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Innovative development of the *Octopus* (cf) *tetricus* fishery in Western Australia

FRDC Project No **2010/200**

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Abbreviations

DOF	Developmental Octopus Fishery
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CPUE	Catch Per Unit of Effort
CSLPF	Cockburn Sound Line and Pot Fishery
GLM	Generalised Linear Model
MCMC	Monte Carlo Markov Chain
MPA	Modal Progression Analysis
NPUE	Number Per Unit of Effort
PSR	Potential Scale Reduction factor
SIA	Stylet Increment Analysis
SBPR	Spawning Biomass Per Recruit
YPR	Yield Per Recruit
WAFIC	Western Australian Fishing Industry Council

Executive Summary

In 2010 the broad-scale introduction of a new gear type, the trigger trap, saw a 260% (33 t in 2009 to 119 t in 2010) increase in octopus landings in the Western Australian Developmental Octopus Fishery (DOF). Deployed in waters previously unfished by the DOF, initial catches demonstrated that trigger traps were more efficient and captured a different component of the population, compared to open-ended shelter pots traditionally used in the fishery. This shift caused a surge of interest in commercial octopus fishing. Thus, creating a need to build a solid research foundation on the biology and population dynamics of the key species, to help ensure the ecologically and economically sustainable developmental of the octopus fishery. Conducted by the Department of Fisheries Western Australia, during 2010 – 2014, this project provided a unique opportunity to investigate a new phase of a fishery at inception.

Octopus has always been a byproduct of the rock lobster fishery, however targeted fishing for octopus was established in 2001, and fishing effort during the first nine years of the DOF was constrained to a small number of operators in specific inshore (shallower than 20 m) locations. This restriction was a product of the tendency of the light weight shelter pots to be buried in exposed waters. The heavier, larger and active trigger trap was designed specifically to catch the target species *Octopus* (cf) *tetricus* and enable fishing in a wider variety of habitats. The success of the trigger trap was typified by its rapid ascension as the dominant gear type (landing 95% of all catch in 2012) in the fishery and the expansion of the fleet from 6 vessels (5 shelter and 1 trigger pot vessels) in 2009 to 17 (4 shelter and 13 trigger pot vessels) by 2013. With vessels operating from Kalbarri in the north to Busselton in the South at depths up to 40 m, this rapid transformation of the DOF is a significant expansion.

Determining the size of the resource and sustainable harvest rates requires detailed information on the growth, maturation, mortality and recruitment of the population, all of which are underpinned by age data. The present study was the first of its kind to age a wild population of octopus, using a combination of direct and indirect ageing methods. Through the discovery of a strong relationship between the number of growth rings found in a stylet (reduced internal shells) and stylet weight, the ages of 3500 octopuses were obtained, using stylet weight as a proxy for age. Maximum age was calculated at ~1.5 years for both males and females, with males maturing at ~240 days compared to ~380 days for females. This information enabled the construction of life history profiles of the stock in relation to gear type. Thus revealing, trigger traps were ~15 times more effective than shelter pots and caught predominantly (75%) mature males weighing >1 kg, whereas shelter pots caught a mixture of males and females that mostly weighed <1 kg and were immature. Spawning occurred throughout the year with six monthly hatching pulses during transitional temperatures. Spatial differences in average size of the catch indicated that offshore migration to reef habitats for spawning may be occurring.

The life history profile was combined with spatially explicit commercial catch and effort data, and a dedicated depletion study, to determine density estimates (individuals / km^2). The extent of harvestable area by trigger trap (depths 20 – 50 m) across the western and southern coasts of Western Australia, were calculated at ~34,000 km^2. The harvestable area was split

into four fishing zones for ease of analysis and management. Density and area estimates were used to determine biomass and abundance estimates, for three distinct scenarios: precautionary, conservative and possible. The precautionary scenario was based on the assumption that the present percentage (7%) of area fished in the main fishing zone represents the extent of optimal fishing grounds for each zone. The precautionary and possible scenarios, expanded upon this at 20% and 30% of each zone being optimal fishing grounds, respectively. Overall biomass estimates ranged from 8,626 t (precautionary) to 12,605 t (possible). The biomass and abundance estimates, along with the biological data were then used in a per-recruit model to determine a range of sustainable harvest levels for each scenario. From the lowest estimation of 879 t to the highest of 2261 t, it appears likely that the DOF should be able to realistically maintain landings in the proximity of ~1000 t per year. Thus indicating there is considerable room for expansion in the fishery, which could lead to the development of a significant industry for Western Australia.

Progression from a 200 t to a 1000 t fishery will require progressive and conscientious development of the DOF on distinct spatial and temporal scales. For the short life span, fast growth rates, high fecundity, semelparity and minimal overlap between generations, observed in the *O.* (cf) *tetricus* population, are typical traits of cephalopod stocks. Such characteristics, along with a tendency to be strongly influenced by environmental variables (namely temperature) indicate that the *O.* (cf) *tetricus* population will most likely experience high fluctuations in abundance from year to year. Therefore to minimise the potential impacts of fishing pressure on stocks and in turn such fluctuations on economic sustainability, it is recommended that expansion is incrementally increased, using total catch limits for each fishing zone. To determine the efficiency and validity of such an approach, will require monthly monitoring of catch rates, annual fishery assessments and ongoing biological monitoring.

The present study has provided a detailed depiction of the DOF's harvest potential, across large expanses of unfished areas. As the fishery progressively develops, further information will be obtained on the extent of optimal and sub-optimal habitats in each zone, thus providing insights into how the population may respond to fishing effort on local and regional scales. By providing a detailed life history profile for *O.* (cf) *tetricus*, this study has also established a strong foundation for future research on *O.* (cf) *tetricus* trophic role and the potential ecological impacts of octopus fishing. Information that will be essential to maintain the fisheries social licence to operate as the fishery expands.

Keywords

Octopus (cf) *tetricus*, fisheries biology, age, reproduction, sustainable harvest potential, population dynamics, per-recruit modelling.

1 Introduction

The developmental octopus fishery

During 1979 – 1981 Japanese researchers investigated the feasibility of a commercial octopus fishery in Western Australia, in response to the high level of octopus predation and bycatch in the West Coast Rock Lobster Fishery (WCRLF) (Joll 1977b). A major finding of this research was the existence of a substantial octopus population and the need for an adequate gear type to harvest it (Kimura 1980; Kimura and Isomae 1981; Kimura et al. 1978). By the late 1990s the Department of Fisheries, Western Australia, implemented a developmental strategy for octopus fishing, issuing six exemption licenses to investigate the possibility of starting a commercial octopus fishery. However, the rules governing octopus fishing gear stipulated that the methods used to catch octopus must not produce bycatch, or be in competition with other fisheries that use baited pots. Consequently, the resultant Developmental Octopus Fishery (DOF) established in 2001 was restricted to using unbaited passive shelter pots, set on a demersal longlines.

Shelter pots are an open-ended passive gear, which relies on octopuses using the pots as hides, in refuge limited environments. With an approximate volume of 6 lt, an opening of 16.9 cm^2 and a mean weight of 3.5 kg, shelter pots are generally soaked for 15-25 days and set on demersal longlines of approximately 500 pots per line (Figure 1a & b). Predominantly set at depths shallower than 20 m, shelter pot fishing has been restricted to protected waters, to prevent loss and burying of gear in sediment by wave action. During 2007 - 2009, licensees of the DOF developed and trialled a new trigger trap design. Trigger traps are an active gear, which relies on the octopus' need to find shelter in refuge limited habitats as well as exploiting their hunting instincts and curiosity. The traps are baited with a bright orange rubber crab that is illuminated with a led light (Figure 2 a). When the crab is grasped by an octopus a trap door is triggered at the entrance, enclosing the octopus. Trigger traps have an approximate volume of 15 lt, an opening of 12.8 cm^2 and are set on steel cradles in groups of three traps with a mean weight of 45 kg per cradle (Figure 2 a). Due to the trapping mechanism of trigger traps, they have considerably shorter soak periods at a mean of 11 days. A cradle of trigger traps can either be set as a single unit of gear or connected to a demersal longline ranging from 10 to 50 cradles per line (Figure 2 b). This new gear type has the following advantages over shelter pots: a) deployment in previously inaccessible habitats, b) a much shorter soak-period and c) considerably higher catch per unit of effort (CPUE).

The innovation of the trigger trap provided impetus to draft an adaptive management strategy for the DOF during 2008 – 2009. Developed by the Department of Fisheries Western Australia and the Western Australian Fishing Industry Council (WAFIC), the major outcomes from this strategy were the approval of effort expansion and the instigation of the present study in 2010. With the central role of examining the population dynamics and harvest potential of this resource, the present study falls within the FRDC strategic challenge (1) Natural resource sustainability: "to maintain and improve the management and use of aquatic natural resources to ensure their sustainability" (FRDC 2009).

The introduction of the adaptive management strategy and a broad-scale shift from shelter pots to trigger traps in 2010, resulted in a further ~400% annual catch increase (33 t in 2009 to 170 t in 2010) (Figure 3). Thus, the introduction of the trigger trap finally met the gear requirement identified by the Japanese researchers (Kimura 1980). This shift in the predominant gear type used in the fishery, also resulted in an escalation in effort, with the number of vessels in the fishery expanding from six to 17, the quantity of fishing days per year increasing by 240% and the spread of exploration into new waters (Figure 4 a, b, c). Despite this rise in catch, effort and investment, the fishery remains a non-licensed developmental fishery, still managed through limited entry (five exemption holders) and restrictions on gear allocations. Hence there is a strong need to determine the fishing efficiency of trigger traps and how this relates to sustainable harvest rates for the fishery in presently fished and unfished zones.

As a burgeoning industry, commercial octopus fishers would like to see changes in the management of the fishery that would allow for further expansion of effort into unfished areas. So far, the Department of Fisheries has resisted calls for a major expansion of the octopus fishery, due to the paucity of stock assessment and biological information. The present study was instigated to form a solid basis for research advice to help ensure the future expansion of the fishery occurs in a controlled and sustainable manner. Information that will also assist in the transition of this developmental fishery to fully managed status. As a managed fishery the objectives and limitations of octopus fishing will be defined in a management plan, thus providing security to the WA government that the fishery is managed on sustainability principles, as well as explicit recognition of the cost, values, and benefits of an octopus fishery licence, providing certainty to stakeholders.

Species profile

The target species of the DOF is *Octopus* (cf) *tetricus*, an endemic species of the south-west temperate waters of Australia, ranging from Shark Bay in the north to the South Australian border in the south-east (Figure 5). *Octopus* (cf) *tetricus* is closely related to *Octopus tetricus*, on the east coast of Australia and New Zealand, and the cosmopolitan *Octopus vulgaris* species complex (Amor 2011; Guerra et al. 2010; Soledad Acosta-Jofré et al. 2012). The documented depth range for *O.* (cf) *tetricus* is 5 - 70 m, it inhabits rocky reefs, seagrass meadows and sandy substrates (Edgar 1997; Norman and Reid 2000). O. (cf) tetricus is a medium sized species (max = 4 kg) with a merobenthic (with paralarval stage) life history strategy, laying ~100000 eggs that take ~30 days to hatch (Joll 1976) (Figure 6). Hatchlings spend ~50 days as paralarvae in the water column before settling on the benthos (S. Kolkovski, pers. comm.)(Figure 7). Incidences of other octopus species being caught in the fishery are highly irregular, with occasional reports of fishers in northern waters catching *Octopus cyanea* and south coast fishers *catching Macroctopus maorum*.

Published research on the biology of *O.* (cf) *tetricus* has primarily focused on captivity studies on reproduction, growth and food intake (Joll 1976; Joll 1977a; Joll 1978; Joll 1983). Information on essential biological parameters for fisheries assessment, including: age, age at maturity, hatch months, growth rates, recruitment pulses and reproductive scheduling between genders, are all unknown for this species and are addressed in the present study. The development of a strong biological profile for *O.* (cf) *tetricus* will have flow-on effects for the study of the biology, ecology and fisheries of other octopus species, in particular *O. tetricus* and *O. vulgaris*.

Octopus predation in the West Coast Rock Lobster Fishery (WCRLF)

The DOF is a product of and highly connected to the WCRLF. Predation by *O.* (cf) *tetricus* on pot caught western rock lobsters, has had major economic implications for the WCRLF (Figure 8). The WCRLF is Australia's most valuable single species wild capture fishery, with a commercial catch of 6647 t and a value of $241 million in 2013 (de Lestang et al. 2013). Octopus landings in the WCRLF have been gradually declining from a peak of 140 t in 2002 to 27 t in 2013. However, octopus CPUE has not declined, nor has the reduction in landings been attributed to the catch increase in the DOF. Conversely changes in the management arrangements for the WCRLF have dramatically altered the dynamics of the fishing fleet. Following a crash in settlement indicators in 2008/9, effort was reduced by 70% and Individually Transferable Quotas (ITQs) introduced during 2012/13 (de Lestang et al. 2013). This has resulted in the fishery now operating on a four day fishing / three day closure weekly harvest cycle and fishing throughout the year. There has been a concern from the commercial fishing industry that the 3 day closure may increase the predation rate on lobsters. Due to the high level of interconnectedness between the WCRLF and the DOF, it is an imperative that an understanding of how these fisheries influence each other is acquired, especially as the DOF looks to explore larger areas that are traditionally WCRLF fishing grounds.

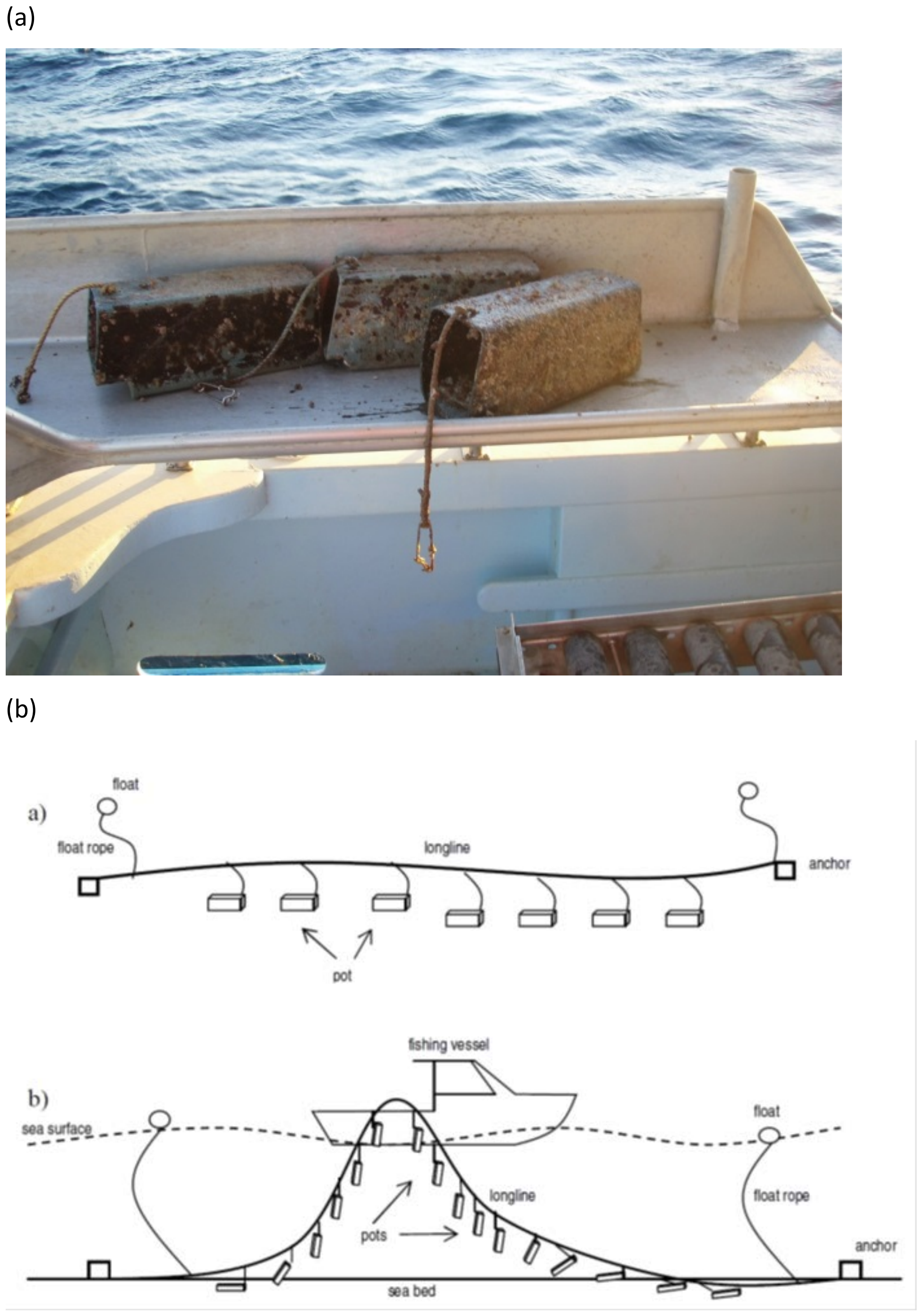


Figure 1 a) octopus shelter pots, b) a schematic of shelter pots fixed to and being hauled on a demersal longline

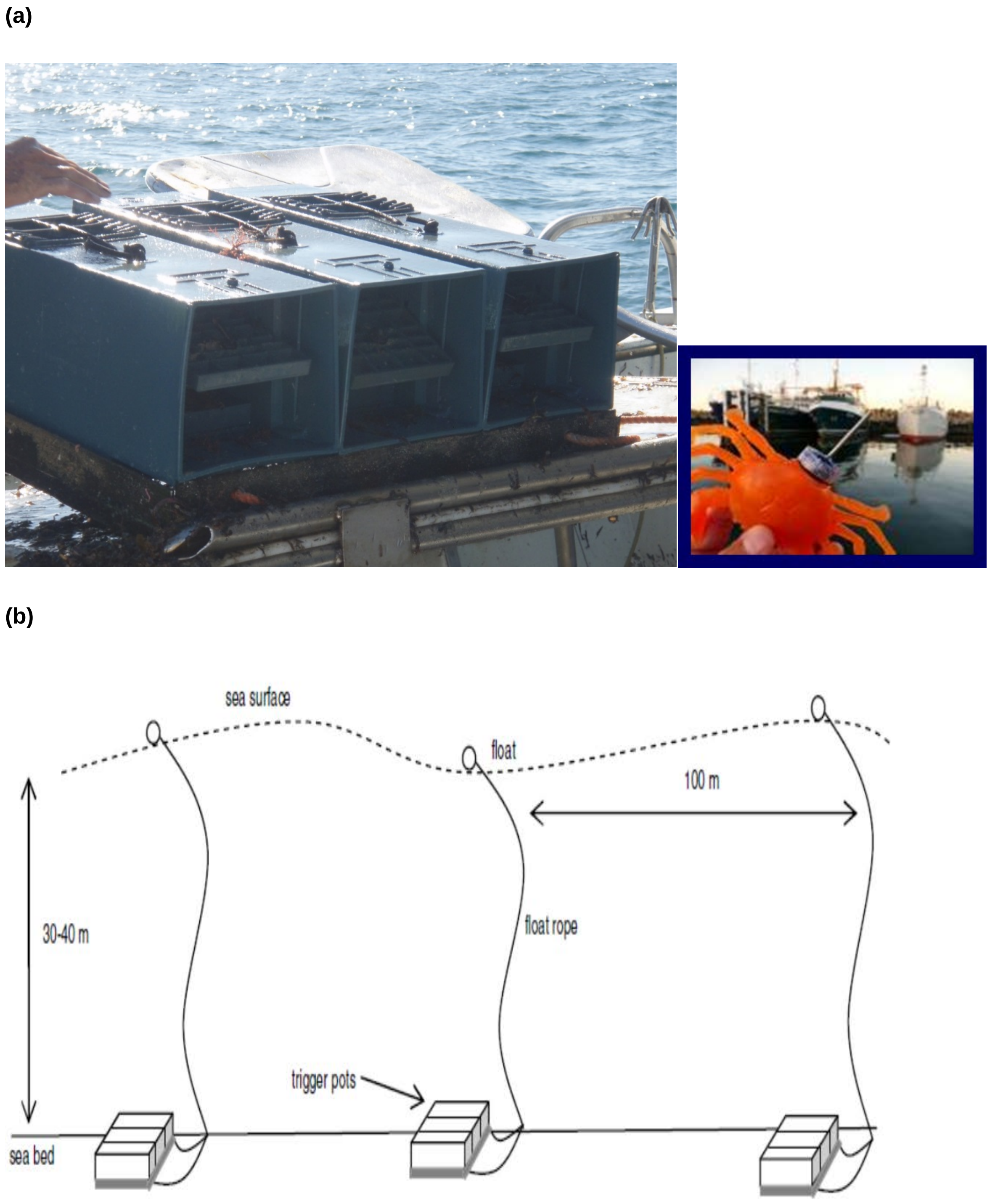


Figure 2 a) a cradle of octopus trigger traps and the rubber bait crab and b) cradle configuration for the drop and haul method. Trigger traps are also set on a demersal longline as per Figure 1b.

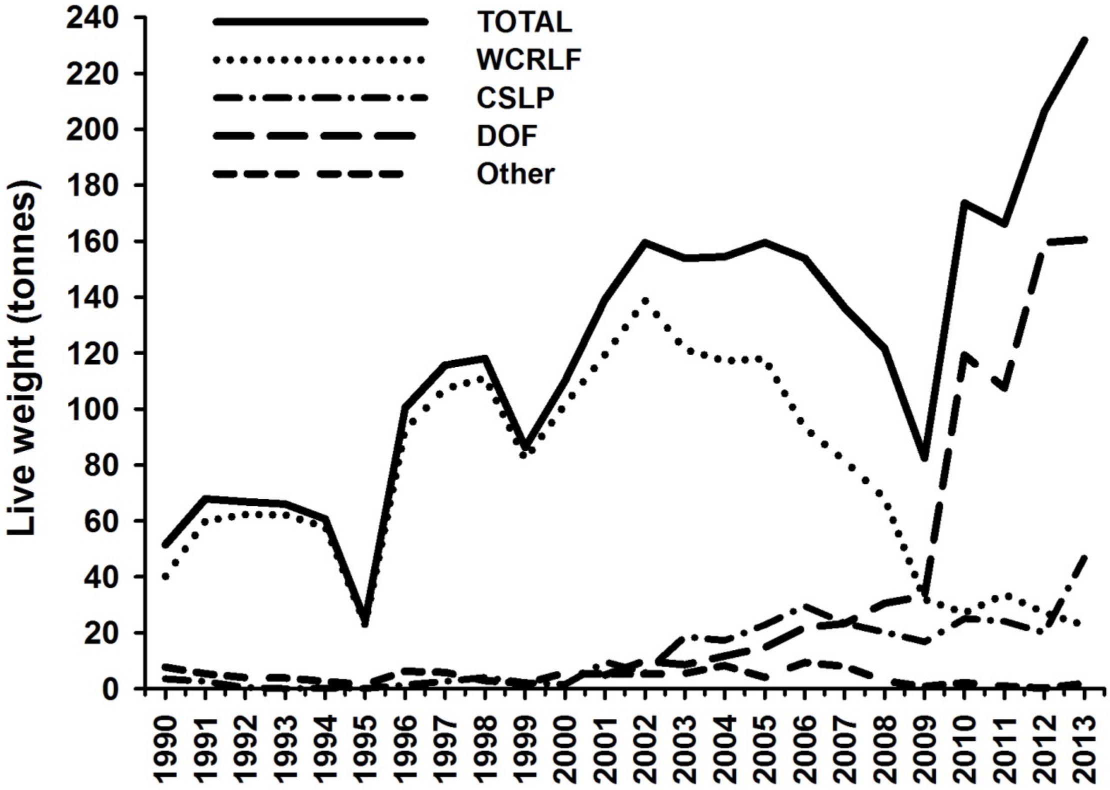


Figure 3 Total octopus landings in Western Australia during 1990 – 2013. Catch is divided between the main sectors – WCRLF (West Coast Rock Lobster Fishery), CSLPF (Cockburn Sound Line and Pot), DOF (Developmental Octopus Fishery) and other, which is bycatch from trawl and miscellaneous pot fisheries

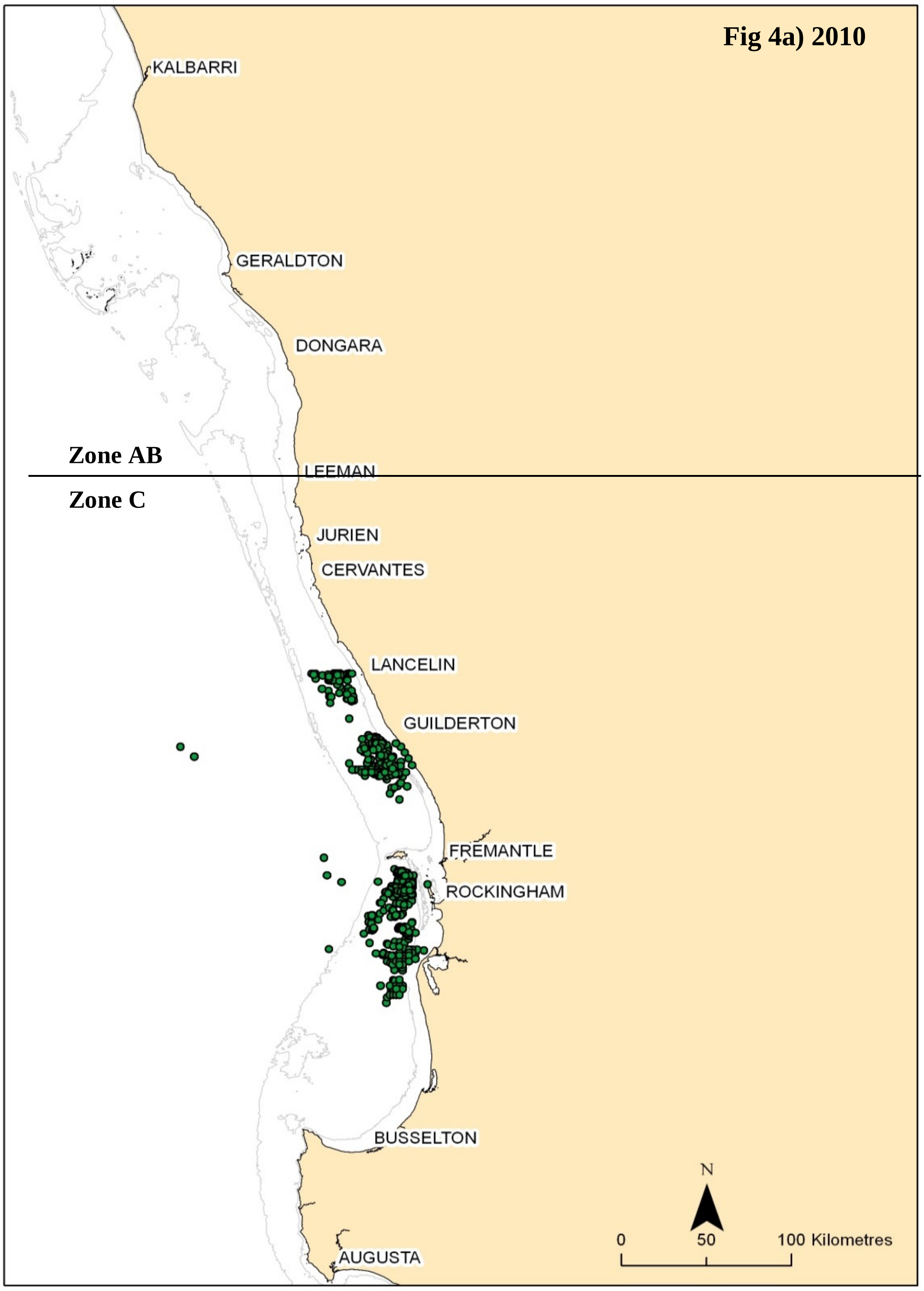
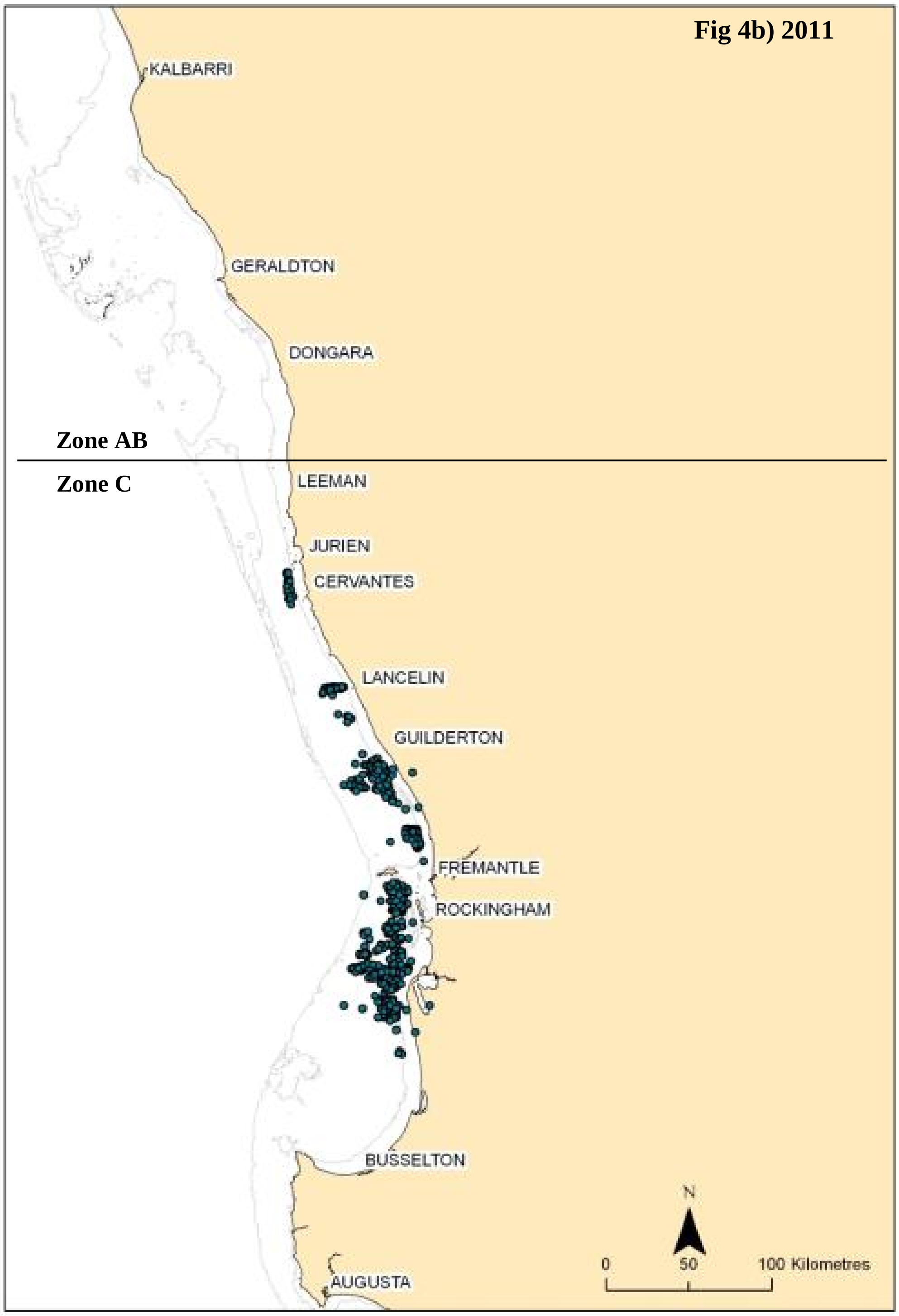


Figure 4 a, b and c Maps of the spread of fishing effort in the Developing Octopus Fishery during 2010 – 2012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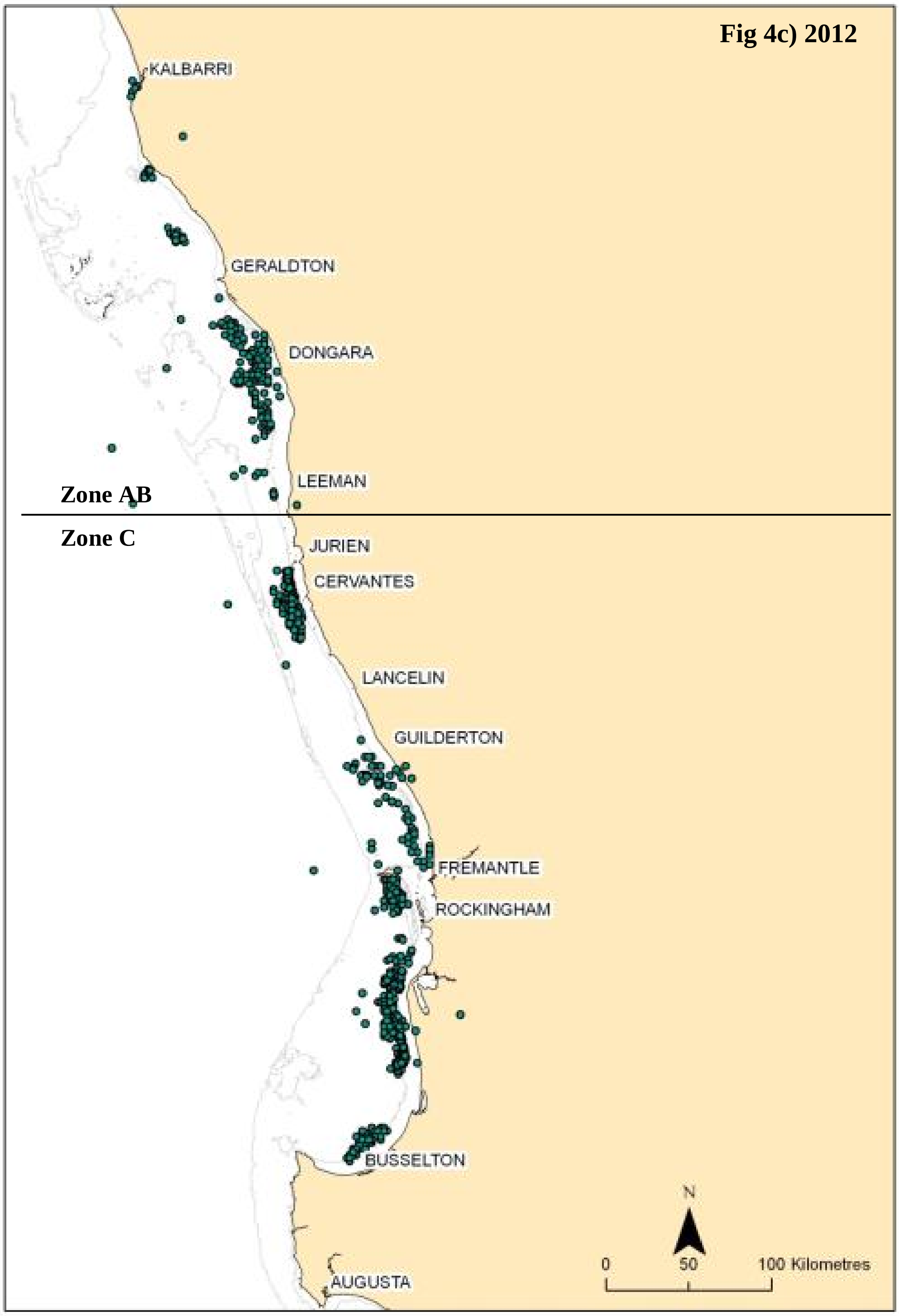
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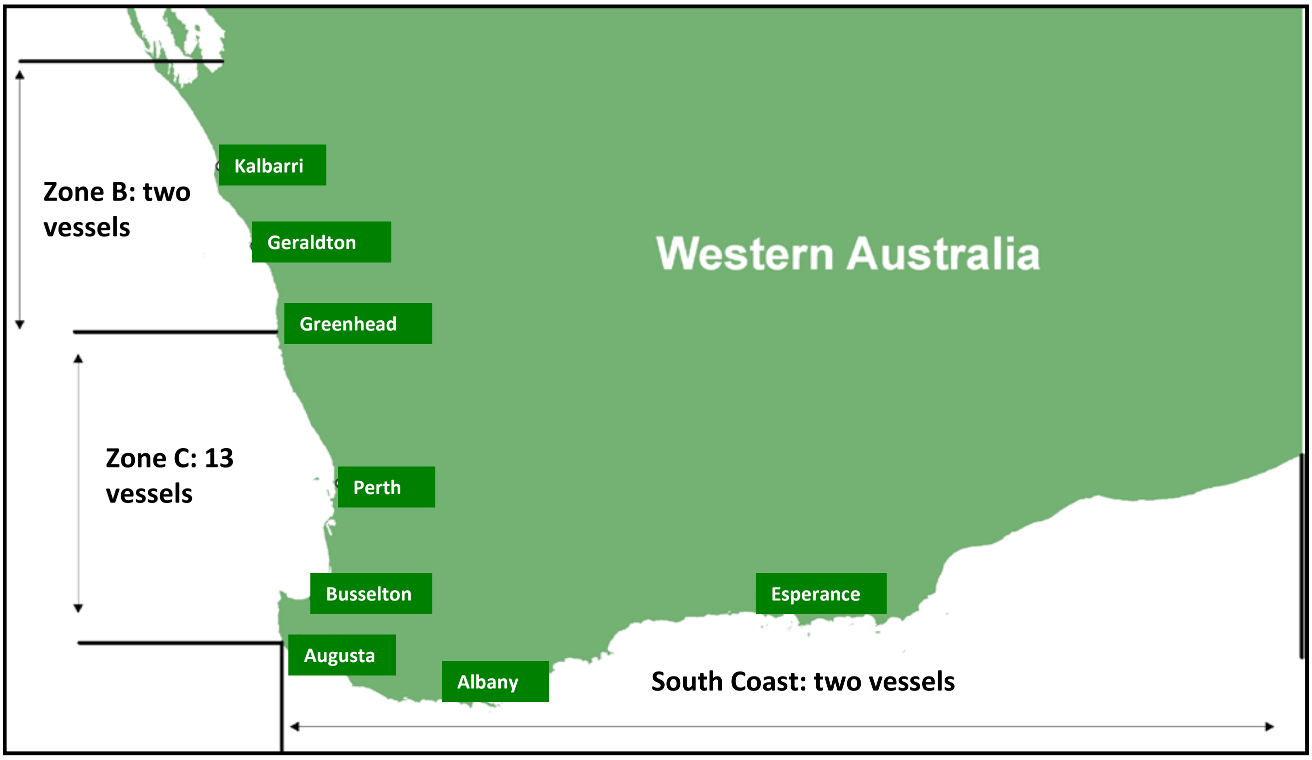


Figure 5 **Range of distribution for *Octopus* (cf) *tetricus* and current partitioning of the fishery.**

Figure 6 ***Octopus* (cf) *tetricus***

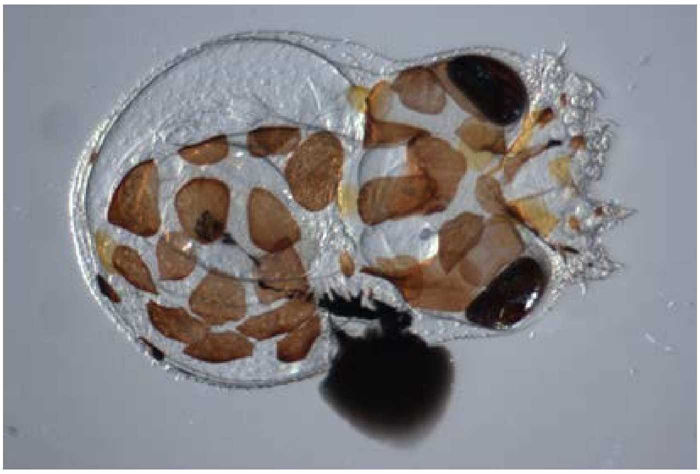


Figure 7 ***Octopus* (cf) *tetricus* paralarva**

Figure 8 **Pot used for commercial lobster fishing**

2 Objectives

The central aim of this study is "*to provide a solid research foundation on the biology and population dynamics of O. (cf) tetricus to help ensure the ecological and economic sustainability of the DOF*." The following objectives were identified to assist in achieving this aim:

1. To describe the general life history of *O. tetricus* in WA, including age, growth and reproductive biology
2. Determine the fishing efficiency of octopus trigger traps
3. Estimate potential harvest from octopus fisheries
4. Calculate the effects of fishing closures on octopus predation rates on rock lobsters.

Report structure

To help address the objectives of the study, a standard report format has been applied (i.e. methods, results and discussion), with further partitioning into the following distinct components, for ease of navigation:

- **Age determination**: identifying and validating appropriate methods to determine the age profile of the population. This section addresses objective 1 above.
- **Life history**: utilisation of age information and reproductive data, to build a biological profile of the population in relation to gear type. This section addresses objective 1 above.
- **Gear efficiency**: direct comparison of the catchability of the two gear types used in the fishery (shelter pots and trigger traps) and the estimation of biomass ranges through a depletion study. This section addresses objective 2 above.
- **Biomass and sustainable harvest**: application of the biological and gear efficiency information, in appropriate assessment models, to make a range of sustainable harvest estimates across different fishing zones. This section addresses objective 3 above.
- **Octopus predation on lobsters**: tracking of octopus predation rates in the WCRLF over the past 32 years and its relationship with multiple temporal and spatial variables, including changes in management arrangements in the WCRLF. This section addresses objective 4 above.

3 Method

3.1 Age determination

3.1.1 Background

This section addresses part of objective 1. Objective 1 is to describe the general life history of *O. tetricus* in WA, including age, growth and reproductive biology. The acquisition of age data enables the quantification of growth, maturation, mortality and recruitment in wild populations. Information that is essential to the ecological stewardship of marine environments and sustainable development of fisheries (King 1995). Despite this, methods of age determination that are rapid, reliable and accurate are lacking for many taxa (Campana 2001). Octopuses are one such taxon. Their biological attributes of plastic life histories, possession of few hard body parts and semelparity, can confound the application of standard approaches used to compile population age profiles (Semmens et al. 2004).

Numerous methods have been trialled to determine octopus age structures, including: indirect methods such as Modal Progression Analysis (MPA) and direct methods such as Stylet Increment Analysis (SIA). MPA uses mantle length as a proxy for age to identify cohorts in a population, and controversially does not account for the high growth variability observed in captive octopus studies (López-Rocha et al. 2012; Semmens et al. 2004). Stylets are reduced remnant internal shells found in the mantle musculature of many octopus species (Bizikov 2004; Figure 9, Figure 10). SIA utilises concentric rings found in the microstructure of stylets as a proxy for age, in a similar manner statoliths are used in squid and otoliths are used in teleost (Doubleday et al. 2006; Leporati et al. 2008b). The common divide between these methodologies is time/cost versus accuracy/precision. MPA has the positive attributes of: low cost, fast processing times, and low specialist knowledge requirements, which enables the acquisition of large sample sizes. Conversely MPA is believed to provide a low level of accuracy and precision due to assumptions on the strength of the relationship between length and age (Semmens et al. 2004). Alternatively, SIA can provide accurate and precise estimates of age. However, SIA has a relatively slow processing time, requires expensive equipment, and considerable specialist knowledge, which ultimately reduce the potential to collect large sample sizes. Consequently, an efficient method of octopus age determination is lacking, hindering the progress of octopus population studies. Therefore, in spite of research efforts into SIA, MPA continues to be the practical choice, particularly in places where octopuses are a major source of protein and income, but specialist equipment and knowledge are unavailable (Jabeur et al. 2012; López-Rocha et al. 2012). To address this, direct and indirect ageing methodologies were combined, to determine whether stylet weight can be used as a rapid, reliable and accurate proxy for age in merobenthic octopus populations. With the following specific objectives of: a) validating stylet increment periodicity, b) identifying age profiles of males and females, and c) investigating the relationship between age and mantle length.

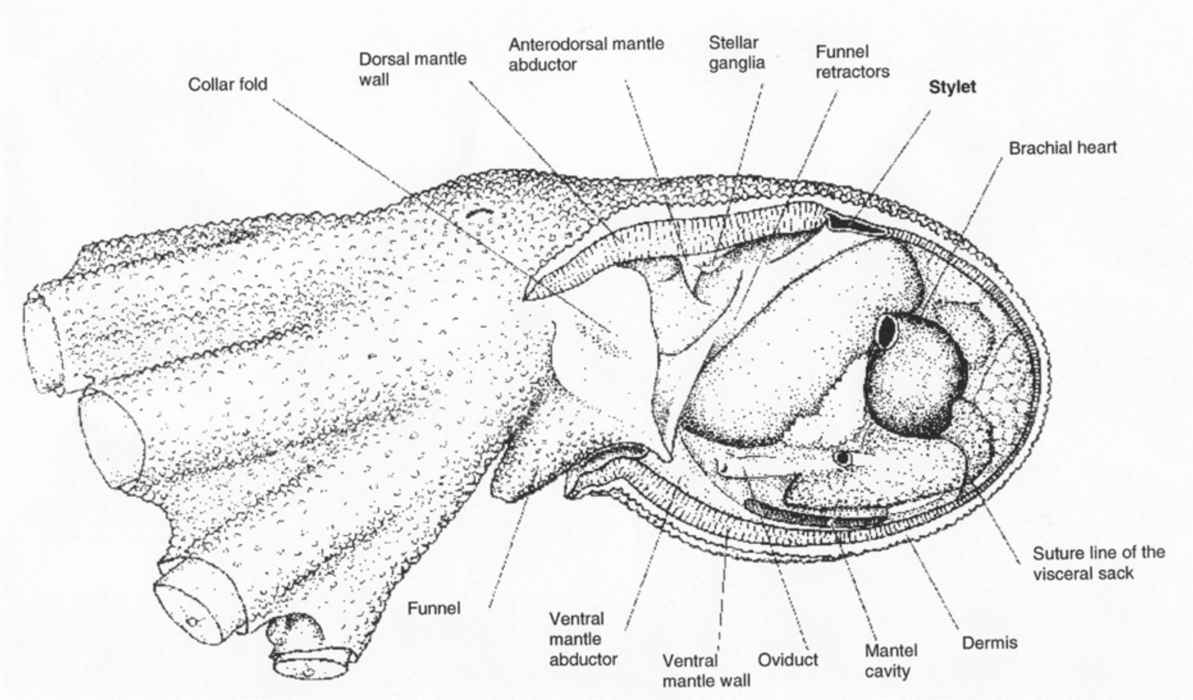


Figure 9 Location of a stylet in the mantle musculature of an octopus

Figure 10 Extracted stylet from ***Octopus (cf) tetricus*** (actual length 35 mm)

3.1.2 Age validation

To effectively conduct SIA on a wild *O.* (cf) *tetricus* population, the periodicity of stylet increment formation needed to be confirmed (Doubleday et al. 2006). To achieve this wild octopuses were collected from the developmental octopus fishery, using commercial octopus trigger traps on four occasions during June 2011 and April, June, August 2012. All captured octopuses were housed in plastic tanks (volume 250 - 5000 lt) in a flow through system at ambient water temperatures (19 - 21°C) and provided with hides. Whilst in captivity the octopuses were fed dead prawns (family Penaeidae) and pilchards (family clupeidae). Three methods were trialled to validate stylet increment periodicity in captive adult *Octopus* (cf) *tetricus*: injection with oxytetracycline (OTC), immersion in Alizarin complexone (AC) and injection with calcine.

The OTC trail (June 2011) was based on the methods used by Hermosilla et al., (2010), to validate increment periodicity on wild caught *O. vulgaris*. Three *O.* (cf) *tetricus* (size range = 1700 – 2100 g TW) were injected with 124 mg / kg of OTC on two occasions 36 days apart. The two injections were applied so counts could be made between each mark. The OTC failed to display any marks on any of the stylet sections under magnification with a compound microscope and UV light, and was therefore not pursued further.

The AC trial (April 2012) was based on the methods used by Fuentes et al., (2000), to mark the stylets of *O. vulgaris* paralarvae. Six octopuses (size range = 1680 – 3000 g TW) were immersed in individual baths of AC solution at two different concentrations of 60 and 90 mg/L for periods of four hours. The octopuses were euthanised at 4, 22, 30, 66 and 77 days after immersion. Two females laid eggs during the experiment and were kept alive until the eggs hatched, for periods of 66 and 77 days after injection. The AC showed some general staining on the stylets for two animals, yet the increments were illegible. For all other animals the AC failed to display any marks on the stylet sections.

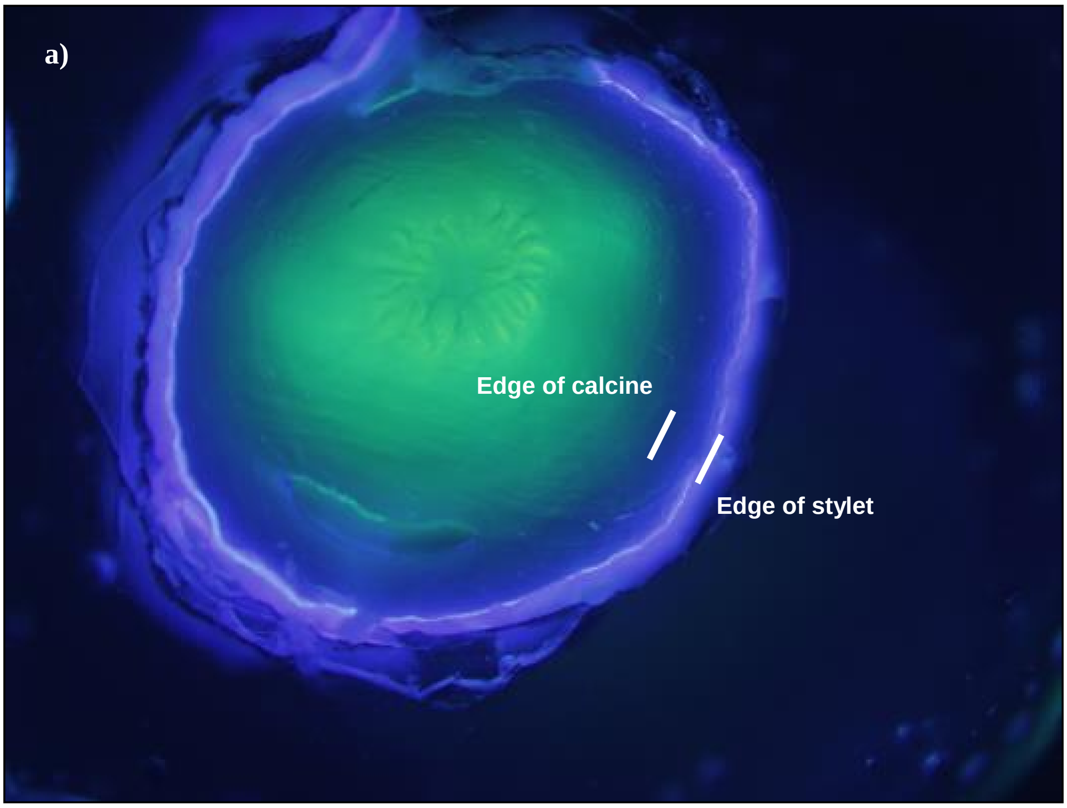
The calcine trial (June and August 2012) was based on methods commonly used to mark otoliths in teleosts. The solution was mixed at a concentration of 25 mg/ml and administered at 10 mg/kg live weight. To make 50 ml of solution, 0.9 g of NaCl was dissolved in 16.56 ml of distilled water and 1.33 g of $NaHCO_3$ dissolved in 33.4 ml of distilled water. Two-thirds of each solution where then mixed together and 1.25 g of calcine added. The pH of the solution was maintained at 7.0 - 7.5 by adding the remaining $NaHCO_3$. The solution was filtered through a syringe screw-in filter with a glass micro-fibre disc fitted. Sixteen octopuses (size range = 1136 – 3316 g TW) were collected from the wild, injected with calcine solution and held in captivity. One octopus died the day following the injection. The other octopuses were euthanised at periods of 5, 15, 24, 35, 45, 55 and 67 day intervals. Two females also laid eggs during this experiment and were kept alive until the eggs hatched, for periods of 35 and 66 days after injection.

All stylet sections were embedded in thermoplastic cement (Crystal Bond^{TM} 509) as detailed by Doubleday et al., (2006). To view the calcine marks on the stylets, an Olympus BX51 compound microscope with a U-MWB2 UV filter and a DP70 camera were used at 200x magnification. Three to five clear images were captured at different locations around the structure of each stylet. For each image five non-consecutive counts, using a hand counter, were performed from the chemical mark to the edge of the stylet section. The mean of all counts taken from each stylet (15 to 25 images per stylet) was then compared with the number of days between injection and death, to validate stylet increment periodicity (Figure 11).

3.1.3 Sample collection

For the aging aspect of the study, sampling was confined to monthly biological samples acquired from the DOF during February 2008 – June 2012, from waters between 31°S and -33°S on the Western Australian coast at depths of 5 – 40 m. Both shelter pots and trigger traps were used to collect samples. A total of 3,492 octopuses were dissected during the sampling period. During dissection each octopus was measured for the following parameters: dorsal mantle length (DML) and mantle weight (MW). Only the mantle and visceral mass of the octopus were available for biological examination, with the arms retained by fishers for commercial sale. A sub-sample of 574 whole octopuses ranging in total weight (TW) between 0.6 – 2900 g (353 females and 221 male) were used to determine the relationship between TW and MW. A strong positive linear relationship ($r^2 = 0.9585$) was identified enabling MW to be used as a proxy for TW, by applying a conversion factor of 3.87 (Figure 12). Noting that a lack of large gravid females (TW = >3000g) in the samples may have an influence on the conversion factor.

All dissected octopuses ($n = 3,492$) had their stylets extracted and preserved in 70% ethanol. The preserved stylets were dabbed on a wooden board to remove excess liquid and weighed to the nearest 0.001 g. To test if there was a difference in the weights of left and right stylets within a single octopus, the stylet weights of 108 octopuses were weighed to the nearest 0.001 g. A paired t-test revealed that there were not significantly differences in the weights between stylets from the same animal ($t = 0.182$, $df = 212$, $p = 0.855$), so stylets were chosen randomly.



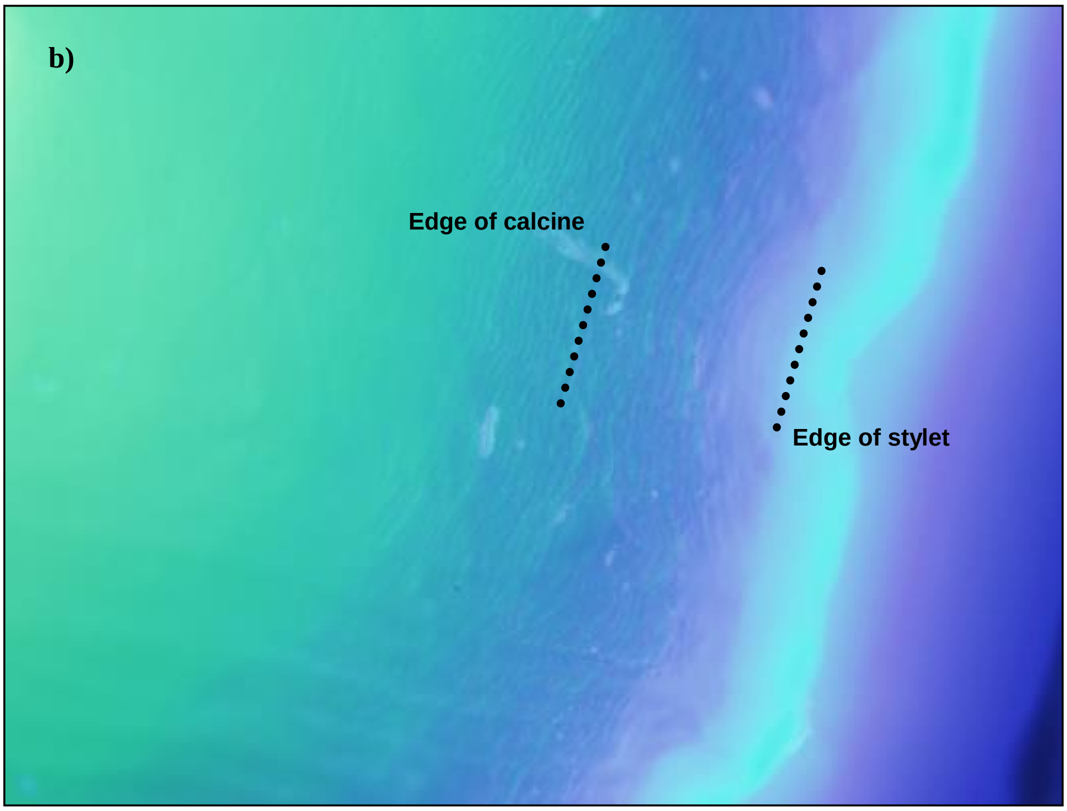


Figure 11 Concentric rings from a sectioned stylet from a calcine injected *Octopus* (cf) *tetricus* at a) 40× magnification and b) 200× magnification, under a UV filter. Images taken 23 days after injection.

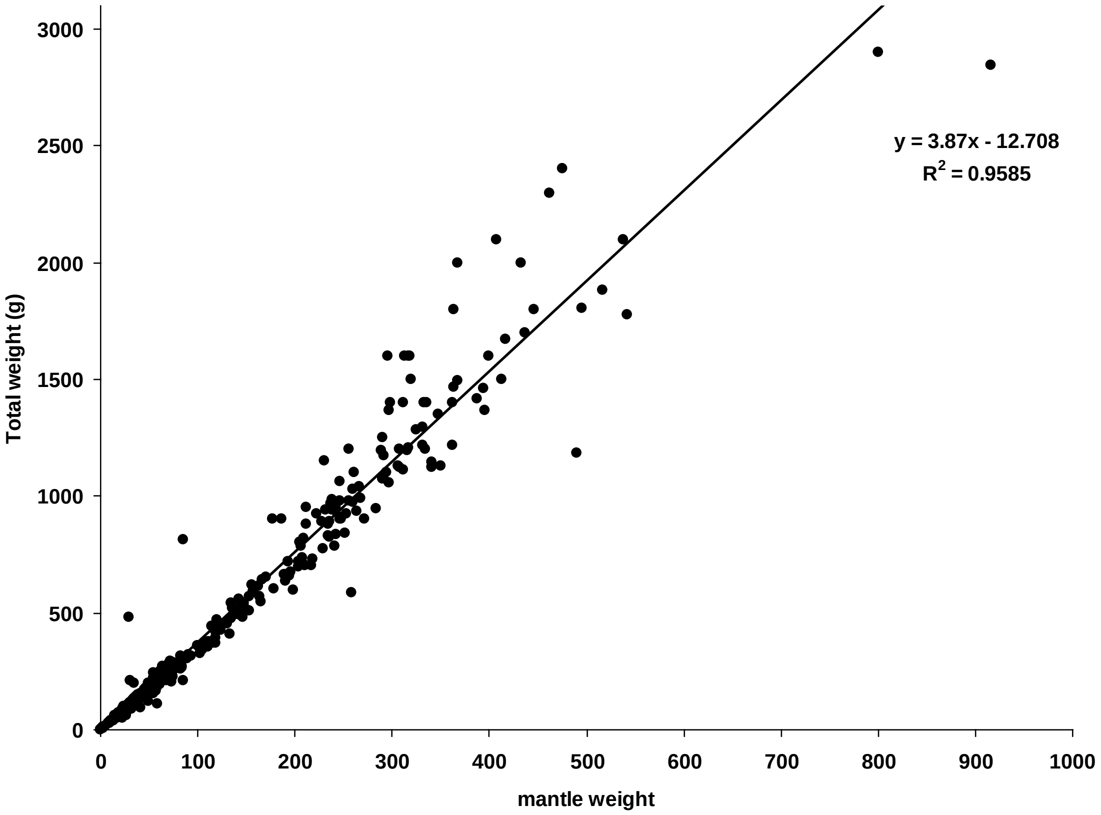


Figure 12 Mantle weight vs total weight for wild caught *Octopus (cf) tetricus* (*n* = 574)

3.1.4 Stylet increment analysis

A sub-sample of 251 stylets were selected for SIA following the methods described by: Doubleday et al., (2006); Leporati et al., (2008b), and Barratt and Allcock (2010). Stylets were extracted, stored in 70% ethanol, sectioned, preserved in LR White Resin ™, ground and polished on lapping film and a pellon disk with alumina powder. Each section was then captured at 400x magnification on a compound microscope (Nikon Eclipse 80i) connected to a video camera (Jenoptik) and viewed on a computer using ProgRes software. The saved images were then stitched together using Pixelmator software. The composite images of the stylet sections were graded on clarity and consistency throughout the visual plane, as follows: i) highly visible increments without any significant obstructions through the visual course of the stylet, ii) good clarity and visibility of increments, only minor obstructions in the visual course that can be adequately navigated around and iii) Poor readability, major obstruction in the visual course of the stylet, discarded. The number of concentric rings from the nucleus to the outer edge was then counted using a hand counter (Figure 13). To ground truth stylet increment counts, two representative samples from an eight stylet reference collection, were counted at the commencement of each day of increment analysis. The reference collection comprised of small, standard and large stylets, all of which were classified as highly visible with minimal obstructions through the course of the stylet plain. Due to the lack of data on the timing of stylet formation in paralarvae, it was assumed the nucleus was formed at hatching, similar to holobenthic (without paralarval stage) octopus species (Doubleday et al. 2006).

Two non-consecutive counts were made for each section and a third performed if the difference between counts was >10%. If the two closest counts (of the 3) were >5% from the mean, the stylet was excluded from the analysis. Stylets that met the 5% precision rule were investigated to see if there was bias in the percentage of discards, at 30 day age intervals. A double blind test was applied to determine ageing error, with the assistance of two independent readers experienced in SIA. The readers were selected for their expertise and independence; having aged biologically similar species of octopus and not been trained in the method by each other. Each reader was given 10 complete stylet images that had met the 5% precision rule. The readers provided two independent counts of each stylet image, without knowledge of the original count, weight of the stylet, or the morphological and biological attributes of the octopuses. The two independent readers counted different stylets from each other. Paired t-tests were applied to determine if there was a significant difference between Reader 1 and each of the two independent researchers.

Application of age data

The relationship between stylet weight and increment number was explored to determine if stylet weight could be used as a proxy for age for the rest of the biological samples. The correlation between mantle length and age was also investigated as a means of ascertaining the suitability of MPA as a comparable ageing methodology for this species.

Hatch dates were estimated by back-calculating age data from the haul date of each individual. Instantaneous growth rates were calculated for males and females, to enable comparison with other studies and determine if the age estimates provided realistic growth rates. Instantaneous growth rate was calculated using the following:

$$G = \frac{\ln Wt_2 - \ln Wt_1}{\Delta t} \qquad (1)$$

where Wt_1 and Wt_2 are the individual weights at times t_1 (hatch) and t_2 (capture), and Δt is the time interval in days between two periods (age) (Forsythe and Van Heukelem 1987). A nominal size at hatching of 0.0014 g was used, based on the weight of *O. vulgaris* hatchlings (Villanueva 1995).

Figure 13 Concentric rings from a stylet section of an *Octopus* (cf) *tetricus* stylet at 400x magnification. Graded as highly visible increments without significant obstructions

3.2 Life history

3.2.1 Background

This section addresses part of objective 1. Objective 1 is to describe the general life history of *O. tetricus* in WA, including age, growth and reproductive biology. Octopus populations typically demonstrate fast growth rates, short semelparous life cycles and high fecundity (Hanlon and Messenger 1996; Mangold 1983). Factors which make them seem relatively resilient to fishing pressure and environmental perturbations, compared to many teleost species (Faure et al. 2000). However, as a consequence of these attributes, octopus populations have minimal overlap between generations, a predicament that can leave them without a buffer from poor recruitment (Boyle 1990; Rocha et al. 2001). This mixture of adaptability and susceptibility, can lead to sharp and sporadic fluctuations in the distribution and abundance of octopus populations (Sobrino et al. 2002). To determine the causes of or to forecast for such fluctuations, it is essential to have a sound knowledge of the life history of the species targeted and the potential impacts fishing practices may have on recruitment dynamics. This is particularly relevant for developmental fisheries, which are generally data poor due to their short time series and typically lack research attention commensurate with their unidentified economic potential (Perry et al. 1999). The acquisition of broad-scale age data obtained from stylet weights, enabled viable estimates of previously unobtainable life history variables for a merobenthic octopus species, such as: age at maturity, hatch months, growth rates, recruitment pulses and reproductive scheduling between genders. Information that is vital in determining sustainable harvest estimates for the fishery.

3.2.2 Sample collection and maturation

Reproductive biology data was recorded for all individuals used in the ageing study (*n* =3,494), plus a further 3850 octopuses for which age information was unavailable. Data was accessed from the present study, and earlier work of Larsen (2008) and Franken (2010). These individuals were included to strengthen analysis on differences in catch composition between shelter pots and trigger traps. The reproductive data collected, included: whole male reproductive complex (MRW) and whole female reproductive complex (FRW), whilst noting the presence of sperm in the oviducts. Gonadosomatic index (GSI) was calculated for all females and males using the following equation: GSI = (GW / (TW – GW) x 100. Mean GSI at 50 day age classes was compared between genders, to determine level of reproductive investment with age (Otero et al. 2007). Maturity stages were determined by visual identification of the macroscopic features of the gonads. The classification of gonad stages was adapted from several sources including: Sánchez and Obarti (1993) for *Octopus vulgaris*, Cortez et al. (1995) for *Octopus mimus* and Quetglas et al. (2005) for *Octopus salutii* (Table 1) (Figure 14 a, b, c, d and Figure 15 a, b, c, d, e). To verify the visual difference between immature and spent females, 8 females with eggs were collected form the wild and held in captivity. Following their post-brooding senescence, the reproductive organs of each female were visually compared to those of known immature females.

Table 1 Maturation stages of *Octopus* (cf) *tetricus*.

Gonad Stage	Male	Female
(I)	Spermatophoric organ transparent and whitish	Ovary whitish, very small no signs of granulation
(II)	Spermatophoric organ with white streaks of sperm	Ovary yellowish with signs of granulation
(III)	Needhams sack full of spermatophores	Ovary very large, yellow/orange to a clear colour if in the process of laying eggs. Oviducts and oviducal glands enlarged
(IV)	N/A	Ovary flaccid, purple in colour with few to no eggs

3.2.3 Data analysis

T-tests were used to determine if significant differences were present between: a) age estimates and weights between males and females caught in shelter pots and b) trigger traps, c) age estimates and weights between shelter pots and trigger traps for females and d) males, and e) ovary weights of females caught in shelter pots and trigger traps.

Total weight (TW), mantle length (ML) and age (days) at maturity, were determined by calculating the point where 50% of the females and males were mature. This was estimated by creating a relative frequency distribution for 50 g and 5 mm size classes and 10 day age classes. The results were then fitted by the least squares method to a logistic curve using the following formula (Leporati et al. 2008a; Tafur et al. 2001):

$$Pi = \frac{1}{1 + e^{(a+bWi)}} \qquad (2)$$

where P*i* represents the relative frequency of the mature individuals in weight, length or age class *Wi*, *a* and *b* are the regression constants, and 50% maturity (weight (MW50%). Length (ML50%) or age (MA50%)) = *a/b*.

Individuals were grouped into hatch months, to determine the influence of temperature at hatching on growth for immature and mature females and males. Monthly satellite-derived sea surface temperatures (SST) for the study area, at a resolution of 1 degree latitude/longitude blocks, were sourced from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in collaboration with the US National Oceanic and Atmospheric Administration (NOAA). Monthly SST data was aligned with back-calculated hatch month frequencies to determine if there were trends between temperature and the number of octopuses hatched. Seasons were defined as austral summer (December to February), autumn (March to May), winter (June to August) and spring (September to November). During January – May 2011 the waters on the west coast of Australia experienced a ‘marine heatwave’, where SST was up to 5°C above average, which was attributed to a very strong La Niña event (Pearce et al. 2011).

3.3 Gear efficiency

3.3.1 Background

This section addresses objective 2. Objective 2 is to determine the fishing efficiency of octopus trigger traps. The trigger trap was designed to be highly selective for *O.* (cf) *tetricus*, for only a medium sized octopus (750 - 4000 g) has the strength, dexterity and ability to contort itself into the trap to set off the trigger. The success of this design is evident in the lack of bycatch recorded in the fishery, including other octopus species, where only infrequent landing of *Octopus cyanea* in northern waters and *Macroctopus maorum* in the southern waters have been observed. The three trigger trap cradle design was based on dimensions and weight of the commercial lobster pot, allowing the gear to be fished with existing lobster pot hauling equipment, and vessels to operate simultaneous in both fisheries. In addition, the majority of fishers presently using trigger traps in the DOF have come from the WCRLF, utilising their existing knowledge of the dynamics of the octopus population.

The initial intention of the drop and pull cradle design, was to enable the targeting of a wider variety of habitats (e.g. in and around reef systems) than what was accessible with lines of shelter pots. Whereas shelter pot usage was confined to protected waters with uniform substrates, resulting in a fleet of smaller sized vessels. The introduction of larger “rock lobster vessels” into the DOF to haul the trigger traps greatly increased individual vessel capacity and range, allowing for greater exploration. In addition, due to the trapping function of the trigger traps, they have markedly shorter soak periods (mean = 11 days) than shelter pots (mean = 25 days) (Figure 16). This higher deployment rate of gear, significantly increases the number of available fishing days per year for each cradle of trigger traps. Hence the immediate future of the DOF is closely tied to the trigger trap. Therefore as a relatively new and innovative gear type, it is an imperative that a) the fishing efficiency of trigger traps is determined in comparison to shelter pots and b) that the catchability of trigger traps is ascertained for different spatial and temporal scales.

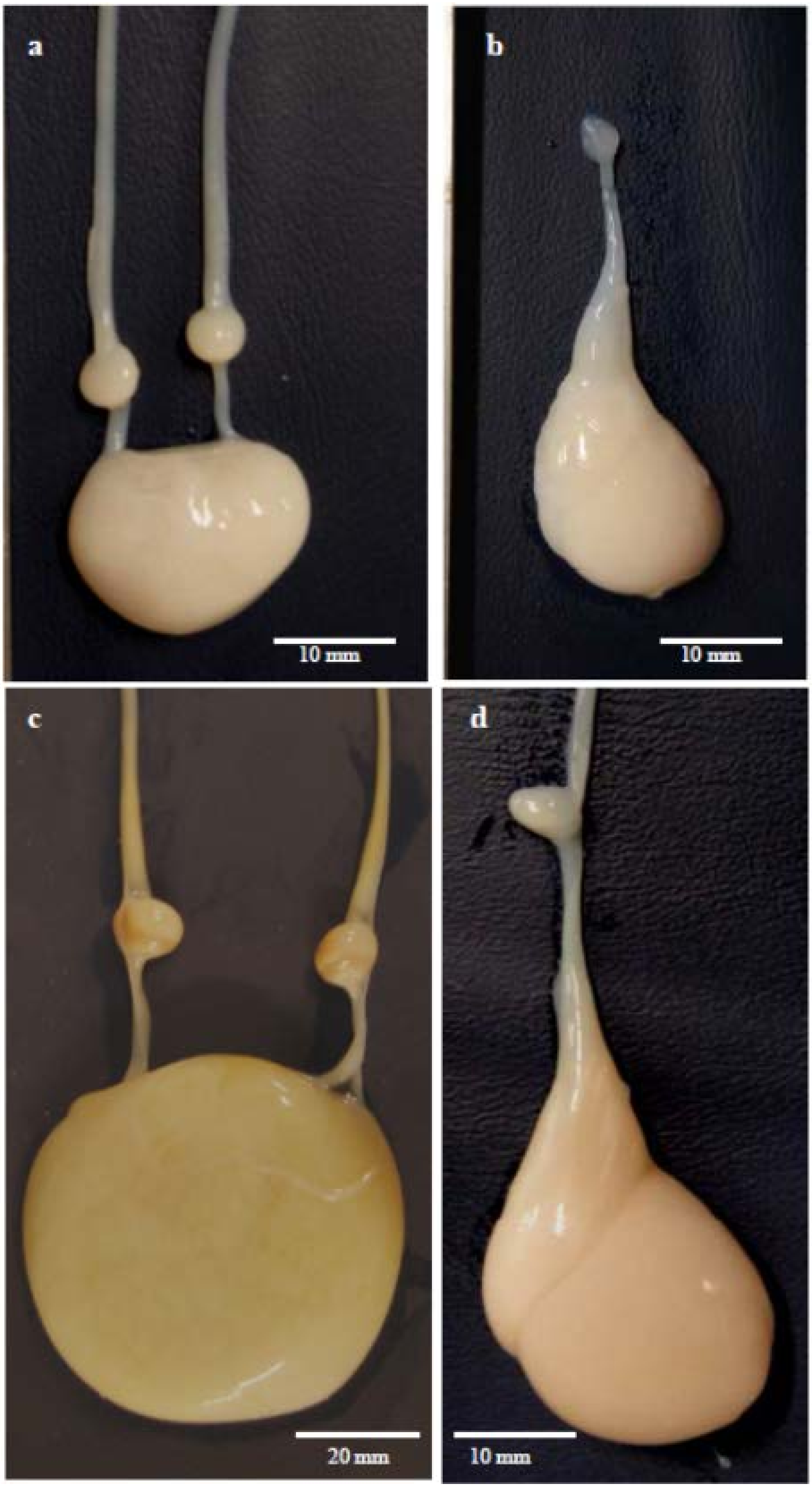


Figure 14 Gonads of *Octopus* (cf) *tetricus* (a) immature female, (b) immature male, (c) maturing female and (d) maturing male (from Larsen 2008)

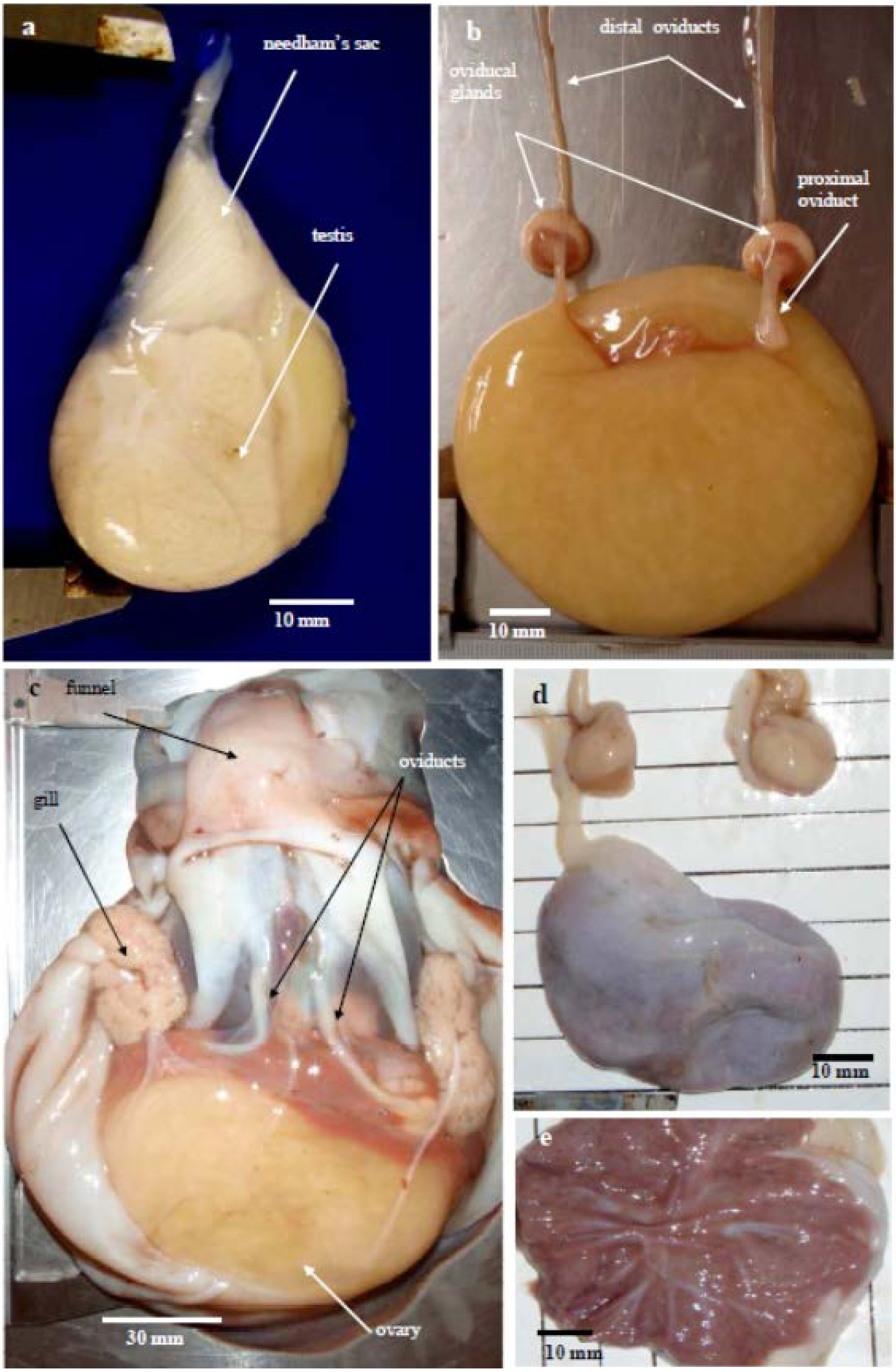


Figure 15 **Gonads of *Octopus* (cf) *tetricus* (a) mature male, (b) mature female, (c) ventral view of visceral cavity of mature female, (d) spent ovary and (e) dissected spent ovary (from Larsen 2008)**

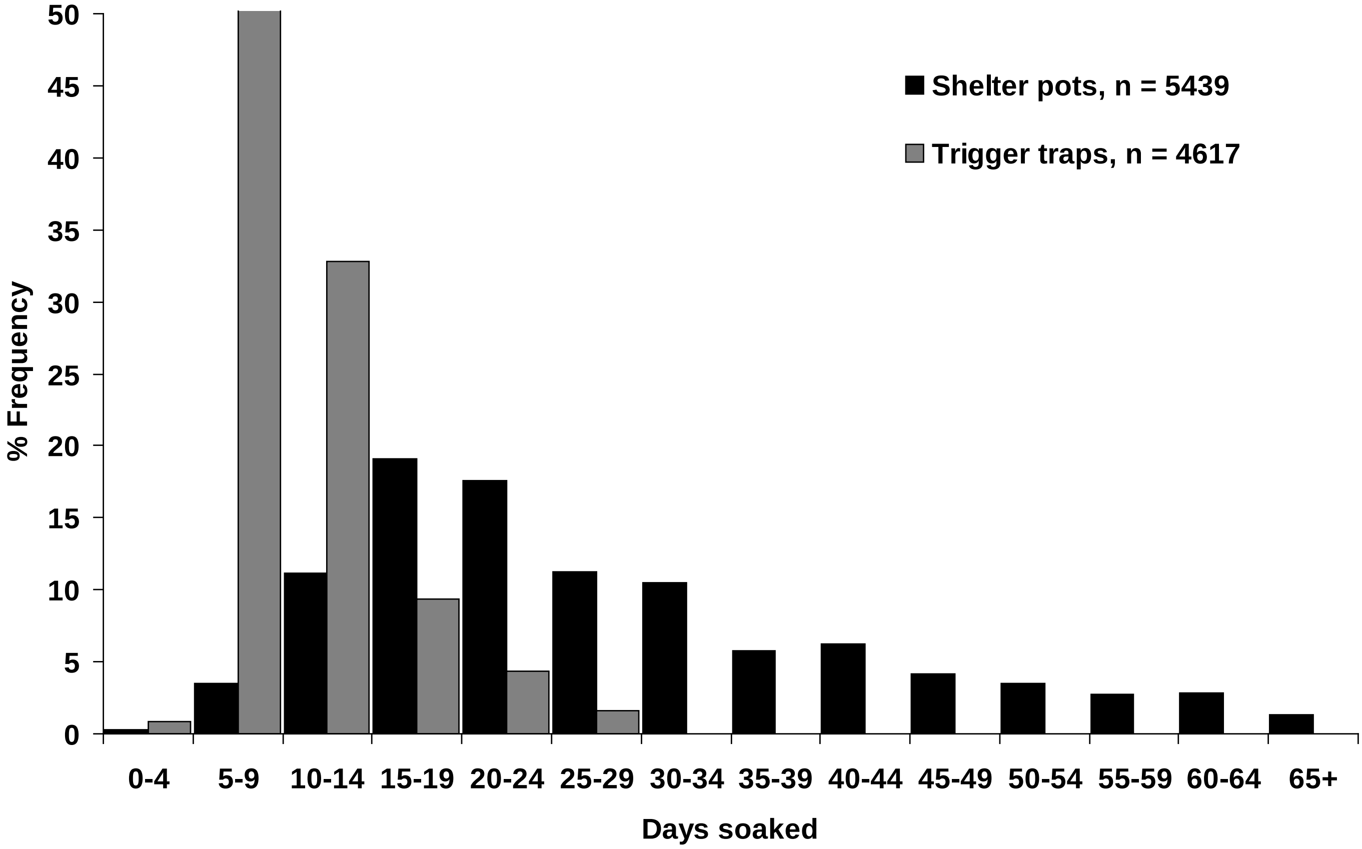


Figure 16 Frequency of soak period for shelter pots and trigger traps

3.3.2 Fishing efficiency of gear

All fishers operating in the DOF are required to fill out a vessel specific daily catch and effort logbook. The logbook captures the following information, for each line of shelter pots or cradles of trigger traps hauled during a single days fishing: GPS location data for the start and end of each line, number of cradles or pots hauled, days soaked, depth and the number of octopus caught (See logbook in Appendix 3). Each logbook also provides a total weight (kg) for the days fishing, following weighing at a processing plant. To provide a viable comparison of fishing efficiency and account for the differences in soak periods between shelter pots and cradles of trigger traps, the theoretical maximum annual gear efficiency C for both gear types using the following equation:

$$C = \frac{T}{h/(p/s)} \qquad (3)$$

where T is total catch, h is number of units hauled, p is survey period in days and s is average soak period. A single unit of gear was considered as a shelter pot or a cradle of three trigger traps. For the present study only fishing data since the broad-scale introduction of trigger traps in May 2010 to July 2013 were used.

3.3.3 Standardised catch rate analysis

A Generalised Linear Model (GLM) was applied to the commercial logbook data to determine spatial and temporal trends in trigger trap catch rates. Measured as catch (in kg) per unit of effort (CPUE), number per unit of effort (NPUE), each catch rate index was investigated for trends by year, month, latitude and depth.. This analysis was performed for trigger traps alone, due to their position as the dominant gear used in the expansion of the fishery.

The model is described as follows:

$$O_c = \beta_{\mathrm{y}} + \beta_{\mathrm{m}} + \beta_{\mathrm{L}} + \beta_{\mathrm{d}} + \varepsilon_i, \tag{4}$$

$$O_n = \beta_{\mathrm{y}} + \beta_{\mathrm{m}} + \beta_{\mathrm{L}} + \beta_{\mathrm{d}} + \varepsilon_i, \tag{5}$$

where O_c is the octopus CPUE and O_n is octopus NPUE, β_{y} is the effect of year, β_{m} is the effect of monthly variation arising from changes in factors varying seasonally, β_{L} is the effect of Latitude, β_{d} is the effect of depth, and $\varepsilon \sim N(0, \theta^2)$. Catch rate data was log-transformed prior to analysis.

3.3.4 Leslie-Delury depletion experiment

During April – July 2013 a depletion experiment was conducted to estimate catchability coefficient (q) of trigger traps and obtain fishery independent estimates of stock density and biomass. The study area was identified by a local commercial fisher as ‘typical’ of the fishing grounds in the region, which had not been fished for more than three months. Located 5 Nm off the coast near the town of Mandurah, the study sites were located within one of the most consistently fished areas since the introduction of trigger traps in 2010 and was deemed representative of the fishery (Figure 17a).

A total of 72 cradles of trigger traps were deployed in two separate sites (denoted as M1 and M2). Each site contained 36 cradles (Figure 17a). Located three nautical miles apart to minimise inter-grid sampling effects, each grid was set in a 6 x 6 cradle configuration with approximate equal distancing between cradles (Figure 17b). It was initially planned that the area fished would be 0.5 km^2 (Figure 17b), however logistical and weather issues on the initial day of trap deployment resulted in the traps covering larger areas; these were 1.5 km^2 for grid M1 and 0.85 km^2 for grid M2. The difference in area enabled a depletion comparison at different gear densities. All cradles were hauled on the same day and redeployed in the same GPS location. Depth range was consistent between the two grids at 24 – 28 m. The number of octopus in each cradle was recorded and collected for biological sampling. In addition, the occurrence of faulty traps or triggered without an octopus were noted. Each trap was hauled ten times over the course of an 84 day period. A soak period of seven days was maintained for the majority of the survey, apart from weeks five and six when poor weather periods extended soak periods to 17 and 11 days, respectively. Biological information in accordance with the fishery dependent biological sampling program, were recorded during dissections in the laboratory. The depletion survey was conducted with a commercial fishing vessel and operated by a commercial fisher, with direction from on-board research staff.

To estimate abundance in the M1 and M2 grids and the catchability coefficient (*q*), the Leslie and DeLury depletion methods were applied (Leslie and Davis, 1939; DeLury 1947). The population was treated as completely closed (i.e. without recruits, immigrants, emigrants or natural mortality), as a product of the information available, and made possible by the short duration of the experiment (Hilborn and Walters 1992). While acknowledging that the populations were unlikely to be strictly closed, it was assumed that the positive influence of immigration on abundance was balanced by the negative effects of natural mortality and emigration. Equations were sourced from Hilborn and Walters (1992).

The Leslie method utilised cumulative catch data and an abundance index based on catch rate at time t (y_t) in the following model:

$$y_t = qN_1 - qK_{t-1} \qquad (6)$$

where q is the catchability coefficient, N_1 is initial population size and K_{t-1} is cumulative catch (in numbers) taken prior to time t.

The DeLury method utilised cumulative effort data and an abundance index based on log-transfomed catch rate at time t (y_t) in the following model:

$$\log_e[y_t] = \log_e[qN1] - qE_t \qquad (7)$$

where E_t is fishing effort (days fished). A linear regression was performed across all sampling dates, both methods and both grids to determine population density and catchability (Hilborn and Walters 1992).

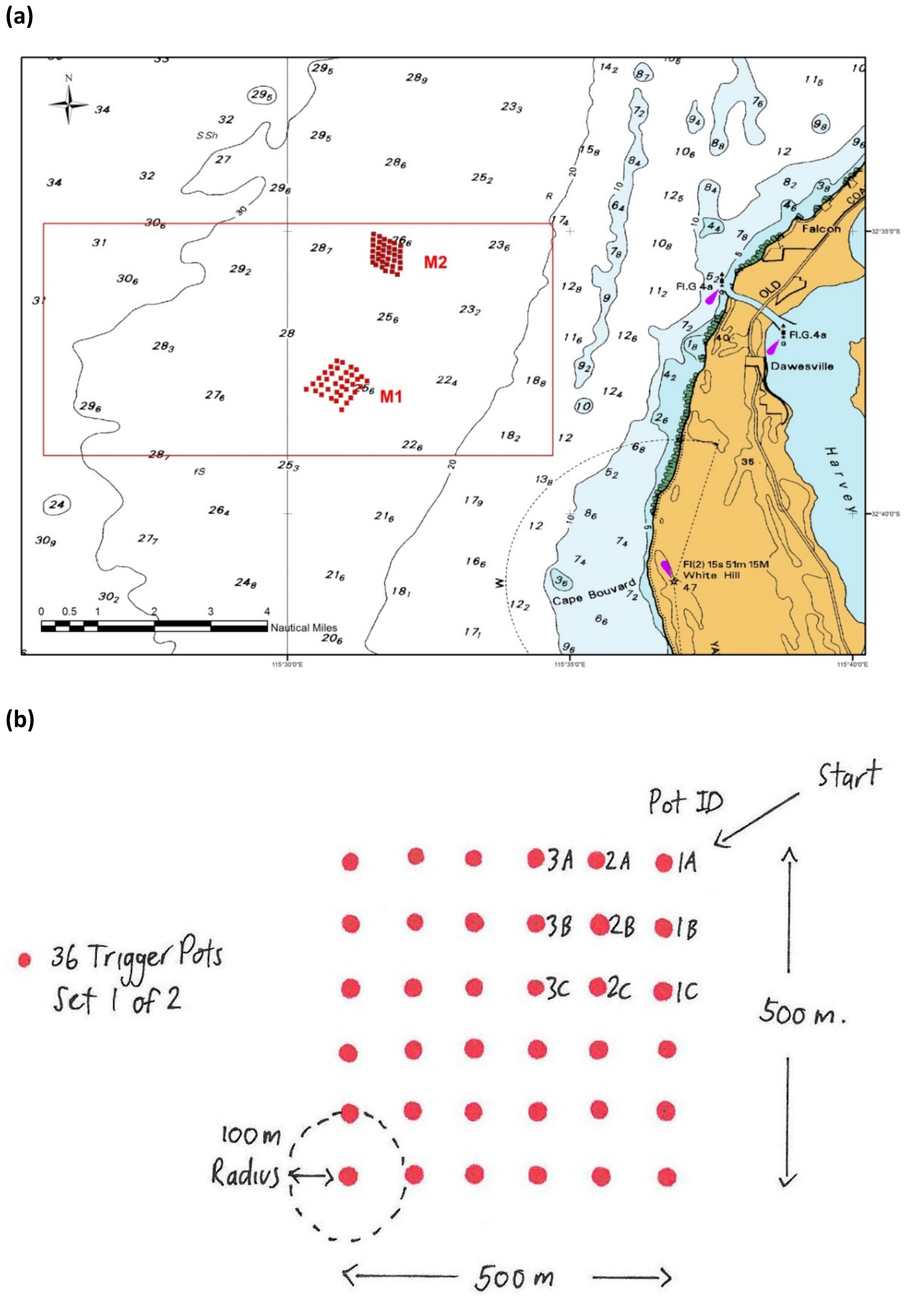


Figure 17 (a) Map of two sites (M1 and M2) near Mandurah, Western Australia (32°35'S; 115°33'E), where the Leslie-DeLury depletion experiments were undertaken; (b) Experimental array design for each site. Red circles indicate the location of each trigger pot, which were set approximately 100 m apart

3.4 Biomass and sustainable harvest

3.4.1 Background

This section addresses objective 3. Objective 3 is to estimate potential harvest from octopus fisheries. A variety of approaches have been applied (e.g. cohort analysis, yield per-recruit models, depletion experiments) to assess exploited cephalopod stocks, with varying levels of success (Pierce and Guerra 1994). This lack of a standard approach has created considerable debate on the suitability of applying methods typically used for teleost and other marine invertebrate taxa, to assess cephalopods stocks (Pauly 1998). A common argument for the development of cephalopod specific strategies is the sporadic and often extreme variability observed in cephalopod population dynamics, which can result in plagues or plummeting catch rates (Diallo et al. 2002; Garstang 1900; Jackson and Domeier 2003). This variability is a product of a range of factors including: short life spans, fast growth rates, high fecundity, strong susceptibility to environmental perturbations, the central ecological role cephalopods play in a variety of habitats and semelparity (Boyle and Rodhouse 2005). In addition to these inherent factors, calculating biomass and sustainable harvest estimates for the DOF had the added complexity of being a developmental fishery, with vast expanses of unfished waters across two coasts, in sub-tropical and temperate waters, covering an array of habitats and depths. This challenge was addressed by utilising the life history and fishing efficiency information derived from: the sampling programs, depletion experiment and commercial logbook data, to build a biological profile of *O.* (cf) *tetricus* and ascertain densities in the currently fished zones. To extrapolate this information across other areas, the fishing grounds were divided into four fishing zones, based on the zonation of the WCRLF. Three possible biomass and harvest estimate scenarios are presented on the basis of differing extents of optimal and non-optimal harvest areas in each zone. This approach was applied to account for the present lack of detailed habitat data in unfished areas.

A per-recruit model was constructed for the DOF using the age data, to ascertain if current fishing pressure is at a sustainable level and to identify a range of biological reference points for potential future harvest scenarios. A major consideration in the construction of the per-recruit model was *O.* (cf) *tetricus'* semelparity. Semelparity is frequently overlooked in cephalopod population assessments, with an assumption of a constant natural mortality for all individuals of commercial age applied. Thus, leading to biased biological reference point estimates from the model (Hendrickson and Hart 2006). Alternatively, to effectively assess the stock dynamics of a semelparous species like *O.* (cf) *tetricus* requires explicit details on the mortality of both spawning and post-spawning females. However, addressing such considerations can be problematic for short time series, such as the three years of trigger trap fishing available for the DOF. This was taken into consideration in the present study, with estimates of instantaneous rates of total mortality for non-spawning females and spawning females used to deduce fishing mortality (F). Per-recruit modelling was then performed to relate estimates of fishing mortality to biologically meaningful reference levels. This was achieved by using an augmented form of a model used by Hendrickson and Hart (2006) for *Illex illecebrosus*. Biological reference points (e.g. $F_{0.1}$, B_0) were calculated from the outputs of these models to provide a point of comparison between present and probable harvest levels.

Due to the strong and frequent impacts environmental factors (namely temperature) can have on octopus life cycles, it is essential to consider their influence on biomass estimates (Forsythe 1993; Forsythe and Van Heukelem 1987). For the DOF, the present focus area for the expansion of the fishery is the west coast. Stretching across five degrees of latitude from sub-tropical to temperate waters, this body of water is dominated by the southward flowing Leeuwin Current and to a lesser degree the northward inshore Capes Current. During the midst of the present study, in summer 2010/2011, a marine "heatwave" occurred in this region, bringing temperatures up to 5°C above average for that time of the year (Pearce et al. 2011). The implications of this La Nina driven event are only now becoming apparent for the broader marine ecosystems (Pearce and Feng 2013). Specific information for the *O.* (cf) *tetricus* is currently unavailable, however possible implications are discussed.

3.4.2 Estimating harvestable area and stock biomass

Arc GIS software was used to calculate the extent of harvestable area on the west coast between latitudes 28° - 35° (Figure 18) and on the south coast between Albany and the South Australian border (Figure 19). A depth profile of 20 – 50 m was used for the area estimation, commensurate with the current deployment depths of trigger traps, noting that *Octopus tetricus* is also found in significant numbers in waters less than 20m. The calculations excluded existing and planned marine parks, and shipping channels. For ease of interpretation and translation into present management arrangements, the coast was also separated into the zones used in the WCRL fishery: Zone A = Abrolhos Islands, Zone B = latitudes 27 – 30, Zone C = latitudes 30 – 33 and the south coast (Figure 18 and Figure 19).

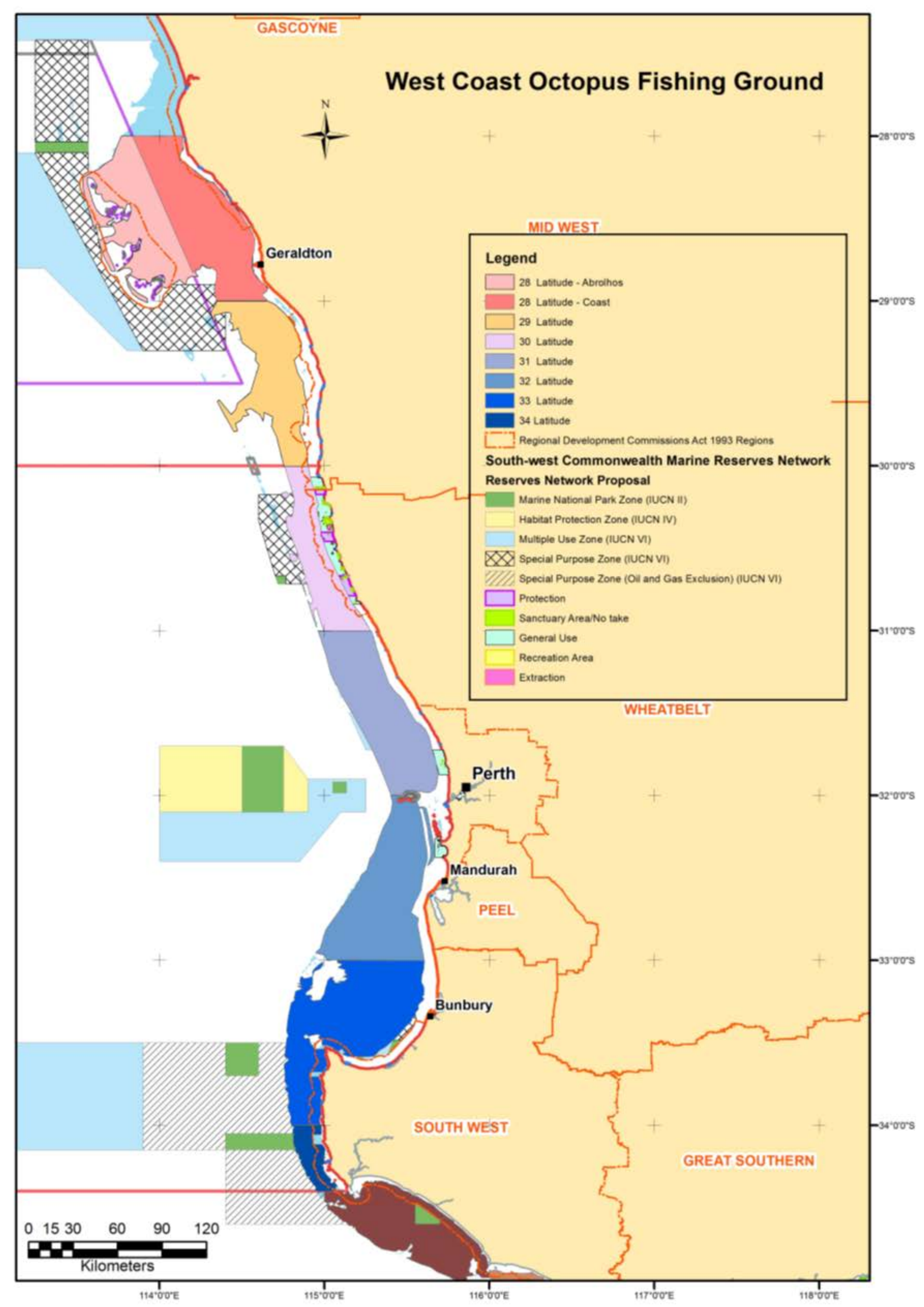


Figure 18 Map of the octopus fishing zones (by 1 degree Latitude) of the west coast of Western Australia. The marine reserves network is also shown

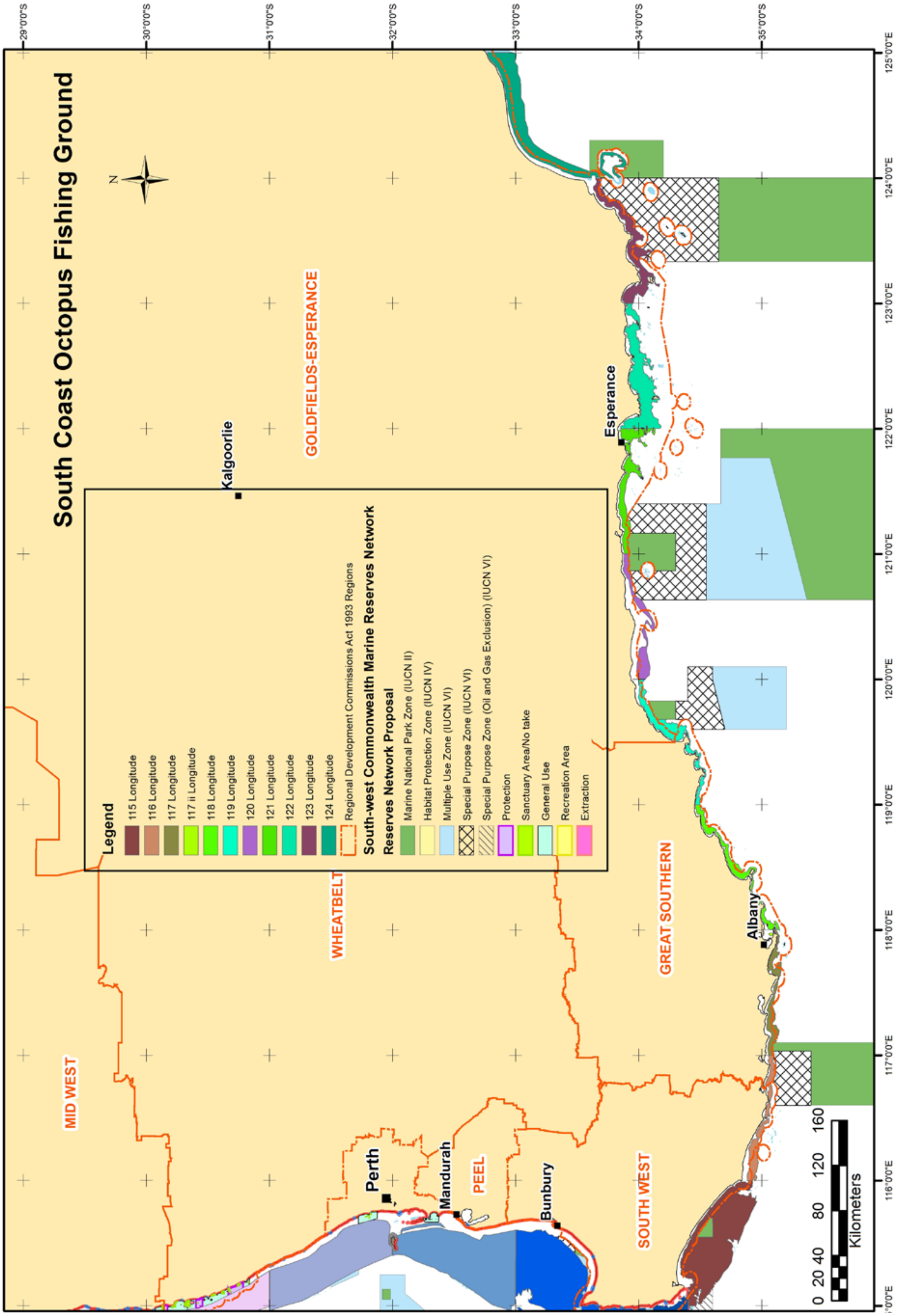


Figure 19 Map of the octopus fishing zones (by 1 degree longitude) of the south coast of Western Australia

The spatially explicit daily logbook data was used to ascertain the area fished each year by each commercial fishing vessel. The start and end GPS points of a group of cradles deployed over 1 day were used to determine linear distance of fished area. The width of the fishing area was then estimated by dividing the distance by the number of cradles hauled. Total area fished was calculated from the multiplication of distance x width. These estimates also allowed a calculation of an average area fished per pot. To account for fishers returning to the same grounds and overlapping effort, the area fished by each line was combined to form a polygon using the statistical software package R, with the overlap subtracted (Figure 20). An assumption of equal catchability between cradles was applied discarding variables such as: mechanical issues with the gear (e.g. faulty doors, fouling on the bait crab, burying of pots after storms) and the influence of small scale habitat differences.

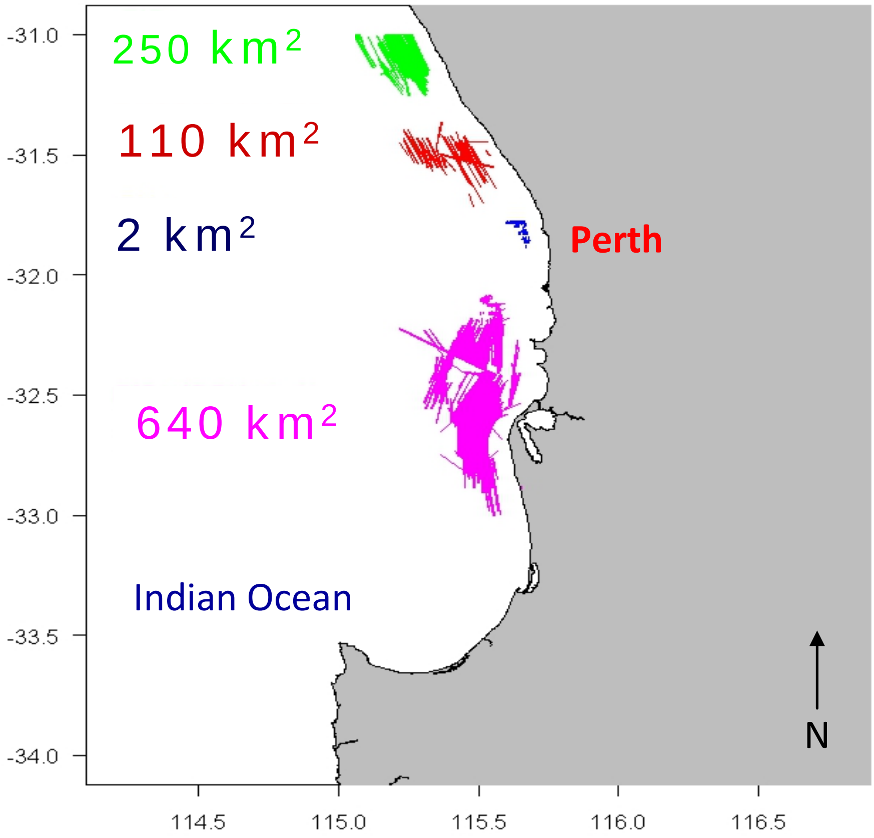


Figure 20 Map of polygons of areas fished in the C zone during 2010 by 4 different vessels

Biomass and abundance estimates were made for each fishing zone under three scenarios (Precautionary, Conservative and Possible). The estimates utilised knowledge of the total harvest area (Figure 18, Figure 19), area currently fished by the fishing fleet (see Figure 20 for an example), plus anecdotal evidence from fishers in both the DOF and WCRLF. Combined together, these various data sources indicated that *O.* (cf) *tetricus* is found across all depths and habitats, but with a sporadic and patchy rather than a uniform distribution. To account for this variability in density across the existing fishing grounds, and account for yet unexplored habitats, the three scenarios provided a range of potential biomass estimates using the concepts of "optimal" and "non-optimal" habitat. In "optimal" habitat, densities of octopus were assumed to be those estimated from the current fished area (~ 1500 km^2 of a total area estimate of ~ 30,000 km^2), whereas densities of octopus in "non-optimal" habitat were assumed to be only 30% of density in "optimal" habitat. The scenarios involved making informed assumptions regarding two key parameters, namely 1) total habitat area by habitat type, and 2) mean density of octopus.

Scenario 1 (precautionary): The current annual coverage of fishing operations in zone C was estimated at 1,002 km^2, compared to the total area of 14,310 km^2, or 7% of the total area. The 1,002 km^2 was assumed to be the complete extent of "optimal" fishing grounds for that zone, which had a mean density of 435 octopus km^{-2}. The remaining 93% was considered "non-optimal", with a biomass density of 30% of the optimal waters (130 octopus km^{-2}). The 30% biomass density was chosen as a precautionary measure. The same density for optimal and non-optimal waters was applied across all zones.

Scenario 2 (conservative): A hypothetical annual area of optimal fishing grounds in zone C of 20% of total, with the remaining 80% classified as non-optimal, having 30% of the biomass density of the optimal waters. The same density for optimal and non-optimal waters was applied across all zones.

Scenario 3 (possible): A hypothetical annual area of optimal fishing grounds in zone C of 30%, with the remaining 70% classified as non-optimal and having 30% of the biomass density of the optimal waters. The same density for optimal and non-optimal waters was applied across all zones.

The commercial daily logbook data was used to determine number per unit of effort (NPUE), which was the number of octopus caught per trigger trap hauled. Mean NPUE for each zone was based on April samples. April was used because it was consistently the peak catch rate (NPUE) and therefore maximum population biomass. Based on an average of an 11 day soak time for pots, a catchability coefficient (q) of 0.117 was derived from the results of the depletion experiment (see Results). An estimate of population (P) exploited by each trigger trap was derived by diving NPUE by the catchability coefficient, i.e . P = NPUE / q. Octopus density (D; km^{-2}) for each fishing zone was then calculated by $D = P / \bar{A}$, where $\bar{A}$ is the mean area fished per pot (0.0176 km^2). $\bar{A}$ for each vessel ($\bar{A}_V$) was obtained by dividing the total area fished (A_V) by the number of traps hauled (T_V), for each vessel per year ($\bar{A}_V = A_V / T_V$). The combined mean for all vessels ($\bar{A}$) included vessels that set cradles individually and those that connected cradles to demersal longlines.

Biomass estimates (B) were determined by multiplying the total area (A_T; km^2) of each strata (optimal; non-optimal) by the mean weight per octopus (W; kg) and then by octopus density (D) relevant to that strata (i.e. $B = A_T \times \mathrm{W} \times D$). Mean octopus weights of 1.44 kg for zones A / B and 1.58 kg for zones C / south coast, were applied due to latitudinal differences in the size of octopus (see Results).

3.4.3 Per-recruit analysis

Only female data were used in the per-recruit analysis, due to their functional role as semelparous spawners in the population. Females were classified as pre-spawning and spawning to identify spawners in the population. To differentiate between pre-spawning and spawning females, stage four and highly gravid stage three females with a FRW >80 g were classified as spawning. All other females were regarded as pre-spawning.

3.4.3.1 Fitting the model

The model accounts for the two-stage mortality inherent with the life history of *O.* (cf) *tetricus*, following the methods applied to the assessment of northern shortfin squid (*Illex illecebrosus*) by Hendrickson and Hart (2006). A maturity function $R(t)$ was incorporated to allocate individuals at age (in months, *t*) in the modelled population into pre-spawning ($N(t)$) and spawning ($S(t)$) components of the stock, upon which different rates of natural mortality (M_n, M_s) were applied, respectively. The Hendrickson and Hart (2006) model was fitted to data sampled from the DOF, which was reformulated to estimate the total mortalities of the pre-spawning and spawning components, denoted as Z_n and Z_s, respectively. This model is defined accordingly:

$$R(t) = \left(1 + e^{-B(t-A_{50})}\right)^{-1} \tag{8}$$

$$N(t) = N_0 \cdot e^{-[Z_n \cdot (t-a_0) + \int_{a_0}^{t} R(\tau)\mathrm{d}\tau]} \tag{9}$$

$$S(t) = e^{-(Z_n+Z_s)\cdot t} \cdot \int_{a_0}^{t} R(\tau) \cdot N(\tau) \cdot e^{(Z_n+Z_s)\cdot\tau} \mathrm{d}\tau \tag{10}$$

The functional form used to model $R(t)$ differed to the polynomial equation used by Hendrickson and Hart (2006) in that it was a simple logistic equation (Eqn. 8), where A_{50} was the estimated age at which 50% of females have attained effective maturity and B represented the slope at the inflection point of the curve. The age a_0 corresponds to the age prior to the first effectively mature female sampled, with N_0 being the number of non-spawning females in the population at that age, following Hendrickson and Hart (2006). Monthly age classes were applied due to insufficient data at a finer scale (Table 2 and Table 3). This model reformulation assumed that fully recruited fishing mortality. F_{tr}, was applied to octopuses in all age classes older than $a_{0.}$

Ageing errors were explicitly incorporated into the population models. For each octopus *j*, estimates of age (days, *X*) from each stylet reading *i* were subtracted from the mean of those estimates and then rescaled to the time step of months:

$$Y_{ij} = \frac{12 \cdot (X_{ij} - \bar{X}_j)}{365.25} \tag{11}$$

A Gaussian probability density function ($N(0, \sigma_Y^2)$) was then used to calculate an ageing error vector using the calculated variance of *Y* values σ_Y^2:

$$\Theta = (0.003\ 0.044\ 0.241\ 0.425\ 0.241\ 0.044\ 0.003) \qquad (12)$$

to convolve with the modelled numbers of mature and non-mature octopuses at age following Hendrickson and Hart (2006).

A fixed estimate for M_n = 2.36 yr^{-1} (0.197 $month^{-1}$) calculated using Hoenig's (1983) equation for molluscs using the maximum observed age (t_{max}) of 1.56 years (see Results). This was considered applicable for both males and females as they have similar longevities and was contingent upon the assumption that inferred longevity from t_{max} was largely reflective of survival prior to spawning and imminent death. However, it is possible that M_n = 2.36 may have been an overestimate since the Hoenig (1983) model did not account for two-stage mortality and the observed t_{max} was for a fished stock. Estimates of the instantaneous fishing mortality F_{tr} and M_s were determined as $F_{tr} = Z_n - M_n$ and $M_s = Z_s - F_{tr}$. Therefore, any possible overestimation of the input value for M_n would have resulted in an underestimation of F_{tr} and overestimation of M_s relative to the estimated Z_s. Accordingly, a sensitivity analysis was done to explore the effect of different inputted values of M_n on results.

The software package AD Model Builder (Otter Research Ltd, 2013) was used for the model fitting and parameter estimation. Data were pooled across years and months for analysis. Pooling data across months assumed that similar rates of mortality [Z_n, Z_s] and maturation would be reflected in samples collected in different months. This was considered reasonable, because mature females were observed in all months with some breeding seasonality. Additionally, no clear modal progression in sampled age frequency distributions was apparent across months, noting that these specimens were sampled from landed catches of trigger traps, of which some younger and older aged individuals were excluded (Table 2). This was taken to indicate year-round maturation, spawning, and post-spawning mortality for multiple cohorts in this stock. Pooling across years assumed no annual variation in mortality or maturation rates over the period of data collection (2010 - 2012).

Initial attempts to estimate all four model parameters [Z_n, Z_s, B, A_{50}] failed due to high correlations, especially between B and **ln** (Z_s) (positive), A_{50} and **ln** (Z_s) (negative), A_{50} and B (negative) and between B and **ln** (Z_n) (negative). Thus, constraints were applied to B and A_{50} in the form of informative priors generated by fitting the logistic model $R(t)$ (Equation 8) to the 2010 female maturity-at-age data, convolved with the ageing error vector Θ. The maximum likelihood estimates of B and A_{50} for the 2010 data were 1.10 and 13.67, with standard deviations 0.30 and 0.39. Assuming Normal prior distributions of $\mathrm{B} \cong N(1.10, 0.30^2)$ and $A_{50} \cong N(13.67, 0.39^2)$, $R(t)$ was fitted to the maturity data from 2011 and 2012, convolved with the ageing error vector Θ to obtain posterior estimates of B and A_{50} with priors incorporated in the objective function. The objective function consisted of four components:

1) Maturity data collected in 2011 and 2012 using a binomial log-likelihood calculated for the age range over which effectively mature females were sampled, from age a_0+1 (10 months) to $t_{\max}$ (17 months):

$$L_1 = \sum_{t=10}^{17}\left[\ln\binom{N_t}{k_t} + k_t \ln(\phi_t) + (N_t - k_t)\ln(1-\phi_t)\right] \tag{13}$$

2) Mortality data (multinomial log-likelihood), as formulated in Hendrickson and Hart (2006) was calculated from the age t_r at peak age frequency (12 months; assumed to be the age at full recruitment to the fishery) to $t_{\max}$:

$$L_2 = \ln\left[\frac{N!}{k_{12}!k_{13}!\ldots k_{17}!}\right] + \sum_{t=12}^{17} k_t \ln(qt) \tag{14}$$

3) prior likelihoods:

$$L_3 = -\ln\left(0.30\sqrt{2\pi}\right) - \frac{(B-1.10)^2}{2(0.30)^2} \text{ and } L_4 = -\ln\left(0.39\sqrt{2\pi}\right) - \frac{(A_{50}-13.67)^2}{2(0.39)^2} \tag{15}$$

4) The composite negative loglikelihood used for Bayesian modelling was:

$$L = -(L_1 + L_2 + L_3 + L_4) \tag{16}$$

Penalty functions were also implemented to ensure that $Z_{\mathrm{n}} \le Z_{\mathrm{s}}$ and to ensure the expected proportions at age in the multinomial log-likelihood did not equal zero. Locally (but wide) uniform priors for the total instantaneous mortality parameters to be estimated, i.e., $Z_{\mathrm{n}} \cong U(M_{\mathrm{n}}, e^{1.0})$; $Z_{\mathrm{s}} \cong U(M_{\mathrm{n}}, e^{3.0})$ were used for Bayesian estimation, by setting them as bounded parameters in ADMB. Equal weightings were applied to binomial and multinomial log-likelihoods and prior components of the composite objective function.

A Bayesian model-fitting approach was employed using a composite likelihood, with a Monte Carlo Markov Chain (MCMC) algorithm used to generate posterior values for the estimated model parameters and calculated quantities of interest (F_{tr}, $\mathrm{M_s}$). Initial values for three MCMC chains were initiated using starting values randomly sampled from the prior distributions. A minimum of 100,000 iterations were run for each chain, with every 100th value (thinning interval) saved and the first half of those 1000 values discarded to allow for the burn-in phase of the MCMC algorithm (Gelman et al. 2004). At the end of each MCMC run, the distribution of potential scale reduction factor (PSRF), values for each parameter, the multivariate PSFR and autocorrelation plots were inspected to assess convergence using the coda package in the software program R (R Core Development Team, 2013). Satisfactory convergence was achieved where all PSRF and multivariate PSRF values below 1.1 (Gelman et al. 2004). In addition, convergence of PSFR statistics were also monitored by inspecting plots of PSFR calculated for binned iterations of retained posterior values (Brooks and Gelman 1998). Acceptable convergence was achieved where the median PSRF values were consistently below 1.1 and the 97.5th percentiles of PSRF were consistently below 1.2 in these plots (Brooks and Gelman 1998). If these conditions were not met, the MCMC analysis was repeated with an increased length of burn-in, number of iterations and thinning interval. For this analysis, satisfactory convergence was not achieved until 25,600,000 iterations had been run for each chain.

Data used for estimation of priors on B and A_{50} (2010 data) and for fitting the full model (2011 - 12 data combined) are presented in Table 2 and Table 3. Summary statistics from these retained values, including the 95% credibility interval (taken as the 2.5th and 97.5th percentiles) and median of estimated parameters and derived quantities of interest (e.g., F_{tr}) were then obtained from the retained distribution of posterior estimates. Fitted values were calculated using the medians of posterior distributions for comparing graphically with the observed maturity at age and age frequency data for graphically assessing how well the fitted model approximated the data. Retained posterior values of estimated parameters were also used to calculate posterior distributions of the fitted values and thus obtain 95% confidence envelopes from the 2.5th and 97.5th percentiles of these calculated values.

3.4.3.2 Per-recruit modelling

Per-recruit model formulation required further specification for the numbers of non-spawning and spawning females in Equations 2-3:

$$N(t) = N_i \cdot e^{-M_\mathrm{n} \cdot t - \int_{t_f}^{t} F(\tau)\mathrm{d}\tau} \qquad \text{for} \quad t < a_0 \tag{17a}$$

$$N(t) = N_0 \cdot e^{-M_\mathrm{n} \cdot (t - a_0) - \int_{a_0}^{t} R(\tau)\mathrm{d}\tau - \int_{t_f}^{t} F(\tau)\mathrm{d}\tau} \qquad \text{for} \quad a_0 \le t \tag{17b}$$

$$\text{where:} \qquad N_0 = N_i \cdot e^{-M_\mathrm{n} \cdot a_0} \tag{17c}$$

and where N_i was the initial number of non-spawning females at age 0. The equation for fully-recruited fishing mortality with age for per-recruitment modelling was obtained by multiplying F_{t_r} with model estimated selectivity at age, $F(t) = s(t) \cdot F_{t_r}$. The equation for $s(t)$ was a logistic equation with the same functional form as Equation 8 with slope and average age parameters estimated $B_s = 1.04, A_{50_s} = 9.90$ by fitting this model to selectivity coefficients. Selectivity coefficients for ages younger than t_r were calculated as the ratios of the observed age frequencies to back-calculated fully available frequencies, $\varsigma(t-1) = \varsigma(t) / \exp(-M_\mathrm{n})$ from $t_r \to t_c$ where t_c was age of the youngest observed age frequency. This model was fitted by maximising the same form of log likelihood as formulated for L_2. Note that the estimated average age selected from this model fit, $A_{50s} \approx a_0 + 1$, supported the selected location of knife-edged selectivity assumed in estimating $Z_\mathrm{n}, Z_\mathrm{s}, B, A_{50}$ with the simpler model (Equations 8 - 10).

The equation for the numbers of spawning females at age with fishing followed the general formulation of Hendrickson and Hart (2006):

$$S(t)=\frac{\int_{a_0}^{t} R(\tau)\cdot N(\tau)\cdot J(\tau)\mathrm{d}\tau}{J(t)} \tag{18a}$$

where: $J(t)=e^{(M_\mathrm{n}+M_\mathrm{s})\cdot(t-a_0)+\int_{a_0}^{t}F(\tau)\mathrm{d}\tau}$ (18b)

Yield-per-recruit (YPR) and Spawning Biomass Per Recruit (SBPR) models for females in the age range a_0 to t_max were based on the equations of Hendrickson and Hart (2006):

$$\mathrm{YPR}=\int_{a_0}^{t_\mathrm{max}}[N(\tau)+S(\tau)]\cdot F(\tau)\cdot W(\tau)\mathrm{d}\tau \tag{19}$$

$$\mathrm{SBPR}=\int_{a_0}^{t_\mathrm{max}} S(\tau)\cdot W(\tau)\mathrm{d}\tau \tag{20}$$

and $W(t)$ is the weight at age relationship for females $W(t)=0.0134\cdot t^{1.9782}$.

The retained 1,500 posterior values from the Bayesian analyses were then used as inputs into Equations 13 - 17 in order to transfer posterior estimates and uncertainty about those values into results from per-recruitment modelling.

Sensitivity analyses of those results were then done for varying input values of M_n from $0.5\times\frac{1}{12}$ to $\hat{Z}_\mathrm{n}$, (*M*=0.5 was suggested by Caddy (1996) as a plausible lower bound for semelparous invertebrates). Sensitivity analyses were also conducted for varying average ages of full selectivity, t_f from 1 to t_max. This was done to account for uncertainties arising from the capture of smaller, younger females by the shelter-pot fishers and to evaluate potential impacts of future shifts in gear selectivity for octopuses of different sizes and ages, on *YPR* and *SPR*. Alternative formulations for $N(t)$ and $S(t)$ were required for modelling *YPR* and *SPR* using knife-edged selectivity for a range of different values for t_f and are provided in Appendix 1.

3.4.3.3 Estimation of sustainable catch limits

The model formulas for calculating $N(t)$ and $S(t)$ were summed to calculate unscaled population abundances (i.e., $A(t)=N(t)+S(t)$) for each of the following values for F_{t_r} in the set *D* (F_{t_r} scenarios): $F_{t_r}\in D=\{0,\hat{F}_{2011,2012},F_{SPR_{0.2}},F_{SPR_{0.3}},F_{SPR_{0.4}}\}$. Monthly mortality rates, $Z(t)$, for each F_{t_r} scenario were thus due to the combined influence of Z_n and Z_s, assuming no net migration and stable age distributions. The $Z(t)$ values were calculated by subtracting from one the ratio of the change in unscaled abundance from one month to the next, $Z(t)=1-A(t-1)/A(t)$. Monthly harvest rates $H(t)$ were then calculated by subtracting the $Z(t)$ for the $F_{t_r}=0$ scenario from the $Z(t)$ for each of the other fished F_{t_r} scenarios. For the case where $F_{t_r}=\hat{F}_{2011,2012}$ the unscaled abundances at age $A(t)$ were scaled to estimates of population abundance at age $\hat{A}(t)$ using the three abundance scenarios for $\hat{A}$ in the set ($\hat{A}_1$

(precautionary) = 5.57 x 10^6, $\hat{A}_2$ (conservative) = 7.02 x 10^6 and $\hat{A}_3$ (possible) = 8.14 x 10^6) and observed relative frequencies of octopus at age $C(t)$ sampled for fully recruited ages:

$$\text{for } t_r \rightarrow t_{\max}: \quad \hat{A}(t) = \left(\hat{A} \cdot \sum_{t=t_r}^{t_{\max}} \left(\frac{C(t)}{\sum_{t=t_c}^{t_{\max}} C(t)} \right) \right) \cdot \frac{A(t)}{\sum_{t=t_r}^{t_{\max}} A(t)} \qquad (21)$$

The $\hat{A}(t)$ for fully recruited ages and calculated $Z(t)$ values were then used to back-calculate $\hat{A}(t)$ for age classes younger than t_r for the $F_{t_r} = \hat{F}_{2011,2012}$ scenario:

$$\text{for } t_r \rightarrow t_c: \quad \hat{A}(t-1) = \frac{\hat{A}(t)}{1 - Z(t-1)} \qquad (22)$$

The $\hat{A}(t)$ for other scenarios belonging to the set G, which we have denoted as $\hat{A}_G(t)$, where $F_{t_r} \in G = \{F_{t_r} : F_{t_r} \in D \text{ and } F_{t_r} \neq \hat{F}_{2011,2012}\}$ were then calculated accordingly:

$$\hat{A}_{\mathrm{G}}(t) = \hat{A}(t) \cdot \frac{A_{\mathrm{G}}(t)}{A(t)} \qquad (23)$$

Estimates of catch at each age (numbers of octopus) were then calculated as the product of monthly harvest rates with estimated abundances $\hat{C}(t) = H(t) \cdot \hat{N}(t)$. Catch biomass' at age were calculated by multiplying the $\hat{C}(t)$ by corresponding values of $W(t)$, which were then summed over all months to get annual estimates of catch corresponding to each F_{t_r} scenario. Catch estimates were calculated for differences in $W(t)$ for males and females, in order to demonstrate the range of uncertainty in results due to the sex-specific differences in weight and unknown sex ratios of future catches in unfished areas.

Table 2 **Summary of estimated ages of female *Octopus* (cf) *tetricus* (in months) sampled from the landed catches of commercial trigger traps in different months of the year, pooled across years 2010 – 2012**

Month	N	Minimum age (months)	Mean age (months)	Age mode(s) (months)	Maximum age (months)
Jan	14	8	10.5	9,10	14
Feb	120	3	10.2	12,14	16
Mar	90	6	11.6	9,11	15
Apr	48	5	9.7	12	16
May	43	8	11.7	9,11	15
Jun	148	6	10.5	12	17
Jul	22	8	12.2	10	15
Aug	102	8	12.7	12	17
Sep	40	8	10.9	12	13
Oct	7	10	12.3	10	15
Nov	53	6	10.3	11	14
Dec	21	6	10.1	11,12	14

Table 3 **Female age and maturity data**

	2010			2011 & 2012		
Age (months)	N	N mature	Mature %	N	N mature	Mature %
10	50	1	2.00%	70	1	1.43%
11	36	3	8.33%	96	9	9.38%
12	31	8	25.81%	99	17	17.17%
13	23	5	21.74%	67	11	16.42%
14	9	5	55.56%	51	23	45.10%
15	3	3	100.00%	18	10	55.56%
16	1	1	100.00%	6	2	33.33%

3.4.4 Empirical modelling of the effects of environment on potential harvest

The north-south orientation of the west coast (zones A, B and C), relative uniformity of oceanic processes (minimal river outflow and upwelling), bathymetry (consistent shelf area) and coastal topography (few embayment’s or peninsula’s), enabled latitude to be used as an environmental proxy for Sea Surface Temperature (SST). Daily logbook data was used to derive an index of octopus size (mean weight in kg). Average size was then modelled with a GLM incorporating: year, month, latitude (29-30° S, 30 – 31°S, 31 -32°S, 32 -33°S, 33 - 34°S) and depth, to establish the importance of latitude (as a proxy for environment) for determining individual biomass, in comparison to other factors. The model is described as follows:

$$O_i = \beta_\mathrm{y} + \beta_\mathrm{m} + \beta_\mathrm{L} + \beta_\mathrm{d} + \varepsilon_i \,, \qquad (24)$$

where O_i is the octopus average weight index, β_y is the effect of year, β_m is the effect of monthly variation arising from changes in factors varying seasonally, β_L is the effect of Latitude on octopus weight, β_d is the effect of depth on octopus weight, and $\varepsilon \sim N(0, \theta^2)$.

3.5 Octopus predation on lobsters

3.5.1 Background

This section addresses objective 4. Objective 4 is to calculate the effects of fishing closures on octopus predation rates on rock lobsters. In-pot octopus predation of rock lobsters in the WCRLF, is easily identified by the way octopuses dismember a lobster’s exoskeleton around the cephalothorax (Joll 1977b). The uniqueness of this method of killing and consuming a lobster, enables the identification of octopus predation without an octopus present. The possibility of an octopus species other than *O.* (cf) *tetricus* being responsible for lobster predation in the WCRLF is minimal, due to most other species found in the region are either too small or do not frequent the habitats in which rock lobster fishing occurs (Norman and Reid 2000). Lobster fishing is less developed on the south coast with annual catches ranging 50 – 80 t per year (How and Stadler 2013). In addition to *Panulirus cygnus*, the southern rock lobster (*Jasus edwardsii*) is also caught in the south coast lobster fishery and are preyed upon my *Macroctopus maorum* as well as *O.* (cf) *tetricus*. The smaller economic imperative of the south coast fishery has prevented research into the impacts of octopus predation on catch rates in this zone.

3.5.2 Predation analysis

The rate of octopus predation on lobsters in the WCRFL has been documented in a fishery commercial monitoring program since 1980. The monitoring program involves a randomised survey of lobster catch rates and ancillary data, such as octopus present or predating, on rock lobsters. Lobster pots are randomly sampled across various depth (range = 0 – 50 m) and locations (from Kalbarri (28° latitude) to Fremantle (32° latitude)) to determine the lobster catch rate, sex composition, and octopus predation rates. The commercial rock lobster fishery monitoring program data for the period of 1980 – 2012, was used to derive 2 abundance indices for octopus predation in the WCRLF in relation to effort (i.e. potlifts): O_1 = daily estimates of catch by the number of octopus caught per 1000 potlifts; O_2 = the number of pots with evidence of octopus predation per 1000 potlifts. O_1 and O_2 were then modelled with a Generalised Linear Model (GLM) incorporating: year, month, soak time (number of days pots were left in the water), location, and depth, to establish which were the most important in determining octopus predation rates. The model is described as follows:

$$\log(O_i + 0.01) = \beta_{\mathrm{y}} + \beta_{\mathrm{m}} + \beta_{\mathrm{s}} + \beta_{\mathrm{l}} + \beta_{\mathrm{d}} + \varepsilon_i\,, \tag{25}$$

where O_i is the octopus index, β_{y} is the effect of year, β_{m} is the effect of monthly variation arising from changes in factors varying seasonally, β_{s} is the effect of soak time on octopus abundance, β_{l} is the effect of location on octopus abundance, β_{d} is the effect of depth on octopus abundance, and $\varepsilon \sim N(0, \theta^2)$.

4 Results

4.1 Age determination

4.1.1 Age validation

This section addresses part of objective 1. Objective 1 is to describe the general life history of O. tetricus in WA, including age, growth and reproductive biology. Of the three validation methods tested (OTC, AC, and calcine), only the calcine treatment was successful, with 12 of the 15 injected octopus displaying calcine marks. A strong linear relationship ($r^2 = 0.98$) was observed between the number of increments counted (periodicity = 0.92, confidence intervals range = 0.82 – 1.01) and number of days, following treatment with calcine for the successfully stained male octopuses (*n* = 9) (Figure 21). Thus, indicating that stylet increments are deposited daily for males. However, the three females injected with calcine provided inconclusive results. These females either laid eggs or were about to lay eggs prior to termination of the experiment. For each female, the calcine mark stained to the margin of the stylet margin/edge suggesting that for females, stylet increment formation may cease at or just before the deposition of eggs. Without irrefutable evidence of the contrary, the present study assumed that prior to spawning females form daily growth rings throughout the course of their lives in a similar manner to males. The three unsuccessful marked octopuses were all males and occurred during the second batch of injections in August 2012. All unsuccessful injections were the result of handling error, where due to insufficient needle penetration, the calcine remained in the flesh of the octopus and was not taken up by the stylet.

4.1.2 Stylet increment analysis

A strong power curve relationship between age and stylet weight was identified across all aged octopuses ($r^2 = 0.8$), and was strengthened by the 5% precision rule ($r^2 = 0.91$) (Figure 22a). Age estimates were highly correlated between females and males at 0.956, and demonstrated very similarly shaped power curves for age versus stylet weight (Figure 22b). This strong positive curve-linear relationship between stylet weight and increment number, combined with the results from the age validation, supports the use of stylet weight as a proxy for age in *O.* (cf) *tetricus*. For all 3280 stylets weighed (1108 females and 2384 males), both females ($r^2 = 0.8884$) and males ($r^2 = 0.8165$) demonstrated a strong relationship between stylet weight and total weight (Figure 23). However, for females this relationship was strongly influenced by ovary weight, particularly for individuals weighing >2000 g. In addition, there were fewer females with stylets weighing >0.35 g than males, suggesting a shorter maximum age. However, this may be a product of the smaller number of females sampled and selectivity of gear or the potential effects of females ceasing to form increments during spawning.

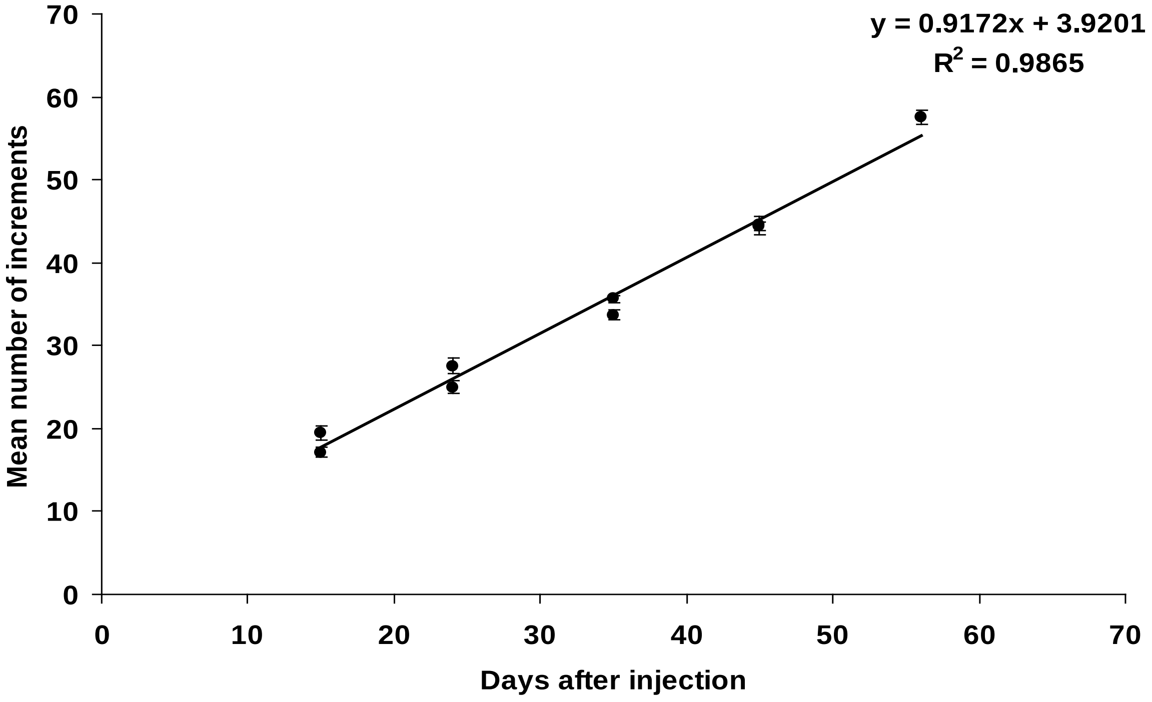


Figure 21 **Mean stylet increment count (±SE) subsequent to calcine injection as a function of days post-injection**

Of the 251 stylets aged, 132 stylets (52%) met the 5% precision rule (see section 1.4 for description of precision rule). The successfully aged octopuses had age ranges of 91 – 677 days, stylets weights of 0.005 – 0.59 g and total weights of 112 – 3682 g. The percentage of discards for the 5% precision rule did not show any distinct patterns of bias across age classes, with the bulk of octopus aged between 180 – 450 days. The mean number of images taken to capture all rings across the plane of a stylet for octopuses aged <200 days was 3.7, where octopus aged >450 days the mean number of images was 12.7. A paired *t*-test revealed that the counts from Reader 1 (Leporati) were not significantly different (t = 1.07, df 9, p = 0.309) from Reader 2 with a mean difference of 27.3 increments and a correlation of 0.873 (Figure 24a). A consistent and significant difference (t = 3.88, df 9, p = 0.003) was identified between readers 1 and 3, with a mean difference of 103.3 increments and a correlation of 0.953. The difference in results between Reader 1 and Reader 3 was evaluated from the estimated parameters of a regression of Reader 3 on Reader 1 counts. The regression indicated that that Reader 3 had increasingly higher counts for larger stylets than Reader 1 (Figure 24b).

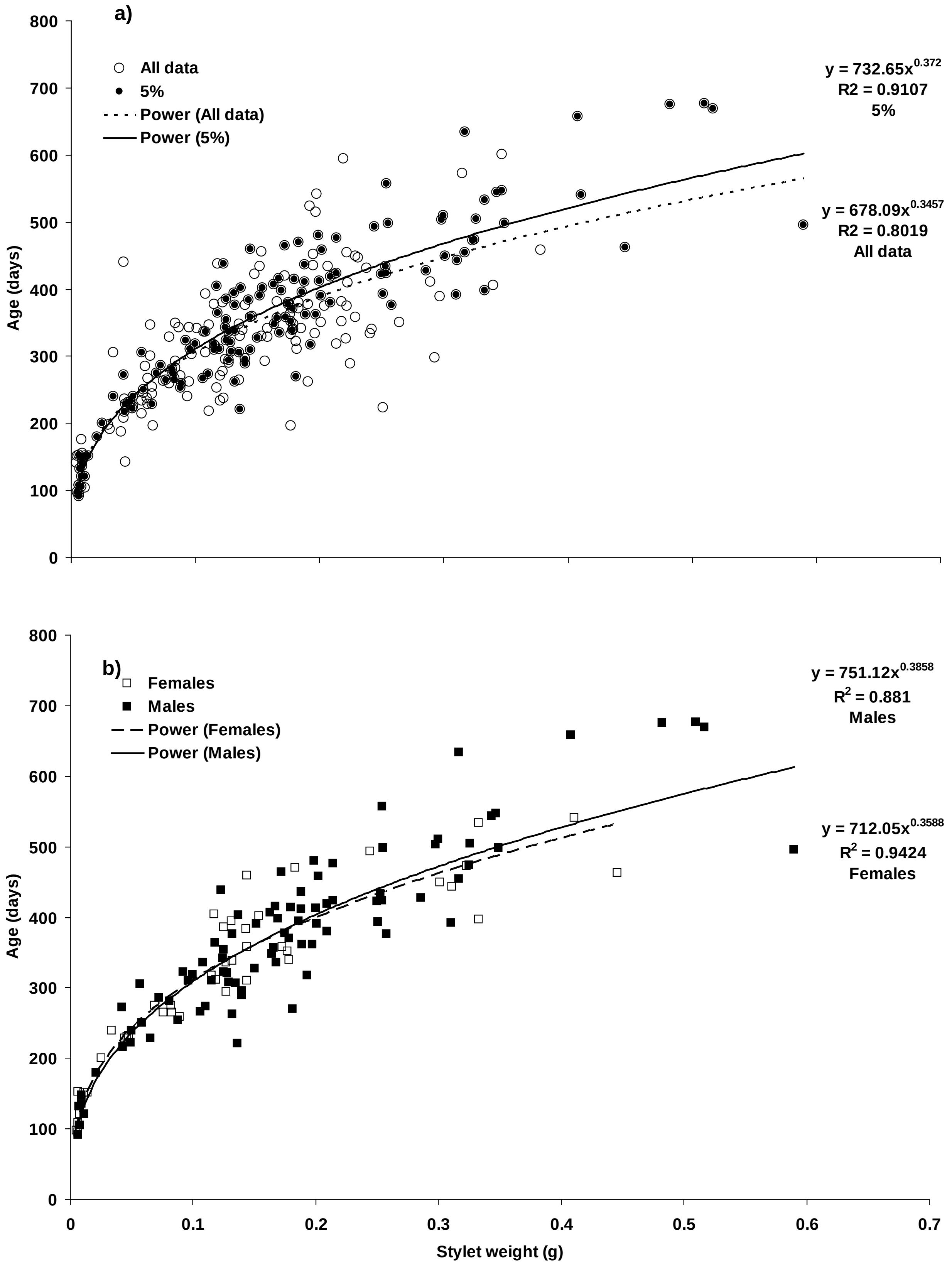


Figure 22 Age estimates (number of increments) as a function of stylet weight for (a) all octopus, and (b) by sex. In (a) data divided into all data (white dot), and data which met the 5% precision rule (see section 1.4 for a description of the 5% precision rule)

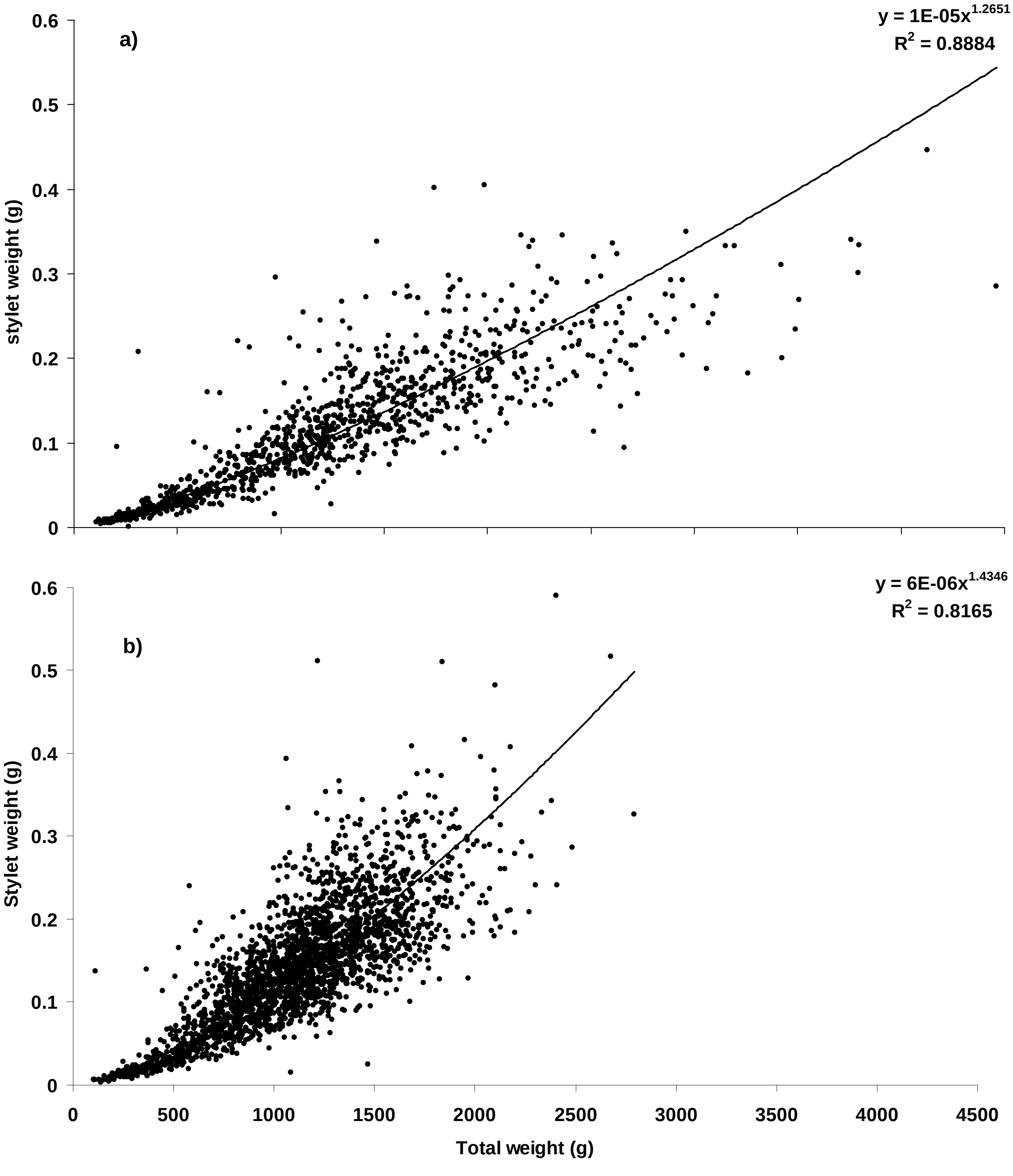


Figure 23 Stylet weight vs total weight for (a) female and (b) male *Octopus* (cf) *tetricus*

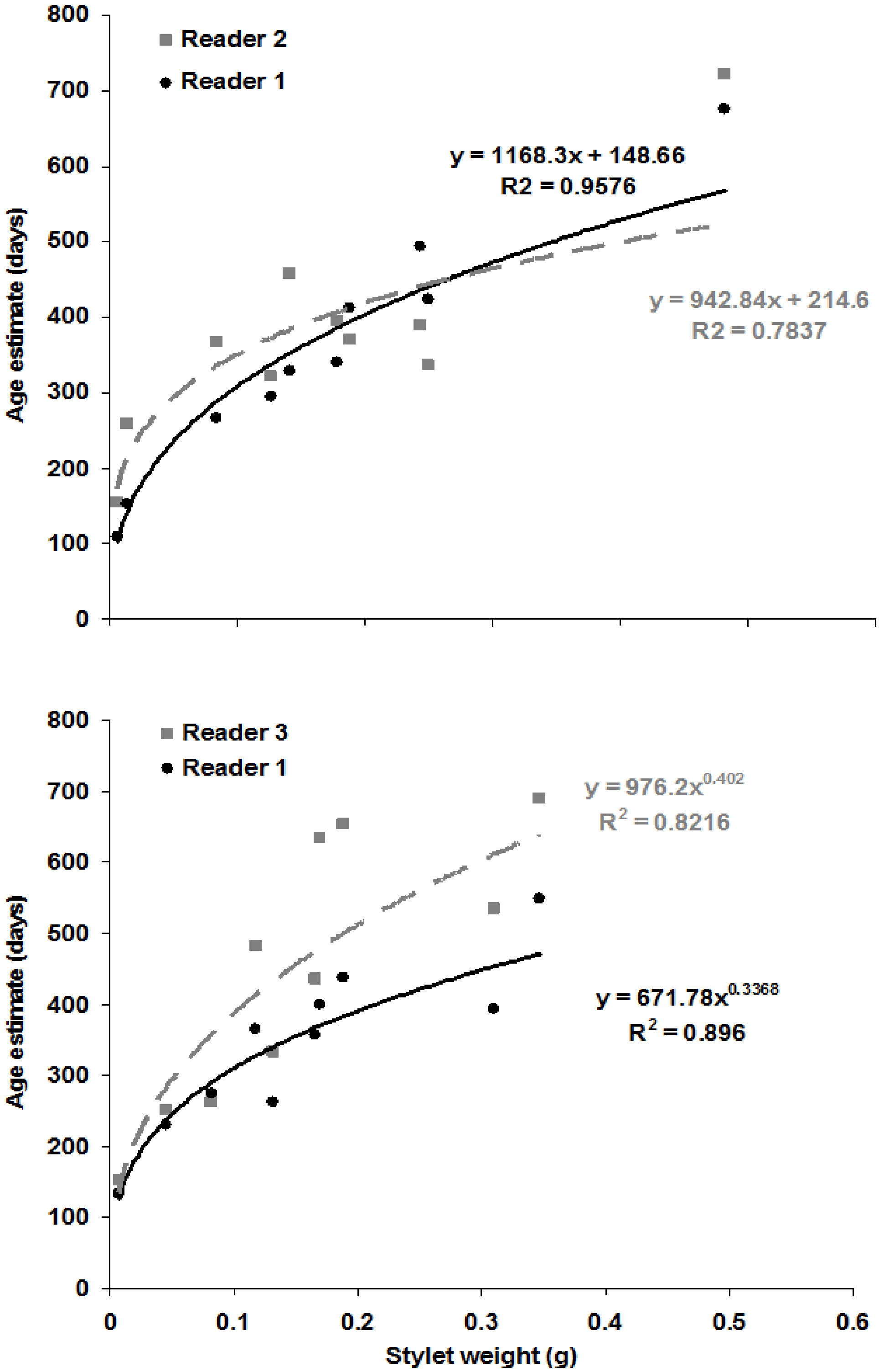


Figure 24 Comparison of age estimates between (a) reader 1 (SCL) and reader 2, and (b) reader 1 (Leporati) and reader 3, for *n* = 10 stylets of varying weight (0.01 to 0.48 g)

4.1.3 Application of age data

Age estimates were derived from the power curve relationships in Figure 22b for males and females, for the remaining 3280 octopuses (1108 females and 2384 males) from the biological samples. Ages ranged from 94 – 542 days (mean = 303 days) for females and 84 – 601 days (mean = 339 days) for males (Figure 25). Percentage frequency of females and males at 50-day age classes revealed that both females and males were predominantly aged between 300 – 400 days. Females demonstrated a higher proportion of younger octopuses between 100 – 300 days than males. Both sexes had sharp drops in representation at 450 days onwards (Figure 25). Mantle length was shown to have a strong relationship with age for both females (r^2 = 0.85) and males (r^2 = 0.80) (Figure 26 a, b).

Total weight ranged from 108 – 4460 g (mean = 1217 g) for females and 104 – 2079 g (mean = 1105 g) for males. Growth rates ranged from 2.69 – 12.1% bw d^{-1} (mean = 4.9% bw d^{-1}) for females and 2.08 – 13.6% bw day^{-1} (mean = 4.2% bw d^{-1}) for males.

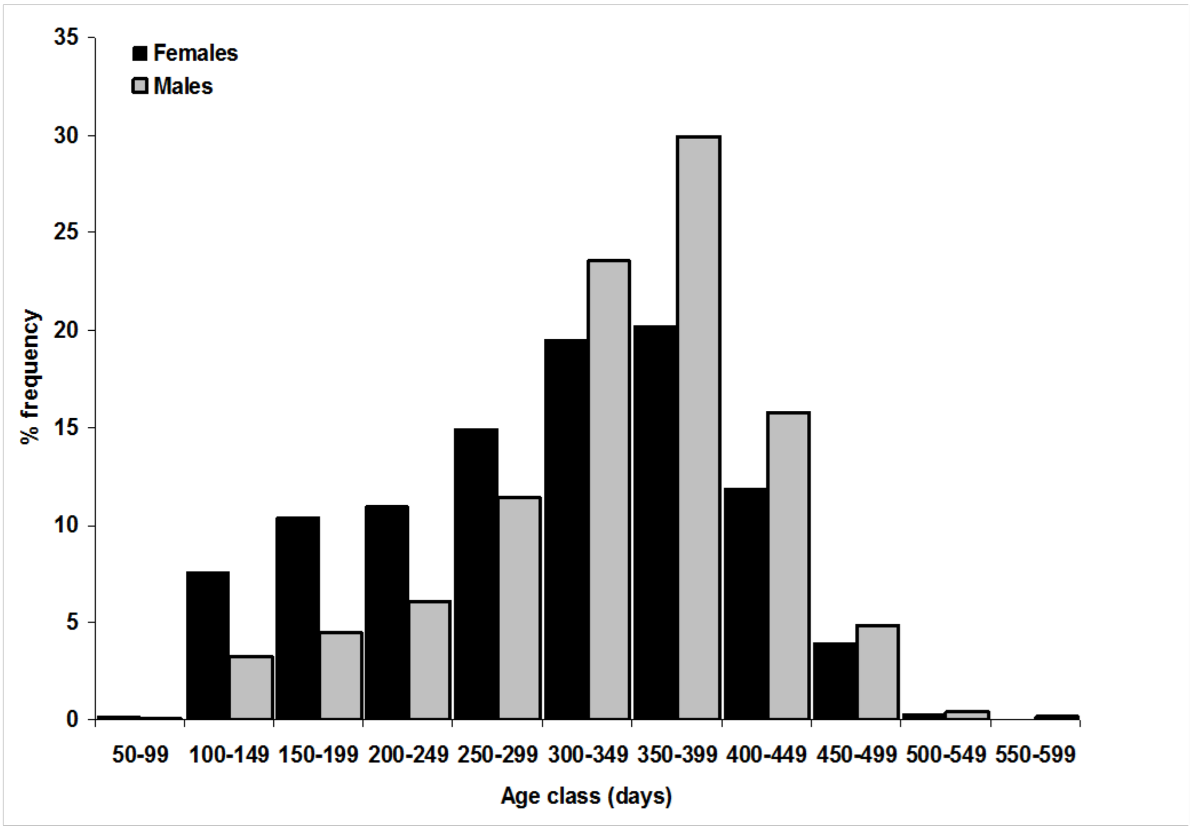


Figure 25 Comparison of age frequency distribution for females and males *Octopus (cf) tetricus*, *n* = 3470

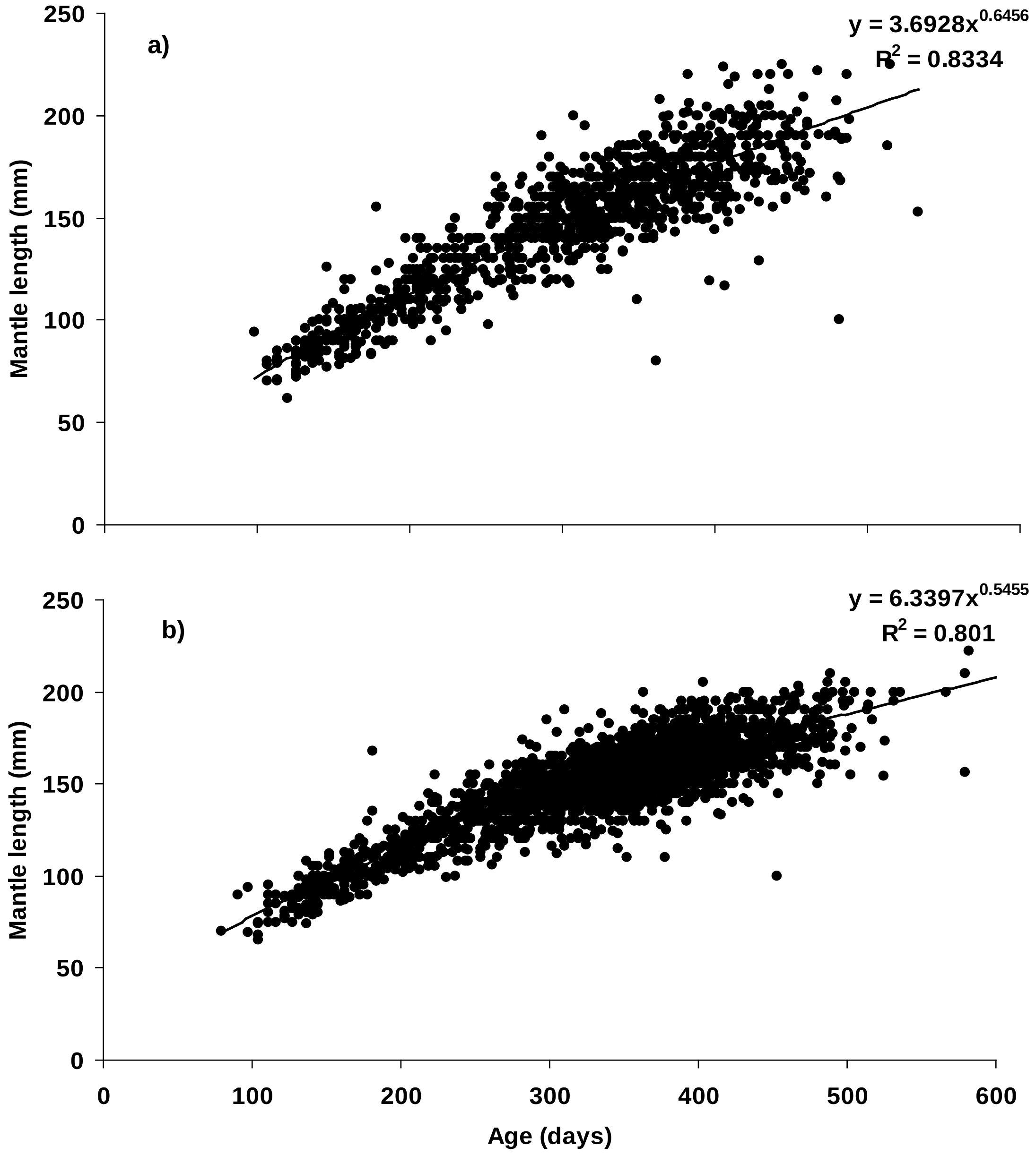


Figure 26 **Mantle length (mm) as a function of age (days) in (a) female and b) male *Octopus* (cf) *tetricus* sampled from the octopus fishery**

4.2 Life history

This section addresses part of objective 1. Objective 1 is to describe the general life history of *O. tetricus* in WA, including age, growth and reproductive biology. Sex ratios varied between gear types, with females averaging 57% and 24% of shelter pot and trigger trap catches, respectively (Table 4). Male domination of trigger trap catches was across all years and months. However, a distinct monthly pattern was evident, with an increase in the proportion of females during March/April (autumn) and the highest proportion of males during

October/November (spring) (Figure 27). For shelter pots, biological sampling data was not complete for all seasons across all years. However, the available data revealed relatively consistent sex ratios across all months, years and depths, with a slight bias towards females in the catches ranging 50 -59%.

Females caught in shelter pots were significantly (t = -30.61, df 1108, p = 0.00) younger (mean = 215 days shelter; mean = 350 days trigger) and significantly (t = -35.56, df 2729, p = 0.00) lighter (mean = 754 g shelter; mean = 1520 g trigger) than females caught in trigger traps (Table 4). Males caught in shelter pots were also significantly (t = -39.46, df 2382, p = 0.00) younger (mean = 211 days; mean = 360 days trigger) and significantly (t = -40.04, df 4608, p = 0.00) lighter (mean = 711 g shelter; mean = 1207 g trigger) than males caught in trigger traps (Figure 28). The maximum weight for females caught in trigger traps was 4400 g compared to 2700 g for males (Table 4). No significant difference was evident in the ages of females and males caught in shelter pots (t = 0.69, df 701, p = 0.48), however, trigger trap caught males were significantly (t = -3.75, df 2788, p = 0.00) older than trigger trap caught females. Whereas, females caught in both shelter pots (t = 2.52, df 2889, p = 0.01) and trigger traps (t = 20.02, df 4448, p = 0.00) weighed significantly more than males (Table 4).

Female ovary weights were significantly different between shelter pots and trigger traps (t = -26.47, df 2743, p = 0.00), averaging 3 g (range = 0.05 – 81 g) for shelter pots and 45 g (range = 0.1 – 482 g) for trigger traps. Females with ovaries weighing >80 g were considered highly gravid, with only one found in the shelter pot samples and 161 found in the trigger traps. Incidences of spent females were also very low with only 22 (0.8%) identified across all gear types, depth and years. All of the 22 spent females were caught in trigger traps, 17 of which came from a single vessel, during a single days fishing at 40 m deep. The reproductive stage for each of the 17 females was verified during processing and the abnormality of the event noted. The eight brooding females maintained in captivity confirmed that there was no confusion in the classification of immature and spent females.

Weight, length and age at 50% maturity were 1794 g, 182 mm and 379 days for females; and 941 g, 128 mm and 243 days for males (Figure 29, Figure 30, Figure 31). Weight at 50% maturity was more variable for females than males, due to the influence of ovary weight (Figure 29a). The younger age at maturity for males and retiring of brooding females to lairs, translates to males actively mating for up to six months longer than females of equivalent age.

Table 4 Age and growth for shelter pot and trigger traps from biological sampling (standard error)

		Females		Males	
		Shelter pot	Trigger Trap	Shelter pot	Trigger Trap
All biological data	Sample size	1655	1078	1239	3371
	Weight range (g)	33 – 2689	146 – 4460	36 – 2181	111 – 2790
	Mean weight (g)	754 (11.84)	1522 (19.52)	711 (11.26)	1207 (6.25)
Age data	Sample size	378	732	326	2058
	Age range (days)	56 – 461	121 – 542	84 – 441	132 – 601
	Mean age (days)	215 (3.96)	350 (2.52)	211 (3.9)	360 (3.42)
	Growth range (% bw day^{-1})	3.12 – 12.16	2.69 – 9.5	3.18 – 13.63	2.39 – 9.16
	Mean growth (% bw day^{-1})	6.54 (0.10)	4.1 (0.03)	6.6 (0.10)	3.89 (0.04)

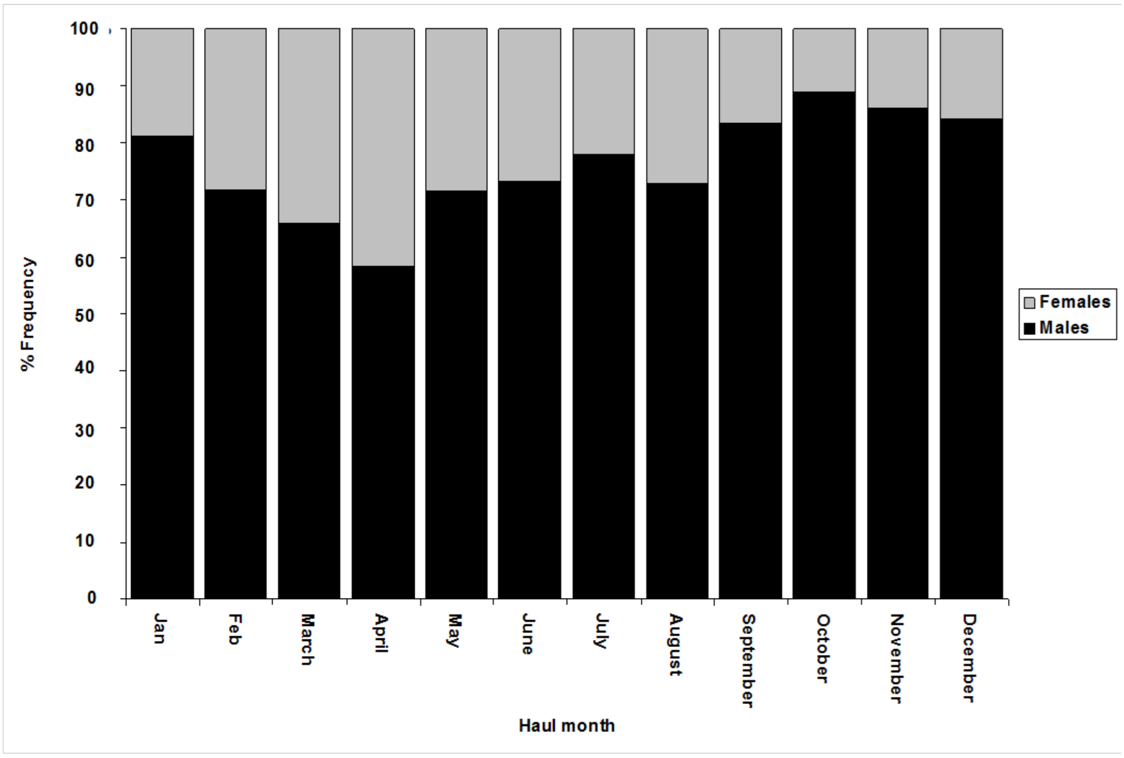


Figure 27 Percent frequency of male and female *Octopus (cf) tetricus* caught each month with trigger traps, during 2008 to 2012 (*n* = 4544)

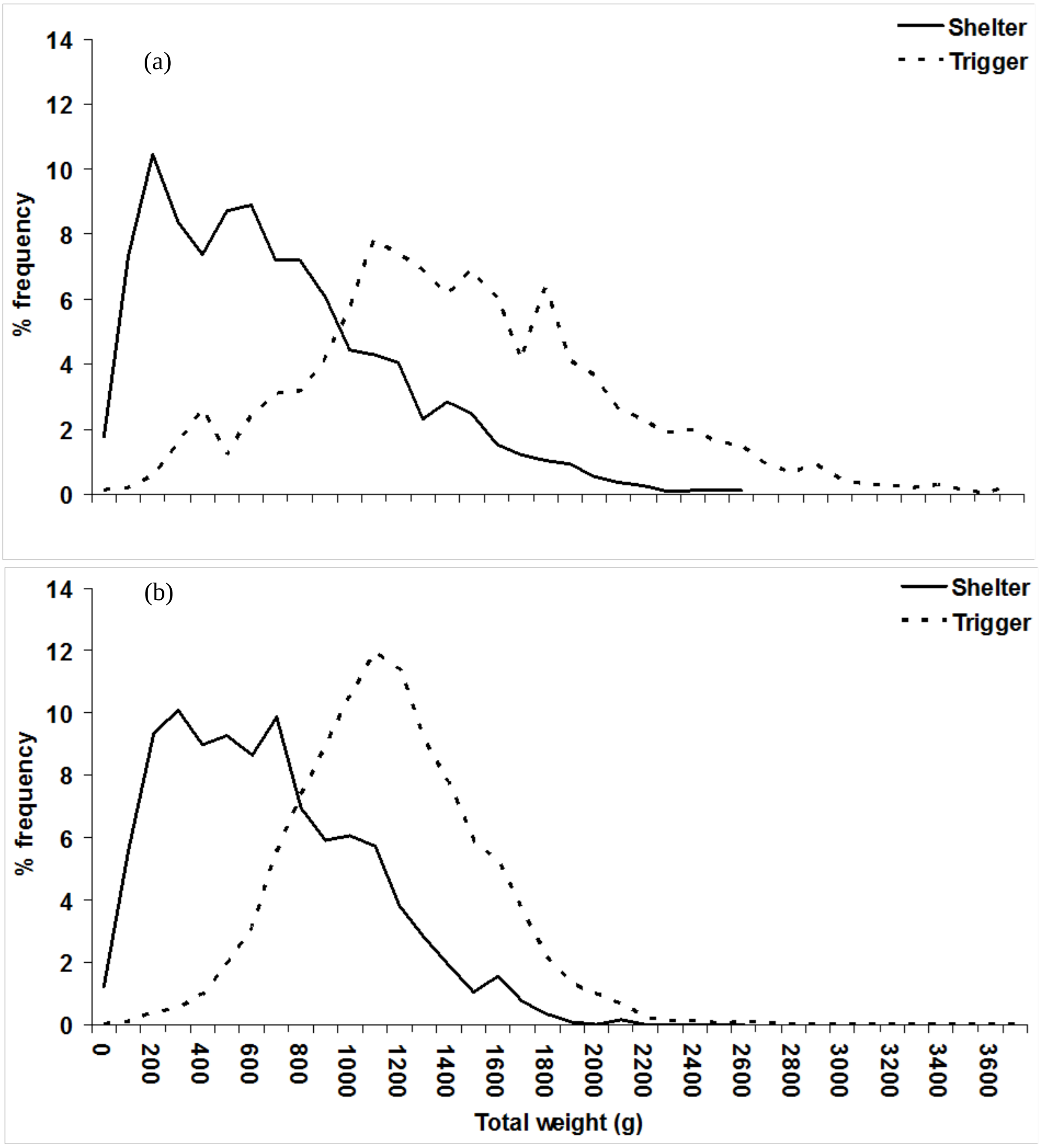


Figure 28 Percentage frequency for total weight of (a) female (*n* = 2733) and (b) male (*n* = 4610) *Octopus (cf) tetricus*, in 200 g size classes, for shelter pots (black line) and trigger traps (broken line)

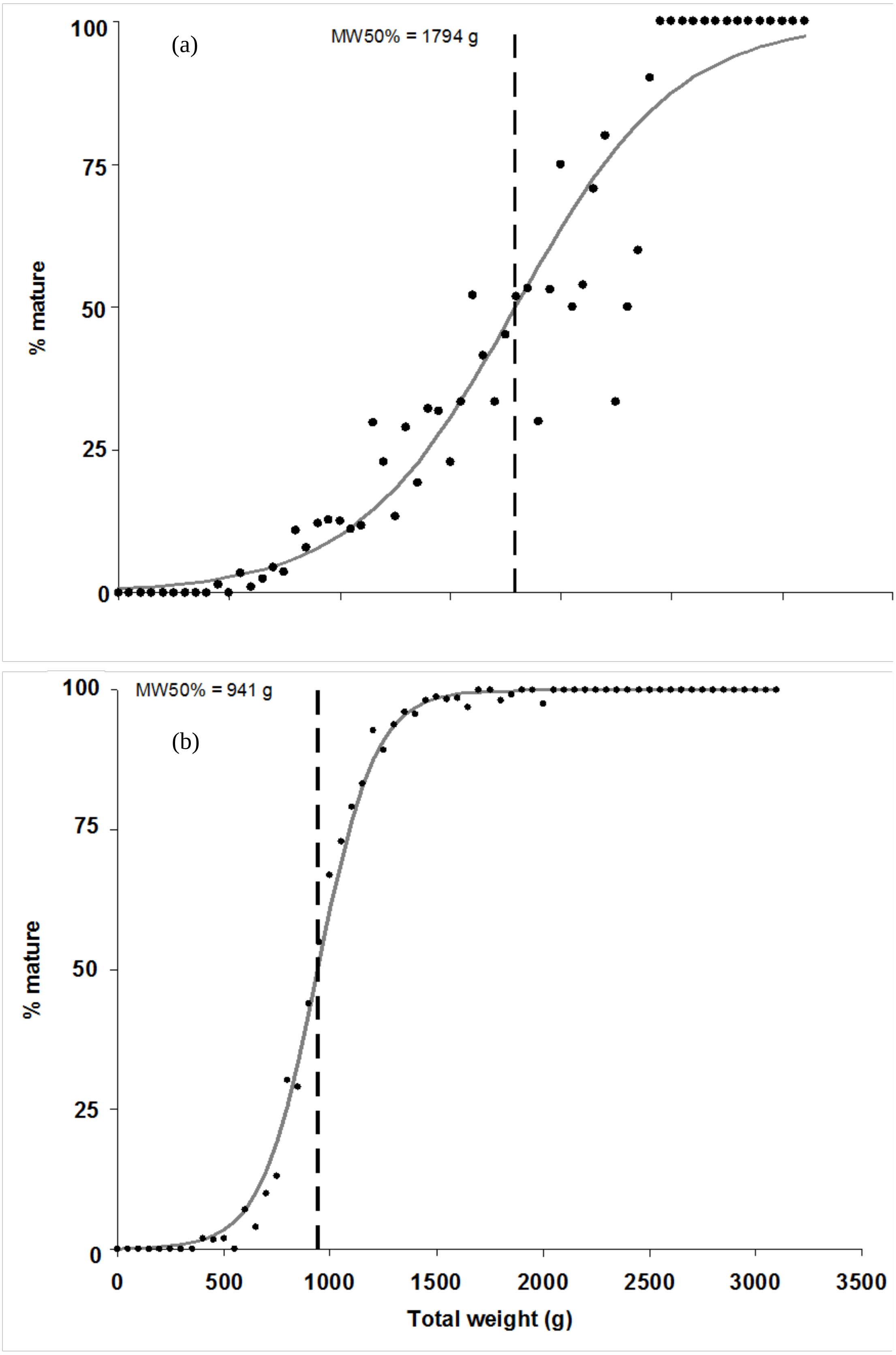


Figure 29 Size (total weight) at 50% maturity (MW50%) for *Octopus (cf) tetricus* (a) females *n* = 2603 and (b) males *n* = 4397, covering all depths and gear types in 50 g weight classes

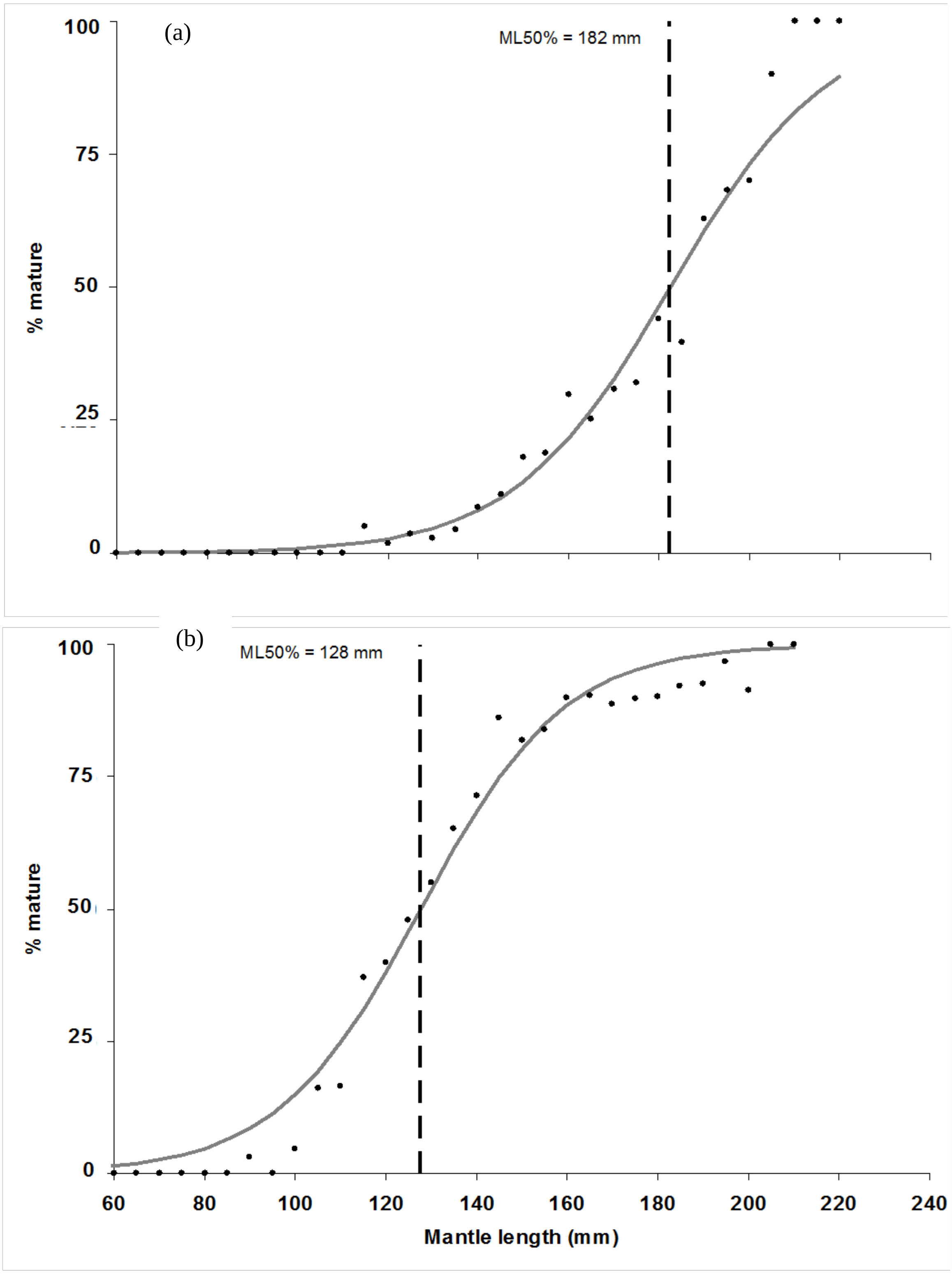


Figure 30 Length (mantle length) at 50% maturity (ML50%) for *Octopus (cf) tetricus* (a) females *n* = 2631 and (b) males *n* = 4480, covering all depths and gear types in 5 mm size classes

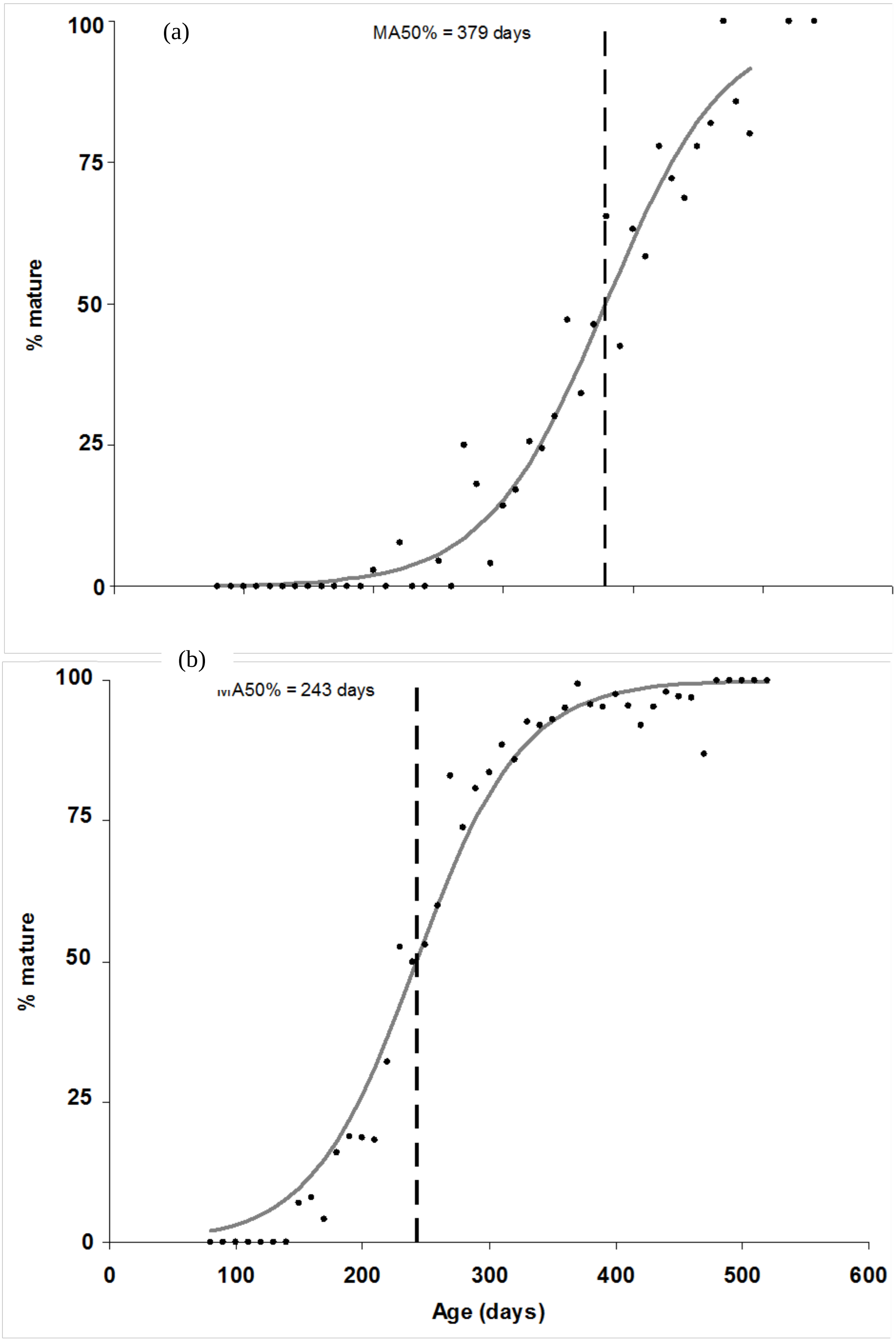


Figure 31 Age (days) at 50% maturity (MA50%) for *Octopus (cf) tetricus* (a) females *n* = 1083 and (b) males *n* = 2304, covering all depths and gear types in 10 day age classes

Total weight had a positive power curve relationship with age for both females (r^2 = 0.89) and males (r^2 = 0.81). The strength of the age / size relationship weakened following maturation, suggesting two-phased growth. This was particularly relevant for females, where as a function of maturation/increased ovary size, females older than 400 days demonstrated considerably higher TW (>2000 g) than males of equivalent ages (Figure 32a & b). As previously identified there is a possibility that females may cease forming rings at the onset of spawning. Prior to the onset of female maturation, both sexes demonstrated similar growth trajectories. This trend corresponded with mean female GSI, increasing rapidly at 250 days, peaking at 450 days and declining thereafter. Male GSI steadily increased until 250 days and reached a plateau from there on (Figure 33). A large proportion of the total weight of highly gravid females was attributed to reproductive organs, with gonads typically exceeding 250 g to a maximum of 482 g and a GSI of 13.5 (mean GSI = 4.5). Male reproductive organs had little impact on total weight with a mean GSI = 1.3.

The age profile of the shelter pots and trigger traps were very similar for females and males. For both sexes shelter pots caught primarily octopuses aged <350 days, whereas trigger traps caught octopuses >250 days. Age at maturity confirms that shelter pots almost caught exclusively immature females and a mixture of mature and immature males. Trigger traps caught a mixture of immature and mature females and close to no immature males (Figure 34a & b). Differences in age profiles between gear types were also evident across depth classes, with a distinct spike in age at 20 – 24 m (Figure 35).

Immature females and males demonstrated very similar patterns in growth rates across hatch months. A distinct increase in growth rates with rising temperature was evident for both sexes until SST reached 21°C in March 2010, followed by a dramatic drop in growth rates at 22°C, the peak temperature for that period. This pattern was repeated in 2011 where female growth rates peaked 21°C and dropped at 23°C, whereas males demonstrated two peaks, one at 21°C and another at 24°C, followed by plummeting of growth rates at 25°C (Figure 36a). Growth rates of mature females and males demonstrated less consistency across hatch months than immature animals, and did not demonstrate discernible relationships with SST (Figure 36 b).

Mature females (n = 421) were present throughout each month of the sampling years. Back calculated hatch dates for all age data, revealed three distinct hatching pulses every ~6 months (Figure 37). These hatching pulses occurred during periods of transitional temperatures: October to December 2009 (spring/summer), June and July 2010 (winter), November to January 2010 - 11 (spring/summer). Peak maximum and minimum SST for the sampling years occurred during March (autumn) and September (spring), respectively (Figure 37). This corresponds with the highest and lowest mean-monthly temperatures per annum for the study region. This trend in back-calculated hatch months was not influenced by gear type, sampling regime or gender.

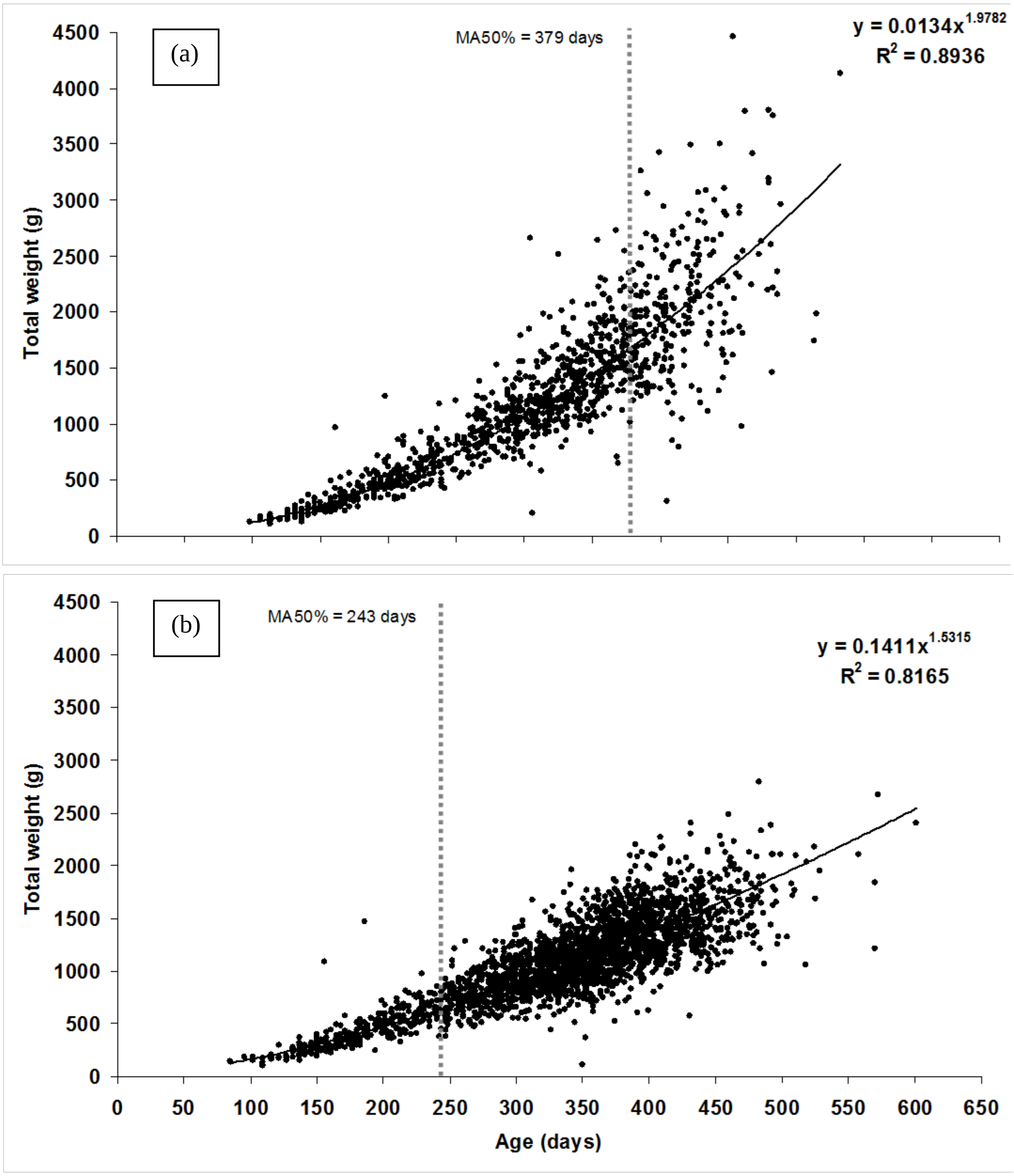


Figure 32 Total weight vs age for (a) female and (b) male *Octopus (cf) tetricus* across all depths and gear types. Dotted grey lines depict age at 50% maturity for each gender

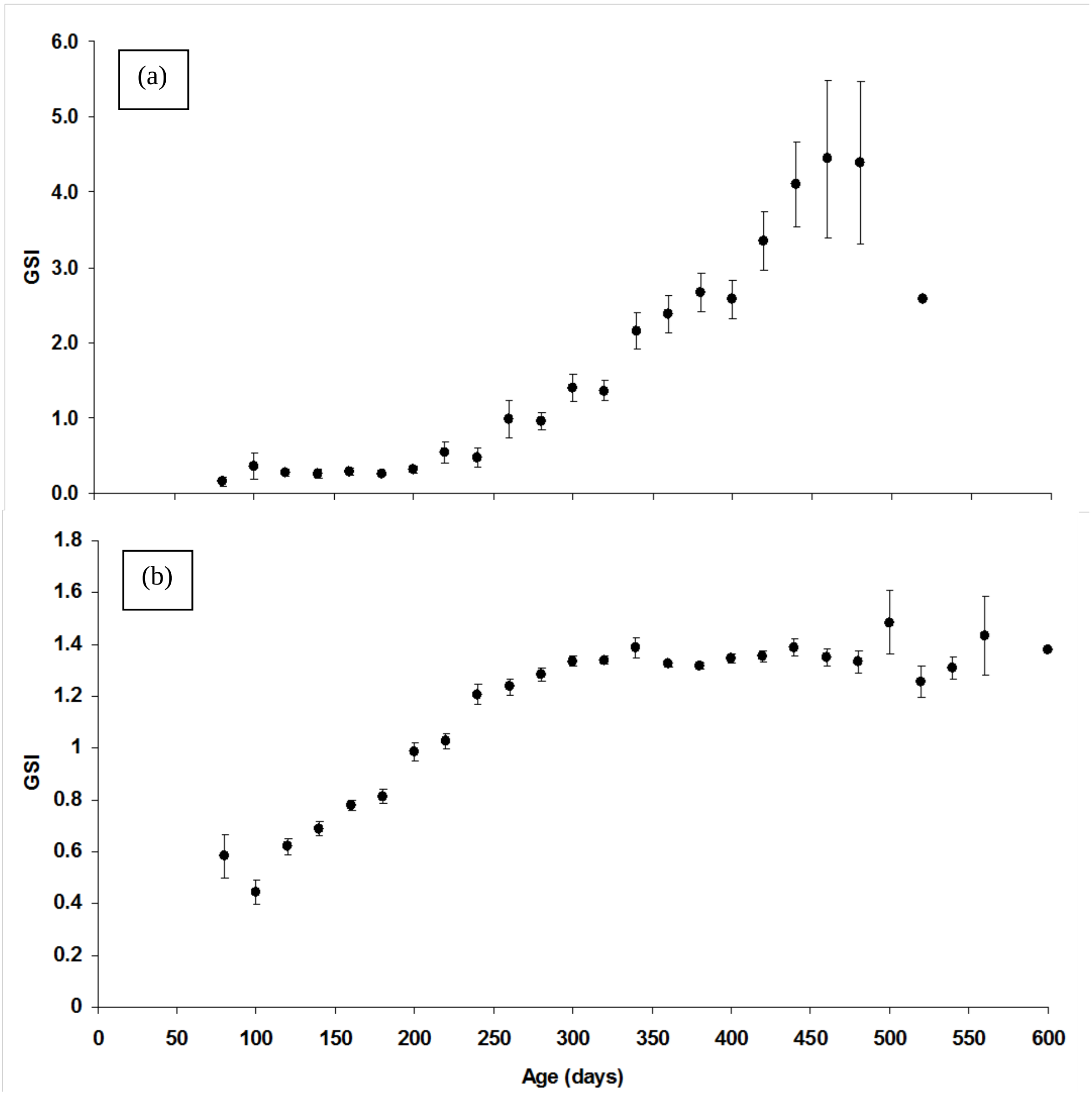


Figure 33 Mean Gonado-Somatic-Index per 50 day age class for (a) female and (b) male *Octopus (cf) tetricus*. Error bars are SE.

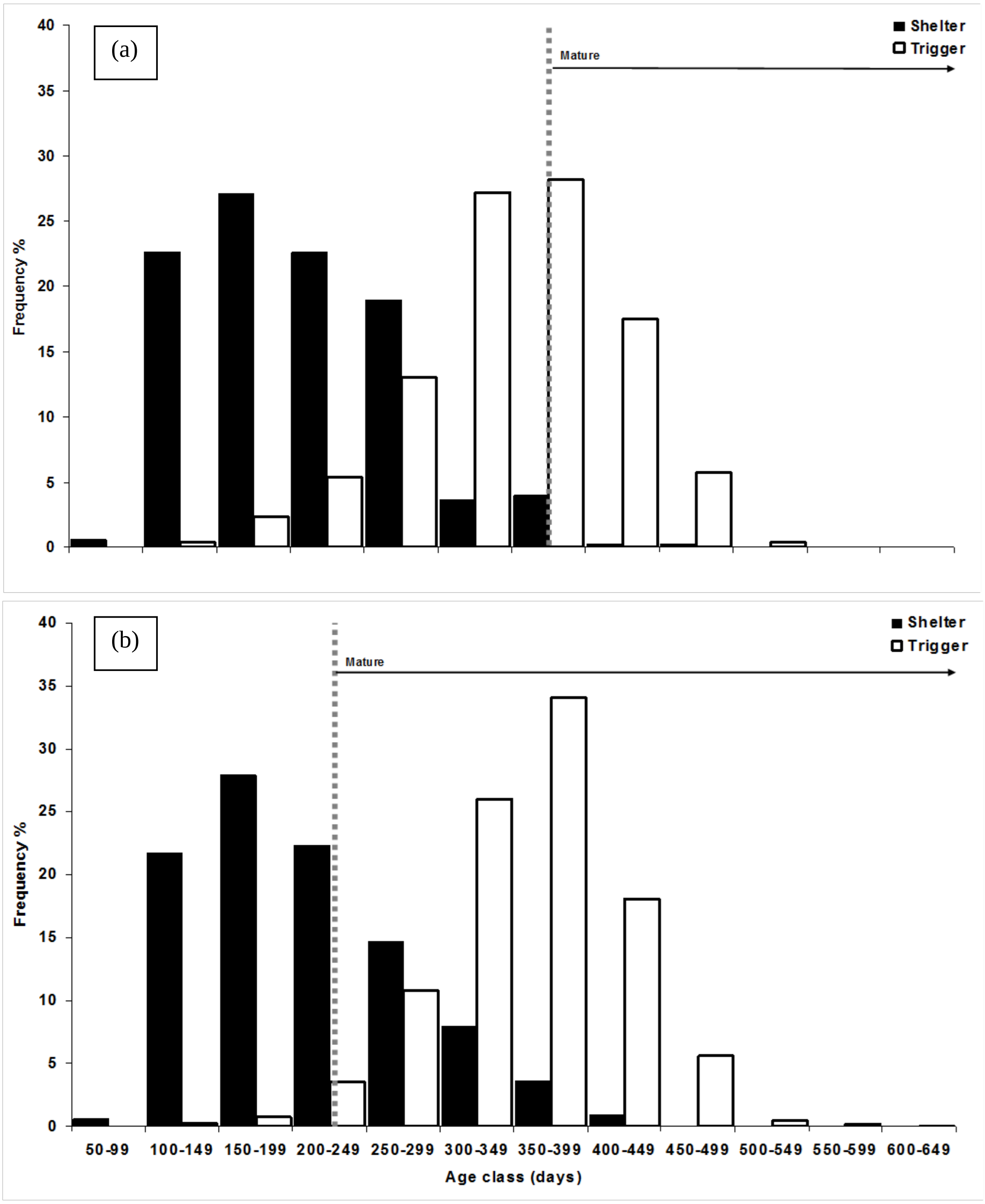


Figure 34 Percentage frequency for 50 day age classes of (a) female and (b) male *Octopus (cf) tetricus* caught in shelter pots (back bars) and trigger traps (white bars). Dashed lines represent age at 50% maturity at 379 days for females and 272 days for males

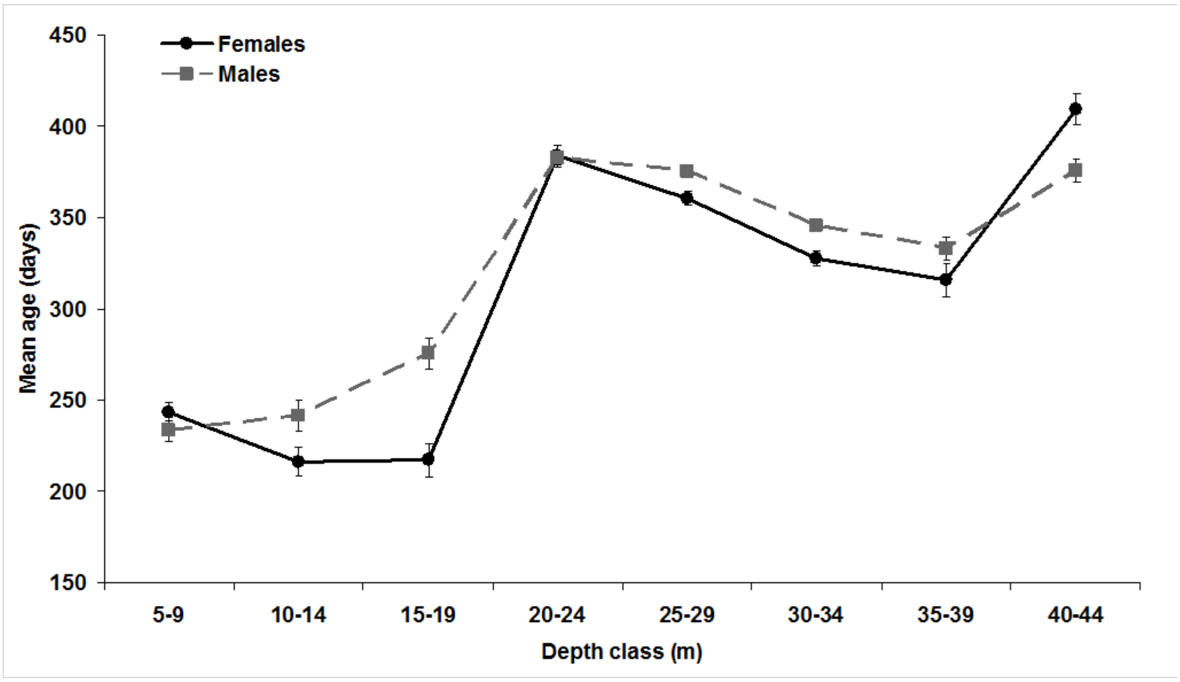


Figure 35 Mean age (±SE) per 5 m depth class for female (black line) and male (grey line) ***Octopus*** **(cf)** ***tetricus*** **caught in both shelter pots and trigger traps**

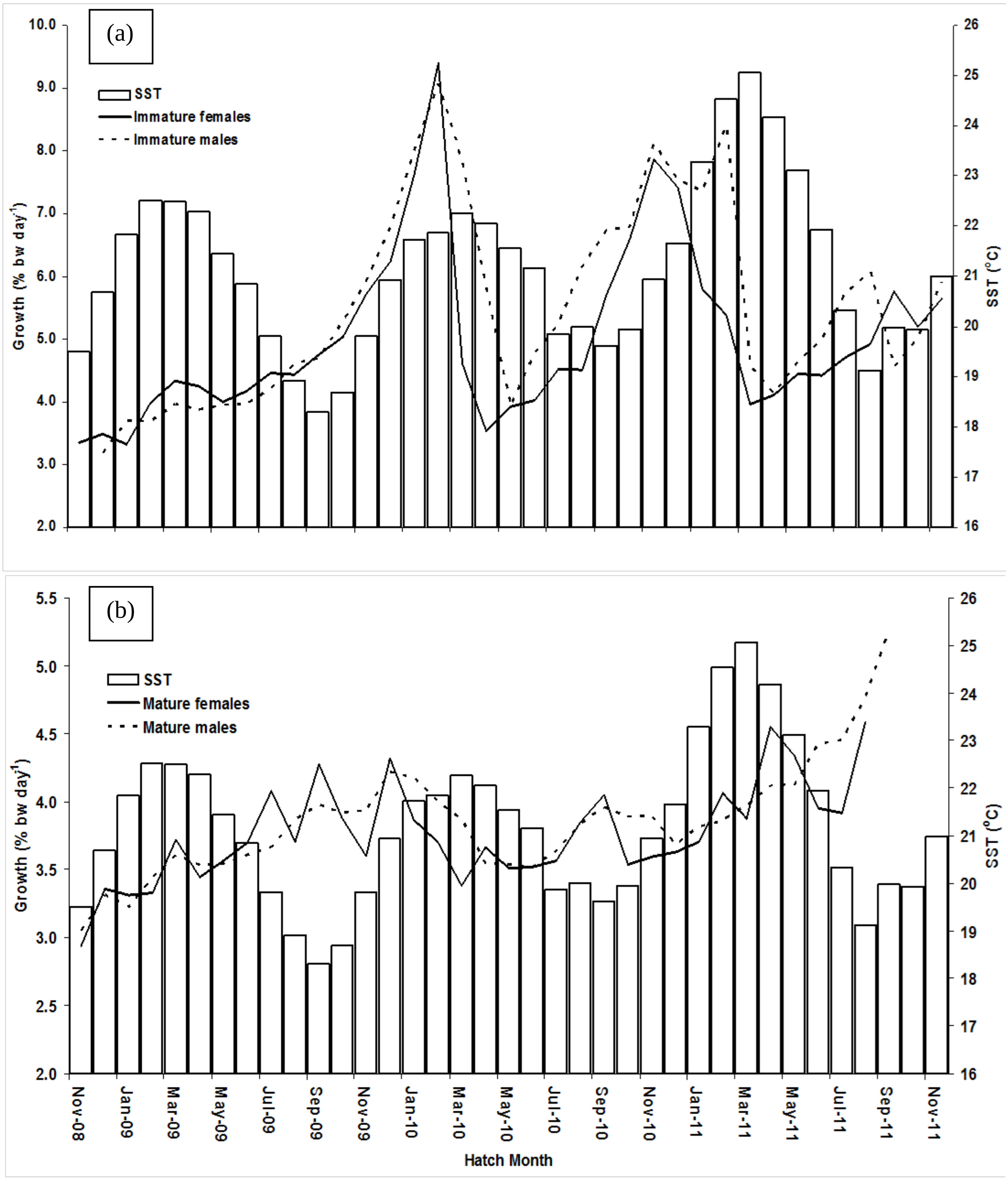


Figure 36 Mean instantaneous growth rate (% bw d^{-1}) for (a) immature and (b) mature *Octopus* (cf) *tetricus* caught in both shelter pots and trigger traps, females = black lines, males = broken lines. Bar graph depicts the mean sea surface temperature (SST °C) for each hatch month

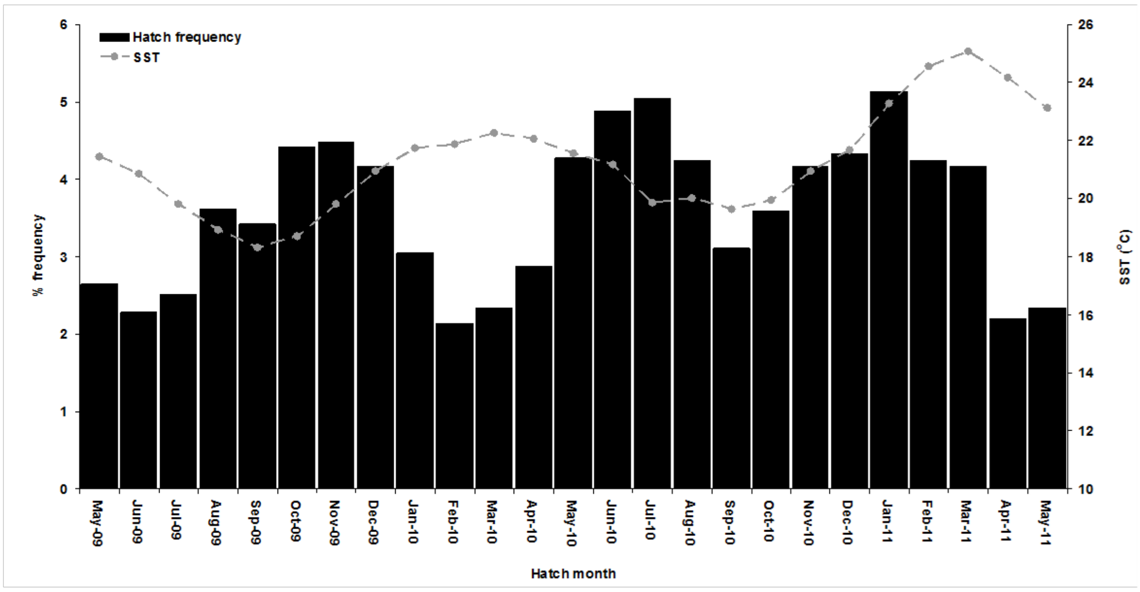


Figure 37 **Frequency of individual *Octopus* (cf) *tetricus* per hatch month for years 2009 – 2011 (black bars) and mean monthly sea surface temperature (SST °C) (grey line), *n* = 3494**

4.3 Gear efficiency

4.3.1 Comparison of gear types

This section addresses objective 2, which is to determine the fishing efficiency of octopus trigger traps. A data set of 540,000 pot lifts for a catch of 621 tonnes of *Octopus* cf *tetricus* over the period 2010 to 2014 was used to estimate the mean catch rate of 1.15 kg per cradle. Based on an average soak-time of 11.2 days, a 304 day fishing year (10 months), an average catch rate of 1.15 kg/pot, the maximum theoretical cradle hauls in a year (27), adjusted for a 10% gear failure rate (24), results in maximum annual cradle efficiency of 28 kg/cradle. A similar data set of 46 t were caught from 251,317 shelter pot provided the average shelter pot catch rate of 0.18 kg per pot. Based on a mean soak period of 25 days and the average catch rate of 0.18 kg/pot, the maximum number of pot hauls in a year (12.2), adjusted for a 10% gear failure rate (10.7), results in a maximum annual cradle efficiency of = 2.0 kg/year. Hence, over the course of a year a single cradle of trigger traps catches on average 14 times more than a single shelter pot. For management purposes of requiring a fixed conversion rate efficiency between the two pots, a figure of 15:1 was advised. For example, a fisher with a 10,000 shelter pot allocation could convert this to a trigger pot allocation of 670 pots (10000/15). The conversion rate of 15:1 represents the current state of knowledge, and will be improved as the fishery evolves. The shift from shelter pots to trigger traps as the primary gear used in the DOF and the immediate impact this had on total catch is evident in Figure 38.

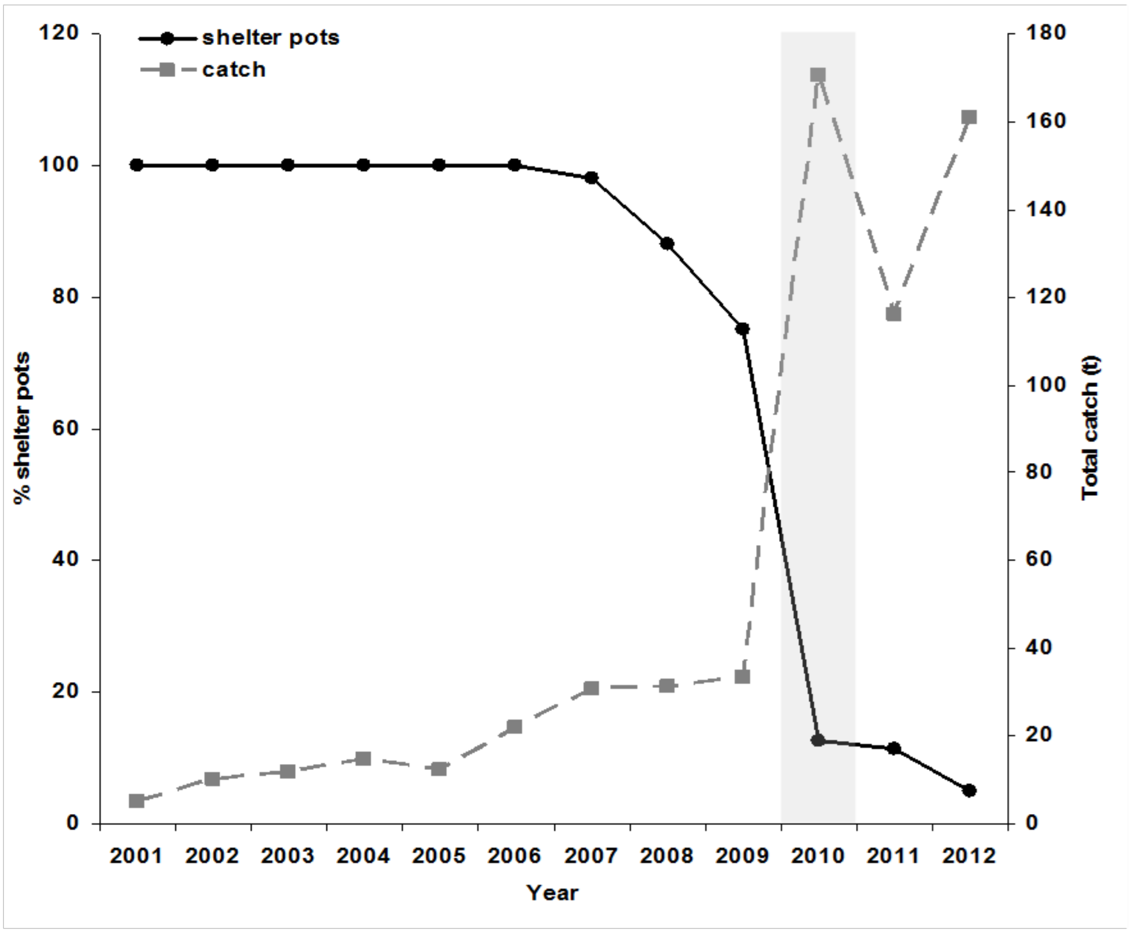


Figure 38 Temporal trends in % of octopus catch taken by shelter pots and total catch

4.3.2 Standardised catch rate analysis

Spatial and temporal trends in catch and effort revealed a reduction in the number caught per trap lift, and catch (kg) per trap lift after the first year of broad-scale deployment of trigger traps in 2010 (Figure 39). These catch rate indices displayed similar intra-annual monthly patterns, with a decline during December – January and peaks during March and August (Figure 40). Latitude and depth did not have an influence on catch rates (Figure 41 and Figure 42).

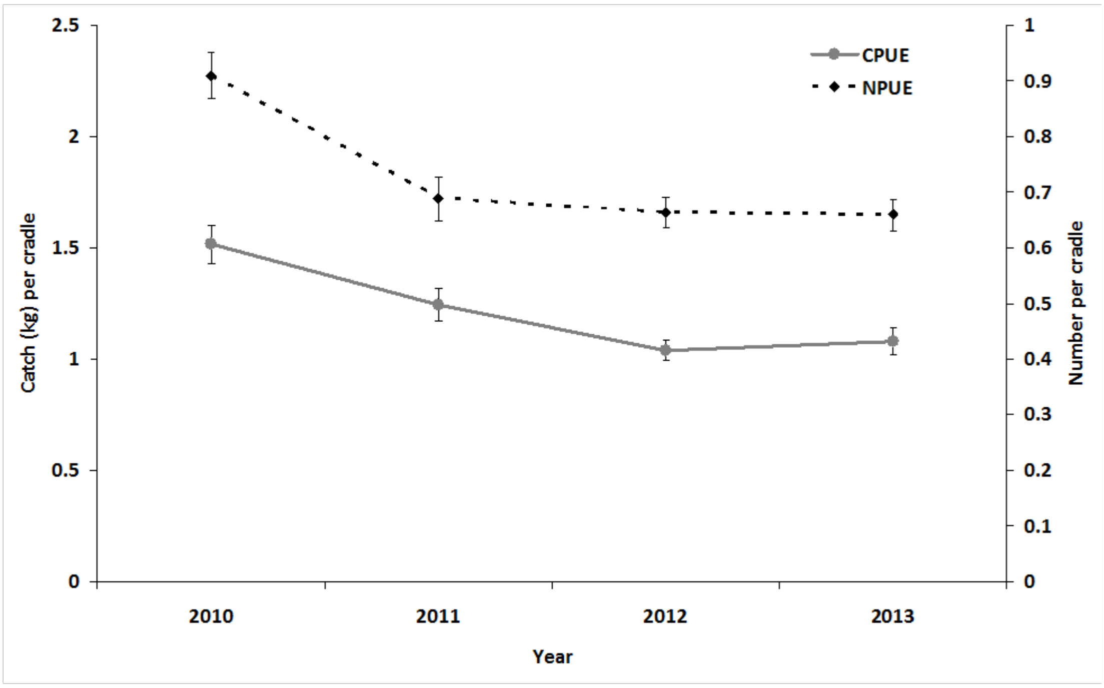


Figure 39 Catch per unit effort (kg per cradle) and number per unit effort (number per cradle) of *Octopus tetricus* by year. Catch units (kg) in whole weight. Trends estimated from standardisation model (see section 3.3)

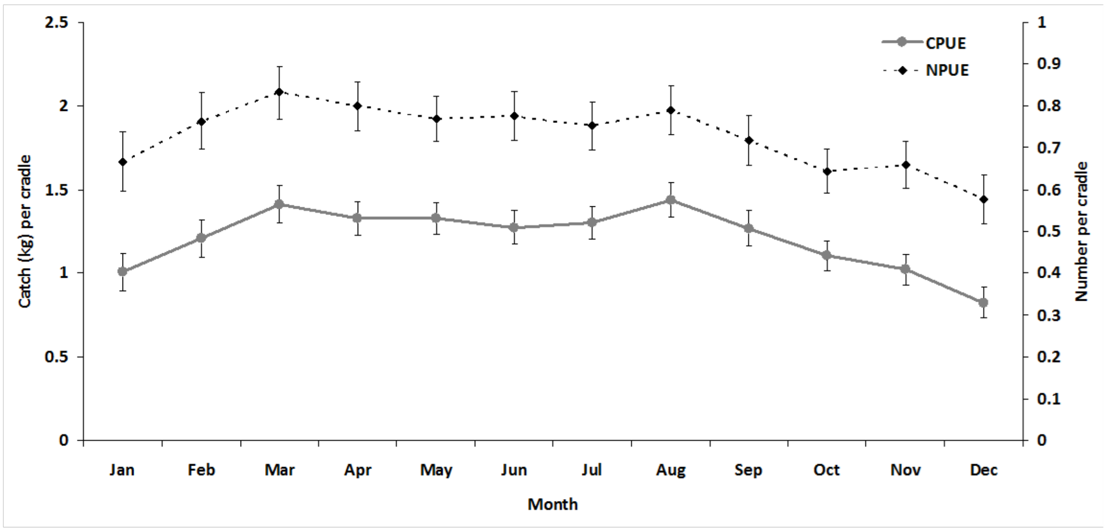


Figure 40 Catch per unit effort (kg per cradle) and number per unit effort (number per cradle) of *Octopus tetricus* by month. Catch units (kg) in whole weight. Catch units (kg) in whole weight. Trends estimated from standardisation model (see section 3.3)

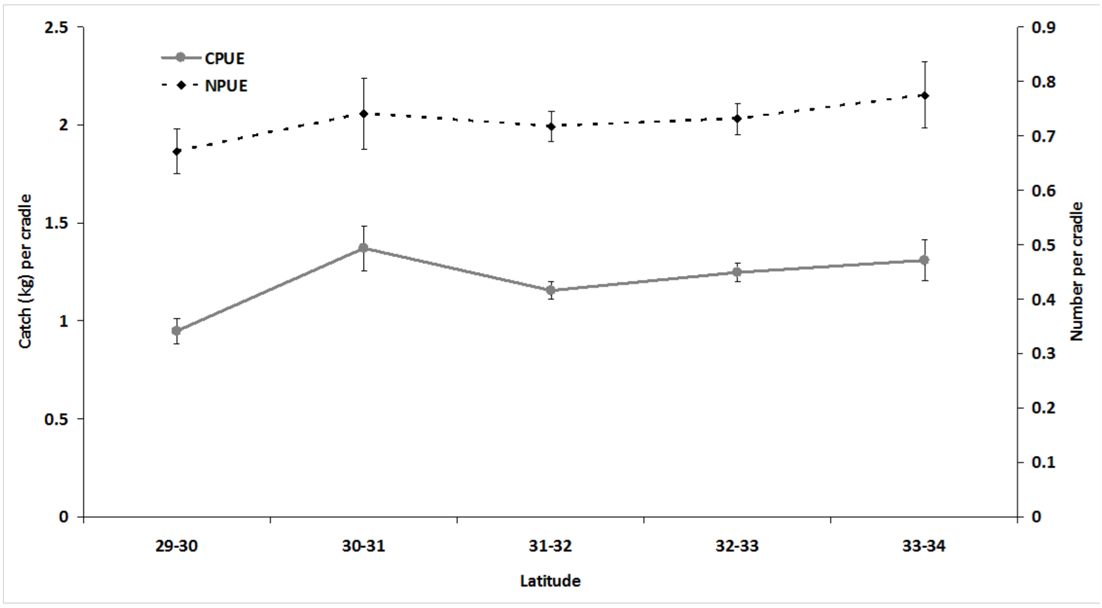


Figure 41 Catch per unit effort (kg per cradle) and number per unit effort (number per cradle) of *Octopus tetricus* by Latitude. Catch units (kg) in whole weight. Catch units (kg) in whole weight. Trends estimated from standardisation model (see section 3.3)

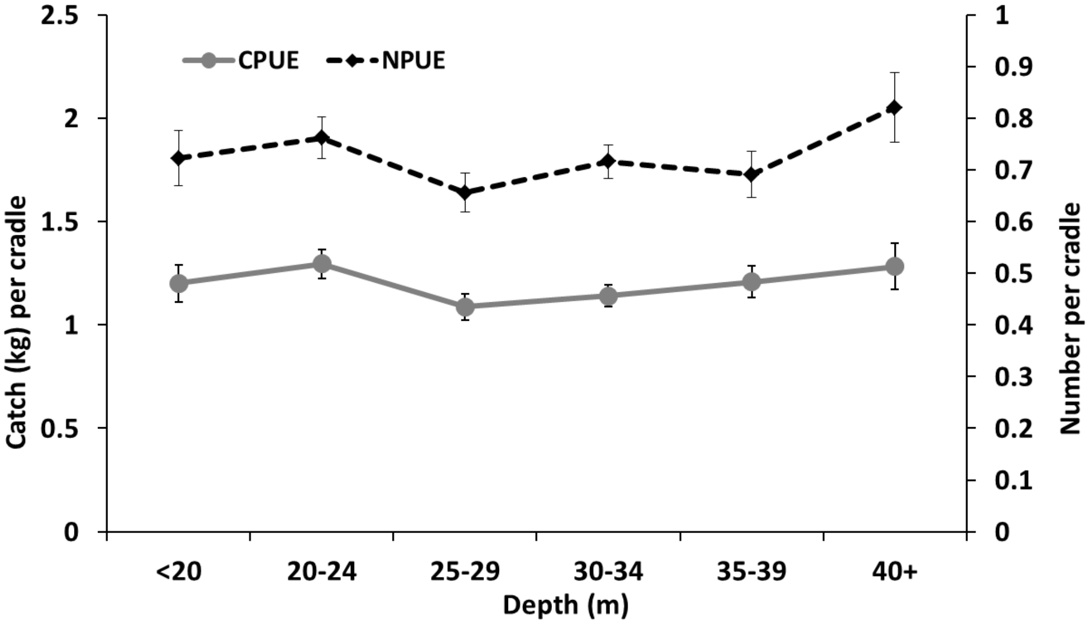


Figure 42 Catch per unit effort (kg per cradle) and number per unit effort (number per cradle) of *Octopus tetricus* by depth. Catch units (kg) in whole weight. Catch units (kg) in whole weight. Trends estimated from standardisation model (see section 3.3)

4.3.3 Leslie-DeLury depletion study

A total of 733 octopuses were caught during the depletion study, totalling 1130 kg for an average of 1.5 kg per cradle lift. Individual octopus weights were not significantly different (t- 0.269, df 702 p = 0.787) between sites. In addition, both sites had similar sex ratios with M1 and M2 catching on average 73% and 67% males, respectively. Females caught across both sites and all surveys weighed significantly more on average at 1.5 kg than males at 1.2 kg (t = 10.29, df 702, p = 0.000).

Catch rate per day followed a very similar pattern of decline across both sites (Figure 43) with a ~50% decline in CPUE over the duration of the survey. Estimates of the catchability coefficient (q) of the trigger traps ranged from 0.0094 (0.94%) to 0.017 (1.17%) with a mean of 0.0102 (1.02%) per soak day (Figure 43).

Population estimates for M1 (area = 1.5 km^2), were 671 and 756 individuals, for the Leslie and Delury methods, respectively. Population estimates for the smaller M2 site at (area = 0.8 km^2), were 632 and 650 individuals for the Leslie and Delury methods, respectively. Mean density estimates for each site, combining both methods were: M1 = 475 ind/km^2 and M2 = 754 ind/km^2. Mean densities for each method combining both sites were: Leslie = 564 ind/km^2 and Delury = 618 ind/km^2. In light of these results, a general population estimate for the octopus population was 591 ind/km^2.

The frequency of individual traps triggering without capturing an octopus, were low and close to identical for both sites, at 2.6% for M1 and 2.9% for M2. Only one cradle in M2 was lost during the study in the second last survey. Throughout the duration of the depletion study no females with eggs were found in any of the trigger traps. The proportion of mature females caught was 28%, whereas 93% of males caught were mature. Bycatch was minimal at a frequency of 2.4% and was comprised of 25 Bastard Red Cod (*Pseudophycis breviuscula*), 15 Cobbler (*Cindoglanis macrocephalus*), two Blue Ring Octopus (*Haplochlaena spp*) and one eel (unidentified). All bycatch were caught in un-triggered traps, were alive, healthy and returned to the water.

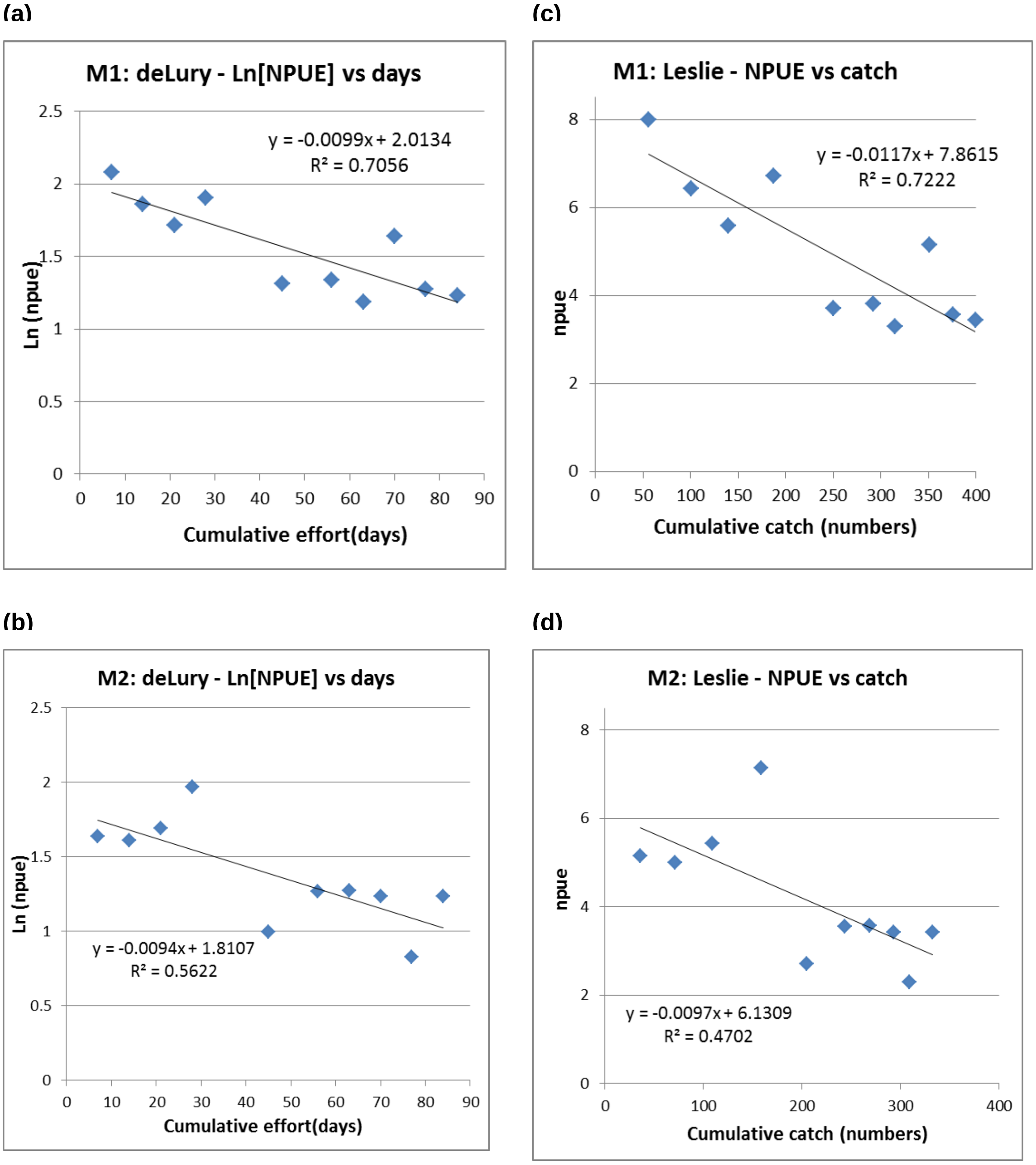


Figure 43 Log$_e$NPUE (number caught per day) and NPUE for the depletion experiments. a) Site M1 Delury, b) Site M2 Delury, c) Site M1 Leslie, d) Site M2 Leslie. Each data point (blue diamond) is the daily catch rate and cumulative effort (a, b) or catch (c, d) from 36 trigger traps. Traps were deployed 10 times in the identical location (see Figure 17) over an 85 day period between March and May 2013. Slopes represent estimated catchability coefficient (*q*; per day) of the gear

4.4 Biomass and Sustainable Harvest

4.4.1 Estimating stock biomass and harvestable area

This section addresses objective 3. Objective 3 is to estimate potential harvest from octopus fisheries. As detailed in section 3.4.2, the method for estimating stock biomass was to multiply the area of the fishery (km^2) by the mean density (per km^2) of octopus. The total harvestable area for the west and south coast combined at depths of 20 – 50 m was estimated at 34,105 km^2. The extent of the fishable area for each zone was as follows: Zone A = 3,115km^2, Zone B = 6,936 km^2, Zone C = 14,310 km^2 and South Coast 9,744 km^2 (Table 5).

The current area fished each year in Zone C covers 1000 - 1300 km^2 the equivalent of 7 - 9% of the fishable area for that zone. In Zone B 190 km^2 or 2.7% of the total fishable area is currently being fished, whereas targeted octopus fishing has not commenced in Zone A. In the South Coast Zone there are two operators using shelter pot longlines, in two distinct areas around Albany and Esperance (Figure 19b). The area covered by these shelter pot operators is presently unknown, however, it is expected to be <3% of the fishable area. The three biomass and abundance estimate scenarios, provided the following values 8626 t or 5 569 091 individuals for Scenario 1, 10 875 t or 7 021 204 individuals for Scenario 2 and 12 605 t or 8 138 214 individuals for Scenario 3 (Table 5).

4.4.2 Per-recruit model

The per-recruit model demonstrated an overall goodness-of-fit with maturity at age (Figure 44). The fitted model approximated maturity-at-age observations with a broader confidence envelope than for mortality-at-age observations, which were better approximated by the model. The wide 95% confidence envelope for the fitted maturity-at-age represented a combination of higher unexplained variation arising from the binomial log-likelihood and the influence of prior specifications used for the Bayesian model.

The estimated fishing mortality, when converted to a monthly harvest rate ($\hat{F}_{2011-12}$), was below the maximum model-predicted YPR and above 50% of the unfished SBPR (Figure 45). Uncertainty about the ($\hat{F}_{2011-12}$), however, when shown as a 95% credibility interval on plots was broad (Figure 45 and Figure 46). Nevertheless, the ($\hat{F}_{2011-12}$) credibility interval was below the lower bound for the $F_{0.1}$ 95% credibility interval and although it overlapped the 95% credibility interval for the SBPR at 40% and 30% of the unfished level (SPR$_{0.4,}$ SPR$_{0.3}$ respectively) it was below the 95% credibility intervals for SPR$_{0.2}$ (Figure 46). This demonstrated that although the estimated level of fishing mortality was highly uncertain, it can be ascertained that at 2011 and 2012 levels of fishing there was a low probability that the SBPR was overfished or that growth overfishing was occurring.

Table 5 **Biomass and abundance estimates across each fishing zone for three scenarios (Precautionary, Conservative and Possible).**

Scenario 1: Precautionary (7% optimal area)							
Zone	**Total area (km2)**	**Optimal area (km2)**	**Non-optimal area (km2)**	**Biomass optimal area (t)**	**Biomass non-optimal area (t)**	**Biomass (t)**	**Abundance (individuals)**
A	3,115	218	2,897	137	544	681	472,690
B	6,936	486	6,450	304	1,212	1,516	1,052,512
C	14,310	1,002	13,308	767	3,058	3,825	2,405,756
South Coast	9,744	682	9,062	522	2,082	2,605	1,638,133
TOTAL	**34,105**			**1,730**	**6,896**	**8,626**	**5,569,091**

Scenario 2:Conservative (20% optimal area)							
Zone	**Total area (km2)**	**Optimal area (km2)**	**Non-optimal area (km2)**	**Biomass optimal area (t)**	**Biomass non-optimal area (t)**	**Biomass (t)**	**Abundance (individuals)**
A	3,115	623	2,492	390	468	858	595,941
B	6,936	1,387	5,549	869	1,042	1,911	1,326,949
C	14,310	2,862	11,448	2,192	2,630	4,823	3,033,045
South Coast	9,744	1,949	7,795	1,493	1,791	3,284	2,065,268
TOTAL	**34,105**			**4,943**	**5,932**	**10,875**	**7,021,204**

Scenario 3: Possible (30% optimal area)							
Zone	**Total area (km2)**	**Optimal area (km2)**	**Non-optimal area (km2)**	**Biomass optimal area (t)**	**Biomass non-optimal area (t)**	**Biomass (t)**	**Abundance (individuals)**
A	3,115	935	2,181	585	410	995	690,750
B	6,936	2,081	4,855	1,303	912	2,215	1,538,055
C	14,310	4,293	10,017	3,288	2,302	5,590	3,515,575
South Coast	9,744	2,923	6,821	2,239	1,567	3,806	2,393,834
TOTAL	**34,105**			**7,415**	**5,190**	**12,605**	**8,138,214**

Estimates of SPR (i.e., the ratio of SBPR at 2011 and 2012 levels of fishing effort to the unfished SBPR) were demonstrated to consistently decrease with decreasing age at knife-edged selectivity (t_f) and M_{n} (Figure 47 a and b). Although the uncertainty of the estimated SPR was shown to be relatively broad, changes in the point estimate for SPR were not observed to fall below $\mathrm{SPR}_{0.3}$ for the plausible ranges of inputted values for t_f and M_{n} and did not fall below $\mathrm{SPR}_{0.4}$ until relatively low values were used as inputs (i.e., $t_f = 3, M_{\mathrm{n}} = 0.67$). The probability of growth overfishing, as indicated by decreasing $F_{0.1}$ to fall within the 95 % credibility interval for $\hat{F}_{2011,2012}$, was demonstrated when the t_f fell below 6 months of age and when the inputted M_{n} fell below 0.18 (Figure 47 c,d). The $F_{0.1}$ estimate was also demonstrated to be highly sensitive to any increase in M_{n} above 0.2, which is a value only slightly (< 0.01) higher than the fixed M_{n} used for model fitting. This reflects the changing shape of the YPR curve from that shown in Figure 45, as inputted M_{n} increased above 0.2, corresponding to a predicted decreasing curvature of the YPR curve, which tends towards an asymptotic and infinite maximum at unrealistically high values of F_{t_r}.

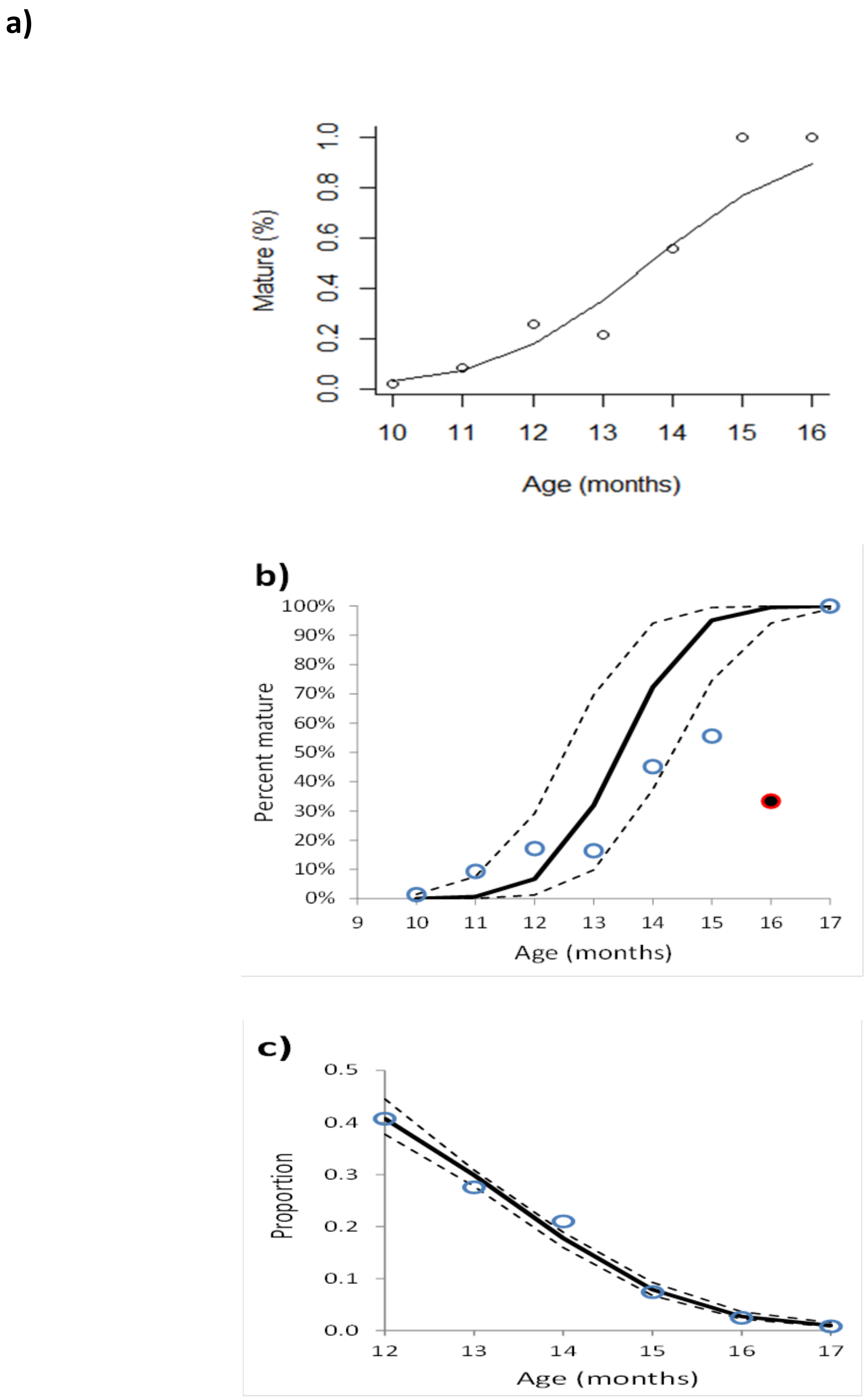


Figure 44 Model fit. a) Fit of reduced model to percent mature for 2010 data, to generate prior distributions for B and A_{50}; b) fit of full model to percent mature data during 2011 - 2012 using priors on B and A_{50}; c) fit of full model to fully-recruited proportions at age sampled during 2011 – 2012. Dashed lines = 95% credibility intervals, suspected outlier shown as filled circle (N=6)

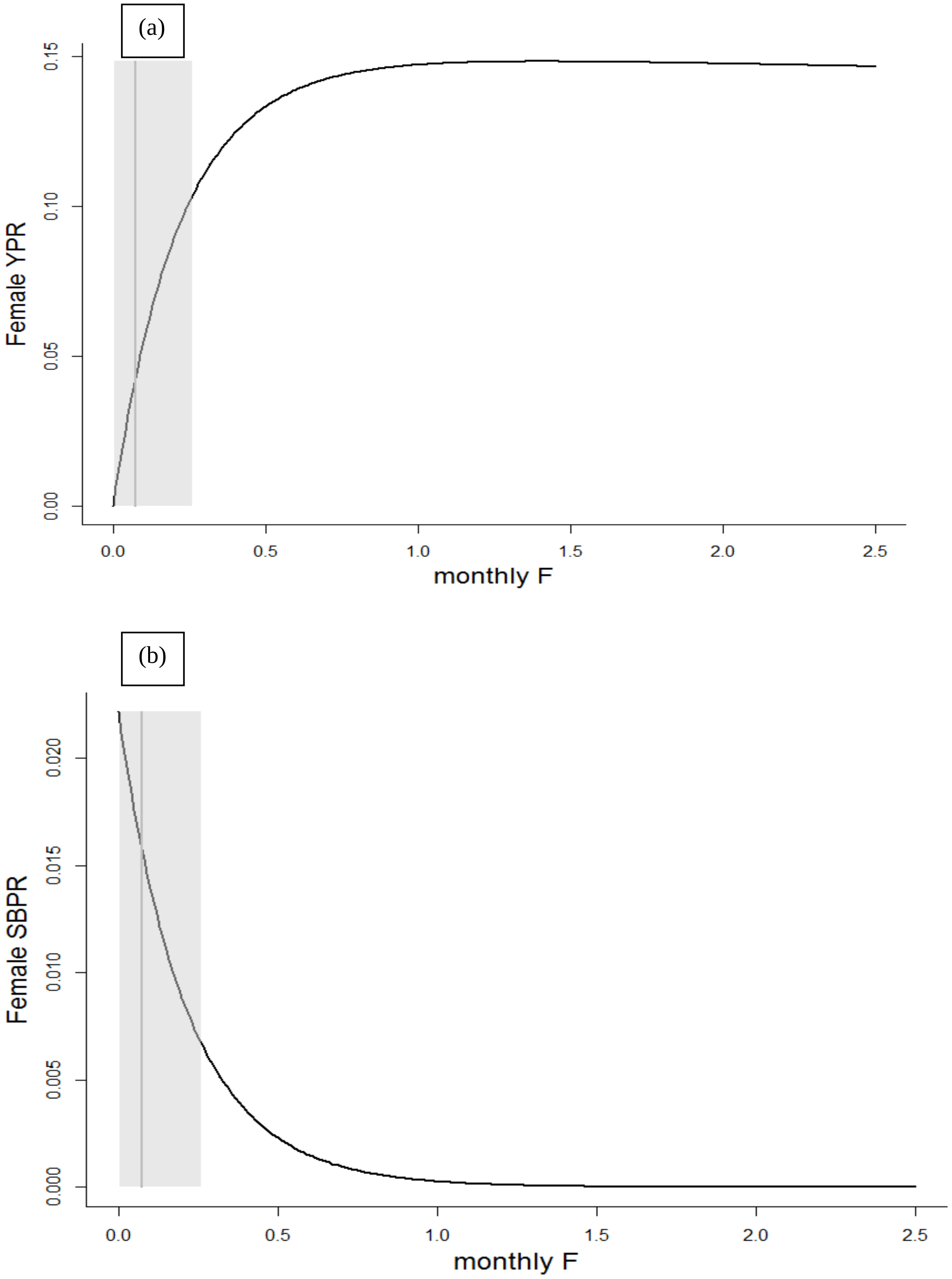


Figure 45 **Results from per-recruit analyses. a) Yield-per recruit; b) Spawning Biomass per recruit (SBPR) with monthly *F*. Vertical line shows Bayesian posterior median of fishing mortality from fit of full model to data sampled in 2011 and 2012 combined, as a monthly *F*, with shaded area encompassing 95% credibility interval for this estimate**

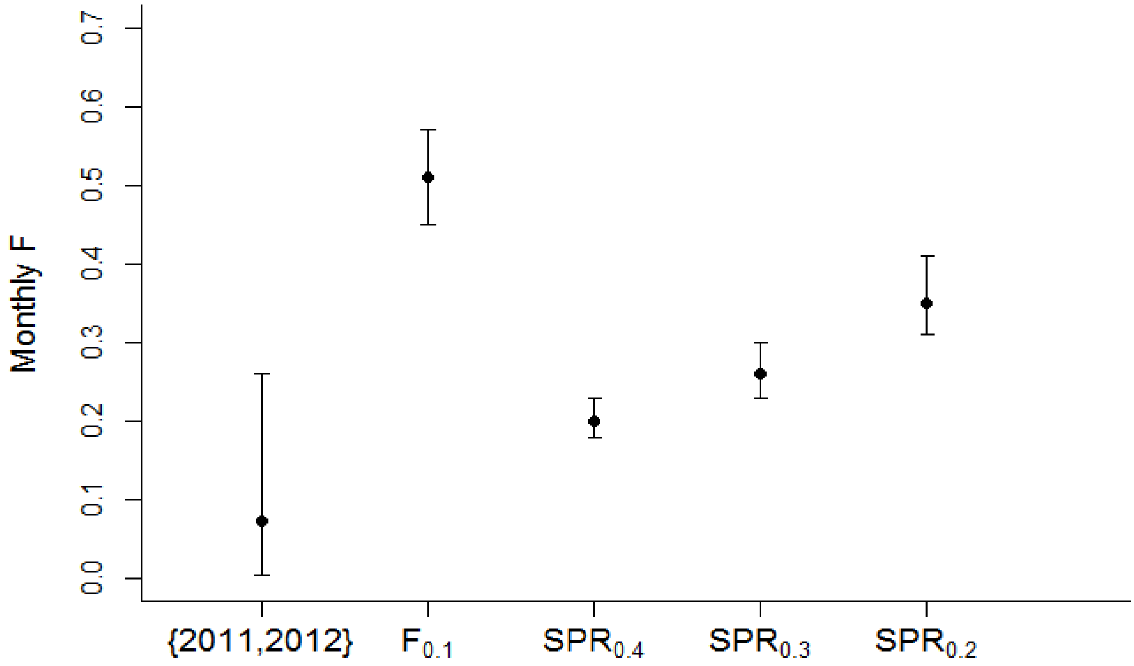


Figure 46 **Per-recruit results in relation to conventional reference levels for fisheries management. Error bars represent 95% credibility intervals for all estimates. '$F_{0.1}$'=*F* corresponding to the point on the YPR curve where the rate of change is 10 % of the rate at the origin; '$SPR_{0.4}$','$SPR_{0.3}$','$SPR_{0.2}$'= *F* corresponding to the SBPR at 40 %, 30 % and 20 % of the unfished level, respectively**

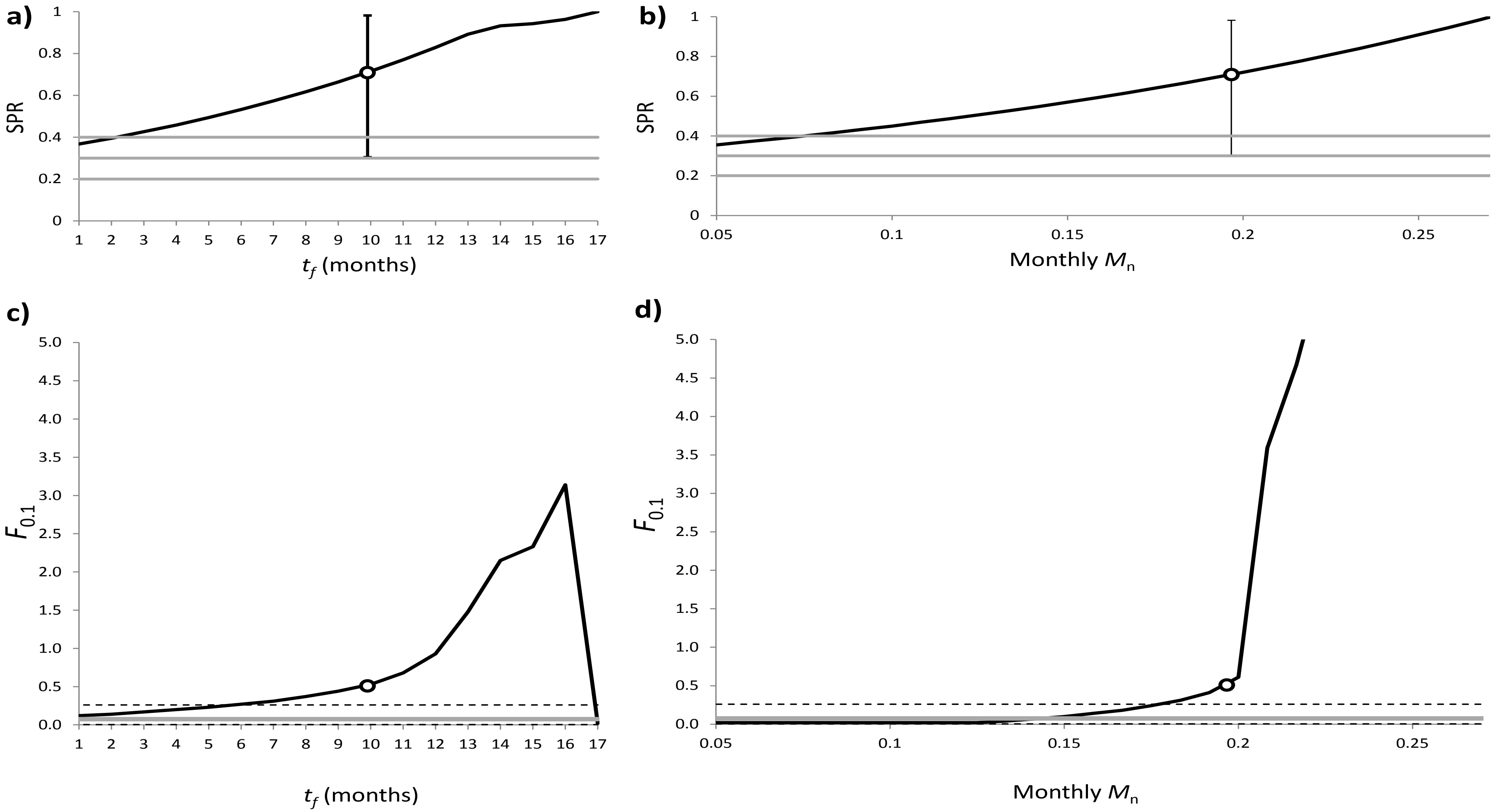


Figure 47 Sensitivity analyses of relating per-recruit estimates to reference levels. Sensitivity analyses conducted for estimated SPR (a, b) and $F_{0.1}$ (c, d). 'SPR'= SBPR as a proportion of the unfished level. Open circles represent estimates from changing input values for t_f, the age at knife-edged selectivity (a, c) and monthly natural mortality of non-spawning individuals, M_n (b, d). Error bars are 95 % credibility intervals about the estimate of SPR using results from the Bayesian analysis. Horizontal lines in (a, b) are $SPR_{0.4}$, $SPR_{0.3}$, $SPR_{0.2}$ and in (c, d) are the estimated monthly $\hat{F}_{2011-12}$ and bounds of the 95 % credibility interval for that estimate

4.4.3 Sustainable harvest

Sustainable catch limit ranges for the precautionary, conservative and possible scenarios, demonstrated that the current catch of 240 t is far less than the lowest estimate for the precautionary scenario at $SPR_{0.4}$ = 879 t. The highest catch limit for the possible scenario at $SPR_{0.2}$ =2261 t (Table 6).

Table 6 Sustainable harvest ranges (t) set at spawning biomass per recruit (SPR) levels 0.2, 0.3 and 0.4, for three abundance scenarios (precautionary, conservative and possible). Ranges are based on male and female weight at age for the lower and higher estimates, respectively

Scenario	$SPR_{0.2}$ sustainable catch limit range (t)	$SPR_{0.3}$ sustainable catch limit range (t)	$SPR_{0.4}$ sustainable catch limit range (t)
Precautionary	1202 - 1547	1031 - 1337	879 - 1145
Conservative	1516 - 1950	1300 - 1685	1108 - 1444
Possible	1757 - 2261	1507 - 1953	1284 - 1673

4.4.4 Empirical modelling of the effects of environment on potential harvest

Mean octopus weight increased towards southerly latitudes, with octopuses caught in Busselton (latitude 33.5° S) on average 260 g or 18% bigger than those caught in Dongara (latitude 29.5° S) (Figure 48). A strong negative correlation of -0.94 was evident between mean octopus size and mean SST by latitude, this was a very linear relationship (R^2 = 0.88) signifying the relevance of using latitude as a proxy for temperature (Figure 49).

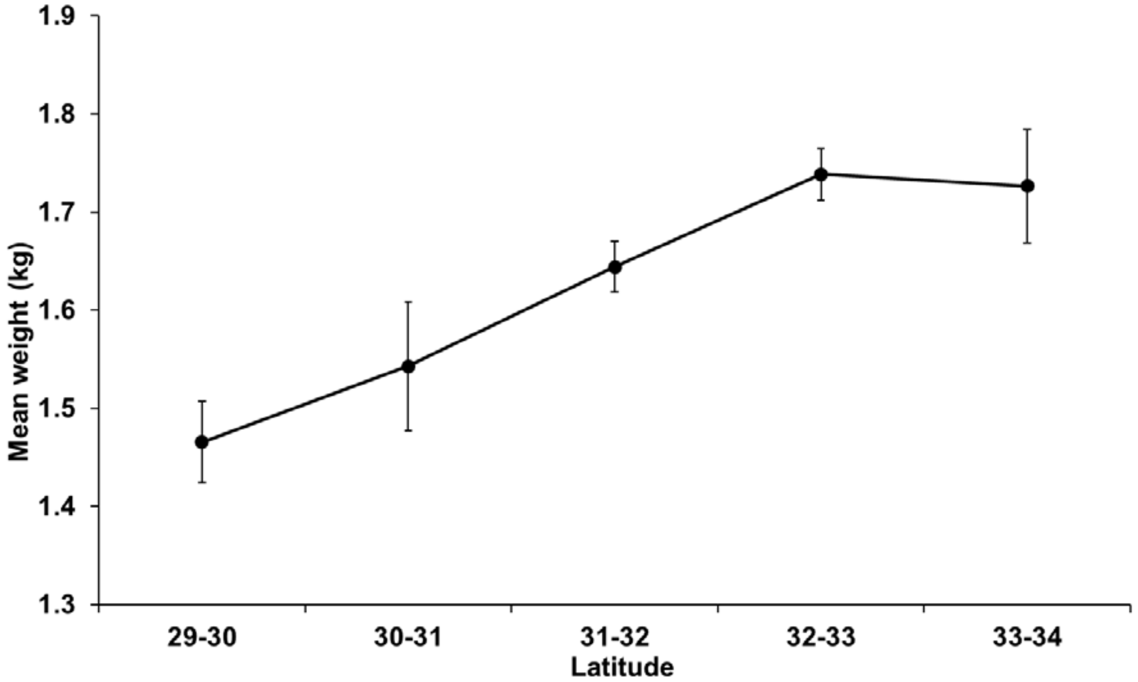


Figure 48 Mean weight of *O.* (cf) *tetricus* by latitude for the west coast of Western Australia

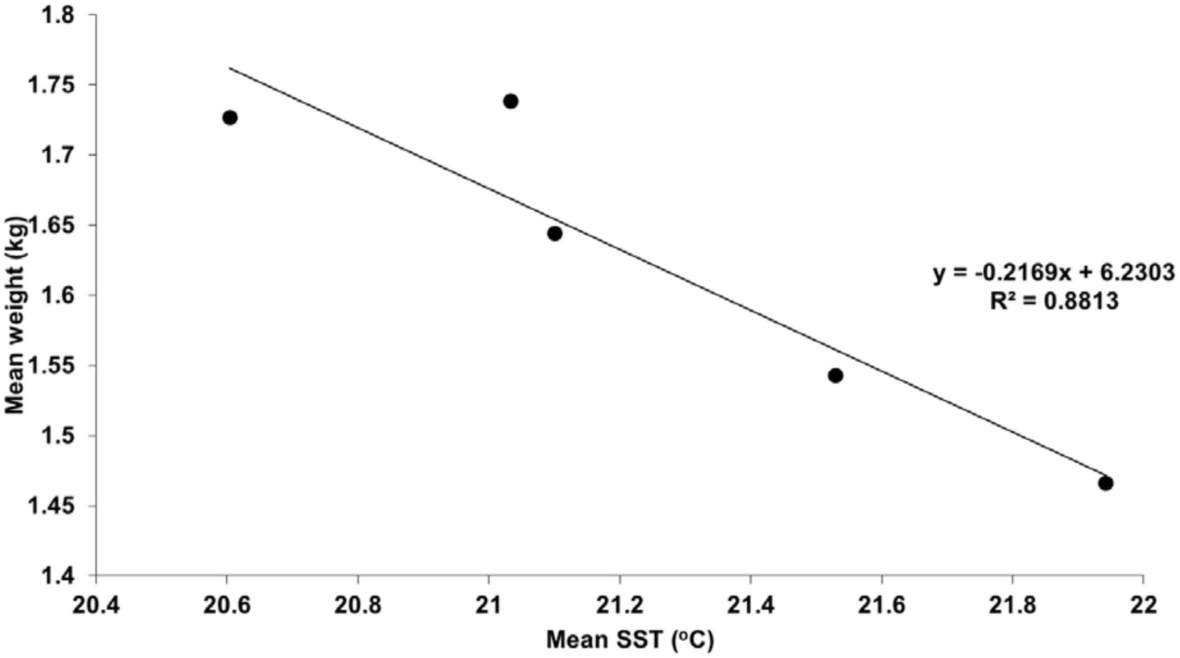


Figure 49 Mean weight of *O* (cf) *tetricus* vs mean temperature by latitude

4.5 Octopus predation on lobsters

This section addresses objective 4. Objective 4 is to calculate the effects of fishing closures on octopus predation rates on rock lobsters. During 1990 – 2012 the commercial lobster research monitoring data revealed that the incidence of octopuses being either present or signs of their predation in lobster pots, was significantly higher than the number of octopus actually caught in the traps (t = -13.779, df 20, P = 0.00). On average, the incidence of octopuses entering the traps was three times higher than the actual number of octopus caught (Figure 50). This indicates that if lobster pots were designed to catch octopus they would land at least three times the actual recorded number, the equivalent of >100 t during peak years (Hart et al. 2013).

A total of 509 vessels took part in research sampling during 1980 – 2012 (mean = 175 vessels per year), with a high incidence of repeated vessel use across years. During this period a total of 414,491 lobster pots were sampled (mean = 12,461 per year). Octopus predation was greatest during the warmer months December – March and decreasing with colder temperatures, noting that lobster fishing traditionally did not occur during the coldest months July - October. Close to 90% of sampling occurred in waters shallower than 30 m, with the following spread of effort < 10 m = 39%, 11 – 20 m = 25%, 21 – 30 m = 25%, 31 – 40 m = 5%, 41 – 50 m = 2% and > 50 m = 3%. Octopus predation decreased with increasing depth (Figure 51). The majority of pots samples were soaked for one day (76%), octopus predation was shown to consistently increase with soak period (Figure 52).

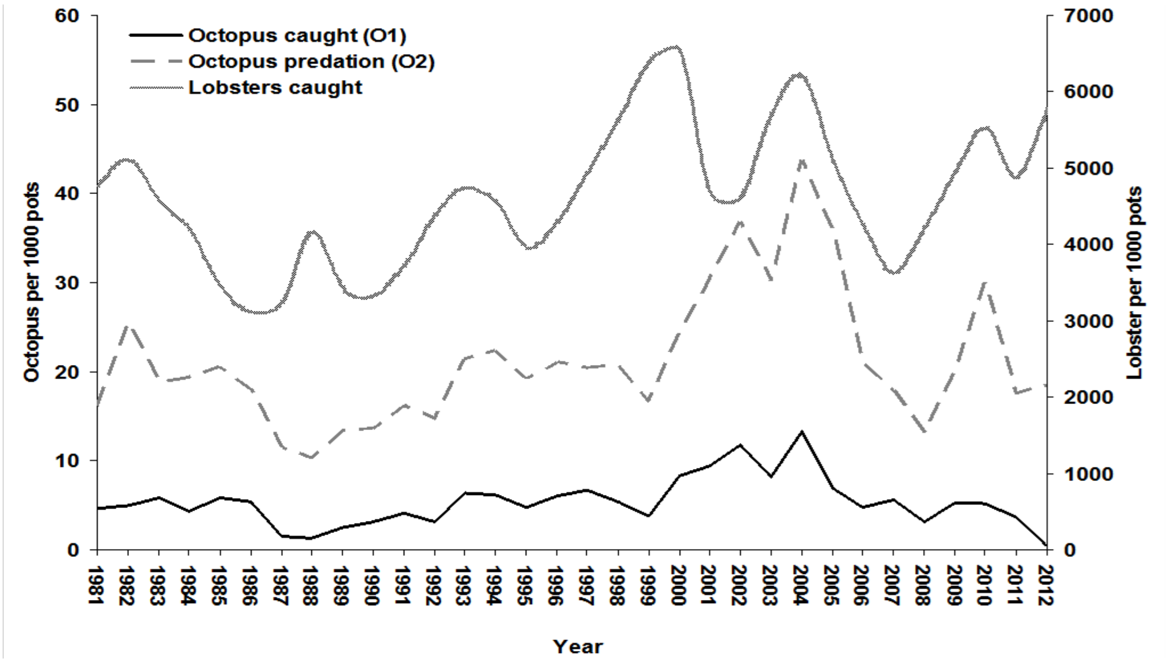


Figure 50 Predation rates of octopus in lobster pots. O1 = octopus per 1000 lobster pot hauls (black line), 02 = evidence of octopus predation per 1000 lobster pot hauls (grey broken line) and number of lobster caught per 1000 lobster pot hauls (smooth black line)

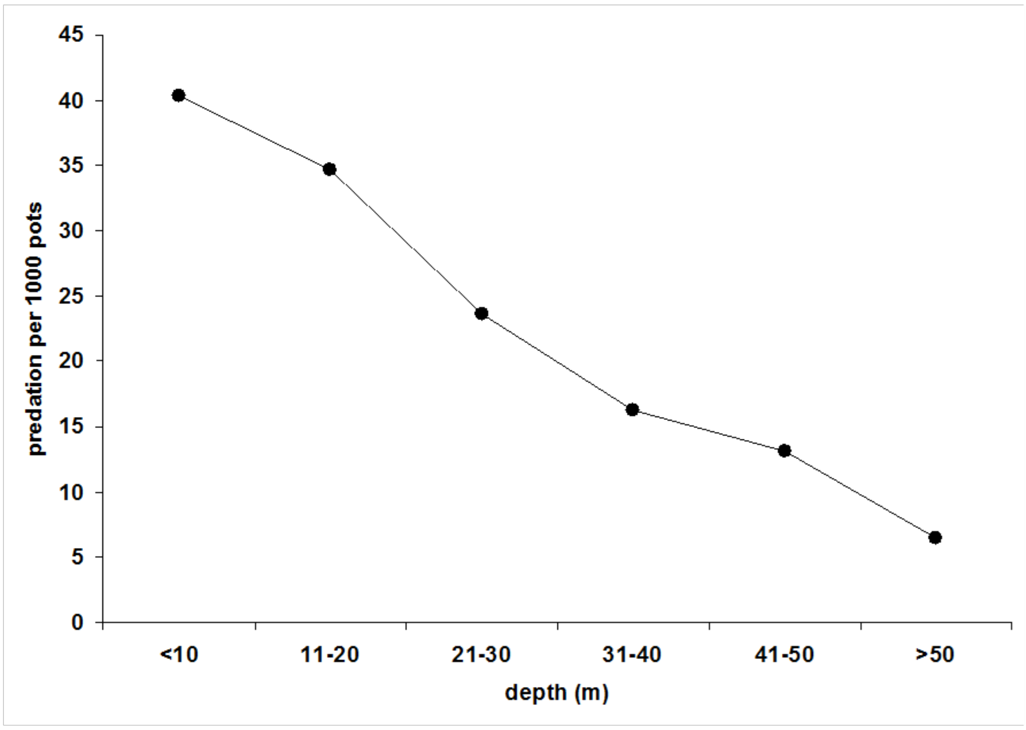


Figure 51 Octopus predation per 1000 lobster pot hauls at 10 m depth contours between 10 – 50 m

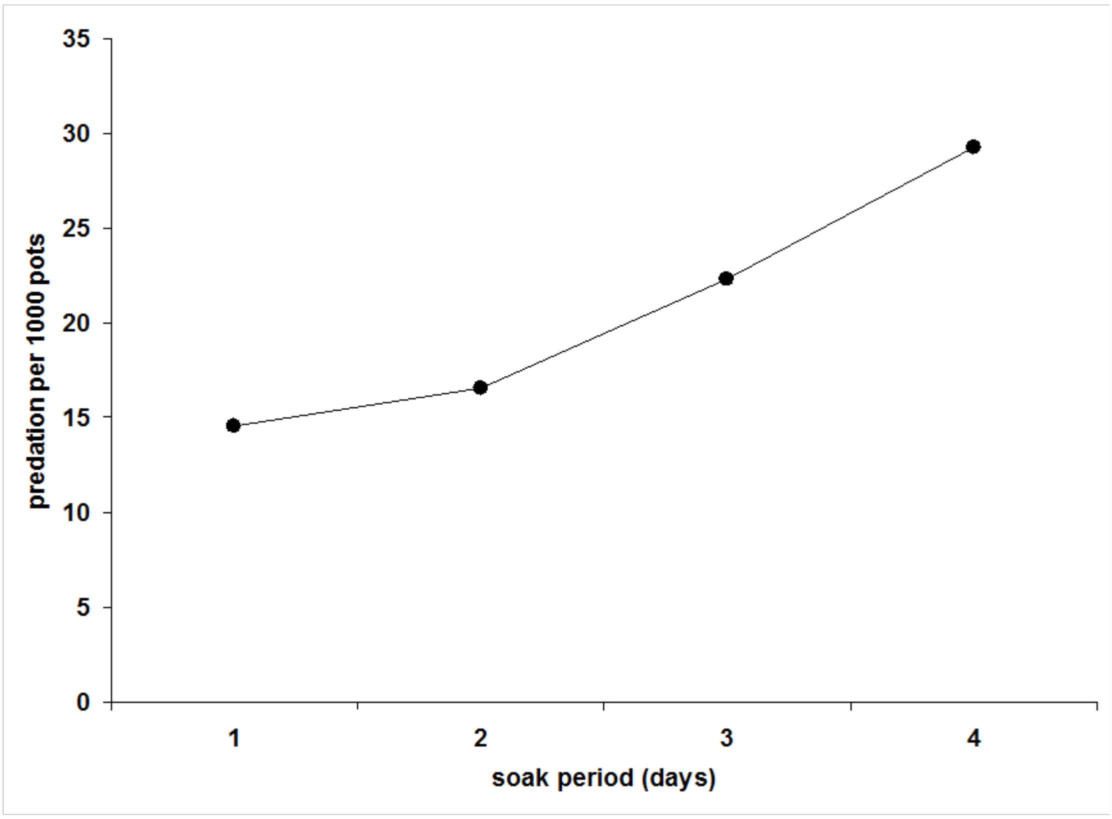


Figure 52 **Octopus predation per 1000 lobster pot hauls per soak day**

5 Discussion

The developmental octopus fishery has the potential to be a significant fishery for Western Australia. With current harvest rates estimated to be well below sustainable levels and less than 4% of potential fishing waters presently being utilised, it is likely that the DOF could sustain landings of ~1000 t per year, and potentially 2000 t or more. By providing a solid research foundation on the biology and population dynamics of *O.* (cf) *tetricus*, the findings from this study will assist future research and management of the DOF, thus helping to ensure the ecological and economic sustainability. The lynch pin of this research is the broad scale age data. As the first study to effectively identify a means of ageing a large portion of a wild octopus population with a verified method, this research has provided a unique insight into the population and enabled the calculation of abundance estimates for a short time series on a highly dynamic species.

Age determination (Objective 1)

Stylet weight is a rapid, reliable and accurate proxy for age in *O.* (cf) *tetricus*. This finding enables the ageing of a large representative sample from a wild population, in a short time frame. Thus providing, an efficient method of octopus age determination that is grounded by the accuracy of SIA, yet has the flexibility and scope of Modal Progression Analysis (MPA).

Validating stylet increment periodicity with calcine was shown to be an accessible and easy method for *O.* (cf) *tetricus*, as demonstrated by the 75% success rate in stylet markings. Ultimately, to unequivocally validate stylet increment periodicity and natal ring formation, in a merobenthic octopus species, known age animals would need to be used (Doubleday et al. 2011). Unfortunately, the challenges of rearing octopus paralarvae in captivity continue to prevent this from occurring (Vaz-Pires et al. 2004). Thus, making calcine an appropriate alternative compared to alizarine complexone or oxytetracycline, which in the present study did not prove to be viable options, in spite of reported success elsewhere (i.e. *Octopus vulgaris* (Hermosilla et al. 2010).

The validation equation (Figure 21) calculated a ring periodicity of 0.92 per day, rather than 1 per day. The 95% confidence intervals for this parameter revealed a range of 0.82 to 1.01. Therefore, given the difficulty of executing a successful validation experiment, the technical complexities associated with extracting a successful ring count, and the low number of animals used in this experiment ($n = 9$), these results are considered preliminary and a more comprehensive experiment is required. In the absence of further verification, and a viable justification for using 0.92 rings per day, the assumption of one ring per day as is current convention in the literature, was applied. Application of this assumption revealed sensible estimates of demographic parameters such as maximum age and growth, commensurate with the known biology of this and similar species (Joll 1977a; Joll 1983).

The effective application of SIA requires diligence to ensure consistency in the preparation of the sections and conducting of counts. With the disparity in counts between Readers 1 and 3, revealing that experienced researchers can vary greatly in how they count rings. An unsurprising result given that the average stylet has >300 increments across approximately eight stitched images, with high variations in how a researcher chooses the best visual course through the plane of a stylet for each individual count. Regardless, no bias was evident across age classes for the SIA sub-sample and the proportion of readable stylets was high. Despite the inherent challenges of SIA, once a solid basis is constructed, application of stylet weight as a proxy removes any need for continued processing of stylets, and repeated counts or expertise knowledge. This provides an unprecedented level of detail on the age profile of an exploited octopus population, and a method that can be trialled on any merobenthic octopus species that can be held in captivity for multiple days.

The onset of spawning coincides with senescence, for semelparous female octopuses, as a female octopus will reside to her lair, lay eggs, stop eating, tend to her eggs until hatching and die soon after (Mangold 1987). Males on the other hand continue to mate and hunt. This change in biological priority helps to explain: a) why calcine treated females appeared to cease forming stylet increments at the onset of spawning, b) the weakening of the relationship between stylet weight and total weight for large females (>2500 g) older than 500 days, and c) the disparity in longevity estimates, between females and males. Further investigations are required to verify this possible phenomenon and determine the potential implications on growth, recruitment and mortality estimates, for this fished population.

Age at formation of the first increment (natal ring) for *O.* (cf) *tetricus*, or any other merobenthic octopus species, is presently unknown. As described by Doubleday et al., (2011), the inability to determine when the natal ring is formed can result in unreasonable growth estimates and the calculation of relative rather than absolute age. Although this is an essential consideration, the present study does not appear to be significantly compromised by this fact. Age and growth estimates by Doubleday et al., (2011) for *Macroctopus maorum* were 73 – 224 days for octopuses with a mean weight of 6 kg, resulting in a mean growth rate of 11.2% BW d^{-1}. In comparison, the maximum age range for the present study was 84 - 601 days, mean weight of ~1 kg and a mean growth rate of 4.4% BW d^{-1}. Thus, demonstrating that unlike *M. maourum*, the age and growth profile of *O.* (cf) *tetricus* is well within the range of other octopus species, including: *Octopus pallidus* (mean = 3.1% bw d^{-1} (Leporati et al. 2008b)) *Octopus maya* (mean = 3.3% bw d^{-1} (Domingues et al. 2007) and *Octopus joubini* (mean = 4.62% bw d^{-1}(Forsythe 1984)). Admittedly, absolute age cannot be claimed in the present study. However, the only alternative is to apply a standardised age at natal ring formation, which could result in a uniform shifting of age ranges, which would have minimal impact on the results. Factors that were avoided in the present study, which may have hindered Doubleday et al., (2011) results for *M. maorum* were lack of image clarity under magnification, use of crystal bond alone which can lead to stylet desiccation, and lack of stylet increment periodicity verification. In addition, *M. maorum* has a soft sheath around its stylets, which is crumbly in composition and rapidly deteriorates under magnification. The influence this sheath has on age estimates has not been quantified, nor has it been observed in other octopus species that have provided successful SIA images (i.e. *O.* (cf) *tetricus*, *Octopus pallidus*, *Octopus australis* and *Octopus tetricus*) (pers. obs. SCL). The uniqueness of stylet structure and composition between species is not unusual, and should be taken into consideration when attempting SIA on a new species (Bizikov 2004).

The strong relationship between age and stylet weight was also translated to dorsal mantle length, indicating that age is very closely related to animal size for *O.* (cf) *tetricus*. This finding complies with Castanharti and Tomás (2012) who observed a correlation between mantle length and beak increments (age) in wild caught *Octopus vulgaris*, another merobenthic species. However, is contrary to those of Leporati et al. (2008b) who found no relationship between octopus size/stylet weight and age for wild caught *Octopus pallidus*. A holobenthic species, *Octopus pallidus* lays ~200 large eggs with hatchlings that immediately take up a benthic lifestyle without spending time as paralarvae (Leporati et al. 2008a). In addition, this size/age relationship does not comply with the high individual growth variability observed in numerous captive octopus studies (Forsythe 1984; Forsythe and Hanlon 1988). Therefore, in principle the present study supports the length/age relationship that underpins MPA. This is a very significant observation, for it suggests that a large number of age and growth studies, which have applied MPA to wild octopus populations, are of more intrinsic value than the results from captive growth studies indicate (Semmens et al. 2004). However, as observed in *O. pallidus*, this is unlikely to be a universal rule for all octopus species, as it may be an issue strongly associated with the intricacies of holobenthic and merobenthic life history strategies. The majority of captive growth studies that refute the relevance of MPA, are based on holobenthic species and have a tendency to investigate juvenile growth (Forsythe and Hanlon 1988; Leporati et al. 2007; Segawa and Nomoto 2002). Whereas, most applications of MPA on wild populations are based on merobenthic species and investigate growth in a fisheries context with broad biotic and abiotic variables (Cortez et al. 1999; Jabeur et al. 2012; López-Rocha et al. 2012). Therefore, it is an imperative when investigating the age of any octopus species, that age is substantiated with a suitable and verified direct ageing methodology (i.e. SIA, BIA or LQ), before any indirect ageing methods are applied.

The interpretation of stylet microstructure and morphology as a means of ageing octopus is very much in its infancy, compared to the use of statoliths to age squid (Clarke 1966). Over the past four decades, the use of statolith morphometric measurements as a proxy for age has been a highly contentious issue. Numerous studies have investigated the use of statolith weight, lengths and shapes as potential proxies for age for various squid species (Chen et al. 2012; Villanueva 1992). However, statolith morphometry has been largely discredited as a mechanism for ageing, due to the high variability observed in statolith growth and formation under different environmental conditions (namely temperature) and life stages (Thomas and Moltschaniwskyj 1999). As previously stated, Leporati et al. (2008b) provided similar conclusions for the stylet morphology of *Octopus pallidus*, a trend that was expected to continue, but has not eventuated for *O.* (cf) *tetricus*. Although, it is necessary to observe the lessons learnt from statolith ageing, stylets are not statoliths. Apart from the presence of growth rings (in squid statoliths), the two structures differ in composition, function, location and morphology. Therefore, to identify the potential pitfalls of using stylet morphology as a proxy for age, a greater understanding of the functionality, morphology and development of stylets, for both merobenthic and holobenthic species is required.

The present study has provided the largest known application of an age verified data set, for a wild octopus population. This research has provided an efficient method of octopus age determination for this species and potentially other similar species (i.e. *Octopus tetricus* and *Octopus vulgaris*). A method, that following initial investment in precision and quality, can render large sample sizes, with fast processing times and minimal expertise knowledge requirements, at relatively low costs.

Life history (Objective 1)

The application of broad-scale age information has revealed that *O.* (cf) *tetricus* breeds throughout the year, with hatching pulses occurring approximately every six months. Maximum longevity for both genders was estimated at ~1.5 years. For females, this short life span, average age at maturity of 12 months and semelparous life history, has resulted in a ~six month spawning window. However, the ability of females to mate prior to maturation and store sperm for up to 16 weeks (Joll 1976), helps to ensure females can lay eggs when necessary, rather than being completely bound by environmental cues. Even though a greater prevalence of females was identified during autumn, this was a weak signal and may be attributed to peak effort occurring at this time of the year (unpublished data). Hence, the lack of a distinct hatch season evident in sampling, complies with the tendency of octopus populations to not form spawning aggregations to the extent of many squid and cuttlefish species (Boyle and Boletzky 1996).

Back calculated age-at-hatching estimates enabled hatching pulses to be identified by age, rather than documenting the frequency of mature animals by season alone. Identified across years, the six-monthly hatchling pulses occurred at periods of equivalent temperatures, during the spring, winter and summer. Noting, the average warmest and coolest months each year, for the study area, occur during early autumn and early spring, respectively. Semi-annual spawning peaks during transitional temperatures have also been observed in *Octopus vulgaris*. For example: i) in the eastern Mediterranean, Katsanavakis and Verriopoulos (2006) observed continual spawning with peaks during winter/spring and summer/autumn and ii) on the north-west coast of Africa, Hatanaka (1979) also witnessed year round spawning, with peaks in mature females during autumn and spring.

Continual spawning throughout the year ensures that two or more generations are present within the population at any given time. However, cross-generational breeding is minimised, due to reproductive scheduling. Males mature on average 4.5 months earlier than females and continue to spawn until their demise, providing them with potentially a 12 month viable mating-period. This gives males the opportunity to mate with numerous mature and immature females during their lives, thus enhancing the probability of reproductive success. However, due to the later maturation of females, six month spawning window and short life span of the species, males have minimal opportunity to mate with the next generation. Incidence of males having a smaller size at maturity than females have been observed in many octopus species including: *Octopus vulgaris* (Silva et al. 2002), *Octopus pallidus* (Leporati et al. 2008a), *Eledone moschata* (Silva et al. 2004) and *Octopus magnificus* (Smith et al. 2006).

The growth trajectory of females and males followed very similar patterns until the onset of maturation. Where the total weight of females rose sharply reaching maximum sizes (4000 g) far exceeding those of the males (~2500 g) for animals >1 year of age. Increased investment in reproductive development significantly contributed to this additional weight in mature individuals, as demonstrated by GSI, thus supporting the existence of two-phased growth (Mangold 1983; Semmens et al. 2011). However, a potential limitation on the suitability of SIA for brooding females is that they may cease forming stylet increments at the onset of spawning. Although, this potential issue suggests that the age estimates of spawning females may be underestimated, the results provided are far less limiting than MPA, which does not account for the contraction of size in spent females or the rounding of the mantle with ovary development (Semmens et al. 2004).

Sea surface temperature at hatching had a strong influence on the subsequent growth rates of immature females and males, which largely corresponds with the principles of the Forsythe effect. Where “as hatching occurs over a period of increasing water temperatures, each monthly cohort will encounter warmer temperatures and thus grow significantly faster than cohorts hatched only weeks previously” (Forsythe 2004). Alignment of the Forsythe Effect with the six-month hatching pulses, indicates that octopuses hatched during periods of ascending temperatures have potentially higher growth rates than those during periods of descending temperatures. These temperature effects on growth rates signify the potentially strong influence hatching pulse timing may have on recruitment dynamics (Demarcq and Faure 2000). However, to unravel the influence various biotic and abiotic variables may have on the *O.* (cf) *tetricus* population and fishery, will require a longer time series with a focus on consistency and large sample sizes, which is currently being put into effect.

The reduced growth rates of immature octopuses hatched during peak temperatures, indicates that temperatures >22°C are above the optimum for this species. Long-term temperature data (1982 - 2012) indicates that monthly temperature averages >23°C are infrequent for the study area, having occurred on 24 occasions over the past thirty years (6.5%), eight of which were in the last two years. Declining growth rates and increased mortality have been observed in captive *O.* (cf) *tetricus* paralarvae and juveniles at temperatures >22°C (S. Kolkovski pers. comm.). Furthermore, similar temperature effects have been observed for juvenile and mature *Octopus vulgaris* in captivity at temperatures >23°C (Aguado Gimenez and Garcia Garcia 2002), with temperatures between 10 – 20°C regarded as optimal for grow-out of this closely related species (Vaz-Pires et al. 2004).

The present study can only provide relative rather than absolute age. Thus, what is represented as hatch month may be settlement month, which challenges the validity of declaring the six-month pulse pattern as hatching, when it could be during settlement? However, until the development phase at formation of the first stylet increment is identified, the question remains open. Therefore, to ensure consistency across the analysis, the present study maintains that formation of the first stylet increment is at hatching. To help solve this issue and get a better understanding of the dynamics of the population, pre-recruitment sampling is required with emphasis on paralarval distribution and abundance patterns in context to a range of biotic and abiotic factors (e.g. salinity, habitat, oceanographic conditions) (André et al. 2009).

The strong differentiation in the size and age composition of octopus caught by the two gear types has played a defining role in the development of the fishery since 2010. Age at recruitment for both genders ranged from 100 - 150 days and 250 – 300 days for shelter pots and trigger traps, respectively. The prevalence of immature animals caught in shelter pots increases the likelihood of negative impacts on future recruitment, in comparison to trigger traps. This is compounded by high proportion of immature females caught in shelter pots, whereas trigger traps predominantly caught mature males. In addition, due to *O.* (cf) *tetricus*' semelparity and the low survival rate of unattended egg clutches, any female removed from the population will not contribute to recruitment (Boyle 1990). The actual threat of shelter pots having a detrimental impact on the population is fairly minimal due to their low catch rates, localised effort and the transition of the fishery towards trigger traps. In effect, the reduction of shelter pot effort (now <5% of catch) acts as a proxy for a size-based management strategy. For example, in Asturias north-west Spain a minimum capture weight of 1 kg is exercised to protect recruits, particularly females (Fernández-Rueda and García-Flórez 2007). Thus, the introduction of trigger traps and their subsequent surpassing of shelter pots as the primary gear type in DOF in <3 years, has potentially made shelter pots redundant. However, as the fishery expands along the western and southern coasts of Western Australia with trigger traps or any other gear type, catch composition will need to be monitored to ensure that any negative effects of size and gender selectivity are abated.

Due to the lack of overlap between gear types at common depth ranges, it was not possible to independently decipher the influence of gear and depth on catch composition. However, several valuable inferences can be made from the present results, which provide new and unique insights into the population. One such consideration is the influence of pot volume. Pot volume has been shown to have a positive correlation with octopus size in other fisheries (Barry et al. 2009; Sobrino et al. 2011). A single trigger trap has 2.5 times the volume of a shelter pot (15 vs 6 lt), however, an octopus is unaware of this until it enters the trap and triggers the device. In addition, during captivity studies, shelter pots were used to house full-sized brooding females (>2 kg), providing ample room. This suggests that in the shallow (5 - 15 m) habitat limited environments (seagrass beds and sand) in which the shelter pots are set, large octopuses if present would most likely utilise shelter pots and out compete smaller octopuses (Leporati et al. 2009).

The high proportion of mature males in trigger trap catches may be attributed to the trigger trap being an active gear type and the tendency for males to actively hunt and look for mates, whilst females of equivalent age are either approaching maturation or tending to their eggs. In addition, the lack of highly gravid or spent females in trigger trap catches indicates that females do not generally use the trigger traps as lairs in which to lay their eggs. Instead, females are most likely using the series of reefs that lie along the Western Australian coastline between 32° to 33°S around the 20 m contour line, to brood their eggs (i.e. Five Fathom Bank, Coventry Reefs, Murray Reefs and Bouvard Reefs). The majority of trigger trap fishing has occurred adjacent to these reefs on sand and rubble dominated environments in waters 20 – 40 m deep. Thus, a plausible depiction of the life history for *O.* (cf) *tetricus* may consist of a) paralarvae hatch and are at the mercy of the currents for ~50 days (S. Kolkovski, pers. comm.), b) settle on the benthos then move to protected inshore waters, c) females move offshore to rocky temperate reefs to mature and find appropriate lairs in which to brood their eggs, and d) males follow the females and continue to hunt and look for potential mates.

The movement and migration of octopuses to appropriate habitats for brooding, has been proposed for several species including: *Octopus tetricus* in New Zealand (Anderson 1997), *Octopus magnificus* in South Africa; (Smith et al. 2006), *Octopus insularis* in Brazil and *Octopus vulgaris* in Greece (Katsanevakis and Verriopoulos 2004). The purpose of such migrations is to ensure females have suitable habitat to brood their eggs, that there are large enough aggregations of mature males and females to enable breeding, and access to a suitable food source (Semmens et al. 2007). To test the reef migration hypothesis and to determine the influence of depth on gear catch composition, future fisheries-independent sampling of reef habitats and the deployment of trigger traps in waters shallower than 20 m, are required.

Gear efficiency (Objective 2)

A single cradle of trigger traps has 15 times the maximum annual fishing efficiency of a single shelter pot. This differentiation in the efficiency of the two gear types is a product of the catch composition and shorter soak period of trigger traps, and the reason behind their immediate impact on the DOF. In addition to their greater fishing power, trigger traps are more suited than shelter pots for use in more exposed waters and can be deployed in complex habitats as a single unit of gear. These attributes have effectively opened up the Western Australian coast line to octopus fishing. In this light, the future of shelter pot fishing appears non-existent. However, with great expanses of water covering >34,000 km^2 to be explored and the catchability of trigger traps yet to be properly tested in waters shallower than 20 m, it is possible that a mixture of shelter pot and trigger trap fishing may be applicable for some regions. This will be addressed by two additional depletion surveys off Busselton (latitude 33.5°S) and Dongara (latitude 29.5°S). This future research will determine the influence of latitude and depth on density and catch composition of trigger traps, by spreading effort across 10 – 40 m depth contours using the same grid pattern as the first depletion study.

Trigger trap catch rates (NPUE – number caught per pot lift and CPUE – kg caught per pot lift) from the commercial daily logbook data were not impacted upon by spatial considerations of latitude and depth, but showed similar patterns with the temporal factors of year and time. The initially high annual rates of NPUE and CPUE for 2010, compared to subsequent years, may have been a product of accessing “virgin” biomass. However, the higher catch rates during 2010 were not a product of octopus size, for mean octopus weight during 2011 was higher. This complies with the short life span and dominance of males in the catch composition, where even though a virgin biomass may have been accessed the turnaround time in the population would have diminished the possible effects of size-selective fishing mortality. Instead a more likely explanation for the drop in catch rates is fleet dynamics. By the end of 2010 the high catch had flooded the market, resulting in the following scenario in 2011: a) a significant drop in beach price, b) many fishers reducing their effort, c) extension of soak periods and d) several fishers (three out of eight) leaving the fishery. These three fishers had landed 40% of the 2010 catch. In 2012 the catch rates of existing fishers had risen slightly from 2011 levels and by all accounts stabilised. However, 2012 also saw the introduction of several new fishers start up in waters north of latitude 31°S, in the C and B zones. These new fishers had significantly lower catch rates as they explored new waters, organised processing operations and generally caught smaller octopuses.

The escalation of landings in the DOF during 2010, demonstrated that octopus stocks are considerably larger than what could've been surmised prior to the introduction of trigger traps. However, expansion was restricted during 2011 - 2013, in anticipation of the results from the present study and management arrangements in regards to allocation. Hence, the present study has a) met the objective of determining trigger trap fishing efficiency, b) provided a detailed account of trigger trap and shelter pot catch composition and c) given insights into the potential impacts each gear type may have on the population. The results of this research will assist in the development of allocation strategies as the fishery transitions into fully managed status.

The depletion study demonstrated very similar catch rates and composition to those from the commercial fishery data, signifying its relevance and applicability for extrapolation across other areas. For the purposes of the present study, the site of the depletion study was regarded as optimal habitat, given its proximity to grounds that consistently return high catch rates. The general population estimate of 591 ind/km^2 is regarded as a viable estimate if not highly conservative, providing an average ~6 ind per ha (Belcari et al. 2002). In addition, the selectivity of the trigger traps for large mature males, does not account for spawning and post-spawning females, which are not selected by either shelter pots or trigger traps. This absence of most likely a large proportion of the population indicates that this density estimate may be a minimum for optimal grounds. In addition, the general lack of bycatch confirms that trigger traps are highly selective for *O.* (cf) *tetricus*, with low incidence of traps triggering without capture. Commercial fishers have reported that cradles of trigger traps have higher catch rates when new /clean than with fouling. This may be a product of the visual role the traps have in luring an octopus or an olfactory response to the plastic (Boyle and Rodhouse 2005). The condition of the traps was monitored during the depletion study to ensure fouling would not influence results. The duration of the study was kept within the typical period fishers recover their gear for cleaning (~12 weeks) (A. Coughlan pers. comm.).

Biomass and sustainable harvest estimates (Objective 3)

Precautionary biomass and abundance estimates suggest that the *O.* (cf) *tetricus* population in Western Australia is in the proximity of 8,600 t to 12,600 t. This is considerably less than initial estimates by Kimura (1980) of 30,000 t, whose study was based on the development of suitable gear and the marketability of the product, rather than biology or abundance estimates. We acknowledged that octopus distribution and abundance will be highly patchy, with strong correlations with substrate types (i.e. hard structures on soft substrates or penetrable areas on hard substrates) and prey availability (Katsanavakis and Verriopoulos 2004; Leite et al. 2009). However, until: 1) more detailed information is available on the habitat requirements of *O.* (cf) *tetricus*, 2) the spawning sites for females are identified, and 3) habitat profiles have been constructed for each fishing zone, the current biomass estimations, which are suitably conservative for a preliminary investigation, are considered applicable.

The total fishable area of 34,105 km^2 is considered a tentative estimate given the restricted depth range (20 – 50 m) applied, compared to the known depth range of the species of 5 – 70 m. In addition, the selectivity of the trigger traps towards large, mature and older males had an influence on restricting biomass estimates. Hence, the biomass estimates provided represent harvestable, rather than total biomass. Therefore, by inadvertently protecting semelparous females and immature males, the potential impacts of trigger trap fishing on future recruitment is reduced, an issue which undermines many other octopus fisheries (Leporati et al. 2009; Sauer et al. 2011). In context to these biologically advantageous yet analytically difficult idiosyncrasies of the DOF, it is an imperative to update present estimates with new information from all fishing zones. To achieve this, consistent and detailed biological sampling across zones and depth contours will need to be instigated and maintained. This will require considerable research effort given the short life span of the species, subsequent fast turnaround of generations and the populations susceptibility to both local and regional environmental variables.

Despite the relatively short history of trigger trap fishing in the DOF, the per-recruit model provided biologically appropriate values, with fishing mortality of fully recruited octopuses (F_{t_r}) not overlapping with $F_{0.1}$ and $F_{SPR0.2}$ and below point estimates for $F_{0.3}$ and $F_{0.4}$. Thus indicating current levels of catch are sustainable for the DOF. The process of combining outputs from the per-recruit analyses with estimates of available population abundance enabled estimates of catches in relation to SPR reference levels. By accounting for this species' semelparous life history, the present study demonstrates how the model developed by Hendrickson and Hart (2006) can be applied for octopus stock assessment. However, the lack of post spawning females in the samples, may have contributed to biased estimates of Z_{s} and M_{s}. A product of the selectivity of the gear, to address this issue would require fishery-independent sampling involving a range of methods that would target both genders equally and access all life stages (Hartwick et al. 1988).

The adoption of a Bayesian approach and a fixed value for M_{n} were applied to address strong correlations inherent among the model parameters. Despite these steps, there remained high uncertainty in the estimated F for the stock. In addition, uncertainty due to under representation of mature females was likely to have contributed to the difficulty in estimating model parameters. Hence, further research on alternative methods to help avoid these constraints, such as fitting the model to additional data or through further revision of model structure, would benefit the reduction of uncertainty in stock assessment advice. For example, an improved understanding of within-year cohort dynamics would greatly reduce uncertainty in assessment modelling and provide scope for fitting a revised model to a larger (cohort-specific) dataset.

To help account for the potentially high variability in the population, when determining the stock status of the DOF, assessments should be conducted on an annual basis (Boyle 1990). In addition, monthly monitoring of catch and effort may also be of assistance for identifying the resilience or susceptibility of stocks to the impacts of localised fishing pressure or significant events such as the marine heatwave. Ideally, the development of a recruitment index would greatly assist in the setting of appropriate catch and/or effort limits for individual cohorts on an annual basis. This would be particularly useful if future research can identify if (multiple) recruitment events are significantly variable from year to year. Until this is achieved, the present precautionary approaches have provided a relevant basis for sustainable development of the fishery.

The three abundance scenarios presented (precautionary, conservative and possible) for all fishing zones combined, provided viable sustainable harvest rationales, which would effectively turn the DOF into a fishery of significant size and value, by Western Australian standards (Fletcher and Santoro 2013). Ranging from 879 t (precautionary $SPR_{0.4}$) to 2261 t (possible $SPR_{0.2}$), the lower estimate is conservative and more suited to a longer lived species, yet would still constitute a catch increase 4 times current landing in the fishery (2013 catch = 240 t). Whereas, the maximum estimate is reliant on a higher consistency of catch rates across a vast expanse of diverse waters, that would see catches increase 14 times current level. Regardless, the economic viability of any significant expansion in the DOF would need to be maintained through a detailed and adhered to plan, to ensure market flooding as experienced in early 2011, does not reoccur.

The probability of catches approaching biologically based limits in the short term, are presently constrained by the current efficiency of trigger traps, latent effort and the remoteness of many unexplored areas (especially on the south coast). Although maximum cradle efficiency is calculated at 44 kg $year^{-1}$ per cradle, the most successful fishers are presently landing 30 kg $year^{-1}$ per cradle. In addition the current allocation of 15,000 cradles, are presently only working at 25% efficiency, which is mostly attributed to latent effort. This may change if pot allocation reached considerably higher levels, for example 40,000 trigger traps. However, to minimise the possibility of generating more latent effort, it is an imperative to increase the efficient usage of gear as opposed to providing allocation for potential catch limits. This is only achievable if the management instruments implemented progressively expand the fishery, on defined spatial and temporal scales. A possible approach is setting catch limits in each zone in alignment with biological reference points then allocating gear entitlement accordingly. As a hypothetical example if Zone C had a TAC of 350 t (precautionary scenario) ~11,500 cradles (at an efficiency of 30 kg $year^{-1}$) would need to be allocated to make TAC achievable. However, given the inherent uncertainty with the short time series, such a means of allocation could be regulated by incremental progressions of TAC and allocation in accordance with research monitoring and assessment of catch rates and gear efficiency.

At present, landings, effort and subsequently research into the DOF have focussed on fishing zone C. This zone is considered to be the central to the distribution of the species and home to the capital city of Perth and associated infrastructure. Although, the fishing grounds in zones A and B are more remote, infrastructure is adequate due to the activities of the WCRLF and other established fisheries. The south coast of WA on the other hand, is subjected to the vagaries of the Southern Ocean and has less available infrastructure. This will result in the south coast developing at a latter period than the west coast. For these reasons and as detailed in the biology and abundance analyses, it is important to maintain the high level of spatial and temporal resolution in the fishery and research data of the fishery.

Empirical modelling of the effects of environment on potential harvest

The strong relationship between, mean octopus weight, temperature and latitude is aligned with the findings that animals hatched at temperatures >22°C had generally lower growth rates than those hatched at slightly lower temperatures. This may be related to the thermal tolerance of *O.* (cf) *tetricus*. The known extent of *O.* (cf) *tetricus'* northern distribution is Shark Bay (26°S latitude), where mean monthly SST during 1982 - 2012 exceeded 22°C (mean = 23.5°C) ~77% of the time. The impacts of temperature on the biological process of octopuses, is well documented and is considered a major driver for all biological processes (Forsythe and Van Heukelem 1987). Hence events such as the marine heat wave (Pearce and Feng 2013) are bound to have an impact on the population, which will most likely vary greatly with latitude. For example, the processes that may cause mortality or a reduction in growth in northern latitudes could result in bolstering stocks in southern latitudes. This has been observed in the range extension of *Octopus tetricus* on the east coast of Australia as a product of the strengthening of the East Australian Current (Leporati pers. obs.) Apart from strictly biological implications, the ecological alterations associated with events such as the marine heat wave can also have a strong influence on octopus populations. For example, the marine heat wave led to a dying off of abalone stocks and assumedly other sessile marine invertebrates in northern waters, taxa which are general prominent octopus prey (Pearce et al. 2011). In addition, the high temperatures led to vast reductions in seagrass coverage and complexity a known habitat for immature *O.* (cf) *tetricus*. Yet to be proven, events such as these and their impacts on how octopus stocks may fluctuate in the DOF need to be considered when managing this resource. Overall, there is a large array of information required to gain a true understanding of how environmental variables may impact upon the dynamics of this population across a vast stretch of water covering tropical and temperate zones.

Octopus predation on lobsters (Objective 4)

Octopus predation data from the commercial rock lobster monitoring program in the WCRLF, revealed that octopus predation of lobsters far exceeds (at least three times) octopus landings. Thus suggesting the octopus population is considerably larger than what the WCRFL byproduct landings suggest. Although the WCRLF commercial monitoring program provides an underestimation of the stock, this valuable data source covering 32 years and sampling from hundreds of vessels, provides additional indices and points of comparison for the DOF. As two highly interconnected fisheries, the DOF is in effect a product of the WCRLF, as a reaction to octopus predation and the utilisation of the vast fleet infrastructure of the WCRLF. In addition, several vessels operating in the DOF are also actively fishing in the WCRLF.

Although both fisheries are interconnected and access the same octopus stocks, the results from this study suggest present fishing pressure is not impacting upon octopus landings in each fishery. This is indicated by the consistency of octopus predation in lobster pots over the past three years. Even though, declines in octopus landings suggest the contrary, this could be a product of the changes in the management and fleet dynamics of the WCRLF and resultant increased numbers of lobster caught per pot. Anecdotal evidence suggests that the greater numbers of lobsters in a pot reduces the likelihood of octopus capture. This phenomenon could not be identified in the octopus predation per 1000 pot data. It should also be noted that *O.* (cf) *tetricus* is not considered to be primary predator of *Panulirus cygnus* in the wild, due to their slower swimming speed and the defence mechanisms of lobsters in escapable locations (Cobb 1981; Joll 1977b).

Within pot predation was shown to increase with the duration of soak period, due to the greater provision of time for an octopus to locate a lobster pot. Joll (1977b) demonstrated in aquaria that octopuses are inclined to hold residencies in lobster pots over long soak periods and consume more lobsters. The trend of decreasing predation with increasing depth followed the trend of decreasing relative abundance of octopuses with depth. This result is counter-intuitive to the results from catch rates displayed by the deeper water trigger traps. However, abundance does not count for octopus size.

6 Conclusion

Objectives of this project were to establish biological parameters, estimate pot efficiencies, determine sustainable harvest level, and establish octopus predation rates on lobsters. All objectives were met. This project has been unique in that opportunities to evaluate the size of a fisheries resource in concert with its developmental are rare and challenging. The key challenge is that of constructing realistic estimations for extrapolation across broad unfished water, when time series and data are short. However the opportunity to research and manage a cephalopod fishery at the start of its development instead of in retrospect, far outweighs any potential inaccuracies. A range of innovative approaches were devised in the present study, including:

a) the development of a method to rapidly, accurately and cost effectively age large samples for a wild merobenthic octopus population, thus providing the largest known data set of its kind in the world;

b) the utilisation of age data to identify hatching pulses, plus the detection of spawning windows and their influence on reproductive scheduling;

c) the design and implementation of a fishery specific daily catch and effort log book, providing high spatially resolved data at the onset, for a previously economically insignificant fishery;

d) the development and application of species specific per-recruit model, which incorporates verified age data and semelparous life history for a wild octopus population.

These approaches have provided a solid research foundation on the biology and population dynamics of *O.* (cf) *tetricus*, which will help to ensure the ecological and economic sustainability of the DOF. However, despite the advances made by this research, the DOF is subject to the inescapable variability of cephalopod populations. Variability that was poignantly described by Boyle and Rodhouse (2005) as "….behaviour of (cephalopod) populations suggests the terrestrial analogy of the desert locust whose populations fluctuate dramatically, reaching plague proportions and creating famines". This dramatic depiction of cephalopod stock variation signifies the necessity for fluid development and management strategies for the expansion of the DOF. To achieve this, research monitoring and management arrangements must be reappraised on an annual basis. Thus, maintaining relevance with the short residency times of standing stocks and the influence fishing pressure and environmental variables can have on stock fluctuations.

7 Implications

Three planned outcomes and benefits were detailed in the project agreement and have been met as follows:

1. **Increased knowledge of octopus stocks;**

Biological information was compiled for shelter pot and trigger trap catches, including age profiles, growth rates, size and age at maturity, recruitment pulses and reproductive scheduling. Despite the short time series, this work constitutes what is Australia's largest biological data set on any octopus species, exploited or otherwise. On an international context, the inclusion of detailed age information enabled the exploration of age at maturity and hatching effects on the population, something that has been limited for merobenthic species.

The commercial daily logbook data provided a unique insight into the dynamics of a developing fishery, thus providing the best opportunity for the resource to be exploited in a sustainable manner. The combination of the spatially explicit catch and effort data and the depletion experiment, enabled viable estimates of biomass and abundance in fished and unfished waters. The inclusion of lobster fishery bycatch information provided an insight into how the two fisheries interact and how this may influence the population as a whole.

2. **An expanded octopus fisheries (100 to 300+ tonnes);**

Since the inception of this project (2010), total annual landings have increased slowly and the maximum catch to date is 240 t. This is due to restrictions on allocation and the time required for other exemption holders to catch up with those that originally developed the trigger trap. This issue has been resolved with the recommendations from an independent allocation panel being accepted, and pot allocations granted to participants as per the recommendations. The fishery is now on a phased expansion target to achieve 630 - 1000 tonnes, with a total trigger pot allocation of 22,500 across the entire fishery.

Other developments in the fishery since the 2010 include: i) expansion of the fleet from six to 17, ii) the exploration of new areas across the west coast, iii) the development of a new processing plant in Geraldton and iv) the establishment of markets where demand consistently exceeds demand. All of these aspects indicate a desire by industry to genuinely invest in and expand the fishery.

3. **Formal management of the Western Australian Octopus fishery.**

The DOF is presently going through the process of transitioning from a developmental to an interim managed fishery. The present report will be the primary document used to convey research advice to fisheries managers, the commercial fishing industry and all other stakeholders. The key information conveyed in this research, i.e. i) calculation of gear fishing efficiency and composition, ii) detection of possible habitat partitioning, iii) construction of a biological profile, iv) identification of hatching pulses and reproductive scheduling, iv) density and abundance estimates and vii) provision of potential sustainable harvest scenarios, have already facilitated this transition,. In context to the short time series available, this level of information for a developmental fishery has exceeded expectations.

8 Recommendations

To maintain the high level of spatial and temporal resolution of the catch and effort data, the daily logbook recording system should be continued. In addition, all other reporting requirements should be streamlined to minimise any double handling of data. Dedicated and consistent biological sampling from all fishing zones is required to retain the integrity of the time series. This will aid in the identification of inter and intra-annual trends in growth, reproductive scheduling and recruitment. Information from these sources will assist in the annual assessment of the fishery and monthly monitoring of catch rates for each zone.

8.1 Further development

The productivity of waters in the northern expanses of the DOF is only beginning to be explored. As the major lobster fishing grounds, it is of keen interest for both fisheries, how targeted commercial octopus fishing in this region will fair. However, in comparison to the west coast, the south coast has received minimal attention from commercial fishers and researchers alike. With considerable difference in oceanographic process and climatic conditions to the west coast, transferability of findings from one coast to the other is limited. Characterised by strong south westerly winds from the Southern Ocean, the south coast is dominated by a rugged granite and limestone coastline with a narrow shelf region, compared to the sandy expanses of the Indian Ocean west coast. Suitable gear and vessel types, to efficiently access and fish large expanses of this coast, are yet to be trialled in this region.

The determination of trends in the movement and migration patterns, and habitat preferences for all life history stages and genders, is essential for a true indication of the potential impacts of fishing on the population. In addition, such information will assist in the ecological impacts of octopus fishing. Specific areas that require research attention include: octopus predation of lobsters within and outside of lobster pots, paralarval survival rates and dispersal patterns, and variations in *O.* (cf) *tetricus'* trophic roles at different life stages. Further research into such factors will help to enable an ecosystem based approach to the management of the fishery and the maintenance of the fisheries social licence to operate.

9 Extension and Adoption

Research progress and outcomes have been conveyed to industry throughout the project's duration, including: presentations at Annual Management Meetings, time spent on commercial fishing vessels (>15 trips), industry meetings, and continual discussions and correspondence with exemption holders, fishers and processors.

The research team has worked closely with the Department of Fisheries management team on all aspects of the fishery. Areas of specific focus were gear efficiency and allocation. This report has been used by the Department of Fisheries, Western Australia to develop a Management Plan for the Octopus Interim Managed Fishery in Western Australia. Key recommendations on zone delineation, gear efficiency and sustainable harvest levels have been used to set the allocation and access rules for the fishery. The fishery has been recommended for a phased development to 1000 tonne capacity ($10-$12 million GVP).

As part of the broader scientific community, the research team maintained and strengthened ties with a variety of universities, research institutes and government agencies throughout Australia, including: The University of Tasmania, Murdoch University, Museum Victoria, La Trobe University, New Castle University, Australia Museum, Museum of Western Australia, Museum Victoria, NSW Fisheries, South Australian Research and Development Institute, Department of Primary Industries Water and Environment (Tas.) and Fisheries Victoria. These relationships were of mutual benefit covering a variety of biological, ecological and fisheries management issues.

9.1 Project coverage

The project was covered in the FRDC's *Fish* magazine in March 2011.

During October 2012, Dr Leporati travelled to Brazil to attend the Cephalopod International Advisory Council's (CIAC) triennial symposium. The premier cephalopod conference in the world, Dr Leporati participated in a pre-symposium workshop on cephalopod population dynamics and presented a talk at the symposium on the results from the current study titled: *"Estimating harvestable biomass of the Octopus* (cf) *tetricus fishery in Western Australia."* Tangible outcomes from attendance at this symposium include assistance from colleagues on validating stylet increment counts and further research into the genetic differentiation between *O.* (cf) *tetricus* and *O. tetricus*.

10 Glossary

Cradle: A gear configuration of three trigger traps set on a steel base;

Holobenthic: An octopus species that resides to the benthos directly after hatching and does not undertake a paralarval develop stage;

Mantle: The hood of an octopus;

Merobenthic: An octopus species that has a paralarval stage in its life history;

Shelter pot: An open-ended plastic pot used to capture octopus;

Soak period: Number of days fishing gear has been left in the water;

South Coast: The south coast of Western Australia stretching from Augusta in the west to the South Australian border in the east;

Stylet: A reduced vestigial shell found in the mantle musculature of octopus;

Trigger trap: A plastic pot baited with a rubber crab that triggers a trap door when handled by an octopus;

West Coast: for the purposes of this study the west coast of W.A. is limited to Shark Bay to Augusta.

11 Project materials developed

Three scientific papers have been produced from this project

1) Leporati, SC, Hart AM, Larsen R, Franken LE, De Graaf MD (2015). Octopus life history relative to age, in a multi-geared developmental fishery. *Fisheries Research* 165: 28-41.
2) Leporati, SC, Hart AM (2015). Stylet weight as a proxy for age in a merobenthic octopus population. *Fisheries Research*. 161: 235-243.
3) Marriott RJ, Leporati SC, Hart AM, Stephenson P, Hart DR, Hendrickson LC (submitted). Per-Recruitment assessment for a developing octopus fishery. *ICES Journal of Marine Science*

12 Appendices

Appendix 1: Per-recruit model explanations

For cases when per-recruit models were evaluated for $t_r < a_0$, the formulas for $N(t)$ and $S(t)$ were modified accordingly:

$$N(t) = N_i \cdot e^{-M_{\text{ns}} \cdot t} \quad \text{for} \quad t < t_r \tag{A.1}$$

$$N(t) = N_i \cdot e^{-M_{\text{ns}} \cdot t - \int_{t_r}^{t} H(\tau)\,\mathrm{d}\tau} \quad \text{for} \quad t_r \le t < a_0 \tag{A.2}$$

$$N(t) = N_0 \cdot e^{-M_{\text{ns}} \cdot (t - a_0) - \int_{a_0}^{t} R(\tau)\,\mathrm{d}\tau - \int_{a_0}^{t} H(\tau)\,\mathrm{d}\tau} \quad \text{for} \quad a_0 \le t \tag{A.3}$$

$$S(t) = \frac{\int_{a_0}^{t} R(\tau) \cdot N_0 \cdot e^{M_{\text{sp}} \cdot \tau - \int_{a_0}^{t} R(\tau)\,\mathrm{d}\tau}\,\mathrm{d}\tau}{J(t)} \quad \text{for} \quad a_0 \le t \tag{A.4}$$

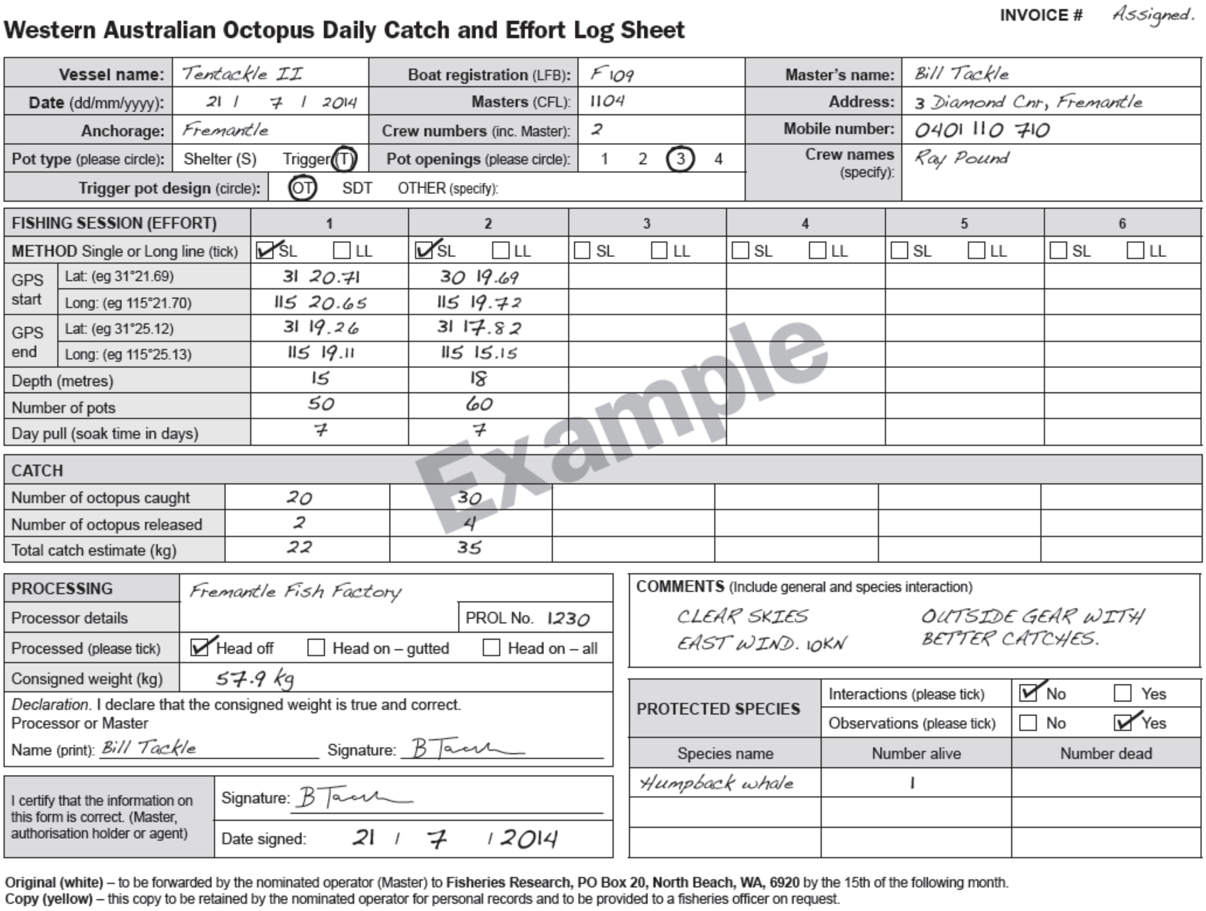
where: $N_0 = N_i \cdot e^{-M_{\text{ns}} \cdot a_0 - \int_{t_r}^{t} H(\tau)\,\mathrm{d}\tau}$

Appendix 2: Staff

Researchers and project staff involved in project:

- Dr Anthony Hart Principal Research Scientist
- Dr Stephen Leporati Research Scientist
- Dr Ross Marriott Senior Research Scientist
- Mr David Murphy Senior Technical Officer

Appendix 3: Log sheet used to record daily catch and effort in the developmental octopus fishery.



INVOICE # Assigned.

Western Australian Octopus Daily Catch and Effort Log Sheet

Vessel name:	Tentackle II	**Boat registration** (LFB):	F 109	**Master's name:**	Bill Tackle
Date (dd/mm/yyyy):	21 / 7 / 2014	**Masters** (CFL):	1104	**Address:**	3 Diamond Cnr, Fremantle
Anchorage:	Fremantle	**Crew numbers** (inc. Master):	2	**Mobile number:**	0401 110 710
Pot type (please circle):	Shelter (S) Trigger [✓ (T)]	**Pot openings** (please circle):	1 2 [✓ 3] 4	**Crew names** (specify):	Ray Pound
Trigger pot design (circle):	[✓ OT] SDT OTHER (specify):				

FISHING SESSION (EFFORT)		1	2	3	4	5	6
METHOD Single or Long line (tick)		☑ SL ☐ LL	☑ SL ☐ LL	☐ SL ☐ LL	☐ SL ☐ LL	☐ SL ☐ LL	☐ SL ☐ LL
GPS start	Lat: (eg 31°21.69)	31 20.71	30 19.69				
	Long: (eg 115°21.70)	115 20.65	115 19.72				
GPS end	Lat: (eg 31°25.12)	31 19.26	31 17.82				
	Long: (eg 115°25.13)	115 19.11	115 15.15				
Depth (metres)		15	18				
Number of pots		50	60				
Day pull (soak time in days)		7	7				

CATCH						
Number of octopus caught	20	30				
Number of octopus released	2	4				
Total catch estimate (kg)	22	35				

PROCESSING	Fremantle Fish Factory	
Processor details		PROL No. 1230
Processed (please tick)	☑ Head off ☐ Head on – gutted ☐ Head on – all	
Consigned weight (kg)	57.9 kg	

Declaration. I declare that the consigned weight is true and correct.
Processor or Master
Name (print): Bill Tackle Signature: B Ta

I certify that the information on this form is correct. (Master, authorisation holder or agent)
Signature: B Ta
Date signed: 21 / 7 / 2014

COMMENTS (Include general and species interaction)

CLEAR SKIES
EAST WIND. 10KN

OUTSIDE GEAR WITH
BETTER CATCHES.

PROTECTED SPECIES			
	Interactions (please tick)	☑ No	☐ Yes
	Observations (please tick)	☐ No	☑ Yes
Species name	Number alive	Number dead	
Humpback whale	1		

Original (white) – to be forwarded by the nominated operator (Master) to **Fisheries Research, PO Box 20, North Beach, WA, 6920** by the 15th of the following month.
Copy (yellow) – this copy to be retained by the nominated operator for personal records and to be provided to a fisheries officer on request.

13 References

Aguado Gimenez, F.; Garcia Garcia, B. 2002. Growth and food intake models in *Octopus vulgaris* Curvier (1797): influence of body weight, temperature, sex and diet. Aquaculture International. 10:361-377.

Amor, M. 2011. Deciphering the taxonomic status and phylogenetic relationships of an Australasian octopod species complex: A combined morphological and molecular approach. Department of Genetics. Melbourne: La Trobe University.

Anderson, T.J. 1997. Habitat selection and shelter use by *Octopus tetricus*. Mar Ecol Prog Ser. 150:137-148.

André, J.; Pecl, G.T.; Grist, E.P.M.; Semmens, J.M.; Haddon, M.; Leporati, S.C. 2009. Modelling size-at-age in wild immature female octopus: a bioenergetics approach. Mar Ecol Prog Ser. 384:159-174.

Barratt, M.; Allcock, L.A. 2010. Ageing octopods from stylets: development of a technique for permanent preparations. ICES J Mar Sci. 67:1452-1457.

Barry, P.D.; Tamone, S.L.; Tallmon, D.A. 2009. Evaluation of the capture efficiency and size selectivity of four pot types in the prospective fishery for North Pacific giant octopus (*Enteroctopus dofleini)*. Fisheries Bulletin. 198:39-44.

Belcari, P.; Cuccu, D.; Gonzáles, M.; Srairi, A.; Vidoris, P. 2002. Distribution and abundance of *Octopus vulgaris* Cuvier, 1797 (Cephalopoda: Octopoda) in the Mediterranean Sea. Sci Mar. 66:157-166.

Bizikov, V.A. 2004. The shell in Vampyropoda (Cephalopoda): morphology, functional role and evolution. Ruthenica. 3:1-88.

Boyle, P.R. 1990. Cephalopod biology in the fisheries context. Fish Res. 8:303-321.

Boyle, P.R.; Boletzky, S.v. 1996. Cephalopod populations: definitions and dynamics. Philos Trans R Soc Lond B Biol Sci. 351:985-1002.

Boyle, P.R.; Rodhouse, P.G. 2005. Cephalopods: ecology and fisheries. Oxford: Blackwell Science.

Brooks, S.P.; Gelman, A. 1998. General methods for monitoring convergence of iterative simulations. Journal of Computational and Graphical Statistics. 7:434-455.

Caddy, J.F. 1996. Modelling natural mortality with age in short-lived invertebrate populations: definition of a strategy of gnomonic time division. Aquat Living Resour. 9:197-207.

Campana, S.E. 2001. Accuracy, precision and quality control in age determination, including a review of the use and abuse of age validation methods. J Fish Biol. 59:197-242.

Castanhari, G.; Tomás, A.R.G. 2012. Beak increment counts as a tool for growth studies of the common octopus *Octopus vulgaris* in southern Brazil. Boletim do Instituto de Pesca (Sao Paulo). 38:323-331.

Chen, X.; Lu, H.; Liu, B. 2012. Sexual dimorphism of statolith growth for the south patagonian stock of *Illex argentinus* off the exclusive economic zone of Argentina. Bull Mar Sci. 88:353-362.

Clarke, M.R. 1966. A review of the systematics and ecology of oceanic squids. Adv Mar Biol. 4:91-300.

Cobb, J.S. 1981. Behaviour of the Western Australian Spiny Lobster, *Panulirus cygnus* Geroge, in the field and laboratory. Aust J Mar Freshw Res. 32:399-409.

Cortez, T.; Castro, B.G.; Guerra, A. 1995. Reproduction and condition of female *Octopus mimus* (Mollusca: Cephalopoda). Mar Biol. 123:505-510.

Cortez, T.; Gonzalez, A.F.; Guerra, A. 1999. Growth of *Octopus mimus* (Cephalopoda, Octopodidae) in wild populations. Fish Res. 42:31-39.

de Lestang, S.; Thomson, A.; Rossbach, M.; Baudains, G. 2013. West Coast Rock Lobster Fishery Status Report. in: Fletcher W.J., Santoro K., eds. Status Reports of the Fisheries and Aquatic Resources of Western Australia 2012/13: The state of the Fisheries. Perth: Department of Fisheries, Western Australia.

Demarcq, H.; Faure, V. 2000. Coastal upwelling and associated retention indices derived from satellite SST. Application to *Octopus vulgaris* recruitment. Oceanologica Acta 23:391-408.

Diallo, M.; Jouffre, D.; Caverivière, A.; Thiam, M. 2002. The demographic explosion of *Octopus vulgaris* in Senegal during the summer 1999. Bull Mar Sci. 71:1063-1065.

Domingues, P.M.; López, N.; Muñoz, J.A.; Maldonado, T.; Gaxiola, G. 2007. Effects of a dry pelleted diet on growth and survival of the Yucatan octopus, *Octopus maya*. Aquac Nutr. 13:273-280.

Doubleday, Z.; Semmens, J.M.; Pecl, G.T.; Jackson, G. 2006. Assessing the validity of stylets as ageing tools in *Octopus pallidus*. J Exp Mar Biol Ecol. 338:35-42.

Doubleday, Z.A.; White, J.; Pecl, G.T.; Semmens, J.M. 2011. Age determination in merobenthic octopuses using stylet increment analysis: assessing future challenges using *Macroctopus maorum* as a model. ICES J Mar Sci. 397:8-12.

Edgar, G.J. 1997. Australian Marine Life: the plants and animals of temperate waters. Melbourne: Reed Books.

Faure, V.; Inejh, C.A.; Demarcq, H.; Cury, P. 2000. The importance of retention processes in upwelling areas for recruitment of *Octopus vulgaris*: the example of the Arguin Bank (Mauritania). Fish Oceanogr. 9:343-355.

Fernández-Rueda, P.; García-Flórez, L. 2007. *Octopus vulgaris* (Mollusca: Cephalopoda) fishery management assessment in Asturias (north-west Spain). Fish Res. 83:351-354.

Fletcher, W.J.; Santoro, K. 2013. Status reports of the fisheries and aquatic resources of Western Australia 2012/13: The state of the fisheries. Perth: Department of Fisheries, Western Australia.

Forsythe, J.W. 1984. *Octopus joubini* (Mollusca: Cephalopoda): a detailed study of growth through the full life cycle in a closed seawater system. J Zool Lond. 202:393-417.

Forsythe, J.W. 1993. A working hypothesis of how seasonal temperature change may impact the field growth of young cephalopods. in: Okutani T., O'Dor R.K., Kubodera T., eds. Recent advances in cephalopod fisheries biology. Tokyo: Tokai University Press.

Forsythe, J.W. 2004. Accounting for the effects of temperature on squid growth in nature: from hypothesis to practice. Mar Freshw Res. 55:331-339.

Forsythe, J.W.; Hanlon, R.T. 1988. Effect of temperature on laboratory growth, reproduction and life span of *Octopus bimaculoides.* Mar Biol. 98:369-379.

Forsythe, J.W.; Van Heukelem, W.F. 1987. Growth. in: Boyle P.R., ed. Cephalopod life cycles. London: Academic Press.

Franken, L.E. 2010. The Western Australian Developmental Octopus Fishery: Assessment, Development and Biology. Unpublished Report to the Department of Fisheries. 102p.

FRDC. 2009. Social Sceinces Research Coordination Program (SSRCP) - Strategic Plan 2009 - 2012. Canberra: FRDC.

Fuentes, L.; Iglesias, J.; Moxica, C. 2000. Marking octopus (*Octopus vulgaris*) paralarvae statoliths with alizarian complexone. J Mar Biol Assoc U K. 80:533-554.

Garstang, M.A. 1900. The plague of octopus on the South Coast, and its effect on the Crab and Lobster Fisheries. J Mar Biol Assoc U K. 6:260-273.

Gelman, A.; Carlin, J.B.; Stern, H.S.; Rubin, D.B. 2004. Bayesian Data Analysis. Florida: Chapman and Hall/CRC.

Guerra, A.; Roura, A.; Gonzáles, A.F.; Pascual, S.; Cherel, Y.; Pérez-Losada, M. 2010. Morphological and genetic evidence that *Octopus vulgaris* Cuvier, 1797 inhabits Amsterdam and Saint Paul Islands (southern Indian Ocean). ICES J Mar Sci. 67:1407-1407.

Hanlon, R.T.; Messenger, J.B. 1996. Cephalopod behaviour. Cambridge: Cambridge University Press.

Hart, A.M.; Murphy, D.; Leporati, S.C.; Joll, L.M. 2013. Octopus Fishery Status Report in: Fletcher W.J., Santoro K., eds. Status reports of the fisheries and aquatic resources of Western Australia 2012/2013. Perth: Department of Fisheries, Western Australia.

Hartwick, E.; Robinson, S.; Ambrose, R.; Trotter, D.; Walsh, M. 1988. Inshore-Offshore comparison of *Octopus dofleini* with special reference to abundance, growth and physical condition during winter. Malacologia. 29:57-68.

Hatanaka, H. 1979. Studies on the fisheries biology of common octopus off the northwest coast of Africa. Bulletin of Far Seas Fisheries Research Laboratory. 17:13 - 124.

Hendrickson, L.C.; Hart, D., R. 2006. An age-based cohort model for estimating the spawning mortality of semelparous cephalopods with an application to per-recruit calculations for the northern shortfin squid *Illex illecebrosus*. Fish Res. 78:4-13.

Hermosilla, C.A.; Rocha, F.; Fiorito, G.; Gonźalez, A.F.; Guerra, A. 2010. Age validation in common octopus *Octopus vulgaris* using stylet increment analysis. ICES J Mar Sci. 67:1458-1463.

Hilborn, R.; Walters, C.J. 1992. Quantitative fisheries stock-assessment. New York: Chapman and Hall Inc.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fish Bull. 82:898-903.

How, J.; Stadler. 2013. South Coast Crustacean Fisheries Report: Statistics Only. in: Fletcher W.J., Santoro K., eds. Status reports of the fisheries and aquatic resources of Western Australia 2012/13: The State of the Fisheries. Perth: Department of Fisheries, Western Australia.

Jabeur, C.; Nouira, T.; Khoufi, W.; Mosbahi, D.S.; Ezzeddine-Najai, S. 2012. Age and growth of *Octopus vulgaris* Cuvier, 1797, along the east coast of Tunisia. J Shellfish Res. 31:119-124.

Jackson, G.D.; Domeier, M.L. 2003. The effects of an extraordinary El Niño / La Niña event on the size and growth of the squid *Loligo opalescens* off Southern California. Mar Biol (Berl). 142:925-935.

Joll, L.M. 1976. Mating, egg-laying and hatching of *Octopus tetricus* (Mollusca Cepalopoda) in the laboratory. Mar Biol. 36:327-333.

Joll, L.M. 1977a. Growth and food intake of *Octopus tetricus* (Mollusca: Cephalopoda) in aquaria. Aust J Mar Freshw Res. 28:45-56.

Joll, L.M. 1977b. The predation of pot-caught Western Rock Lobster (*Panulirus Longipes cygnus*) by octopus. Perth: Department of Fisheries and Wildlife Western Australia.

Joll, L.M. 1978. Observations on the Embryonic Development of *Octopus tetricus* (Mollusca: cephalopoda). Aust J Mar Freshw Res. 29:19-30.

Joll, L.M. 1983. Octopus tetricus. in: Boyle P.R., ed. Cephalopod life cycles. London, New York: Academic Press.

Katsanavakis, S.; Verriopoulos, G. 2004. Abundance of *Octopus vulgaris* on soft sediment. Sci Mar. 68:553-560.

Katsanavakis, S.; Verriopoulos, G. 2006. Seasonal populaiton dynamics of *Octopus vulgaris* in the eastern mediterranean. ICES J Mar Sci. 63:151-160.

Katsanevakis, S.; Verriopoulos, G. 2004. Den ecology of *Octopus vulgaris* Cuvier, 1797, on soft sediment: availability and types of shelter. Sci Mar. 68:147-157.

Kimura, Y. 1980. Report on the second-phase survey for commercial harvesting of octopuses in Western Australian waters.: National Federation of Fisheries Cooperative Associations of Japan.

Kimura, Y.; Isomae, H. 1981. Report on the third-phase survey for commerical harvesting of octopuses in Western Australian waters.: National Federation of Fisheries Cooperative Associations of Japan.

Kimura, Y.; Isomae, H.; Owada, T. 1978. Report on investigation for commerical fishing of octopus in Western Australia waters.: National Federation of Fisheries Cooperative Associations of Japan.

King, M. 1995. Fisheries biology, assessment and management. Oxford: Fishing News Books.

Leite, T.S.; Haimovici, M.; J., M.; Lins Oliveria, J.E. 2009. Habitat, distribution, and abundance of the commercial octopus (*Octopus insularis*) in tropical oceanic island, Brazil: Information for management of an artisnal fishery inside a marine protected area. Fish Res. 98:85-91.

Larsen, R. J. 2008. The Western Australian Developmental Octopus Fishery: species composition and aspects of morphology and biology. Unpublished Honours thesis. Murdoch University, Western Australia, 116p.

Leporati, S.C.; Pecl, G.T.; Semmens, J.M. 2007. Cephalopod hatchling growth: the effects of initial size and seasonal temperatures. Mar Biol. 151:1375-1383.

Leporati, S.C.; Pecl, G.T.; Semmens, J.M. 2008a. Reproductive status of *Octopus pallidus*, and its relationship to age and size. Mar Biol. 155:375-385.

Leporati, S.C.; Semmens, J.M.; Pecl, G.T. 2008b. Determining the age and growth of wild octopus using stylet increment analysis. Mar Ecol Prog Ser. 367:213-222.

Leporati, S.C.; Ziegler, P.E.; Semmens, J.M. 2009. Assessing the stock status of holobenthic octopus fisheries: is catch per unit effort sufficient? ICES J Mar Sci. 66:478-487.

López-Rocha, J.A.; Arellano-Martínez, M.; Ceballos-Vázquez, B.P.; Velázquez-Abunder, I.; Castellanos-Martínez, S.; Torreblanco-Ramírez, E. 2012. Use of length-frequency analysis for growth estimation of the Californian two-spotted octopus *Octopus bimaculatus* Verril 1883 of the Gulf of California. J Shellfish Res. 31:1173-1181.

Mangold, K. 1983. Food, feeding and growth in cephalopods. Mem Mus Vic. 44:81-93.

Mangold, K. 1987. Reproduction. in: Boyle P.R., ed. Cephalopod Life Cycles Vol 2 Comparative Reviews. London: Academic Press.

Norman, M.; Reid, A. 2000. Squid, cuttlefish and octopuses of Australasia. Melbourne: CSIRO.

Otero, J.; Gonźalez, A.F.; Pilar Sieiro, M.; Guerra, A. 2007. Reproductive cycle and energy allocation of *Octopus vulgaris* in Galician waters, NE Atlantic. Fish Res. 85:122-129.

Pauly, D. 1998. Why squid, through not fish, may be better understood by pretending they are. S Afr J Mar Sci. 20:47-58.

Pearce, A.; Lenanton, R.; Jackson, G.; Moore, J.; Feng, M.; Gaughan, D. 2011. The "marine heat wave" off Western Australia during the summer of 2010/11. Fisheries Research Report. Perth: Department of Fisheries, Western Australia.

Pearce, A.F.; Feng, M. 2013. The rise and fall of the "marine heat wave" off Western Australia during summer of 2010/11. Journal of Marine Systems:139-156.

Perry, R.I.; Walters, C.J.; Boutillier, A. 1999. A framework for providing scientific advice for the management of new and developing invertebrate fisheries. Rev Fish Biol Fish. 9:125-150.

Pierce, G.J.; Guerra, A. 1994. Stock assessment methods used for cephalopod fisheries. Fish Res. 21:225-285.

Quetglas, A.; Gonzalez, A.F.; Franco, I. 2005. Biology of the upper-slope cephalopod *Octopus salutii* from the western Mediterranean Sea. Mar Biol. 146:1131-1138.

Rocha, F.; Guerra, A.; Gonzalez, A.F. 2001. A review of reproductive strategies in cephalopods. Biol Rev. 76:291-304.

Sánchez, P.; Obarti, R. 1993. The biology and fishery of *Octopus vulgaris* caught with clay pots on the Spanish Mediterranean coast. in: Okutani T., O'Dor R.K., Kubodera T., eds. Recent Advances in Fisheries Biology. Tokyo: Tokai University Press.

Sauer, W.W.; Potts, W.; Raberinary, D.; Anderson, J.; Sylvio Perrine, M.J. 2011. Assessment of current data for the octopus resource in Rodrigues, western Indian Ocean. Afri J Mar Sci. 33:181-187.

Segawa, S.; Nomoto, A. 2002. Laboratory growth, feeding, oxygen consumption and ammonia excretion of *Octopus ocellatus*. Bull Mar Sci. 7:801-813.

Semmens, J.M.; Doubleday, Z.A.; Hoyle, K.; Pecl, G.T. 2011. A multilevel approach to examining cephalopod growth using *Octopus pallidus* as a model. J Exp Biol. 214:2799-2807.

Semmens, J.M.; Pecl, G.; Villanueva, R.; Jouffre, D.; Sobrino, I.; Wood, J.W.; Rigby, P. 2004. Understanding octopus growth: patterns, variability and physiology. Mar Freshw Res. 55:367-377.

Semmens, J.M.; Pecl, G.T.; Gillanders, B.M.; Waluda, C.M.; Shea, E.K.; Jouffre, D.; Ichii, T.; Zumholz, K.; Leporati, S.C.; Katugin, O.N.; Shaw, P.W. 2007. Approaches to resolving cephalopod movement and migration patterns. Rev Fish Biol Fish. 17:401-423.

Silva, L.; Ramos, F.; Sobrino, I. 2004. Reproductive biology of *Eledone moschata* (Cephalopoda: Octopodidae) in the Gulf of Cádiz (south-western Spain, ICES Division IXa). J Mar Biol Assoc U K. 84:1221-1226.

Silva, L.; Sobrino, I.; Ramos, F. 2002. Reproductive biology of the common octopus, *Octopus vulgaris* Cuvier, 1797 (Cepahlopoda: octopodidae) in the Gulf of Cádiz (SW Spain). . Bull Mar Sci. 71:837-850.

Smith, C.D.; Groeneveld, J.C.; Maharaj, G. 2006. The life history of the giant octopus *Octopus magnificus* in South African waters. Afri J Mar Sci. 3-4:561-568.

Sobrino, I.; Juarez, A.; Rey, J.; Romero, Z.; Baro, J. 2011. Description of the clay pot fishery in the Gulf of Cadiz (SW Spain) for *Octopus vulgaris*: Selectivity and exploitation pattern. Fish Res. 108:283-290.

Sobrino, I.; Silva, L.; Bellido, J.M.; Ramos, F. 2002. Rainfall, river discharges and sea temperature as factors affecting abundance of two coastal benthic cephalopod species in the Gulf of Cadiz (SW Spain). Bull Mar Sci. 71:851-865.

Soledad Acosta-Jofré, M.; Sahade, R.; Laudien, J.; Chiappero, M.B. 2012. A contribution to the understanding of phylogenetic relationships among species of the genus *Octopus* (Octopodidae: Cephalopoda). Sci Mar. 76:311-318.

Tafur, R.; Villegas, P.; Rabi, M.; Yamashiro, C. 2001. Dynamics of maturation, seasonality of reproduction and spawning grounds of the jumbo squid *Dosidicus gigas* (Cephalopoda: Ommastrephidae) in Peruvian waters. Fish Res. 54:35-50.

Thomas, R.; Moltschaniwskyj, N.A. 1999. Ontogenetic changes in size and shape of statoliths: implications for age and growth of the short-lived tropical squid *Sepioteuthis lessoniana* (Cephalopoda: Logliginidae). Fisheries Bulletin. 97:636-645.

Vaz-Pires, P.; Seixas, P.; Barbosa, A. 2004. Aquaculture potential of the common octopus (Octopus vulgaris Cuvier, 1797): a review. Aquaculture. 238:221-238.

Villanueva, R. 1992. Interannual growth differences in the oceanic squid *Todarodes angolensis* Adam in the norhtern Benguela upwelling system, based on statolith growth increment analysis. J Exp Mar Biol Ecol. 159:157-177.

Villanueva, R. 1995. Experimental rearing and growth of planktonic *Octopus vulgaris* from hatching to settlement. Can J Fish Aquat Sci. 52:2639-2650.