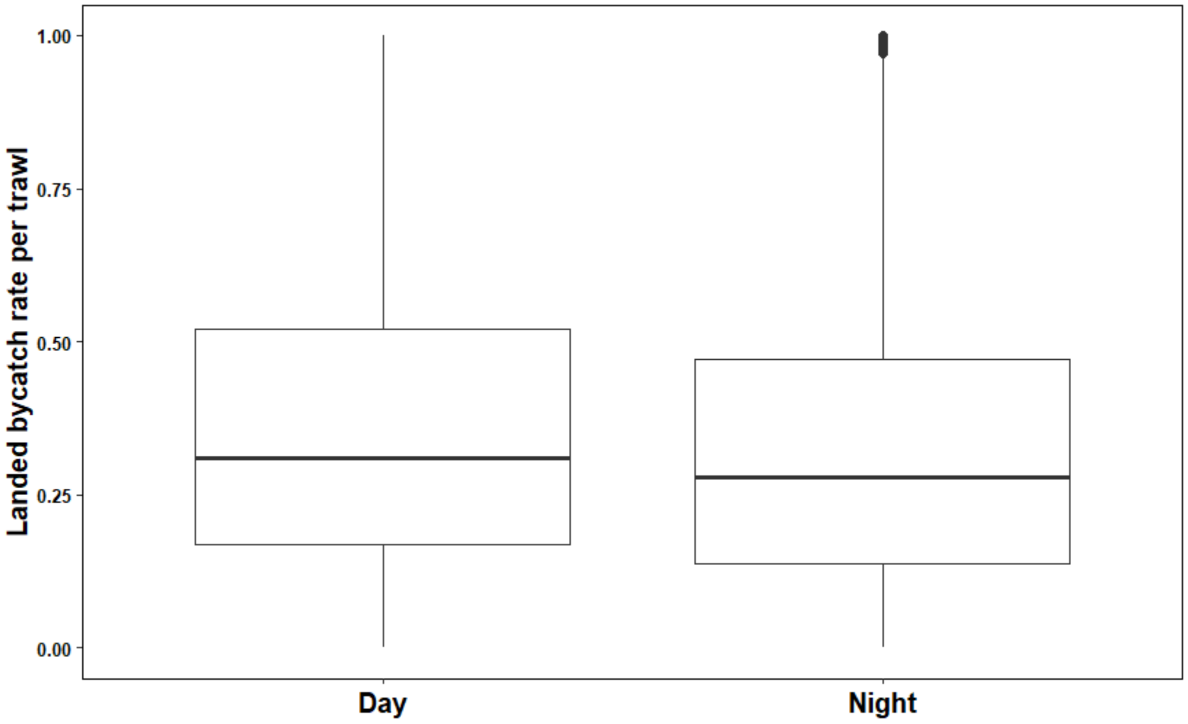


*Figure 12. A boxplot of the landed bycatch rate in the day (05:00 to 17:00) and night trawls. Five summary statistics are visualized, the median, the first and third quartiles and two whiskers. The upper and lower whisker extends from the edge of the box to the largest and smallest value, but no further than 1.5 * IQR (inter-quartile range). Data beyond the end of the whiskers are called "outlying" points and are plotted individually.*

Bycatch rate differed significantly among the depth groups 60 to 70 m (mean = 0.36, sd = 0.259), 70 to 80 m (mean = 0.34, sd = 0.232), 80 to 90 m (mean = 0.38, sd = 0.247), 90 to 100 m (mean = 0.42, sd = 0.269), 100 to 110 m (mean = 0.38, sd = 0.266), 110 to 120 m (mean = 0.30, sd = 0.219), (H = 4955.2, DF_{groups}= 5, P<0.001). The pairwise tests showed that all depth groups differed significantly. The depths with the lowest bycatch rates were 110 m to 120 m and the depths with the highest bycatch rates were 90 m to 100 m (figure 13).

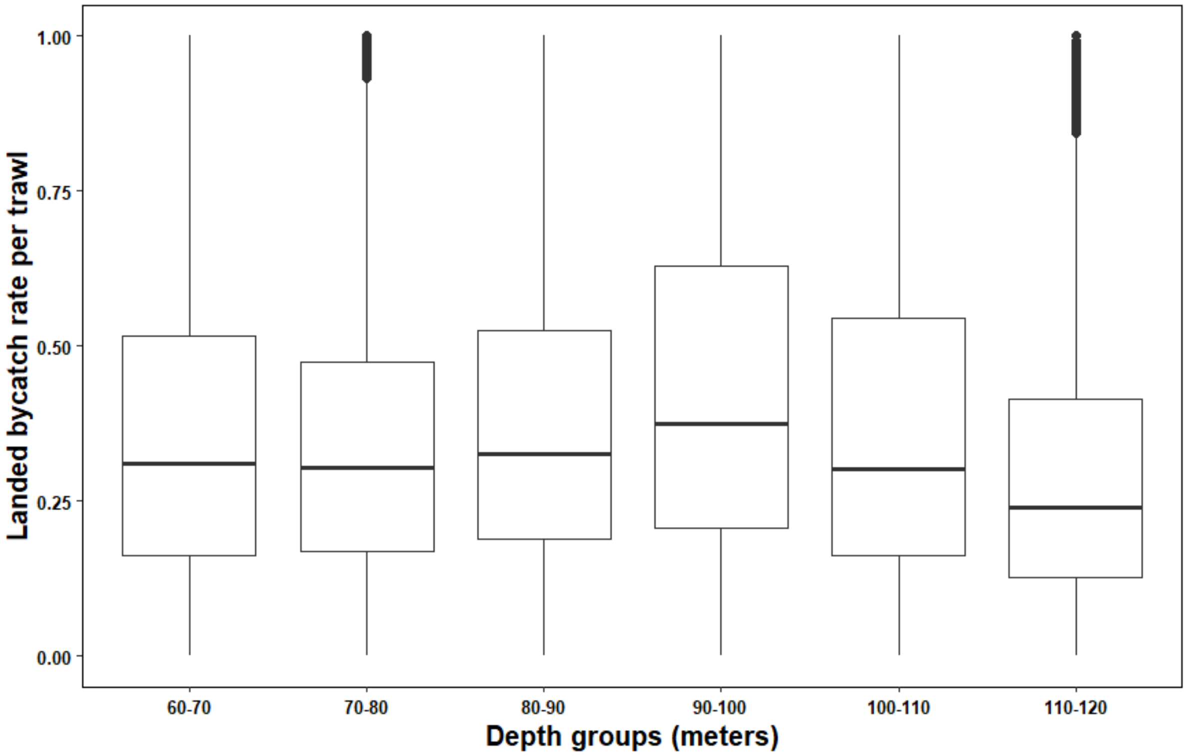


*Figure 13. A boxplot of the landed bycatch rate per depth (meters) group. The depths were grouped into ten-meter groupings starting at 60 m and ending at 120 m. Five summary statistics are visualized, the median, the first and third quartiles and two whiskers. The upper and lower whisker extends from the edge of the box to the largest and smallest value, but no further than 1.5 * IQR (inter-quartile range). Data beyond the end of the whiskers are called "outlying" points and are plotted individually.*

Discussion

Yearly trends in the effort, landed catch, cpue, and bycatch rate

The decrease in effort from 1990 to 2019 was a result of a decrease in the number of active vessels in the fishery. DFFE has attributed the decrease in the number of vessels to a combination of vessels moving to the offshore hake trawl fishery and vessels not being replaced as they aged out of the fishery (DEFF, 2020). The inshore trawl fishery only accounts for a small portion of the total profits of the hake fishery but represents the most ecologically damaging portion of the fishery (MSC, 2022). Therefore, apart from profit incentives, there has also been environmental pressure to migrate effort from the inshore trawl fishery to the offshore (Walmsley, et al., 2006).

The vessels’ changed the amount and duration of their trips from fewer, longer trips to more frequent shorter trips, but had almost no change in trawling behaviour. The change in fishing behaviour is most likely explained by some external pressure which selects for shorter trips. The markets in South Africa have increasingly moved toward more diverse fresher fish products, which selects for shorter fishing trips (Cawthorn, et al., 2011).

The landed target catch decreased from 1990 to 2019, but there was only a small decrease in the TAC for *M. capensis* and *A. pectoralis* (DEFF, 2020). After 1995 the landed bycatch showed a similar trend to the landed target catches but were less variable. Bycatch landings are likely less variable because target landings are made up of two species, while bycatch landings are made up of 43 species. The decrease in total landings was explained well by the decrease in the number of vessels in the fishery, indicating again that vessels did not change in efficiency throughout the study period.

Despite the number of vessels in the fishery decreasing from 1990 to 2019, the number of rights holders increased. Rights holders are not required to own fishing vessels, and many rights holders fulfil their quotas using catch agreements (DAFF, 2010). The increase in the number of rights holders in the fishery is an attempt by the government to create a more equal fishery with participants from previously disadvantaged backgrounds (Feike, 2020). However, the 2015 reallocation of rights was contested in court and the rights allocation process was suspended (Feike, 2020), resulting in a severe reduction in the number of trips made, and catch landed during the 2017 fishing year (DEFF, 2020).

The years that landed catches are not well explained by the number of vessels in the fishery are 1999 to 2001, 2008 to 2009, and 2014 to 2019. The increases in landings during these years were due to increases in the cpue of both target and bycatch landings. The increases in cpue indicate either an increase in abundance of the species or an increase in retention of species by the vessels. The interesting feature of the cpue cycle is that the periodicity is increasing. If a longer time series can be obtained a pattern could be modelled, allowing for the fishery to factor these changes into its management.

Bycatch and target cpue trends showed similar annual trends over the study period, however, there were several years when the two trends diverged. The difference between target and bycatch cpue suggests that bycatch landings are not completely dependent on target catch landings as would be expected if no bycatch targeting were practised in the fishery.

Unlike the previous studies on bycatch in the inshore trawl fishery, in this study, the cpue was calculated based on landed catches, and not total catches (Walmsley, et al., 2007; Attwood, et al., 2011). Therefore, the cpue values could be confounded by a change in the retention or discarding rate of a species. Differences in cpue between the two studies can be used to infer the presence or lack of discarding practices in the fishery.

The choice of which species to land and which to discard is a complex issue that factors in the value of the species, the processing cost, and the discarding regulations in the fishery (Walmsley, et al., 2007). The inshore trawl fishery has a low discard rate when compared to other trawl fisheries (Attwood, et al., 2011; Davis, et al., 2009). The low discard rate suggests that landed catch rates are similar to total catch rates, however the discard rate is not uniform for all species as commercially valuable species are preferentially retained (Attwood, et al., 2011). Therefore, catch estimates from landed records will be more accurate for the commercially valuable species.

The increase in the landed bycatch rate could indicate an increase in the targeting of bycatch, an increase in the availability of bycatch species, or a decrease in the catch of the target species. Five of the top bycatch species are either depleted or under heavy fishing pressure, and four are at optimal levels (DEFF, 2020). Of the two target species *M. capensis* showed declining abundances from the 1990s to 2014 and *A. pectoralis* showed steady abundances throughout the study period, expect for one drop from 2012 to 2016 (DEFF, 2020). Because the cpue of bycatch did not increase the increase in bycatch rate is likely due to decreases in target species abundances.

Seasonal patterns in the effort, landed catch, cpue, and bycatch rate

Total effort did not change across the seasons, but the fishing behaviour of vessels did. Both the number and duration of trips increased from summer to winter, while the number of trawls decreased. Due to its upward vertical migration at night, *M. capensis* is mainly trawled during the day (Payne, 1989). Winter has shorter days, resulting in less daylight for trawling. Therefore, as the days become shorter and the number of trawls made a day decreases trips durations must increase to maintain the same number of hours trawled (Stewart & Japp, 2019). Additionally, as the temperature decreases in winter the fish can be kept fresher for longer, also allowing for the increase in trip duration. The increase in the number and duration of trips could be a strategy to offset the decrease in the number of trawls made a day and maintain total effort across the year.

The total effort remained constant across the year, while the target species cpue decreased. The decrease in cpue should have therefore resulted in a decrease in landed target catches. However, no significant difference in target landings across the seasons was detected. An explanation for this is that the statistical power of the test was not sufficient to detect the difference in target landings but was sufficient to detect a difference in the target cpue.

Target species landings decrease from summer to winter, while bycatch landings increase. The pattern in target and bycatch landings across the seasons could be due to either a change in the abundance of the species or a re-direction of effort from target species to bycatch species. While *A. pectoralis* is not associated with any known seasonal migrations, *M. capensis* is believed to migrate inshore during winter in response to the temperature changes along the Agulhas Bank (Millar, 2000). There is evidence of several abundantly caught bycatch species, such as *A. inodorus*, migrating inshore in winter in response to the change in water temperatures (Japp, et al., 1994; Griffiths, 2000). Therefore, patterns in target and bycatch landings across the seasons are likely due to a combination of an increased abundance of bycatch species over the Agulhas Bank and a re-direction of effort from the target species to the bycatch species.

The most likely explanation for this re-direction of effort during the second half of the year is to avoid fulfilling target species quotas for the year too soon. If effort is redirected in winter to bycatch species it would not show up as a change in total hours but would result in an increase in cpue, and so would be hard to detect. The opposite pattern of bycatch landings and cpue to target species suggests that vessels are redirecting effort to bycatch species to reduce the proportion of the target species in the catch, perhaps to prolong the fulfilment of the quota.

Hypothesis testing

Trawls targeting *A. pectoralis* only account for 20% of the landed catch but result in a significantly higher bycatch rate than trawls targeting *M. capensis*. The high bycatch rate in *A. pectoralis* trawls could be due to these trawls occurring over shallower and more diverse grounds (Smale, et al., 1993). Alternatively, as *A. pectoralis* is not as abundant as *M. capensis* and has smaller quotas (Stewart & Japp, 2019), vessels trawling for *A. pectoralis* could be targeting commercially valuable bycatch species to supplement their profits.

The majority of trawls are made during the day due to the vertical diurnal migration of *M. capensis* (Payne, 1989) and have a higher cpue than night trawls. Day trawls are expected to have lower bycatch rates due to the decrease in *M. capensis* in night trawls, as found in previous studies (Attwood, et al., 2011). However, in this study, day trawls were found to have higher bycatch rates than night trawls. The previous study used total catch to estimate the bycatch rate (Attwood, et al., 2011), while in this study landed catches were used. Therefore, the decreased bycatch rate during day trawls found in this study as compared to previous studies could indicate that there is an increase in discarding practices during night trawls as compared to day trawls.

Trawls starting in each depth category have significantly different landed bycatch rates. Trawls at depths between 90 and 100 m result in the highest landed bycatch rates, while those at depths between 110 and 120 m result in the lowest landed bycatch rates. The fact that the highest landed bycatch rates occur in depths of 90 to 100 m and not 60 to 70 m is surprising as *A. pectoralis,* which is associated with higher bycatch rates than *M. capensis*, is mostly caught at depths between 60 to 70 m (Japp, et al., 1994). However, as the two target species were combined when assessing landed bycatch rate per depth group the *M. capensis* influence is dominating the analysis.

Conclusion

The fishery has decreased in size, which has led to a decrease in total landings, and hence bycatch landings. Therefore, the volume of bycatch landed has decreased from 1990 to 2019, however, the landed bycatch rate has increased. Therefore, while less total bycatch is being landed, the proportion that is bycatch in the fishery is increasing. This latter trend may be perceived as problematic if the statistic is viewed in isolation.

The fishery spreads its effort evenly over the year, but the bycatch landings increase in the second half of the year, while target landings decrease. The increase in bycatch landings is associated with an increase in landed bycatch rate in the second half of the year and indicates a partial re-direction of effort towards bycatch species in the second half of the year.

The landed bycatch rate is significantly higher in trawls targeting *A. pectoralis* than those targeting *M. capensis*, and highest in trawls made at depths between 90 and 100 m. These findings could be used to adjust bycatch management strategies to encourage trawls that result in lower bycatch rates. Trawls during the day result in higher landed bycatch rates than those during the night, despite previous evidence suggesting that the opposite is true of total bycatch rates. Therefore, our findings, when compared to those of previous studies of discard rates using observer records, suggest that the discarding of bycatch is increased at night, resulting in lower landed bycatch rates.

CHAPTER 3: DETERMINANTS OF LANDED CATCHES IN THE INSHORE TRAWL FISHERY

Abstract

The inshore trawl fishery has a diverse catch composition with more than 130 species recorded in their catches. So far, the catch has been described but there are still no studies on determinants of the catch composition. In this chapter, I used multivariate analysis to describe the variation in landed catch composition among the variable’s *year*, *month*, *vessel*, and *area*. I then used two PERMANOVA models to model the catch composition per trip and trawl. The years clustered into three groups at an 85% similarity (1990 to 1999, 2012 to 2015, and the remaining years in the period 2000 to 2019), the months into three at a 94% similarity, the vessels into five with a 78% similarity, and the areas into six at an 87% similarity. The landed catch composition per trip was influenced by the *vessel* ($F(1, 21) = 32.7$, $p < 0.001$, $R^2 = 0.31$), *year* ($F(1, 29) = 16.0$, $p < 0.001$, $R^2 = 0.21$), and *season* ($F(1, 3) = 30.0$, $p < 0.001$, $R^2 = 0.04$). For the second model, five vessels were compared for two years, while ‘simultaneously’ operating in ten grid cells. The landed catch composition per trawl was influenced by the *grid cell* ($F(1, 9) = 15.5623$, $p < 0.001$, $R^2 = 0.12$), *vessel* ($F(1, 4) = 25.2$, $p < 0.001$, $R^2 = 0.08$) and *year* ($F(1, 1) = 22.9$, $p < 0.001$, $R^2 = 0.02$). These models will help management to evaluate regulations to help restrain the catches of vulnerable bycatch species.

Introduction

Determinants of catch composition

It is important to know the determinants of the variation in the landed bycatch to create effective management that will result in rehabilitating the currently overfished and vulnerable species back to sustainable levels (Roberson & Wilcox, 2021; Kennelly & Braodhurst, 2021). If the landed bycatch composition can be modelled, then the effect of various management strategies can be evaluated, and more effective bycatch regulations created. When bycatch is managed properly it will add more value to the inshore trawl fishery and decrease inter-fishery conflicts (Visser, 2015; SADSTIA, 2019).

The species assemblage of the Agulhas Bank has changed substantially over the last 25 years, with a decrease in previously abundant species such as *Pterogymnus laniarius* (Panga), *Genypterus capensis* (Kingklip), and *Argyrosomus inodorus* (Silver kob) and increases in previously scarce species such as *Chelidonichthys* species (Gurnards), *Trachurus capensis* (Horse mackerel), *Squalus* species (Dog sharks), and *Merluccius* species (Cape hakes) (Japp, et al., 1994; Currie, 2017). The change in the population sizes of many species has affected the biodiversity available to inshore trawl fishing vessels and could be responsible for the decrease in *T. capensis* and increase in *Chelidonichthys* recorded in the landings of inshore trawl vessels operating out of Port Elizabeth between the years 1968 and 1995 (Booth & Hecht, 1998).

Seasonal migrations can also affect the availability of bycatch to vessels during the year. Many species on the Agulhas Bank show large seasonal fluctuations (Brandao, 2021; Japp, et al., 1994; Scott, 1949). Species such as *G. capensis*, *A. inodorus, Lophius vomerinus* (monk)*, Rhabdosargus globiceps* (White stumpnose) and *P. laniarius* migrate inshore during winter and offshore during summer in response to temperature changes (Badenhorst & Smale, 1991; Booth & Hecht, 1998). In summer, catches of *A. pectoralis* increase and during spring and autumn catches of *T. capensis* and *Chelidonichthys* species both increase (Booth & Hecht, 1998).

Bycatch in the inshore trawl fishery

Many bycatch species in the inshore trawl fishery are commercially valuable and landed bycatch constitutes around 36% of the fisheries profits (Walmsley, et al., 2007). Therefore, there is an incentive for vessels in the inshore trawl fishery to target bycatch species to increase profits, as shown in a previous study of the bycatch rate in the fishery (Greenston, 2014). Some bycatch species have even been termed ‘joint-product’ or ‘semi-targets’ by the fishery (SADSTIA, 2019).

The differences in bycatch among vessels can be attributed to three main causes: differences in the fishing gear, the area in which the vessel trawls, and differences in the fishing behaviour of the vessel (Roberson & Wilcox, 2021). The amount that each of these components determines the rate of the bycatch landed will inform the management that will be most effective in managing the bycatch. In this study the fishing behaviour of a vessel is defined as all decisions made by the skipper, besides those of where to trawl. Therefore, fishing or skipper behaviour includes the speed, length, and duration of the trawl, as well as all decisions on discarding and retention of catches.

Aims and objectives

The determinants of landed composition in the fishery were assessed. First by describing the landed catch composition in the fishery, and then describing how catch composition changes among years, months, vessels, and areas. The landed catch composition per trip will be modeled using the variables year, season, and vessel to ascertain what proportion of the landed catch composition is determined by the vessel, and what proportion is determined by environmental factors. The landed catch composition of a subset of vessels fishing in the same areas at the same time will then be modelled to ascertain how much of the landed catch composition determined by the vessel is due to the area the vessel is fishing, and how much is due to the fishing behaviour of the vessel.

(Roberson & Wilcox, 2021), The vessels fishing behaviour, encompassing the targeting and discarding practices of the skipper, is known to affect the catch composition landed (Hilborn, 1985; Marchal, et al., 2006). To differentiate the effect of skipper targeting and discarding of catch, I will compare the findings of landed catches with those of total catches in previous studies that used observer data (Walmsley, et al., 2007; Attwood, et al., 2011).

Methods

Data filtering and cleaning

The records contained species codes for all species landed in a trip and trawl. Species codes that could not be linked to a real species, genus, family, clade, or categorical group were removed. In addition, three species codes did not represent one species but were categorical groups representing a mixture of species that shared similar morphological traits: *Teleostei demersal*, *Teleostei redfish*, and *Selachii*. *Teleostei demersal* and *Teleostei redfish* could not be assigned to any species and so were removed from the records.

Selachii was a combination of *Mustelus* (houndshark) and *Galeorhinus galeus* (soupfin shark). In trawl records, these two shark species were recorded as *Selachii* but were usually split into the two respective species in the trip records. Trawl records of *Selachii* were split into the two species using the proportion of each in the trip record. However, not all trip records split the Selachii records, resulting in many unsorted *Selachii* records in the trip records. All unsorted Selachii records were split into the respective species based on the proportion of these two species in the disaggregated landing records of the vessel.

Calculation of landed catch composition

Annual landed catch composition was calculated by summing the landed mass of each species in each year and dividing it by the total mass landed that year. The average annual landed catch composition was then calculated.

Cluster analysis of the variables *year, season, vessel*, and *grid cell*

The *year, season, vessel*, and *grid cell* variables were used to aggregate the landed catch values. The year includes all thirty years between 1990 and 2019; the seasons include the four seasons summer, autumn, winter, and spring; the grid cells include 54 of the 20’ x 20’ commercial grid cells with more than 30 records that cover the inshore trawl grounds; the vessels include the 72 vessels that recorded trips in the inshore trawl fishery between 1990 and 2019. Only the species that made up 99% of the annual average catch composition by weight were included in the analysis.

A cluster analysis was run on all four variables using a Bray-Curtis similarity matrix (Bray & Curtis, 1957) of their catch compositions and an “average” clustering method. The cluster analysis was cut at a dissimilarity of 15% for years and grid cells, 5% for seasons, 22% for vessels, and 13% for grid cells.

Results of the cluster analysis were displayed using dendrograms and multi-dimensional scaling (MDS) plots. The average catch composition of each group identified in the cluster analysis was graphed using bar graphs. The SIMPER procedure was used to determine the defining species of each group, and the species responsible for the differences among the groups.

Data used in the PERMANOVA models

The model of catch composition per trip used trip catches from all 30 years from 1990 to 2019, all four seasons, and the 22 vessels that operated for more than 50% of the years in the study period. For the model of catch composition per trawl only vessels that all fished in the same areas during the same years and seasons were included. The areas were defined by the 20’ x 20’ commercial grid system that covers the inshore trawl grounds. Five vessels fished in the same ten grid cells during the same two years, in every season.

The landed catches per trip and trawl were normalised to remove the effect of volume change over time by dividing the landed catch of each species by the total landed catch. The normalised landed catch values were then transformed using a square root transformation to downweigh the effect of the high *M. capensis* abundances. Only the species that made up 99% of the annual average catch composition by weight were included in the analysis. The analysis did not include all species to avoid the species-sample matrix table from being dominated by zeros. Bray-Curtis similarity matrixes were calculated for trip and trawl datasets.

PERMANOVA models

To model the landed catch composition per trip, a semi-crossed PERMANOVA model with the Bray-Curtis similarity matrix as the dependent variable and *year*, *season*, and *vessel* as explanatory variables were used. The *years* (n=30) and *seasons* (n=4) were set as fixed variables and the *vessels* (n=22) as a random variable.

To model the landed catch composition per trawl a fully crossed PERMANOVA model with the Bray-Curtis similarity matrix as the dependent variable and *year, season*, *grid cell,* and *vessel*, as explanatory variables were used. The *years* (n=2), *seasons* (n=4), *vessels* (n=5), and *grid cells* (n=10) were set as random variables.

For both models, the datasets were too large to run using the available computing power. Therefore, ten iterations of each model were run on random subsets of 35% of trip records and 25% of trawl records. The following important model outputs were averaged across the ten iterations for both models: R^2, F statistic, and P value. Model goodness-of-fit was obtained by examining plots of the standardised residuals for each iteration.

Rstudio (2020) was used to undertake all analyses.

Results

Annual average catch composition

The two target species *M. capensis* and *A. pectoralis* made up 58.7% and 5.4% of total landings respectively. The remaining landings (bycatch) included a further 43 taxa. Thirty-three of these taxa were identified to species level, three to genus

(*Chelidonichthys, Mustelus, Squalus*), five to family (*Istiophoridae, Mugilidae, Ommastrephidae, Scombridae, Sepiidae*), and two to order (*Octopoda, Rajiformes*). Of the bycatch, *T. capensis and Rajiformes* (skates) had the highest recorded landed catches, both higher than *A. pectoralis.*

Despite the fishery landing fish against 45 species codes (taxa), just 13, including the two target species, made up 99% of the annual average landed catch composition by mass (Table 1). *M. capensis* contributed the most, followed by *T. capensis*, *Rajiformes*, and *A. pectoralis*. The 13 species codes included ten biological species, two genera (*Chelidonichthys* and *Mustelus)*, and one order (*Rajiformes*). In total, four Chondrichthyes (*Galeorhinus galeus, Mustelus, Rajiformes, and Callorhynchus capensis),* one cephalopod (*Loligo reynaudii*) and eight teleosts appear in the top 13 species codes.

According to the International Union for Conservation of Nature (IUCN), of the ten species codes identified to species level, five are classified as least concern (*M. capensis, T. capensis, P. laniarius, C. capensis*, and *L. reynaudii*), two as vulnerable (*A. inodorus* and *R. globiceps*), one as critically endangered (*G. galeus*), one as data deficient (*A. pectoralis*), and one has not been assessed (*G. capensis*) (Mann, et al., 2014; Mann, et al., 2014; Lwamoto, 2015; Smith-Vaniz, et al., 2018; Allcock & Taite, 2019; Fennessy & Winker, 2020; Finucci & Pacoureau, 2020; Walker, et al., 2020).

While the status of the *A. pectoralis* stock is uncertain, fishing pressure has decreased substantially in recent years and catches have remained below the TAC since 2000 (DEFF, 2020). Therefore, the current fishing pressure is considered optimal (DEFF, 2020). According to local studies, the *G. capensis* was in decline around the 1950s but has since shown a recovery in its west coast stock (Japp, et al., 1994; Brandao, 2021). However, the south coast stock is decreasing, which is a cause for concern in the inshore trawl fishery (DEFF, 2020).

Based on their distributions, the *Mustelus* species caught in the inshore trawl are most likely *Mustelus capensis* and *Mustelus palumbes*. The species are listed as endangered and least concern respectively according to the IUCN (Pollom, et al., 2020; Jabador, et al., 2021). The *Mustelus* stocks are currently at optimal levels but are subject to heavy fishing pressure that could cause the species to decline in the future (DEFF, 2020).

Both species of *Chelidonichthys* found in South African waters (*C. capensis* and *C. queketti*) are listed as least concern (Motomura, et al., 2018; Motomura, et al., 2018). The two *Rajiformes* species found in inshore trawl fisheries landings, *Raja clavata* and *Raja straeleni*, are listed as near threatened and data deficient, respectively. However, specifically in South Africa, *Raja straeleni* is classified as least concern (Smale, 2009; Ellis, 2016; Froese & Pauly, 2016).

Table 1. The annual average landed catch in kg for the inshore trawl fleet between 1990 and 2019. The top thirteen are listed. C.P: Cumulative percentage of the total catch. Percentage refers to the percentage by weight of each species in the total catch. Both percentages are rounded to one decimal place.

	Scientific name	*Common name*	*Landed mass (t)*	*Percentage (%)*	*C.P (%)*
1	*Merluccius capensis*	Shallow water hake	*5826*	*59.2*	*59.2*
2	*Trachurus capensis*	Horse mackerel	*988*	*10.0*	*69.2*
3	*Rajiformes*	Skates	*781*	*7.9*	*77.1*
4	*Austroglossus pectoralis*	East coast sole	*540*	*5.5*	*82.6*
5	*Pterogymnus laniarius*	Panga	*483*	*4.9*	*87.5*
6	*Callorhynchus capensis*	St joseph shark	*390*	*4.0*	*91.5*
7	*Chelidonichthys*	Gurnard	*227*	*2.3*	*93.8*
8	*Loligo reynaudii*	Chokka squid	*152*	*1.6*	*95.3*
9	*Argyrosomus inodorus*	Silver kob	*137*	*1.4*	*96.7*

10	*Galeorhinus galeus*	Soupfin shark	*72*	*0.7*	*97.4*
11	*Genypterus capensis*	Kingklip	*66*	*0.7*	*98.1*
12	*Rhabdosargus globiceps*	White stumpnose	*45*	*0.5*	*98.6*
13	*Mustelus*	Houndshark	*43*	*0.4*	*99.0*

Cluster analyses

Years group into three clusters at a 15% dissimilarity based on their catch compositions: 1990 to 2002, 2012 to 2015, and the remaining years in the period 2003 to 2019 (figure 1). The years 2012 to 2015 form a very distinct cluster, with the highest dissimilarity to the rest of the years. In the MDS the years cluster in chronological order (figure 2). There is a trend of a decreasing proportion of *T. capensis* and increasing proportions of *Rajiformes, P. laniarius,* and *C. capensis* in the landings across the years (figure 3).

The clusters within-group similarities range from 91% to 92%. Years in all clusters are all defined by their proportions of *M. capensis* and *Rajiformes*. The high impact of these species can be attributed to the sensitivity of SIMPER analyses to high abundances. The years in cluster one are also defined by their high proportions of *T. capensis*, years in cluster two by their high proportions of *P. laniarius*, and years in cluster three by their high proportions of *Callorhinchus capensis* (St Joseph shark).

The dissimilarities between clusters one and two, and two and three are both 16%. The dissimilarity between clusters one and three are 28%. Years in cluster one are distinguished from those in cluster two by a lower proportion of *C. capensis* and *Galeorhinus galeus* (Soupfin shark). Cluster three is distinguished from those in clusters one and two by a higher proportion of *C. capensis* and a lower proportion of *M. capensis* and *T. capensis*.

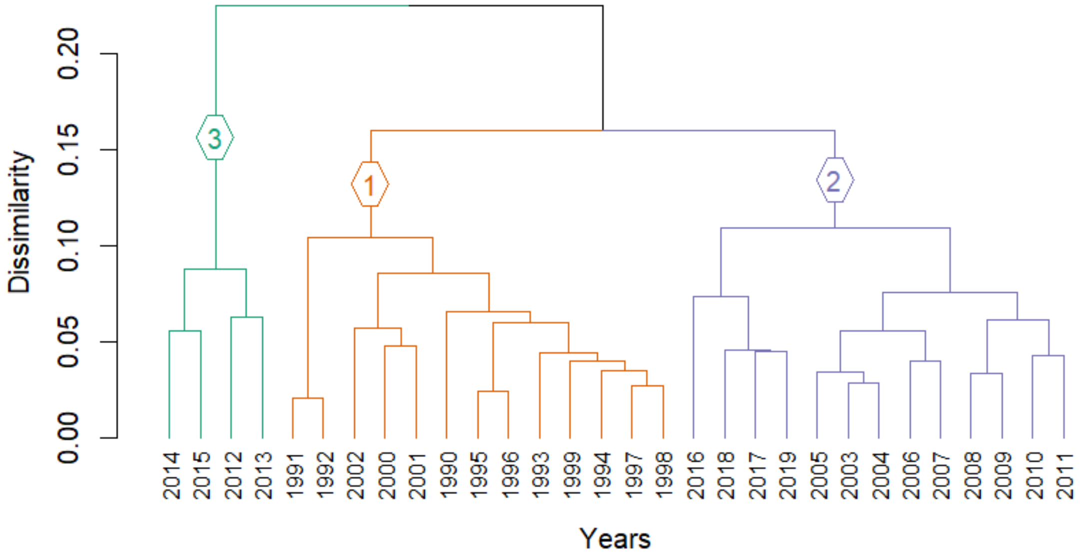


Figure 1. Dendrogram of the hierarchical cluster analysis (Average) of the average landed catch composition per year. The ordinate axis indicates the proportion of dissimilarity between merged clusters The dendrogram was cut at a 15% dissimilarity and the leaves were coloured and numbered according to the groupings.

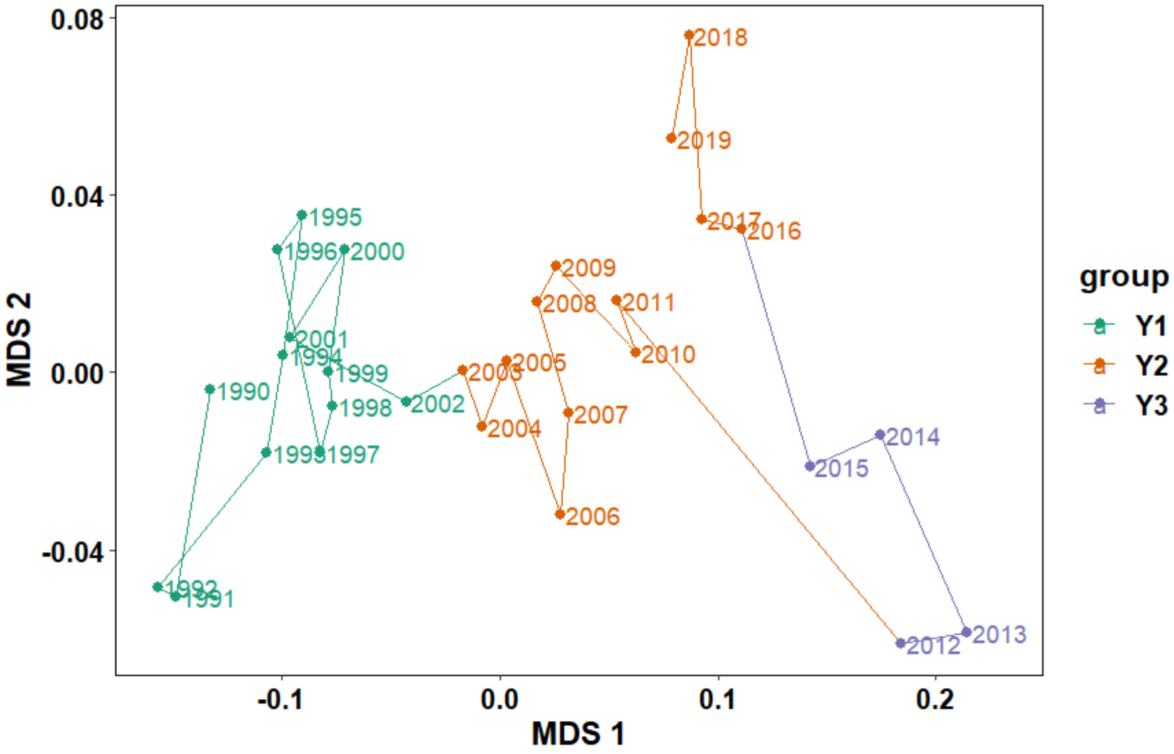


Figure 2. Multidimensional scaling (MDS) plot visualising the level of similarity of years based on their catch compositions. The years are coloured by the groupings found in a cluster analysis cut at a 15% dissimilarity, and a line was drawn between temporally adjacent years.

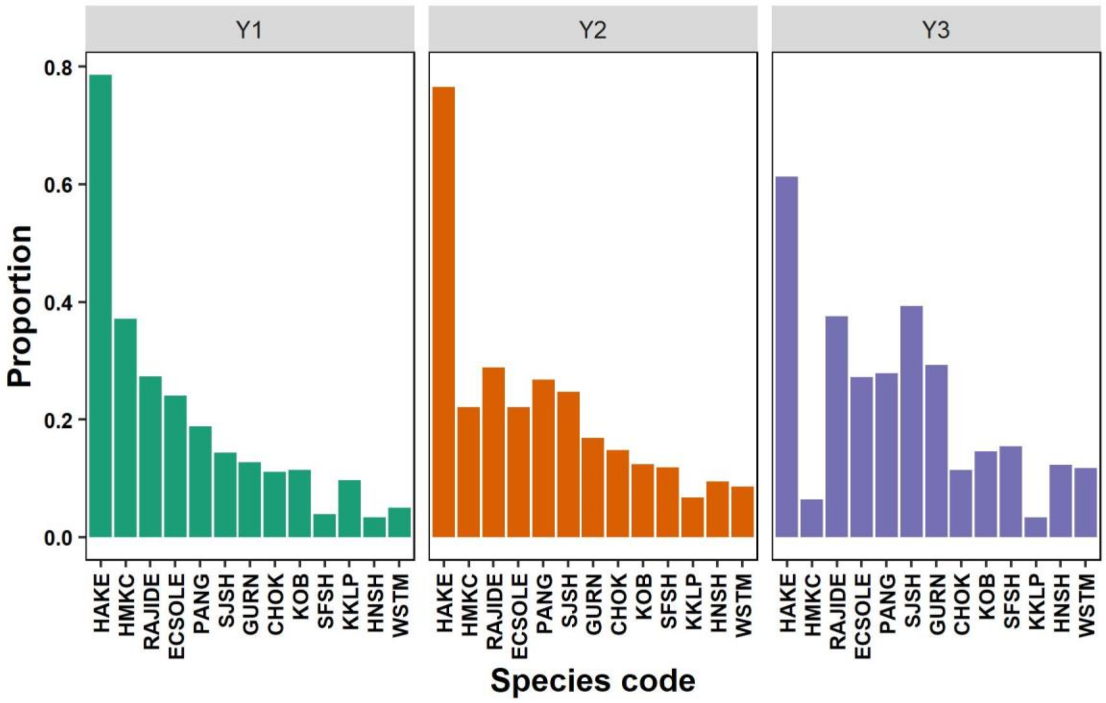


Figure 3. Bar graphs of the normalised and square root transformed catch composition for each of the clusters identified by the cluster analysis. The clusters were identified in a cluster analysis which grouped the years at a 15% dissimilarity based on average catch composition per trip such that Y1) 1990 to 2001, Y2) 2002 to 2011 and 2016 to 2019, and Y3) 2012 to 2015 and was cut at a 15% dissimilarity. Only the 13 species that made up 99% of the annual average landed catch composition by mass in the inshore trawl fishery are shown. The graphs are labelled with the species abbreviation such that HAKE = *Merluccius capensis*, HMCK = *Trachurus capensis*, RAJIDE = *Rajiformes*, ECSOLE = *Austroglossus pectoralis*, PANG = *Pterogymnus laniarius*, KOB = *Argyrosomus inodorus*, SJSH = *Callorhinchus capensis*, GURN = *Chelidonichthys*, CHOK = *Loligo reynaudii*, KKLP = *Genypterus capensis*, WSTM = *Rhabdosargus globiceps*, SFSH = *Galeorhinus galeus*, HNSH = *Mustelus*.

Months group into three clusters at a 6% dissimilarity based on their catch composition: 1) January to May 2) October to December 3) June to September (figure 4). The months cluster into two main clusters separating the year into two almost equal halves. The second half of the year is then clustered into two more groups (figure 4). From the MDS we can see that the seasons summer, winter, and spring all group together, while the months in autumn do not (figure 5). The main difference between the first half of the year and the second is a drop in the proportion of *M. capensis* landed in the second part (figure 6).

The clusters within-group similarities range from 96% to 97%. Months in cluster one, two, and three are all defined by their proportions of *M. capensis, T. capensis*, and *Rajiformes*.

Between-group dissimilarities range from 6% to 9%. The months in cluster one are distinguished from those in cluster two by a lower proportion of *P. laniarius* and *A. inodorus* and those in cluster three by a lower proportion of *Rajiformes* and *A. inodorus*. The months in cluster two are distinguished from those in cluster three by a lower proportion of *Rajiformes* and a high proportion of *L. reynaudii* and *Chelidonichthys*.

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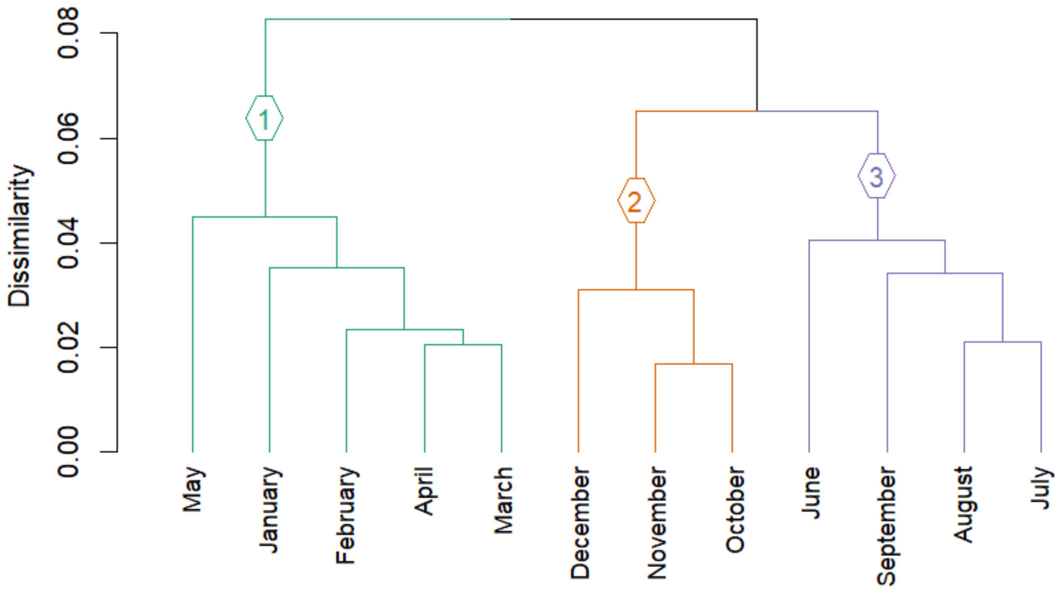

Figure 4. Dendrogram of the hierarchical cluster analysis (Average) of the average landed catch composition per month. The ordinate axis indicates the proportion of dissimilarity between merged clusters. The dendrogram was cut at a 6% dissimilarity and the leaves were coloured and numbered according to the groupings.

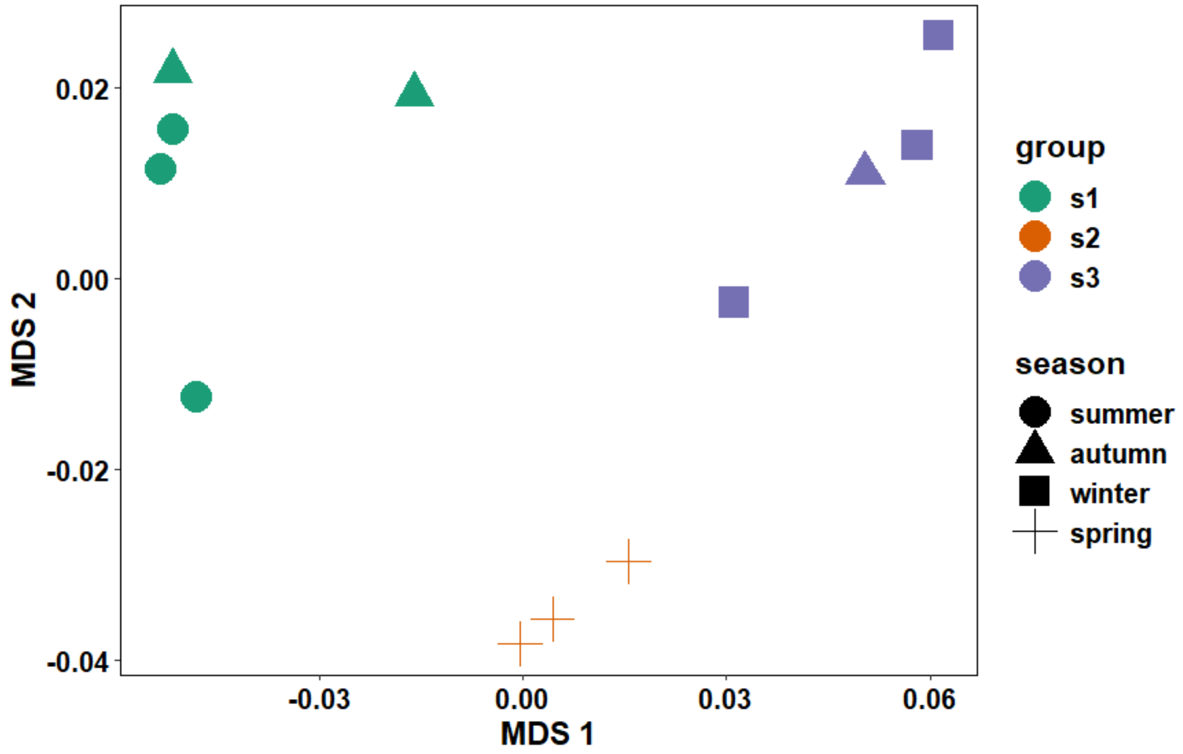

Figure 4. Multidimensional scaling (MDS) plot visualising the level of similarity of months based on their catch compositions. The months are coloured by the groupings found in a cluster analysis cut at a 22% dissimilarity and are shaped by the season.

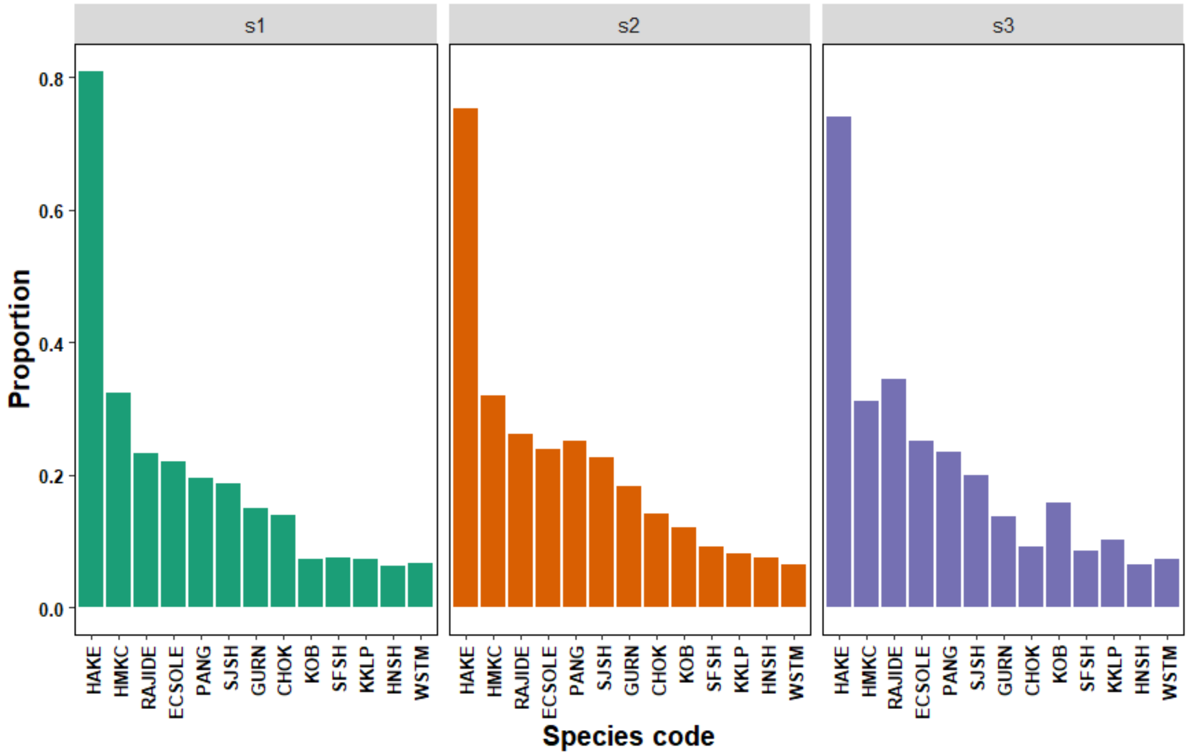

Figure 5. Bar graphs of the normalised and square root transformed catch composition for each of the clusters identified by the cluster analysis. The clusters were identified in a cluster analysis which grouped the months at a 6% dissimilarity based on average catch composition per trip such that S1) January to May, S2) June to September, and S3) October to December. Only the 13 species that made up 99% of the annual average landed catch composition by mass in the inshore trawl fishery are shown. The graphs are labelled with the species abbreviation such that HAKE = *Merluccius capensis*, HMCK = *Trachurus capensis*, RAJIDE = *Rajiformes*, ECSOLE = *Austroglossus pectoralis*, PANG = *Pterogymnus laniarius*, KOB = *Argyrosomus inodorus*, SJSH = *Callorhinchus capensis*, GURN = *Chelidonichthys*, CHOK = *Loligo reynaudii*, KKLP = *Genypterus capensis*, WSTM = *Rhabdosargus globiceps*, SFSH = *Galeorhinus galeus*, HNSH = *Mustelus*.

Vessels group into five clusters at a 22% dissimilarity based on their catch compositions. There are four main clusters and one smaller cluster (containing only two vessels). Most vessels group into cluster three (Figure 6). In the MDS we can see that vessels group by the target species (figure 7). Three clusters (clusters one, four, and five) contain only *M. capensis* directed vessels, one cluster (cluster three) contains majority *M. capensis* directed vessels and nine *A. pectoralis* directed vessels, and one cluster (cluster two) only *A. pectoralis* directed vessels (figure 8).

Cluster one is not included in the simper results as both vessels made less than 15 trips in less than five years. The clusters within-group similarities range from 84% to 93%. Vessels in all *M. capensis* clusters are all defined by their proportions of *M. capensis* and *T. capensis*. Vessels in cluster three are also defined by their high proportions of *Rajiformes* and vessels in clusters four and five by their high proportions of *P. laniarius*. Vessels in cluster two are defined by their high proportions of *A. pectoralis, M. capensis,* and *Rajiformes*.

The dissimilarities among all clusters range between 24% and 25% except between clusters two and four and clusters two and five which have dissimilarities of 40% and 32% respectively. Vessels in cluster two are distinguished from those in cluster four and five by a lower proportion of *T. capensis* and a higher proportion of *A. pectoralis* and *Rajiformes*. Vessels in cluster two are also distinguished from those in cluster three by a lower proportion of *T. capensis* and a higher proportion of *A. pectoralis,* but there is a smaller difference in proportions between cluster two and three than cluster two and clusters four and five. Vessels in cluster three are distinguished from those in clusters four and five by a higher proportion of *A. pectoralis* and a lower proportion of *T. capensis*. Vessels in cluster four are distinguished from those in cluster five by a higher proportion of *T. capensis* and a lower proportion of *P. laniarius* and *C. capensis*.

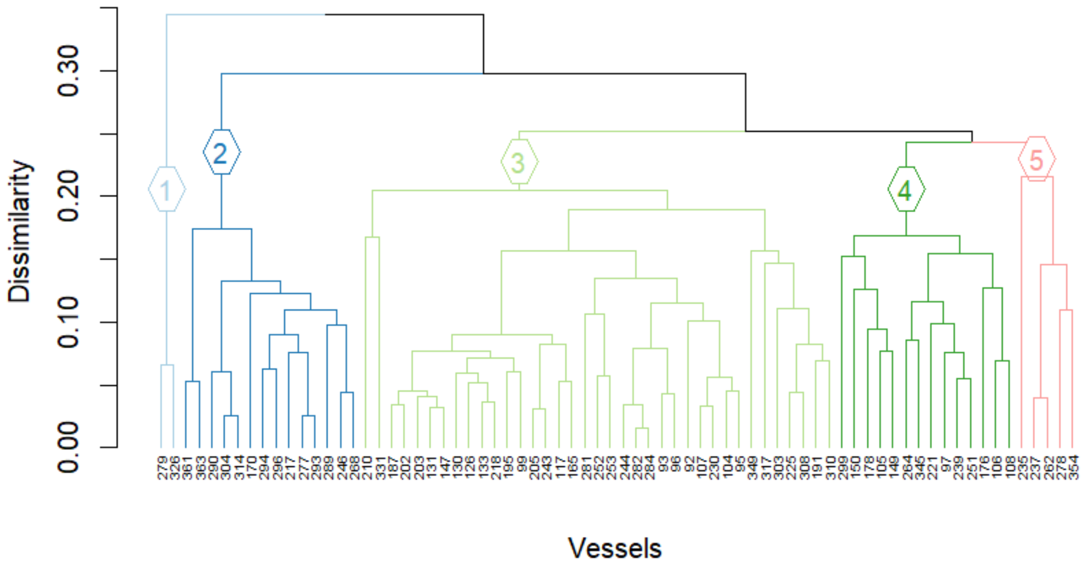

Figure 6. Dendrogram of the hierarchical cluster analysis (Average) of the average landed catch composition per vessel. The ordinate axis indicates the proportion of dissimilarity between merged clusters The dendrogram was cut at a 22% dissimilarity and the leaves were coloured and numbered according to the groupings.

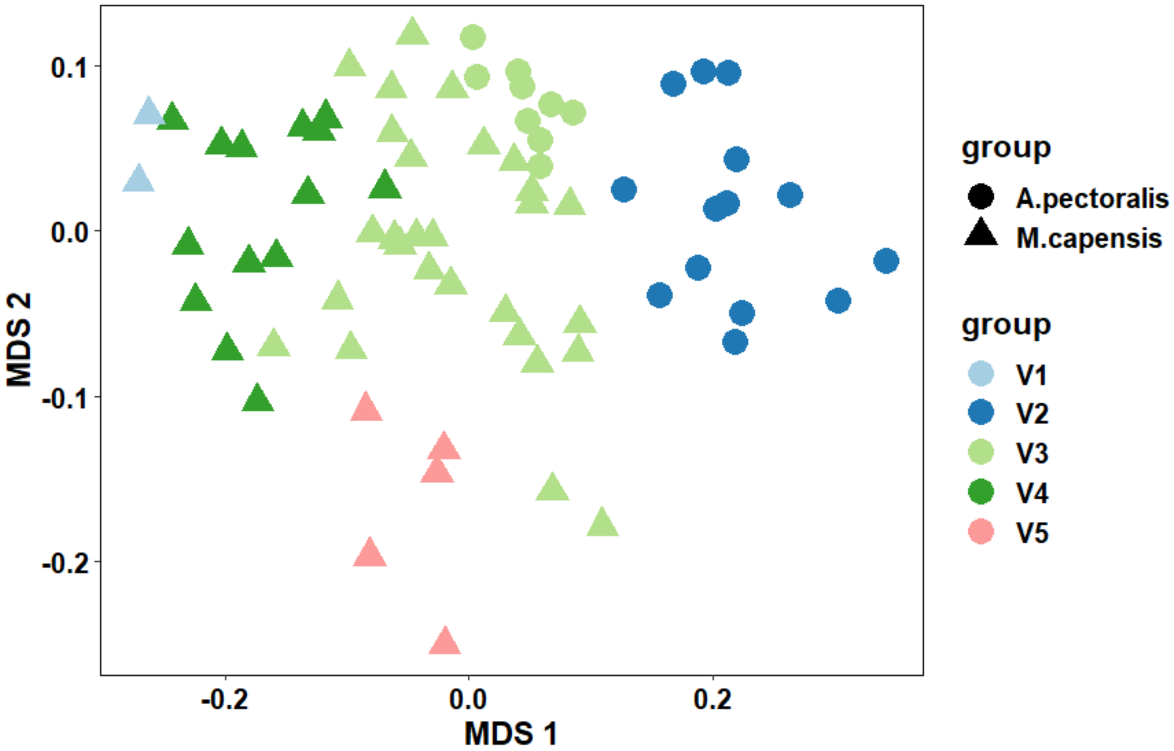

Figure 7. Multidimensional scaling (MDS) plot visualising the level of similarity of vessels based on their catch compositions. The vessels are coloured by the groupings found in a cluster analysis cut at a 22% dissimilarity and are shaped by the species that they target. If both target species were targeted in less than 70% of the trawls the vessel is classified as 'both'.

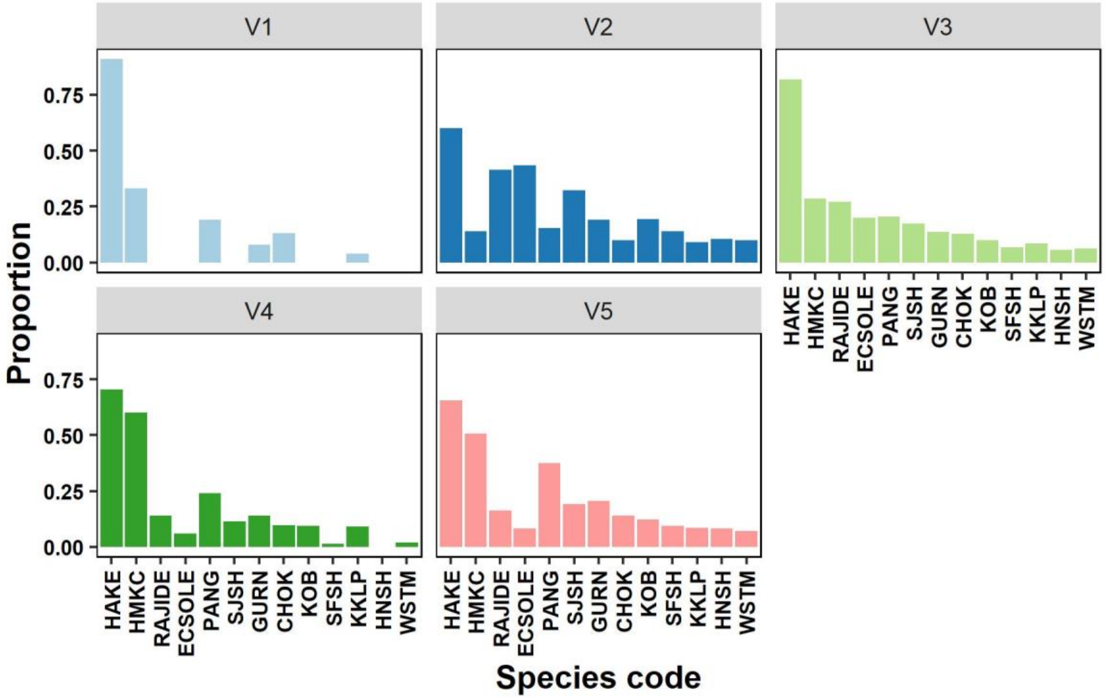

Figure 8 Bar graphs of the normalised and square root transformed catch composition for each of the clusters identified by the cluster analysis. The clusters were identified in a cluster analysis which grouped the vessels at a 22% dissimilarity based on average catch composition per trip. Only the 13 species that made up 99% of the annual average landed catch composition by mass in the inshore trawl fishery are shown. The graphs are labelled with the species abbreviation such that HAKE = *Merluccius capensis*, HMCK = *Trachurus capensis*, RAJIDE = *Rajiformes*, ECSOLE = *Austroglossus pectoralis*, PANG = *Pterogymnus laniarius*, KOB = *Argyrosomus inodorus*, SJSH = *Callorhinchus capensis*, GURN = *Chelidonichthys*, CHOK = *Loligo reynaudii*, KKLP = *Genypterus capensis*, WSTM = *Rhabdosargus globiceps*, SFSH = *Galeorhinus galeus*, HNSH = *Mustelus*.

The grid cells group into nine clusters at 15% dissimilarity based on their catch composition (figure 9). Cluster one and two are combined into cluster two and clusters six, seven, and nine are combined into cluster nine in figures 10 and 11 as clusters one, six, and seven only contain one grid cell each.

The clusters within-group similarities range from 89% to 92%. *M. capensis* makes up more than 50% of the catch compositions of all groups and therefore has the largest effect on within-group similarity for all clusters. Grid cells in clusters two and eight are defined by their proportions of *T. capensis* and *P. laniarius* and lie on the eastern side of the inshore trawl grounds. Grid cells in clusters four and nine are defined by their proportions of *Rajiformes* and *T. capensis* and lie in the central part of the inshore trawl grounds. Grid cells in cluster five lie next to clusters four and nine and are defined by their proportion of *Rajiformes* and *A. pectoralis*. Grid cells in cluster three lie on the western edge of the inshore trawl grounds and are defined by their proportion of *Chelidonichthys* and *P. laniarius*.

The dissimilarities among the clusters range between 24% and 25%. Grid cells in cluster two are distinguished from those in all other clusters by a higher proportion of *T. capensis*. Grid cells in cluster three are distinguished from those in all other clusters by a higher proportion of *Chelidonichthys*. Grid cells in cluster four are distinguished from those in all other clusters by a higher proportion of *A. pectoralis* or *Rajiformes*. Grid cells in cluster five are distinguished from those in all other clusters by a higher proportion of *A. pectoralis*. Grid cells in cluster eight are distinguished from those in clusters four, five and nine by a higher proportion of *P. laniarius* and a lower proportion of *Rajiformes*. Grid cells in cluster eight are also distinguished from those in cluster three by a higher proportion of *T. capensis* and a lower proportion of *C. capensis* and those in cluster two by a higher proportion of *M. capensis* and a lower proportion of *A. pectoralis.*

Cluster three represents the area on the eastern edge of the inshore trawl grounds, cluster five, four, and eight represent the inshore areas along the coast from east to west, cluster nine represents the central area further offshore and cluster two represents the western edge (figure 11).

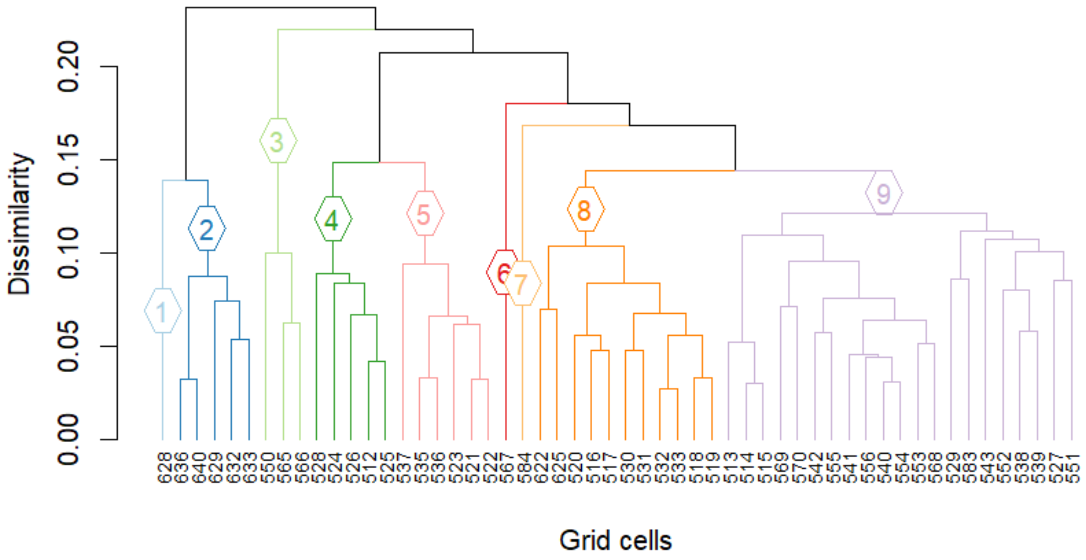

Figure 9. Dendrogram of the hierarchical cluster analysis (Average) of the landed catch composition per grid cell. The ordinate axis indicates the proportion of dissimilarity between merged clusters. The dendrogram was cut at a 13% dissimilarity and the leaves were coloured and numbered according to the groupings.

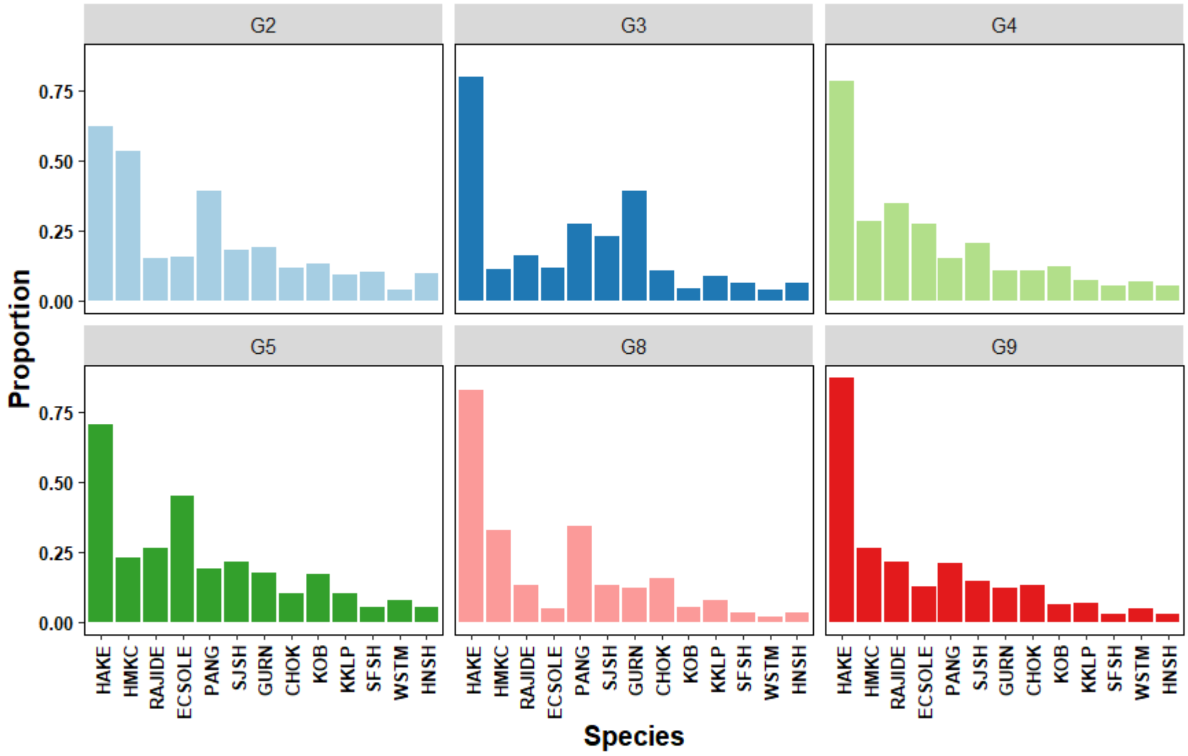

Figure 10. Bar graphs of the normalised and square root transformed catch composition for each of the clusters identified by the cluster analysis. The clusters were identified in a cluster analysis which grouped the grid cells at a 13% dissimilarity based on average catch composition per trawl. Only the 13 species that made up 99% of the annual average landed catch composition by mass in the inshore trawl fishery are shown. The graphs are labelled with the species abbreviation such that HAKE = *Merluccius capensis*, HMCK = *Trachurus capensis*, RAJIDE = *Rajiformes*, ECSOLE = *Austroglossus pectoralis*, PANG = *Pterogymnus laniarius*, KOB = *Argyrosomus inodorus*, SJSH = *Callorhinchus capensis*, GURN = *Chelidonichthys*, CHOK = *Loligo reynaudii*, KKLP = *Genypterus capensis*, WSTM = *Rhabdosargus globiceps*, SFSH = *Galeorhinus galeus*, HNSH = *Mustelus*.

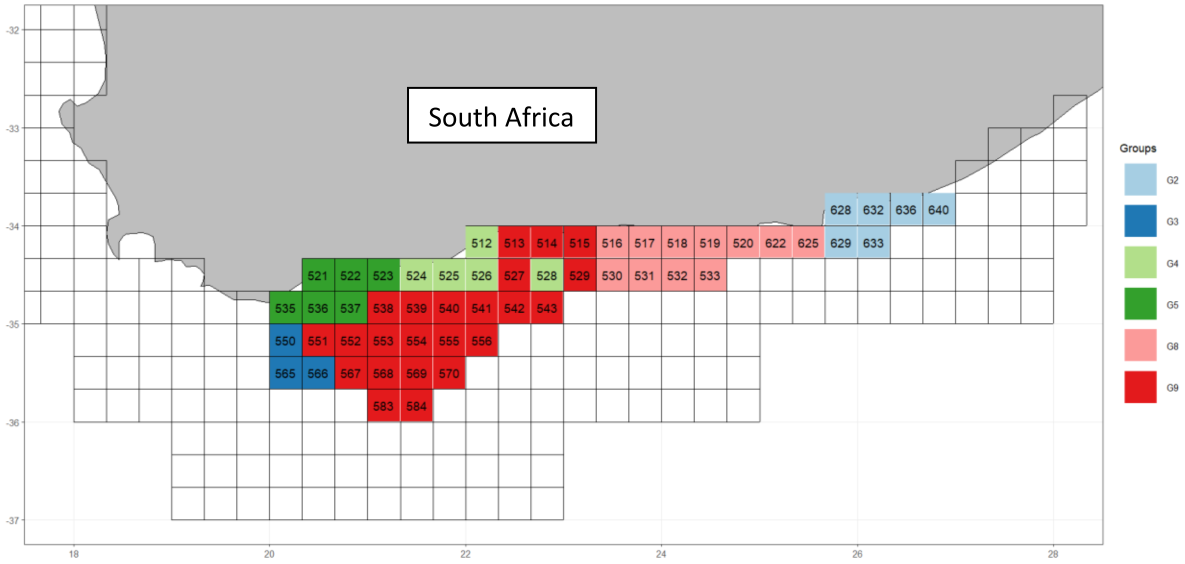

Figure 11. A map showing the South African coast and it's commercial 20' by 20' grid. The grid cells within the inshore trawl grounds are coloured according to the five main clusters identified in a cluster analysis which grouped the grid cells based on average catch composition per trawl and was cut at a 13% dissimilarity.

PERMANOVA models

A PERMANOVA model explains 95% of the variation in catch composition per trip. *Vessel* explains the greatest amount of variation, followed by *year*, and the *vessel-year* interaction (Table 2). *Season*, as well as its interactions with *year* and *vessel*, explains very little variation, despite being significant. All variables except for the *year-season-vessel* interaction term are significant.

Table 2. PERMANOVA using Bray-Curtis as a distance metric for the species composition of each trip using the average result of 10 models each on a random subsample of 35% of the records. Df: degrees of freedom; SS: sum of squares; MS: mean sum of squares; F.model: F value by permutation, R^2: R squared value, Pr(>F): p-values.

	Df	*SS*	*MS*	*F.Model*	*R^2*	*Pr(>F)*	
Year	29	9.943	0.34286	16.041	0.21241	0.001	***
Season	3	1.924	0.64142	30.009	0.04111	0.001	***
Vessel	21	14.676	0.69887	32.697	0.31353	0.001	***
Year: Season	83	3.584	0.04318	2.02	0.07656	0.001	***
Year: Vessel	285	11.126	0.03904	1.826	0.23769	0.001	***
Season: Vessel	58	1.766	0.03044	1.424	0.03772	0.001	***
Year: Season: Vessel	56	1.354	0.02418	1.131	0.02893	0.137	
Residuals	114	2.437	0.02137		0.05205		
Total	649	46.81			1		

**** <0.001; ** <0.01; *<0.05*

A PERMANOVA model explains 58% of the variation in the catch composition per trawl (Table 3). *Grid cell* explains the greatest amount of variation, followed by *vessel.* Only three interaction terms explain more than 4% of the variation in the data: *season-grid code*, *vessel-grid code*, and *season-vessel-grid code*. The *year-season* and *year-season-vessel-grid code* interaction terms explain the least amount of variation. All variables are significant.

Table 3. *PERMANOVA results using Bray-Curtis as a distance metric for the species composition of each trip using the average result of 10 models, each on a random subsample of 25% of the records. Df: degrees of freedom; SS: sum of squares; MS:*

mean sum of squares; F.model: F value by permutation, R^2: R-squared value, Pr(>F): p-values.

	Df	*SS*	*MS*	*F.Model*	*R^2*	*Pr(>F)*	
Year	1	3.226	3.2257	53.299	0.02934	0.001	***
Season	3	3.777	1.2589	20.802	0.03435	0.001	***
Grid code	9	11.305	1.2561	20.756	0.10283	0.001	***
Vessel	4	8.533	2.1333	35.249	0.07762	0.001	***
Year: Season	3	0.428	0.1426	2.356	0.00389	0.012	*
Year: Grid code	9	2.364	0.2626	4.34	0.0215	0.001	***
Season: Grid code	27	5.316	0.1969	3.253	0.04836	0.001	***
Year: Vessel	4	4.138	1.0345	17.093	0.03764	0.001	***
Season: Vessel	12	3.009	0.2507	4.143	0.02737	0.001	***
Grid code: Vessel	36	5.314	0.1476	2.439	0.04833	0.001	***
Year: Season: Grid code	26	3.556	0.1368	2.26	0.03234	0.001	***
Year: Season: Vessel	12	1.56	0.13	2.148	0.01419	0.002	**
Year: Grid code: Vessel	31	3.643	0.1175	1.942	0.03314	0.001	***
Season: Grid code: Vessel	68	6.637	0.0976	1.613	0.06037	0.001	***
Year: Season: Grid code: Vessel	8	0.835	0.1043	1.724	0.00759	0.032	*
Residuals	765	46.298	0.0605		0.42113		
Total	1018	109.938			1		

*** <0.001, **<0.01, *<0.05

Discussion

Annual average catch composition

The landed catch composition in the inshore trawl fishery from 1990 to 2019 decreased in diversity compared to the landed catch composition from 1967 to 1995 (Booth & Hecht, 1998). However, the number of species that made up 98% of the landed catch by weight increased (Booth & Hecht, 1998). The decrease in diversity could indicate a decrease in bycatch or an increase in bycatch discarding in the fishery. The increase in the number of species that make up the majority of the catch composition in the inshore trawl fishery's landings compared to previous landed catches could be a result of declining catches of the target or bycatch species (Currie, 2017), or market shifts influencing vessels to diversify landings (Cawthorn, et al., 2011). As the bycatch rate was found to be increasing over the study period, it is more likely that the increase is due to a decrease in target species.

When compared with total catches from previous studies using observer data, the landed catch composition from 1990 to 2019 is less diverse, and fewer species made up 98% of the landed catch (Attwood, et al., 2011). The lower diversity of species compared to total catches could be indicative of the discarding of less valuable species and selective retention of marketable species by the vessels (Attwood, et al., 2011).

It is difficult to estimate the amount of dumping by a fishery, and even more difficult to differentiate the dumping rate by vessel or species without extensive observer records (Pitcher, et al., 2002). Using the observer records available discarding in the fishery was estimated at 10% (Attwood, et al., 2011), which is low when compared to similar fisheries globally (Davis, et al., 2009; Kennelly & Braodhurst, 2021). However, due to the low observer rate in the fishery (Andrews, et al., 2015), there have not been any studies on the correlation between vessels, species, or areas and discard rates.

The two target species made up the majority of the landed catch composition, due to the high proportion of *M. capensis*, which alone made up 58% of the landed catch composition. *A. pectoralis,* however, was only the fourth most abundantly landed species despite being a target. Usually, the target species in a fishery is the most abundant and makes up the majority of landings (Scheffer, et al., 2005; Davis, et al., 2009) . This raises the question of why *T. capensis* and *Rajiformes,* the two bycatch species that are landed in higher proportions than *A. pectoralis*, are not considered target species and their catches are not receiving at least as much management attention as *A. pectoralis*.

While bycatch is a concern in the inshore trawl fishery (Andrews, et al., 2015), all bycatch is not necessarily problematic (Hall, et al., 2000). Bycatch that is harvested sustainably and profitably marketed should be encouraged (Pikitch, et al., 2004). An argument could be made that spreading the harvest across the ecosystem is better than the selective removal of only one or two species (Cochrane, et al., 2007). A greater spread of species also diversifies market options (Cawthorn, et al., 2011). Bycatch becomes a problem either when it is discarded, or when catches exceed the optimal fishing pressure for the species, leading to declines in the populations (Hall, 1996).

While landing vulnerable bycatch species is not ideal, it is worse to catch and then discard these species as due to the nature of otter trawling most discards do not survive. Discards lead to damaging effects on the species affected and the ecosystems it occurs in (Hall, et al., 2000), and leads to incorrect estimates of fishing pressures (Alverson, 1999). Therefore, fisheries management aims to get vessels to decrease their catches of vulnerable bycatch species, without encouraging an increase in discarding (Hilborn, et al., 2015).

Initially, it is reasonable to assume that species with depressed or declining populations should have regulations limiting their catches in the inshore trawl fishery. However, if vessels are controlling their catch compositions through discarding and not targeting, decreasing the amount of a species permitted to be landed will not result in a decrease in the amount caught, just an increase in the amount discarded. Further, as a previous study found that the decline in species was linked to habitat loss rather than fishing pressure (Currie, 2017), a decrease in fishing pressure may not be effective in helping to revive the species in the inshore trawl fishery.

Catch composition shifts

Interannual variability

Over the last century, the species assemblage over the inshore Agulhas Bank has undergone a significant shift, with the decline of previously abundant reef-associated species and the increase of less abundant soft substrate associate species (Currie, 2017). However, the sweeping changes reported by Currie (2017) almost certainly happened during the initial decades of the fishery. By comparison, little seems to have changed over the last 30 years as evidenced by the low dissimilarity in landed catch composition.

Landed catches are likely to be more conservative than total catches due to the selectivity of the fishery. Nevertheless, the species that made a disappearance in the early stages of the fishery are predominantly of commercial interest (*R. globiceps* and *A. inodorus*) (Griffiths, 2000), and it is probably true to assume that the impact on these species occurred very early on in the fishery and that the last thirty years represent a period of depleted but stable abundances.

Of the four *chondrichthyan* species only two are recorded over the entire study period, namely *Rajiformes* and *C. capensis*. Both *G. galeus* and *Mustelus* only show up in landing records from 2000 onwards. In the trawl records pre-1999, many shark catches were recorded in trawls, but as they were not required to be weighed and recorded in the trip records there are no associated landing weights (Attwood, 2012). Therefore, we know that they were caught by the fishery but were not recorded effectively enough for us to know in what quantities.

Landed catch showed a chronological change, and not a random inter-annual change, indicating that there are long-term shifts in the underlying species assemblages, as highlighted by Currie, (2017), or gradual shifts in fishing behaviour (either targeting or discarding) (Roberson & Wilcox, 2021). Fishing behaviour may respond to market shifts (Cawthorn, et al., 2011).

From 1967 to 1995 the catch per vessel of the most commercially important bycatch species, namely *T. capensis, P. laniarius*, and *G. capensis,* decreased, while catches of previously unexploited species of *Chelidonichthys* and *C. capensis* increased (Booth & Hecht, 1998). From 1967 onwards the contribution of *M.*

capensis to the total catch composition increased, and the contribution of bycatch species decreased (Booth & Hecht, 1998). Between 1967 and 1995 *M. capensis* catches went from 32% to 47% of the catch, and now contribute 58%. Catches of *T. capensis* went from 41% to 35% of the catch and now contribute just 9%. Similarly, *P. laniarius* catches went from 17% to 7%, and now contribute just 5% (Booth & Hecht, 1998).

The increase in the proportion of *M. capensis* in the catches could indicate that vessels increased the selectivity of their landed catches, by targeting or discarding them. As the MSC certification for hake has improved exportation to foreign markets (Lallemand, et al., 2016), the value of *M. capensis* has increased, creating a greater incentive to land more *M. capensis* in comparison to bycatch species. Despite the increasing proportion of target species in the catch composition, the bycatch composition has become more diverse, possibly due to the decline in population sizes of previously abundant bycatch species (Griffiths, 2000).

The decrease in the proportion of *T. capensis* and *P. laniarius* landings could be a result of a decrease in the targeting of these species, an increase in discarding, or a decrease in abundance. While discarding a valuable species seems illogical, it may be possible in the case of *T. capensis* to avoid exceeding the bycatch reserve allocated to *T. capensis* landings in the inshore trawl fishery (DAFF, 2010). However, *P. laniarius* have no catch limitations that would motivate skippers to discard it, and the abundance of the species has increased since 1990, therefore targeting of the species may have decreased (Gray, et al., 2007).

A. inodorus is the most commercially valuable species in the linefishery (Mann, 2013), making its decline extremely worrying for the linefishery, and was one of the species highlighted to require increased catch restrictions in the linefishery (Griffiths, 2000). However, despite a 70% decrease in effort in the linefishery resulting in a large decrease in catches of *A. inodorus* (Griffiths, 2000).

There have been no catch regulations for *A. inodorus* in the inshore trawl fishery (DAFF, 2010), which lands comparable volumes as the linefishery. However, unlike the linefishery, no age or size restrictions are stopping the inshore trawl fishery from marketing immature *A. inodorus*, which are caught in high volumes in the inshore trawl fishery due to the overlap of *M. capensis* with the nursery grounds of *A. inodorus* (Griffiths, 1997).

Seasonal variability

There was very little variation in landed catch composition across the months. The main variation was a separation between May and June, splitting the year into almost equal halves. The distinction between the two halves of the year could be due to the documented seasonal migrations of bycatch species, like that of *A. inodorus* and *Rajiformes* inshore during winter in response to temperature changes (Badenhorst & Smale, 1991; Japp, et al., 1994; Millar, 2000).

However, some of the variations could be due to skipper behaviours influencing catch and landed composition (Roberson & Wilcox, 2021), as *M. capensis* also migrates inshore during winter, but experiences a decrease in the catch composition in the second half of the year (Millar, 2000). Vessels could be increasing the targeting, or decreasing the discarding of bycatch species in the second half of the year as they get closer to fulfilling their target species quotas, to ensure they can keep fishing.

Variation among vessels

Vessels active between 2007 and 2011 were grouped into five clusters based on bycatch rates, with the same ratio of one *A. pectoralis* directed group and three *M. capensis* directed groups (Greenston, 2014). Vessels in the inshore trawl fishery have quotas for both species. However, it is usual for a vessel to primarily target only one of the target species, as the vessel, gear, and trawling locations differ between the two species (DEFF, 2020). Vessels that target *A. pectoralis* are usually smaller and fish inshore over the muddy sole grounds, while vessels that target *M. capensis* are usually bigger and trawl further offshore (Walmsley, et al., 2007), to take advantage of the fact that *M. capensis* increases in size with depth (Millar, 2000). Therefore, it is unsurprising that both studies found a difference in bycatch rate and composition based on the species targeted by the vessel.

The *A. pectoralis* cluster showed high proportions of *Rajiformes, C. capensis* and *A. inodorus*, suggesting that either the distributions of these species overlap with those of *A. pectoralis*, or that the vessels are targeting these species. The *M. capensis* directed vessels make up the majority of the fishery due to the greater abundance of *M. capensis* on the inshore trawl grounds (DEFF, 2020). The *M. capensis* clusters all had high proportions of *T. capensis* and *P. laniarius*, which may also suggest that the distributions of these species overlap with *M. capensis*.

It has been suggested that any vessels with a bycatch rate higher than 25% are targeting bycatch (Leslie, 2004). Using the 25% metric, only vessels in clusters one and two could be considered as not targeting bycatch. However, as these are landed catches, without knowing the extent of discarding in the fishery, it is impossible to know if these bycatch rates are a true reflection of the bycatch rates in the fishery.

Spatial variation

M. capensis made up the majority of landings in all areas, as was found in the analysis of total catches over the Aguhlas Bank (Attwood, et al., 2011). Unfortunately, there has been no analysis on the spatial aggregation of bycatch rate or catch composition of the inshore trawl fishery, therefore it is impossible to compare how landings and catches differ spatially.

The eastern side of the inshore trawl fishing grounds showed more homogeneity in the landings and was defined by high *T. capensis* landings, which matches their known distributions (Smith-Vaniz, et al., 2018). The western side of the inshore trawl grounds showed more heterogeneity in landings and was defined by *Chelidonichthys*. The species assemblage of the Agulhas Bank is stratified by depth and longitude, so it follows that so are the catches (Smale, et al., 1993).

The middle grounds showed a similar catch composition, despite suggestions that community structure east and west of 22 degrees east are significantly different (Walmsley, et al., 2007). The groupings of grid cells found in this study are very similar to those found in a previous study that looked at the clustering of inshore trawl grids based on total catches (Attwood, et al., 2011).

In the previous study, seven areas were identified, which is one more than the six identified in this study (Attwood, et al., 2011). The extra group is due to the area contained within cluster eight in the analysis of this study being split into an inshore and offshore group in the previous study (Attwood, et al., 2011). The areas in the previous study were distinguished by a dissimilarity of 25%, compared to the 13% in this study (Attwood, et al., 2011). The greater dissimilarity and heterogeneity of catches over the area compared to landings indicates that vessels could have engaged in discarding behaviours.

Determinants of landed catch composition

It is important to understand the cause of the differences in catch composition for the management of the inshore trawl fishery. Initially, I assumed that season would determine a large portion of landed catch composition, because of the documented species migrations (Badenhorst & Smale, 1991; Japp, et al., 1994), the change in weather, and the change in fishing incentives across the seasons. However, while there is seasonal variation, this only explained a very small portion of the landed catch composition. As stated before, the similarity in landed catch composition across seasons could be explained by the change in trawling locations and times of vessels in response to the seasonal changes mentioned above.

The years explained 20% of the variability of the landed catch composition, indicating a significant shift in species composition over the study period. The interaction between vessel and year is due to changes in the landed catch composition of vessels over the study period. Vessels are most likely changing their landed catch compositions in response to market shifts, areas fished and changes in the efficacy of reporting.

The vessel effect was the greatest determiner of landed catch composition. The vessel effect could be due to physical differences among the vessels, differences in areas fished, or differences in fishing behaviours. Fishing behaviour includes physical characteristics (e.g. horsepower) and the choices of the skipper which influence targeting of species such as the speed of the trawl, the weight and the spread of the doors and the decisions regarding the discarding of species (Roberson & Wilcox, 2021).

Of the variation in landed catch composition, 10% can be attributed to differences in fishing areas, and 7% to the differences in fishing behaviour and physical characteristics of the vessels. The variation explained by the fishing behaviour and physical characteristics of the vessels was unable to be effectively split in this study. However, in the inshore trawl fishery vessels have strict regulations on size, horsepower, and gear (DEFF, 2020), making it unlikely that physical differences would have an overriding impact on the landed bycatch.

It is critical to the management of the inshore trawl fishery to untangle the effect of targeting versus discarding on the landed catch composition (Bellido, et al., 2011; Bethoney, et al., 2017). The behaviour of vessels that land catches with low diversity might be considered ‘better’ than vessels that land more diverse catches if no discarding was practised. However, if vessels with a low catch diversity are discarding bycatch species, while vessels with higher species diversity are not, the opposite would be true. Therefore, equating a diverse bycatch as unsustainable might be flawed in logic.

Understanding what is driving the variation among vessels will require more information on the interactions between the fish population, the fleet dynamics, the abilities of the processing sector, and the trends in the markets (Hilborn, 1985). Fleet dynamics were defined as a right holder’s investment in the fishery, effort allocation, harvesting efficiency, and discarding and retentions behaviours (Hilborn, 1985). Effort allocation includes where and when vessels choose to fish. Other fisheries with highly spatially structured species assemblages also found a high area effect in their catch compositions (Acheson, 1975; Hilborn & Ledbetter, 1985).

Harvesting efficiency is harder to define, relating to the skill of the fisherman, and the vessel specifications (Hilborn, 1985). Studies have found that harvesting efficiency is affected by different factors in different fisheries (Hilborn, 1985; Gulland, 1956). In demersal trawl fisheries tonnage has been linked to the power of a vessel, which suggests that any decrease in catch quotas in these fisheries will affect high-powered vessels the most (Gulland, 1956).

The variation among vessels in the inshore trawl fishery are due to differences in physical characteristics, targeting behaviour, and discarding behaviour. Some vessels may be fishing for rights holders with vast processing capabilities that can easily deal with and profit from a diverse catch, while some may be dealing with rights holders that are only able to market the target species, and so profit less from bycatch, or a rights holder falling between these two, that only desires a specific bycatch species. Therefore, which bycatch species are desirable, and therefore targeted or retained, could change in response to market changes, abundance changes, and regulation changes.

Conclusion

The landed catch composition in the inshore trawl fishery is similar to other shallow water trawl fisheries, in that it contains a large number of species but with only a few making up the majority of the catch (Branch, 2006; Costa, et al., 2008). The landed catch composition had a gradual change over the study period from abundant shoaling species to less abundant reef-associated species, which is the opposite trend of the shift in species assemblage on the Agulhas Bank over the last century (Currie, 2017). This change was probably influenced by the recent increase in *P. laniarius* and *A. argyrozona* populations (Mann, et al., 2014; Mann, et al., 2014). There was very little seasonal variation in landed catch composition, but as noted in chapter two, bycatch increased in the second half of the year, as was seen in all species besides *L. reynaudii*.

The vessel was the greatest determinant of landed catch composition, and the area of the trawl was the main reason for the difference among the vessels. The areas showed distinct groupings based on landed catch composition, which were almost the same as the area groupings found using total pre-discard catches (Attwood, et al., 2011). This indicates that if there is discarding, it is unlikely to differ by area, and that area could be an important management tool to control the catch composition in the fishery. However, there is scope to manage the fisheries' bycatch through the management of skipper behaviour.

To manage bycatch through skipper behaviour it must first be determined if the difference in landed catch composition found in this study is a result of the targeting practices of the vessels or the discarding practices. From comparisons between landed and total catches (Attwood, et al., 2011) there is evidence to suggest at least part of the difference is due to discarding practices.

CHAPTER 4: SUGGESTIONS FOR MANAGEMENT OF BYCATCH IN THE INSHORE TRAWL FISHERY, WITH RESPECT TO THE FINDINGS OF THIS STUDY

Global bycatch management

The management of bycatch has always presented a challenge (Alverson & Hughes, 1996; Beddington, et al., 2007; Marchand, 1933). While bycatch mitigation has long been a component of fisheries management (Beddington, et al., 2007; Alverson & Hughes, 1996), the management of discards has received greater attention, especially after public concern over the discarding of charismatic marine mammals (Hall, 1996; Alverson & Hughes, 1996)., Managers have focused more on the discarded or unutilized portion of the catch, than on the bycatch, or the unmanaged but utilized portion of the catch (Davis, et al., 2009).

To decrease bycatch, managers can either increase the number of species in the fishery which are targeted and managed, decrease the amount of bycatch caught or increase the amount of discarded bycatch that survives (Beddington, et al., 2007; Costello, et al., 2008; Bellido, et al., 2011). The most common method is to decrease the amount of bycatch caught through a decrease in either total effort or the bycatch per unit effort (BPUE) (Hall, et al., 2000). However, the indiscriminate nature of fishing gear, the distribution overlap of many marine species and many other socio-economic factors complicate this type of management (Beddington, et al., 2007).

For fisheries with highly indiscriminate fishing gear, such as multispecies trawl fisheries, a decrease in proportion of bycatch caught is much harder to achieve and often not an appropriate goal for the fishery (Bellido, et al., 2011). In these fisheries, many of the species are not discarded but kept and marketed or become future target species as resources and markets change (Davis, et al., 2009). Therefore, ensuring biologically safe harvests of all species, rather than increased selectivity of catches, is more appropriate.

In some instance increasing selectivity of catches can be more detrimental to the ecosystem than a well-managed and controlled harvest of all components of the ecosystem (Bellido, et al., 2011). Removal of only select species and size classes can cause imbalances in the ecosystem which has an impact on all species and ultimately the fisheries (Hall, et al., 2000). Ecosystem-based management has begun incorporating wider catch which includes a better representation of the ecosystem, in some fisheries to minimize the effects on the ecosystem as well as any one species (Cochrane, et al., 2007; Zhou, et al., 2019). This requires a switch to regulations for catch compositions rather than catch quotas for only target species.

Marine-protected areas (MPAs) are used in both traditional and ecosystem-based management (Attwood, 2012; Bellido, et al., 2011; Cochrane, et al., 2007; Diamond, et al., 2010; Gilman, et al., 2019; Hilborn, et al., 2003). Time or area closures protect important habitats or species within the ecosystem by limiting access to them (Pikitch, et al., 2004). MPA's can have various levels of restriction such as no-take areas, reserves with restricted access, and seasonal closures of spawning grounds (Garcia & Cochrane, 2005). The species abundance, size, biodiversity (Halpern, 2003), and fecundity (Palumbi, 2004), have all been shown to increase within MPA. When home to migratory species, MPA's can also increase harvests for adjacent fisheries (Gell & Roberts, 2003).

MPA's can increase the resilience of an ecosystem, protecting it from uncertainty by acting as a safety net (Grafton & Kompas, 2005), and are an essential management tool to ensure healthy ecosystems. However, a MPA does not solve any of the underlying issues which lead to overfishing (Hilborn, et al., 2003). Crucially MPA's can result in reallocation of effort, which would still result in the overall degradation of the ecosystem (Hilborn, et al., 2003). Therefore, while MPAs are important to implement, it is necessary to consider the specific circumstances of each fishery and its goals to create a beneficial MPA (Hilborn, et al., 2003; Pikitch, et al., 2004).

The two bycatch mitigation strategies with the most success in multiple species fisheries have been individual transferable quota systems (ITQ) and cooperative management systems (Costello, et al., 2008). Co-operative management is the next step forward from traditional top-down fisheries management, as it transfers the regulatory control from the government to fishery collectives or communities (Greenston & Attwood, 2013). ITQs are an extension of individual quotas that create a trading market for quotas (Squires, et al., 1998), and are one tool which can be used in a cooperative management system (Beddington, et al., 2007).

In a cooperative management system, the government only acts to set fishery wide limits and regulations based on the biology of the resource. The fishery cooperative is essentially self-governed and takes responsibility for implementing and enforcing the government's regulations (Greenston & Attwood, 2013). This type of self-governance is particularly effective if traditional fisheries governance is weak or underfunded (Field, et al., 2013).

The ability to self-manage gives a fisher a greater sense of ownership and responsibility for the resource and leads to increased sustainable practices in the fishery (Field, et al., 2013). As well as ITQs, fishery cooperatives can utilise closure of core habitats, increased gear selectivity, or fisher incentives in their management of the fishery (Beddington, et al., 2007). However, the real advantage of a cooperative management approach is that the fishery is given collective rights to the resource and control over its management (Greenston & Attwood, 2013). Self-governed bycatch management has been successful in decreasing bycatch and helping to maintain stock health but has also caused decreased harvests (Witherell & Pautzke, 1997).

To ensure effective ecosystem-based management in fisheries the causes of overfishing and environmental degradation must be identified. Historically fisheries management used regulations such as gear and effort restrictions to try decrease overfishing (Crowder & Murawski, 1998; Hall, et al., 2000). However, as these regulations do not address the factors leading to overfishing, mainly overcapitalisation and the ‘race for fish’, fishers were still incentivised to maximise individual catches to the detriment of the resource and environment. The success of management systems such as ITQs or co-management can be attributed to their ability to address these factors and create incentives for sustainable fishing (Grafton, et al., 2006).

Systems that incentivise sustainable fishing are the most crucial component of any fishery management (Grafton, et al., 2006). While ecosystem-based management prioritises fishery-ecosystem interactions, it ignores the effect of the fishers' behaviour. Therefore, to be successful, management requires proper incentives for fishers to change their behaviour. The four main strategies to ensure fishers are incentivised to fish sustainably are, long-term individual harvest rights, stakeholder participation, priced ecosystem services, and research and monitoring (Grafton, et al., 2006).

Studies suggest that in fisheries management, an increased emphasis should be placed on exclusive property rights, community-orientated management, and increased stakeholder participation (McCay, et al., 2011). Fisheries management is most effective when regulations are supported by non-regulatory measures (Field, et al., 2013). Public awareness campaigns such as the MSC sustainability label have been extremely effective at supporting fisheries management (Field, et al., 2013; Blackmore, et al., 2015). Based on international mixed-species trawl fisheries the most effective bycatch management is a combination of individual catch quotas, complete observer coverage, a lower number of fishery participants, effective enforcement of regulations which are supported by the industry, appropriate penalties, and the ability for fishers to have some control over the management of their bycatch (Diamond, et al., 2010).

Management recommendations for the inshore trawl fishery

This study has determined that a substantial portion of the variation in landed bycatch in the inshore trawl fishery is determined by the vessel. The vessel controls its landed catch compositions through a combination of fishing behaviours and discarding practices, and the areas they select to trawl.

Bycatch management needs to be able to both monitor the catches of bycatch species and restrain catches of species that are under excessive fishing pressure to ensure the sustainability of their populations (Attwood, 2012). When creating effective management strategies for the inshore trawl fishery it is important to consider the degree to which vessels in the fishery are dependent on the bycatch landed. As the thirteen species that made up 99% of the landed catch composition by mass are all commercially valuable and marketed, decreasing their bycatch could create negative economic effects in the fishery, and lead to a redistribution of effort to other potentially vulnerable target species (Walmsley, et al., 2006).

An important component of any bycatch regulation is that it does not lead to an increase in discarding (Alverson, 1999; FAO, 2022). Currently, the inshore trawl fishery has a low discard rate as compared to similar global trawl fisheries (Davis, et al., 2009; Attwood, et al., 2011). Discarding leads to many negative ecosystem effects, and a loss of potential food (Bellido, et al., 2011; Pingguo, 2019). Therefore, the utilisation of bycatch, as opposed to discarding it at sea, is one of the goals of the ecosystem management used to manage the fisheries in South Africa (Cochrane, et al., 2007).

Trawls targeting *M. capensis* have significantly lower bycatch rates than trawls targeting *A. pectoralis*. However, the two nominal targets have overlapping habitats (Badenhorst & Smale, 1991). Therefore, splitting the fishery by target species would not result in an effective split of the fishery (Badenhorst & Smale, 1991). It has been proposed that managing the fishery based on an area-by-area basis rather than by target species could produce better results for management of bycatch species (Attwood, et al., 2011). Area restrictions are an effective way of managing catches in a fishery (Hilborn, et al., 2003; Diamond, et al., 2010). This is supported by the findings of this study as the areas were able to be effectively split based on catch composition.

However, there are already several marine protected areas in the inshore trawl grounds, as well as a trawl ring fence initiative restricting trawling to historically trawled areas (Attwood, 2012). Further area restrictions could result in decreased target landings, profits, and redistribution of effort and hence would need great consideration. One solution to this could be to instead limit the hours per area for vessels.

For the top bycatch species either catch quotas or catch restrictions could be introduced. Most of the top thirteen species in the inshore trawl fisheries landings have been assessed and have up-to-date information on their population sizes which could inform quotas for their catches in the inshore trawl fishery that would result in a recovery of their populations (Mann, et al., 2014; Mann, et al., 2014; Lwamoto, 2015; Smith-Vaniz, et al., 2018; Allcock & Taite, 2019; Fennessy & Winker, 2020; Finucci & Pacoureau, 2020; IUCN, 2020; Walker, et al., 2020).

A similar system working on bycatch allowances rather than quotas was proposed to limit catches of vulnerable species without the legal difficulties of an ITQ system (Attwood, 2012). Unfortunately, this would have the same problems with discarding, as the observer program in the fishery is currently far from covering 100% of the trawls. In similar circumstances increasing the control fishers have over the resources has helped to combat the discarding problem, without the need for increased observer coverage, which could be an effective solution in the inshore trawl fishery.

An increase in fisher control over catch compositions would be an effective management strategy when considering the evidence provided in this study. The vessels can control their catch compositions, and bycatch rates, based on the area fished, the species targeted, and the depth fished. Therefore, if properly incentivized they could change the catch compositions to decrease landings of vulnerable species, without compromising the landings of valuable species that are not currently of concern. However, this would only work if the differences in landings are only a result of differences in targeting behaviours, which was not found to be the case.

In the inshore trawl fishery, the bycatch consists of a mixture of vulnerable species that are currently fished at unsustainable levels and species of no ecological concern that are fished below the estimated threshold fishing pressures for their populations. Therefore, a blanket decrease of bycatch would not be an ideal solution, especially when considering the high commercial value of these species. Therefore, the fact that vessels have a degree of control of their landed catch compositions suggests that they could adjust the proportions of species to create a more sustainable catch composition. Creating a more sustainable catch composition would help to alleviate fishing pressures on vulnerable species, without compromising the profits of the fishery, and therefore will not create incentives to increase discards.

Further research

The next step would be to look at the individual vessels and see how they are influencing their landed catches. We can then ask the question: are some vessels better at avoiding bycatch than others? If so, what behaviours can be linked to this ability? Further, are all bycatch species equally easy to avoid? If so, what are the characteristics of the bycatch species that influence how easy or hard it is to avoid them?

Answering these questions will allow for a clearer picture of the causes and state of bycatch in the inshore trawl fishery. This knowledge will in turn allow for increasingly effective management of bycatch. Bycatch management must be improved in the inshore trawl fishery as the bycatch rate is increasing, and the ecological status of many of the bycatch species is decreasing, impacting the environment, profits, and adjacent fisheries (Visser, 2015). Effective bycatch management is essential to the continuation of the MSC certification of the hake trawl fishery, which is essential to the profitability of the fishery (Andrews, et al., 2015; Lallemand, et al., 2016).

Further research will require improved data from fisheries observers as the observer data in the studies compared to in this study are already more than 10 years old (Walmsley, et al., 2007; Attwood, et al., 2011). The area analysis could also be improved by increasing the spatial resolution of the data, either through smaller grid cells, or utilising vms data available in the fishery.

Conclusion

In this study, I set out to describe yearly and seasonal variations in the volume and composition of catch in the inshore trawl fishery. While the volume of catch decreased over the years, the bycatch rate increased. The catch composition showed a significant shift, from previously abundant shoaling species such as *T. capensis* to less abundant reef species, such as *P. laniarius* and *A. argyrozona*. The decrease in *T. capensis* could potentially be due to increased discarding or decreased targeting, while the increase in *P. laniarius* and *A. argyrozona* is more likely to be due to the recent increase in their population sizes. The seasonal variability in catches showed a decrease in target catch volume and proportion in the second half of the year, which is consistent with the assumption of vessels increasing landings of bycatch species in the second half of the year when quotas for target species run out.

Vessels were found to have the greatest effect on the differences in landed catch composition. The greatest portion of the vessel effect was due to the difference in the areas trawled by the vessels. Areas showed distinct groupings based on landed catch compositions, that closely matched the area groupings based on total unsorted catches. The spatial variability of catches highlights the variability in species assemblages across the Agulhas Bank, by depth and longitude. Further the similarity between total (Attwood, et al., 2011) and landed catches indicate that if discarding is practised in the fishery, it does not have large spatial variability.

There was also a significant vessel behavioural effect on the landed catch composition in the fishery, which is explained by the differences in the vessels physical characteristics, targeting, and discarding practices. The fact that the vessels behaviour has been proven to have a significant effect on the landed catch composition will allow vessel variability to be considered when creating bycatch management regulations, such as bycatch allowances.

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