

Bycatch in the South African
midwater trawl fishery for
horse mackerel (*Trachurus capensis*)
as established from observer records

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Abstract

The South African midwater trawl fishery targets adult horse mackerel (*Trachurus capensis*) on the Agulhas Bank. The bulk of the catch is taken by a single midwater trawler. The bycatch of this fishery is investigated by analysing observer records from 2004 to 2014 to report on bycatch composition, volumes and temporal and spatial patterns. Small fauna were analysed by extrapolation of sample weights and large fauna were counted. The midwater trawl fishery was estimated to have caught 25 415 t annually, with a bycatch rate of 6.9% of the total catch, by weight. Bycatch species with the highest average annual catches were chub mackerel (*Scomber japonicus*), redeye roundherring (*Etrumeus whiteheadi*), ribbonfish (*Lepidopus caudatus*) and hake (*Merluccius* spp.). Large fauna bycatch species included Cape fur seals (*Arctocephalus pusillus*), sharks (15 species), sunfish (*Mola mola*) and cetaceans (two species). Temporal analysis revealed significant differences between day-time and night-time CPUE for nine species, and significant differences in seasonal CPUE for 17 species. Spatial analysis of small fauna species composition and of large fauna species composition identified three groups in each. The 100% observer coverage is high compared to other South African fisheries, and, although the average sampling rate of 1.56% is low, an increase in the sampling rate might not be feasible owing to the size of catches. The bycatch rate in this fishery is low compared to other South African trawl fisheries but similar to global midwater trawl bycatch rates. There are species overlaps with various fisheries, namely the demersal trawl, small pelagic, linefishery, shark longline and squid fisheries, yet the total catch estimates from this fishery are generally small relative to catches taken in the target fisheries.

Introduction

Bycatch is regarded as one of the most persistent problems affecting the state of marine ecosystems (FAO, 2010). The non-selective nature of fishing gear results in many species being caught when only a few are targeted. The removal of large volumes of unwanted catch leads to the waste of marine resources if it is discarded or under-utilised. Trawl, longline and gillnet fisheries are associated with high rates of bycatch (Alverson *et al.*, 1994; Kelleher, 2005; Harrington *et al.*, 2005a; Davies *et al.*, 2009). Reporting of bycatch is generally poor, leading to problems with stock assessments and management. The bycatch problem has contributed to the decline of many species, including those considered rare, endangered or vulnerable (FAO, 2010). The conservation of marine ecosystems and sustainable harvesting of fish stocks depend on rigorous management strategies. The assessment and management of bycatch has been recognised as an important component of these strategies (Alverson *et al.*, 1994).

Various attempts have been made to assess the level of global bycatch. The first assessment undertaken by the Food and Agriculture Organization of the United Nations (“FAO”) estimated that global annual discards from commercial fisheries amounted to an average of 27 million tonnes, or approximately 27% of the global catch (Alverson *et al.*, 1994). The analysis was carried out across fisheries, by gear, target species and fishing areas and reported that the highest quantities of discards were from the Northwest Pacific region while the highest proportion of discards was generated by the tropical shrimp trawl fisheries, producing over a third of the global total (Alverson *et al.*, 1994).

Approximately a decade later, another assessment carried out by Kelleher (2005) estimated the global annual discards to be approximately 7.3 million tonnes, approximately 8% of the

global catch. As the two assessments used different approaches in their estimations they are deemed incomparable, however the results did suggest a reduction in discards which was attributed to an increased utilisation of bycatch as well as a reduction in unwanted catch (Kelleher, 2005). The cause of the reduction in bycatch might not be entirely positive, as it is suggested that it could also have been as a result of declining non-target catches (Zeller & Pauly, 2005). A more recent assessment by Davies *et al.*, (2009) estimated the global annual bycatch at 38.5 million tonnes (40.4% of the total marine catch), however this study defined any unmanaged catch as bycatch and in certain cases this led to entire fisheries included as bycatch.

The difficulties in attempts to assess global bycatch are often compounded by the confusion surrounding the definitions and terms used, specifically the sometimes interchangeable terms “bycatch” and “discard” (Kelleher, 2005). Bycatch has been defined as “that portion of the catch returned to the seas as a result of economic, legal or personal considerations plus the retained catch of non-targeted species” (McCaughran, 1992). This definition was considered misleading as it did not separate the discarded portion of bycatch from that which is retained and utilised (Hall, 1996). Hall (1996) went on to define bycatch as the “portion of the capture that is discarded at sea dead because it has little or no economic value or because its retention is prohibited by law” while the catch is separated into target catch and non-target catch (all other species that are retained and utilized). Davies *et al.*, (2009) has suggested a simpler definition of bycatch as “catch that is either unused or unmanaged”. In this sense, bycatch includes the portion of the catch without specific management measures in place to ensure sustainability. For the purposes of this study, all non-target catch, whether retained and utilised or discarded is referred to as bycatch.

To address the bycatch problem, a better understanding of the variety of effects fisheries have on ecosystems and biodiversity is imperative (Pauly *et al.*, 2002; Zhou *et al.*, 2010; Garcia *et al.*, 2012), as these effects are vast (Kelleher, 2005). These include the decline in trophic levels by the removal of large predators, the removal of large numbers of fish, and the removal of prey, all of which can impair the integrity of the ecosystems (Pauly *et al.*, 2002; Pikitch *et al.*, 2004). These changes can result in simplification of food webs and reductions in biodiversity that can cause fish stocks to become sensitive to stressors such as environmental fluctuations (Jackson *et al.*, 2001; Pauly *et al.*, 2002).

There are a variety of other important bycatch concerns. Undocumented discards can lead to the underestimation of the fishing mortality, which results in overestimations of sustainable yields (Alverson *et al.*, 1994). The removal of threatened species or the unsustainable removal of non-threatened species will accelerate the decline of these species, and is particularly problematic for certain marine mammals, sea birds, sea turtles and elasmobranchs (Alverson *et al.*, 1994; Hall, 1996). Bycatch can also cause conflict between fisheries which can arise when bycatch of a certain fishery is the target species in another fishery (Hall, 1996) and, if unmanaged, can lead to the closure of fisheries (Hall *et al.*, 2000).

The declining trend in global marine fisheries and the recognition of the extensive impacts of fisheries on marine ecosystems have emphasised the need for a transformation in fisheries management that encompasses the entire ecosystem (Pikitch *et al.*, 2004). In October 2001 the Reykjavik Conference on Responsible Fisheries in the Marine Ecosystem acknowledged the need to adopt and implement ecosystem approaches to fisheries (EAF) management (Sinclair *et al.*, 2002), however clear concept definitions and implementation guidelines were needed. These were provided by the FAO with the definition as follows: “an ecosystem

approach to fisheries strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries” (FAO, 2003).

The FAO Guidelines on EAF (FAO, 2003) provide direction on how to translate the EAF concept into “operational objectives, indicators and performance measures”, and includes the issue of bycatch reduction. Bycatch objectives should strive to avoid extinction of species, retain ecosystem integrity, reduce waste in fisheries and inter-fishery conflicts (Hall, 1996; Pikitch *et al.*, 2004). These objectives need to be incorporated into management protocols that consider entire ecosystems and therefore across multiple fisheries, not on individual fisheries levels, with the goal to achieving balanced harvesting (Zhou *et al.*, 2010; Garcia *et al.*, 2012). Increased selectivity on an individual fishery basis alters biodiversity and ecosystem functioning which could negatively affect fisheries production, whereas moderate fishing pressure across a wide range of species and sizes conserves biodiversity and has been shown to maximise overall production (Zhou *et al.*, 2010; Garcia *et al.*, 2012). More specifically management measures should increase the utilisation of bycatch to reduce discards (Garcia *et al.*, 2012).

Where bycatch mitigation measures are deemed necessary, two main approaches are possible: either total effort reduction, or a reduction in the bycatch at the same level of effort (Hall, 1996; Hall *et al.*, 2000). If the bycatch is concentrated in a specific area or during a specific season, a temporal or spatial closure of the area may be necessary. Reductions in bycatch without changes to fishing effort can be attained through a variety of methods including changes to gear and equipment, changes to deployment and retrieval of gear, training of

fishers and via management strategies (Alverson *et al.*, 1994; Hall, 1996; Hall *et al.*, 2000). Changes to gear in certain fisheries have proved highly successful, and examples of these include Turtle Excluder Devices, sorting grids and changes to the mesh in trawl nets, bird-scaring lines attached to longlines and sorting grids and panels added to purse-seine gear (Hall *et al.*, 2000).

Assessment of the ecosystem impacts of bycatch and discards as well as the efficacy of subsequent mitigation methods dictate that adequate monitoring must be undertaken. Bycatch is caused by a wide variety of complex factors; data provided from fisheries-dependant records such as landings and catch logs lack much of the information necessary to identify, assess and mitigate problems (Hall, 1996; Kelleher, 2005). This results in an increased reliance on on-board observer data composed of a combination of environmental, biological, ecological and technological information (Hall, 1996). As the observer data is regarded as the most reliable source of information, research priorities should include the development of these observer programmes (Hall, 1996). Careful consideration should be given to the design of the observer protocol, keeping management objectives in mind, to ensure that the degree of observer coverage and sampling frequency will result in an adequate level of precision (Babcock *et al.*, 2003).

In South Africa, the recognition of the need to implement an ecosystem approach to fisheries management led to the adoption of the Marine Living Resources Act of 1998 (Cochrane *et al.*, 2009). The Act acknowledges the need for conservation of the resources while utilising them optimally and specifically addresses bycatch in stipulating “the need to protect the ecosystem as a whole, including species which are not targeted for exploitation”.

One of the measures implemented in the move towards an ecosystem approach to fisheries management was the South African Offshore Resources Observer Programme (OROP), in operation since 2002. Observers are deployed in commercial fisheries to collect information to aid fisheries management; however observer coverage varies across fisheries sectors mainly owing to logistical problems (RFA, 2010). Observer data collected provides information that not only aids bycatch assessments, but could also aid assessments on stock structure and compliance (RFA, 2010).

Bycatch assessments using data from the observer programme have previously been carried out in the South African demersal trawl and longline fisheries (Walmsley *et al.*, 2007; Petersen *et al.*, 2008; Attwood *et al.*, 2011). Walmsley *et al.* (2007) analysed the bycatch and discarding in the demersal trawl fishery and found that the bycatch rate was between 21% and 47% on the south coast, depending on the fishing area, while on the west coast, the bycatch rate was between 9% and 38%. A subsequent analysis on the inshore demersal trawl fishery, which operates off the south coast, estimated the bycatch rate at 42% (Attwood *et al.*, 2011). An extensive study by Petersen *et al.* (2008) assessed the bycatch of seabirds, turtles and sharks in the longline and demersal trawl fisheries and estimated seabirds to be caught at a rate of 0.44/1000 hooks and turtles at a rate of 0.04/1000 hooks. The most common sharks caught in the longline fishery are blue sharks and mako sharks, and these were estimated to be caught at a rate of 11.7 and 1.8/1000 hooks and 1.4 and 0.9/1000 hooks, respectively (Petersen *et al.*, 2008).

The South African midwater trawl fishery is a commercial fishery that targets adult horse mackerel (*Trachurus capensis*). This is a semi-pelagic species found all along the South African coast, although adult horse mackerel stocks aggregate on the Agulhas Bank, near the

continental shelf break, where they are targeted in this fishery (Figure 1). Owing to the behaviour of this species, specifically vertical migration patterns, the horse mackerel biomass has not been established with a high degree of confidence and it is therefore managed by a Precautionary Management Catch Limit (PMCL) (DAFF, 2012), which in 2014 was set at 50 615 tonnes. The Total Allowable Catch (TAC) issued to long-term rights holders in the midwater trawl industry was set at 38 115 tonnes for 2014. The remainder of the PMCL is held as a bycatch reserve for the demersal trawl sector which is known to take adult horse mackerel as bycatch.

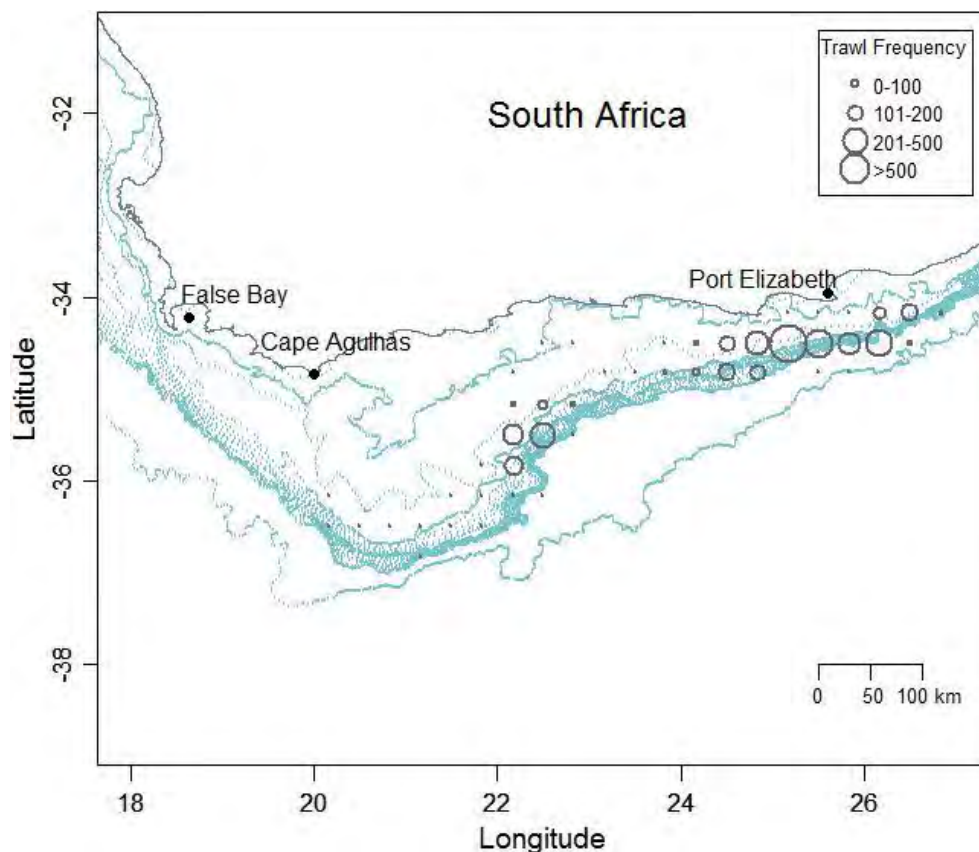


Figure 1. A map of the South African south coast showing the location and frequency of midwater trawls targeting horse mackerel (*Trachurus capensis*) monitored by observers on the *Desert Diamond* between August 2004 and March 2014.

Juvenile horse mackerel form bycatch in the small pelagic purse seine fishery on the west coast of South Africa, and so a further Precautionary Upper Catch Limit (PUCL) of horse mackerel is enforced in this fishery to control the bycatch of juvenile horse mackerel. The

bulk of the catch is taken by a single midwater trawler, the *Desert Diamond*, the largest South African registered commercial fishing vessel. Horse mackerel is processed in whole form, block frozen on board mainly for central and southern African markets (Oceana, 2014).

According to the MLRA, midwater trawling is defined as fishing with “any net which can be dragged by a fishing vessel along any depth between the seabed and the surface of the sea without continuously touching the bottom”. Midwater trawling is therefore seen as less destructive to the physical marine environment, however, as trawl nets are largely non-selective there is bycatch hauled along with the targeted horse mackerel. Owing to the high diversity of the Agulhas Bank, commercial fisheries operating in this area are known to have large proportions of bycatch (Japp *et al.*, 1994). Bycatch in the midwater trawl fishery is reported to contain some of the demersal species, such as hake (*Merluccius spp.*), as well as other meso-pelagic species that migrate through the water column, such as chub mackerel (*Scomber japonicus*) and ribbon fish (*Lepidopus caudatus*) (Japp *et al.*, 1994; Sauer *et al.* 2003). Hake are the main target species in the demersal trawl fishery and any unregulated bycatch of these species could cause inter-fishery conflict (Japp *et al.*, 1994). The effects on dolphins, pelagic sharks and sunfish (*Mola mola*) are also a concern (DEAT, 2005a), as the exploitation rates of these species could be unsustainable.

Management has recognised that there is a need to minimise the bycatch and have stipulated certain permit conditions (DAFF, 2014). The minimum mesh size of trawl nets is 75 mm, to allow for the escape of small fish. To overcome the hake bycatch problem, the fishery has strict hake bycatch limits in place. The hake bycatch must be less than 2% of the horse mackerel catch in any given year, and must be less than 4% for any one landing. The total bycatch must be less than 20% of the horse mackerel landed weight. Permit conditions also

require that observers be allowed access to monitor compliance with the permit regulations, and, as the bulk of midwater trawling is carried out by one dedicated vessel, observer coverage is 100%.

To enhance our understanding of the extent of the midwater trawl fishery impact on the marine ecosystem, a bycatch assessment is needed. This dissertation presents the first comprehensive analysis of the midwater trawl fishery observer records and aims to present catch composition, volumes and temporal and spatial patterns. This study was motivated by concerns over the sustainability of bycatch species and inter-fishery conflicts.

Methods

Data collection – the observer programme

Fishery observers were appointed to the *Desert Diamond* from 31 August 2004 to 31 March 2014. One or two observers were appointed per trip, with a total of 48 observers appointed throughout the study period. The observers were instructed to observe, sample and record all trawls. For each trawl, the emptying of the net was observed and an estimate of the total catch weight was noted. Prior to the voyage commencing 19 October 2006 this was a visual estimation only and corresponded to the vessel's logged catch weight. Thereafter, the total catch weight was also calculated by the observers using chokers as net markers. Chokers are straps running longitudinally around trawl nets, and can be used to calculate an estimate of the volume of the catch in the net, and subsequently the catch weight.

Trawl details

Observers recorded information regarding each trawl, such as the geographical coordinates, date, depth, speed and wind direction and force. Trawl times were also recorded, including the net shooting time, net-on-bottom time, start-haul time and the net-on-board time.

Small fauna

The trawl net was emptied and small fauna directed into holding ponds below deck while large fauna, such as seals, sharks and dolphins, remained on deck. From the ponds a conveyor belt transported the catch to a processing area where selected fish were removed for further processing. The conveyor belt transported the remainder of the catch to a fishmeal plant.

Observers were instructed to take several random sub-samples from each trawl. Sub-samples were taken throughout the processing period to reduce bias. The instruction was to take a minimum sample weight (i.e. the combined mass of all sub-samples) of 1% of the total catch weight. Samples were sorted by species and the weight of each species recorded. Observers were seldom able to sample small trawls (≤ 1000 kg) as processing was typically completed before observers could make their way below deck to start sampling.

The bulk of the fish and invertebrates were identified to the species level, however certain taxa were only identified to higher levels. To resolve disparities in taxonomic resolution, certain taxonomic groups were combined. All unidentified fish were consolidated in one category for analysis.

Large fauna

Live large fauna were released as soon as possible. Crew were requested to set the dead large fauna aside. Observers recorded the number of each species brought on board, and, if possible, the length and weight of each animal. As the length and weight measurements of the large species were not consistently recorded, only the counts of each species present in trawls were used in this study.

Data analysis

Trawl depth

Differences in day-time and night-time maximum trawl depth were tested using the Mann-Whitney test with the normal approximation for larger samples (Zar, 1984). Day-time trawls

were those between 05:00 and 18:00 and night-time trawls between 18:00 and 05:00. Trawls that occurred over both day-time and night-time were excluded from the test.

Catch weight per trawl

The calculated catch weight of each trawl was used as the preferred measure of catch weight but these were not available prior to 19 October 2006. A least squares linear regression was performed to test the relationship between the calculated catch weight and the estimated catch weight per trawl. A 1:1 relationship was expected. Regardless of the strength or nature of the relationship, trawls for which estimated catch weights fell outside of the 99% prediction interval were excluded from this study. To back-calculate catch weights prior to 19 October 2006, the linear regression was used:

$$CW = a * EW + b \quad \text{(Equation 1)}$$

where CW is the calculated catch weight and EW is the estimated catch weight.

The weight of the catch of each small fauna species per trawl was extrapolated from sample weights. The total sample weight was calculated by totalling the sample weights of each species:

$$v_i = \sum_s u_{si} \quad \text{(Equation 2)}$$

where v_i is the weight of the sample in trawl i , and u_{si} is the weight of species s in the sample of trawl i , both in kilogrammes. The fraction of the sample weight, of species s , in the total sample weight was then multiplied by the catch weight:

$$w_{si} = \frac{u_{si}}{v_i} * w_i \quad \text{(Equation 3)}$$

where w_{si} is the weight of species s in trawl i , and w_i is the total catch weight estimate of trawl i , both in kilogrammes.

The calculation of the weight of hake per trawl was amended in August 2009 to account for a bias in hake catch estimates. Hake separate from other species in the holding pond and rise to the top of the pond. Because fish are discharged from below the pond, hake tend to be transported to the processing area last. Hake are therefore not randomly distributed in the processing sequence. The solution was for observers to weigh all hake to obtain a total hake trawl weight. Prior to 29 July 2009, the weight of hake per trawl was extrapolated from sample weights. Thereafter the hake sample weight was recorded as the total trawl weight. This meant that the hake weights had to be added to the total sample weights in the calculations of the trawl weights of the other small fauna species.

Catch per unit effort

Catch per unit effort (CPUE) of the small fauna was calculated by dividing the total weight of each species in a trawl by the duration of the trawl:

$$CPUE_{si} = \frac{w_{si}}{e_i} \quad (\text{Equation 4})$$

where $CPUE_{si}$ is the catch per unit effort of species s in trawl i , and e_i is the duration of trawl i , in hours. The duration of the trawl was calculated as the time between net-on-bottom and start-haul times. CPUE of the large fauna species was calculated by dividing the number of individuals of each species by the duration of the trawl:

$$CPUE_{si} = \frac{c_{si}}{e_i} \quad (\text{Equation 5})$$

where c_{si} is the count of individuals of species s in trawl i . Trawls of duration less than 30 minutes were excluded from the CPUE calculations.

Diel patterns

Differences in day-time and night-time CPUE data were tested for all species using the Mann-Whitney test with the normal approximation for larger samples (Zar, 1984). The Bonferonni correction was applied to account for multiple comparisons. Trawls that occurred over day-time and night-time were excluded from the test.

Seasonal patterns

Differences in seasonal CPUE were tested for all species using the Kruskal-Wallis test with the Bonferonni correction. Pairwise comparisons between seasons were carried out using the Mann-Whitney test. Season 1 included trawls from January to March, Season 2 from April to June, Season 3 from July to September, and Season 4 from October to December.

Spatial patterns

Multivariate analyses were carried out on small fauna and large fauna separately. In each analysis, the data for each species were aggregated into the 20'' x 20'' grid blocks used to report commercial landings. The $CPUE_{si}$ values in each grid block were averaged to provide \overline{cpue}_{sg} values, where g is the grid block. Catch composition was compared among grid blocks using the \overline{cpue}_{sg} values from each grid block. Grid blocks with less than 10 trawls were excluded, unless the grid block formed part of a group of contiguous grid blocks. For some analyses, grid averages were calculated for the two day and night strata or the four seasonal strata. To limit the analysis to species composition as opposed to catch rate, the \overline{cpue}_{sg} values were converted to proportions of the average total CPUE of the grid block and day/night or seasonal strata, where appropriate. Analyses were carried out in the Primer statistical package. The proportions were fourth root transformed to down-weight the impact of highly abundant species as there were two orders of magnitude difference between the

most and least abundant species. A resemblance matrix was calculated using the Bray-Curtis measure of similarity to determine dissimilarity among grid blocks (Clarke and Warwick, 2001).

Cluster analysis was carried out using group average linking to construct a dendrogram for each analysis. Similarity levels of 80% and 55% were used to define communities of small and large fauna respectively. SIMPER was used to identify species contributing to the similarity within groups and dissimilarity among groups.

Permutational multivariate analysis of variance (PERMANOVA) was performed to test the effects of season, time of day and location (central and east Agulhas Bank) on small fauna catch composition. The central Agulhas Bank lies between 22°E and 23°E and the eastern Agulhas Bank lies between 24°E and 27°E (Figure 1).

The PERMANOVA analysis on the large fauna catch composition did not test the effect of location owing to a lack of data across all levels of all factors, therefore the analysis included the effects of season and time of day only. Analyses were conducted on fourth root transformed data, to reduce the influence of highly abundant taxa, using Bray-Curtis dissimilarities. All factors were treated as fixed and 999 permutations were performed under a reduced model. SIMPER was once again used to identify indicator species.

Generalised linear models (GLMs) were performed in R 3.1.2 using the stats package (R Core Team, 2014) to investigate the response of the CPUE of the most common large fauna species, namely Cape fur seals, copper sharks, mako sharks and sunfish, to location, time of day and season. Owing to a large number of zero values and overdispersion (the ratio of

residual deviance to degrees of freedom ≥ 1.5), the quasi-poisson error distribution was used.

Models were of the form:

$$\begin{aligned} C\widehat{PUE} = & \alpha + \beta_1 location + \beta_2 time\ of\ day + \beta_3 season + \beta_4 location * time\ of\ day + \\ & \beta_5 location * season + \beta_6 time\ of\ day * season + \beta_7 location * time\ of\ day * \\ & season + \varepsilon \end{aligned} \tag{Equation 6}$$

where ε is the error.

Average annual catch estimates

The total annual catch estimates of small fauna species were calculated by summing the weight of the total catch of each species per trawl in the year. As the large fauna data comprised counts, an average weight for each species was used to calculate the large fauna total annual catch per species. Where available, weights of individual large fauna were used to calculate an average weight for a species. Data on individual masses were unavailable for bigeye thresher sharks, ragged-tooth sharks, eagle rays, bull rays, blue stingrays, butterfly rays, spearnose skates, bigeye tuna, longfin tuna, Atlantic bonitos, Cape gannets and Atlantic yellow-nosed albatrosses. In these cases an average mass of 126.4 kg was assumed for bigeye thresher sharks (Kohler *et al.*, 1995), 42.3 kg for ragged-tooth sharks, 10.0 kg for eagle rays, 14.3 kg for bull rays, 8.9 kg for blue stingrays, 22.1 kg for butterfly rays, 20.7 kg for spearnose skates (Dicken *et al.*, 2012). An average mass of 10.0 kg was assumed for bigeye tunas, 12.7 kg for longfin tunas (Mann, 2013), 1.6 kg for Atlantic bonitos (Nottestad *et al.*, 2013), 2.6 kg for Cape gannets and 2.2 kg for Atlantic yellow-nosed albatrosses (Sinclair *et al.*, 2011). The total annual catches per species were averaged across the years to yield average annual catch estimates per species.

Results

Sample size and exclusions

During the study period 4303 trawls were observed, which is 84.5% of trawls. In 3173 of these trawls the catch weight was calculated by the observer whereas in the remaining 1130 trawls catch weights were visual estimates. Linear regression revealed a strong positive relationship between the calculated catch weight and the estimated catch weight ($n=3173$, $r^2 = 0.91$, $p < 2.2e^{-16}$) (Figure 2). The 99% prediction interval excluded 110 (2.2%) trawls. The exclusion of trawls with duration less than 30 minutes resulted in a further 113 (2.2%) exclusions.

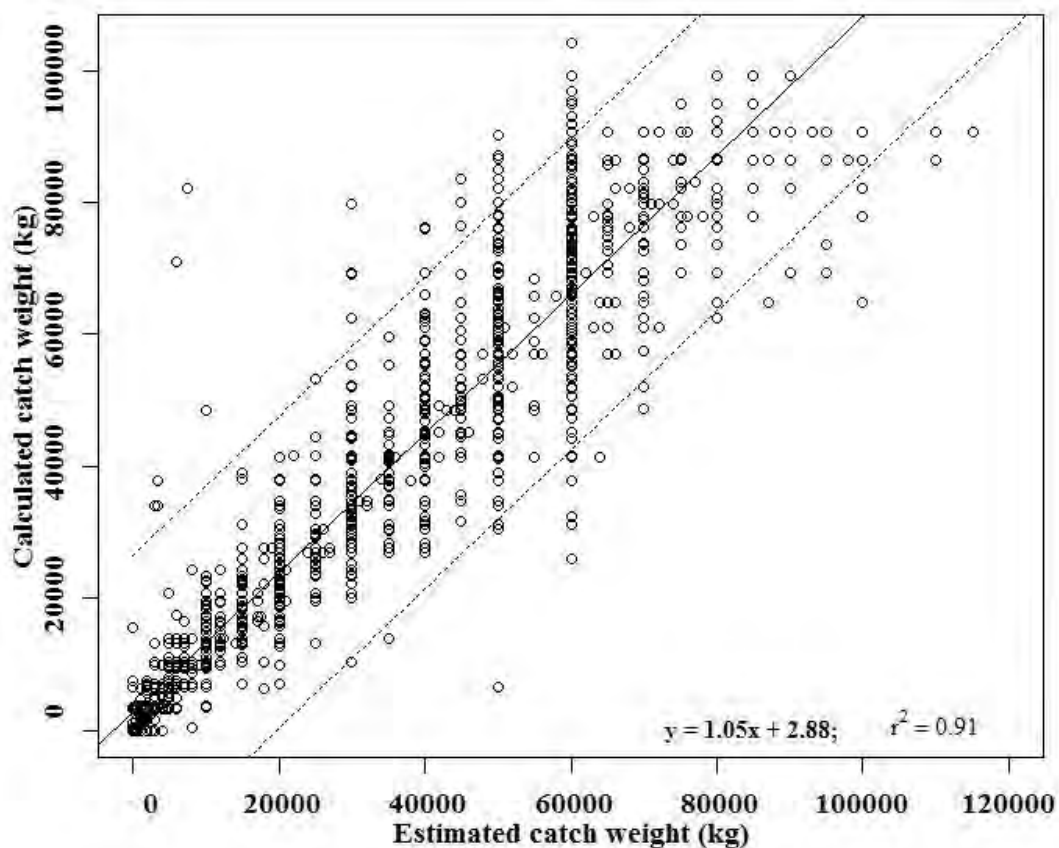


Figure 2. Midwater trawl estimated net weight versus calculated net weight with regression line and 99% prediction intervals.

Trawling behaviour

The midwater trawl fishery showed a strong diel pattern, with roughly 85% of trawls being set at night (from 18:00 to 05:00), and a third of all trawls being set between 18:00 and 21:00 (Figure 3A). Typically one trawl was set per night but a second trawl was set approximately every fifth night. Approximately every fifth day a day-time trawl was also set (from 05:00 to 18:00). The average trawl duration was 2.3 h in day-time and 2.2 h at night.

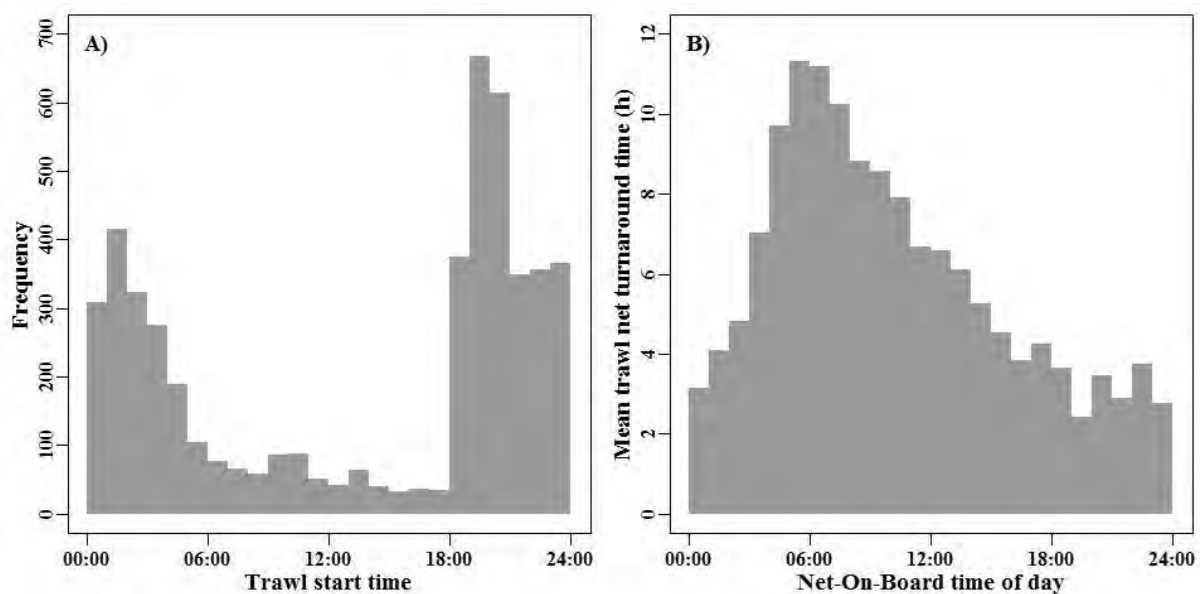


Figure 3. A) Frequency of midwater trawls per time of day trawl is started and B) Mean turnaround time based on time of day net-on-board.

The average net turnaround time (the time between net-on-board and deployment of the subsequent net) was 7.3 h for trawls hauled on board during the day (05:00 to 18:00) and 3.2 h at night (Figure 3B). The longest average net turnaround time occurred when trawl nets were brought on board between 05:00 and 06:00 (11.3 h).

There was a significant difference between the day-time and night-time mean trawl depth (day-time average 207 m, night-time average 115 m; $n_{\text{day}} = 298$, $n_{\text{night}} = 2179$, $Z = 19.2$, $p < 0.001$). The majority of day-time trawls (72.4%) were dragged at a depth range between

100 and 300 m (Figure 4A), whereas 69.9% of night-time trawls were dragged at a narrower depth range of between 50 and 150 m (Figure 4B).

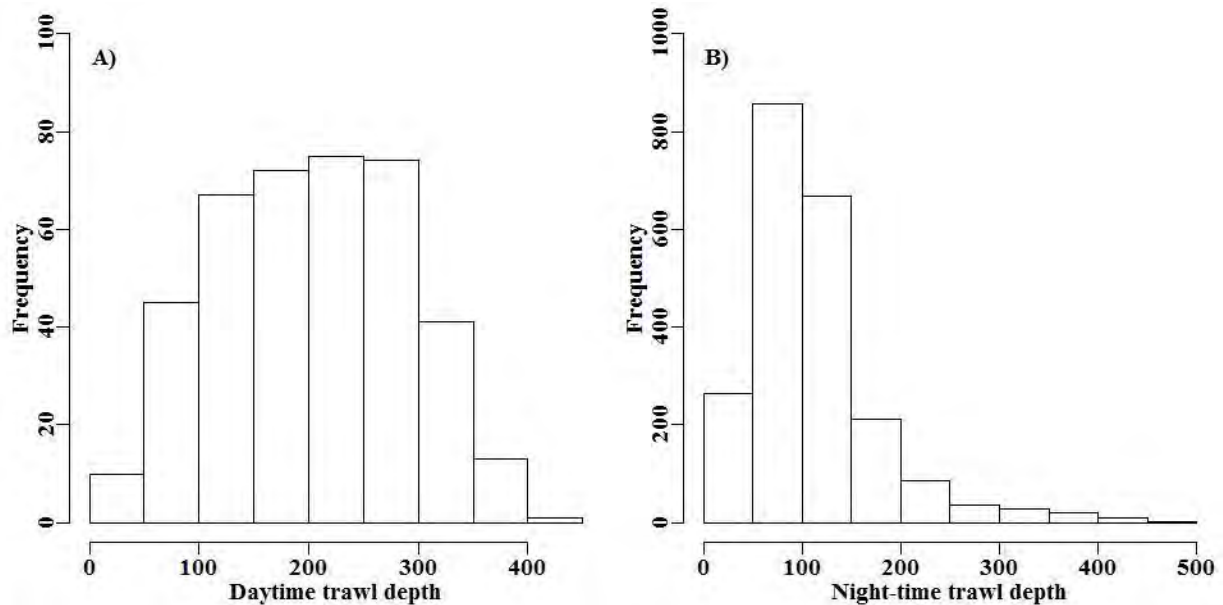


Figure 4. A) Frequency of day-time trawl depth and B) night-time trawl depth.

Species composition

There were 87 nominal species recorded. At a broad taxonomic level, teleosts made up 99.7% of the total catch by weight. The remaining 0.3% was made up of chondrichthyans, cephalopods, mammals and birds. Horse mackerel dominated catches, constituting 93.1% by weight (Table 1). Species that overlap with the small pelagic fishery, redeye roundherring, sardines and anchovies, constituted 1.5% of the catch. Hake, which constituted 0.9% of the catch, overlap with the demersal trawl fishery. Species that overlap with the linefishery, namely snoek, carpenter and geelbek, constituted 0.1% of the catch. Chokka squid, which constituted 0.09% of the catch, is the primary target of the squid fishery. Sharks, which constituted 0.05% of the catch, overlap with the shark longline fishery.

Table 1. Annual average catch estimates for the midwater trawl fishery, 2005-2013.

Common Name	Genus	Species	Catch (t)	Percentage
Horse mackerel	<i>Trachurus</i>	<i>capensis</i>	23671.9	93.14
Chub mackerel	<i>Scomber</i>	<i>japonicus</i>	737.6	2.90
Redeye roundherring	<i>Etrumeus</i>	<i>whiteheadi</i>	345.1	1.36
Ribbonfish	<i>Lepidopus</i>	<i>caudatus</i>	248.5	0.98
Hake	<i>Merluccius</i>	spp.	232.1	0.91
Sardine	<i>Sardinops</i>	<i>sagax</i>	39.2	0.15
Large fauna	(See table 2)		31.7	0.12
Snoek	<i>Thyrsites</i>	<i>atun</i>	25.3	0.10
Other species			25.2	0.10
Chokka squid	<i>Loligo</i>	<i>vulgaris</i>	23.1	0.09
Carpenter	<i>Argyrozona</i>	<i>argyrozona</i>	9.1	0.04
Red Mullet	<i>Emmelichthys</i>	<i>nitidus nitidus</i>	7.0	0.03
Skipjack Tuna	<i>Katsuwonus</i>	<i>pelamis</i>	6.8	0.03
Gurnard unidentified	<i>Chelidonichthys</i>	spp.	3.7	0.01
Red squid	Family Ommastrephidae		2.8	0.01
Dory unidentified	<i>Zeus</i>	spp.	2.2	0.01
Geelbek	<i>Atractoscion</i>	<i>aequidens</i>	1.2	0.00
Angelfish	<i>Brama</i>	<i>brama</i>	1.0	0.00
Anchovy	<i>Engraulis</i>	<i>encrasicolus</i>	0.4	0.00
Dogshark unidentified	<i>Squalus</i>	spp.	0.4	0.00
Lanternfish	<i>Lampanyctodes</i>	<i>hectoris</i>	0.1	0.00
Total			25414.6	

Total catch estimates

The *Desert Diamond* midwater trawler was estimated to have caught 25 415 t annually, of which horse mackerel catches dominated at 23 672 t (Table 1). After horse mackerel, species with the highest catches were chub mackerel, redeye roundherring and ribbonfish with annual catches averaging 738, 345 and 249 t respectively. Catches for hake, the most important demersal trawl species, averaged 232 t annually. Catches for important linefish species, snoek, carpenter and geelbek averaged 25.3, 9.1 and 1.2 t respectively. Estimates of annual catches of large fauna species averaged 31.7 t annually, of which Cape fur seals dominated with 10.1 t (Table 2). Annual catches of sharks averaged 13.8 t with the Carcharhiniformes and the Lamniformes having averaged 8.9 t and 4.9 t respectively. Catches of other species of bycatch concern, namely sunfish (*Mola mola*) and dolphins (order Cetacea) averaged 3.2 and 0.3 t, respectively.

Table 2. Annual average catch estimates of large fauna for the midwater trawl fishery, 2005-2013 (+calculated as the percentage of the total annual average catch weight of the midwater trawl).

	Common Name	Genus	Species	Mean weight (kg)	Mean Count	Estimated Catch (t)	Catch per order (t)	Percentage +
Order Carnivora	Cape fur seal	<i>Arctocephalus</i>	<i>pusillus</i>	95.1	106.4	10.11	10.11	0.04
Order	Copper shark	<i>Carcharhinus</i>	<i>brachyurus</i>	96.2	48.1	4.63	8.9	0.03
Carcharhiniformes	Dusky shark	<i>Carcharhinus</i>	<i>obscurus</i>	90.5	20.2	1.83		
	Hammerhead shark	<i>Sphyrna</i>	<i>zygaena</i>	125.2	8.7	1.09		
	Blue shark	<i>Prionace</i>	<i>glauca</i>	68.3	10.3	0.70		
	Blacktip shark	<i>Carcharhinus</i>	<i>limbatus</i>	30.0	16.9	0.51		
	Soupin shark	<i>Galeorhinus</i>	<i>galeus</i>	40.0	1.5	0.06		
	Bull shark	<i>Carcharhinus</i>	<i>leucas</i>	60.0	0.7	0.04		
	Catshark unidentified	<i>Holohaelurus</i>	spp.	1.6	0.1	0.00		
	Houndshark unidentified	<i>Mustelus</i>	spp.		0.6			
Order	Mako shark	<i>Isurus</i>	<i>oxyrinchus</i>	65.0	41.6	2.71	4.9	0.02
Lamniformes	Thresher shark	<i>Alopias</i>	<i>vulpinus</i>	228.6	8.6	1.97		
	Bigeye thresher shark	<i>Alopias</i>	<i>supercilius</i>	126.4	1.0	0.12		
	Porbeagle shark	<i>Lamna</i>	<i>nasus</i>	15.0	1.4	0.02		
	Ragged-tooth shark	<i>Carcharias</i>	<i>taurus</i>	42.3	0.1	0.01		
Order Perciformes (Billfish)	Broadbill swordfish	<i>Xiphias</i>	<i>gladius</i>	166.0	22.5	3.73	3.8	0.01
	Black Marlin	<i>Istiompax</i>	<i>indica</i>	110.0	0.4	0.05		
	Sailfish	<i>Istiophorus</i>	<i>platypterus</i>	30.0	0.1	0.00		
	Marlin unidentified				0.3			
Order Tetraodontiformes	Sunfish	<i>Mola</i>	<i>mola</i>	76.4	42.0	3.21	3.2	0.01

Continued

Table 2. Continued

Order	Common Name	Genus	Species	Mean weight (kg)	Mean Count	Estimated Catch (t)	Catch per order (t)	Percentage⁺
Myliobatiformes	Manta ray	<i>Manta</i>	<i>birostris</i>	75.0	5.0	0.37	0.4	0.00
	Eagle ray	<i>Myliobatis</i>	<i>aquila</i>	10.0	1.1	0.01		
	Bull ray	<i>Pteromylaeus</i>	<i>bovinus</i>	14.3	0.3	0.00		
	Blue stingray	<i>Dasyatis</i>	<i>chrysonota</i>	8.9	0.3	0.00		
	Butterfly ray	<i>Gymnura</i>	<i>natalensis</i>	22.1	0.1	0.00		
	Pelagic stingray	<i>Pteroplatytrygon</i>	<i>violacea</i>	4.0	0.3	0.00		
	Devil ray	<i>Mobula</i>	spp.		0.1			
	Stingray unidentified				0.3			
	Ray unidentified				0.6			
	Order Cetacea	Bottlenose dolphin	<i>Tursiops</i>	<i>truncatus</i>	164.2	1.4	0.23	0.3
Common dolphin		<i>Delphinus</i>	<i>delphis</i>	80.0	1.2	0.10		
Order Perciformes Family Scombridae	Bigeye tuna	<i>Thunnus</i>	<i>obesus</i>	10.0	2.8	0.03	0.1	0.00
	Yellowfin tuna	<i>Thunnus</i>	<i>albacares</i>	20.0	1.0	0.02		
	Skipjack tuna	<i>Katsuwonus</i>	<i>pelamis</i>	8.0	2.4	0.02		
	Longfin tuna	<i>Thunnus</i>	<i>atalunga</i>	12.7	0.3	0.00		
	Atlantic bonito	<i>Sarda</i>	<i>sarda</i>	1.6	0.3	0.00		
	Cape gannet	<i>Morus</i>	<i>capensis</i>	2.7	4.6	0.01	0.0	0.00
Class Aves	Atlantic yellow-nosed albatross	<i>Thalassarche</i>	<i>chlororhynchos</i>	2.2	0.1	0.00		
	Spearnose skate	<i>Rostroraja</i>	<i>alba</i>	20.7	0.7	0.01	0.0	0.00
Order	Opah	<i>Lampris</i>	<i>guttatus</i>	40.0	0.1	0.01	0.0	0.00
Lampriformes								
Total	Total					31.66		

Day/night patterns

Significant differences between day-time and night-time CPUE were detected for five of the small fauna species (Table 3). Species with higher CPUE at night were horse mackerel (night-time average 30 818 kg h⁻¹, day-time average 18 598 kg h⁻¹; n_{day} = 471, n_{night} = 2473, Z = -11.4, p<0.001), chub mackerel (night-time average 1 000 kg h⁻¹, day-time average 887 kg h⁻¹; n_{day} = 471, n_{night} = 2473, Z = -3.0, p = 0.017) and gurnards (night-time average 4.3 kg h⁻¹, day-time average 0.3 kg h⁻¹; n_{day} = 471, n_{night} = 2473, Z = -1.0, p = 0.009). Those with higher CPUE in the day were hake (night-time average 91 kg h⁻¹, day-time average 1 341 kg h⁻¹; n_{day} = 471, n_{night} = 2473, Z = 4.8, p<0.001) and angelfish (night-time average 0.0 kg h⁻¹, day-time average 4.3 kg h⁻¹; n_{day} = 471, n_{night} = 2473, Z = 0.6, p<0.001).

The difference in day-time and night-time CPUE detected in the horse mackerel is significant, however the CPUE in the day and at night are both high with the night-time CPUE almost two-thirds of the day-time CPUE. Similarly, the chub mackerel CPUE in the day and at night are not vastly different. The hake CPUE in the day, however, is almost 15 times higher than the CPUE at night. The day-time and night-time CPUE of gurnards and angelfish are low. The night-time CPUE of gurnards is 15 times higher than the day-time CPUE, whereas the night-time CPUE of angelfish is over 100 times higher than day-time CPUE.

Significant differences between day-time and night-time CPUE were detected for four of the large fauna species. Species with higher CPUE in the day were broadbill swordfish (night-time average 0.006 individuals h⁻¹, day-time average 0.093 individuals h⁻¹; n_{day} = 471, n_{night} = 2473, Z = 2.1, p<0.001), manta rays (night-time average 0.001 individuals h⁻¹, day-time average 0.3 individuals h⁻¹; n_{day} = 471, n_{night} = 2473, Z = 0.3, p = 0.003) and thresher sharks

Table 3. Mann-Whitney results of diel differences for midwater trawl small fauna species, *p*-values adjusted with the Bonferonni correction, significant values indicated with * (the greater mean CPUE values are underlined for species with significant differences).

Common Name	Genus	Species	Day		Night		Mann-Whitney Results		
			Mean CPUE (kg h ⁻¹)	Mean CPUE (kg h ⁻¹)	Mean CPUE (kg h ⁻¹)	Mean CPUE (kg h ⁻¹)	Z	adj p	sig
Horse mackerel	<i>Trachurus</i>	<i>capensis</i>	18597.7	<u>30818.4</u>	30818.4	30818.4	-11.4	<0.001	*
Hake	<i>Merluccius</i>	spp.	<u>1341.1</u>	91.0	91.0	91.0	4.8	<0.001	*
Chub mackerel	<i>Scomber</i>	<i>japonicus</i>	887.2	<u>999.5</u>	999.5	999.5	-3.0	0.017	*
Redeye roundherring	<i>Etrumeus</i>	<i>whiteheadi</i>	738.5	377.3	377.3	377.3	-2.3	0.098	
Ribbonfish	<i>Lepidopus</i>	<i>caudatus</i>	378.3	207.9	207.9	207.9	1.4	1.000	
Sardine	<i>Sardinops</i>	<i>sagax</i>	98.4	55.6	55.6	55.6	0.0	1.000	
Other species			86.5	19.6	19.6	19.6	0.3	1.000	
Chokka squid	<i>Loligo</i>	<i>vulgaris</i>	20.5	28.4	28.4	28.4	-0.5	1.000	
Snoek	<i>Thysites</i>	<i>atun</i>	0.8	26.9	26.9	26.9	-0.7	0.080	
Red squid	Family Ommastrephidae		19.4	1.7	1.7	1.7	0.5	1.000	
Red mullet	<i>Emmelichthys</i>	<i>nitidus nitidus</i>	1.2	19.8	19.8	19.8	0.1	1.000	
Carpenter	<i>Argyrozona</i>	<i>argyrozona</i>	0.0	11.2	11.2	11.2	-0.2	1.000	
Skipjack tuna	<i>Katsuwonus</i>	<i>pelamis</i>	0.0	6.3	6.3	6.3	-0.3	1.000	
Angelfish	<i>Brama</i>	<i>brama</i>	<u>4.3</u>	0.0	0.0	0.0	0.6	<0.001	*
Anchovy	<i>Engraulis</i>	<i>encrasicolus</i>	2.3	0.3	0.3	0.3	0.4	0.557	
Gurnard unidentified	<i>Chelidonichthys</i>	spp.	0.3	<u>4.3</u>	4.3	4.3	-1.0	0.009	*
Geelbek	<i>Atractoscion</i>	<i>aequidens</i>	0.0	1.2	1.2	1.2	0.0	1.000	
Dory unidentified	<i>Zeus</i>	spp.	0.9	1.1	1.1	1.1	0.1	1.000	
Dog shark unidentified	<i>Squalus</i>	spp.	0.0	0.7	0.7	0.7	-0.1	1.000	
Lanternfish	<i>Lampanyctodes</i>	<i>hectoris</i>	0.0	<0.1	<0.1	<0.1	0.0	1.000	

(night-time average 0.008 individuals h^{-1} , day-time average 0.046 individuals h^{-1} ; $n_{day} = 471$, $n_{night} = 2473$, $Z = 0.8$, $p < 0.001$). Copper sharks displayed higher CPUE at night (night-time average 0.061 individuals h^{-1} , day-time average 0.001 individuals h^{-1} ; $n_{day} = 471$, $n_{night} = 2473$, $Z = -1.8$, $p < 0.001$). The day-time CPUE of manta rays and thresher sharks are 300 and 57 times higher than at night, respectively. Copper sharks displayed the reverse, with night-time CPUE being over 60 times higher than day-time CPUE.

Seasonal patterns

Significant differences in seasonal CPUE were detected for 13 of the small fauna species (Table 4). Post-hoc analyses of the small fauna species revealed varying seasonal patterns of abundance across the species (Table 5). Horse mackerel, hake and ribbonfish had the highest abundances during season 1, while chub mackerel, redeye roundherring, snoek, anchovy and gurnards had the highest abundances during season 3. Chub mackerel was the only small fauna species where differences between all seasons were significant. The abundances of horse mackerel, snoek and gurnards during season 3 were significantly different to the abundances during all other seasons.

The greatest differences in CPUE between seasons were noted in skipjack tuna and snoek. Snoek CPUE during season 3 was approximately 500 times higher than during season 4. Skipjack tuna were most abundant in season 2, and the CPUE was approximately two orders of magnitude larger than the CPUE in seasons 3 and 4. Hake CPUE during seasons 1 and 4 were almost an order of magnitude higher than during seasons 2 and 3. Anchovy were absent during season 2.

Table 4. Kruskal-Wallis results of seasonal differences for small fauna species, *p*-values adjusted with the Bonferonni correction and significant values indicated with * .

Common Name	Genus	Species	Kruskal-Wallis results		
			χ -squared	adj <i>p</i>	sig
Horse mackerel	<i>Trachurus</i>	<i>capensis</i>	37.21	<0.001	*
Hake	<i>Merluccius</i>	spp.	287.84	<0.001	*
Chub mackerel	<i>Scomber</i>	<i>japonicus</i>	279.66	<0.001	*
Redeye roundherring	<i>Etrumeus</i>	<i>whiteheadi</i>	127.39	<0.001	*
Ribbonfish	<i>Lepidopus</i>	<i>caudatus</i>	19.26	0.005	*
Sardine	<i>Sardinops</i>	<i>sagax</i>	55.31	<0.001	*
Other species			102.60	<0.001	*
Chokka squid	<i>Loligo</i>	<i>vulgaris</i>	12.68	0.108	
Snoek	<i>Thyrsites</i>	<i>atun</i>	90.09	<0.001	*
Red squid	Family Ommastrophidae		16.39	0.019	*
Red Mullet	<i>Emmelichthys</i>	<i>nitidus nitidus</i>	9.49	0.468	
Carpenter	<i>Argyrozona</i>	<i>argyrozona</i>	5.12	1.000	
Skipjack Tuna	<i>Katsuwonus</i>	<i>pelamis</i>	28.46	<0.001	*
Angelfish	<i>Brama</i>	<i>brama</i>	18.30	0.008	*
Anchovy	<i>Engraulis</i>	<i>encrasicolus</i>	29.41	<0.001	*
Gurnard unidentified	<i>Chelidonichthys</i>	spp.	44.59	<0.001	*
Geelbek	<i>Atractoscion</i>	<i>aequidens</i>	4.85	1.000	
Dory unidentified	<i>Zeus</i>	spp.	5.94	1.000	
Dog shark unidentified	<i>Squalus</i>	spp.	4.15	1.000	
Lanternfish	<i>Lampanyctodes</i>	<i>hectoris</i>	5.45	1.000	

Table 5. Kruskal-Wallis post-hoc results of differences in small fauna CPUE across seasons, *p*-values were adjusted with the Bonferonni correction, significant values indicated with *, the largest mean CPUE values are underlined.

Species	Adjusted <i>p</i> -values					Mean	sd
	Season						
Horse mackerel <i>Trachurus capensis</i>	1	1	2	3		<u>25660.4</u>	30964.9
	2	1.000	-	-		23492.0	27572.6
	3	<0.001 *	0.001 *	-		19785.9	24441.5
	4	1.000	1.000	<0.001 *		24369.3	28782.6
Hake <i>Merluccius</i> spp.	1	1	2	3		<u>486.7</u>	3359.5
	2	0.002 *	-	-		41.7	257.1
	3	<0.001 *	1.000	-		59.9	617.6
	4	<0.001 *	<0.001 *	<0.001 *		363.5	1741.7
Chub mackerel <i>Scomber japonicus</i>	1	1	2	3		754.2	3717.8
	2	<0.001 *	-	-		319.9	2112.1
	3	<0.001 *	<0.001 *	-		<u>1060.6</u>	3774.7
	4	<0.001 *	<0.001 *	0.018 *		952.2	4589.7

Continued

Table 5. *Continued*

Species	Adjusted <i>p</i> -values					Mean	sd
	Season						
Redeye roundherring <i>Etrumeus</i> <i>whiteheadi</i>	1	1	2	3		431.6	2651.0
	2	1.000	-	-		168.7	1647.1
	3	<0.001 *	<0.001 *	-		<u>466.7</u>	2474.2
	4	<0.001 *	<0.001 *	0.001 *		281.8	1888.5
Ribbonfish <i>Lepidopus caudatus</i>	1	1	2	3		<u>297.8</u>	1855.9
	2	1.000	-	-		171.1	711.5
	3	1.000	1.000	-		118.3	435.5
	4	1.000	0.134	0.006 *		238.1	1135.3
Sardine <i>Sardinops sagax</i>	1	1	2	3		54.0	1349.5
	2	1.000	-	-		44.6	686.0
	3	<0.001 *	<0.001 *	-		20.4	197.2
	4	0.004 *	<0.001 *	1.000		<u>78.1</u>	1177.8
Other species	1	1	2	3		14.0	117.3
	2	1.000	-	-		7.9	93.5
	3	0.221	0.004 *	-		12.0	63.7
	4	<0.001 *	<0.001 *	<0.001 *		<u>60.5</u>	1049.8
Snoek <i>Thyrsites atun</i>	1	1	2	3		9.0	196.8
	2	1.000	-	-		3.4	39.1
	3	<0.001 *	0.001 *	-		<u>61.2</u>	485.7
	4	1.000	0.320	<0.001 *		0.1	3.6
Skipjack tuna <i>Katsuwonus</i> <i>pelamis</i>	1	1	2	3		4.8	63.5
	2	1.000	-	-		<u>23.2</u>	210.0
	3	1.000	0.013 *	-		0.2	4.5
	4	1.000	0.003 *	1.000		0.3	8.0
Anchovy <i>Engraulis</i> <i>encrasicolus</i>	1	1	2	3		0.1	2.7
	2	1.000	-	-		0.0	0.0
	3	1.000	0.509	-		<u>1.2</u>	24.7
	4	0.023 *	0.002 *	1.000		0.4	4.5
Gurnard unidentified <i>Chelidonichthys</i> spp.	1	1	2	3		1.6	20.0
	2	1.000	-	-		1.2	14.2
	3	0.001 *	0.007 *	-		<u>7.3</u>	53.5
	4	1.000	1.000	<0.001 *		1.4	27.8

Significant differences between seasonal CPUE were detected for four of the large fauna species. These were Cape fur seals ($\chi^2 = 73.6$, d.f. = 3, $p < 0.001$), broadbill swordfish ($\chi^2 = 64.6$, d.f. = 3, $p < 0.001$), dusky sharks ($\chi^2 = 30.0$, d.f. = 3, $p < 0.001$) and blue sharks ($\chi^2 = 40.1$, d.f. = 3, $p < 0.001$).

The post-hoc analyses of the large fauna species revealed that Cape fur seals occurred in highest abundances during season 3, broadbill swordfish during season 4 and dusky and blue sharks during season 1 (Table 6). The differences in abundances of Cape fur seals across the four seasons were significant between seasons 1 and 3, 2 and 4 and between 3 and 4. The abundance of broadbill swordfish in season 4 was significantly different to abundances occurring in all other seasons, as was the difference between abundances in seasons 2 and 3. The differences in the abundances of dusky sharks across all seasons was only significant between seasons 1 and 4, while the abundances of blue sharks in seasons 1 and 2 were significantly difference to the abundances occurring in seasons 3 and 4.

Table 6. Kruskal-Wallis post-hoc results of differences in large fauna CPUE across seasons, *p*-values were adjusted with the Bonferonni correction, significant values indicated with * (largest mean CPUE values are underlined).

Species	Adjusted p-values						Mean	sd
	Season							
Cape fur seal	1	1		2		3	0.06	0.41
<i>Arctocephalus</i>	2	1.000		-		-	0.12	0.89
<i>pusillus</i>	3	<0.001 *		0.688		-	<u>0.17</u>	0.82
Order Carnivora	4	1.000		0.002 *		<0.001 *	0.02	0.17
Broadbill swordfish	1	1		2		3	0.01	0.11
<i>Xiphias gladius</i>	2	0.089		-		-	0.00	0.00
Order Perciformes	3	1.000		0.016 *		-	0.01	0.07
(Billfish)	4	<0.001 *		<0.001 *		0.008 *	<u>0.05</u>	0.28
Dusky shark	1	1		2		3	<u>0.05</u>	0.75
<i>Carcharhinus</i>	2	0.602		-		-	0.00	0.07
<i>obscurus</i>	3	1.000		1.000		-	0.01	0.17
Order Carcharhinidae	4	<0.001 *		1.000		0.860	0.00	0.04
Blue shark	1	1		2		3	<u>0.02</u>	0.29
<i>Prionace glauca</i>	2	1.000		-		-	0.02	0.16
Order Carcharhinidae	3	0.002 *		0.040 *		-	0.00	0.03
	4	<0.001 *		0.006 *		1.000	0.00	0.01

Spatial patterns

Small fauna

The aggregation of CPUE data by commercial grid blocks yielded \overline{cpue}_{sg} data for 55 grid blocks. The exclusion of grid blocks with less than 10 trawls reduced this to 21 grid blocks for spatial analysis.

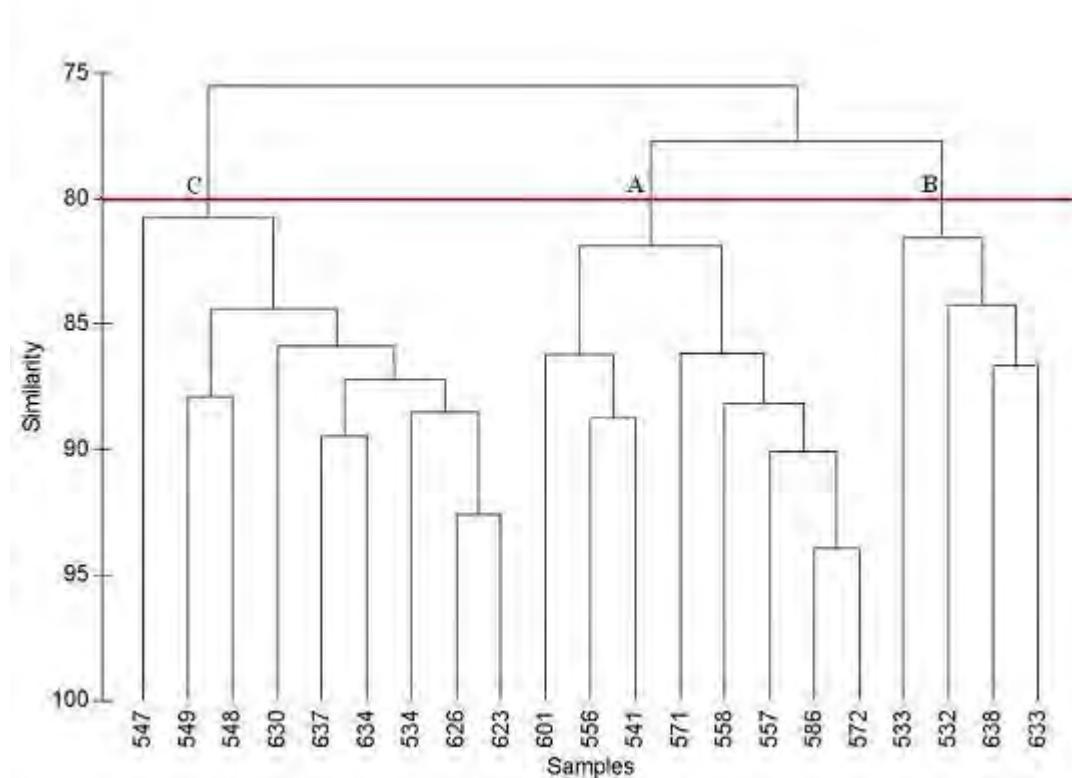


Figure 5. A dendrogram showing the similarity in midwater trawl small fauna catch composition among commercial grid-blocks.

Cluster analysis identified three groups of grid blocks at the 80% similarity level (Figure 5). Groups A and C included contiguous grid blocks, while group B included two sets of two contiguous grid blocks (Figure 6). Group B grid blocks lay adjacent to group C, on the eastern Agulhas Bank, with group A on the central Agulhas Bank. Groups A and B were more similar to each other (76% similarity) than to group C.

SIMPER analysis showed that the high similarity in species composition within the three groups (group A = 84.7%, group B = 83.3% and group C = 85.0%) was driven by high proportions of horse mackerel and chub mackerel. The relatively high proportion of hake in group C sets this group apart from groups A and B. Group A is set apart from groups B and C by the relatively high proportion of redeye roundherring.

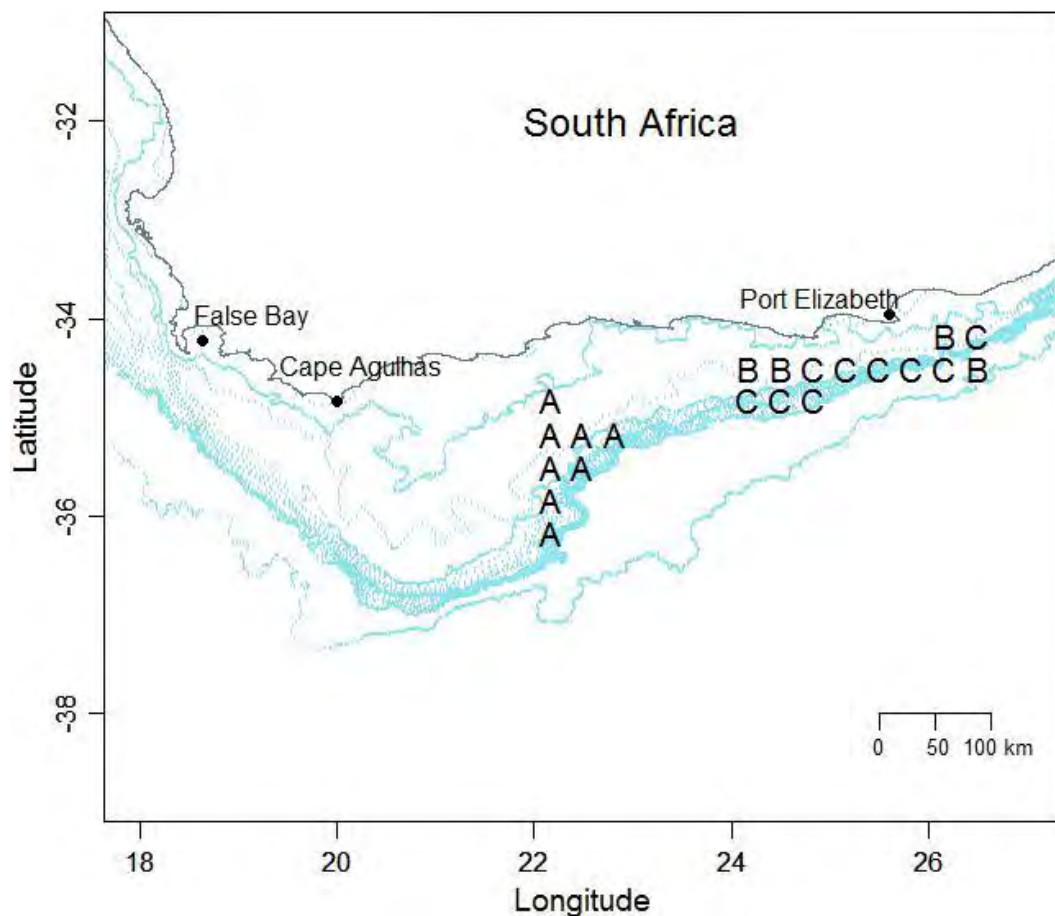


Figure 6. A map of the South African south coast showing groups A, B and C identified by cluster analysis of midwater trawl small fauna catch composition at the 80% similarity level.

Cluster analysis of species composition on the groups separated by day and night revealed that group C showed clear separation by day and night with a high level of similarity within groups and a high level of similarity between the groups (with one exception) (Figure 7).

SIMPER analysis revealed higher rates of similarity within the night groups than day groups, driven by high proportions of horse mackerel. Dissimilarities between groups were driven by higher proportions of redeye roundherring and chub mackerel at night in *A* and *B* groups and higher proportions of hake, redeye roundherring and chub mackerel during the day in *C* groups.

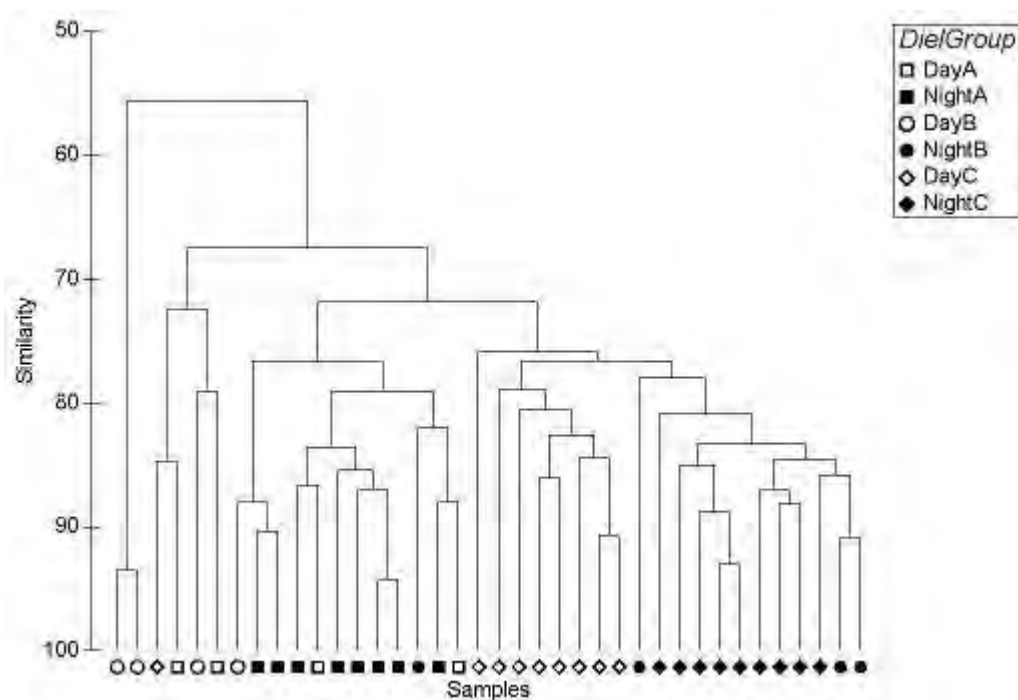


Figure 7. A dendrogram showing the similarity in small fauna catch composition among grid-blocks categorised by a combination of groups (defined at an 80% similarity level) and day/night.

The non-metric multidimensional scaling (MDS) ordination of species composition of groups separated by season revealed that group *C* had a higher rate of similarity between seasons than groups *A* and *B*, especially groups 1*C* and 4*C* (Figure 8). Group 2*C* showed a higher similarity with *B* groups across seasons. Group 4*A* showed a lower level of similarity to *A* groups during the remaining seasons and a higher level of similarity to *B* groups.

SIMPER results revealed high levels of within group similarities across seasons, driven by high proportions of horse mackerel. Seasonal differences between A groups were driven by redeye roundherring, sardine and snoek while seasonal differences between B groups and seasonal differences between C groups were driven by hake and chub mackerel.

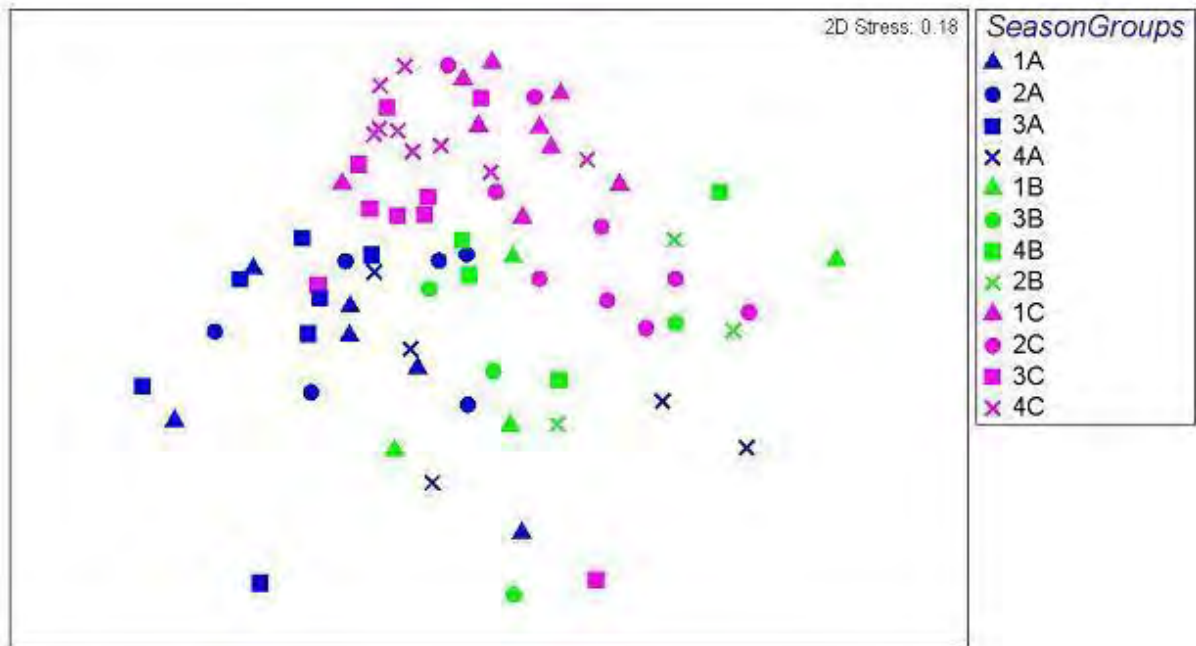


Figure 8. A MDS ordination of assemblages of small fauna catch compositions among grid blocks categorised by groups (defined at an 80% similarity level) and seasons.

The PERMANOVA analysis of catch composition revealed Location, Diel and Season to be significant factors, while Location*Season was the only significant interaction effect (Table 7).

SIMPER analysis on the location factor revealed a higher rate of similarity within the Central group (74.1%) than the East group (69.3%), driven by high proportions of horse mackerel. Dissimilarity between locations was driven by higher proportions of chub mackerel and redeye roundherring on the central Agulhas Bank and higher proportions of hake on the east Agulhas Bank.

Table 7. PERMANOVA results indicating the influences of location, time of day and season on small fauna community assemblages (significant values indicated with *, unique perms indicated the number of unique permutations run).

Source	df	SS	MS	Pseudo-F	<i>p</i> -values	sig	Unique perms
Location	1	4580.1	4580.1	11.332	0.001	*	998
Diel	1	2066.3	2066.3	5.1124	0.003	*	999
Season	3	4440.2	1480.1	3.662	0.001	*	997
LocationxDiel	1	905.31	905.31	2.24	0.065		999
LocationxSeason	3	2954.2	984.74	2.4365	0.007	*	999
DielxSeason	3	1400.8	466.94	1.1553	0.312		999
Res	112	45266	404.16				
Total	124	65858					

Large fauna

The exclusion of trawls with absences of large fauna reduced the number of grid blocks with 10 or more trawls to 13.

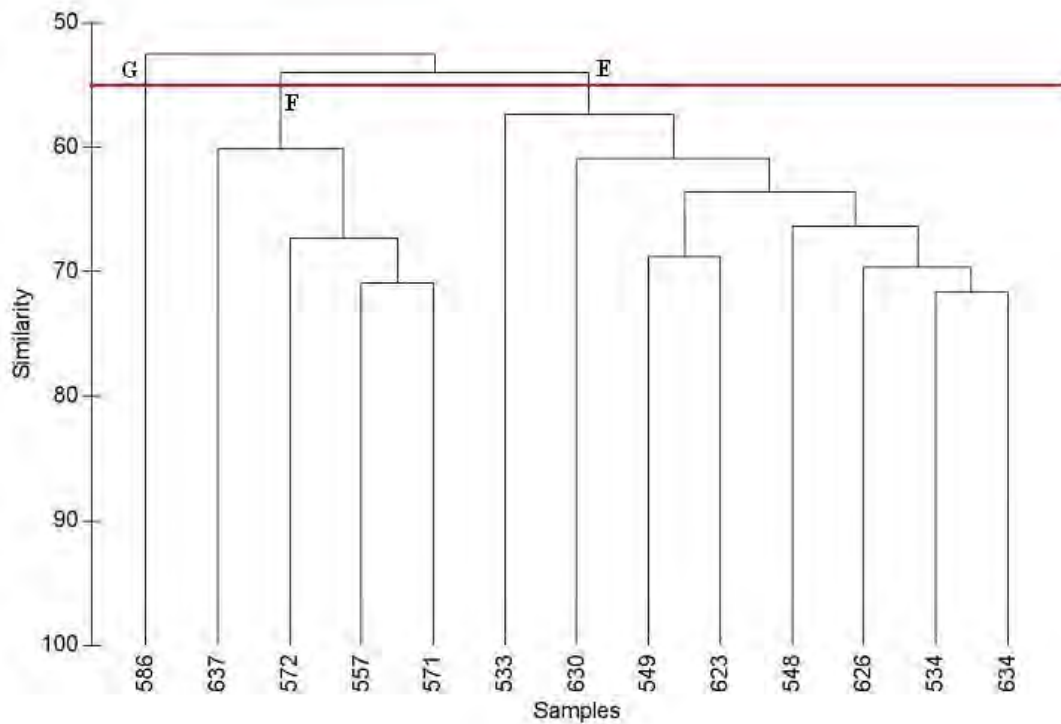


Figure 9. A dendrogram showing the similarity in midwater trawl large fauna catch composition among commercial grid-blocks.

Cluster analysis identified three groups of grid blocks at the 55% similarity level (Figure 9). Groups E included contiguous grid blocks, while group F included one grid block that was not contiguous and group G was composed of a single grid block (Figure 10). Group E grid blocks occurred on the eastern Agulhas Bank, with the isolated group F grid block laying adjacent to them. The remainder of group F grid blocks occurred on the central Agulhas Bank, with group G adjacent.

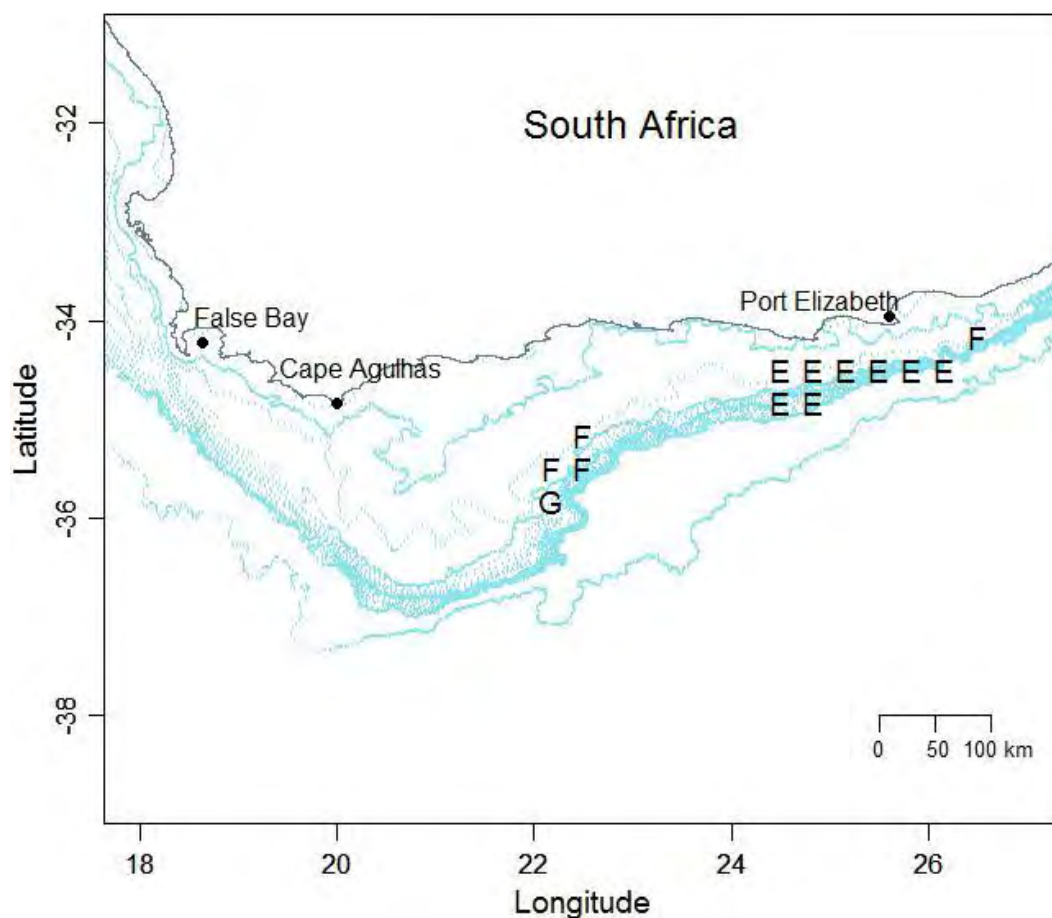


Figure 10. A map of the South African south coast showing groups E, F and G identified by cluster analysis of midwater trawl large fauna catch composition at the 55% similarity level.

SIMPER analysis revealed that the within group similarity was marginally higher in group F (64.4%) than group E (62.7%). In group F this was driven by hammerhead sharks and Cape fur seals and group E similarity was driven by Cape fur seals and mako sharks. Group E was the only group with broadbill swordfish, dusky and blacktip sharks present, while group G

was the only group with raggedtooth sharks present. Group G also showed an absence of hammerhead sharks and manta rays, while group F showed an absence of bottlenose dolphins. Group G had a higher proportion of blue sharks than the other groups while group F had a higher proportion of hammerhead sharks than group E.

Cluster analysis of species composition on the groups separated by day and night revealed that group E separated out by day and night with the *NightE* group showing a higher level of within group similarity (Figure 11). The groups did not cluster out clearly with the *NightE* group forming a cluster with the majority of grid blocks from the *NightF* group and the *DayE* group forming two clusters, one of which contained the single grid block from group G (*NightG*). The two grid blocks that formed group *DayF* showed high dissimilarity.

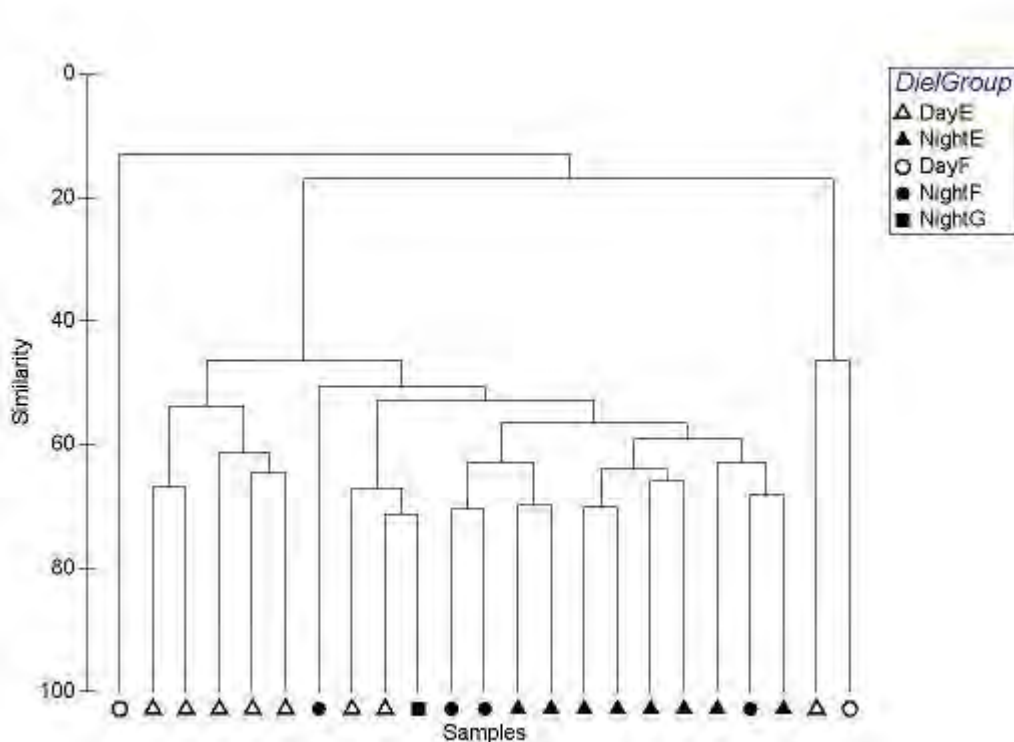


Figure 11. A dendrogram showing the similarity in large fauna catch composition among grid-blocks and day/night (groups defined at a level of similarity of 55%).

SIMPER analysis revealed higher rates of similarity within night groups than day groups driven by Cape fur seals in both day and night groups, and sunfish in the day group and copper sharks in the night group. The dissimilarity between day and night groups was driven by higher proportions of Cape fur seals, copper sharks and mako sharks at night and higher proportions of broadbill swordfish in the day.

The non-metric multidimensional scaling (MDS) ordination of species composition of groups separated by season revealed that group E has a higher rate of similarity between seasons than groups F and G (Figure 12). Group 2F showed a higher similarity with E groups across seasons, while the 2G and 3G groups show dissimilarity to each other.

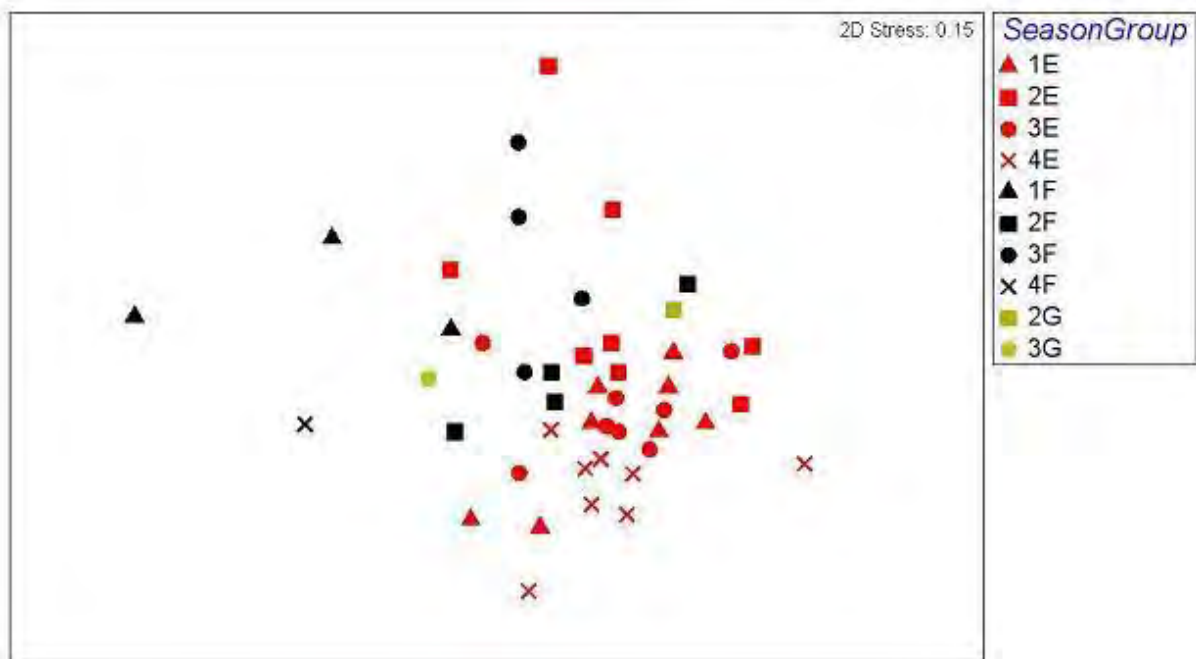


Figure 12. A MDS ordination of assemblages of large fauna catch composition among grid-blocks (groups defined at a level of similarity of 55%) and seasons.

SIMPER results showed that within group similarities was driven by high proportions of Cape fur seals and sunfish in seasons 1, 2 and 3, and mako sharks and sunfish in season 4. Dissimilarities between seasons were driven by Cape fur seals, sunfish, broadbill swordfish and hammerhead, mako and copper sharks.

The PERMANOVA analysis of catch composition revealed Diel and Season to be significant factors, while Diel*Season was the only significant interaction effect (Table 8).

Table 8. PERMANOVA results indicating the influences of time of day and season on large fauna community assemblages (significant values indicated with *, unique perms indicated the number of unique permutations run).

Source	df	SS	MS	Pseudo-F	p-values	sig	Unique perms
Diel	1	10370	10370	5.5392	0.001	*	999
Season	3	17938	5979.5	3.1939	0.001	*	999
DielxSeason	3	12503	4167.7	2.2261	0.003	*	999
Res	64	1.20E+05	1872.2				
Total	71	1.58E+05					

The generalised linear models showed that location had a significant influence on the CPUE of sunfish, Cape fur seals, copper sharks and mako sharks (Table 9). Time of day and season had significant influences on the CPUE of Cape fur seals and copper sharks. Season as well as the interaction effect of location and season had a significant influence on the CPUE of mako sharks.

Table 9. GLM results indicating influences of location, time of day and season on sunfish, Cape fur seal, copper shark and mako shark CPUE (significant values indicated with *).

	Df	Deviance	Resid. Df	Resid. Dev	p-value	sig
(Call = Sunfish ~ Location * Diel * Season)						
			2929	867.65		
Location	2	42.55	2927	825.11	<0.001	*
Diel	1	0.82	2926	824.29	0.545	
Season	3	2.93	2923	821.36	0.727	
Location*Diel	1	0.17	2922	821.18	0.780	
Location*Season	4	4.99	2918	816.19	0.693	
Diel*Season	3	1.19	2915	815.00	0.912	
Location*Diel*Season	3	0.00	2912	815.00	1.000	
Call = Cape fur seal ~ Location * Diel * Season						
			2929	2122.62		
Location	2	110.77	2927	2011.85	<0.001	*
Diel	1	39.92	2926	1971.93	<0.001	*
Season	3	189.14	2923	1782.79	<0.001	*
Location*Diel	1	2.50	2922	1780.28	0.322	
Location*Season	4	2.62	2918	1777.67	0.906	
Diel*Season	3	13.39	2915	1764.27	0.154	
Location*Diel*Season	3	0.05	2912	1764.23	0.999	
Call = Copper shark ~ Location * Diel * Season						
			2929	1103.95		
Location	2	53.89	2927	1050.06	<0.001	*
Diel	1	60.25	2926	989.81	<0.001	*
Season	3	29.34	2923	960.47	0.004	*
Location*Diel	1	0.01	2922	960.47	0.960	
Location*Season	4	11.13	2918	949.33	0.278	
Diel*Season	3	1.16	2915	948.17	0.912	
Location*Diel*Season	3	0.00	2912	948.17	1.000	
Call = Mako shark ~ Location * Diel * Season						
			2929	1005.26		
Location	2	42.63	2927	962.63	<0.001	*
Diel	1	1.37	2926	961.26	0.338	
Season	3	26.43	2923	934.83	<0.001	*
Location*Diel	1	0.35	2922	934.48	0.627	
Location*Season	4	23.52	2918	910.96	0.003	*
Diel*Season	3	2.03	2915	908.94	0.714	
Location*Diel*Season	3	0.00	2912	908.94	1.000	

Discussion

Observer coverage and sampling size

The 1% minimum sample rate was achieved with a mean sample rate of 1.56% of the total catch by weight. This rate is however, very low and can lead to increased sampling errors, especially for rare species. Heales *et al.*, (2003) determined that increasing sample size taken from prawn trawls led to increases in the accuracy of species abundance estimates. A sample of 10% of the catch weight led to sampling error of approximately 80% for „rare“ species (less than one individual per 10 kg), and approximately 25% for „abundant“ species (five or more individuals per 10 kg).

The decrease in error of bycatch proportion with an increase in sample size can be demonstrated using the midwater trawl bycatch rate. The standard error of the bycatch proportion is estimated from the sample by using a finite population correction, as the size of the population is known (Zar, 1984):

$$s_{\hat{p}} = \sqrt{\frac{\hat{p}\hat{q}}{n-1} \left(1 - \frac{n}{N}\right)} \quad (\text{Equation 7})$$

where \hat{p} is the proportion of bycatch in the sample, \hat{q} is the proportion of horse mackerel in the sample, n is the sample size and N is the population size. As the sampling fraction (n/N) increases, the finite correction ($1 - n/N$) decreases, resulting in a decrease in the standard error. Using the average proportions of bycatch (0.069) and horse mackerel (0.931), and the average sample size of 722 kg (1.56% of the average catch weight), gives a standard error of the bycatch proportion of 0.0094. An increase in the sampling rate from 1.56% to 5% would result in a decrease in the standard error by almost half to 0.0051, while an increase in the sampling rate to 10% would result in a standard error decrease of almost two-thirds, to 0.0035.

An increase in the midwater trawl sample size is, however, unrealistic with only one or two observers appointed per trip. The *Desert Diamond* is a large freezer trawler towing a net with an opening of 60 x 100 m, and from 2004 to 2014 the catch weight averaged 46 308 kg per haul, with the maximum recorded at over 99 000 kg. A sample of 1.56% of the mean catch weight is approximately 722 kg, and of the maximum catch weight is over 1540 kg. In the inshore demersal trawl fishery, the sampling rate achieved by observers was much higher, at 20.2% of total catch weight, while the average catch weight was approximately 820 kg per haul (Attwood *et al.*, 2011), resulting in a smaller average sample size of approximately 165 kg. The sampling rate in the midwater trawl fishery is therefore limited by the observer's physical ability to sort and measure the species in such large samples. An increase in the sampling rate will require additional observers per trip, or the implementation of alternative methods of monitoring and reporting catches, such as on-board video cameras with software capable of measuring and identifying different species of fish.

The 100% observer coverage in the South African midwater trawl fishery suggests that the accuracy and precision of the bycatch estimate is limited by the size of the samples. Upon initiation, OROP attempted to achieve 20% coverage across fishing sectors, however, owing to logistical and other constraints, the actual rates of coverage in fisheries, other than the midwater trawl fishery, are much lower (RFA, 2010). Large fleet sizes can lead to logistical problems - the small pelagic (purse-seine) fleet is made up of approximately 100 vessels, while the demersal trawl fishery is made up of approximately 80 vessels in the offshore fleet and 35 vessels in the inshore fleet (DEAT, 2005b; DEAT, 2005c; DEAT, 2005d). Observer coverage in the offshore trawl sector was reported at 12% of trips for wetfish vessels and 7% for freezer vessels, while coverage in the small pelagic sector was reported at 5.3% of trips (RFA, 2010). Observer coverage in the inshore trawl sector from 2002 to 2006 was reported

at 5.5% of trips (RFA, 2010), with the total number of trawls observed from 2003 to 2006 determined to be 2.9 - 4.4% (Attwood *et al.*, 2011). As the majority of the catch in the midwater trawl fishery is taken by a single vessel, the *Desert Diamond*, the same logistical constraints do not apply and 100% observer coverage with regards to trips was achieved during the study period.

The low sampling rate in the midwater trawl sector is not unique to the South African observer programme. Midwater trawlers are generally large, with the world's largest fishing vessels being midwater freezer-trawlers (Pálsson, 2005; Hofstede & Dickey-Collas, 2006; Borges *et al.*, 2008). These vessels tow large trawl nets and observer sampling rates are limited by the same constraints as the South African midwater trawl observers. Observer coverage is generally lower in midwater trawl sectors from other regions, as many of these sectors are made up of fleets of vessels. The Dutch pelagic freezer-trawlers operating in European waters tow trawl nets with openings of up to 60 x 120 m and between 2002 and 2005, observer coverage of these vessels ranged from 4-9% (Borges *et al.*, 2008). Dutch freezer-trawlers also operate in the waters off Mauritania and from 1999 to 2003 observers covered 16% of trips and samples of a minimum of 20 kg per 50 t of catch were taken, equating to a minimum sampling rate of 0.04% (Borges *et al.*, 2008). The Icelandic blue whiting fishery has a fleet of midwater freezer-trawlers towing nets with openings of typically 110 m x 160 m catching an average of 210 t per haul in 2003 (Pálsson, 2005). Catches in this fishery were not observed on-board, however inspectors sampled catches during landings of entire trips, and coverage was 9.4% of trips while the sampling rate was 0.25 - 0.5% of the catch by weight (Pálsson, 2005). The New Zealand jack mackerel fishery has regular observer coverage and between 1999 and 2001 this was 19 - 23% of trawls (Anderson, 2004).

Spatial coverage of the fishery

Midwater trawls occur along the Agulhas Bank shelf break from 20°E to 27°E. However trawls are concentrated in two distinct areas – off Mossel Bay on the central Agulhas Bank (between 22°E and 23°E) and off Port Elizabeth on the eastern Agulhas Bank (between 24°E and 27°E). During the study period the average number of trawls was consistent throughout the year, except during autumn (season 2), where the frequency of trawls was approximately 30% lower than the rest of the year. On average the number of trawls occurring on the eastern Agulhas Bank was roughly three times greater than those occurring on the central Agulhas Bank. During autumn and winter (seasons 2 and 3) this ratio was reduced to twice as many trawls occurring on the eastern Agulhas Bank. During spring and summer trawling shifted eastwards, with the ratio increasing to eight times and four times as many trawls occurring on the eastern Agulhas Bank as on the central Agulhas Bank, in spring and summer, respectively.

The Agulhas Bank is a highly diverse system supporting a number of commercial fisheries, including the inshore and offshore demersal trawl fisheries, the commercial linefishery, the small pelagic purse-seine fishery and the longline fishery (DAFF, 2012; Japp *et al.*, 1994). The inshore demersal trawl fishery operates on the Agulhas Banks between Cape Agulhas and the Great Kei River, with trawls concentrated at depths of 80-110 m (Attwood *et al.*, 2011), and spatial overlaps occurring with approximately 35% of the midwater trawl fishery grounds. The offshore demersal fishery operates in areas deeper than 110 m on the Agulhas Bank, although the bulk of this fishery operates on the west coast (DAFF, 2012). At the 1° grid level, the longline fishery operates over the vast majority of the Agulhas Bank (Petersen *et al.*, 2008), with a large spatial overlap with the midwater trawl fishery. The bulk of the purse-seine fishery also operates on the west coast, with a small fleet operating out of Port

Elizabeth, however these vessels operate more inshore with no spatial overlap with the midwater trawl fishery (C. van der Lingen, pers. comm.).

Small versus large fauna

The separation of large fauna before the small fauna are placed in the holding ponds means that the entire catch of large fauna are easily inspected by observers. The unit of sampling for large fauna species is thus the whole tow while the weight of samples of small fauna species are raised to trawl level. Observers were seldom able to weigh the large fauna and so the average weight of individuals had to be estimated to obtain a total average annual catch estimate in this fishery.

Few midwater trawl bycatch studies included analyses of small and large fauna (Berrow *et al.*, 1998; Pierce *et al.*, 2002), whereas studies that do report large fauna tend to focus on marine mammals, particularly cetaceans (Morizur *et al.*, 1999; Du Fresne *et al.*, 2007; Fortuna *et al.*, 2010).

Zeeberg *et al.* (2006) analysed the large fauna bycatch of midwater trawls off Mauritania and reported bycatch including billfish, sharks, sea turtles, manta rays, sunfish and dolphins. The mix, at a genus or family level, is similar to the South African midwater trawl fishery, with the exception of sea turtles in the Mauritanian bycatch and Cape fur seals in the South African bycatch.

Catch composition

Species assemblage and bycatch rate

The species diversity of the South African midwater trawl fishery is a third less (87 species) than the species diversity of the inshore trawl fishery (137 species) on the Agulhas Bank (Attwood *et al.*, 2011). The bycatch rate of the midwater trawl fishery is vastly lower (6.9%) than the inshore trawl fishery which has the second highest bycatch rate of South African fisheries, of approximately 42%. As the annual average catch estimate for the midwater trawl fishery is higher (25 415 t) than the inshore trawl fishery (17 434 t), the annual average bycatch estimate for the midwater trawl fishery is 1 743 t, almost a quarter of the annual average bycatch estimate for the inshore trawl fishery (7 277 t). The east coast prawn trawl fishery has the highest bycatch rate of South African fisheries and is reported to be over 80% (Fennessy & Groeneveld, 1997). This pattern of increasing bycatch rates from midwater to demersal to prawn trawling follows global trends (Alverson *et al.*, 1994; Chuenpagdee *et al.*, 2003; Kelleher, 2005) with bycatch and discarding rates in midwater trawling known to be low (Berrow *et al.*, 1998; Pierce *et al.*, 2002; Hofstede & Dickey-Collas, 2006; Borges *et al.*, 2008).

While midwater trawl bycatch rates are generally low, there is variation in bycatch rates and species assemblages across regions and target species. In Iceland a large midwater trawl fleet targets blue whiting (*Micromesistius poutassou*) in Icelandic and Faroese waters (Pálsson, 2005). The bycatch rate in this fishery was estimated at 0.64% and the catch composition consisted of 12 species of fish and cephalopod, while saithe (*Pollachius virens*) and silver smelt (*Argentina silus*) accounted for the bulk of the bycatch (88% by weight) (Pálsson, 2005). Two theories were proposed for the low bycatch rate in this fishery: limited spatial

overlap of the target and other species, particularly with respect to depth, and the poor state of the bycatch fish stocks (Pálsson, 2005).

The Dutch pelagic freezer-trawlers operating in European waters constitute a highly seasonal fishery targeting herring (*Clupea harengus*), mackerel (*Scomber scombrus*), horse mackerel (*Trachurus trachurus*) and blue whiting at different times of the year (Borges *et al.*, 2008). Borges *et al.* (2008) determined that approximately 10% of the catch was discarded, with ~80% of discards consisting of the four target species, however a target species is also defined as a bycatch species as seasons and targets change. Of the other fish species caught, the most common were boarfish (*Caprus aper*), sardine (*Sardina pilchardus*) and striped red mullet (*Mullus surmuletus*) (Borges *et al.*, 2008).

Midwater trawlers in Scotland target mackerel (*Scomber scombrus*), herring (*Clupea harengus*) and argentines (*Argentina silus*) (Pierce *et al.*, 2002). Catches analysed in these fisheries included 17 species of bony fish, four species of shark, one species of squid and one species of sea bird (Pierce *et al.*, 2002). The bycatch rate in the herring fishery was 2.3% with mackerel and haddock (*Melanogrammus aeglefinus*) making up the bulk of the bycatch (Pierce *et al.*, 2002). The mackerel fishery had a bycatch rate of 0.9% with horse mackerel (*Trachurus trachurus*) and ling (*Molva molva*) as the most common bycatch species (Pierce *et al.*, 2002). The bycatch rate in the argentine fishery was 11%, while the majority of this (9.5% of the fishery) was made up of blue whiting (*Micromesistius poutassou*) (Pierce *et al.*, 2002).

Dutch pelagic freezer-trawlers operating in Mauritanian waters target round sardinella (*Sardinella aurita*), flat sardinella (*Sardinella maderensis*), pilchard (*Sardina pilchardus*),

chub mackerel (*Scomber japonicus*) and cunene horse mackerel (*Trachurus trecae*) (Hofstede & Dickey-Collas, 2006). The bycatch rate was estimated at 5.8% and a total of 130 different species were identified in the catches including horse mackerel (*Trachurus trachurus*), false scad (*Caranx rhonchus*), hairtail (*Trichiurus lepturus*), bonito (*Sarda sarda*), little tuna (*Euthynnus alleteratus*) and skipjack tuna (*Katsuwonus pelamis*) (Hofstede & Dickey-Collas, 2006). Although the remainder of the bycatch species were not listed in the study by Hofstede and Dickey-Collas (2006), it was reported that vessels generally targeted small pelagics, such as sardinella and pilchards, that inhabit the near surface area of the water column while mackerel and horse mackerel generally inhabit deeper waters.

The U.S. Atlantic mackerel fishery targets mackerel (*Scombrus scombrus*) using midwater trawlers and the bycatch rate in this fishery was estimated at less than 1% (Harrington *et al.*, 2005b). Owing to temporal and spatial overlap with the herring fisheries, a large proportion of the catch (55%) was made up of Atlantic herring (*Clupea harengus*) and blueback herring (*Alosa aestivalis*) that was landed and counted against the herring quota, and so was not included as bycatch (Harrington *et al.*, 2005b). The remainder of the bycatch included spiny dogfish (*Squalus acanthias*) and alewife (*Alosa pseudoharengus*) (Harrington *et al.*, 2005b).

The midwater trawl fishery targeting Chilean jack mackerel (*Trachurus murphyi*) in Chilean waters has a bycatch rate estimated at 4.5% (Pérez Matus *et al.*, 2005). The catch consisted of 21 species and bycatch primarily consisted of chub mackerel (*Scomber japonicas*), pomfret (*Brama australis*) and squid (*Loligo gahi*) (Pérez Matus *et al.*, 2005).

The jack mackerel fishery in New Zealand is based on two New Zealand species, *Trachurus declivis* and *Trachurus novaezelandiae*, and the Chilean jack mackerel with the species

generally not distinguished on catch records (Anderson, 2004). The bycatch rate in this fishery was estimated at 44% with almost 95% of this made up of quota species or other commercial species that were usually retained (Anderson, 2004). A total of 93 species were recorded in the catches and the majority of the bycatch was composed of barracouta (*Thyrsites atun*), blue mackerel (*Scomber australasicus*), red mullet (*Emmelichthys nitidus*) and common warehou (*Seriolella brama*) (Anderson, 2004).

The South African midwater trawl diversity is more similar to the New Zealand jack mackerel fishery than other midwater trawl fisheries. The New Zealand midwater trawl fishery has a similar mix, at a genus or family level, however the abundances of the most common bycatch species in the New Zealand fishery are much higher. A comparison between the New Zealand jack mackerel catch data and survey data revealed that the abundances of the main bycatch species (such as barracouta and blue mackerel) were much higher in the catch data which could be as a result of targeting of non-target species at certain times (Anderson *et al.*, 2000).

The catch composition of the South African midwater trawl fishery includes demersal species, such as hake, gurnards, dorries, soupfin sharks and porbeagle sharks, as well as pelagic species such as sardines, chub mackerel, blue sharks and mako sharks. Horse mackerel are known to inhabit a wide vertical profile (Japp *et al.*, 1994) and bycatch species therefore, include those that overlap spatially with horse mackerel in the pelagic zone as well as the benthic zone.

Large fauna

The most common large fauna bycatch species in this fishery is the Cape fur seal with an annual average catch rate of 106.4 individuals (0.20 per tow). The presence of Cape fur seals in the vicinity of horse mackerel schools is expected as horse mackerel are one of the dominant fish species in the diet of Cape fur seals on the south coast of South Africa (David, 1987). Bycatch of grey seals (*Halichoers grypus*) was reported in the herring midwater trawl fishery in the Celtic Sea at a much lower rate of 0.05 seals per tow, however the extrapolation of this rate for the entire fishery resulted in an estimate of 60 individuals per year (Berrow *et al.*, 1998).

Sunfish occur worldwide in temperate and tropical seas however, there is a paucity of data on the biology and ecology of these fish (Pope *et al.*, 2010). While sunfish is not a commercially important species, populations may be affected by fishing pressure with high levels of bycatch previously reported in many fisheries, including the South African longline fishery (295 sunfish per year) (Pope *et al.*, 2010) and midwater trawl fisheries (264 sunfish per year) (McDonnell, 2006). Results from this study demonstrate that bycatch of sunfish in this fishery occurs at a much lower rate than previously reported, with an average annual catch rate of 46 individuals (0.08 individuals per tow).

Cetacean bycatch has been reported in various midwater trawl fisheries, with bycatch rates of 0.05 to 0.19 individuals per tow in Mauritania, 0.06 to 0.10 individuals per tow in the northeast Atlantic, 0.057 individuals per tow in New Zealand and 0.001 individuals per tow in the Adriatic Sea (Morizur *et al.*, 1999; Zeeberg *et al.*, 2006; Du Fresne *et al.*, 2007; Fortuna *et al.*, 2010). Midwater trawlers operating off Mauritania caught predominantly common dolphins (*Delphinus delphis*), bottlenose dolphins (*Tursiops truncatus*), and, along

the European shelf margin, white-sided dolphins (*Lagenorhynchus acutus*) (Zeeberg *et al.*, 2006) while the northeast Atlantic midwater trawl fisheries reported catches of white-sided dolphins and common dolphins (Morizur *et al.*, 1999). In the New Zealand jack mackerel fishery, bycatch of common dolphins was reported (Du Fresne *et al.*, 2007), and in the Adriatic Sea, bycatch of bottlenose dolphins in Italian midwater trawls was reported (Fortuna *et al.*, 2010). Two species of dolphins were reported in the South African midwater trawl fishery, bottlenose and common dolphins, and these were caught at comparatively low rates of 0.0027 and 0.0024 individuals per tow (or 1.4 and 1.2 individuals per year), respectively. Cetacean bycatch in midwater trawls was reported to occur almost exclusively at night in the fisheries operating in the northeast Atlantic, Mauritania and New Zealand (Morizur *et al.*, 1999; Zeeberg *et al.*, 2006; Du Fresne *et al.*, 2007), however results from this study did not show any difference between day-time and night-time CPUE of dolphins.

It is estimated that an average of approximately 160 sharks were caught each year by the South African midwater trawl fishery for the period 2005-2013, with copper sharks (*Carcharhinus brachyurus*) and mako sharks (*Isurus oxyrinchus*) caught most often. Bycatch of sharks in this fishery is considerable lower than reported by freezer trawlers operating in Mauritania, with the annual removal of 1000-2000 sharks reported, the majority of these being hammerhead sharks (Zeeberg *et al.*, 2006). In South Africa, sharks are reportedly caught in 12 fisheries, six of which target sharks while the remainder catch sharks as bycatch (DAFF, 2012). One such fishery is the South African pelagic longline fishery for tunas and swordfish which caught an annual average of 43 000 pelagic sharks for the period 1998-2005 (Petersen *et al.*, 2009), approximately 270 times greater than the midwater trawl fishery. Although the midwater trawl fishery catches comparatively low numbers of sharks as bycatch, seven of the species caught – dusky sharks (*Carcharhinus obscurus*),

hammerhead sharks (*Sphyrna zygaena*), soupfin sharks (*Galeorhinus galeus*), mako sharks, thresher sharks (*Alopias vulpinus*), bigeye thresher sharks (*Alopias superciliosus*) and porbeagle sharks (*Lamna nasus*) - are classified as Vulnerable (IUCN, 2014).

Utilisation

Fish targeted by midwater trawls are utilised in a variety of ways. Many of the world's pelagic fisheries, such as the Icelandic blue whiting and Chilean jack mackerel fisheries, produce fishmeal (Péron *et al.*, 2010). Others, such as the Dutch pelagic freezer-trawlers, fish exclusively for human consumption and process fish on board (Pierce *et al.*, 2002; Hofstede & Dickey-Collas, 2006; Borges *et al.*, 2008). These fisheries that fish for human consumption reported discarding of fish, including commercial and target species of commercial size (Hofstede & Dickey-Collas, 2006; Borges *et al.*, 2008). The South African midwater trawl fishery makes full use of the catch as it utilises horse mackerel for human consumption and bycatch is reduced to fishmeal.

Species overlap with other fisheries

The PUCL of horse mackerel imposed on the small pelagic fishery is set to limit the catch of juveniles caught on the west coast of South Africa to ensure that recruitment to the Agulhas Bank is not affected by removal of juveniles (DAFF, 2012). However, when an unusually large number of juvenile horse mackerel are caught in the small pelagic fishery, this PUCL can result in a closure of the fishery before the TAC of anchovy is met. In 2011, when this occurred, the PUCL was increased from 5 000 t to 12 000 t, which was 27.3% by weight of the PMCL of adult horse mackerel set for the Agulhas Bank in 2011. On the Agulhas Bank the purse-seine fishery catches horse mackerel as bycatch, however catches are not more than

200 t per year (C. van der Lingen, pers. comm.). The demersal trawl fishery also catches a considerable proportion of horse mackerel as bycatch. This fishery is allocated 28% of the PMCL of adult horse mackerel on the Agulhas Bank, which equated to 12 500 t in 2011.

There are 18 species caught as bycatch in the midwater trawl fishery that are targeted in other fisheries. However the extent of stock sharing is low. The total allowable catch (TAC) of hake across the various sectors that target hake (deep sea demersal trawl, inshore demersal trawl, hake longline and hake handline) was 144 671 t in 2012 (DAFF, 2012). The annual average bycatch of hake in the midwater trawl fishery (232 t) is 0.2% of the TAC for hake (Table 10). The 2011 landings data for the small pelagic fishery reported that catches for sardine, anchovy and redeye roundherring were 90 000 t, 120 000 t and 65 000 t respectively. The annual average bycatch of these species in the midwater trawl fishery make up less than 0.1% of the sardine and anchovy landings, and 0.5% of the redeye round herring landings. The 14 t of sharks caught per annum as bycatch in this fishery, make up 0.7% of the 2000 t bycatch reserve in the longline fishery. The landings data from the linefishery reported that 408 t of geelbek, 263 t of carpenter and 6360 t of snoek were caught in 2010. Bycatch of these species caught in the midwater trawl fishery amounted to 0.3% (1 t), 3.5% (9 t) and 0.4% (25 t) of catches of geelbek, carpenter and snoek respectively. The 2010 landings data from the chokka squid fishery reported that 10 000 t was landed in 2010. The annual average bycatch of chokka squid in the midwater trawl fishery amounted to 23 t which is equivalent to 0.2% of the 2010 catches. This shows that the quantities of bycatch of overlap species in the midwater trawl fishery are low in comparison to quantities caught by the target fisheries.

Table 10. Impact of bycatch of species targeted in other fisheries, and impact of bycatch of horse mackerel in other fisheries (TAC and landings data obtained from DAFF 2012).

Fishery	Hake	Small pelagics		Shark longline	Linefishery		Squid fishery		
Target	Hake	Sardine	Anchovy	Redeye roundherring	Sharks	Geelbek	Carpenter	Snoek	Chokka squid
TAC/ Landings data (t)	144671 (2012 TAC)	90000	120000	65000	2000 (2011 Bycatch limit)	408	263	6360	10000 (2010 Landings data)
Annual average bycatch in midwater trawl fishery (t)	232	39	0.4	345	14	1	9	25	23
Bycatch as % of TAC/ Landings	0.2%	<0.1%	<<0.1%	0.5%	0.7%	0.3%	3.5%	0.4%	0.2%
Catch limit of horse mackerel allocated to fishery in 2011 (t)	12500		12000		-	-			-
Catch limit as % of horse mackerel PMCL	28.4%		27.3%						

Day/night patterns

The nocturnal bias of midwater trawls reflects the pelagic nature of horse mackerel at night. Horse mackerel are found close to the sea bed during the day where they are reported to feed, exploiting the aggregations of copepods and euphausiids near the bottom during this time (Pillar & Barange, 1998; Barange *et al.*, 2005). At sunset horse mackerel ascend into the midwater and the exact reason for this is unclear, however stomach fullness was shown to decrease at night therefore it is thought to be for reasons other than feeding (Pillar & Barange, 1998; Barange *et al.*, 2005). One hypothesis is that it is owing to predator avoidance of demersal species such as hake (Pillar & Barange, 1998).

Similar patterns of diel migration have been observed in Cunene horse mackerel (*Trachurus trecae*) off Angola, where fish aggregated near the seabed by day and ascended into the pelagic zone at night where they dispersed (Vaz Velho *et al.*, 2010). Jack mackerel (*Trachurus murphyi*) off Chile are reported to display a diel migration pattern described as „atypical“ of *Trachurus* species, where jack mackerel were distributed at mid-depth during the day and aggregated closer to the surface at night in a phase of active foraging (Bertrand *et al.*, 2004). Chilean jack mackerel inhabit oceanic waters (not the shelf or shelf-break habitat common to other *Trachurus* species) where prey are inaccessible during the day at depths below the vertical distribution of jack mackerel, which is limited by the oxycline (Bertrand *et al.*, 2006). Jack mackerel are thought to conserve energy during the day by resting until prey become available to jack mackerel at night when they migrate towards the surface (Bertrand *et al.*, 2006).

The diel pattern of migration is confirmed in the midwater trawl catches with day-time CPUE of horse mackerel at approximately 60% of night-time CPUE. This pattern is further

reinforced by the higher catch rate of horse mackerel in the day in the inshore demersal trawl fishery (Attwood *et al.*, 2011).

The inshore demersal trawl fishery also produced higher catches of hake during the day, which suggested that hake also leave the seabed at night (Attwood *et al.*, 2011), however catches of hake in the midwater trawls contradicted this pattern, with higher catch rates of hake in the midwater during the day.

The significantly deeper mean depth of day-time trawls indicates that the horse mackerel are targeted when feeding closer to the seabed during the day, however the lower CPUE of horse mackerel during the day suggests that this is not as efficient as the targeting of horse mackerel at night. This is because the day-time targeting of horse mackerel is influenced by bottom type, as trawl gear can become damaged if contact is made with the seabed (R. Cooper, pers. comm.). Therefore day-time trawling is carried out close to the seabed if trawling over a sandy or muddy bottom. If the bottom type is rocky or very uneven there is a greater risk of damaging or losing the net, and trawling is only carried out if horse mackerel are located higher in the water column resulting in a wider trawling depth range during the day.

Seasonal and spatial patterns

Higher catch rates of horse mackerel in summer compared to winter correspond to findings by Hecht (1990) who suggested an east-west spawning migration of horse mackerel during winter. As the proportion of trawls that occurred on the central Agulhas Bank increased during autumn it suggests that the east-west shift in trawling is possibly owing to the migration of horse mackerel during this period. Although catch rates of horse mackerel were

lower in winter, they were still high, almost 77% of summer catch rates, while Hecht (1990) reported winter catch rates of horse mackerel approximately 40% of summer catch rates. This could again be owing to the east-west shift in trawling during autumn and winter. Higher catch rates were noted during spring and summer for other species such as hake, ribbonfish, sardines, broadbill swordfish, dusky sharks and blue sharks, while catch rates for species such as chub mackerel, redeye roundherring, snoek, skipjack tuna, anchovy, gurnards and Cape fur seals were higher in autumn and winter.

The majority of trawling occurred on the eastern Agulhas Bank where horse mackerel are known to be more abundant (Japp *et al.*, 1994; Uozumi *et al.*, 1984), however analyses of catch composition revealed that the proportion of horse mackerel in catches on both the eastern and central Agulhas Bank is high. The disjunct distribution of horse mackerel on the Agulhas Bank mirrors distribution patterns found in a demersal trawl survey carried out in the early 1980's that noted horse mackerel average sizes increasing offshore and eastwards (Uozumi *et al.*, 1984). Catch composition analysis also revealed that the proportion of hake in catches was higher on the eastern Agulhas Bank, while the proportion of redeye roundherring and chub mackerel in catches was higher on the central Agulhas Bank.

Trawling behaviour

Besides the nocturnal bias, the trawling behaviour of the midwater trawl fishery differed from that of the inshore demersal trawl fishery in various respects. The frequency of trawls was higher in the inshore demersal trawl fishery with an average of four trawls in day-time and two more trawls at night in approximately a third of voyages (Attwood *et al.*, 2011). The average net turnaround time in the inshore demersal trawl fishery was also much shorter at 13.2 min (Attwood *et al.*, 2011). This is likely to be owing to the vastly larger capacity of the

midwater trawl net with the catch averaging over 46 000 kg per haul while the inshore demersal trawl catch from 2003 - 2006 averaged 820 kg per haul (Attwood *et al.*, 2011). This suggests that the frequency of midwater trawls is limited by the speed of processing of the catch. High rates of bycatch will likely lead to delays in the net turnaround time as the emptying of the holding ponds is limited by the speed of the fishmeal processing plant (R. Cooper, pers. comm.).

Conclusions

The 100% observer coverage in the midwater trawl fishery is very high compared to other South African fisheries and is achievable owing to the majority of catches being taken by a single trawler. The average sampling rate of 1.56% is however very low, leading to a high likelihood of errors and an increase in the sampling rate is not feasible with only one or two observers appointed per trip, owing to the size of midwater trawl nets and therefore catches. An increase in the sampling rate will be possible only with additional observers appointed per trip, or the implementation of alternative methods of monitoring and reporting catches, such as on-board video cameras with software capable of measuring and identifying different species of fish.

The catch of non-target species in the South African midwater trawl fishery is 6.9% which is low compared to other South African trawl fisheries however similar to global midwater trawl bycatch rates. Absolute volumes of bycatch are also low compared to other South African trawl fisheries.

There are species overlaps with various fisheries, namely the demersal trawl, small pelagic, linefishery, shark longline and squid fisheries, however the total catch estimates from the midwater trawl fishery are small relative to catches taken in the target fisheries.

As the bycatch in this fishery includes vulnerable species, particularly certain sharks, further investigations should be focused on finer scale assessments in an effort to reduce catches of these species that are vulnerable to exploitation. Further studies should include analysis of data using decision support software, such as Marxan, to identify areas and times where

reductions in trawling could achieve targets for bycatch reduction while minimising negative impacts on the midwater trawl industry.

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