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Factors relating to catch per unit effort in the exploratory *Octopus vulgaris* pot fishery of South Africa

By

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DECLARATION

I, **Sanjay John**, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

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ABSTRACT

The initial phase of the South African fishery for *Octopus vulgaris* saw great interest from fishers to invest. This initial interest however, was not carried over into actual fishing as many applied for the right, but never started fishing. A lack of knowledge on how to best harvest octopus in South Africa, proved to be the downfall of the initial phase from 2003 to 2009. After efforts made by the then Department of Environmental Affairs and Tourism, as well as individuals in the fishery, a greater knowledge on octopus fishing practices was garnered from Australian octopus stake holders. This knowledge was applied to the South African fishery and saw one right holder start consistent fishing in the False Bay area, although four rights were allocated. Consistent data collection from 2014 to 2019 allowed for the completion of this study after a lack of data in initial phases. The Australian trigger trap was the gear deployed during this period, which was very different from the PVC pots used from 2003 to 2009. The change in gear came about because of the belief that the Australian-made gear was more stable in South African waters i.e. it provided a den site for octopus that would not be moving around in the strong currents.

On-board and Factory weight data from False Bay was collated into various databases for analyses and verification. Since databases shared similar factors, gaps in data were filled in order to calculate the CPUE (catch per unit effort). Statistical analyses and standardisation of affecting factors and CPUE was conducted in R studio. CPUE is an important factor related to the management and monitoring of exploited species. CPUE was then plotted against various factors in order to determine their effects. The greatest influence on CPUE was found to be month, season and area, found to have statistically significant differences within years. These factors were tested using an ANOVA test. In order to determine which months, seasons or areas were statistically significant, the Tukey's Honest Significant Difference test was used. Influences of these factors skewed the relationship between CPUE and inferred abundance, requiring standardisation. Month and Area were standardised to remove their effect on nominal CPUE to view the index of abundance trends of *O. vulgaris* in the False Bay Area based on standardised CPUE. A Generalised additive model was used to standardise data for analyses of CPUE, independent of factors that would cause an effect.

Standardised CPUE trends revealed peaks in the population abundance in summer and spring, size distribution followed the same trend with medium and small animals but large animals were more prevalent in the autumn and winter months, and accounted for the greatest volume by weight, being caught in autumn. The fishing vessel (Albatross) harvested 178.7 tons between 2014 and 2019. The on-board database revealed a total of 77500 octopuses caught from 2016 to 2019, accounting for 77% of the total weight at 138.6 tons. The estimated total number of octopus caught was 101088 with an average catch percentage for False Bay of 43.5% per opening, with a mean mass of 1.8 kg per octopus caught and mean number of 0.99 octopus per pot. The west of False Bay had more pots checked (46301), number of octopus caught (43159) and number of days fished (135). However mean CPUE was higher in the east of False Bay (1.08 octopus/pot/line) compared to the west (0.94) and were found to be statistically significantly different between the two management zones.

The findings in this study provide much needed scientific knowledge regarding the *O. vulgaris* fishery in False Bay, South Africa. The Department of Fisheries Forestry and Environment may make informed management decisions regarding the sustainable utilisation of the target species and continue to monitor the progress thereof. Based on results found in this study, it is recommended that the effort applied to the fishery be reduced from two right holders per fishing zone to one. Currently operations are commencing in this way, due to only one right holder fishing in the False Bay area. The restriction on gear currently applied, should be retained as the current number of 6000 pots shows no indication of adversely affecting the population of *O. vulgaris*.

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DEDICATION

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GLOSSARY

Exploratory fishery – Generally applied to a new fishery in order to explore gear types to be used, best fishing practices and best fishing areas.

Experimental fishery – Often follows the exploratory fishery were more stringent scientific experimental frameworks are put in place in order to collect data relating to fishing and the population being targeted.

Precautionary approach – this approach to fisheries management exercises prudent foresight in order to avoid undesirable situations by taking into account the slow recovery rate of fisheries should these situations arise, as fisheries are difficult to control, not well understood and can change environmentally and from a human values standpoint (FAO, 1996).

TAE – Total allowable effort

FAO – Food and agriculture organisation

MLRA – Marine living resources act

EAF – Environmental approach to fisheries

BGI – Blue growth initiative

TROM – Target resource oriented management

Pot – PVC octopus pot with a cement foot, commonly used in octopus fisheries, passive (provides a shelter for octopus, no bait or lure).

Trap – Australian designed octopus catching devise, active (uses lure to attract octopus).

“Pot” – One catching unit attached to the long line, either a single pot or cradle with up to three pots or traps).

DAFF – Department of Agriculture Forestry and Fisheries

LED – Light emitting diode

SCV – Comma separated values

CPUE – Catch per unit effort

ANOVA – Analysis of Variance

HSD – Honestly significant difference

GAM – Generalised additive model

CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

Octopus vulgaris (Cuvier 1797) is a benthic cephalopod, which inhabits temperate, subtropical and tropical seas of both the southern and northern hemispheres (Mangold, 1983; Roper *et al.* 1984; Norman *et al.* 2013 and De Luca *et al.* 2014). Historically the species is considered to be cosmopolitan (Roper *et al.* 1984), being first reported in the Mediterranean Sea and Eastern North Atlantic and then from the subtropical waters of Australasia, Europe, Africa, Asia and the Americas (Amor *et al.* 2016). Studies however (Söller *et al.* 2002; Leite *et al.* 2008; Amor *et al.* 2014, 2015; Gleadall 2016) have made the suggestion that populations previously known as *O. vulgaris* may be part of a complex of morphologically similar but genetically distinct *vulgaris*-like species i.e. the '*O. vulgaris* species complex' (Amor *et al.* 2016). *Octopus vulgaris* was considered to have a southern African distribution from Lüderitz (Namibia) on the west coast to Kwa-Zulu Natal (approximately Durban) on the east coast according to (Smale *et al.* 1993), however the species has also been found in Angola (De Beer & Potts, 2013) and Mozambique (Silva et al. 2009). The species occurs from the coastline to the continental shelf edge (± 200 m depth) and is described as a mobile species, able to live in different biotopes e.g. muddy and sandy bottoms, rock, coral reefs and sea-grass (Mangold 1983; De Beer and Potts 2013; Sonderblohm *et al.* 2014). However, it should be noted that, specimens have been found at a depth of 317m in the Gulf of Cadiz (Silva *et al.* 2002) though they are more abundant in shallower waters (Roper and Sweeny 1981; Belcari and Sartor 1999; Belcari *et al.* 2002).

The species displays a life cycle of 12 – 14 months with egg care by females, until hatching occurs, that die at the end of this process (Domain *et al.* 2002; Iglesias *et al.* 2004; Boletzky & Villanueva 2014). The incubation of the eggs ranges from 22 – 25 days at 25^{o}C to 120 days at 13^{o}C (Mangold & Boletzky 1973; Mangold 1997; Caveriviere 1999; Martins 2003). The hatchlings then enter the planktonic stage and are referred to as 'paralarvae' (used to describe the difference between the morphology and ecology of the planktonic stages of cephalopods and their adult form). Young & Harman (1988) defined paralarva as "a cephalopod of the first post-hatching growth stage that is pelagic in near-surface waters during the day and that has a distinctly different mode-of-life from that of older conspecific individuals". The duration of the paralarval stage is temperature-dependent and ranges from between 47 – 54 days at 21.2°C to between 30 – 35 days at 23°C (Imamura 1990; Villanueva 1995), after which settlement occurs and an approximate growth rate of 3% daily (Mangold & Boletzky 1973).

Octopus vulgaris is carnivorous and opportunistically feeds on bony fish, crustaceans, molluscs and polychaetes (Mangold 1983; Sonderblohm *et al.* 2014). This varied diet is seen along the South African coastline, with dominant prey species being brown mussels on the subtropical east coast (Smale & Buchan 1981), abalone and crustaceans on the cold temperate south-west coast (Smith 1999), and teleosts, octopus and crustaceans on the south-east coast (Oosthuizen & Smale 2003). In order to avoid competition and predation, this and many other octopus species select shelters or dens in which they spend most of their time, during daylight hours (Mather 1988).

The species is considered to be an important exploitable resource, owing to their short life span, rapid growth rate, firm texture and high meat recovery (Paust 1988). These characteristics contribute to a high commodity value, with approximate costs according to the European price report (FAO 2017) of 10 EUR per kg for small animals and 11 EUR per kg for large animals (T1 refers animal > 4 Kg, according to Pescaluna factory grading, priced at €14.25 if frozen at sea (FAS) (FAO 2018). This high market value drives an active fishery for the species. However, effort is predominantly small-scale, with pots, traps, fyke nets and set nets the dominant gear types (Anon 1981; Wurtz and Repetto 1983; Sanchez and Obarti 1993).

The global cephalopod species harvest has risen from approximately 600 000 t in the 1950's to more than 3 million tonnes in 2004, increasing to over 4 million tonnes, ten years later in 2014 (FAO yearbook 2007; 2016). *O. vulgaris* landings make up more than 50 % of global landings for Octopods, with imports of octopus to the US averaging US$ 1.6 billion (Leporati *et al.* 2009; Amor *et al.* 2014; Rocliff & Harris 2016) their economic potential is evident. The largest octopus fishery in the world is the Saharan fishery, which operates off the northwest African coast between Cape Blanc (21°N) and Cape Boojador (26°N) (Balguerias *et al.* 2000; Bravo deLaguna & Balguerias 1993; Hatanaka 1979; Hernandez-Garcia 1995; Guerra 1997). The European Atlantic Coast, Mediterranean Sea, Japanese waters, and Venezuela host the other important fisheries for octopus (Guerra 1997). Considering the species afore mentioned characteristics and contribution to fisheries around the world, the species was seen as a suitable candidate for exploitation as a small-scale fishery in South Africa (Smith 1999).

In October 2003, a five-year experimental fishery for the *O. vulgaris* was initiated by the Department of Environmental Affairs and Tourism, along the South African coast (Mbande 2016). However, the initial phase of the fishery did not yield sufficient catch data to evaluate the experiment, due to numerous difficulties. Vandalism of fishing gear, where buoys, traps and the long lines were cut and could not be recovered. The breakage and loss of gear due to sub-standard gear and adverse weather conditions. The lack of experience working with the new gear and the lack of technical expertise of how to correctly deploy gear (where, how, orientation with the coastline). The aforementioned issues coupled with the high start-up costs, as the initial cost exceeded R250 000 just for the fishing gear (buoys, ropes, pots, clips, anchors, chain), excluding the vessel and winches; adverse weather conditions along the South African coast and the rigidity of the experimental framework (restrictions on pot type, number of pots per line, distance between pots, orientation of line deployment in relation to coastline and deployment depth) compounded the difficulties experienced. This led to a change from an experimental framework to an exploratory framework four months later (Mbande 2016), where the aforementioned experimental guidelines were relaxed so as to allow for fishing to proceed. In this phase rights holders were allowed to explore different gear types and configurations as well as deploy the gear in whichever way they deemed necessary to produce the best results. All gear designs, modification and deployment plans were first assessed by the inshore resources research section of DAFF before being applied. However, the lack of a continuous time series of catch data points from this period did not allow adequate examination in order to make any inferences regarding the population at that time.

In 2012 the Department of Agriculture Forestry and Fisheries (DAFF) started the process of a second phase of exploration on *O. vulgaris*. With more suitable guidelines being set at the beginning of this phase in 2013, it was hoped that this would coax greater numbers of right holders into using their permits. This was however not the case and to date six rights holders (from 15 applicants) have shown various levels of activity, two in the False Bay area, one in Plettenburg Bay, Mossel Bay, Gaansbaai and Saldanha Bay, with four years of usable data being collected in the False Bay area only. The fisheries data collected, included soak time, number of traps deployed, GPS location of lines, sea surface temperatures, number of animals caught and total weight of catch for each trip. CPUE values calculated from these variables will provide inferred indicators of abundance for False Bay, and together with GPS positions will provide possible density and distributional information regarding seasonal variations of O. *vulgaris* within the bay.

The type of gear used during this second phase of fishing moved away from the shelter pots that were exclusively used during the first phase, to Australian trigger traps, which have become the standard gear type for the fishery in its current guise. During their initial use, these traps where used as intended with a plastic crab lure with pressure triggered light source, which acted as “bait”. Due to the cost of constant replacement of these lights, the fishers began to use the traps with a non-functioning light and crab lure setup i.e. as a shelter pot. Of the collected catch data, these traps were only used with lures until the end of 2016. The initial start-up costs for gear (traps, ropes, crab lures, pressure triggered lights, anchors, buoys, winches, boat), per vessel, has increased greatly. Costs rose from the pot setup, which used smaller vessels (more or less 6m) known in the western cape as “chukkies”, with total initial costs at approximately R600 000 to over R10 million, which use specialized winches and larger vessels i.e. deck boats (over 10m); however, this change in gear has seen more stable fishing, justifying the cost, according to the fishers. The gear was reported to cope with the South African weather extremes better, as fishers have seen fewer losses and breakages due to these factors and a presumed better catch with the traps. The cost of the gear has undergone further increases as the experimental octopus fishery has had to modify their fishing gear to curb whale entanglement incidences. Unfortunately, the pot catch data is insufficient to make any comparisons of catch efficacy between the two gear types for the False Bay area, the pot system is still considered to be the cheaper alternative, making new entrants into the experiment consider hybrid alternatives of both systems, in order to achieve the most adequate compromise between cost and fishing stability.

It should be noted, however, that octopus populations exhibit year to year fluctuations over large temporal and spatial scales, and the influence of various environmental conditions on early life phases are believed to be the cause of these fluctuations, affecting recruitment (Agnew 2000) and the future harvestable biomass (Rodhouse 2001 and Otero *et al.* 2008). These fluctuations in recruitment should be noted when considering the South African octopus populations being targeted for exploitation. Standardised CPUE is widely used in marine conservation of a species as a more accurate indication of abundance and in the management of fisheries as a stock assessment tool (Hilborn & Walters 1992; Harley *et al.* 2001; Erisman *et al.* 2011). Standardising CPUE is a means of removing the effects of various factors that affect the proportionality of abundance to CPUE (Maunder and Punt 2004).

1.2 Statement of Research Problem

The current *O. vulgaris* exploratory fishery has been in operation since 2003, albeit at different levels of effort. The problem presents itself as to what the way forward would be for this fishery. With good fisheries data collected, what are the trends in CPUE (used as an index of abundance) of the target species? Can the population of *O. vulgaris* in False Bay sustain a fully commercial fishery?

Currently, very little is known about the *O. vulgaris* experimental fishery in False Bay, South Africa. After the initial season (2003 – 2009) of experimentation on this fishery, the catch data collected did not provide substantial evidence to conclude that the fishery was sustainable from a fishing or harvestable stock point of view.

From an environmental standpoint there is no local knowledge with regard to the effect of temperature or any other environmental factor on the harvestable population of *O. vulgaris*. For instance, little is known about the effect of seasonal sea surface temperatures on recruitment to the fishery (future harvestable population) (Mangold & Boletzky 1973; Mangold 1997; Caveriviere 1999; Rodhouse 2001; Martins 2003; Otero *et al.* 2008) or how temperature may affect distributional variations within False Bay.

1.3 Aim of the Study

Provide a detailed description of the exploratory *O. vulgaris* fishery being conducted in False Bay South Africa as well as calculate standardised CPUE values, and determine the relationships between CPUE, sea surface temperature, depth, fishing practices and distribution within False Bay.

1.3.1 Objectives

- Provide a detailed description of the *O. vulgaris* exploratory fishery
- Determine correlations that may exist between variations in temperature and catch
- Investigate seasonal trends in catch and effort, and distributional links thereunder of *O. vulgaris* in the False Bay area
- Determine, the extent to which catch is affected by adjustments in fishing practices (i.e. increases in the number of pots deployed, variations in soak time etc.)
- Standardise CPUE for the False Bay *O. vulgaris* exploratory fishery

1.4 Significance of the study

Many of the world's most valuable (e.g. tunas) and vulnerable species (e.g. sharks) have their primary indices of abundance based on catch per unit effort data collected from fishers (Maunder & Punt 2004). Examining catch and effort data collected from the experimental *O. vulgaris* fishery currently underway in False Bay, to calculate CPUE values, will allow for the development of preliminary management strategies based on the inferred abundance obtained from these values. The need to optimize and expand the *O. vulgaris* fishery in South Africa is a priority for both DFFE and the rights holders currently investing in this fishery. With the fishery seemingly "standardising" itself in terms of gear and the types of vessels required, to set and haul said gear, the task of calculating a standardised CPUE will be made "simpler" with fewer variables to consider as the catch method is "standardised". With the False Bay octopus fishery as a template, the development of a substantial time series of CPUE data from various areas around South Africa can be attained in the future. Importantly, CPUE values, independently, are not an indication of the actual abundance of the species, but by examining catch and effort trends, a better understanding of the *O. vulgaris* population in False Bay can be attained. These CPUE values will become an important part of models used to determine relative abundance indices, which, will allow for the development of optimised management protocols and lay the groundwork for an extensive assessment of the *O. vulgaris* fishery in South Africa.

CHAPTER 2: LITERATURE REVIEW

The Marine Living Resources Act (MLRA), 1998 (Act No.18 of 1998) calls for the optimum utilisation and ecologically sustainable development of marine living resources. It further requires the need to achieve economic growth; human resource development; capacity building and employment opportunities in fisheries, while protecting the ecosystem, which includes non-target species. Using precautionary approaches in respect to the management and development of marine living resources, so as to conserve these resources for present and future generations. The pertinent goals of the act revolve around sustainable utilization of marine living resources, through the exploitation of unused (new) and the conservation of overexploited marine resources, providing equal access to these resources for all South Africans, to enable economic growth among coastal communities (Oosthuizen 2004).
Knowing the mandate of the Marine Living Resources Act (MLRA), the need to supply more fish protein for human consumption (FAO 2016) and global fisheries in decline (Zeller and Pauly 2005), the need to utilise unexploited and alternative fish stocks has been investigated in studies such as Perry *et al.* (1999).

Fishery stocks are considered to be any group of a fish species that is available for exploitation in a given area (Milton & Shaklee 1987). Hilborn & Walters (1992) considered stocks as arbitrary groups of fish, large enough to maintain itself through reproduction, with individuals of similar life history characteristics. In fisheries where multiple stocks are differentially exploited, an understanding of stock structure is vital, in order to produce appropriate management regulation (Ricker 1981).

Marine invertebrate stocks and the fisheries they support have existed for many centuries, others show rapid growth and many have just begun (Anderson *et al.* 2011). As at 2013, invertebrate fisheries contributed a share by value of 63,7% and share by weight of 37.9% of internationally traded fisheries products, a better yield than that of, what would be considered, traditional fin-fish fisheries (share by value 36.3%, share by weight 62.1%) (FAO 2016). With this in mind, the evidence to move towards invertebrate fisheries, which command a higher value per weight, is evident. The marine cephalopod, *O.vulgaris* is a species that shows potential as a candidate for exploitation (Hatanaka 1979; Bravo de Laguna & Balguerias 1993; Hernandez-Garcia 1995; Guerra 1997 Anon 1981; Wurtz and Repetto 1983; Mangold 1983; Paust 1988; Smale *et al.* 1993; Sanchez and Obarti 1993; Smith 1999; Smith & Griffiths 2002; Ooshuizen & Smale 2004; Sonderblohm *et al.* 2013; FAO 2017, 2018).

Further evidence of the need to utilize unexploited marine resources in South Africa, such as *O. vulgaris,* is bolstered by assessments on national line-fish resources (approximately 200 species) which show levels of pre-exploitation biomass collapses for many species, albeit to a small fraction (Mann 2013). The status of South African Marine Fisheries Resources report (2022) found that of the 61 fisheries stocks assessed, 39% was found to be of concern and 25% were over-exploited. Of the economically important species listed, the stocks of abalone (*Haliotis midae*), west coast rock lobster (*Jasus lalandii*) and the tuna species, were considered to be severely depleted. The proper management and sustainable exploitation of *O. vulgaris* may aid to some degree, in reducing the pressure being applied to these previously mentioned economically valuable species, should fishers of these species decide to target *O. vulgaris*, also deemed valuable on international markets (Leporati *et al.* 2009, Amor *et al.* 2014, Rocliff & Harris 2016; FAO 2017).

Many South African invertebrate species have not been considered for exploitation, although these same species have been utilised in other parts of the globe for decades, *O. vulgaris* would be such an example (Hatanaka 1979; Bravo deLaguna & Balguerias 1993; Hernandez-Garcia 1995; Guerra 1997; FAO 2018). Cephalopods make up a share per value of the previously mention invertebrates global contributions of 6.4% and share per weight of 3.8% (FAO 2018). *O. vulgaris*, is important to the global cephalopod fisheries (Hatanaka 1979; Bravo deLaguna & Balguerias 1993; Hernandez-Garcia 1995; Guerra 1997; Sauer, et al. 2019) with landings of 165 000 tonnes in 1996 (FAO 1998), and continues to make up a large part of the global landings for Octopus species (Leporati *et al.* 2009). The species was identified as suitable for exploitation in South Africa because of its suitable characteristics in terms of ecology, biology, catchability and marketability (Anon 1981; Wurtz and Repetto 1983; Mangold 1983; Paust 1988; Sanchez and Obarti 1993; Smale *et al.* 1993; Smith 1999; Smith & Griffiths 2002; Smith 2003; Oosthuizen 2003; Ooshuizen & Smale 2004; Sonderblohm *et al.* 2013; FAO 2017) Oosthuizen & Smale 2003), and considered underutilised.

The importance of advancing this experimental fishery to a small-scale commercial phase is emphasised by mandates such as, FAO's "Blue Growth Initiative" (BGI) launched in 2013 (FAO 2016). This initiative was designed with sustainable capture fisheries and economic growth from aquatic ecosystems as its mandate, with the aim of enhancing the implementation of the FAO Code of Conduct for Responsible Fisheries ("the Code") and ecosystems approach to fisheries (EAF) (FAO 2016).

"Blue Growth Initiative" Aims:

- Ensure the sustainable utilization of marine resources through the removal of harmful fishing practices and overfishing, while promoting growth and improving conservation.

- Ensure cooperation between countries.
- Act as a mediator to expedite policy development, investment and innovation in support of food security, poverty alleviation, and the sustainable management of aquatic living resources (FAO 2016).

Initiatives and mandates such as these will play an important role, when the management of the new fishery for *O. vulgaris* will come under consideration. These management practices will likely be formulated with sustainability of target and non-target species, the environment and the livelihoods of the current experimental right holders and the people they employ in mind. The environment and species concerned with this possible new small scale commercial fishery, are however not simple and cannot be studied in isolation of one another.

The management of this future small-scale commercial fishery will inevitably be approached from a multidimensional point of view and take into account the environment; the target species, the anthropogenic impact and economic viability, and consider how these factors interact with each other in order to best manage the future of this fishery, and thus can be considered EAF management (Shannon *et al.* 2004; Shannon *et al.* 2006; Cochrane *et al*. 2009).

2.1 Ecosystem Approach to Fisheries (EAF)

The EAF framework was developed, based on the principals and concepts from the long process of building the foundations for sustainable development, with the wellbeing of humans and the ecosystem as its aim (Garcia *et al.* 2003). The 1995 “FAO Code of Conduct for Responsible Fisheries” was the reference framework for sustainable fisheries and addresses practically all of the ecosystem considerations, principals and conceptual goals of an EAF (Garcia *et al.* 2003). It is the culmination, binding and organisation of international instruments of great relevance to EAF, spanning three decades (Garcia & Cochrane 2005). The implementation guidelines for EAF formally emerged at the 2001 Reykjavík Conference on Responsible Fisheries in the Marine Ecosystem (FAO 2002, 2003).

The goal of EAF is “To balance the diverse societal objectives, by taking into account the knowledge and uncertainties about biotic, abiotic and human components of the ecosystem and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries” (FAO 2003). In other words, EAF management is aiming to contribute to the sustainable utilisation of ecosystems by strengthening already existing management frameworks by improving their implementation and reinforcing their ecological relevance

(Garcia *et al.* 2003), but also take into account the socio-economic and policy components related to the fishery under review.

The most specific issues in EAF relate to the impact of fisheries on the environment (biodiversity and habitat) and the impact of the environment on fisheries (natural variability and climate change) (Garcia & Cochrane, 2005). In order to address these issues managers will be required to take account of these impacts when setting objectives and attempts to meet these objectives will need to be supported by sound scientific advice and effective management and decision making (Jennings 2005).

Many of the principals found in EAF share similarities with goals found in the MLRA shown in detail below.

The Marine Living Resources Act, 1998 (Act No.18 of 1998) of South Africa, Chapter 1 (Section 2)

- *the need to achieve optimum utilization and ecologically sustainable development of marine living resources;*
- *the need to conserve marine living resources for both present and future generations;*
- *the need to apply precautionary approaches in respect of the management and development of marine living resources;*
- *the need to utilize marine living resources to achieve economic growth, human resource development, capacity building within fisheries and mariculture branches, employment creation, and a sound ecological balance consistent with the development objectives of the national government;*
- *the need to protect the ecosystem as a whole, including species that are not targeted for exploitation;*
- *the need to preserve marine biodiversity;*
- *the need to minimize marine pollution;*
- *the need to achieve to the extent practicable a broad and accountable participation in the decision-making processes provided for in this Act;*
- *any relevant obligation of the national government or the Republic in terms of any international agreement or applicable rule of international law; and*
- *the need to restructure the fishing industry to address historical imbalances and to achieve equity within all branches of the fishing industry.*

The formulation of management plans is an important part of implementing EAF, and requires data and information (FAO 2003). Target-resource orientated management (TROM) plans generally have data sets and information already relating to the fishery i.e. area of operation;

gear and vessel types; socio-economic aspects; history of fishery; species distribution; life history; fishery effects on recruitment; abundance; age or size structure of target species; available monitoring data and any management procedure already in place (FAO 2003). This information alone will not be sufficient for an effective EAF, however, using this information and data to describe the direct and indirect effects of the fishery on species and habitats and translating these into policy goals and broad fishery objectives and thereafter, operational objectives, will provide what is needed to implement EAF (FAO 2002, 2003; Garcia & Cochrane 2005; Jennings 2005).

Therefore, the provision of scientific advice is critical for the development of management plans for the small-scale *O. vulgaris* fishery, under the mandates of precautionary approaches and the conservation of target and non-target species (FAO 1995; The Marine Living Resources Act 1998).

2.2 Study Area

False Bay (34°04' - 34°23' S, 18°26' – 18°52' E) an approximately square body of water has a total surface area of 1082 km^2 with a volume of 44 km^3, located on the southwestern coast of South Africa (Spargo 1991), this embayment has been the area of operation for the 15 year-long experimental *O. vulgaris* fishery. The area has a Mediterranean climate, receiving between 40 and 50% of its annual rainfall in the Austral winter, between June and August (Spargo 1991). Winters are dominated by north westerly winds and summers (December to February) by south easterlies, caused by seasonal shifts in the South Atlantic anticyclone (SAA) centred at 30°S (Pfaff *et al.* 2018).

The north of the bay is dominated by linear sandy beaches with eastern and western sides being mountainous and rocky with some sandy beaches (Pfaff *et al.* 2018). Margins of the bay are defined by Cape Point and Cape Hangklip, housing the deepest part of the bay at over 100m in depth which then shallows to the north (Terhorst 1987). Roman Rock, Seal Island, York Shoal, East Shoal, Whittle Rock and Rocky Bank are the more notable rocky pinnacles and high relief reefs within the bay, some of which, rise up to 20m and may impact oceanographic patterns by creating localised upwelling and turbulence (Pfaff *et al.* 2018). The important role of channelling cold, nutrient rich water, upwelled by south-easterly winds (Grundlingh & Largier 1991) into the bay, is carried out by the Hangklip Ridge, a westerly submarine extension of Cape Hangklip (Hartnady & Rogers 1990).

Sea surface temperature (SST) patterns are predominantly driven by wind dynamics, which drive ocean circulation and waves in False Bay (Jury 1987; 1991). The general surface circulation in the bay is clockwise due to prevailing cyclonically-sheared southerly winds (Jury 1991), while currents at the mouth have a typically westward direction, modulated by passing weather, warm Aghulhas rings and tides (Grundlingh & Largier 1991; Nelson *et al.* 1991).

Previous SST studies in False Bay have identified a strong temperature gradient, showing warmer water on the northern and eastern side, with cooler water on the southern and western side, due to an intrusion of cold water from upwelling at Cape Hangklip in summer (Jan – March). In contrast, the SST in the bay becomes more homogenous during the winter months (June – August) as upwelling subsides (Dufois & Rouault 2012).

False Bay is currently utilised by the commercial line fishery which has an average of fifty rights allocated in the area since 2000, while west coast rock lobster and beach seine currently have 39 and 4 respectively. Species exploited commercially in the past include whales, fur seal and sea birds (penguin egg collection and guano scraping) occurred until 1975, 1990, 1968 and 1991 respectively (Pfaff *et al.* 2018).

2.3 Aspects to take under consideration when making generalisations about Cephalopod populations for the purposes of fisheries management

In order to meet as many of the requirements of EAF or any form of management decision regarding a fishery, knowledge surrounding the fishery and the environment is imperative. In the context of the experimental *O. vulgaris* fishery, currently underway in False Bay, knowledge on the effects of various aspects on the population of the target species is imperative for the proper management of the species. These include anthropogenic factors such as fishing pressure, gear type and overall fishing efficiency. Natural factors such as, natural mortality, predation, immigration and emigration and oceanographic conditions (temperature; upwelling; ph; Oxygen) may also cause changes in the population at various stages of the life cycle (Boyle & Boletzky 1996; Lorenco & Pereira 2004; Thiaw *et al.* 2011; Demarcq & Faure 2013; Rodhouse *et al.* 2014).).

2.3.1 Populations (Definition, Distribution and Structure)

In order to better manage any fishery (resource), defining the population, i.e. the harvestable stock, is essential (Bonfil 2005). The term “stock” is often loosely used to mean population, however in the marine environment the term stock refers to the harvestable proportion of the population that is available to the fishery (Boyle & Boletzky 1996). Boyle and Boletzky (1996) loosely define a ‘population’ as “a large group of individuals of the same species that maintain themselves by reproduction in a describable geographic area or habitat, ignoring the precise number of individuals and the encompassed smaller groups of individuals. While Turchin (2003) defined a population as a group of individuals of the same species living together in an area of sufficient size to permit normal dispersal and migration behaviour and in which population changes are largely determined by births and deaths (Rodhouse *et al.* 2014).

Population richness finds its principle from the idea of, the difference between species having a single or very few broadly distributed populations and species containing large numbers of populations (Sinclair 1988). The number of local populations do not necessarily equate to the number of truly distinct populations (Boyle and Boletzky 1996). Allmon (1992) proposed that local populations may be connected together into an ensemble called the metapopulation, by migrating individuals and the existence of an isolate enables population continuity through time and the possibility of becoming the founder of a new species.

Mayr (1970) defines the biological species concept as only the enclosure of something that can be variably structured, because natural populations of actual or potentially interbreeding species groups, which are separate from other such groups, may contain between one and many populations with unique features or traits. *O. vulgaris* is a prime example of displaying the species identity problem (Boyle & Boletzky 1996). This cephalopod was originally reported in the Mediterranean, but later believed to be cosmopolitan after discoveries of populations in other parts of the globe, but, was however found to be part of a larger group of morphologically similar but genetically distinct *vulgaris*-like species, now known as the *O. vulgaris* species complex (Amore *et al.* 2016).

As with most marine organisms of interest to scientific research, the populations of cephalopods are not easily accessible to view and are therefore subject to coarse methods of study and estimation (Boyle & Boletzky 1996). Further complicating the difficulty of establishing generalizations about cephalopod populations are the inherent life cycle characteristics of these populations (Boyle & Boletzky 1996). These characteristics are described by various authors for *O. vulgaris*, their short life span (Paust 1988; Domain *et al.* 2002; Iglesias *et al.* 2004; Pierce *et al.* 2010; Boletzky & Villanueva 2014); size at maturity (early reproductive capability) (Smith & Griffiths 2002; Oosthuizen & Smale 2003; Kivengea *et al.* 2014) and high growth rate (Guerra 1979; Paust 1988; Sanchez *et al.* 1998; Domain *et al.* 2000; Gimenez & Garcia 2002).

The understanding of the geographical distribution of the species population or stock is one of the most important factors for the scientific consideration of its ecology and management (Hermosilla *et al.* 2011). Migration patterns on different scales are also important factors when studying a population, as these will affect the population at various stages of the life cycle

(Boyle & Boletzky 1996; Smith & Griffiths 2002; Oosthuizen & Smale 2003; Semmens *et al.* 2007; Rodhouse *et al.* 2014) and hence the accessible proportion of the harvestable stock over a given period. Benthic octopus species such as *O. vulgaris* have a limited migration and may move no more than 10 kilometers for the duration of their lives (Rodhouse *et al.* 2014). Many studies have been done globally in order to ascertain the species distribution and distributional nuances of the *O. vulgaris* species complex (Roper *et al.* 1984; Costa & Fernandez 1993; Belcari *et al.* 2002; Lourenço & Pereira 2004; Gonzalez *et al.* 2005; Semmens *et al.* 2007; Moreno *et al.* 2009; Hermosilla *et al.* 2011; DeLuca *et al.* 2014; Amor *et al.* 2016). Boyle & Boletzky 1996 describe the inherent fluctuation in the biomass of a cephalopod stock, due to the effects of these factors (life cycle characteristics, migration etc), as highly variable. Initial fluctuations in biomass are caused by the basic life-cycle characteristics and the mortality of the adult population after breeding, which occurs (in temperate conditions) on an annual basis and as a consequence, there may be little to no chance that the adult generations of the population would overlap (Boyle & Boletzsky 1996, Domain *et al.* 2002; Iglesias *et al.* 2004; Boletzky & Villanueva 2014).

A lack of consensus exists among researchers regarding how best to address the modelling of cephalopod population ecology for fisheries purposes, in terms of; the growth model to be applied; how best to resolve basic systematic confusions; the need to attain a cohesive description of the population ecology and how to define populations (Boyle and Boletzky 1996; Boyle & Rodhouse 2005; Rodhouse *et al.* 2014). However, studies conducted in the last two decades have largely addressed the systematic problems and an abundance of knowledge has been accumulated from fisheries research, as a result of fisheries themselves and biological research (Rodhouse *et al.* 2014).

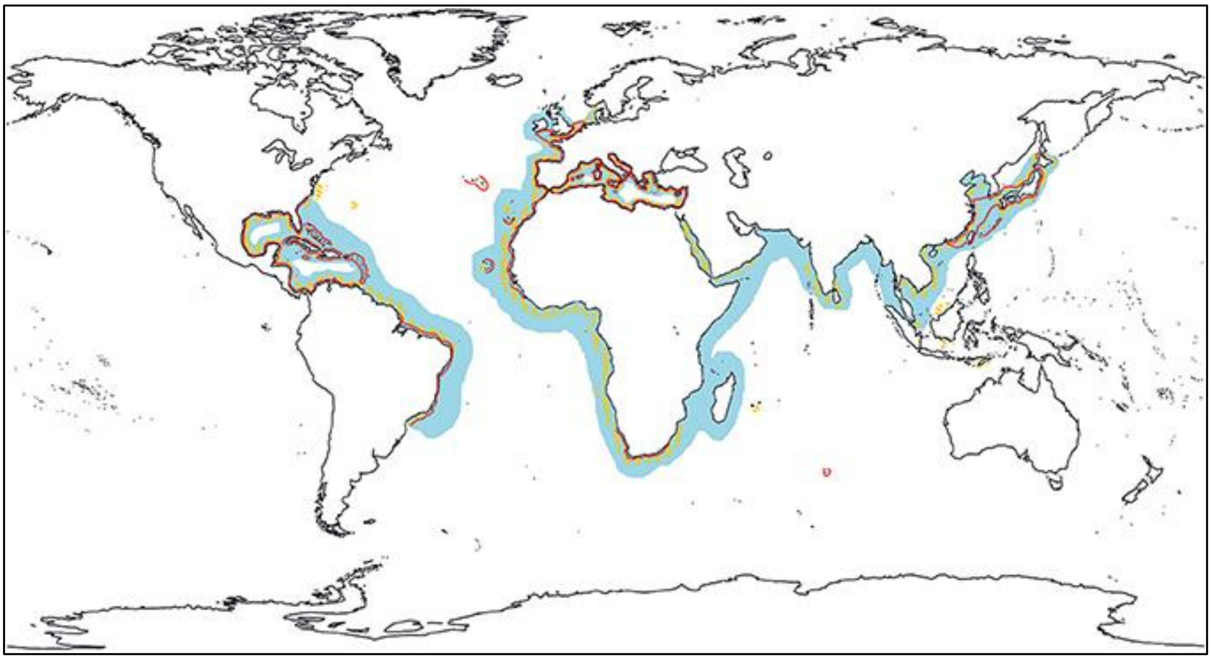

Figure 1: Distribution of Octopus vulgaris after Mangold (1983), Roper *et al.* (1984) and Norman *et al.* (2013), in orange, light blue and red respectively taken from De Luca *et al.* (2014)

2.3.2 Population Dynamics

Of the approximately 800 species of cephalopods, some of which have not yet been described, only 59 have been researched at an adequate level to consider population dynamics studies (Rodhouse *et al.* 2014). For the family Octopodidae, Rodhouse *et al.* (2014) provides clarity of the available knowledge, 119 described species divided according to abundance, the percentage of described species that have been well investigated, the commercial value or potential and the ecological importance of the species. As CPUE is considered to be a measure of the relative abundance of a population, it provides a basis to consider the dynamics of that population over a measured time period. This can then be related to other population parameters such as the size frequency (mass frequency) within that population, used as a size based indicator to determine the effects of fishing on the population (Shin *et al.* 2005)

The two main issues when considering the population dynamics of a cephalopod species, is per capita rate of population change or regulation as defined by stability and oscillations (Rodhouse *et al.* 2014). With basic data available it is possible to devise models to provide explanations for observed change within these issues (Rodhouse *et al.* 2014). In other words the major problems to be addressed or considered when studying the populations of cephalopods is the rate of change of the population being investigated and the stability of those changes verses the irregularities or fluctuations within these changes themselves.

This is defined through the equation:

$$rt = \ln(Nt/Nt\text{-}1)$$

where $\ln(Nt)$ is the natural logarithm of population density over time t and N is the population at time t, which only provides a framework for the quantification of wild populations because of the multitude of variations in population oscillations and stability (Rodhouse *et al.* 2014).

Often conventional fisheries stock assessment and resource management frameworks are used for the purposes of investigating these population changes and oscillations, however, recent approaches have made use of the effects of environmental systems and variables, and understanding their external effects on the population of the cephalopod species of interest (Costa & Fernandez 1993; Sobrino *et al.* 2002; Lourenço & Pereira 2004; Otero *et al.* 2008; Chedia *et al.* 2010; Vargas-Yanez *et al.* 2009; Polanco *et al.* 2010; Thiaw *et al.* 2011; Rodhouse *et al.* 2014; Sonderblohm *et al.* 2014; Otero *et al.* 2015; Scheel 2015).

Pierce *et al.* (2008) acknowledged the importance of considering environmental systems and variables as a key factor in leading, varying and determining cephalopod life cycles and their population dynamics, because of the various empirical models produced that link environmental parameters with density, distribution and recruitment. Many authors show relationships between recruitment (catch data) and environmental temperature (Demarco & Faure 2000; Lorenco & Pereira 2004; Thiaw *et al.* 2011). These relationships however are not considered to be straightforward, as a result of the effects of temperature on various other factors such as, paralarval survival, growth rate, age of juvenile benthic settlement and timing of reproduction and may affect recruitment strength (hence commercial catch) (Pierce and Boyle 2003; Vargas-Yanez *et al.* 2009; Caballero-Alfonso *et al.* 2010). It should be noted that trophic relationships (together with environmental factors), such as prey availability in early life stages, be recognized as important (Vidal *et al.* 2006; Otero *et al.* 2008; Rodhouse *et al.* 2014).

Other oceanographic fluctuations and processes have been shown to affect different stages of the cephalopod life cycle (Rodhouse *et al.* 2014). Currents and upwelling for example play a role in the life cycle, by affecting transportation and retention of paralarvae (Arkhipkin *et al.* 2006; Otero *et al.* 2007; Demarco & Faure 2013; Otero *et al.* 2015) and as a consequence, abundance and recruitment are also affected. The effect of salinity acts in much the same way as temperature on the early life cycle (Paulij *et al.* 1990) but fluctuations in nature are less (Rodhouse *et al.* 2014) examples of these effects in (Nabhitabhata *et al.* 2001; Sen 2004, 2005; Dupavillon and Gillanders 2009). Similarly O^2 and CO^2 concentrations may have effects on cephalopod survival at different stages of their life cycle (Rodhouse *et al.* 2014).

2.3.2.1 Trophic ecology

During the life cycle of cephalopods the, stage of embryonic development, is considered to be probably the least vulnerable to predation Rodhouse *et al.* (2014). Predation at this stage of the life cycle is considered to be of little consequence, as it has little to no impact on the survival of spawning products (Rodhouse *et al.* 2014). In the case of benthic octopods, their egg masses are well hidden in dens, tended to by the adult female until hatching and therefore are unlikely to experience predation from predators (Rodhouse *et al.* 2014). Cephalopods make up the diet of many large marine predators (Clarke 1996; Smale 1996; Piatkowski *et al.* 2001; Santos *et al.* 2001;) but it should be noted that there have been no documented cases of top-down control correlations between predator and cephalopod prey abundance, and should probably not be counted as a factor influencing the population fluctuations in commercially exploited cephalopods (Rodhouse *et al.* 2014).

Food availability would also be a contributing factor to the survival of cephalopods at various stages of their life cycles. Vidal *et al.* (2006) considers food availability as a factor that can cause plasticity in paralarval growth over very short time periods, while Boyle and Boletzky, (1996) state that an important factor contributing to the growth of the biomass of a cephalopod population is the apparent high gross conversion efficiencies of cephalopods, with later experiments such as (Giminez & Garcia 2002) bolstering this statement.

Another factor under trophic consideration is cannibalism, as it can have both a positive and negative effect on a cephalopod population (Ibanez & Keyl 2010; Rodhouse *et al.* 2014). The reasoning behind cannibalistic behaviour can be traced to, the availability of food on various scales, reproductive season, territoriality in octopods and the aggressive predatory nature of cephalopods in general, and is considered generally density dependant (Ibanez & Keyl 2010). Considering this, Ibanez and Keyl, (2010) assumed that, as a reaction to favourable and adverse environmental conditions, cephalopods use cannibalism as a means of regulating their population (i.e. as a population energy storage strategy). In the octopus species *O. vulgaris* and *Enteroctopus megalocyathus* reports of higher frequencies of cannibalistic behaviour were observed during periods of high abundance (Oosthuizen & Smale 2003; Ibanez and Chong 2008; Ibanez & Keyl 2010). Fernandez, (1999), Claessen (2002) and Claessen *et al.* (2004) viewed cannibalism as a possible strategy of population regulation that leads to temporal population fluctuations in said population. Cannibalism however cannot be considered exclusively when considering population fluctuations for a given population of cephalopods and has to be viewed in conjunction with other variables, such as, environmental factors; population density; food availability; body size and sexual dimorphism (Ibanez & Keyl 2010).

2.3.3 Fisheries

Fisheries are an important source of variability in commercially exploited stocks (Rodhouse *et al.* 2014). The potential to deplete target and non-target (by-catch) species due to overexploitation is ever present as has been reported for many of the world's finfish fisheries (Pauly *et al.* 1998; Mann 2013; FAO 2016) and other marine resources (South African State of Marine Resources 2020 FAO 2016). The commercially exploited species of cephalopods, with their high growth rates, short life spans and high fecundity, have evolved well to withstand substantial variations in their population abundance (Rodhouse *et al.* 2014). The global cephalopod species harvest has risen from approximately 600 000 t in the 1950's (Jereb & Roper 2010) to more than 3 million tonnes in 2004, increasing to over 4 million tonnes, ten years later in 2014 (FAO 2007, 2016). However, collapses in cephalopod fisheries have been reported for various species (O'Dor and Coelho 1993; Nakata 1993; Pierce *et al.* 1994; Hanlon 1998; Dawe *et al.* 2000; Hibberd and Pecl 2007; FIGIS 2011; Iwata *et al.* 2010). The causes for these collapses have been attributed to over fishing, environmental effects or a combination of the two (Rodhouse *et al.* 2014). Considering this, it would be wise to monitor fisheries closely in order to gain as much knowledge to find possible ways of curbing these collapses, but here too, this cannot be done exclusively and environmental parameters have to be considered in order to make the best decisions to safeguard stocks against these collapses. The best way to attain that kind of confidence when considering the sustainability of an exploited population would be the ability to forecast or predict what effect the different variables acting on the population would have at different levels.

2.3.4 Assessment and Forecasting

For any management decision to be made, regarding a fishery, some form of assessment is necessary in order to address the major issue with fisheries i.e. sustainability. In order to begin any type of forecasting or assessment the type of data required is important, Pierce & Guerra (1994) state catch data and biological data to be important and that the precise requirements may vary according to the method of assessment being used.

Assessment methods generally fall into two categories, distinguished by their time of occurrence, in-season assessments and post-season assessments, according to (Pierce &

Guerra 1994). Boyle & Boltezky (2005) and Rodhouse *et al.* (2014) however, include pre-season assessments and forecasting, this type of assessment makes use of data collected from experimental surveys on individuals in the pre-recruit stage of their life cycles. The other assessments types make use of the same data types and methodology but have different applications, in-season assessments use incomplete data as they are collected and used during the fishing season to make adjustments to fishing activity, whereas post-season assessments use complete data sets for a season and are used to establish relationships with different variables so as to create management goals or structures for the following season (Pierce & Guerra 1994). Ideally, with unlimited funds a combination of all three methods would be best, but catch data and access to the catch itself, is readily available and does not have major cost implications, which lends itself towards in-season and post-season assessment. Pre-season assessments would likely have major cost implications in terms of funding required to undertake the experimentation to acquire the data.

Assessment methods for most cephalopods will most likely have to be done on a much shorter time-scale, because of their short life span and sensitivity to environmental conditions (Pierce & Guerra 1994). Rodhouse *et al.* (2014) noted that it was the most common practice to adapt simple population dynamics models for cephalopod stocks that do not require age composition data, but rather, requires assessment data (including catch statistics) and suitable models to forecast fisheries stocks, which are varied in the targets of what period should be forecast (e.g. stock size in the next week, next month and next year)" (Boyle and Rodhouse 2005; Caddy 1983; Pierce and Guerra 1994).

2.3.4.1 Commonly used assessment methods for cephalopod population

Rodhouse *et al.* (2014) provides a good description of the various models, examples for each, as well as shortcomings and solutions, being used for cephalopod assessments. The following table gives a brief summary of the various models used, as any one may present the best possible solution for a future assessment of the O. vulgaris fishery in South Africa, given the data available and the cost implications.

Table 1: A summary of assessment methods used for cephalopod fisheries Rodhouse *et al.* (2014)

Assessment Method	Discription	Issues / Negatives	Solutions / Positives
Surplus Production Model	Estimates biomass of a resource for one year (y+1)-the catch (Graham, 1935; Schaefer, 1954)	Age & spatial structure not considered. Difficult to fit model. MSY interpretation difficult, may lead to overestimation of stock (Hilborn & Walters, 1992)	Quick application. Few data data required. Able to be succefully adapted to cephalopod fisheries. Environmental variables can be included (Pierce et al., 2008)
Depletion Method	Estimates the consequances removal of indivuals from the populaion due to natural or fishing mortality and determines the size of the population without fishing activity (Hillborn & Walters, 1992)	Assumes random distribution of population (rarely encountered in cephalopods) Pierce & Guerra,(1994)	Least expensive methodology. Most suitable for data collected over a short period (exploitation does not exceed 1 year) favoured for cephalopod stocks (Boyle & Rodhouse et al., 2014)
Age-structured Models	Virtual population analysis (VPA), number of individuals is estimated by performing a back calculation from the last age class to the first one. Individuals lost to fishing and natural mortality during a year + the number of individuals at the end of the year = > estmated number of individuals for that year (Jouffre et al., 2002; Royer et al., 2002, 2006; Thiaw et al., 2011)..	Requires aqurate data. Age estimate tools for cohort analysis beyond 240 days do not exist for all cephalopod species (cuttlefish) Rodhouse et al., (2014)	Is able to test the exploitation of the stock under different conditions from a fishing and environmental aspect for different cohorts (Rodhouse et al., 2014, references therin)
Two-stage models	Rodhouse et al., (2014) decribes the model in theory as bieng, the population being modelled from the recruitment stage when the abundance is estimated by the addition of recruitment strenght and fully recruited individuals.	Recruitment period and fully recruited phase data must be accurate and clearly distiguishable (Rodhouse et al., 2014)	Is used when data is not accurate enough for a VPA(Rodhouse et al., 2014). Able to be fitted using several time series(Roel and Butterworth, 2000). Can be implemented using numbers or biomass indifferently (Rodhouse et al., 2014).
Forecasting/ general and emperical models	Stock sizes are forecasted using growth survival model and correlation models, using the results attained from experimental abundance survays for juvenile cephalopds using mid-water trawls (Brunetti and Ivanovic, 1992; Kawabata et al., 2006; Kidokoro et al., 2014) and distribution surveys for paralavae using plankton nets(Bower et al., 1999a; Goto, 2002; Murata, 1989; Yamamoto et al., 2007)	Observation errors during preseason assessments may cause a lack of proportionality between recruitment stock size and the results of preseason assessments (Rodhouse et al., 2014).	Useful for newly assesed cephalopod stocks as this assessment method does not require historical data, catches can be forecasted for an individual fishing ground, in-season, with required data sets (Rodhouse et al., 2014).
Fishery dependent data	Incorporates several types of data collected from fisheries on commercial fishing vessels i.e. abundance indexes, bilogical data, CPUE, LPUE, size composition etc. (Hilborn and Walters, 1992; Johnson, 2011; NEFSC, 2011; Rodhouse et al., 2014)	Effort data can be difficult to collect from small-scale and diverse artisanal fisheries (Lourenco and Pereira, 2006). If insufficiant biological data to derive abunance indecies is available the use of CPUE data is confounded, because of misidentification of similar species(Leporati et al., 2009; Rodhouse et al., 2014). Heterogeneous nature of fishing fleets may affect CPUE values (Rodhouse et al., 2014)	Standardization of CPUE removes the heterogenaity of fishing fleet and variations that may occur as a result of spatiotemporal effects (Rodhouse et al., 2014). Data is accessable from factories and rights holders, cost to acuire data is low.
Fishery independent data	Represented by experimental surveys i.e. mid-water trawls, planktonic net surveys, jigging surveys and acoustic surveys (Rodhouse et al., 2014, references therin)	Refer to forecasting	Refer to forecasting

The management of the future commercial fishery for *O. vulgaris* in South Africa will be based, most likely on fisheries-dependant data assessments, as this is the most readily available data set available. Catch data is provided on a monthly basis to the Department of Agriculture Forestry & Fisheries and members of the department collect biological data from fish processing establishments periodically. At present the fishery does operate under an exploratory management basis, which has designated zones for fishing, limited the number of rights holders per area and number of pots deployed per area. This exploratory fishery is operating under a form of effort based management, as a precautionary approach (Punt 2006). This is only an interim solution and will need to be adapted as the fishery grows and becomes a commercial fishery in the future. In order for this to be accomplished a full description of all aspects relating to the exploratory fishery needs to be provided, which is the primary purpose of this study.

CHAPTER 3: DESCRIPTION AND EXPLOITATION PATTERNS OF THE EXPLORATORY OCTOPUS VULGARIS FISHERY IN FALSE BAY (WESTERN CAPE) SOUTH AFRICA

3.1 Introduction

False Bay (34°04' - 34°23' S, 18°26' – 18°52' E), located on the south western coast of Southern Africa, is margined by the two rocky promontories of Cape Point and Cape Hangklip (Figure 3.1). The area has been commercially exploited since the early 1600's (Griffiths *et al.* 2005), however only three fisheries operate in the bay currently i.e. Line-fish, West Coast Rock Lobster and Beach Seine, others such as trawl, purse-seine and gill netting introduced in the 1800's have ceased operations (Pfaff *et al.* 2018). The commercial line fishery has an average of fifty rights allocated in the area since 2000, while west coast rock lobster and beach seine currently have 39 and 4 respectively. Species exploited commercially in the past include whales, fur seal and sea birds (penguin egg collection and guano scraping) occurred until 1975, 1990, 1968 and 1991 respectively (Pfaff *et al.* 2018). Applications for exploratory fishing for underutilised species (Whelk, Sea Urchin, Sea Cucumber and Scallops) have been made for this area, but only *O. vulgaris* has been pursued to its current levels of fishing.

Octopus vulgaris has been considered for exploitation in South Africa as a small scale commercial fishery species (Smith 1999; Oosthuizen 2004). It is the only species targeted in the South African fishery by the exploratory octopus right holders as other species (Brush-tip and Giant Octopus) found in False Bay are released if caught. The species is considered to be an important exploitable resource, owing to their short life span, rapid growth rate, firm texture and high meat recovery (Paust 1988). Octopus catches fluctuated from a minimum of 13 tons in 2014 to a maximum of 50 tons in 2018 as per data collected from False Bay for the 2014 to 2019 period.

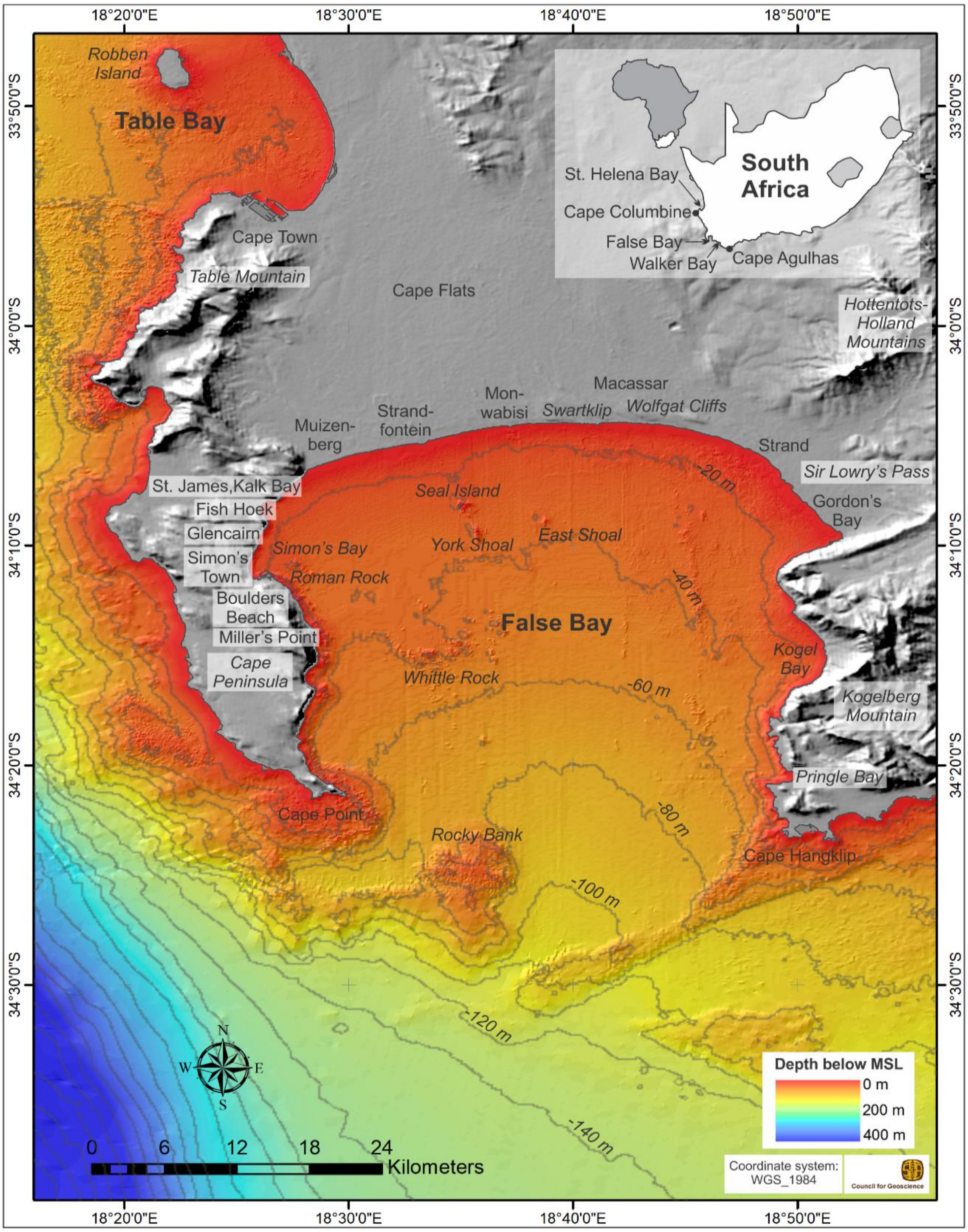

Figure 3.1: False Bay, Western Cape, South Africa (Pfaff *et al.* 2018)

This seeking of shelter has led to the development of fisheries, mainly artisanal, using species specific gear (Silva *et al.* 1998) such as the clay pots in the Gulf of Cadiz (Sobrino *et al.* 2011) or trigger traps in Australia (Leporati *et al.* 2015). Harvesting of the species in many parts of the globe occurs using various fishing gears mainly small-scale gear types, such as previously mentioned pots and traps but also fyke nets and set nets (Anon, 1981; Wurtz and Repetto 1983; Sanchez and Obarti 1993). Some octopus fisheries however, still utilise less selective large scale gear (bottom trawl), used on the Saharan Bank (West Africa, between 21°N and 26°N latitude) (Balguerias 2000).

The reporting of data was an issue that was highlighted by Department of Agriculture Forestry & Fisheries (DAFF) officials, as it was determined that certain data types were not being collected at the time. The lack of certain data was addressed with the development of a separate data form to collect a more holistic view of fishing activities and stricter rules for reporting. The new form would incorporate previously ignored variables such as by-catch, bottom type and temperature and later would include moon phase. These changes to data collection and fishing practices as well as additional gear types were considered in 2012 when DAFF began the process of establishing a second round of exploration in order to collect better data regarding the potential small-scale commercial fishery for *O. vulgaris.* In 2013, at the start of the exploratory fishing season, it was hoped that all 15 applicants would begin fishing in their designated areas, but many of the old problems re-surfaced and the only consistent catch data was collected from one rights holder in the False Bay area beginning in 2014. However, the data from the first two years of the planned five years had substantial gaps in reporting. The problems experienced by the fishery have shown some improvement and in the years following. Data and skills required to harvest *O. vulgaris* in South African waters have improved and allowed the collection of data from other areas, albeit at low quantities. Unfortunately, due to interactions between fishing gear and cetaceans, the fishery was temporarily suspended in False Bay for 9 months beginning in July 2019. The mortality of three whales in close succession of each other was the primary reason to suspend the fishery, pending a meeting held with various stake holders, in order to discuss possible cetacean entanglement mitigation measures to be applied to gear. It was determined that these modifications be applied to all areas fishing for *O. vulgaris* and not just False Bay, where the above mentioned mortalities had occurred. However other areas were to apply the modifications systematically while gear was still in circulation. In False Bay the gear was removed from the water in the months after the suspension and could only be returned to the water once all cetacean mitigation modifications had been completed. Fishing in False Bay re-commenced as of April 2020 with all modifications in place.

The exploratory fishery in South Africa predominantly used basic plastic pots with a cement foot, during the first five-year period (2003 – 2009), due to relatively cheap cost and availability. Another advantage of the gear type is that it is considered a form of passive fishing, no bait is required to catch octopus and animals can enter and leave at any time. However, after numerous difficulties with this gear type, predominantly the lack of stability on the seabed in

South African waters, the fishery moved to the more expensive but more stable Australian trigger trap, as incidents of gear moving were less frequent than the lines with single pots attached, according to fishers. These traps have a more stable configuration as they are deployed on a steel frame housing three individual traps (still described as a pot, representing one catching unit, and will be referred to as such from here on) for a combined total weight of approximately 25 kg per pot. This weight combined with the larger footprint meant greater stability on the seabed and hence less movement of lines. This gear type is considered active in terms of, the use of a silicon crab lure and LED pressure sensitive light to attract animals into the trap. The negative aspect of this gear type was the cost of lures, lights and anodes (fitted to the frame to reduced rusting), which required regular replacement and the potential loss of catch should animals be left in pots for an extended period due to unplanned events that prevent lines from being hauled. This led to the traps being used in a passive form from mid-2016, which meant that, pots were deployed without using the triggering mechanism (trap doors were locked in the open position) or the lures and lights. This gear type also required specific winches and tippers in order to safely operate during retrieval and deployment.

The gear was rigged to a long line and has 25 to 30 pots per line, equating to 75 to 90 individual traps. The number of pots is limited to 6000 per right holder per designated fishing area in accordance with exploratory octopus fishing permit conditions. Lines were soaked for an average of 14 days, predominantly determined by weather, with minimum and maximum soak times of 3 and 66 days respectively and took an average of 2.5 sea days to haul and re-set all deployed lines.

Studies done in South Africa related to the species include a Masters study on the biology and ecology of the species (Smith 1999), aspects of population biology and diet of *Octopus vulgaris* by (Smith 2002; 2003). Other studies include the biology of *Octopus vulgaris* on the east coast of South Africa (Smale and Buchan 1981), population biology of *Octopus vulgaris* on the temperate south-east coast of South Africa (Oosthuizen and Smale 2003) and economic feasibility of an experimental octopus fishery (Oosthuizen 2004). However, there is no literature on fishing for octopus with pots in False Bay or anywhere else in South Africa. The aim of the study, first of its kind in South Africa, is to provide a description of the current exploratory pot fishery in False Bay and the exploitation patterns therein. Analyses of trends in catch per unit effort (CPUE) and the distribution thereof were conducted for all years in the study period for weight and number of octopus. The final analyses will be used to determine possible population trends and success of the fishery from a fisheries perspective and aid in the development of a more accurate management plans using standardised CPUE and distributional maps, should the fishery continue to operate after the exploration phase.

3.2 Materials and Methods

3.2.1 Fisheries Data

All data received from False Bay was obtained from, Albatross, a 10 m tuna deck boat retrofitted to fish for octopus. The area of operation encompassed the entire bay from Cape Point to Cape Hangklip Lighthouse. Data were collated from submissions to DAFF on a monthly basis by the right holder operating in False Bay. During fishing operations, the number of pots per line, number of octopus, temperature, depth, size class (small < 1 Kg, medium 1-2 Kg and Large >2 Kg), GPS co-ordinates, date and by-catch data was collected. Once delivered to factory, weight data was collected before processing. These data were used to determine daily catch rate (CPUE) in number of animals and weight per pot, per line. Information regarding approximate catch size composition (small, medium, large) was obtained, by trained crew, as per data collection requirements. These data types were collected from 2014 to the present day, however usable on board data only began in 2016, but still had gaps due to lost on-board data for October 2017 to March 2018. One hundred and seventeen trips were undertaken from January 2016 to July 2019. Data from the factory receiving the catch was obtained and used for the calculation of mean CPUE from weight and numbers of octopus for all years. Table 3.1 is an outline of the trips made during this time.

Table 3.1: Summary of exploratory octopus fishery on board observations

Year	Month	Pots				Catch			
		Sea days	No. of lines	No. pots checked	Average Temperature °C	No. of Octopus	Small	Medium	Large
2016	January	1	13	430					
	February	3	38	1290		470	67	197	205
	March	6	70	2430	14,72	2204	183	655	1390
	April	2	39	2082	16,37	1226	135	346	745
	May	7	66	2208	15,56	1743	180	898	666
	June	6	65	2134	14,97	1713	152	880	681
	July	3	55	1798	14,30	1009	156	639	214
	August	4	43	1273	15,49	467	90	301	75
	September	1	25	725	15,91	459	43	390	3
	October	3	41	663	16,37	810	383	513	58
	November	2	43	1233	16,40	976	400	420	156
	December	4	59	1621	17,86	1244	371	710	163
2017	January	6	70	1987	17,62	1697	396	1304	47
	February	2	23	723		914			
	March	5	55	1470	16,77	787	207	319	262

	April	4	27	692	16,39	528	113	205	238
	May	6	95	2495	14,12	1601	141	546	943
	June	4	60	849	14,98	612	74	336	202
	July	7	69	1932	14,57	938	86	375	477
	August	1	11	319	14,48	169	8	45	116
	September	0	0	0		0	0	0	0
	October	4	47	1425		2431			
	November	4	36	1115		1928			
	December	4	47	1429		1851			
2018	January	6	65	1899		2153			
	February	5	62	1864		2212			
	March	5	64	1913		2212			
	April	6	120	2941	15,37	2560	352	410	1800
	May	8	119	2886	16,39	2916	125	329	2462
	June	6	86	1942	15,57	1550	112	298	1140
	July	7	89	2086	15,41	2053	316	997	740
	August	2	30	709	14,87	739	268	314	157
	September	5	60	1328	15,19	1640	806	563	271
	October	5	65	1431	16,62	2649	689	1242	718
	November	9	114	2822	16,37	4295	1537	2148	609
	December	11	176	3979	19,24	6549	2337	3100	1110
2019	January	12	174	3865	18,78	4932	815	3463	656
	February	7	83	2030	17,86	2625	200	2155	270
	March	6	86	1859	16,89	2137	130	1749	257
	April	7	141	2989	15,58	2844	241	2234	365
	May	11	199	5211	15,64	4900	322	3879	699
	June	7	110	2315	15,32	1878	176	1540	162
	July	5	69	1559	14,08	731	165	471	95

3.2.2 Fishing gear

The exploratory fishery in South Africa uses the long line fishing method, where pots are attached to a main line and anchored at each end (figure 3.2). The buoy line comprises the anchor, attached to vertical polypropylene line and a length of chain attached to the buoy at the surface. The bottom line carries the pots, and has a configuration that combines the use of sinking and floating polypropylene line. The first pot is at a distance of 25m from the anchor, made up of 15m of sinking line and 10m of floating line. From each pot to the next is 5m of floating line, 20m of sinking line, and 5m of floating. These sections of floating line lie approximately 0.5m off the seafloor. This configuration is replicated along the line until the next anchor. The rationale behind the use of floating line was to preserve the longevity of lines, to reduce abrasion of reef habitats during retrieval, and to allow for ease of retrieval should buoy lines become compromised. The distance between pots (which may be adjusted according to depth) and use of sinking rope, was determined with the possibility of entanglements in mind, such that a whale which may become entangled would still be able to reach the surface to breathe.

This design however, would later be changed to only sinking line on the sea bed and buoys either removed or submerged with the anchor and attached to a time release mechanism. This decision was, undertaken after a gathering of relevant stake holders in a meeting held by DAFF officials on 4 July 2019, due to interactions and subsequent mortality of cetaceans.

The release mechanisms to be used are currently being researched by the University of Cape Town, for efficacy, cost and longevity. Currently three mechanisms have been considered, acoustic; electronic and chemical (slat water switches, a metallic compound that erodes in sea water at different rates). While these mechanisms are being researched the industry has chosen to operate without buoy lines, using a grapnel to retrieve lines. Should buoy line and release mechanisms be used, the 2 m of line attached to the buoy below the sea surface should be sheathed in PVC to avoid line wrapping around cetaceans in the event of interaction.

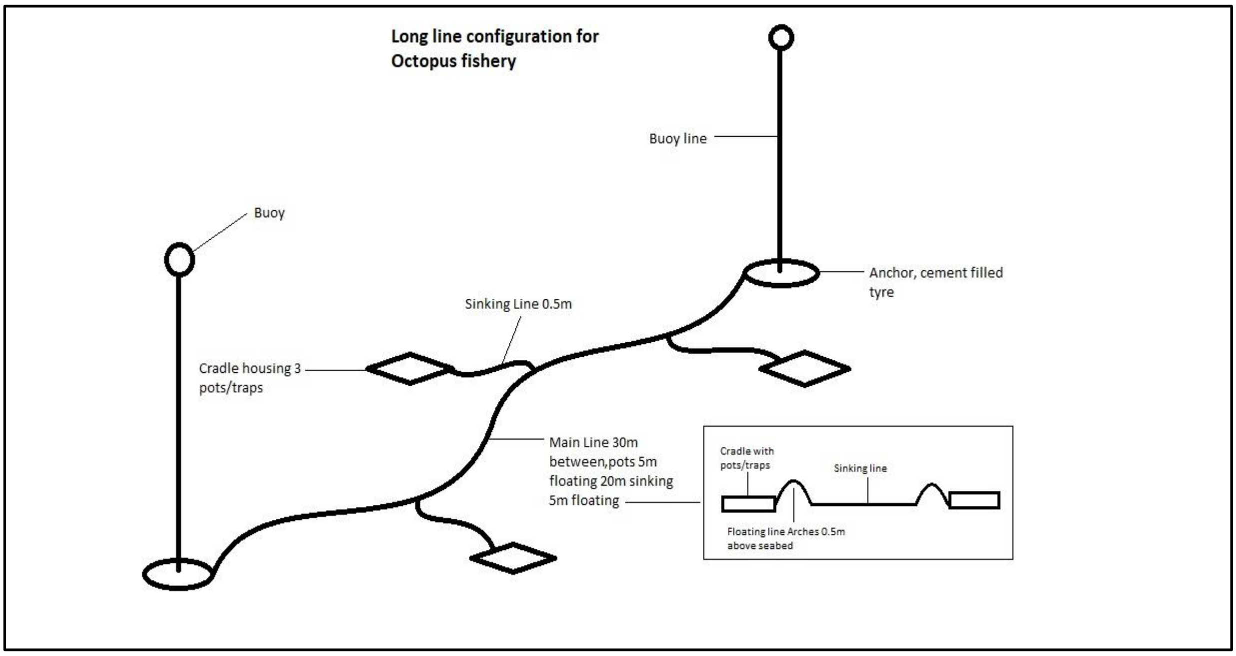

Figure 3.2: Octopus fishery pre-suspension configuration

In the early stages of the fishery a simple plastic pot with a cement foot (figure 3.3) was used and attached to the main line individually. Each line contained one hundred to one hundred and fifty pots. This design was later changed to the Australian trigger trap (figure 3.4) and cradle configuration. Each pot comprises a stainless steel cradle housing three Australian trigger traps. Each trap contains a lure attached to the triggering mechanism and activates the trap door once the lure is pulled, inner configuration seen in (figure 3.5). The hauling process requires specialised winches and a tipper in order to retrieve this gear safely.


Figure 3.3: Ivy Blue PVC pot with cement foot

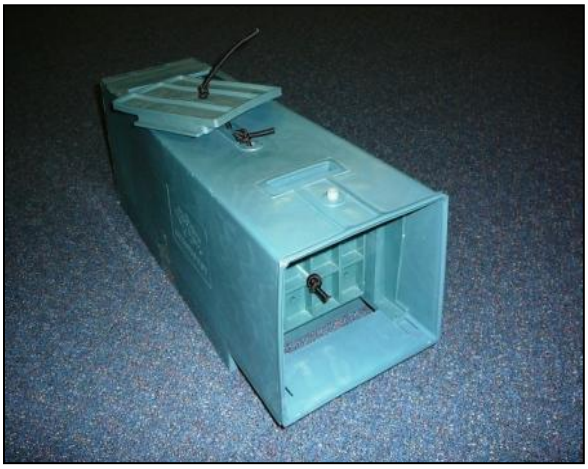
Figure 3.4: Australian trigger trap


Figure 3.5: Cross-section of trigger trap shown in activated position

In the later stages of the fishery, a South African reproduction of the trigger trap (figure 3.6) was produced in order to reduce the cost of importing the australian traps. These pots were similar in dimension to the trigger traps, however did not have any of the triggering mechanism, but allowed the pots to be used in the same configuration as the trigger traps and already existing cradles (figure 3.7). For the duration of this study all data collected were using the trigger pot. 2014 – mid 2016 used the triggering mechanism and thereafter all traps deployed were used in the passive configuration.

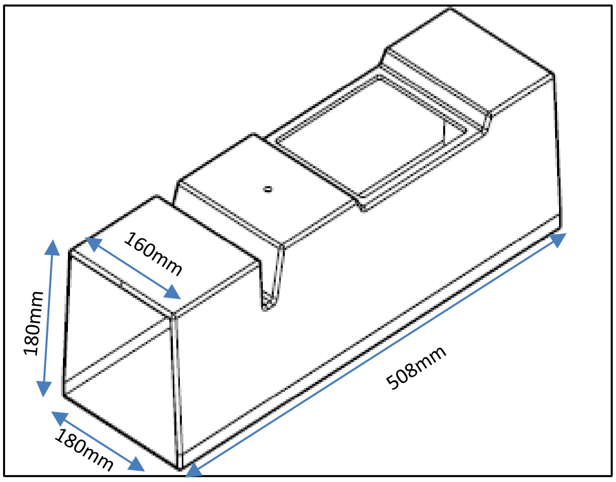

Figure 3.6: South African pot, based on trigger trap

Figure 3.7: SA pots in cradle configuration

3.2.3 Catch Handling

Once pots are retrieved the animals are removed by spraying them with a hypersaline solution, which agitates the animal, causing it exit the trap. Animals are then transferred to a holding tank containing salt water slurry. At the end of the trip all animals are removed from the tank and bagged for transportation to the factory.

Once at the factory animals were weighed in the bag and then put into a cold room until processing. Animals were then removed from the bags cleaned and prepared for grading. Animals were graded once they had been gutted and the beaks removed. Animals were size-graded from T8 (0.1 kg to 0.8 kg) to T1 (> 4 kg). Animals were then vacuum packed in 1kg packs, boxed and prepared for export. Animals were exported primarily to the European and Asian markets.

3.2.4 Data Handling and Analysis

All received data were compiled in databases on Microsoft Excel. These data were normalised by editing to the same formats, cleaned by filling as many gaps as possible, validated by finding and editing inconsistent values and then converted into CSV (comma delimited) format to be used in R studio. It should be noted that some versions of Excel use a semicolon to delimit data when converting to CSV format which was not suitable in R studio. This was addressed by opening up the saved Excel CSV file in notepad and replacing firstly all commas to points and then replacing all semicolons to commas. Seven separate databases were used for this study, each containing overlapping data points and allowed for the comparison between and verification of each (Table 3.2). The predominant data points used for verification between databases were the date, number of animals caught and weight. Databases were formatted to allow uniformity between the same data points, date was formatted to dd/mm/yyyy and weight (Kg). Weight presented an issue during the initial period of sampling as weights recorded were leg weight (mantle and beak removed). This was addressed by calculating the weight loss from total factory weight of animals without bags in later years when whole animals were preferred to just legs. It was found that a 24% weight loss occurred between whole animal weight and leg weight. The 24% weight loss was then added to leg weights in order to normalise weights to whole weight.

Table 3.2*:* Summary of databases with data-point headings

	Data Points							
Factory sampling database	Date	SEX	MASS (g)	Leg only Mass (g)				
Factory catch database + CSV file	Date	Kg leg weight	Kg whole weight	Number of pots	Number of Openings	Catch rate kg legs/pot	Catch rate whole weight/pot	Catch rate Kg leg/openings
	Catch rate whole weight/openings	Number Of Octopus	Mean Octopus Mass	%Catch Success				
On-board database x4 2016 - 2019 + consolidated CSV file	Vessel	Trip No.	Year	Month	Day	No. of Fishing Days	Line. No.	Line Count
	End Latitude	End Longitude	Area Name	Depth (m)	Temp (^{0}C)	Sediment Types	Bycatch	No. Pots
	Start Longitude	Start Latitude	Start Lat.DD	Start Long.DD	No. S	No. M	No. L	No. Octopus
Production database	Vessel	Date	Grading	Input Mass	Output Mass	Waste Mass		

The on-board databases from 2016 to 2019 were consolidated after cleaning and validation. This database presented some challenges in terms of missing data and GPS co-ordinates that were recorded in different formats, namely degrees° minutes' seconds" (34°13'456") or minutes' seconds" (13'456"). These were normalised by converting all co-ordinates to decimal degrees. Co-ordinates were recorded with an area designation attached to each. The missing co-ordinates were addressed by checking databases of other years that contained the same area designation and using that co-ordinate. Maps produced in R studio required data to be formatted to decimal degrees in order to accommodate being plotted using the r package ggplot2. A simple conversion formula (degrees + minutes/60 + seconds/3600) was used in Excel to format all co-ordinates to decimal degrees. These data points were rounded by two, in R studio, in order to allow data points in a 2 mile (4.83 km) radius to be aggregated, this also allowed for data to be separated according to longitude (due to east west split of False Bay according to management zones) to visualise spatial patterns of catch. Shapefiles of False Bay were then read into r using shapefiles package and then manipulated and populated with data, using dplyr, ggsn; prettymap and raster packages, in order to show distribution of catch (figure 3.23), distribution of pot deployment (figure 3.24) and CPUE hotspots (figure 3.25).

Analysis of CPUE and the effect of other variables on it were conducted at various scales. Values were brought into the on-board database from the factory weight database in order to fill gaps in the calculation of CPUE. The number of pots and number of octopus, variables, were skewed when individual variable distributions were visualised to check normality and hence removed during these visualisations. The cleaned data was used to produce visualisations for each of the individual variables by plotting in R studio. All non finite values were removed when plotting. Nominal CPUE was calculated using the number of animals caught and the number of pots checked, per line hauled. CPUE was firstly plotted at various temporal scales (Year, Month and Season) to look for trends without considering the effect of Temperature, Depth or Area (figure 3.10). Thereafter these variables were plotted against CPUE in order to detect any relational trends, dependant (figure 3.11 appendix) and independent (figure 3.12, 3.13 & 3.14 appendix) of temporal scales.

Although some change occurred at different temporal scales for temperature and depth the effect on CPUE was not sufficient to warrant further investigation and was omitted from further analysis. Area division showed some effect on CPUE, and was modelled by month. It should be noted that in terms of the management of the resource, False Bay would be viewed as a single area although split into zones. CPUE was then plotted by temporal scales of month and season for each year to determine if any differences could be viewed between years based on month and season, as the variable Year is generally of greatest interest in fisheries modelling, due to the fact that annual CPUE is used to track abundance (Maunder & Punt 2004)

An ANOVA test was used to ascertain if there were differences in the CPUE by month, season and area. This was followed by a Tukey Honest Significant Difference test. .CPUE data was modelled by month using a generalised additive model (GAM) with CPUE the (dependant variable), month (independent variable), by year. The GAM formula used to model the monthly

CPUE as a factor of the year is as follows: gam(CPUE~s(month,bs=”cc”)+as.factor(year). A cyclic cubic spline was used as a smoothing term with 12 knots to account for the values associated with the temporal covariate of month.

Another component of the description of the fishery was the various sizes of *O. vulgaris* recorded from the catch. Sizes were determined by crew, who have been taught how to categorise animals by weight during on-board trips with scientific staff. Animals were grouped as small (< 1Kg), medium (1 – 2Kg) and large (>2Kg) based on individual animal weights recorded on these trips.. Crew became accustomed to visually identifying the different size classes (due to lack of scales without scientific staff) and were found to be generally correct when checked during times with scientific staff on-board. The error of overlap between size classes was expected, but only occurred with new crew. This data was used to track trends in size during the study, in order to determine possible size trends by season and month across all years.

3.3 Results

3.3.1 Description of the fishery

Fishing occurred throughout the study period, with pot retrieval occurring at an average of every 14 days. Fishing occurred in the bay at depths of 4 – 30 m at an average of 15.9 m. Catches landed by the octopus fishing vessel Albatross for the 2014 – 2019 period reached a maximum of 50, minimum of 17 and an average of 29.9 ±12.7 (SD) tons. Although a change in the way in which traps were used, from active (with lures) to passive (without and locked in an open state), occurred in mid-2016 there was little change in the trend of observed CPUE values. Generally, the fishery was seasonal with peak catches in autumn and summer. However, there was also a peak in spring in 2017 (Figure 3.17). The on-board data revealed that the peak mean seasonal CPUE (octopus/pot) was in summer and spring. Proportional percentage values accounted 23.76 % large, 44.51 % medium, 15.36 % small and 16.37% ungrouped, of all animals caught. Peak monthly mean number of large (SD 2.3), medium (SD 6.2) and small (SD 4.3) octopuses based on on-board observations were found in May, February and November (figure 3.18) with a SD of 1.92 octopus/pot between months based on size. While peak seasonal means of large (SD 2.1), medium (SD 4.8) and small (SD 4.5) octopus occurred in autumn, summer and spring (figure 3.19). The seasonal fluctuation in CPUE remained as such, with autumn producing the highest catches by weight. Twenty-four rows of data were removed during number of pots and number of octopus visualisations. The number of pots hauled and octopus caught, pre and post data removal, respectively (Figure

3.8 appendix). A total of 212; 306; 5 and 8 rows of non-finite values were removed for Temperature, Depth, Number Pots and Number Octopus repectively (Figure 3.9 appendix) .

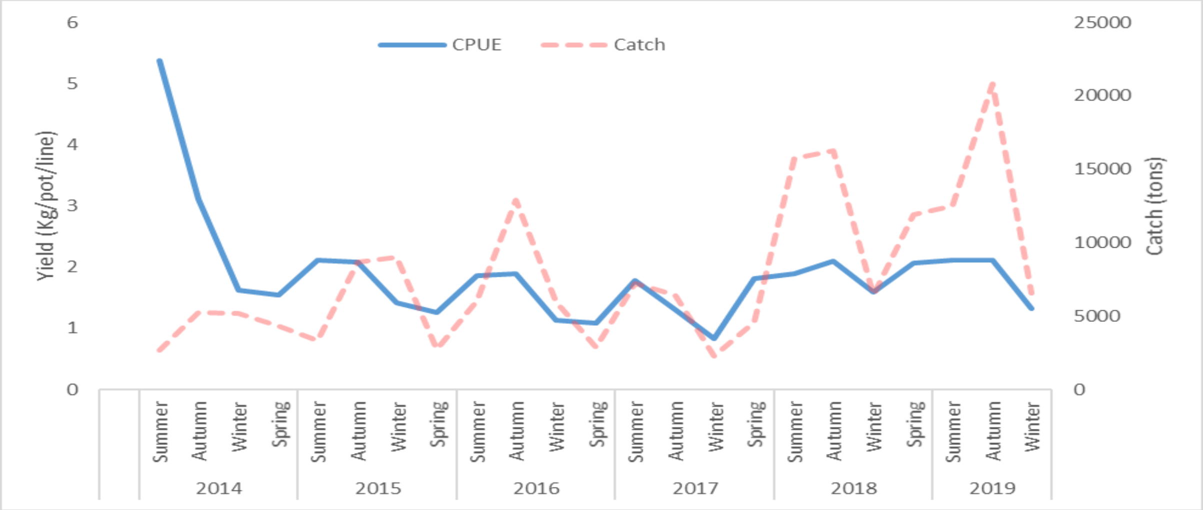

Figure 3.17: Catches (t) and yields (Kg/pot/fishing days) of fishing vessel Albatross for *O. vulgaris* caught in False Bay from 2014 to 2019

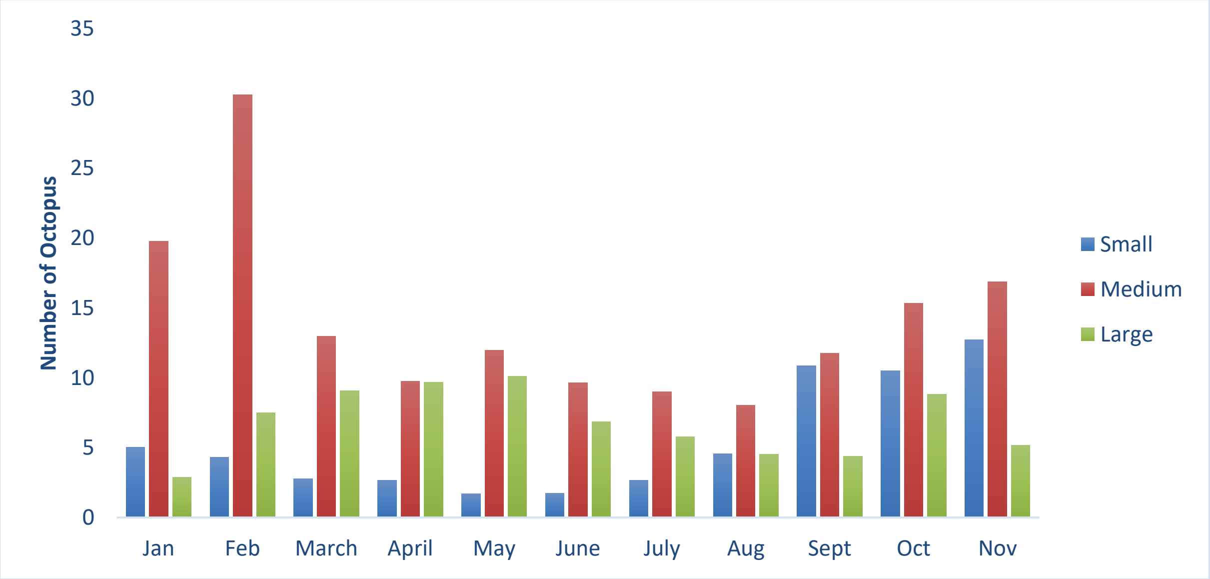

Figure 3.18: Mean number of *O. vulgaris* by size per month

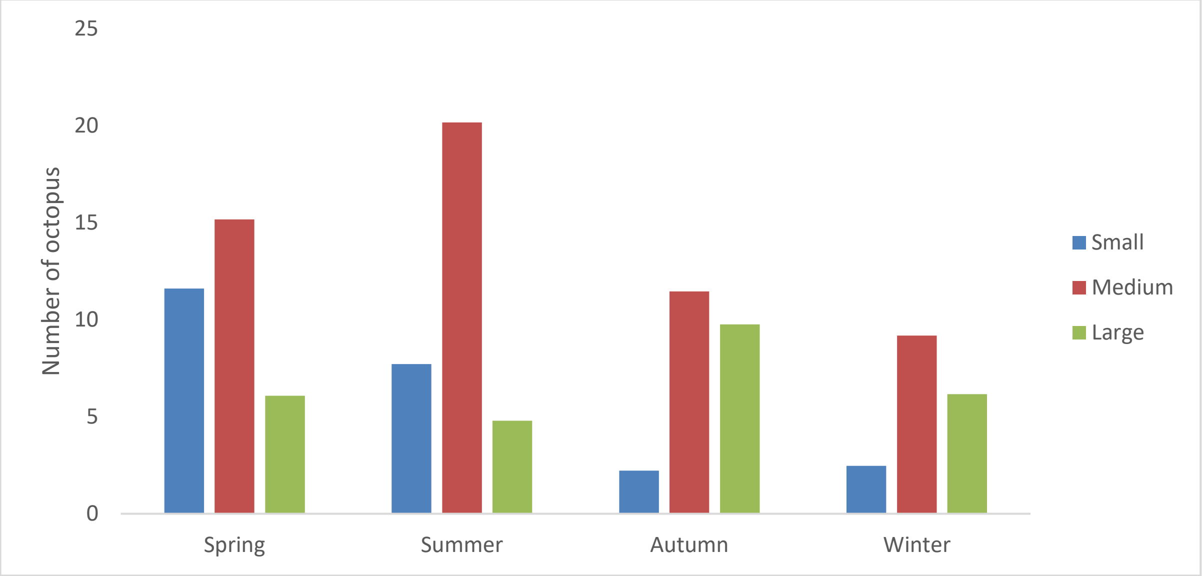

Figure 3.19: Mean number of *O. vulgaris* by size per season

3.3.2 Mapped data

Effort was higher in the west (44114 pots serviced) when compared to the east (20706). A total of 19030 and 20706 octopus were caught in the East and West management zones in False Bay, respectively. Aggregated CPUE showed more hot spots on the west when compared to the east, an indication of the preferred areas of operation used by the fishery in each of the management zones.

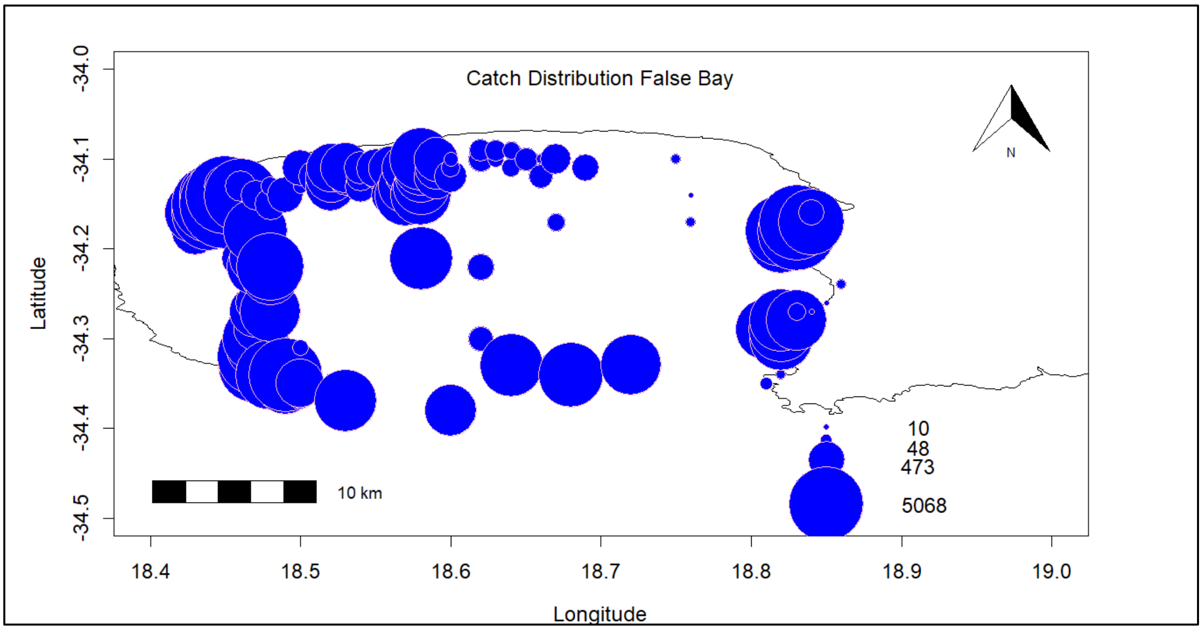

Figure 3.20: Catch density distribution map using consolidated on-board catch database, where dots represent densities of the number of octopus caught in the fishery in False Bay

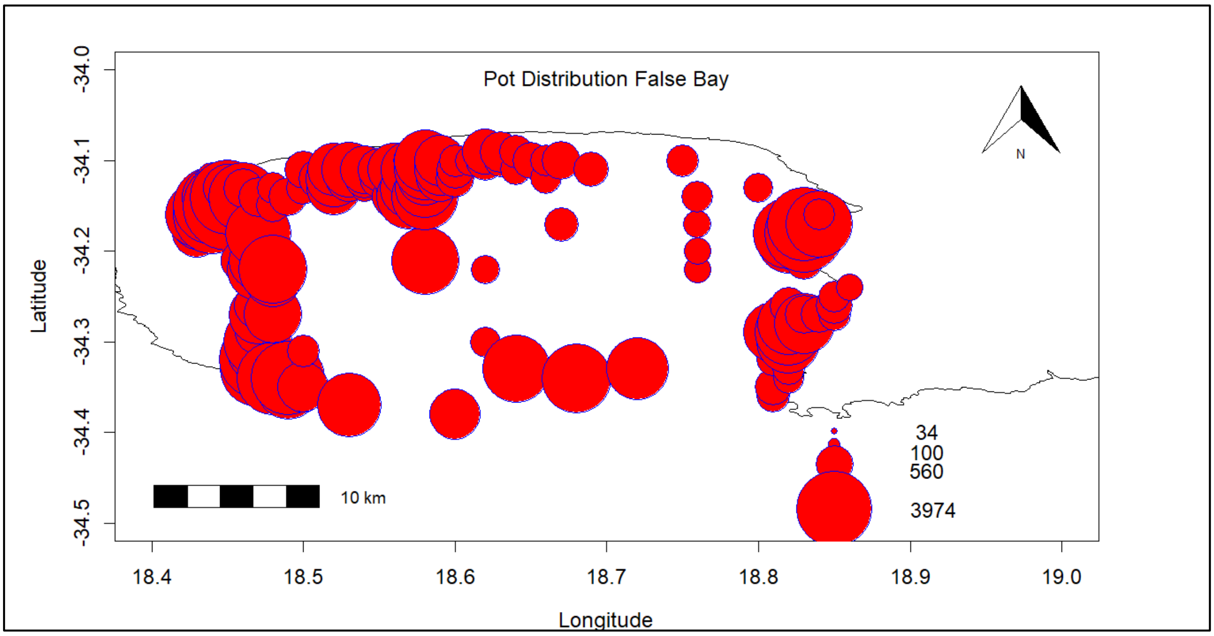

Figure 3.21: Pot density distribution map using consolidated on-board catch database, where dots represent the relative densities of pots in the various areas fished for octopus in False Bay

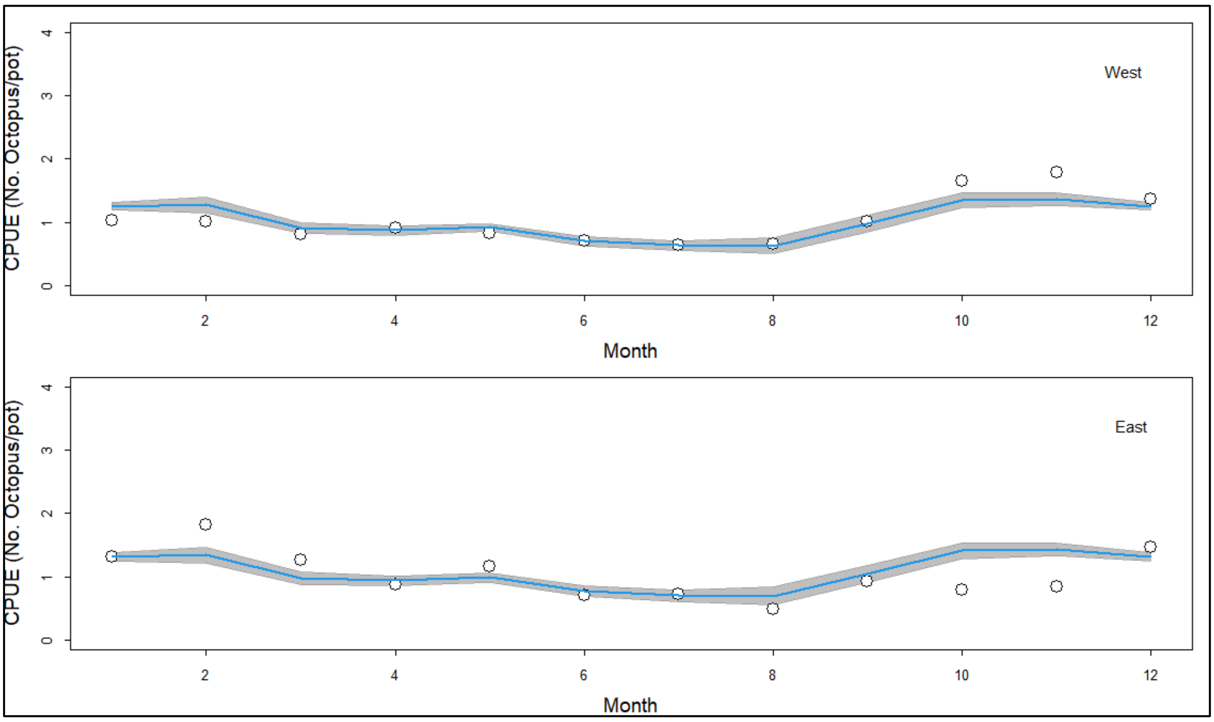

Figure 3.22: GAM modelled mean CPUE per month by area at 95% upper and lower confidence intervals (grey shaded area). Points represent nominal CPUE data of octopus caught in False Bay.

Table 3.3: Fishing Hotspots based on Aggregated CPUE for the octopus fishery in False Bay

False Bay Fishing Areas Hotspots	
West	Kalk Bay
	Fish Hoek
	Glen Cairn
	Millers Point
	Smitswinkel Bay
	Buffels Bay
	Cape Point Area
	Cape Point Deep x4
	Muizenburg
	Strandfontein
	Seal Island
East	Gordons Bay
	Rooi Els
	Rooi Els Deep

Table 3.4: Management zone comparison between CPUE means at 95% family wise confidence levels using TukeyHSD

Comparison	**Difference between means**	**lower confidence limit**	**upper confidence limit**	**Bonferroni adjusted p-values**	**Significant difference ?**
West-East	-0.139333566927099	-0.199546380405934	-0.0791207534482636	5.94680269494496e-06	Y

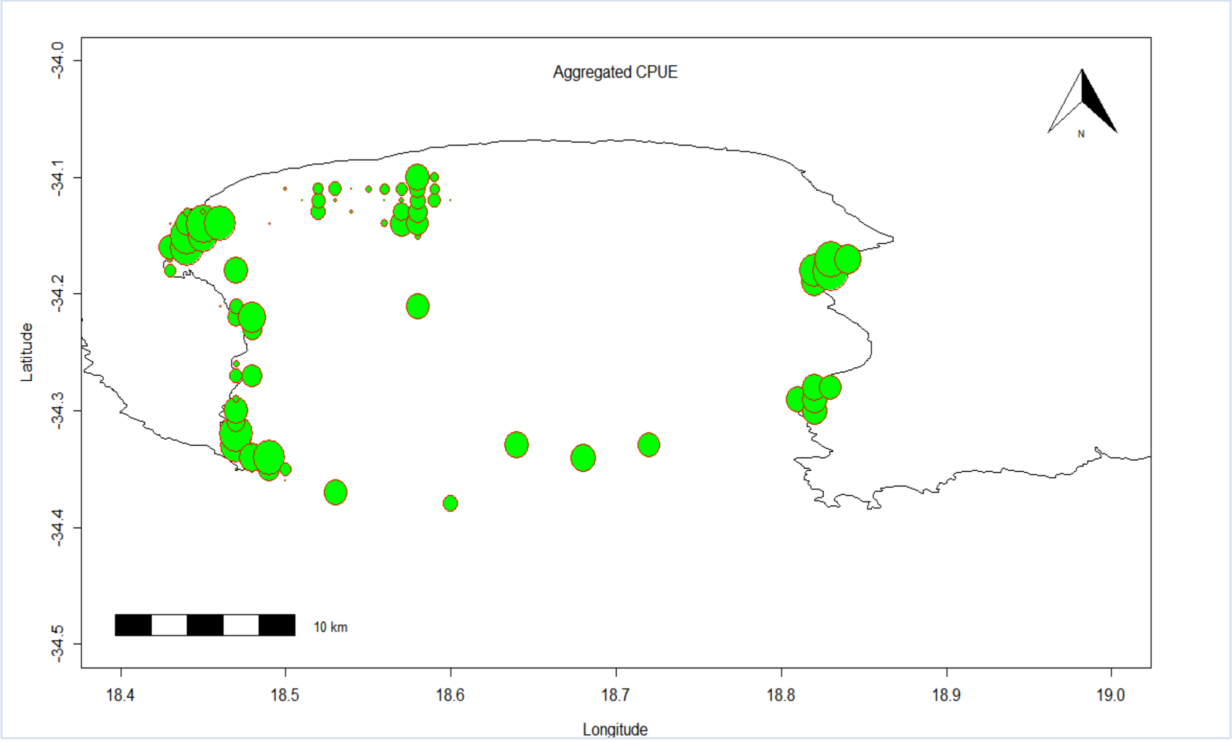

Figure 3.23: Aggregated CPUE of O. vulgaris, to visualise hot spots in False Bay, Western Cape, South Africa, using consolidated on-board data collected between 2016 and 2019

3.3.3 CPUE trends

CPUE (Kg/pot) was not attached to temperature, depth or area and was not used for the production of maps or correlations as data received was not attached to these variables, but rather CPUE (number of octopus/pot/line). However, CPUE (Number of octopus/pot/line), were found to be similar to CPUE (Kg whole weight/pot) (figure 3.24) and produced a correlation coefficient of 0.88 with a positive linear trend (figure 3.25). Since these variables show strong correlation, it was decided that CPUE (number) plotted against temperature, depth and fishing area division would likely show the same trends when plotted with CPUE (weight) as these data were not attached to the factory weight database. It was found that temperature (maximum 22.6°C, minimum 10°C and average 16.26°C) and depth (maximum 30m, minimum 4m and average 15.9m) showed little effect on CPUE over the study period. Area however showed a monthly effect on CPUE and was kept for later analyses.

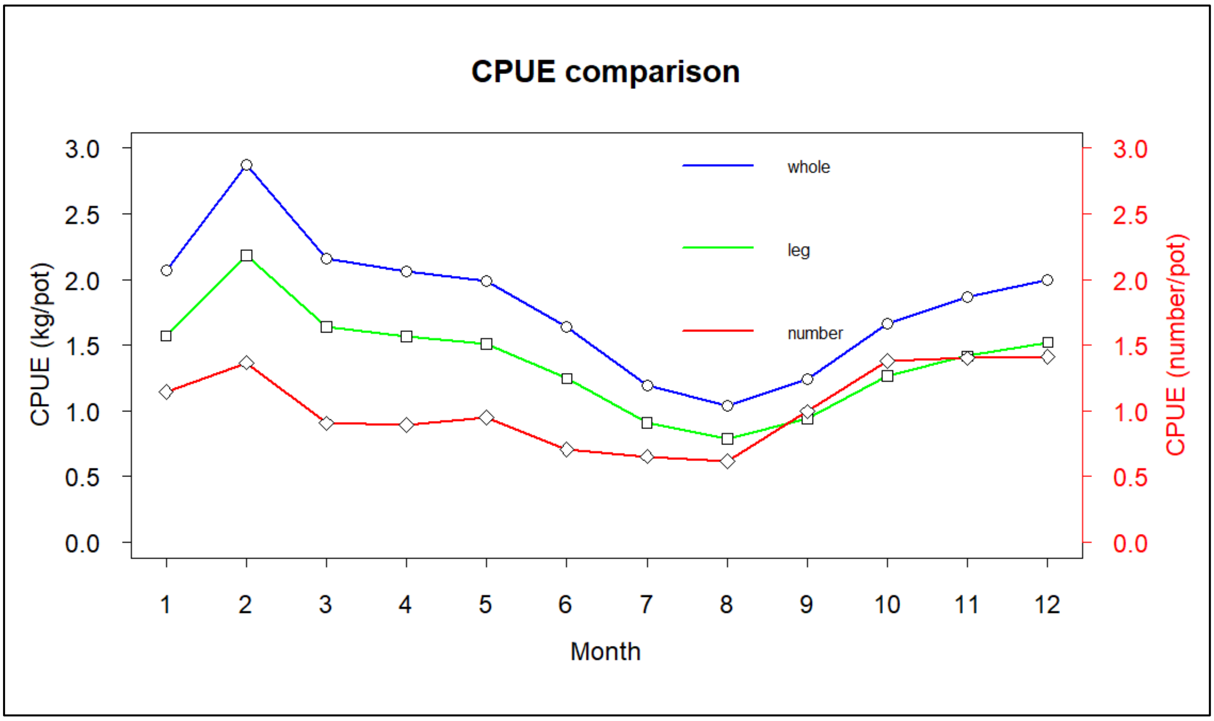

Figure 3.24: Comparisons of CPUE calculated using whole weight, leg weight and number of octopus caught in False Bay. Showing the relatively similar trends between these data.

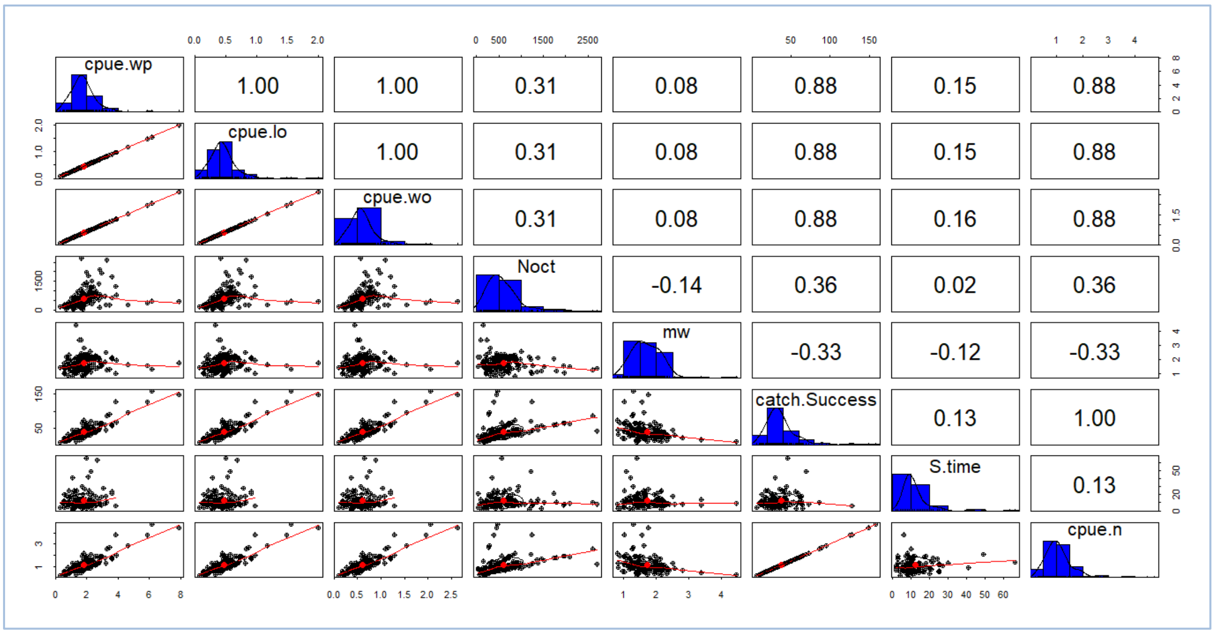

Figure 3.25: Correlation matrix to view the relationship between CPUE by whole weight (cpue.wp) and CPUE by number of octopus caught (cpue.n)

CPUE plotted at different temporal scales revealed an effect by month and season for the study period. Monthly patterns showed mean CPUE at a minimum of 1.14 octopus/pot in January down to 0.61 in August and back up to a maximum of 1.41 in December. Seasonal patterns showed mean CPUE values of 0.92, 1.29, 1.29 and 0.67 octopus/pot with a SD of 0.3 octopus/pot for autumn, spring, summer and winter respectively. CPUE by season, month and management zones showed statistically significant differences at various levels for all years and produced p-values of $< 2^{-16}$ for season and month, with 5.95^{-06} for management fishing zones. The Tukey HSD post hoc analysis provided the statistically significant differences between months (table 3.5 and figure 3.26). Seasonal CPUE comparisons using Tukey HSD was found to be significant for all comparisons except summer and spring, which comparatively, were likely to have statistically similar amounts of fishing and hence CPUE (table 3.6 and figure 3.27).

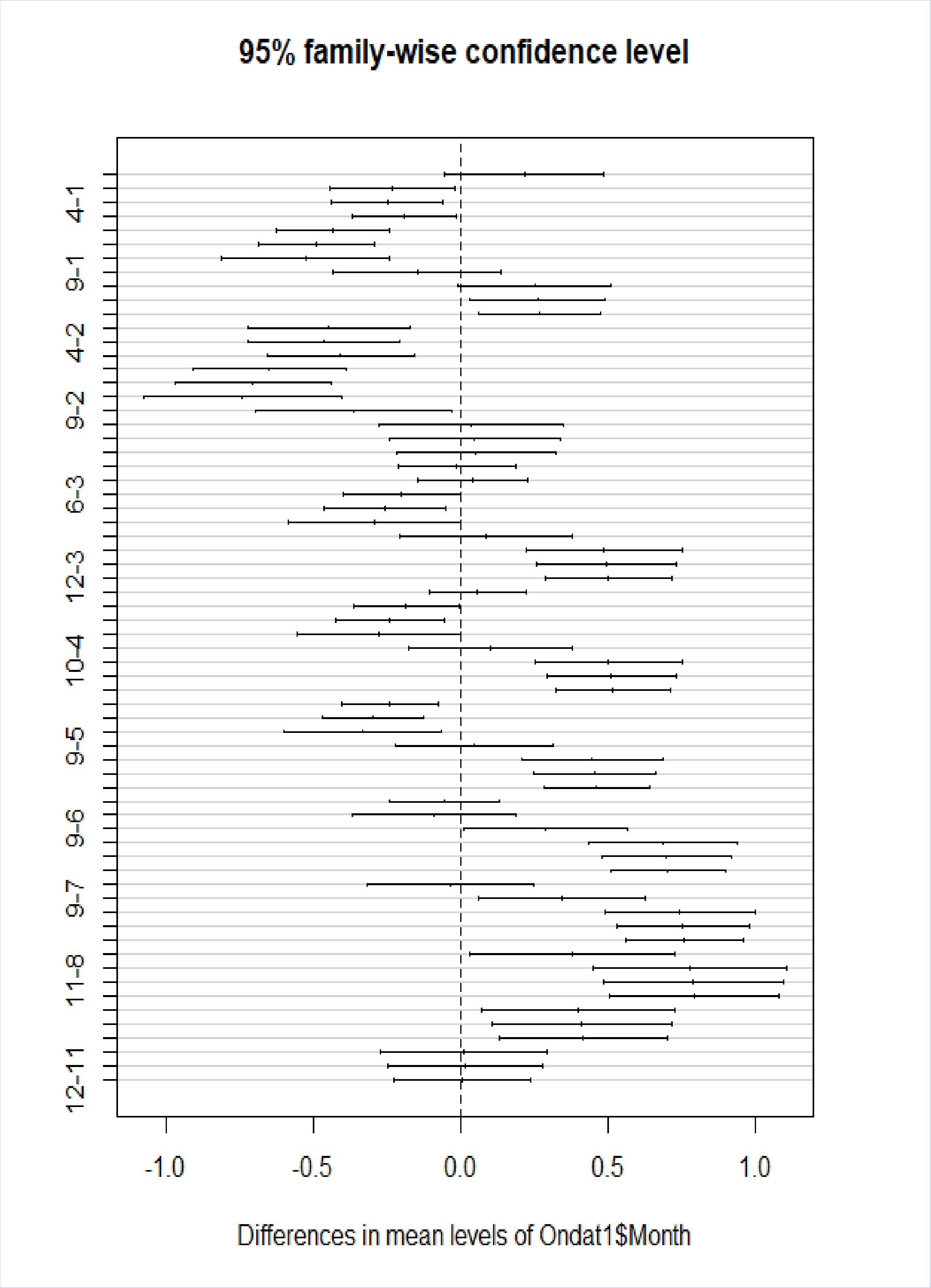

Figure 3.26: Monthly pair wise comparisons of CPUE from month 1 – 12 on the Y axis and means on X axis. Each bar representing a comparison between months January – February (1-2) to December – November (12-11), from the on-board database 1 for month (Ondat1$Month)

Table 3.6: Season wise comparison between CPUE means at 95% family wise confidence levels using TukeyHSD.

Month Compared	**Difference between means**	**lower confidence limit**	**upper confidence limit**	**Bonferroni adjusted p-values**	**Significant difference ?**
Spring-Autumn	0.379597082944255	0.26900358596557	0.49019057992294	0	y
Summer-Autumn	0.364532116633105	0.271544103907656	0.457520129358553	0	y
Winter-Autumn	-0.249710139085571	-0.338301693488356	-0.161118584682787	0	y
Summer-Spring	-0.0150649663111504	-0.135700322784059	0.105570390161758	0.988562963892781	n
Winter-Spring	-0.629307222029826	-0.746587153101681	-0.512027290957972	0	y
Winter-Summer	-0.614242255718676	-0.715090811329913	-0.513393700107439	0	y

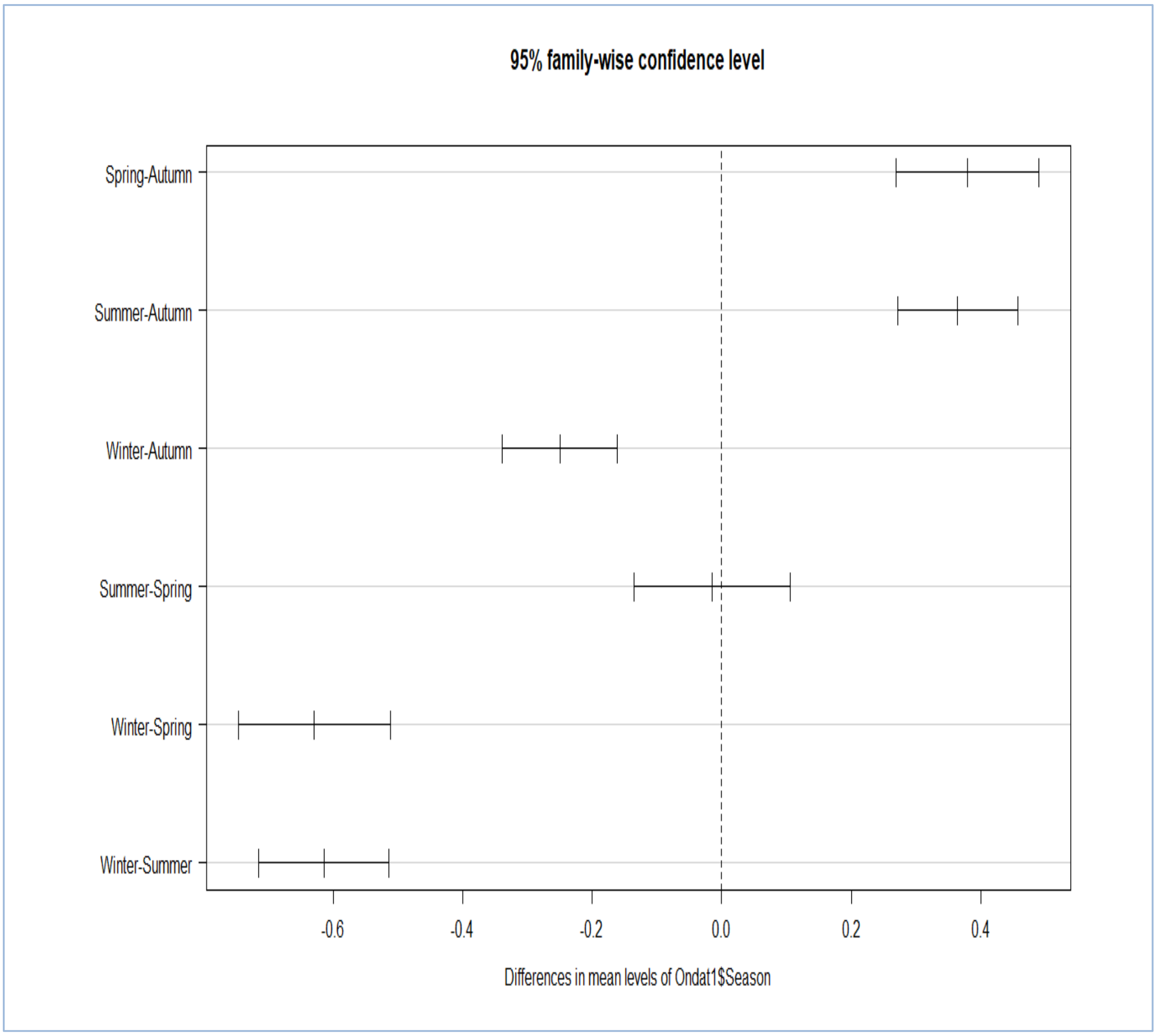

Figure 3.27: Seasonal pair wise comparison of mean CPUE for *O. vulgaris* caught in False Bay showing summer and spring to have no statistical significant difference. From the On-board Database 1 for Season (Ondat1$Season).

3.3.4 Standardised CPUE

The models showed significant effects of month on CPUE within years and between areas. Although significant, the model outputs explain a rather low deviance, as noted below (table 3.7). All models assumed a normal distribution of the data. There was no transformation applied to the predictions based on the link function of “identity”. Standardised CPUE showed a decreasing trend from February to August, thereafter increasing from September to February for both CPUE by number and weight (figure 3.29 and 3.30).

Table 3.7: Summary of, GAM based, temporal models for CPUE, for weight, number and area of *O. vulgaris* caught in False Bay

	Year		**Year**		**Area**	
Parameter	**CPUE (Kg/pot)**		**CPUE (No./pot)**		**CPUE (No./pot)**	
Family	Gaussian		Gaussian		Gaussian	
Link function	Identity		Identity		Identity	
Adjusted R^2	0.353		0.186		0.116	
Deviance explained (%)	38.3		18.9		11.9	
GCV	0.64054		0.44755		0.48551	
	e.d.f.	***p-value***	**e.d.f.**	***p*-value**	**e.d.f.**	***p*-value**
Covariate						
s(Month)	3.304	$<2^{-16}$***	8.274	$<2^{-16}$ ***	8.661	$<2^{-16}$ ***
AVOVA test of models						
as.factor (year)	5	2,87^{-08}***	3	$<2^{-16}$ ***		
as.factor (Areadiv)					1	0.0255*

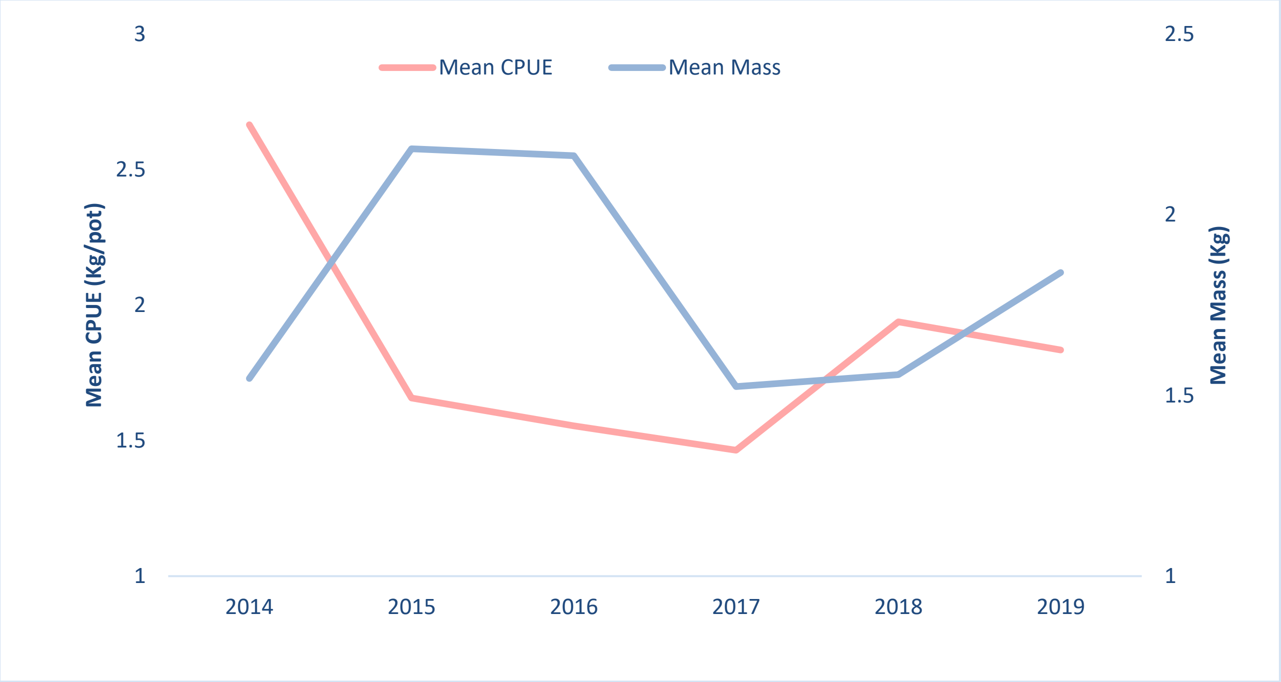

Figure 3.28: Mean CPUE and mean mass comparison for all years in the study for *O. vulgaris* caught in False Bay

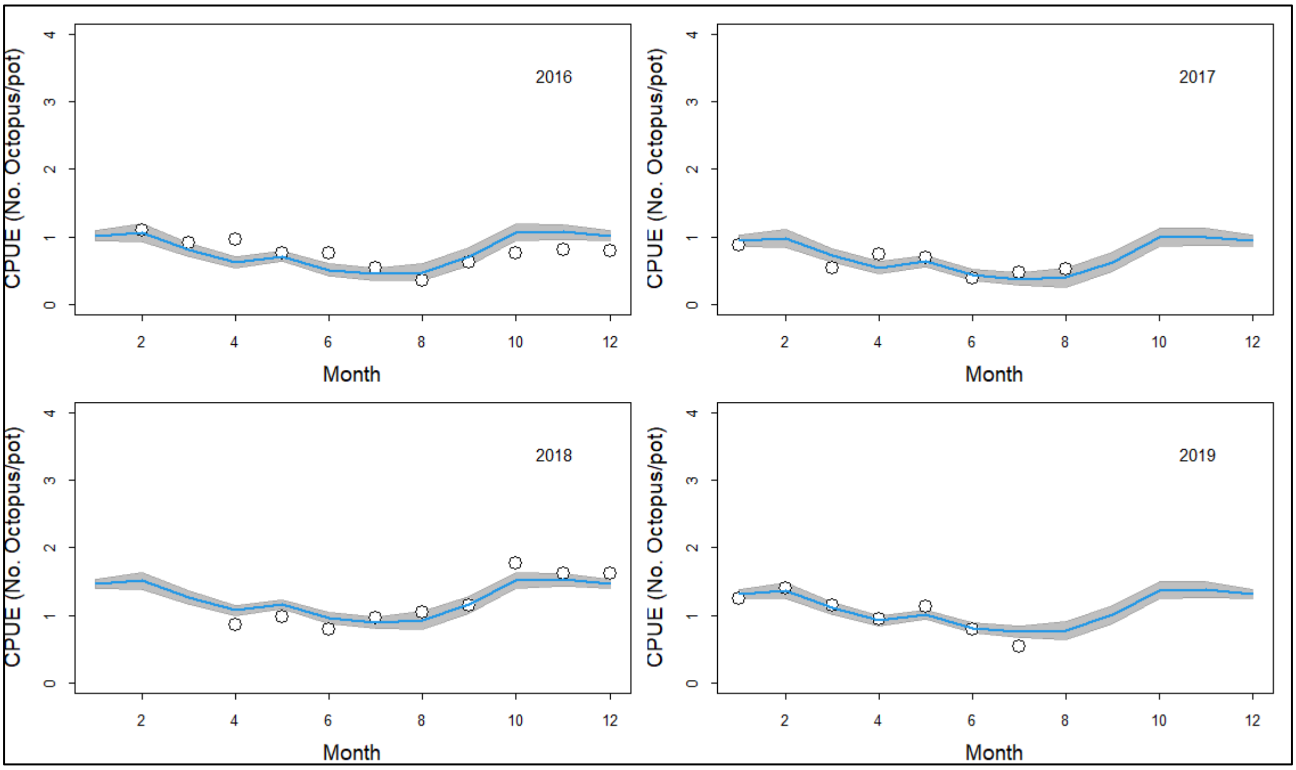

Figure 3.29: GAM modelled mean CPUE (number of octopus/pot/line) (blue line) per month by year at 95% upper and lower confidence intervals (grey shaded area). Points represent un-modelled data for *O. vulgaris* caught in False Bay from 2016 to 2019. Blue line represents the trend of modelled CPUE independent of the effects of monthly variation in catch by number.

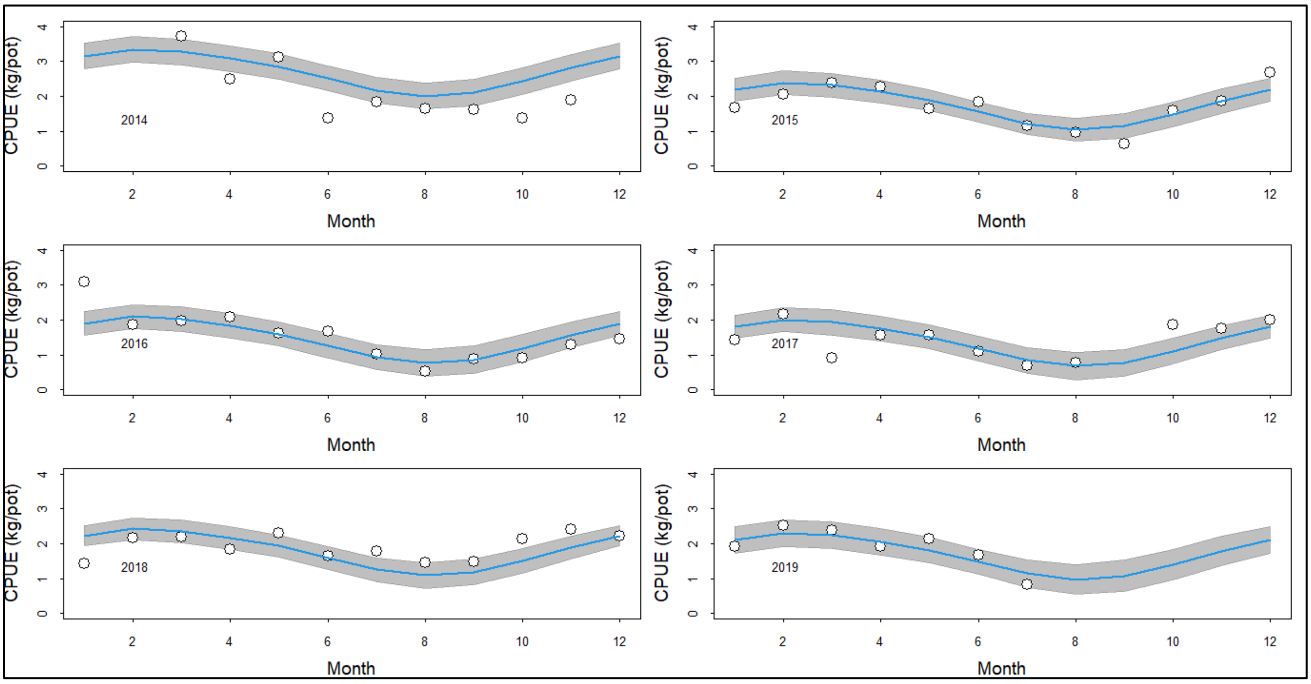

Figure 3.30: GAM modelled mean CPUE (kg/pot/line) (blue line) per month by year at 95% upper and lower confidence intervals (grey shaded area). Points represent un-modelled data for *O. vulgaris* caught in False Bay between 2014 and 2019. Blue line represents the trend of modelled CPUE independent of the effects of monthly variation in catch by weight.

3.4 Discussion

Factory weight data collected, for the False Bay area, during the period from 2014 to 2019 showed a total catch by weight of 178.7 tons. The on-board database revealed a total of 77500 octopuses caught from 2016 to 2019, accounting for 77% (138.6 tons) of the total weight. Although the area had four rights allocated, only a single right holder showed consistent fishing. This same right holder with the vessel Albatross was commissioned to collect gear of the right holder in the east, due to the unfortunate sinking of the vessel associated with the east permit. This occurred for two months and then the east was allocated to the west right holder (per their request to the department), as it was not being utilised. The area was split into east (Monwabisi to Palmiet River) and west (Hoek van die Bobbejaan to Monwabisi). There were a greater number of pots set in the west when compared to the east, which corresponded to the catches for each area. This was an indication of the amount of fishing conducted, were the east side accounted for 32.36% of the total days spent fishing from 2016 to 2019. Distribution of pots and hence catch in the False Bay area were examined in order to determine any trends in the population. Although the percentages of pots checked (figure 3.20), number of octopus caught (figure 3.21) and number of fishing days favour the west, the mean CPUE for the area favoured the East and were found to be, statistically, significantly different between the two management areas. The hot spot map to visually represent aggregated CPUE showed Gordons Bay and Rooi Els, of 17 localities, to have the greatest aggregated CPUE on the east side. Of the 62 localities fished in the west, aggregated CPUE, showed 11 localities as hot spots (table 3.3). This likely relates to the preference of fishers to deploy pots in those areas based on initial catch numbers in the early exploratory stages of the fishery before good data collection. The aggregate function by GPS co-ordinates and CPUE in R studio pooled the data in these areas, due to the likely above mentioned trend by the fisher. However, mean CPUE was found to be, relatively higher in the east at 1.08 octopus/pot/line compared to the west at 0.94 and statistically, significantly different (table 3.4).

Other factors, related to fishing, which may have contributed to effort being applied more in the west, can be attributed to closer distance to mooring harbour in Kalk Bay and to preferred fishing grounds. The tendency of fishers to operate more in some months than others, can possibly be attributed to a combination of monthly weather patterns, availability of crew and fishing may have coincided with increased sightings of tuna on fishing grounds (and thus time spent on tuna grounds between soak times for pots), the vessel also fishes for tuna during the year.

The (per opening) catch rate for False Bay was found to be 43.5% with a mean mass of 1.8 kg per octopus caught. However since each cradle was considered as a single catching unit (pot) the mean number of 1.02 octopus per pot was recorded. This weight of 1.8 kg per a pot was above the mean mass (1kg) for octopus caught in a similar fishery, using the same gear, for *Octopus tetricus* in Western Australia (Hart *et al.* 2018). O. *vulgaris* caught in Izmir Bay, Turkey, using fyke nets, produced catch rates of 98.6% in weight with 96% percent of animals greater than 1 kg (Kara *et al.* 2016). Mean monthly mass for octopus caught in the Mallorca fishery was found to 1.5 kg (Quetglas *et al.* 1998). False Bay seems to produce octopus between 0.5 and 1 kg greater than other comparative fisheries. Other catch rates from fisheries with similar sized octopus were reported at 27.8%, 45 – 90% and 6 – 40% for South Carolina, West Coast of Florida and Spanish Mediterranean respectively (Oosthuizen, 2004). All lower than the 102% per catching unit for False Bay.

Month was found to be the covariate that explained the greatest effect on CPUE, within years, as a consequence of the above mentioned factors. Standardised mean monthly CPUE for each year of the data showed no statistically significant differences between years from 2015 to 2019. However, it should be noted that 2014 showed a significant difference when compared to other years. CPUE values for 2014 may show, statistically, significant difference to other years due to the start of the fishery after a break of 5 years without fishing, where according to (Maunder et al. 2006), as fish are removed from a population the average size of fish and abundance of said population will decrease, before stabilising. This was in fact true for mean nominal CPUE (SD 0.44 Kg/pot) as with modelled CPUE which followed the trend mentioned above, however mean mass (SD 0.31 Kg) did not, and when correlated to CPUE (kg/pot) produced a coefficient of -0.45, a moderately inverse relationship (figure 3.28). The initial low mean mass may indicate that, during the start of the fishery, octopuses out competed for prime den sites made use of the newly introduced pots for dens. The mean mass of octopus caught then increased for the 2015 and 2016 seasons as individuals may have become more accustomed to these new den sights, increasing competition, where larger animals out competed smaller ones . However den sights may not be solely responsible for this. A reduction in intraspecific competition for food may have occurred after the start of the fishery in 2014, allowing individual growth rates to increase, contributing to the higher mean mass in 2015 and 2016. The effect on the population mentioned by (Maunder et al. 2006) of size reduction in a harvested population becomes evident post 2016 (figure 3.28).

After the initial high modelled CPUE values of 2014 the population likely stabilised, hence the lower CPUE by weight for other years all being statistically no different from each other. This trend was not isolated to False Bay, a similar trend was observed in another fishery for octopus, south-west Madagascar, where increases in CPUE were found after a period of no fishing (Benbow *et al.* 2014).

The modelled trend for *O. vulgaris* in the False Bay area alludes to a higher abundance in the spring and summer months when compared to autumn and winter months for all years in the dataset (figure 3.29). The time taken for hatched octopus to reach 50g after settlement is approximately 4 months (Domain et al. 2000), using an approximate 3% increase in body mass per day (Mangold & Boletzky 1973), the time taken for octopus from hatching to 500 g (approximate mean size for small group) is approximately nine months. It can be hypothesized that animals born in summer reach this size by spring, the peak of small recruited size group, to a size of approximately 1.5 Kg (mean medium size) by summer which is the peak of medium sized animals 2 to 3 months later. Large animal group peaked in autumn due to animals reaching >2 Kg in the following months taking approximately 4 weeks to reach a maximum recorded size of 5.1 Kg. The decrease in the number of large animals subsequent to the peak in autumn may be an indication of natural mortality at the end of their expected lifespan of 12 – 24 months. This would explain the higher catches by weight in the summer and autumn months as medium and large animals accounted for the greater proportions of the total recruited population. Winter and Spring months are likely the biological peaks for spawning (highest numbers of small animals found in Spring and Summer), although spawning does occur year round as small animals are found throughout the year, confirming the theory proposed by (Smith and Griffiths 2002). The combined population proportion of medium and small animals are found to be greatest in Spring and Summer. These months show the greatest abundance of octopus based on the modelled dataset of mean monthly CPUE (number of octopus/pot) by year, following a similar trend from 2016 to 2019 (figure 3.29) as modelled CPUE (Kg/pot) (figure 3.30).

After standardisation for the monthly effect on mean CPUE by area the significant difference was reduced to (p-adjusted, 0.0255), therefore based on modelled mean monthly CPUE, the abundance of octopus in each of the management zones shows little difference between months for modelled data. Other trends in the data may be due to factors not collected as part of the data set, of which may be aggregation of food sources and preferred den sites, based on substratum. Which may be a part of the reason for fluctuations in standardised CPUE of octopus caught.

Temperature is considered to be a major contributing factor to the influence on CPUE in other parts of the world and was the primary environmental factor recorded in this study. Although temperature did not show any relational trend with CPUE, it may still be a factor that contributes to the fluctuations in the population in the False Bay area, noted in the graphic representations of the standardised data. In the Canary Islands, environmental variability due to temperature (SST) was found to have an effect on the abundance of *O. vulgaris* (Hernández-García *et al.* 2002; Caballero-Alfonso *et al.* 2010). It was found that a delay between the variables of abundance and SST can be explained by the influence of water temperature on recruitment, by having an effect on the crucial life phases, i.e. paralarvae survival, growth rates, age of juvenile benthic settlement and time of reproductive peaks (Polanco *et al.* 2010). The strongest and most direct statistical significance was found on a seasonal time scale rather than on an inter-annual time scale (Polanco *et al.* 2010). The parameters of temperature and depth recorded during the study period showed no indication of having an influence on CPUE as found in other studies considering temperature, in the form of SST's (Hernández-García et al. 2002; Caballero-Alfonso et al. 2010).

Factors other than water temperature have been found to have a more direct influence on the life cycle of the species, wave height (Lionello and Sanna 2005; Canellas *et al.* 2010; Rozynski 2010), wind driven ocean circulation (Chhak and Moore 2007), upwelling (Demarq and Faure 2000; Faure *et al.* 2000; Otero *et al.* 2016) and rainfall (Chedia *et al.* 2010). There is a strong possibility of, one or a combination of, these factors, in combination with temperature being the driving forces behind the seasonal variations noted in the False Bay population of *O. vulgaris* being caught. This study did not take into account the above mentioned factors, but these must be considered, should any drastic fluctuations in the population occur. Many factors play a role in creating variations in cephalopod populations and should be included when making management decisions. The above mentioned factors together with pH, salinity, predation, substrate, cannibalism and food availability should be considered when making decisions about the management of the fishery as these have the potential to cause fluctuations in octopus populations (Boyle and Boletzky 1996; Rodhouse *et al.* 2014). The purpose of which would be to move towards an ecosystems approach to fisheries management. These factors, related to the crucial life cycle phases of the *O. vulgaris* population in False Bay, have not been recorded. The need to expand on the environmental and biological data sets is necessary to allow for the sustainable utilisation and scientifically informed management of this potential commercial fishery from an environmental standpoint. However there is also a need to consider the socio-economics of the fishery as these will inevitably influence the productivity of the stake holders involved with this fishery.

The type of management framework currently being applied to the fishery is a hybrid system employing both exploratory and experimental strategies. In a purely exploratory framework no limitations on the number of pots being deployed, the number of people fishing, the areas in which to fish, the size of animals being caught and the number of animals caught. This was utilised in the first phase of this fisheries existence to collect a broad data set regarding the target species. The problem with this is that cephalopod populations are susceptible to over fishing (Rodhouse *et al.* 2014), and should the effort being applied to the fishery go unchecked a collapse may have been possible. Collapses in cephalopod fisheries have been reported for various cephalopod species; northern short finned squid in the North Atlantic (O'Dor and Coelho 1993; Dawe *et al.* 2000); Japanese flying squid (Nakata 1993); long finned squid in the North Atlantic (Pierce *et al.* 1994); southern calamari (Hibberd and Pecl 2007); loliginid squids (Hanlon 1998 and Iwata *et al.* 2010); arrow squid in the Norwegian Sea (FIGIS 2011). All these declines or collapses were attributed to a combination of fishing and environmental effects on the target species. Although the *O. vulgaris* population in False Bay may seem robust against fishing pressure, based on current data, constant monitoring is important to prevent any collapses in this exploited species.

3.5 Conclusion

This description of the current fishery, together with standardised CPUE, for *O. vulgaris* in False Bay have provided much needed information regarding the harvested population, which until now has been managed purely from a conservative standpoint. With this new information, adjustments can be made to better current practices. Knowledge on hotspot areas should allow for the better management of areas. Should any drastic reductions in catch occur, this information may be useful in identifying the areas affected within fishing zones and allow management to close said areas without affecting fishing in areas unaffected.

Using standardised CPUE, and population trends, for *O. vulgaris* in the False Bay area, management decisions can be made with a better consideration of the population abundance independent of fishing, which is likely a major cause for the monthly fluctuations in CPUE. This will allow for better management of the resource in the future, and for a more sustainable fishery for all stakeholders. It should be noted that any decisions made would have to be done with more than just the present knowledge regarding the population, which is based primarily on data retrieved from the fishing industry. In order to provide better management advice independent surveys and the collection of many of the data types not included in this study will have to be included in the future, so as to provide sound advice regarding the O. vulgaris population being targeted in South African waters.

Based on standardised CPUE trends, there is no indication that the fishery was being conducted in an unsustainable manor during the study period, with the current precautionary management plan. With the new knowledge of monthly fluctuations in the abundance of the *O. vulgaris* population and the peaks in size proportion in various seasons for the False Bay area, it allows for the adjustment of the current management plan to incorporate size limitations or closed seasons should the need arise due to sudden decreases in the mean size of animals caught or decreases in catch. Size limitations would likely be based on maturity, as males and females were found to be mature from >170 g and 275g respectively (Smith and Griffiths, 2002). Further investigation into the population biology is still required in order to effectively predict actual spawning and maturity peaks, however current information provides the likely trends in spawning.

As management zones are more for managing the fishery and less so the population, the modelled monthly CPUE by area will serve as an indicator in the event of any drastic fluctuations in the population between zones. In terms of the future management of the octopus population in False Bay, it is likely to be managed as a single area with size limitations and possible closed fishing periods. The existing TAE will need to be addressed as currently only a single right holder has been fishing in the bay. Posing the question of what the actual maximum and ideal efforts are for False Bay. Based on current trends an increase in the number of pots deployed would increase catch, but it isn't known how the increase would affect octopus abundance. The current TAE for the area sits at four right holders, each allowed to deploy 6000 pots, which was never achieved in the area. If it is the decision to maintain the current status quo, it will be necessary to reduce the TAE for False Bay by at least half to 12000 pots and two right holders. These steps will likely further aid in the sustainability of the fishery, but will require close monitoring due to the fact that cephalopod populations have seen collapses attributed to over fishing, environmental effects or a combination of the two (Rodhouse *et al.* 2014).

3.6 References

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CHAPTER 4: CONCLUSION

Octopus fishing throughout the globe has shown the species to be a suitable resource for harvest in commercial and artisanal fisheries. The commercial value of the species is also well documented. In order for South Africa to follow suit and utilise this resource sustainably, a solid foundation of knowledge regarding the fishery and resource population is paramount. With this description and the subsequent standardisation of CPUE, the knowledge of the *O. vulgaris* fishery in South Africa has been vastly improved. The methodology used for the False Bay area will allow for application to other areas currently operating, albeit at lower levels of consistency. The changes in fishing practices and innovation in gear design, has put the fishery at an extremely high standard in terms of the mitigation of cetacean entanglement, rarely considered in other long line fisheries in the area.

The South African exploratory fishery for *Octopus vulgaris* has seen marked change over the years, since its inception in 2003. The most notable being the changes in management, number of right holders per management area, TAE in terms of number of pots allowed per right holder and fishing practices related to the orientation of set gear and preferred gear type being used. Although these changes have come about in order to encourage more fishing activity, the results have improved but remain poor as only 5 out 15 applicants showed any form of fishing with only 3 producing data and one producing reliable continuous data, used in this study. False Bay has produced the most reliable consistent data series, with multiple databases for comparisons.

The False Bay *O. vulgaris* population in the area shows the potential to support a commercial operation, as fluctuations in the population, based on standardised CPUE, do not seem to be adversely affected by current fishing practices. Population fluctuations based on nominal CPUE show statistically significant difference between management zones, month and season. However once standardised show no significant differences. Summer and spring seem to be of greatest ecological importance as these seasons produce peaks in the population and possible breeding activity, although breeding is likely to occur throughout the year. In order to confirm breeding activity, a more in depth study of the population biology is required. It should be noted that many factors affect the distribution and population abundance, this needs further examination in the False Bay area.

Temperature, found to be a major contributor to the life cycle of *O. vulgaris,* showed little effect on CPUE, contrary to other areas comparing this relationship. Similarly depth showed little effect on CPUE in the area. Although these factors show little effect on the CPUE other factors such as ph, salinity, substrate, predation, cannibalism and food availability known to effect the population, were not included in this study and may be causative, when considering the CPUE trends and distribution of the population. Although these factors were not considered in the CPUE trends, the population trends based on CPUE can still be used to manage the fishery in a sustainable manor, but need to be considered for future study as any one of these factors may explain any drastic fluctuations in the population independent from fishing. Temperature may also effect the size distribution of the population being caught, as both small and medium animals were caught in the greatest number during the warmer months and make up the largest proportion of the population being caught in False Bay. Current management practices seem to be adequate. However, it should be noted that, the pot limit was set at 6000 pots to be cautious and there is no data currently available to show that this is the optimal or maximum fishing pressure that can be applied to the area. The right allocation for False Bay was set at 4, but only 1 right holder was operating consistently, and should be taken into account when deciding future levels of TAE based on current data. Although not addressed in this thesis the impact of socio-economic factors on the fishery should not be overlooked. In order to adequately deal with the nuances of a complex fishery all aspects need to be addressed. For example, what would be the minimum catch that would still allow the fishery to be economically viable?

CHAPTER 5: RECOMMENDATIONS

Should the conversion from the exploratory fishery to a commercial fishery occur, it is recommended that the number of right holders for the area be reduced to one per management zone, in order to maintain the currents trends which, according to standardised annual CPUE, show no adverse effects to abundance of the population of *O. vulgaris* in False Bay. TAE levels for the number of pots should be adjusted to 10000 pots per fishing zone if the number of right holders is reduced from two to one. This will effectively reduce the TAE per fishing zone by one quarter of what was originally allowed. Current available data, show that the only area that has the ability to produce a sustainable fishery and be converted into a commercial fishery, is False Bay. There is no indication that the current TAE is fully exploiting the species and will need consideration in the future. Other areas should be allowed to continue fishing but under an exemption or short term right, in order to produce the best results in the shortest time frame, to follow the recommendation for False Bay.

A comprehensive study of ecology and biology of *O. vulgaris,* using animals caught in the fishery to assess seasonal biology and environmental impacts on the population needs to be conducted. Temperature data should be collected at the depth at which samples are collected so as to get a better indication of possible localised distributions of size, number and biology at various temperature ranges. Location data should be attached to biological samples so as to view possible distributional trends in the ecology and biology of the target species. Consistent data retrieval and monitoring of the fishery needs to be made a priority as the potential for collapses of cephalopod fisheries is evident in many parts of the world.

Importantly a study on the socio-economic aspects related to the fishery and the influences thereof. As the sustainability of the fisheries is sure to have links with social and economic variables which may influence the ability of right holders to fully utilise their rights in a sustainable way.

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APPENDICES

Appendix A: Methodological graphs and GAM modelled CPUE tables

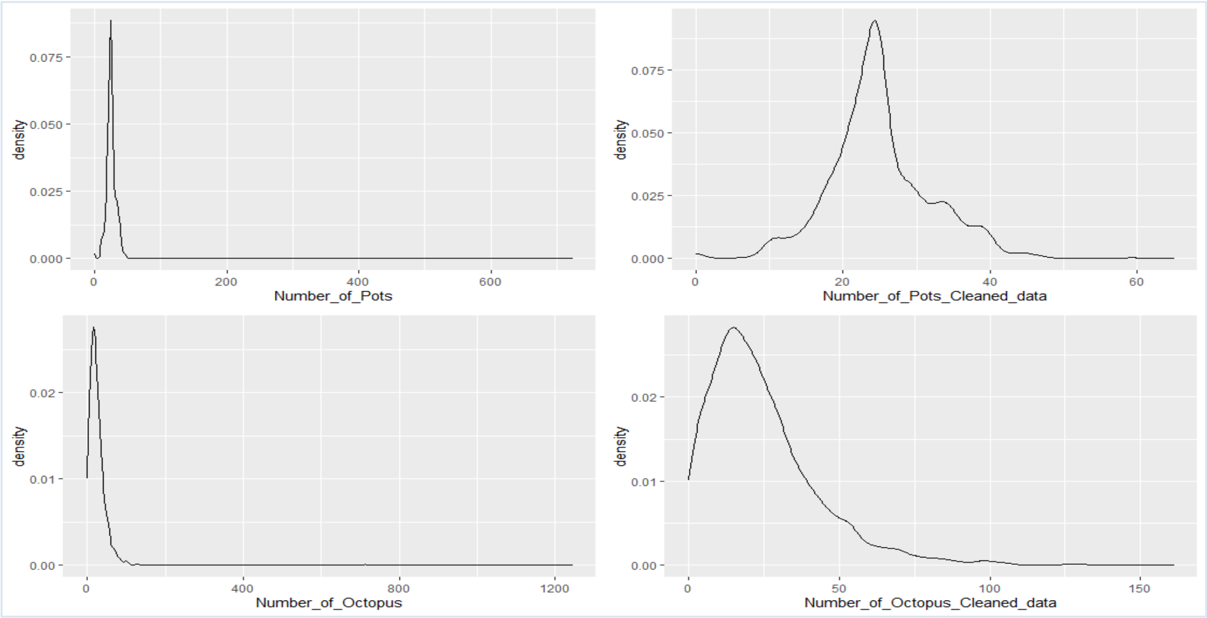

Figure 3.8: Clean data vs Pooled data visualisations of octopus catch data for False Bay

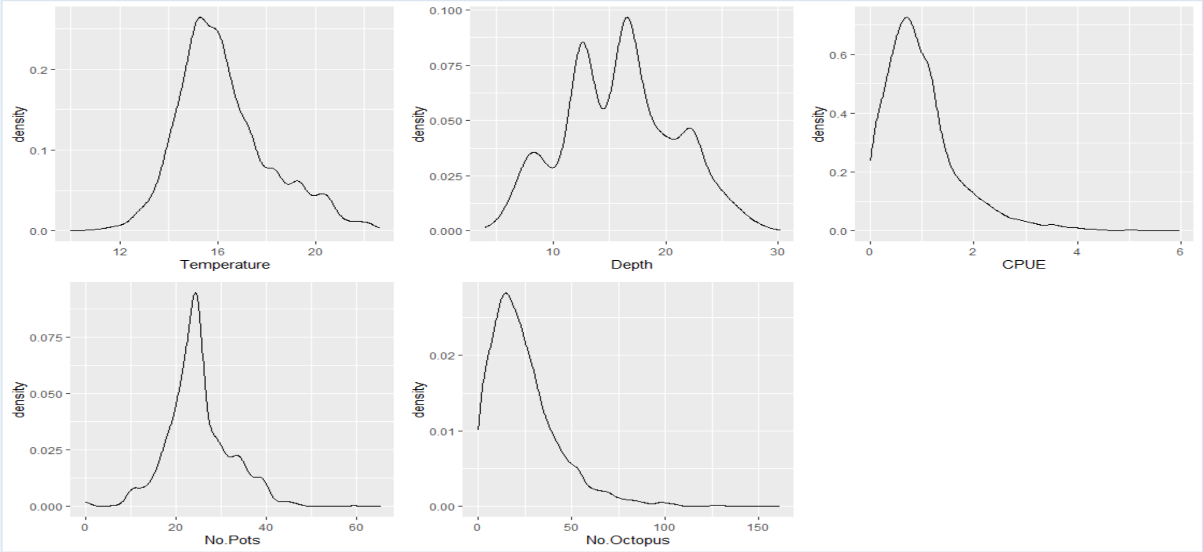

Figure 3.9: Plots showing density distribution of individual variables in order to check normality

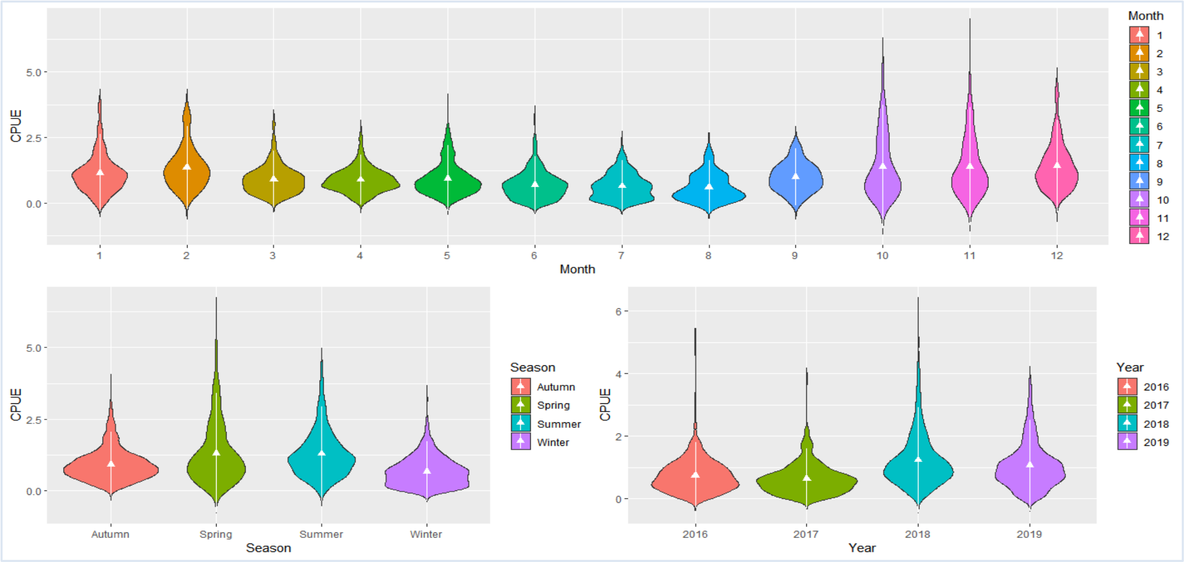

Figure 3.10: Mean CPUE at different temporal scales to view trends by month season and year.

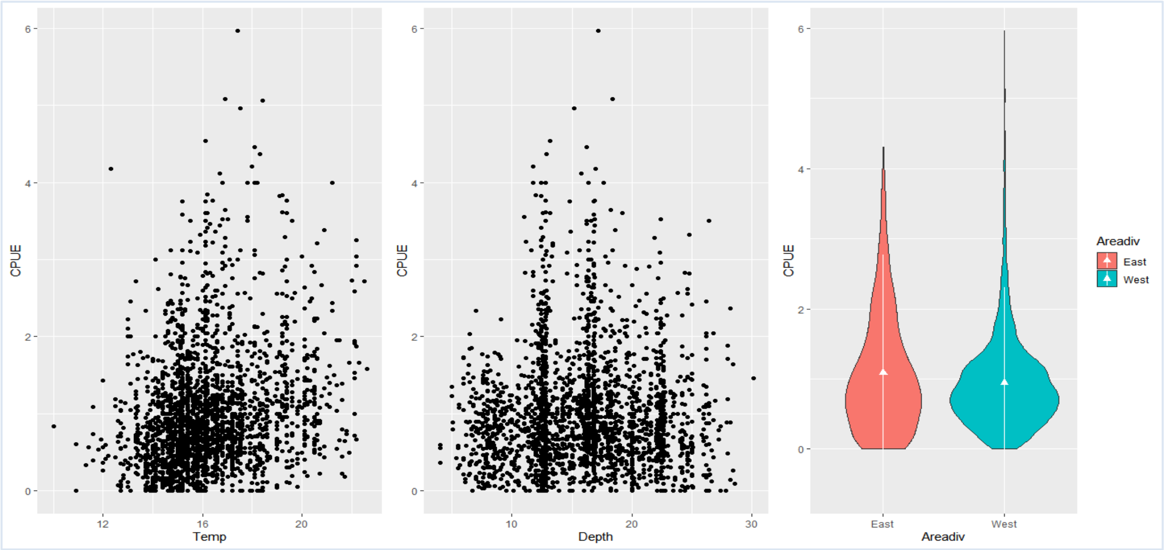

Figure 3.11: CPUE comparisons with Temperature, Depth and Fishing Area Division for all years of octopus catch data in False Bay

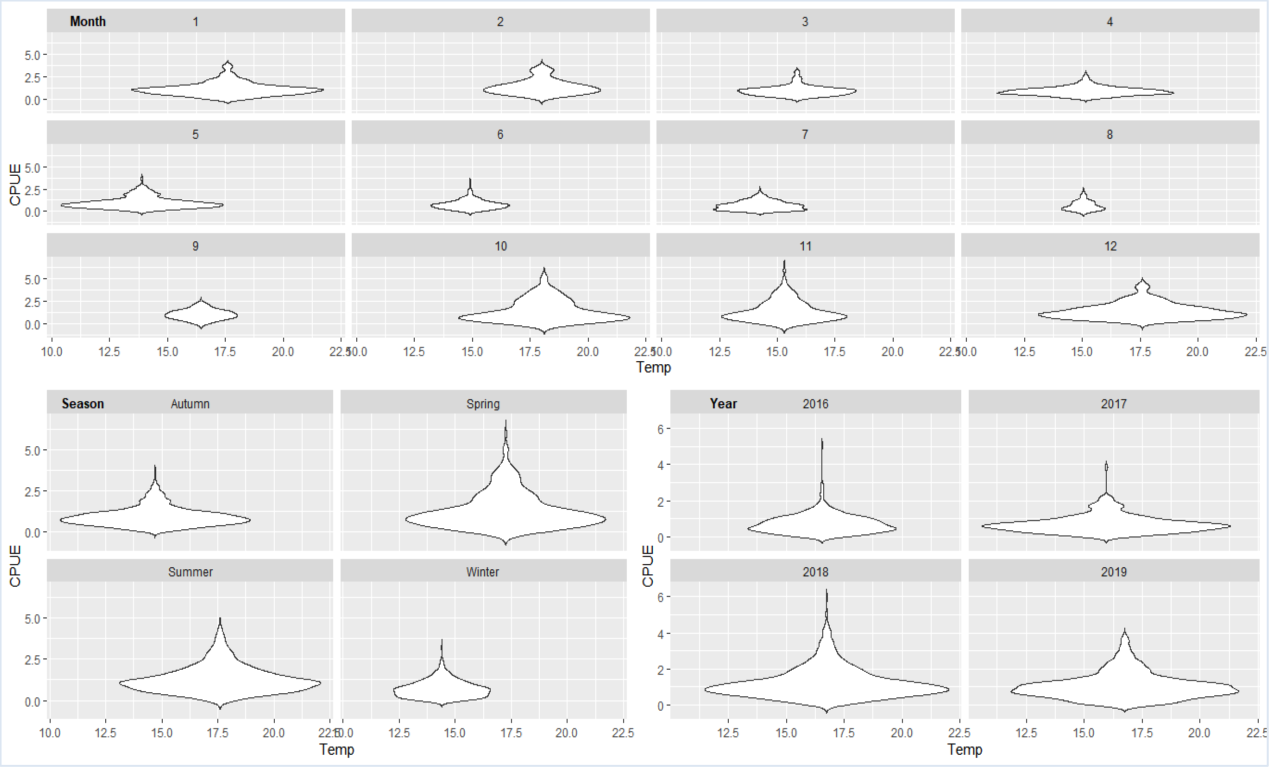

Figure 3.12: CPUE in relation to Temperature at temporal scales of month, season and year.

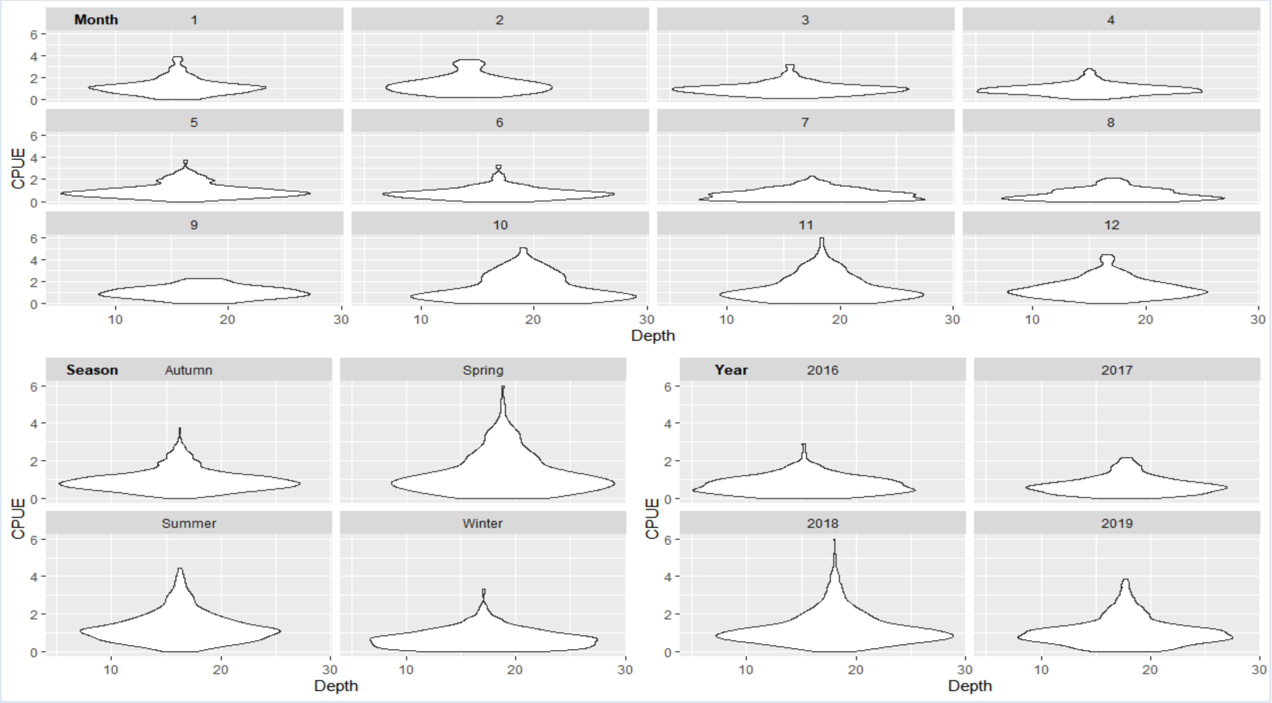

Figure 3.13: CPUE in relation to Depth at temporal scales of month, season and year

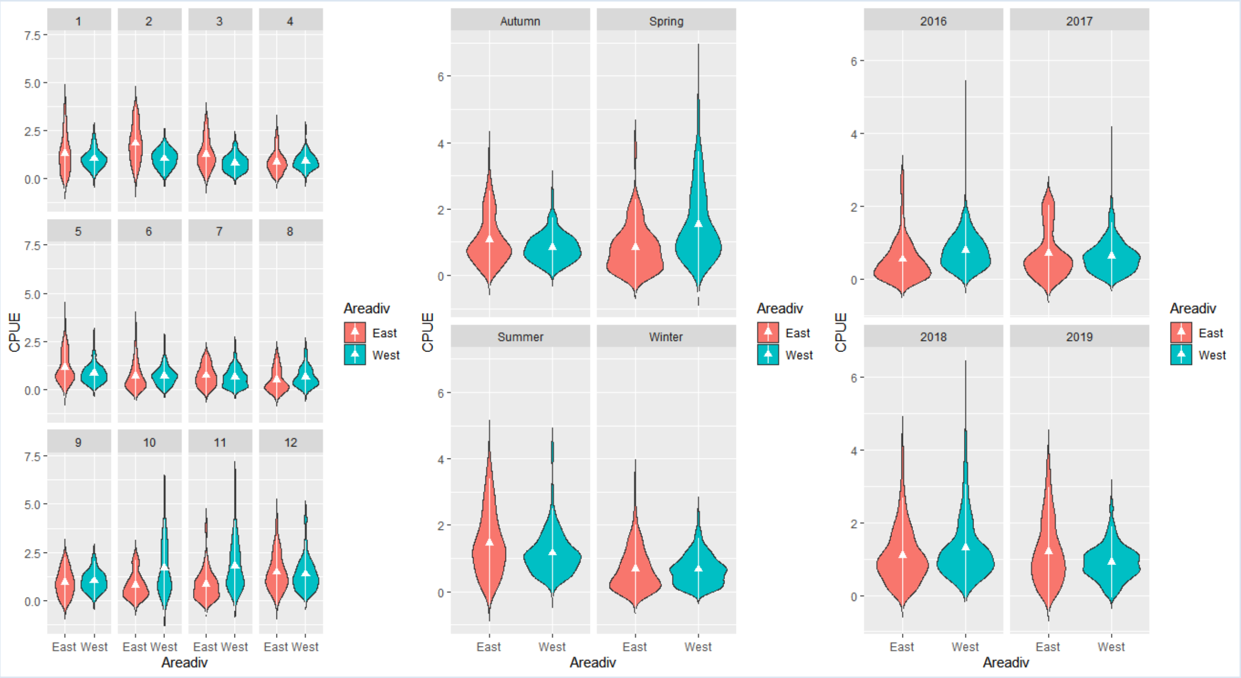

Figure 3.14: CPUE in relation to Fishing Area Division at temporal scales

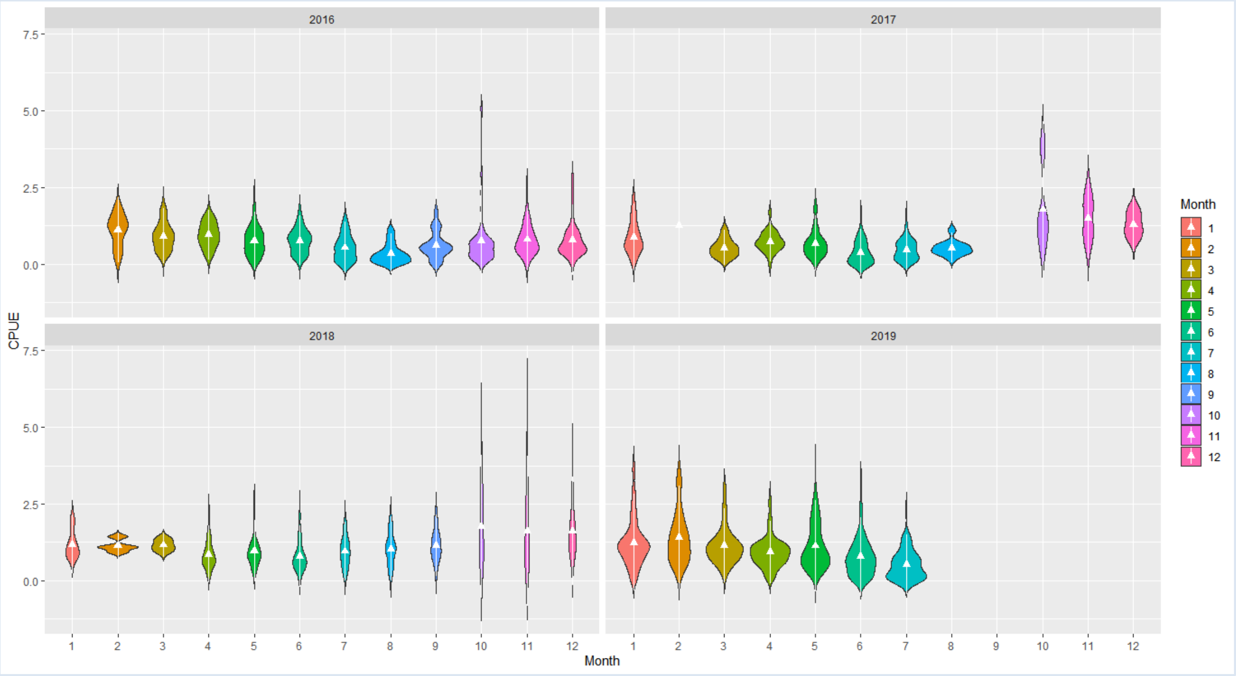

Figure 3.15: CPUE per month trend for each year of on-board catch data collected in False Bay

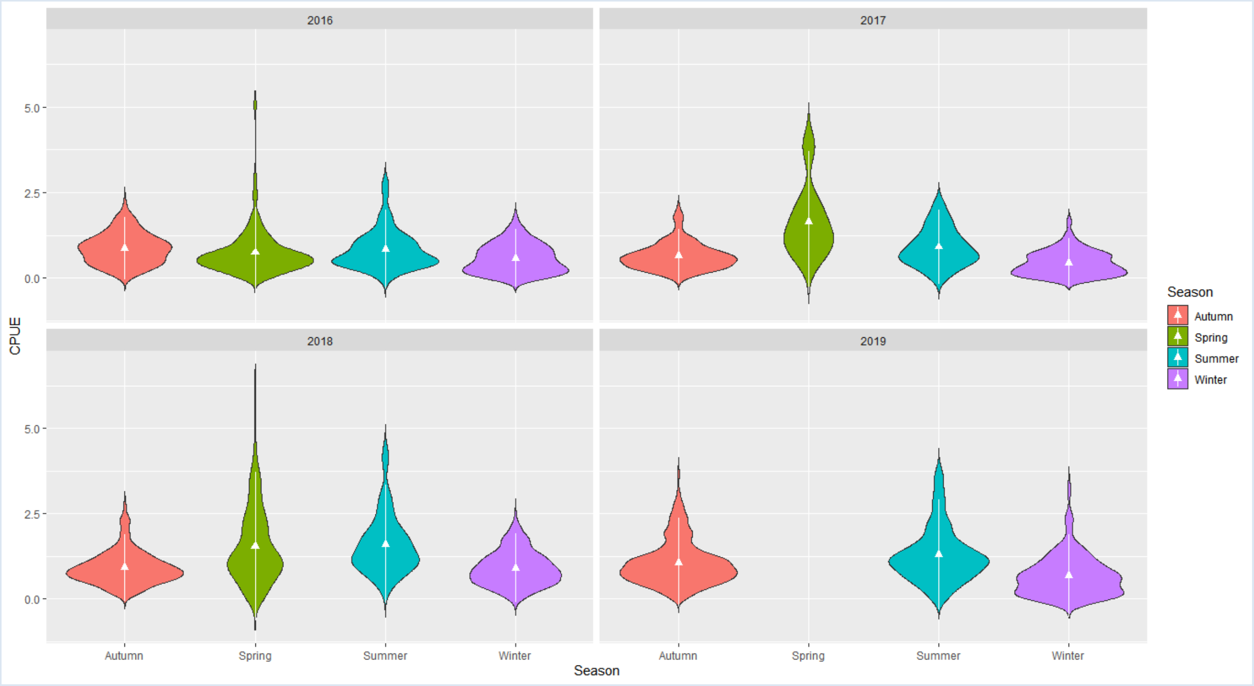

Figure 3.16: CPUE per season for each year of the study for collected on0board catch data

Table 3.5: Month wise comparison between CPUE means at 95% family wise confidence levels using Tukey HSD .

Month Compared	Difference between means	lower confidence limit	upper confidence limit	Bonferroni adjusted p-values	Significant difference ?
Jan - Feb	0.214345963793825	-0.0541034818460244	0.482795409433675	0.273372273511259	n
Jan - March	-0.234463204172346	-0.445828366170087	-0.0230980421746051	0.0152902215881092	y
Jan - April	-0.249638701099696	-0.440354715997536	-0.0589226862018564	0.00116013526447922	y
Jan - May	-0.193338065131087	-0.370617728676655	-0.0160584015855193	0.0189528587656951	y
Jan - June	-0.43565262532812	-0.62713760349823	-0.24416764715801	0	y
Jan - July	-0.491415571868862	-0.688599949653337	-0.294231194084388	0	y
Jan - August	-0.527546512093801	-0.813656007690415	-0.241437016497188	1.21352232929084e-07	y
Jan - Sept	-0.148738894334411	-0.433587152776936	0.136109364108114	0.864863245149496	n
Jan - Oct	0.250815890362904	-0.0087817136015928	0.510413494327401	0.0696263745266517	n
Jan - Nov	0.260536735216315	0.0307888827054062	0.490284587727223	0.0114254163715519	y
Jan - Dec	0.266242991596674	0.060689054232199	0.471796928961149	0.00140704389178903	y
Feb - March	-0.448809167966171	-0.723476752888662	-0.17414158304368	6.38827381704843e-06	n
Feb - April	-0.463984664893522	-0.723097861854494	-0.204871467932549	3.46680404161859e-07	n
Feb - May	-0.407684028924912	-0.657073542753486	-0.158294515096339	6.30707424331689e-06	n
Feb - June	-0.649998589121945	-0.909678290611357	-0.390318887632534	0	y
Feb - July	-0.705761535662688	-0.969671992717865	-0.44185107860751	0	y
Feb- August	-0.741892475887627	-1.07748999371422	-0.406294958061032	0	y
Feb - Sept	-0.363084858128236	-0.697607773394981	-0.0285619428614912	0.0201021807654755	y
Feb - Oct	0.0364699265690789	-0.276831791404076	0.349771644542234	0.999999865358829	n
Feb - Nov	0.0461907714224894	-0.242861345390719	0.335242888235698	0.999996164225954	n
Feb - Dec	0.0518970278028485	-0.218324125452889	0.322118181058586	0.999974488775627	n
March - April	-0.0151754969273502	-0.214548954742889	0.184197960888188	0.99999999862545	n
March - May	0.0411251390412589	-0.145436530252412	0.22768680833493	0.999898020766659	n
March - June	-0.201189421155774	-0.401298576887387	-0.00108026542416151	0.0473503377444969	y
March - July	-0.256952367696516	-0.462521957337254	-0.051382778055778	0.0026190890948693	y
March - August	-0.293083307921455	-0.585035051902134	-0.00113156394077624	0.0480852113046711	y
March - Sept	0.085724309837935	-0.204991544013469	0.376440163689339	0.998356129924124	n
March - Oct	0.48527909453525	0.219256363688958	0.751301825381543	1.79545455836205e-07	y
March - Nov	0.494999939388661	0.258016283673366	0.731983595103955	6.53357368207708e-11	y
March - Dec	0.50070619576902	0.287095338112276	0.714317053425764	0	y
April - May	0.0563006359686091	-0.106495626524799	0.219096898462018	0.993301386400608	n
April - June	-0.186013924228424	-0.364174079256984	-0.00785376919986377	0.031650454137892	y
April - July	-0.241776870769166	-0.426049014125788	-0.0575047274125443	0.0011101146644017	y
April - August	-0.277907810994105	-0.555276135511419	-0.000539486476791529	0.0490311417139797	y
April - Sept	0.100899806765285	-0.175167348674714	0.376966962205284	0.989375900579725	n
April - Oct	0.5004545914626	0.250523681091152	0.750385501834048	3.9359401293737e-09	y
April - Nov	0.510175436316011	0.291409306148731	0.728941566483291	0	y
April - Dec	0.51588169269637	0.3226798160465	0.70908356934624	0	y
May - June	-0.242314560197033	-0.406010991459652	-0.0786181289344144	8.6553416712043e-05	y
May - July	-0.298077506737775	-0.46840572984117	-0.12774928363438	7.5698631873955e-07	y
May - August	-0.334208446962714	-0.602515487895036	-0.0659014060303928	0.00277585781021461	y
May - Sept	0.0445991707966761	-0.222362540092824	0.311560881686176	0.999993911436505	n
May - Oct	0.444153955493991	0.204318718868058	0.683989192119925	1.03228223302665e-07	n
May - Nov	0.453874800347402	0.246717612500386	0.661031988194418	0	y
May - Dec	0.459581056727761	0.279629824697113	0.639532288758409	0	y
June - July	-0.0557629465407421	-0.240830829609463	0.129304936527979	0.997999891644281	n
June - August	-0.0918938867656812	-0.369791504552945	0.186003731021583	0.995439273640517	n
June - Sept	0.286913730993709	0.0103147923857908	0.563512669601627	0.0340236872462412	y
June - Oct	0.686468515691024	0.435950335741155	0.936986695640894	0	y
June - Nov	0.696189360544435	0.476752539945289	0.91562618114358	0	y
June - Dec	0.701895616924794	0.507934632014617	0.895856601834971	0	y
July - August	-0.0361309402249391	-0.317985987987577	0.245724107537699	0.999999623609639	n
July - Sept	0.342676677534451	0.0621019908350455	0.623251364233857	0.00382795810002912	y
July - Oct	0.742231462231766	0.487330421702627	0.997132502760906	0	y
July - Nov	0.751952307085177	0.527524812753256	0.976379801417098	0	y
July - Dec	0.757658563465536	0.558068870232723	0.95724825669835	0	y
Aug - Sept	0.37880761775939	0.0299536089752456	0.727661626543535	0.0199931772059441	y
Aug - Oct	0.778362402456706	0.449802658892257	1.10692214602115	0	y
Aug - Nov	0.788083247310116	0.482559656010847	1.09360683860939	0	y
Aug - Dec	0.793789503690475	0.506017006267481	1.08156200111347	0	y
Sept - Oct	0.399554784697315	0.0720927381051534	0.727016831289477	0.00388760878690686	y
Sept - Nov	0.409275629550726	0.104932810171668	0.713618448929783	0.000693273015612172	y
Sept - Dec	0.414981885931085	0.128463305136998	0.701500466725172	0.000143946064259493	y
Oct - Nov	0.00972084485341052	-0.271129537652937	0.290571227359758	1	n
Oct - Dec	0.0154271012337697	-0.246002206202535	0.276856408670075	0.999999999914192	n
Nov - Dec	0.00570625638035915	-0.226109279198886	0.237521791959605	1	n

Table 2: Modelled mean monthly CPUE by number of weight/pot by year for all years

Month	Year	Predicted Mean CPUE by weight	Standard Error	95% lower control limit	95% upper control limit
1	2014	3.1530393486226	0.187296996534945	2.78593723541411	3.52014146183109
2	2014	3.34717396375362	0.188758291032497	2.97720771332993	3.71714021417732
3	2014	3.27745388576496	0.189161700450961	2.90669695288108	3.64821081864884
4	2014	3.08837636363358	0.188097015335931	2.71970621357515	3.457046513692
5	2014	2.85242070589049	0.185956676709428	2.48794561954001	3.21689579224097
6	2014	2.51831604527447	0.183447043596378	2.15875983982557	2.87787225072337
7	2014	2.1721965184124	0.183376694986739	1.8127781962384	2.53161484058641
8	2014	2.00050150001112	0.189101295102911	1.62986296160941	2.37114003841282
9	2014	2.10641598411658	0.192151666778339	1.72979871723104	2.48303325100212
10	2014	2.4329265539274	0.193071336183098	2.05450673500853	2.81134637284627
11	2014	2.82532919570121	0.193798994121692	2.44548316722269	3.20517522417972
12	2014	3.1530393486226	0.187296996534945	2.78593723541411	3.52014146183109
1	2015	2.19513357089131	0.173972457166882	1.85414755484422	2.5361195869384
2	2015	2.38926818602233	0.174090520685901	2.04805076547797	2.7304856065667
3	2015	2.31954810803367	0.1699570580533	1.9864322742492	2.65266394181814
4	2015	2.13047058590229	0.16272944308675	1.81152087745226	2.44942029435232
5	2015	1.8945149281592	0.154667637043499	1.59136635955394	2.19766349676446
6	2015	1.56041026754319	0.148525274169877	1.26930073017023	1.85151980491615
7	2015	1.21429074068111	0.152655640875331	0.915085684565466	1.51349579679676
8	2015	1.04259572227983	0.167764186650565	0.713777916444721	1.37141352811494
9	2015	1.14851020638529	0.180695515919779	0.794346995182525	1.50267341758806
10	2015	1.47502077619611	0.185695751827718	1.11105710261378	1.83898444977844
11	2015	1.86742341796992	0.1838021894239	1.50717112669907	2.22767570924076
12	2015	2.19513357089131	0.173972457166882	1.85414755484422	2.5361195869384
1	2016	1.90264742818876	0.176929123795383	1.55586634554981	2.24942851082771
2	2016	2.09678204331978	0.177762824513153	1.748366907274	2.44519717936556
3	2016	2.02706196533112	0.178051184824708	1.67808164307469	2.37604228758754
4	2016	1.83798444319973	0.176853069540849	1.49135242689967	2.1846164594998
5	2016	1.60202878545665	0.176405120963734	1.25627474836773	1.94778282254557
6	2016	1.26792412484063	0.177260970429559	0.920492622798697	1.61535562688257
7	2016	0.92180459797856	0.181720281436815	0.565632846362403	1.27797634959472
8	2016	0.750109579577275	0.194281103568184	0.369318616583634	1.13090054257092
9	2016	0.856024063682737	0.202254466692974	0.459605308964508	1.25244281840097
10	2016	1.18253463349356	0.199837451854484	0.790853227858767	1.57421603912834
11	2016	1.57493727526736	0.190562658906458	1.20143446381071	1.94844008672402
12	2016	1.90264742818876	0.176929123795383	1.55586634554981	2.24942851082771
1	2017	1.81846772640565	0.168791465646208	1.48763645373909	2.14929899907222
2	2017	2.01260234153668	0.18035523584982	1.65910607927103	2.36609860380233
3	2017	1.94288226354801	0.184881420802389	1.58051467877533	2.3052498483207
4	2017	1.75380474141663	0.182282250968103	1.39653152951915	2.11107795331411
5	2017	1.51784908367354	0.179353386028822	1.16631644705705	1.86938172029004
6	2017	1.18374442305753	0.179871159421394	0.831196950591598	1.53629189552346
7	2017	0.837624896195458	0.18524143607379	0.47455168149083	1.20069811090009
8	2017	0.665929877794173	0.196943338230192	0.279920934862997	1.05193882072535
9	2017	0.771844361899635	0.197827534948416	0.38410239340074	1.15958633039853
10	2017	1.09835493171045	0.185964531635164	0.733864449705533	1.46284541371537
11	2017	1.49075757348426	0.174142957405737	1.14943737696902	1.83207776999951
12	2017	1.81846772640565	0.168791465646208	1.48763645373909	2.14929899907222
1	2018	2.23071535435227	0.151999874550504	1.93279560023329	2.52863510847126
2	2018	2.4248499694833	0.158480414922966	2.11422835623429	2.73547158273231
3	2018	2.35512989149463	0.163302793047532	2.03505641712147	2.6752033658678
4	2018	2.16605236936325	0.163007406098914	1.84655785340938	2.48554688531712
5	2018	1.93009671162017	0.162860152663571	1.61089081239957	2.24930261084077
6	2018	1.59599205100415	0.165818387620629	1.27098801126772	1.92099609074058
7	2018	1.24987252414208	0.172358737418767	0.912049398801297	1.58769564948286
8	2018	1.07817750574079	0.184678316557123	0.716208005288833	1.44014700619275
9	2018	1.18409198984626	0.18876454139432	0.814113488713389	1.55407049097912
10	2018	1.51060255965707	0.181237263818956	1.15537752257192	1.86582759674223
11	2018	1.90300520143088	0.167805182422349	1.57410704388308	2.23190335897869
12	2018	2.23071535435227	0.151999874550504	1.93279560023329	2.52863510847126
1	2019	2.11667756601063	0.197363858738707	1.72984440288277	2.5035107291385
2	2019	2.31081218114166	0.195945187330169	1.92675961397453	2.69486474830879
3	2019	2.24109210315299	0.194319584634789	1.86022571726881	2.62195848903718
4	2019	2.05201458102161	0.189189034771332	1.6812040728698	2.42282508917342
5	2019	1.81605892327852	0.185543961174883	1.45239275937575	2.17972508718129
6	2019	1.48195426266251	0.187323958526127	1.1147993039513	1.84910922137372
7	2019	1.13583473580044	0.196627508899137	0.750444818358128	1.52122465324274
8	2019	0.96413971739915	0.217062139792651	0.538697923405555	1.38958151139275
9	2019	1.07005420150461	0.229334120635552	0.62055932505893	1.5195490779503
10	2019	1.39656477131543	0.227390698047386	0.950879003142555	1.84225053948831
11	2019	1.78896741308924	0.215578720624971	1.3664331206643	2.21150170551418
12	2019	2.11667756601063	0.197363858738707	1.72984440288277	2.5035107291385

Table 3: Modelled mean monthly CPUE by number of animals/pot by year for all years

Month	Year	Predicted Mean CPUE by number	Standard Error	95% lower control limit	95% upper control limit
1	2016	1.0081407321779	0.0420954991608008	0.925633553822728	1.09064791053307
2	2016	1.10579076908205	0.0625465044332799	0.983199620392821	1.22838191777128
3	2016	0.7685315276647	0.0456023730674322	0.679150876452533	0.857912178876867
4	2016	0.633801455802719	0.0424123864617501	0.550673178337689	0.716929733267749
5	2016	0.707406787721219	0.0414147901437534	0.626233799039462	0.788579776402976
6	2016	0.510602293157939	0.044624886272554	0.423137516063733	0.598067070252145
7	2016	0.449154375132734	0.0468907100189867	0.35724858349552	0.541060166769948
8	2016	0.440186105503486	0.0640777191480834	0.314593775973243	0.56577843503373
9	2016	0.739498698790784	0.0596889682175632	0.622508321084361	0.856489076497208
10	2016	1.08696770869889	0.0591500034787227	0.971033701880593	1.20290171551719
11	2016	1.10867706957554	0.0556266358354655	0.999648863338031	1.21770527581306
12	2016	1.0081407321779	0.0420954991608008	0.925633553822728	1.09064791053307
1	2017	0.952424449874434	0.0436429088712701	0.866884348486744	1.03796455126212
2	2017	1.05007448677859	0.0640027530771613	0.92462909074735	1.17551988280982
3	2017	0.712815245361236	0.049039324955322	0.616698168448805	0.808932322273667
4	2017	0.578085173499255	0.0443669889530281	0.49112587515132	0.66504447184719
5	2017	0.651690505417755	0.0421390585847874	0.569097950591571	0.734283060243938
6	2017	0.454886010854475	0.0459118849936098	0.364898716267	0.54487330544195
7	2017	0.393438092829269	0.0477681311173241	0.299812555839314	0.487063629819224
8	2017	0.384469823200022	0.0698097333260792	0.247642745880907	0.521296900519137
9	2017	0.68378241648732	0.0671865924203299	0.552096695343474	0.815468137631167
10	2017	1.03125142639543	0.065935233042999	0.902018369631148	1.1604844831597
11	2017	1.05296078727208	0.0617403419339009	0.931949717081634	1.17397185746253
12	2017	0.952424449874434	0.0436429088712701	0.866884348486745	1.03796455126212
1	2018	1.44816610212278	0.0350937698738712	1.37938231316999	1.51694989107557
2	2018	1.54581613902693	0.0633133337580039	1.42172200486125	1.66991027319262
3	2018	1.20855689760958	0.0462506602885508	1.11790560344402	1.29920819177514
4	2018	1.0738268257476	0.0377373655670869	0.999861589236113	1.14779206225909
5	2018	1.1474321576661	0.0360818590076354	1.07671171401114	1.21815260132107
6	2018	0.950627663102823	0.0420696742630665	0.868171101547213	1.03308422465843
7	2018	0.889179745077618	0.0436475757778883	0.803630496552956	0.974728993602279
8	2018	0.88021147544837	0.0634389468558786	0.755871139610848	1.00455181128589
9	2018	1.17952406873567	0.0573643868447898	1.06708987051988	1.29195826695146
10	2018	1.52699307864377	0.0544424038302467	1.42028596713649	1.63370019015106
11	2018	1.54870243952043	0.0503911114901885	1.44993586099966	1.6474690180412
12	2018	1.44816610212278	0.0350937698738713	1.37938231316999	1.51694989107557
1	2019	1.3100571832914	0.0353596465483151	1.2407522760567	1.3793620905261
2	2019	1.40770722019555	0.0556794401422703	1.2985755175167	1.5168389228744
3	2019	1.0704479787782	0.040729901071805	0.990617372677464	1.15027858487894
4	2019	0.935717906916221	0.0366577227284573	0.863868770368445	1.007567043464
5	2019	1.00932323883472	0.0330922356631686	0.944462456934911	1.07418402073453
6	2019	0.812518744271441	0.0409821219285801	0.732193785291424	0.892843703251458
7	2019	0.751070826246236	0.0445497019444213	0.66375341043517	0.838388242057301
8	2019	0.742102556616988	0.0677330580598228	0.609345762819736	0.874859350414241
9	2019	1.04141514990429	0.0637062069634721	0.916550984255881	1.16627931555269
10	2019	1.38888415981239	0.0619934393089448	1.26737701876686	1.51039130085792
11	2019	1.41059352068905	0.0581891823632623	1.29654272325705	1.52464431812104
12	2019	1.3100571832914	0.0353596465483151	1.2407522760567	1.3793620905261

Table 4: Modelled mean monthly CPUE by number of animals/pot by management area division

Month	False Bay Area division	Predicted Mean CPUE by weight	Standard Error	95% lower control limit	95% upper control limit
1	West	1.25270812455386	0.0333026487904575	1.18743493292456	1.31798131618315
2	West	1.26373180924931	0.0575367173468155	1.15095984324955	1.37650377524907
3	West	0.928739241956998	0.0397062623911822	0.850914967670281	1.00656351624372
4	West	0.852715805415706	0.0343412593886205	0.78540693701401	0.920024673817402
5	West	0.928817423918676	0.0317252184188203	0.866635995817788	0.990998852019564
6	West	0.691735515544522	0.0376741192305357	0.617894241852672	0.765576789236372
7	West	0.635452643534708	0.0403032594976487	0.556458254919317	0.7144470321501
8	West	0.620089666873767	0.0633044592629396	0.496012926718405	0.744166407029129
9	West	0.974602035397882	0.0579054118230678	0.86110742822467	1.0880966425711
10	West	1.36507105720169	0.0558732132053897	1.25555955931912	1.47458255508425
11	West	1.37221841864021	0.0521994412985661	1.26990751369502	1.4745293235854
12	West	1.25270812455386	0.0333026487904575	1.18743493292456	1.31798131618315
1	East	1.31873996905559	0.0352589478928072	1.24963243118569	1.38784750692549
2	East	1.32976365375105	0.0599881033372638	1.21218697121001	1.44734033629208
3	East	0.994771086458735	0.0445721642246426	0.907409644578435	1.08213252833903
4	East	0.918747649917442	0.0380941211119389	0.844083172538042	0.993412127296842
5	East	0.994849268420413	0.0349189074787977	0.926408209761969	1.06329032707886
6	East	0.757767360046258	0.0434790052111334	0.672548509832437	0.842986210260079
7	East	0.701484488036445	0.0468148936680622	0.609727296447043	0.793241679625847
8	East	0.686121511375503	0.0669482330536904	0.55490297459027	0.817340048160736
9	East	1.04063387989962	0.0614717624781027	0.920149225442537	1.1611185343567
10	East	1.43110290170342	0.0588783987954574	1.31570124006433	1.54650456334252
11	East	1.43825026314195	0.0538646898468954	1.33267547104203	1.54382505524186
12	East	1.31873996905559	0.0352589478928072	1.24963243118569	1.38784750692549

Appendix B: Statistical Coding in R studio

```
setwd("F:/Octopus data/R")
 getwd()


#read in databases
 Ondat<-read.csv("Onbrd.csv")
 Ondat1<-read.csv("Onbrd1.csv")
 trend<-read.csv("CPUE.mytrend.csv")
 trend1<-read.csv("CPUE.mytrend1.csv")
 trendar<-read.csv("CPUE.area.csv")


# load required libraries
library(ggplot2)
library(ggpubr)
library(dplyr)
library(gridExtra)
library(cowplot)



 ### data check ###
str(Ondat)
str(Ondat1)
 names(Ondat)
 names(Ondat1)
 summary(Ondat)
summary(Ondat1)


Ondat$Year<-as.factor(Ondat$Year)
 Ondat$Month<-as.factor(Ondat$Month)
 Ondat1$Year<-as.factor(Ondat1$Year)
 Ondat1$Month<-as.factor(Ondat1$Month)
```

```
trend$year<-as.factor(trend$year)
trend1$year<-as.factor(trend1$year)
trendar$Month<-as.factor(trendar$Month)
trendar$Areadiv<-as.factor(trendar$Areadiv)

# Pool data according to GPS co-ordinates
Ondat$Areadiv[Ondat$Long.DD < 18.65]<-'West'
Ondat$Areadiv[Ondat$Long.DD >= 18.65]<-'East'
Ondat1$Areadiv[Ondat1$Long.DD < 18.65]<-'West'
Ondat1$Areadiv[Ondat1$Long.DD >= 18.65]<-'East'
names(Ondat)
names(Ondat1)

### Data visualisation ###
Temperature<-Ondat1$Temp
#Change to visualize continuous, single variable distribution i.e. N.Pots , CPUE, Temp
Depth<-Ondat1$Depth
CPUE<-Ondat1$CPUE
Number_of_Pots_Cleaned_data<-Ondat$N.Pots
Number_of_Octopus_Cleaned_data<-Ondat$N.Octopus
Number_of_Pots<-Ondat1$N.Pots
Number_of_Octopus<-Ondat1$N.Octopus
x1<-ggplot(Ondat1,aes(Temperature))+geom_density(kernel="gaussian")
x2<-ggplot(Ondat1,aes(Depth))+geom_density(kernel="gaussian")
x3<-ggplot(Ondat1,aes(CPUE))+geom_density(kernel="gaussian")
x4<-ggplot(Ondat,aes(Number_of_Pots_Cleaned_data))+geom_density(kernel="gaussian")
x5<gplot(Ondat,aes(Number_of_Octopus_Cleaned_data))+geom_density(kernel="gaussian")
x6<-ggplot(Ondat1,aes(Number_of_Pots))+geom_density(kernel="gaussian")
x7<-ggplot(Ondat1,aes(Number_of_Octopus))+geom_density(kernel="gaussian")
grid.arrange(x1,x2,x3,x4,x5, nrow = 2)
```

```
 grid.arrange(x6,x4,x7,x5, nrow = 2)

 ggdensity(Ondat1$CPUE, fill = "lightgray")
 ggqqplot(Ondat1$CPUE)

 #quick check on distribution
    u=1.5
    d=rpois(10000,u)
    hist(d, breaks=100,freq=FALSE)

# Plot data for distributional analysis
t1<-ggplot(Ondat1,aes(Temp,CPUE))+geom_point()
d1<-ggplot(Ondat1,aes(Depth,CPUE))+geom_point()
a1<-ggplot(Ondat1,aes(Areadiv,CPUE,fill=Areadiv))+geom_violin()+
  stat_summary(fun.data=mean_sdl, fun.args=list(), shape=17,colour="white")
       grid.arrange(t1,d1,a1, nrow = 1)

tm<-ggplot(Ondat1,aes(Temp,CPUE))+geom_violin(trim=FALSE)+
  facet_wrap(Ondat1$Month)
tm + xlim(12,20)
ty<-ggplot(Ondat1,aes(Temp,CPUE))+geom_violin(trim=FALSE)+
  facet_wrap(Ondat1$Year)
ty + xlim(10,20)
ts<-ggplot(Ondat1,aes(Temp,CPUE))+geom_violin(trim=FALSE)+
  facet_wrap(Ondat1$Season)
ty + xlim(10,20)
dm<-ggplot(Ondat1,aes(Depth,CPUE))+geom_violin(trim=FALSE)+
    facet_wrap(Ondat1$Month)
dy<-ggplot(Ondat1,aes(Depth,CPUE))+geom_violin(trim=FALSE)+
    facet_wrap(Ondat1$Year)
ds<-ggplot(Ondat1,aes(Depth,CPUE))+geom_violin(trim=FALSE)+
```

```
    facet_wrap(Ondat1$Season)
    ggdraw()+
       draw_plot(tm, 0, .5, 1, .5) +
       draw_plot(ts, 0, 0, .5, .5) +
       draw_plot(ty, .5, 0, .5, .5) +
       draw_plot_label(c("Month", "Season", "Year"), c(0.04, 0.03, 0.55), c(0.99, 0.49, 0.49), size
= 10)
     ggdraw() +
       draw_plot(dm, 0, .5, 1, .5) +
       draw_plot(ds, 0, 0, .5, .5) +
       draw_plot(dy, .5, 0, .5, .5) +
       draw_plot_label(c("Month", "Season", "Year"), c(0.04, 0.03, 0.55), c(0.99, 0.49, 0.49), size
= 10)

cy<-ggplot(Ondat1,aes(Year,CPUE,fill=Year))+geom_violin(trim=FALSE)+
  stat_summary(fun.data=mean_sdl, fun.args=list(), shape=17,colour="white")
cs<-ggplot(Ondat1,aes(Season,CPUE,fill=Season))+geom_violin(trim=FALSE)+
  stat_summary(fun.data=mean_sdl, fun.args=list(), shape=17,colour="white")
cm<-ggplot(Ondat1,aes(Month,CPUE,fill=Month))+geom_violin(trim=FALSE)+
  stat_summary(fun.data=mean_sdl, fun.args=list(), shape=17,colour="white")
     ggdraw() +
       draw_plot(cm, 0, .5, 1, .5)+
       draw_plot(cs, 0, 0, .5, .5)+
       draw_plot(cy, .5, 0, .5, .5)
  #draw_plot_label(c("Month", "Season", "Year"), c(0.04, 0.03, 0.55), c(0.99, 0.49, 0.49), size
= 10)

     am<-ggplot(Ondat1,aes(Areadiv,CPUE,fill=Areadiv))+geom_violin(trim=FALSE)+
       stat_summary(fun.data=mean_sdl, fun.args=list(), shape=17,colour="white")+
     facet_wrap(Ondat1$Month)
     ay<-ggplot(Ondat1,aes(Areadiv,CPUE,fill=Areadiv))+geom_violin(trim=FALSE)+
       stat_summary(fun.data=mean_sdl, fun.args=list(), shape=17,colour="white")+
```

```
facet_wrap(Ondat1$Year)
as<-ggplot(Ondat1,aes(Areadiv,CPUE,fill=Areadiv))+geom_violin(trim=FALSE)+
  stat_summary(fun.data=mean_sdl, fun.args=list(), shape=17,colour="white")+
facet_wrap(Ondat1$Season)
grid.arrange(am,as,ay, nrow = 1)

ggplot(Ondat1,aes(Month,CPUE,fill=Month))+geom_violin(trim=FALSE)+
  stat_summary(fun.data=mean_sdl, fun.args=list(), shape=17,colour="white")+
  facet_wrap(Ondat1$Year)
ggplot(Ondat1,aes(Season,CPUE,fill=Season))+geom_violin(trim=FALSE)+
  stat_summary(fun.data=mean_sdl, fun.args=list(), shape=17,colour="white")+
  facet_wrap(Ondat1$Year)
```

#test significant differences between means

```
aggregate(CPUE~Year,Ondat1,mean)
aggregate(CPUE~Year,Ondat1,sd)
aggregate(CPUE~Year,Ondat1,median)

modelm <- aov(Ondat1$CPUE~Ondat1$Month)
models <-aov(Ondat1$CPUE~Ondat1$Season)
modela <-aov(Ondat1$CPUE~Ondat1$Areadiv)

summary(modelm)
summary(models)
summary(modela)
```

#Post Hoc test to find which months, seasons are significantly different from each other

```
tkm<- TukeyHSD(modelm)
  sdm<- as.data.frame(tkm[1:1])
```

```
    write.csv(sdm, 'Monthly significant diff.csv')
  tks<- TukeyHSD(models)
    sds<- as.data.frame(tks[1:1])
    write.csv(sds, 'Seasonal significant diff.csv')
  tka<- TukeyHSD(modela)
    sda<- as.data.frame(tka[1:1])
    write.csv(sda, 'Area significant diff.csv')



    #visualise tests
    tukey.month<-TukeyHSD(modelm)
    tukey.season<-TukeyHSD(models)
    tukey.area<-TukeyHSD(modela)
plot(tukey.month)
plot(tukey.season)
plot(tukey.area)

modelmytrend <- aov(trend$Predicted.mean.CPUE~trend$year)
modelmytrend1 <-aov(trend1$yhat~trend1$year)
modelarea <-aov(trendar$yhatar~trendar$Areadiv)

summary(modelmytrend)
summary(modelmytrend1)
summary(modelarea)

trendw<-TukeyHSD(modelmytrend)
sdtrendw<- as.data.frame(trendw[1:1])
write.csv(sdtrendw, 'Weighttrend_sig_diff.csv')
trendno<-TukeyHSD(modelmytrend1)
sdtrendno<- as.data.frame(trendno[1:1])
write.csv(sdtrendno, 'Numbertrend_sig_diff.csv')
```

```
trendarea<-TukeyHSD(modelarea)
sdtrenda<- as.data.frame(trendarea[1:1])
write.csv(sdtrenda, 'Areatrend_sig_diff.csv')

tukey.trendw<-TukeyHSD(modelmytrend)
tukey.trendno<-TukeyHSD(modelmytrend1)
tukey.trendar<-TukeyHSD(modelarea)
```

Appendix C: Coding to standardise CPUE at various levels in R Studio

```
setwd("F:/Octopus data/R")
getwd()

dat = read.csv("oct_catch.csv")
dat1 = read.csv("oct_catch1.csv")
ondat<-read.csv("Onbrd1.csv")

library(reshape2)

# Check headings
names(dat)
names(dat1)
names(ondat)

# do summary
summary(dat)
summary(dat1)
summary(ondat)

# cpue noct/npots

dat$cpue.n <- dat[,13]/dat[,7]

# Aggregate variables
month.cpue1 = aggregate(cpue.wp~month,dat,mean)
month.cpue2 = aggregate(cpue.lp~month,dat,mean)
month.cpue3 = aggregate(CPUE~Month,ondat,mean)
month.npots = aggregate(npots~month,dat,mean)
month.noct = aggregate(Noct~month,dat,mean)
month.area = aggregate(CPUE~Areadiv+Month,ondat,mean)
```

```
month.season = aggregate(CPUE~Season,ondat,mean)
agg.dat1 = aggregate(dat1,by = list(dat$year),FUN = mean)

month<-seq(1,12)

Par = list(mfrow=c(1,1),mar = c(5, 4, 4, 4)+(0.1), mgp =c(3,1,0), tck = -0.02,cex=0.8)
#png(file = "MonthlyCPUE.png", width = 6.5, height = 5, res = 200, units = "in")
par(Par)
plot(cpue.wp~month,month.cpue1,axes=FALSE,ylim=c(0,3),ylab="",xlab="",
    type="n",col="black", main="CPUE comparison")
axis(2, ylim=c(0,3),col="black",las=1)  ## las=1 makes horizontal labels
mtext("CPUE (kg/pot)",side=2,line=2.5)
box()

lines(cpue.wp~month,month.cpue1,lwd=2,col="blue")
points(cpue.wp~month,month.cpue1,pch=21,bg=0,cex=1)
lines(cpue.lp~month,month.cpue2,lwd=2,col="green")
points(cpue.lp~month,month.cpue2,pch=22,bg=0,cex=1)
par(new = TRUE)                          # Add new plot
plot(CPUE~Month,month.cpue3,axes=FALSE,ylim=c(0,3),ylab="",xlab="",type="n")
axis(4, ylim=c(0,3), col="red",col.axis="red",las=1)
mtext("CPUE (number/pot)",side=4,col="red",line=2.5)

lines(CPUE~Month,month.cpue3,lwd=2,col="red")
points(CPUE~Month,month.cpue3,pch=23,bg=0,cex=1)

axis(1,pretty(range(month),10))
mtext("Month",side=1,col="black",line=2.5)

legend("topright",c("whole","leg","number"),col=c("blue","green","red"),lwd=2,bty="n",cex=1.2)
```

```
#dev.off()

#dot chart matrix to look for correlations in variables

library(ggplot2)
library(lattice)
library(psych)
pairs.panels(dat[,], method = , # correlation method
             hist.col = "blue",
             cex.cor = 2,
             density = TRUE,  # show density plots
             ellipses = TRUE) # show correlation ellipses

# Use GAM CPUE by month as a factor of the year
library(mgcv)
# fitted to all observations
fit = gam(cpue.wp ~ s(month,bs="cc", k=12)+as.factor(year),data=dat)
summary(fit)
anova(fit)
plot(fit)

# Prediction dataset
pdat = data.frame(month=1:12,year = max(dat$year) )

# predict
yhat = predict(fit,newdata=pdat)
# get CIs
pr = predict(fit,newdata=pdat,se=TRUE)
yhat = pr$fit
lcl = pr$fit-1.96*pr$se.fit
ucl = pr$fit+1.96*pr$se.fit
```

```
results = data.frame(pdat,yhat,SE = pr$se.fit,lcl,ucl)
write.csv(results,"gam_monthlyCPUE.csv", row.names = FALSE)

m = pdat$month

Par = list(mfrow=c(1,1),mar = c(4, 4, 1, 1), mgp =c(3,1,0), tck = -0.02,cex=0.8)
#png(file = "MonthlyCPUE_CIs.png", width = 6.5, height = 5, res = 200, units = "in")
par(Par)
plot(cpue.wp~month,month.cpue1,ylim=c(0,3),type="n",ylab="CPUE (kg/pot)",xlab="Month")
polygon(c(m,rev(m)),c(lcl,rev(ucl)),col=grey(0.5,0.5),border=grey(0.5,0.5))
points(cpue.wp~month,month.cpue1,pch=21,bg=0,cex=2)
#points(cpue.wp~month,dat,pch=21,bg=0,cex=1)
lines(1:12,yhat,col=4,lw=2)
#dev.off()

gam.check(fit)
```

 # Producing multiple plots of modelled data

```
range(dat$year)
yrs = unique(dat$year)
nyrs = length(yrs)
m = 1:12
ylim= c(0,4)
Par = list(mfrow=c(3,2),mar = c(4, 4, 1, 1), mgp =c(3,1,0), tck = -0.02,cex=0.8)
#png(file = "AnnualMonthlyCPUE_CIs.png", width = 6.5, height = 9, res = 200, units = "in")
par(Par)

results = NULL
for(y in 1:nyrs){
pdat = data.frame(month=m,year = yrs[y] )
```

```
# get CIs
pr = predict(fit,newdata=pdat,se=TRUE)
yhat = pr$fit
lcl = pr$fit-1.96*pr$se.fit
ucl = pr$fit+1.96*pr$se.fit
results = rbind(results,data.frame(pdat,yhat,SE = pr$se.fit,lcl,ucl))

cpue.my = aggregate(cpue.wp~month,dat[dat$year==yrs[y],],mean)
```

 # Plot each year

```
plot(cpue.wp~month,cpue.my,ylim=ylim,xlim=c(1,12),type="n",ylab="CPUE (kg/pot)",xlab="Month")
polygon(c(m,rev(m)),c(lcl,rev(ucl)),col=grey(0.5,0.5),border=grey(0.5,0.5))
points(cpue.wp~month,cpue.my,pch=21,bg=0,cex=2)
lines(1:12,yhat,col=4,lw=2)
legend("topright",paste0(yrs[y]),bty="n")

#dev.off()
}
write.csv(results,"CPUE.mytrend.csv",row.names = F)
```

GAM fitted to all observations for monthly CPUE by number as a factor of year

```
fit1 = gam(CPUE ~ s(Month,bs="cc", k=12)+as.factor(Year),data=ondat)

summary(fit)
anova(fit1)
plot(fit1)

pdat1 = data.frame(Month=1:12,Year = max(ondat$Year) )
# predict
```

```
  yhat1 = predict(fit1,newdata=pdat1)
# get CIs
pr1 = predict(fit1,newdata=pdat1,se=TRUE)
yhat1 = pr1$fit
lcl1 = pr1$fit-1.96*pr1$se.fit
ucl1 = pr1$fit+1.96*pr1$se.fit

results1 = data.frame(pdat1,yhat1,SE = pr1$se.fit,lcl1,ucl1)

write.csv(results,"gam_monthlyCPUEbynumber.csv", row.names = FALSE)

m1 = pdat1$Month

Par = list(mfrow=c(1,1),mar = c(4, 4, 1, 1), mgp =c(3,1,0), tck = -0.02,cex=0.8)
#png(file = "MonthlyCPUE_CIs.png", width = 6.5, height = 5, res = 200, units = "in")
par(Par)
  plot(CPUE~Month,month.cpue3,ylim=c(0,3),type="n",ylab="CPUE (number/pot)",xlab="Month")
   polygon(c(m1,rev(m1)),c(lcl1,rev(ucl1)),col=grey(0.5,0.5),border=grey(0.5,0.5))
   points(CPUE~Month,month.cpue3,pch=21,bg=0,cex=2)
   lines(1:12,yhat1,col=4,lw=2)

gam.check(fit1)
```

 # Producing multiple plots

```
range(ondat$Year)
yrs1 = unique(ondat$Year)
nyrs1 = length(yrs1)
m1 = 1:12
ylim= c(0,4)
```

```
Par = list(mfrow=c(2,2),mar = c(4, 4, 1, 1), mgp =c(3,1,0), tck = -0.02,cex=0.8)
#png(file = "AnnualMonthlyCPUE_CIs.png", width = 6.5, height = 9, res = 200, units = "in")
 par(Par)
 results1 = NULL
 for(y1 in 1:nyrs1){
pdat1 = data.frame(Month=m1,Year = yrs1[y1] )
 # get CIs
pr1 = predict(fit1,newdata=pdat1,se=TRUE)
yhat1 = pr1$fit
lcl1 = pr1$fit-1.96*pr1$se.fit
ucl1 = pr1$fit+1.96*pr1$se.fit

results1 = rbind(results1,data.frame(pdat1,yhat1,SE = pr1$se.fit,lcl1,ucl1))

cpue.my1 = aggregate(CPUE~Month,ondat[ondat$Year==yrs1[y1],],mean)

#Plot each year

plot(CPUE~Month,cpue.my1,ylim=ylim,xlim=c(1,12),type="n",ylab="CPUE (No. Octopus/pot)",xlab="Month")
   polygon(c(m1,rev(m1)),c(lcl1,rev(ucl1)),col=grey(0.5,0.5),border=grey(0.5,0.5))
   points(CPUE~Month,cpue.my1,pch=21,bg=0,cex=2)
   lines(1:12,yhat1,col=4,lw=2)
   legend("topright",paste0(yrs1[y1]),bty="n")

#dev.off()
}
write.csv(results,"CPUE.mytrend1.csv",row.names = F)
gam.check(fit1)
```

 # GAM fitted to monthly CPUE as a factor of the area division

```
# division of area based on longitude
ondat$Areadiv[ondat$Long.DD < 18.65]<-'West'
ondat$Areadiv[ondat$Long.DD >= 18.65]<-'East'
# GAM model
fitar = gam(CPUE ~ s(Month,bs="cc", k=12)+as.factor(Areadiv),data=ondat)
summary(fitar)
anova(fitar)
plot(fitar)

# Prediction dataset
pdatar = data.frame(Month=1:12,Areadiv = unique(ondat$Areadiv) )

# predict
yhatar = predict(fitar,newdata=pdatar)
# get CIs
prar = predict(fitar,newdata=pdatar,se=TRUE)
yhatar = prar$fit
lclar = prar$fit-1.96*prar$se.fit
uclar = prar$fit+1.96*prar$se.fit

results2 = data.frame(pdatar,yhatar,SE = prar$se.fit,lclar,uclar)
write.csv(results2,"gam_monthlybyareaCPUE.csv", row.names = FALSE)

mar = pdatar$Month

Par = list(mfrow=c(1,1),mar = c(4, 4, 1, 1), mgp =c(3,1,0), tck = -0.02,cex=0.8)
#png(file = "MonthlyCPUE_CIs.png", width = 6.5, height = 5, res = 200, units = "in")
par(Par)
plot(CPUE~Month,month.area,ylim=c(0,3),type="n",ylab="CPUE (kg/pot)",xlab="Month")
polygon(c(mar,rev(mar)),c(lclar,rev(uclar)),col=grey(0.5,0.5),border=grey(0.5,0.5))
points(CPUE~Month,month.area,pch=21,bg=0,cex=2)
```

```
#points(cpue.wp~month,dat,pch=21,bg=0,cex=1)
lines(1:12,yhatar,col=4,lw=2)
#dev.off()
gam.check(fitar)

# Producing multiple plots

range(ondat$Areadiv)
area = unique(ondat$Areadiv)
narea = length(area)
mar = 1:12
ylim= c(0,4)
Par = list(mfrow=c(2,1),mar = c(4, 4, 1, 1), mgp =c(3,1,0), tck = -0.02,cex=0.8)
#png(file = "AnnualMonthlyCPUE_CIs.png", width = 6.5, height = 9, res = 200, units = "in")
par(Par)
results2 = NULL
for(a1 in 1:narea){
  pdatar = data.frame(Month=mar,Areadiv = area[a1])
  # get CIs
  prar = predict(fitar,newdata = pdatar,se=TRUE)
  yhatar = prar$fit
  lclar = prar$fit-1.96*prar$se.fit
  uclar = prar$fit+1.96*prar$se.fit

  results2 = rbind(results2,data.frame(pdatar,yhatar,SE = prar$se.fit,lclar,uclar))

  cpue.myar = aggregate(CPUE~Month,ondat[ondat$Areadiv==area[a1],],mean)

  #Plot each year

plot(CPUE~Month,cpue.myar,ylim=ylim,xlim=c(1,12),type="n",ylab="CPUE(No.Octopus/pot)",xlab="Month")
```

```
  polygon(c(mar,rev(mar)),c(lclar,rev(uclar)),col=grey(0.5,0.5),border=grey(0.5,0.5))
  points(CPUE~Month,cpue.myar,pch=21,bg=0,cex=2)
  lines(1:12,yhatar,col=4,lw=2)
  legend("topright",paste0(area[a1]),bty="n")

  #dev.off()
}
write.csv(results2,"CPUE.area.csv",row.names = F)
gam.check(fitar)
```

Appendix D: Code for mapping catch distribution, pot distribution and aggregated CPUE

```
setwd("F:/Octopus data/R")
getwd()

# Load data
FBoct <- read.csv("Mapdat.csv",  head = TRUE)
FBoct1 <- read.csv("Mapdat1.csv", head = TRUE)
FBoct2 <- read.csv("Mapdat2.csv",head = TRUE)
FBoct3 <- read.csv("Onbrdarea.csv", head = TRUE)
# Check headings
names(FBoct)
names(FBoct1)

# Load required libraries
library(ggplot2)  # ggplot() fortify()
library(plyr)
library(dplyr)  # %>% select() filter() bind_rows()
library(rgdal)  # readOGR() spTransform()
library(raster)  # intersect()
library(ggsn)  # north2() scalebar()
library(rworldmap)  # getMap()
library(shapefiles)
library(maps)
library(sf)
library(prettymapr)

### Read in data ###

FBoct$Lat<-round(FBoct$Lat.DD,digits = 2)
```

```
FBoct$Long<-round(FBoct$Long.DD,digits = 2)
FBoct1$Lat<-round(FBoct1$Lat.DD,digits = 2)
FBoct1$Long<-round(FBoct1$Long.DD,digits = 2)
FBoct2$Lat<-round(FBoct2$LatDD,digits = 2)
FBoct2$Long<-round(FBoct2$LongDD,digits = 2)
FBoct3$Lat<-round(FBoct3$Lat.DD,digits = 2)
FBoct3$Long<-round(FBoct3$Long.DD,digits = 2)

names(FBoct)
names(FBoct1)
names(FBoct2)
Sum_Catch<-aggregate(N.Octopus~Lat+Long, FBoct, FUN=sum)
Sum_Pots<-aggregate(N.Pots~Lat+Long, FBoct, FUN=sum)
Sum_Catch1<-aggregate(N.Octopus~Lat+Long, FBoct1, FUN=sum)
Sum_Pots1<-aggregate(N.Pots~Lat+Long, FBoct1, FUN=sum)
Sum_Catch2<-aggregate(N.Octopus~Lat+Long, FBoct1, FUN=sum)
Mean_Cpue<-aggregate(CPUE~Lat+Long,FBoct, FUN=sum)

Q  <- quantile(Sum_Catch[,3], header=TRUE)
Q1  <- quantile(Sum_Pots[,3], header=TRUE)
q  <- quantile(Sum_Catch1[,3], header=TRUE)
q1  <- quantile(Sum_Pots1[,3], header=TRUE)
qcpue<-quantile(Mean_Cpue[,3], header=TRUE)
qcpue1<-quantile(Mean_Cpue1[,3], header=TRUE)

maxo<-max(Sum_Catch1[,3], header=TRUE)
mino<-min(Sum_Catch1[,3], header=TRUE)
```

#Insert map

```
#bathysashp<-read.shp("bathysa.shp")
```

```
#bathysashx<-read.shx("bathysa.shx")
#bathysadbf<-read.dbf("bathysa.dbf")

#bathy<-read.shapefile("bathysa")
#bathy<-convert.to.simple(bathy$shp)
#bathy<-bathy[,-1]

southafricashp<-read.shp("southafrica.shp")
southafricashx<-read.shx("southafrica.shx")
southafricadbf<-read.dbf("southafrica.dbf")

southafrica<-read.shapefile("southafrica")
southafrica<-convert.to.simple(southafrica$shp)
n= nrow(southafrica)
southafrica<-southafrica[104:n,-1]

#Overview Plot
xlim=c(18.4,19)
ylim=c(-34.5,-34)

#windows(width=9, height=6.5)

# Plot catch distribution by grouped GPS co-ordinates

par(mar=c(4,5,2,5)+.1, cex=1.,mex=0.85)
plot(southafrica,type="l",cex=0.01, col="black",
    bg="black",xlab="Longitude",ylab="Latitude",main="",xlim=xlim,ylim=ylim)

points(Sum_Catch[,2],Sum_Catch[,1],bg="blue",pch=21,cex=log((Sum_Catch[,3])),col="pink")
points(18.85,-34.399,bg="blue",pch=21,cex=0.75,col="pink")
```

```
points(18.85,-34.413,bg="blue",pch=21,cex=1.25,col="pink")
points(18.85,-34.435,bg="blue",pch=21,cex= 4,col="pink")
points(18.85,-34.485,bg="blue",pch=21,cex= 8,col="pink")
text(18.911,-34.399,col="black","10")
text(18.911,-34.421,col="black","48")
text(18.911,-34.442,col="black","473")
text(18.915,-34.485,col="black","5068")
text(18.7, -34.01, col="black","Catch Distribution False Bay")

addnortharrow(pos = "topright", padin = c(0.15, 0.15), scale = 0.5,
              lwd = 1, border = "black", cols = c("white", "black"),
              text.col = "black")
addscalebar(plotunit = NULL, plotepsg = NULL, widthhint = 0.25,
            unitcategory = "metric", htin = 0.1, padin = c(0.15, 0.15),
            style = "bar", bar.cols = c("black", "white"), lwd = 1,
            linecol = "black", tick.cex = 0.7, labelpadin = 0.08, label.cex = 0.8,
            label.col = "black", pos = "bottomleft")

#text(Areas[,5]+0.02,Areas[,4]+0.02,paste(Areas[,2]),cex=0.8)
```

 # Plot pot distribution using grouped GPS co-ordinates

```
par(mar=c(4,5,2,5)+.1, cex=1.,mex=0.85)
plot(southafrica,type="l",cex=0.01, col="black",
     bg="black",xlab="Longitude",ylab="Latitude",main="",xlim=xlim,ylim=ylim)

points(Sum_Pots[,2],Sum_Pots[,1],bg="red",pch=21,cex=log((Sum_Pots[,3])),col="blue")

points(18.85,-34.399,bg="red",pch=21,cex=0.75,col="blue")
points(18.85,-34.413,bg="red",pch=21,cex=1.25,col="blue")
points(18.85,-34.435,bg="red",pch=21,cex= 4,col="blue")
```

```
points(18.85,-34.485,bg="red",pch=21,cex= 8,col="blue")

text(18.911,-34.399,col="black","34")

text(18.911,-34.421,col="black","100")

text(18.911,-34.442,col="black","560")

text(18.915,-34.485,col="black","3974")

text(18.7, -34.01, col="black","Pot Distribution False Bay")


addnortharrow(pos = "topright", padin = c(0.15, 0.15), scale = 0.5,

              lwd = 1, border = "black", cols = c("white", "black"),

              text.col = "black")

addscalebar(plotunit = NULL, plotepsg = NULL, widthhint = 0.25,

            unitcategory = "metric", htin = 0.1, padin = c(0.15, 0.15),

            style = "bar", bar.cols = c("black", "white"), lwd = 1,

            linecol = "black", tick.cex = 0.7, labelpadin = 0.08, label.cex = 0.8,

            label.col = "black", pos = "bottomleft")



# Plot aggregated CPUE using grouped GPS co-ordinates


par(mar=c(4,5,2,5)+.1, cex=1.,mex=0.85)

plot(southafrica,type="l",cex=0.01, col="black",

   bg="black",xlab="Longitude",ylab="Latitude",main="",xlim=xlim,ylim=ylim)


points(Mean_Cpue[,2],Mean_Cpue[,1],bg="green",pch=21,cex=log((Mean_Cpue[,3])),col="red")

    text(18.7, -34.01, col="black","Aggregated CPUE")


    addnortharrow(pos = "topright", padin = c(0.15, 0.15), scale = 0.5,

                  lwd = 1, border = "black", cols = c("white", "black"),

                  text.col = "black")

     addscalebar(plotunit = NULL, plotepsg = NULL, widthhint = 0.25,
```

```
unitcategory = "metric", htin = 0.1, padin = c(0.15, 0.15),
style = "bar", bar.cols = c("black", "white"), lwd = 1,
linecol = "black", tick.cex = 0.7, labelpadin = 0.08, label.cex = 0.8,
label.col = "black", pos = "bottomleft")
```