Investigation of the low-catch zone in the Western Rock Lobster fishery

Assess causes and implications of anomalous low lobster catch rates in the shallow water areas near the centre of the Western Rock Lobster fishery

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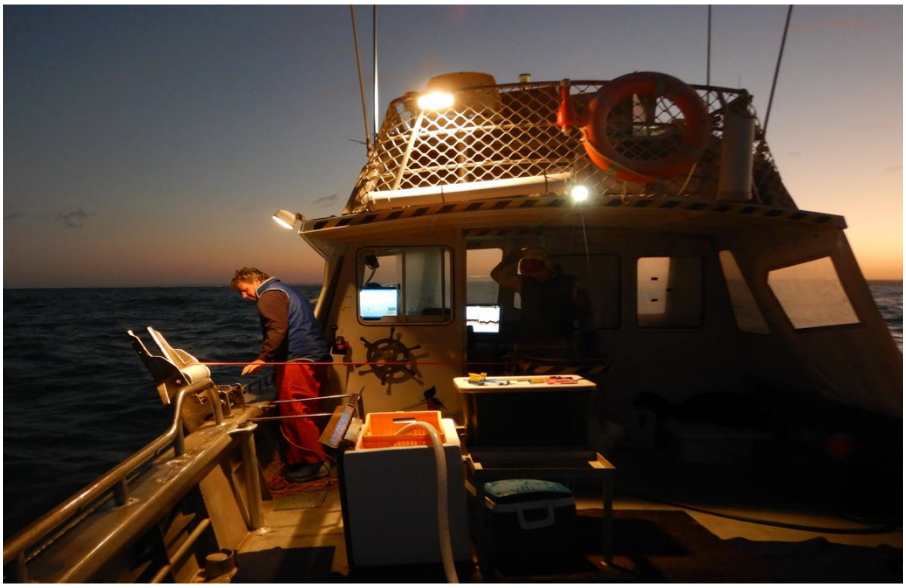

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Further specific acknowledgements are included for each individual study where appropriate.

Executive Summary

Current and former West Coast Rock Lobster Managed Fishery (WCRLMF) fishers have anecdotally observed a trend of low catch rates since the 1990's in the near-shore shallow water areas (<8 m) near the centre of the fishery (Dongara-Leeman). Since the atypically low puerulus counts of 2007-2010, this trend of decreasing catch rates in this area have been reported by fishers to extend out to deeper waters (e.g. to the edge of the shallows, < 20 m). Fishers were concerned that this trend of reduced productivity could be impacting the current stock assessment and has the potential to expand throughout the fishery.

The objectives of this project were to:

- Determine the spatial extent and temporal trends in regions exhibiting abnormally low legal catch rates throughout the lobster fishery.
- Identify the lobster life stage(s) resulting in abnormally low legal catch rates in the main area of low catch rates.
- Examine factors that may be causative of the abnormally low legal catch rates.
- Identify the implications of the low-catch regions to the stock assessment and management of the fishery.

These objectives were achieved, in particular standardised meshed pot catch and release surveys were highly useful to establish the extent of the low catch zone and that sub-legal to early juvenile lobster were found to be indicative of the low catch zone. The iterative assessment process, presented to fishers over multiple workshops, indicated that loss of essential habitat, relating to early juvenile lobster survival or recruitment success, was the most likely causative factor of the low catch zone.

To inform the stock assessment and management of the fishery, the project has highlighted the importance of data on 1) the abundance of sub-legal lobster in near shore habitats and 2) monitoring change in/condition of near shore habitats as a potential indicator of early juvenile lobster survival or recruitment success for the stock assessment and management of the WRL fishery. The project has highlighted that limited historical data is available on these potential indicators, but new FRDC WRL IPA funded projects have subsequently been created to further synthesise available information and collect new data for both early juvenile / pre-recruit lobster abundance (FRDC 2019-159 Independent Shallow Survey) and condition and change in near shore habitats (FRDC 2019-099 Habitat as a limit to Western Rock Lobster recruitment) to further inform the stock assessment and management of the fishery.

This project has demonstrated that the active input of current and former fishers can inform scientific studies and an iterative assessment process, of the potential processes limiting lobster catch rates, presented to fishers over multiple workshops can provide information to further improve the stock assessment and management of the fishery.

Keywords

Western Rock Lobster, fisheries ecology, catch rate, local ecological knowledge, fisher perceptions, puerulus settlement

General Introduction

Despite the generally robust status of the West Coast Rock Lobster Managed Fishery (WCRLMF), with increased biomass of legal sized lobsters and generally high catch rates (Caputi et al., 2015; de Lestang et al 2016), current and former WCRLMF fishers have anecdotally observed a trend of low catch rates since the 1990’s in the near-shore shallow water areas (<8 m) near the centre of the fishery located near Cliff Head, Western Australia (Figure 1, 29”31’S, 114”59’E; Fitzhardinge, J. *pers comms*).

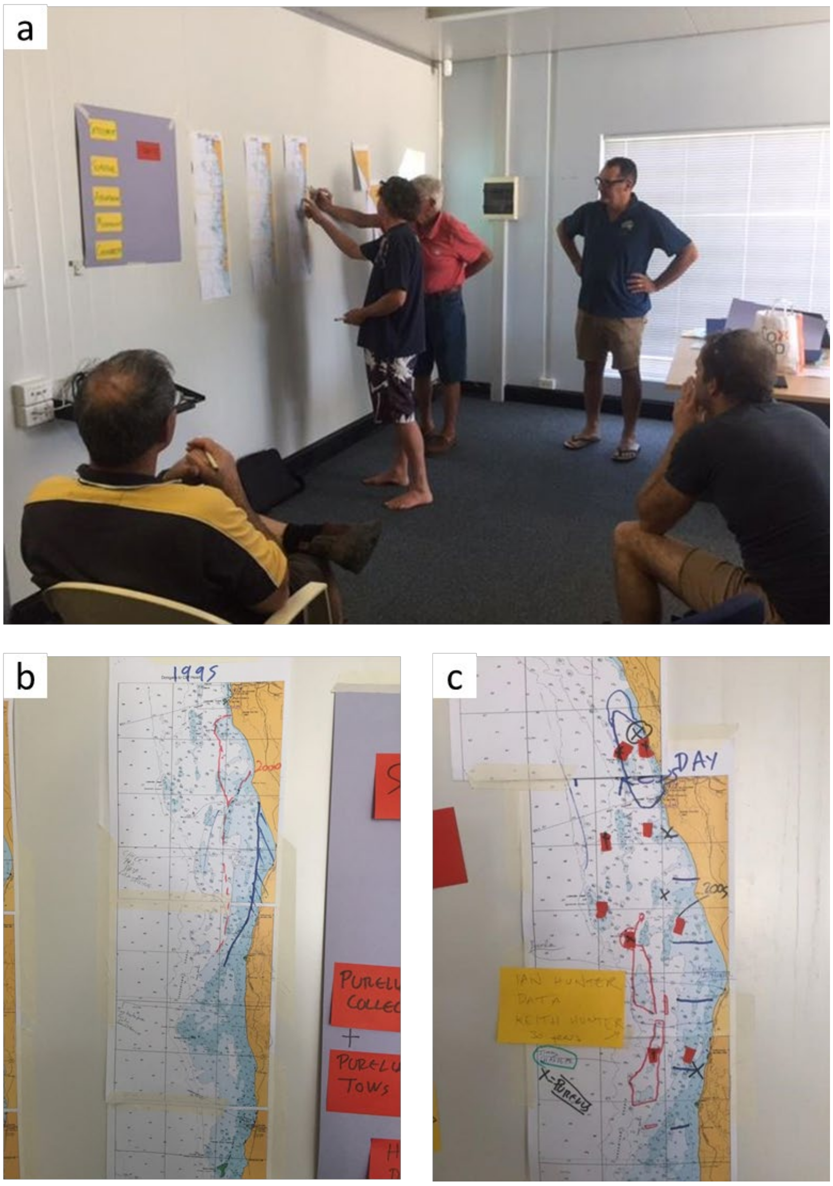

Figure 1 Preliminary workshop held in Port Denison, WA. Participants attending the workshop (a), examples of the maps produced (b-c).

This Low Catch Zone (LCZ) is located near the centre of the otherwise robust fishery and the larger inshore area extending deeper (~30 m) around this zone still produces substantial catches (de Lestang *pers comms*). Historical accounts of the LCZ from the 1970’s to 1990’s suggested this area of coastline, from Dongara to Leeman (~ 80km), supported a large number of fishers with annual lobster catches exceeding 1,000 t, with much of the catch coming from relatively shallow waters (<8 m). Fishers reported a trend of reducing catch rates in the shallows of the LCZ since the 1990s. Since the abnormally low puerulus settlement index observed in 2006 to 2012 fishers have perceived that catch rates have reduced further in this region and that the LCZ was expanding to deeper surrounding waters out to the edge of the shallows (≲ 20 m depth) and further north and south along the coastline. Fishers’ expert knowledge of the progression and spatial extent of the LCZ was documented in a preliminary workshop held in Port Denison, WA (Figure 1). Currently many Western Rock Lobster fishers consider this region to be relatively unproductive compared to other adjacent areas with the area being intermittently fished by only a few fishers (Figure 2, Study 1, Miller et al. 2023).

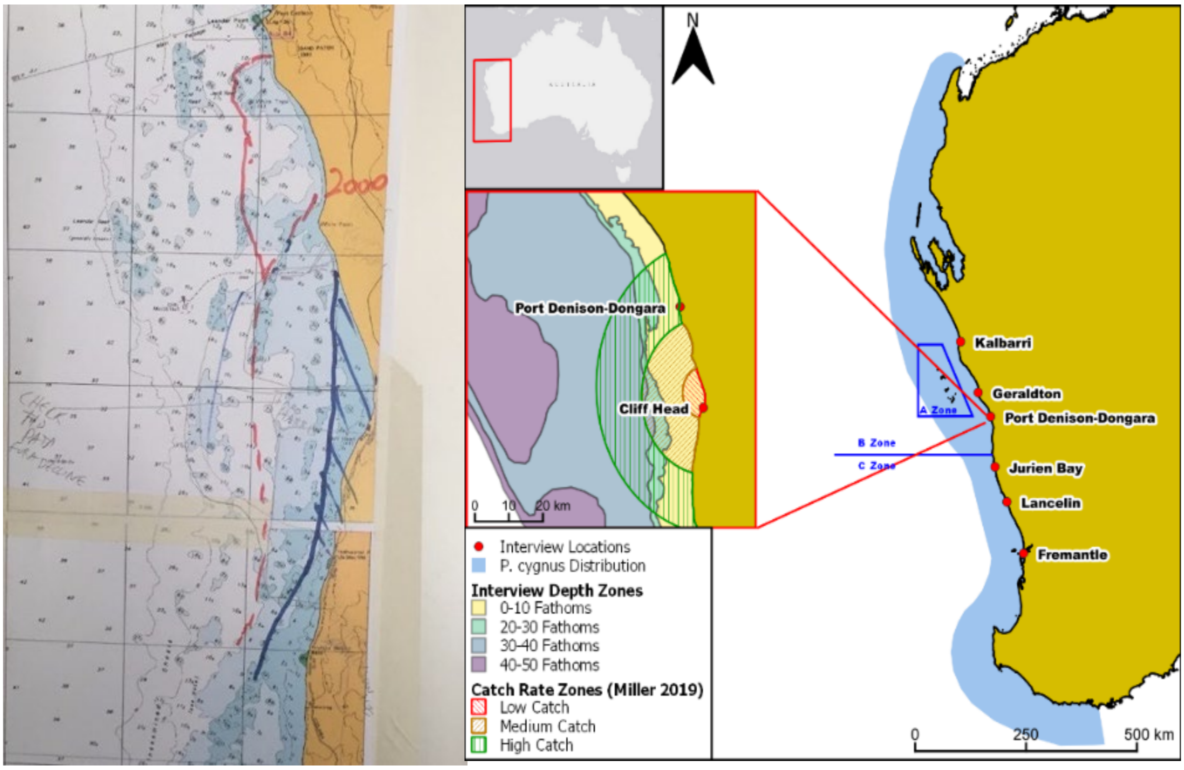

Figure 2 (Left) Hand drawn map developed during an early workshop with fishers at the commencement of this study. (Right) Map showing the distribution of Western Rock Lobster (blue shaded), and other points of interest. Note: the catch rate zones depicted on the inset are stylised estimate drawn from study components (i.e. Study 2 detailed below).

The concerns raised by these expert fishers present a challenge for fisheries science, with all other modern indicators of the fishery suggesting stocks and catch rates should be high, and a challenge of forensic fisheries ecology to both validate and understand the potential process behind this low catch zone.

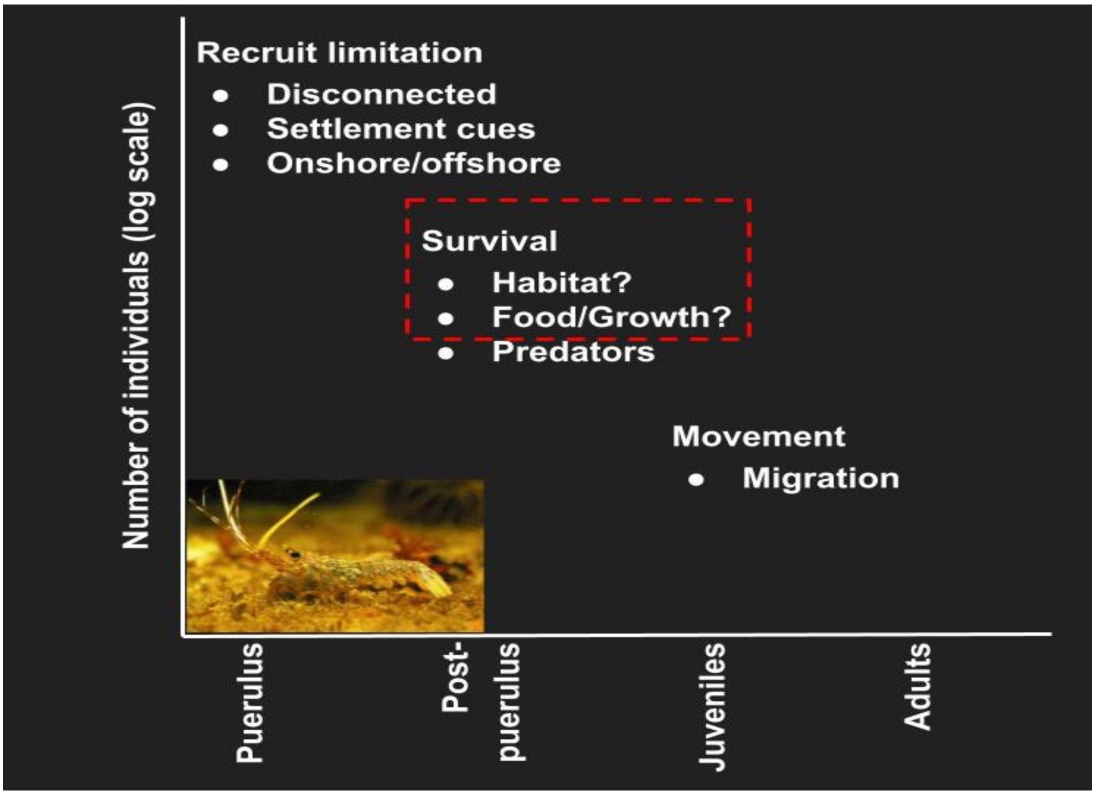

Figure 3 Iterative assessment process, developed through workshops with fishers and informed by the results of prior studies.

This project was aimed at providing increased understanding of the extent and processes responsible for the anomalous low lobster catch rates in the centre of the WCRLMF to better enable the prediction of future trends and management adaptation.

Objectives of the project

The objectives of this project were to:

- Determine the spatial extent and temporal trends in regions exhibiting abnormally low legal catch rates throughout the lobster fishery.
- Identify the lobster life stage(s) resulting in abnormally low legal catch rates in the main area of low catch rates.
- Examine factors that may be causative of the abnormally low legal catch rates.
- Identify the implications of the low-catch regions to the stock assessment and management of the fishery.

This project set out to meet these objectives using an iterative assessment process (Figure 3) informed by the results of prior studies and expert fisher knowledge, through workshops with fishers, documented in the Project Communication section of this report. This approach generated a series of complementary studies which are detailed below.

Studies

A combination of complementary studies was used to address the project objectives. These studies include Study 1 and Study 2 that use a combination of expert fisher knowledge and fisheries independent data to validate fisher perceptions and characterise the Western Rock Lobster populations inside the low-catch and adjacent zones;

- Study 1 - Contrasting fisher perceptions of spatial and temporal changes in lobster catch rate with detailed fishery dependent catch data: a case study of an area with unexpectedly low catches.
- Study 2 - Fine-scale variability in catch and growth rates of Western Rock Lobsters, *Panulirus cygnus*, reveal heterogeneous life-history parameters

Study 3 and Study 4 evaluated the role that oceanographic and settlement processes could play in Western Rock Lobster population structure in the low-catch and adjacent zones;

- Study 3 - Oceanographic processes influence the post-larval supply of Western rock lobster to an area of low abundance of juveniles.
- Study 4 - Examining the settlement of Western Rock Lobster larvae in an area of reduced catches.

Study 5 and Study 6 examined trends in availability of potential recruitment habitats and the potential mechanism whereby Western Rock Lobster respond to the availability of these habitats;

- Study 5 - Tracking change in important recruitment habitats for Australia's most valuable fishery
- Study 6 - Chemotaxis is important for fine scale habitat selection of early juvenile *Panulirus cygnus.*

Study 7 then provided a synthesis of this information and highlights the role of expert fisher ecological knowledge informing fisheries ecology in general and specifically to meet the objectives of the current project;

- Study 7 - Integrating expert fisher ecological knowledge into fisheries management: example of an area of unexpectedly low catch-rate and how its study informed fisheries ecology.

For each study, it is indicated where these studies are published or in preparation for submission for publication. A conclusion section then provides a summary of lessons learned and future recommendations for future informing our understanding of the fisheries ecology of the Western Rock Lobster.

Study 1 - Contrasting fisher perceptions of spatial and temporal changes in lobster catch rate with detailed fishery dependent catch data: a case study of an area with unexpectedly low catches

In preparation for submission to ICES Journal of Marine Science

Authors and affiliations

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A fisher interview underway with (left to right) with Western Rock Lobster fisher Brian Sloper and UWA students Ash Miller and Michael Brooker. Photograph by Tim Langlois.

Abstract

Understanding and reconstructing historical catch rates can be difficult for many fisheries particularly where no adequate or formal catch and effort records exist. Under these circumstances, fisher perceptions on catch rates can be useful to reconstruct spatial and temporal changes in relative catch rate as a proxy for abundance. In the present study we compared fisher perceptions with standardised catch rate data for the West Coast Rock Lobster Managed Fishery (*Panulirus cygnus* George 1962), one of Australia's most valuable and possibly best studied and managed wild capture fisheries, to investigate how fisher perceptions of catch rate could contribute in such a well-known fishery. We used a series of structured career history interviews to elicit fishers' perceptions on the trends and spatial patterns in their catch rates over time. These perceptions were compared against standardised fishery spatial catch rate data along with other variables that may influence catch rate or fisher's ability to recall them. We found information derived from structured career history interviews can provide a level of comparative information to standardised fishery catch rate data at the scale of the fishery, but these perceptions show a decreasing level of congruence with increased recall time and some variation between locations. We also found evidence of an interaction across management zones for this fishery, where perceptions and standardised catch rate data were more closely aligned in the southern management zone than northern. We provide an example of congruence between modern fisher perceptions and fisheries independent catch rates of sub-legal lobster in a case study where data was collected concomitantly across a localised area with unexpectedly low catches. We suggest that fishers' perception of catch rate, and their local ecological knowledge, can provide useful additional data for fisheries management at a finer spatial scale than is typically recorded . We recommend that a formal method for collecting fishers' instantaneous perception of catch rates should be considered and integrated into standard data collection procedures for the West Coast Rock Lobster Managed Fishery, potentially providing an early warning system for areas of concern or unexpected changes of catch rate within the fishery.

Introduction

Obtaining robust data on historical catch rates from before formal records and at a finer scale than formally collected data can be a difficult task. Such data can be useful for avoiding "shifting baselines" whereby low catch rates become an accepted norm (Pauly 1995; Pinnegar and Engelhard 2008; Soga and Gaston 2018). In many fisheries globally, adequate catch and effort records have not been kept, limiting the ability of fisheries scientists and managers to understand catch rate trends. Even where accurate catch and effort data is collected, changes in fishing efficiency or locations can distort the relationship between catch-rates and fish biomass, leading fisheries managers to under- or over-estimate stock conditions (Walters and Pearse 1996).

Recognising these shortcomings, studies have begun to investigate how fisher perceptions and historical knowledge of catch rates might be able to fill knowledge gaps, or complement catch rate analysis, and improve stock assessments. Numerous studies have investigated the relationship between fishers' perceptions and formal or informal catch rates (Neis et al. 1999; such as: Daw, Robinson, and Graham 2011; Zukowski, Curtis, and Watts 2011; O'Donnell, Molloy, and Vincent 2012; Taylor et al. 2017; Santos et al. 2019) or other metrics including underwater visual sampling (Daw, Robinson, and Graham 2011). Santos et al. (2019) highlighted the value of using a combination of fisher knowledge and fishery dependent data to gain a better understanding of spatiotemporal patterns of catch and fishing effort. In the Seychelles, Daw et al (2011) examined the trends in fishers' perceptions and how these related to catch monitoring and underwater visual sampling. This study found that fishers' perceptions of "normal" catches were not significantly different from recent median landing records and that the variation in good and poor catch perception were also indicative of the variability observed in the landing data. In two studies conducted on the same small-scale data-poor seahorse fishery, it was found that fishers tended to overestimate the "typical" catch rates while "bad" catch rates were much more comparable between the two sources (Meeuwig et al. 2005; O'Donnell, Molloy, and Vincent 2012). Meeuwig et al. (2005) also found that while the absolute values derived from fishers varied, the relative estimates of fishing effort across two surveys correspond well and overall the fishers were able to consistently describe seahorse abundance and habitat quality. In the Australian context, a study on the management of the Murray crayfish (*Euastacus armatus* Von Martens, 1866) found that local fisher ecological knowledge (LEK) can be a reliable source of information to improve fisheries management (Zukowski, Curtis, and Watts 2011). Overall, these studies show that fisher perceptions often match logbook reported catch rates remarkably well, suggesting that in fisheries without logbook data, the collation of fisher perceptions may be a useful supplement to whatever data exists. It has also been suggested that fisher perceptions and knowledge can even be useful in fisheries with reliable and standardised catch rate data, helping researchers and managers understand how changes in fishing conditions, methods and locations have affected catch rates at shorter or finer scales (Santos et al. 2019).

The West Coast Rock Lobster Managed Fishery (WCRLF; *Panulirus cygnus* George 1962) is one of Australia's most valuable wild caught single species fisheries typically worth AUD$300-500 million per annum (Caputi et al. 2015; de Lestang, Caputi, and How 2016; Nicolaou and Hammond 2017). The fishery has a long history of detailed research, successful fisheries management and was the first fishery in the world to gain Marine Stewardship Council (MSC) certification in 2000 (Bellchambers et al. 2012). The Western Rock Lobster is found in the temperate waters along the lower western coast of Australia from Northwest Cape, Western Australia to Albany, Western Australia (de Lestang et al. 2012). The greatest abundance of larval settlement, adult lobsters and catches has historically been found to occur near the centre of the species distribution and extent of the fishery between Geraldton and Perth, with juvenile lobsters tending to inhabit shallow coastal reefs (generally <40 m depth) while larger lobsters (typically > 80 mm carapace length) tend to inhabit deeper offshore reefs (Bellchambers et al. 2012).

The WCRLMF is managed across three management zones with the quota for each zone set annually (Figure 4) these management zones assist in distributing effort across the fishery thus allowing for different management controls to be used while the divisions also reflect the different broad scale ecological processes that are likely influencing the recruitment and abundance of the Western Rock Lobster population (Donohue et al. 2010). Prior to 2010, the Western Rock Lobster fishery was managed using input controls, until a period of abnormally low puerulus settlement rates (used as an index for recruitment to the fishery) were encountered for six consecutive settlement seasons (2006/07 to 2011/12; Caputi et al. 2014; Kolbusz, de Lestang, et al. 2021) and this triggered changes to the way in which the fishery was managed (N. Caputi et al. 2014). Since 2010 the fishery has been managed using individual transferable quotas and therefore output controls (Nick Caputi et al. 2015; S. de Lestang, Penn, and Caputi 2018) and these management changes have been attributed to be responsible for the current high levels of estimated spawning biomass across the fishery (de Lestang, Caputi, and How 2016; de Lestang et al. 2021). Subsequent to the period of low settlement and management change, the central west coast of Australia, including key coastal fishing locations was subject to a marine heatwave where sea surface temperatures were up sustained at up to 4°C above usual summer temperatures and significant loss of macroalgae and sea grass beds were seen in certain locations (Arias-Ortiz et al. 2018; N. Caputi et al. 2019; Smale and Wernberg 2013). The impact of this event on Western Rock Lobster is largely unknown but other invertebrate fisheries such as the Shark Bay crab fishery, Roe's abalone (*Haliotis roei* Gray, 1826) fishery and Exmouth prawn fishery the coast were heavily impacted (Caputi et al., 2019).

Despite the apparently healthy status of the WCRLMF, some fishers have been becoming increasingly concerned about an area of reduced catch located near Cliff Head, Western Australia (29"31'S, 114"59'E, hereafter referred to as the low catch zone [LCZ]), in the approximate centre of the fishery and species distribution (Figure 1). Anecdotal reports from fishers have suggested a trend of increasingly low lobster catch rates in this area since the mid 1990's (Brendan Crofts *pers comms*). Fishers also reported that concurrent with the low settlement in the late 2000's, the LCZ expanded along the coastline and into deeper water (out to approximately 20 m depth; Fitzhardinge, J *pers comms*). These accounts contrast with reports that from the 1970's to 1990's the LCZ was a productive area of the fishery, supporting a large number of boats, with annual catch from the stretch of coast (including areas surrounding the LCZ) exceeding 1,000 t per annum. Recently, a yearlong fishery independent survey investigating this area demonstrated a lower abundance of sub-legal lobster within the LCZ compared to surrounding areas (Miller et al. 2023). Miller et al. (2023) did not detect any appreciable differences in catch rates of legal-size lobster across these areas, but suggested that this may be due to lower levels of modern fishing effort in the LCZ compared to surrounding areas, which had relatively high levels of fishing pressure, and that their fishery independent survey was catch and release.

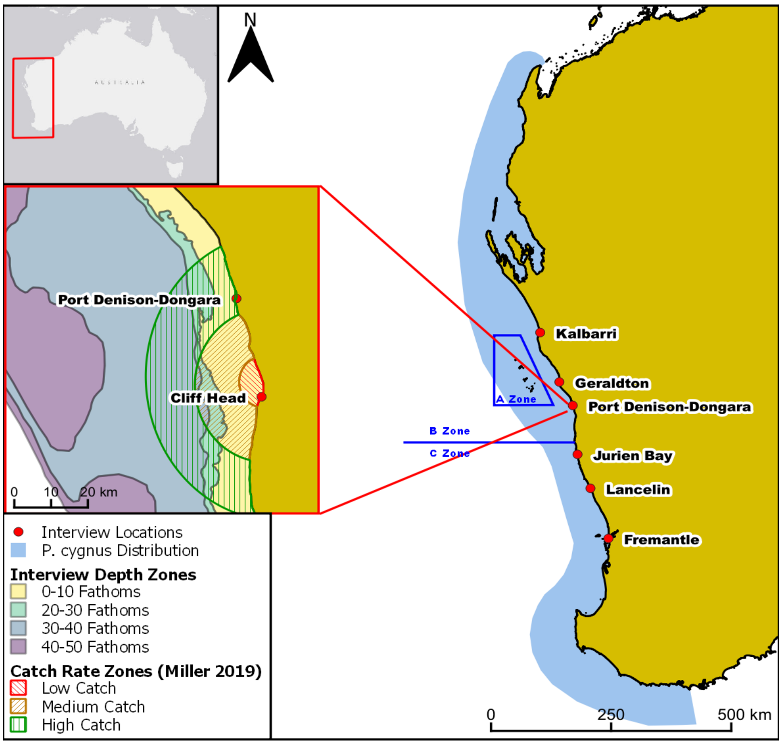

Figure 4 Map showing the distribution of Western Rock Lobster, the survey locations, and other points of interest. Note: the catch rate zones depicted on the inset are estimated from Study 2.

This study set out to investigate the concurrence in spatial and temporal trends between fisher perceptions of catch rates and standardised logbook and fishery dependent catch rates across the coastal regions of the Western Rock Lobster fishery. This concurrence is tested both at the scale of the management region (i.e., ~1000 km's) and across the LCZ and control sites investigated by (2023) to better understand the potential contribution of fisher perceptions and local ecological knowledge to science and management across this highly valuable and well-studied fishery.

Materials and Methods

Fisher Interviews

Survey Deployment

Interviews were conducted with fishers in the West Coast Rock Lobster Managed Fishery using a one-on-one format in coastal towns across the fishery, including; Kalbarri, Geraldton, Port Denison-Dongara, Jurien Bay, Lancelin and Fremantle from April 2018 to July 2018 (Figure 4 and Figure 5). Towns to the north of Kalbarri and south of Fremantle were not included due to most fishers in the fishery having a home port at or between these two locations. The survey was conducted with fishers attending planned regular meetings with their peak body group, referred to as “Coastal Tour'' meetings. These meetings are widely attended by fishers in each region and are jointly run by the peak industry body (Western Rock Lobster Council [WRLC]) and the state government (Department of Primary Industries and Regional Development [DPIRD]). The surveys were conducted before/after each coastal tour meeting. Fishers who were unable to attend the meetings, were also given the opportunity to participate, with the researchers arranging one-on-one meetings at a time and place convenient for each fisher.

Figure 5 Fishers in Kalbarri being interviewed by students on spatial and temporal patterns in catch rate.

Interviews were conducted by four researchers, initially conducting interviews together to ensure consistency, and then conducting independent interviews allowing multiple fishers to be interviewed simultaneously. A total of 46 fishers were interviewed with a response rate of approximately 98%. The primary reason fishers gave for not participating was time constraints, as some fishers were unable to stay after the meetings to complete the survey. Many fishers were happy to arrive early or wait to complete the survey before or after the meetings and responses were largely positive. Fishers with a wide range of experience were interviewed including fishers who have retired and fishers who have recently become the master of a vessel, with the years of experience ranging from 4 to 54 years fishing with an average of 29 years. There were 19 fishers interviewed from the southern “C” Zone and 27 fishers interviewed from northern “B” zone, it should be noted that the Houtman-Abrolhos Islands (“A”) zone was not included in the present study which was restricted to coastal areas of the fishery (Figure 4).

Survey Construction

The survey instrument (refer to Appendices and Project materials developed for Study 1) consisted of three main components. First, fishers were asked for background information, including how many years they had been actively fishing, what months of the year they fish in, their current quota, the number of pots they currently use and their contact details for any follow up questions if required. Second, fishers were asked about their personal recollection of catch rates both spatially and temporally, aided by a map of the areas they regularly fished or had historical knowledge of. For these questions, fishers were asked to map the extent of their usual fishing range splitting this area into four depth zones (0-10, 10-15, 15-20 and 20-30 fathoms) to match distribution of reef lines and fishing zones. Fishers were asked if catch rates had become better/worse/not changed in relation to their experience fishing over the course of their career for each map grid cell and depth zone combination. This was followed by a timeline/graph where the interviewees were asked to draw a line that graphically represents the changes in catch rates for each depth zone, they fished in over the time that they have been fishing. The vertical axis of the graph was scaled from their best catch rates to their worst catch rates and the horizontal axis was scaled with increments of 5 years with fishers only required to complete from when they were actively fishing. To help orient fishers, major events in the fishery were included on the timeline as reference points, e.g., 2010/11 marine heatwave event, the shift to individual transferable quotas in 2010 and effort restrictions on 1993/4.

The Western Rock Lobster life cycle includes a migratory phase, referred to as the “whites’ migration” whereby many of the animals perform a coordinated moult and migrate to deeper water as they reach maturity at around 4 years of age (Bellchambers et al. 2012). For consistency, fishers were asked to only consider catch rates of “reds,” which are the residential non-migratory lobsters that are present the entire year. Finally, fishers were asked to map areas of concern in terms of lobster catch rates and areas that are performing well. The interview concluded with a series of open-ended questions where fishers were asked about probable causes for the increases/decreases in catch rates and what they had done to overcome these changes. The survey duration varied from approximately 20 to 50 minutes depending on the details provided by the fisher. The interviews were conducted in accordance with an approved human ethics protocol from The University of Western Australia, approval number RA/4/20/4296.

Data Preparation

Responses to the survey questions were collated, data from the hand drawn maps of each fishers fishing area digitised as polygons using ESRI ArcMap to provide an indication of the survey's coverage, while the hand drawn plots of catch rates over time were digitised using WebPlotDigitizer in five year increments along with years of interest such as 1993 and 2011 when previously mentioned management changes occurred (Rohatgi 2020; Burda et al. 2017). Each digitised plot of catch rate was scaled from the worst (1) to best (5) fisher's catch rate. This raw fisher score data was collated for each fisher recorded by one-degree latitudinal blocks, depth zones, management zone and year. This data was then summarised to each degree of latitude by averaging the response for each fisher to match the spatial resolution of the Department of Primary Industries and Regional Development (DPIRD) catch returns data collation for further analysis. This summarised data is hereafter referred to as the fisher perceptions data.

Commercial catch returns data

Regional fisheries dependent standardised catch rate rates

As a point of comparison at a broad management-level scale, logbook data was collated to match the fisher perception data. Catch and effort data was collected from three logbook programs: the Fisher Logbook Program (1984 to 2009), the Rock Lobster Quality Management System (RLQMS) (2011 to 2013) and Catch and Disposal Records (CDR) (2013 to present). All three data sources have collected the same core data which includes vessel details, date, weight of lobsters landed, number of pot lifts, "block" fished, depth fished, lobster condition (including whether the lobsters were undersize, berried with eggs, setose, etc...) and meteorological observations on a daily basis. The programs differed in terms of the technologies used for reporting, but are broadly considered to be comparable, though there were slight changes in the resolution of locational (block) data. Therefore, catch per unit of effort (CPUE; kg / pot lift) collated at an annual level for one-degree latitudinal blocks, and three depth zones (0-10 fathoms; 11-20 fathoms; more than 21 fathoms). This reflected the smallest common resolution across the data sources. The Catch Returns Data was plotted in a series of matrices showing the relative catch rates for each year and broken down into each degree of latitude and depth zone.

Standardised fisheries independent catch rate data within the Low Catch Zone

Fine-scale fishery independent catch data for two areas sampled by the fisher perception interviews were matched with fisheries independent catch data derived from a recent study in the region by Miller et al. (2023). The study conducted a year-long study across the LCZ and surrounding areas. The standardised catch rate data was obtained from experimental fishing traps (standard commercial traps with mesh installed and no escape gaps) using a consistent fisher, vessel, and pot design. Trips were conducted monthly at specific sites, and all lobster were released at the site. Due to the limited temporal and spatial overlap of fisher perception interviews with this fishery independent data no formal analysis was conducted, and the data and confidence intervals were simply examined visually for the Low Catch Zone and adjacent High Catch Zone where (refer to Figure 4 for the location of these zones).

Multiple Regression Analysis

Linear Mixed Effect models (LME's) were used to assess congruence between the standardised fishery logbook catch rates and fisher perceptions. As a base model standardised logbook catch rates were modelled as a function of fisher perceptions score (represented numerically as a score from 1 to 5) for corresponding depth, map grid (latitude), year combinations. A random effect was used for fisher to capture the effect of fishers providing multiple scores (different scores for different latitude / depths). Factors that might affect congruence between standardised catch rates and fisher perceptions were investigated by introducing interactions with fisher perceptions in the base model. A range of interacting variables were explored including, the zone of fishers' operations ("B" zone or "C" Zone), the recall time in years, fishers experience (number of years fishing), quota (kg caught), latitude (one-degree increments), and an additional variable that was called "event" (Table 1). The "event" variable in these models was included to account for two key events that occurred near one another; the 2010/11 extreme marine heat wave and the change in fisheries management from input controls to output controls (shift to ITQ). These events could not be separated due to their proximate occurrence and were therefore considered a singular event for the purpose of this study. Model selection was performed using Akaike's Information Criterion (AIC) and Bayesian Information Criteria (BIC) values (Akaike 1998), and the most parsimonious models that were within 2 AIC were included in subsequent analyses.

All data manipulation, analyses and plotting for this study were completed using the R Programming Language (R Core Team 2021) and made use of the following packages dplyr (Wickham et al. 2020), lme4 (Bates et al. 2015), mgcv (Wood 2017), nlme (Pinheiro et al. 2021), ggplot2 (Wickham 2016).

Table 1 Summary of model variables that were included in the iterative approach.

Model Variable	Description
DPIRD Catch Returns	Catch per unit effort derived from fisher reported catch returns submitted to DPIRD.
Fisher Perception	The averaged individual fisher score for catch rates in each study block for each year.
Unique Fisher ID	A unique ID code for each fisher.
Years of Recall	The year for each catch rate observation calculated as years prior to the survey.
Fishers Experience	The number of years that the fisher has been fishing, measures experience.
Quota	The allocated quota that fishers can fish for under the individual transferable quota.
Latitude	The latitude of each observation is allocated to one-degree blocks.
Management Zone	The management zone that the fisher usually operates in (only "B" and "C" zone were included for this study)
Event	A variable to account for the change in management and the extreme marine heatwave ("pre" or "post" event)

Results

Comparison of fisher perception and regional fisheries dependent standardised catch rate

The most parsimonious model (Table 2, Model [1]) included the “fisher perception" variable along with interactions with "years of recall" and the “event” parameter. One other model was within 2 AIC values of the most parsimonious model included “Management Zone" (Table 2). There was a significant positive relationship observed overall between the fisher’s perception scores and the reported catch rates ($p < 0.001$, $F = 18.5$), this is likely driven by the most recent fisher perception catch rate data point which corresponded strongly with the standardised catch rate. There was also a tendency for the fishers perceptions to be somewhat more consistent with reported catch rates in more recent time (i.e. closer to time of perception survey, $p < 0.001$, $F = 841.6$), with trends matching most closely in the southern C zone and driven by the most recent fisher perception data point, but this relationship and in particular the fisher perceptions were variable over time, especially in the northern B zone where variability in fisher perception was particularly large with little trend over time (Figure 6).

Table 2 Summary table for the models produced in the statistical analysis of the fishers' perception data. Interaction terms are underlined. Note: the random effect, "unique fisher ID" was included in all models. Models ordered by AIC. Both conditional and fixed r squared values are presented.

Response	Model	ΔAIC	ΔBIC	r2 (conditional)	r2 (fixed)	DF
DPIRD Catch Returns	(1) Fisher Score + int. with "Event", "Recall" + "FisherID"	0	0	0.827	0.758	5
	(2) Fisher Score + int. with "Recall", "Event", "Management Zone" + "FisherID"	9.7	4.8	0.843	0.723	7

The interactive effect of Zone is evident when fisher perceptions are examined for each management zone separately (Figure 6b and c). With fishers in B Zone generally perceive catches to be worse than the formal catch returns, especially in more recent times, whilst the perceptions of C Zone fishers tend to have a stronger congruence with DPIRD Catch Returns. Although informative, the variation in these models and the underlying data is high, as can be seen in the plots of fisher perception score versus predicted DPIRD CPUE the northern "B" management zone and the southern "C" management zone (Figure 6d and e). Variation in relationship between fisher perception score versus standardised DPIRD CPUE within the northern "B" management zone is greater than for the southern "C" management zone.

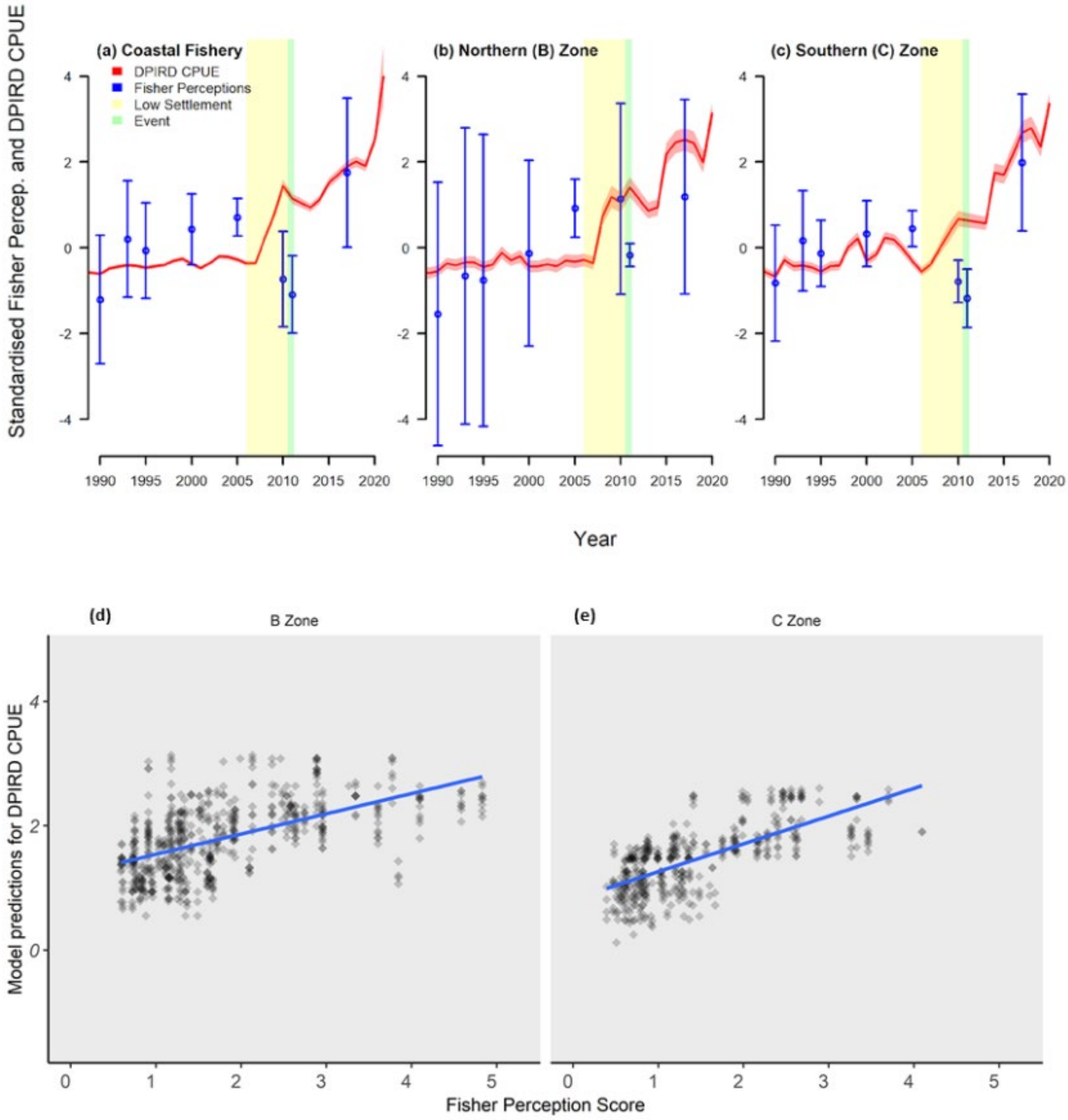

Figure 6 Representation of the relationship between fisher perceptions and the reported catch rates (a) across the fishery (excluding Houtman-Abrolhos), (b) in the northern management area (B-Zone) and (c) in the southern management area (C-Zone). Note: The blue data points are the z-scores for the mean fisher perception scores for each of the interview years and the red data series is the z-scores for the standardised mean DPIRD CPUE for each year. The yellow band denotes the low puerulus settlement years while the green band indicates the change in management of the fishery and the marine heatwave. The model predictions for DPIRD CPUE plotted against the Fisher perception scores for (d) the northern "B" management zone and (e) the southern "C" management zone.

Comparison of fisher perception and standardised fisheries independent catch rates in “Low” and “High” catch zones

Using the fine scale standardised catch rate and fisher perception data we were able to investigate fisher perceptions and catch rate related to the LCZ and adjacent HCZ (Supplementary Figure 8-10). A greater differentiation between standardised catch rate and fisher perceptions of legal lobster catch rates across the LCZ and HCZ, was observed when compared with the catch rate of sub-legal lobster (Figure 7b) than the catch rate of legal lobster (Figure 7a). No formal statistical comparison was undertaken between catch rate and perceptions of catch rate due to lack of replication between locations.

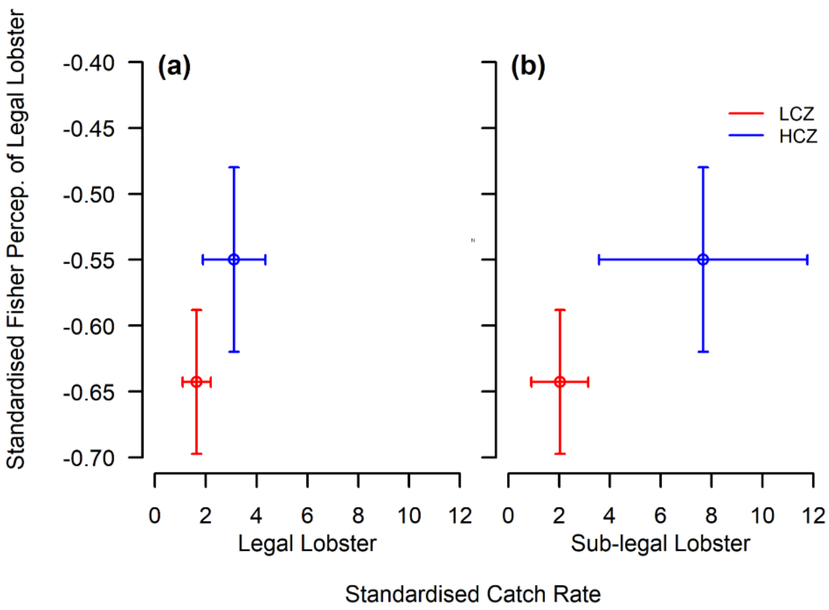

Figure 7 Comparison of the reported fisher perceptions of catch rates in the high and low catch zones in relation to relationship between standardised fisher perceptions and the standardised fisheries independent catch rates (number of lobsters per trap) for legal and sub legal lobsters caught in the high and low catch zones from produced by Miller (2019). The spatial resolution of the data sources meant that only a comparison between the low (LCZ, trapping was conducted near Cliff Head) and high (HCZ; trapping was conducted to the north of Dongara) catch zones could be compared. Standardised catch data from Miller et al. (2023).

Discussion

We found that using structured interviews to elicit fishers' perceptions on the trends in catch rates over space and time can provide a certain level of comparative information to standardised fisheries dependent catch rates at the scale of the fishery, but these perceptions show a decreasing level of congruence with increased recall time and can be highly variable between various locations across the fishery. We also found evidence of an interaction with management zone, where the fishers' perceptions and standardised catch rates were more closely aligned in the southern and more temperate "C" management zone, while there was instead limited congruence and greater heterogeneity in fisher perceptions of catch rate in the northern and more tropical "B" management zone, especially in recent times since the period of low settlement (Figure 6). We suggest that fishers' perception of catch rate, and their local ecological knowledge, can provide useful additional data for fisheries management at a finer spatial scale than that typically recorded for formal catch reporting but we suggest that such data should be collected as close as possible in time to, or instantaneous with, fishing activities.

There have been numerous studies that have previously investigated the relationship between fishers' perceptions and standardised scientific methods using a range of data sources including fisheries dependent (Neis et al. 1999; Ainsworth and Pitcher 2005; Daw, Robinson, and Graham 2011; Zukowski, Curtis, and Watts 2011; O'Donnell, Molloy, and Vincent 2012; Taylor et al. 2017; Santos et al. 2019) and fishery independent data (Daw, Robinson, and Graham 2011; Zukowski, Curtis, and Watts 2011). Some of these studies have found conflicting results between the two data sources such as the review by Ainsworth and Pitcher (2005) found that fishers' expert ecological knowledge agreed with formal stock assessments in only 37% of cases. Concordance was found to improve with fisher experience, and it is also suggested that fishers are more likely to err on the side of pessimism in relation to stock assessments (Ainsworth and Pitcher 2005). The current study found a high level of variation in fisher perceptions in catch rate, for both spatial and temporal trends. This variation was particularly high within the northern and more tropical "B" management zone of the fishery. Previous studies have noted differences in settlement patterns, oceanographic conditions, and lobster growth rate between these two management zones (N. Caputi and Brown 1993). The previously documented Low Catch Zone (LCZ), where contrasting catch rates of sub-legal lobster have been found (Miller et al. 2023 – Study 2) across relatively small spatial scales (i.e. 10-20 km), occurs within the "B" management zone, which may contribute to the greater variation in fisher perceptions of catch rate found across the larger zone.

Although limited to two sites, the examination of fisher perceptions and fishery independent catch rates, across the LCZ and adjacent high catch zone (HCZ), provide an interesting comparison (see also Supplementary Figures 8-10). The greater differentiation between standardised catch rate and fisher perceptions of legal lobster catch rates across the LCZ and HCZ, was evident for sub-legal lobsters (Figure 7b) compared with legal lobsters (Figure 7a). This suggests that fisher perceptions of catch rate may be influenced by the abundance of sub-legal lobsters, and that the fisher perceptions recorded in this study may represent local ecological perceptions of future or potential catch rate. This highlights the potentially useful data that both fisher perception and independent trapping surveys have for providing additional data sources for the management of a fishery.

Discrepancies between the fisher derived expert perception and formal catch record derived data sources can be a useful resource indicating opportunities to investigate patterns that may not be well captured or understood by standard fisheries science practice (Robert Earle Johannes 1981; Huntington et al. 2004; R. E. Johannes, Freeman, and Hamilton 2008; Zukowski, Curtis, and Watts 2011). For example, in the present study the difference between the two management zones may be indicative of different processes affecting either the productivity of the fishery in those areas or that the perceptions of the catch rates in these zones are being affected by regional variations between fishers. The most obvious widespread potential influence on the northern zone is the marine heatwave that occurred in the summer 2010-11 in the region which caused mortalities of a wide range of marine biota and was generally restricted to the northern management B zone (Arias-Ortiz et al. 2018; Caputi et al. 2019; Smale and Wernberg 2013). It has previously been suggested that the perceptions of catch rates held by fishers can integrate additional local ecological knowledge reflecting differences between regions of a fishery that might not be reflected in standard catch returns (Zukowski, Curtis, and Watts 2011; Berkström et al. 2019; Santos et al. 2019).

Previous studies comparing fisher perceptions to standardised fisheries catch data also identified a range of limitations when using fisher interview data to track catch rates and the status of a fishery, principle amongst these was reduced congruence with increasing recall time (O'Donnell, Molloy, and Vincent 2012; Daw, Robinson, and Graham 2011). This deviation between reported catch rates and fisher perceptions are likely to be due to a variety of factors such as the various neurological factors affecting memory-based estimates of trends and the potential for 'cognitive conflicts' in recall based estimates (Daw, Robinson, and Graham 2011). In a study conducted by O'Donnell et al. (2012), fishers were found to overestimate the "typical" catch rates with perceptions of historical catch greatly exceeding the reported catch rates while "bad" catch rates were much more comparable between the two sources. In the case of the WCRLMF, an additional factor to consider is the regular annual presentation of catch rates to fishers at annual management meetings by DPIRD fisheries scientists which may impact on the recall or perceptions of some fishers.

One of the key limitations of the present study was the relatively limited number of fishers interviewed and the resulting level of representativeness. We used an opportunistic or “snow-ball” sampling design whereby all fishers attending planned “Coastal Tour” meetings were interviewed at each location and then also asked to recommend other fishers, providing a relatively consistent number of interviewees at each location. This sampling methodology may not obtain a fully representative sample of fishers as individuals who do not typically attend the regular peak body “Coastal Tour” meetings, or keep in contact with those that do, would have been less likely to be sampled. To improve the overall level of representation of future surveys or methods could use alternative recruitment methods, such as including random selection of licensed fishers combined with telephone or online surveys or integrating perception surveys into instantaneous electronic reporting for fishers to fill out during fishing activities.

We found that, even in the case of a well-researched and managed fishery such as the WCRLMF, structured interviews of the perceptions of commercial fishers still have potential to add-value to our understanding of the fishery. The surveys have the potential to provided information on the status and dynamics of the fishery by integrating and capturing fishers’ expert ecosystem knowledge. This form of additional fisheries data can allow for an understanding of the fishery at finer scales, as demonstrated by our comparison with the relatively small scale (i.e. 10-20 km) of the LCZ, than typically used for traditional fisheries dependent sources. In this study, commercial fishers initially identified the occurrence and location of the LCZ, and subsequent fisheries independent surveys, using meshed lobster pots, confirmed the existence of the LCZ along with its boundaries (Miller et al. 2023). Furthermore, we suggest that regular repetition of the structured perception survey as used by the current study could provide information useful to management, and a useful form of engagement with fishers with the potential to providing early warning signs of change in a fishery. Given our finding of reduced reliability with increasing recall time, corroborated by previous studies in other fisheries (O’Donnell, Molloy, and Vincent 2012; Daw, Robinson, and Graham 2011), a potentially useful option would be to integrate that catch rate perception method used in the current study into instantaneous electronic catch reporting. This could enable fisher perceptions of catch rate to be recorded along with standard fisheries data in a highly cost-effective and structured manner. The abundance distribution of the Western Rock Lobster is predicted to be impacted by climate change (Cheung et al. 2012) and the likely increased occurrence of extreme events including marine heatwaves (Oliver et al.

2019). It is also a fishery that has undergone large adjustments, through the introduction of quota management (Caputi et al. 2015) and associated reduction in fishing effort and general increase in catch rates. Creating an instantaneous reporting system that not only recorded standard catch data but also fishers perceptions of theses catches, in addition to observations of other changes in the marine ecosystem, would provide a structured way to integrate fishers expert knowledge into fisheries assessments.

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Supplementary Material

Data Visualisation

Fisher Interviews

A matrix was used to display the aggregated results of the fisher interview data across time, space, and depth zones (Figure 8).

The data has been summarised into "blocks" with a height of one degree of latitude and a width of 10 fathoms water depth. Eight years of data is displayed across the time series. The number displayed in each cell is the number of responses collected for each "block".

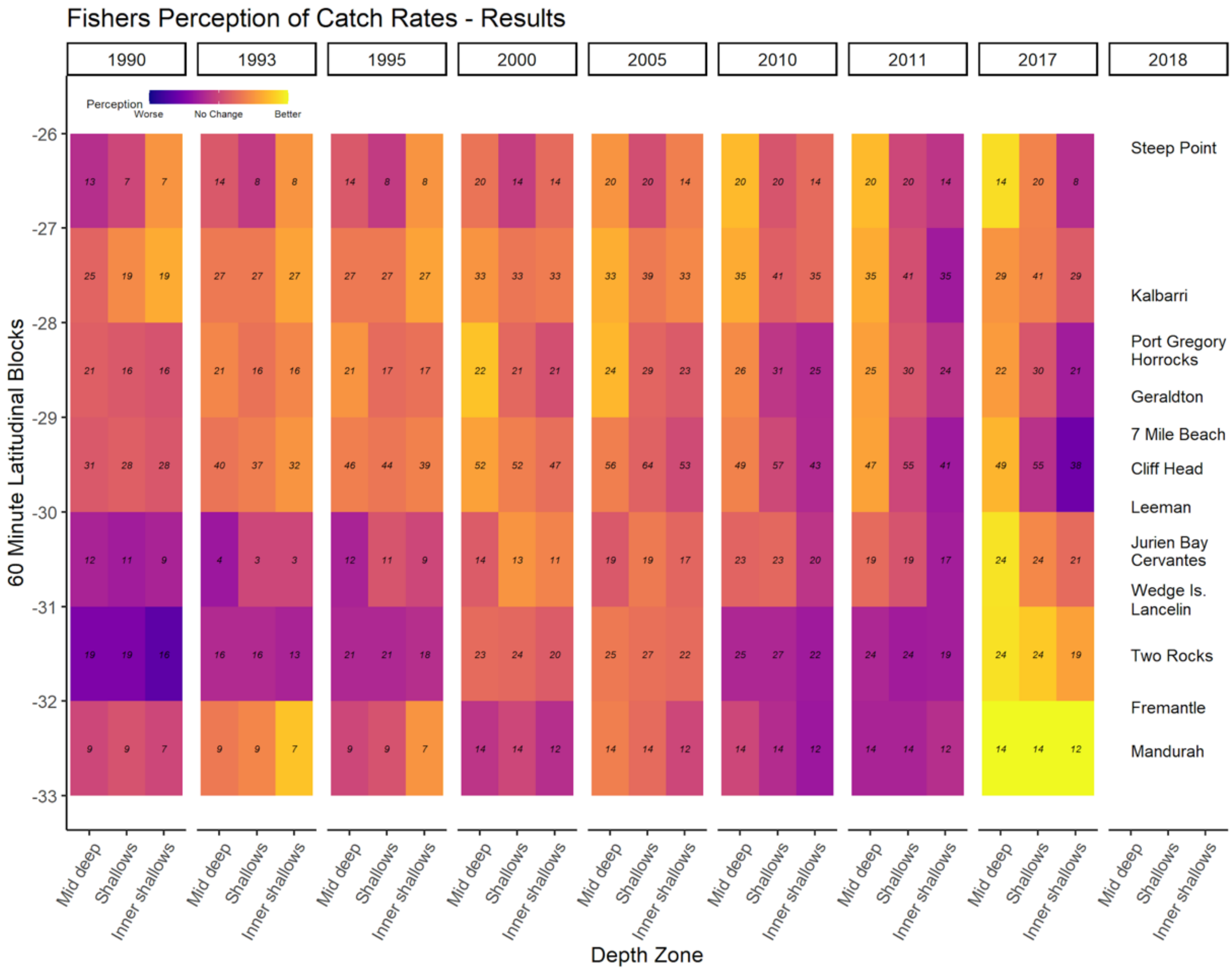

Figure 8 Average aggregated catch rate data obtained from the fisher interviews. Note: This data has been summarised into "blocks" with a height of one degree of latitude and a width of 10 fathoms water depth with the number displayed in each cell being the number of responses for each cell.

A second matrix of the aggregated fisher interview data was produced to display the standard error for each "block." The same blocks were also used for this matrix (Figure 9).

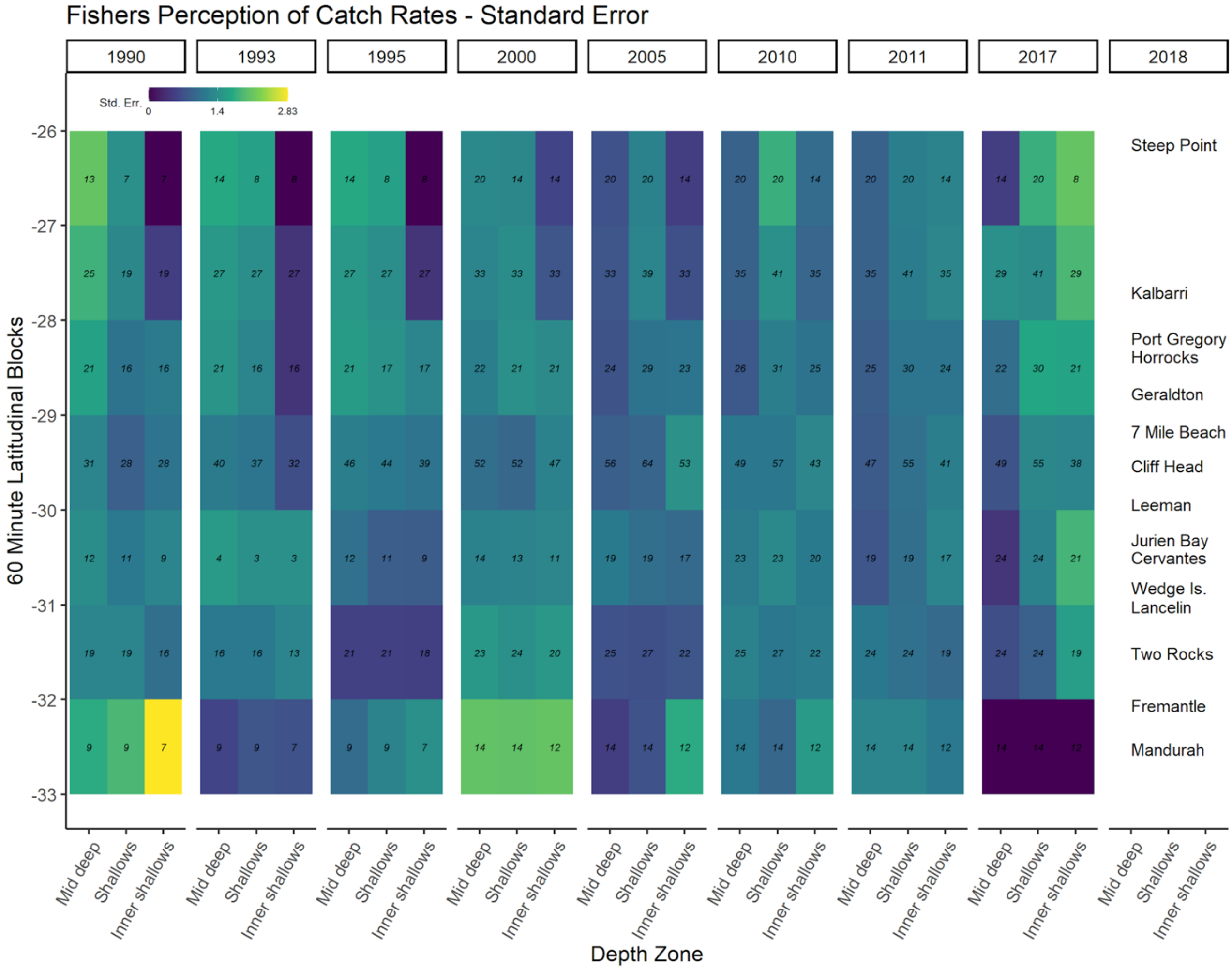

Figure 9 Standard error in aggregated catch rate data obtained from the fisher interviews. Note: This data has been summarised into "blocks" with a height of one degree of latitude and a width of 10 fathoms water depth with the number displayed in each cell being the number of responses for each cell.

DPIRD Catch Returns

The same Matrix was constructed using the DPIRD catch returns data. This data was first converted to catch per unit of effort (CPUE) to standardise the data format (Figure 10) the same "block" dimensions as the fisher interview data were also used for this matrix. This data has a different coverage to the Fisher interview data as much of this data has relied upon the various fisher logbook data sources over the years and some areas were not regularly fished by fishers participating in the logbook system.

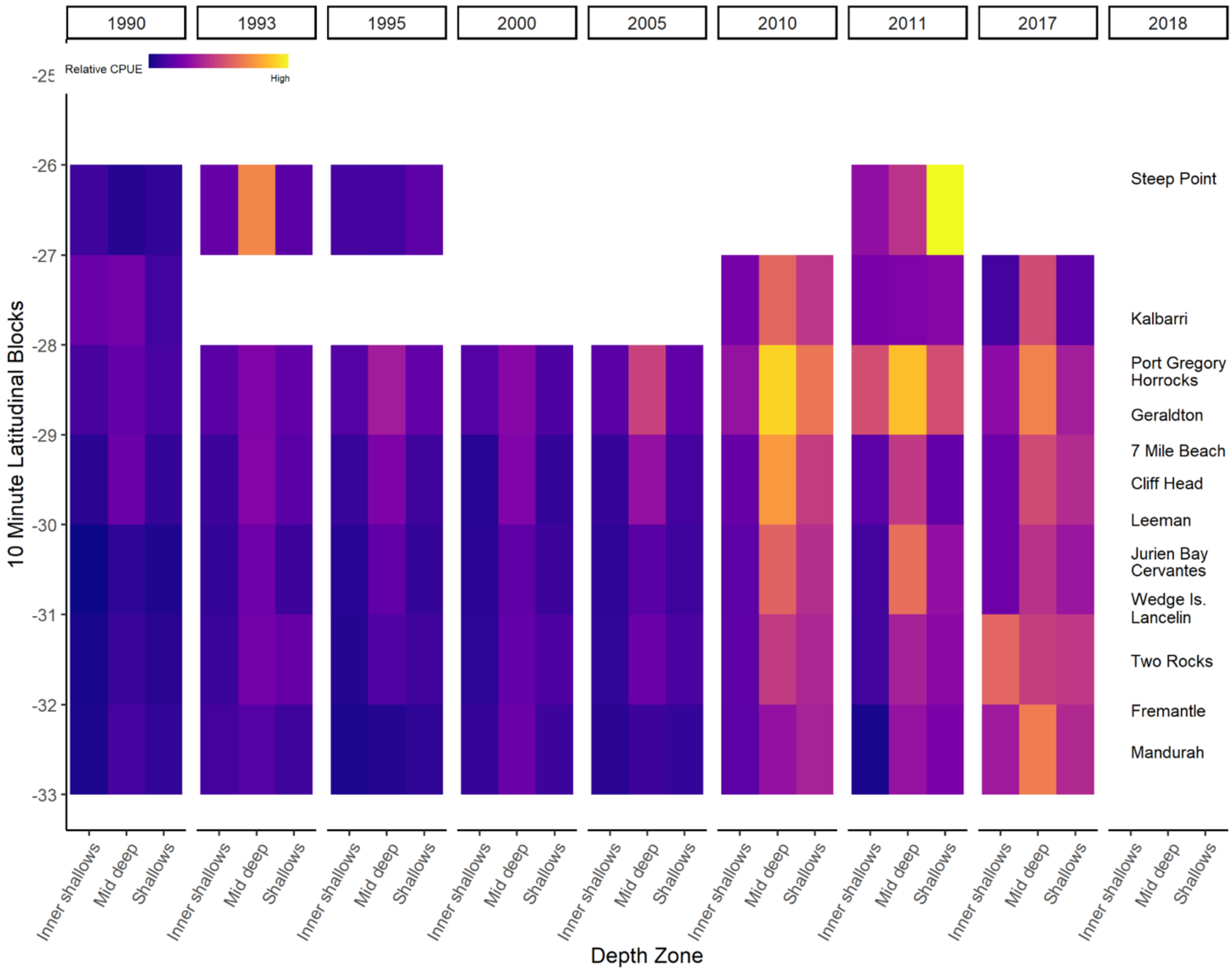

Figure 10 The summarised CPUE data obtained by DPIRD. Note: This data has been summarised into "blocks" with a height of one degree of latitude and a width of 10 fathoms water depth.

Study 2 - Fine-scale variability in catch and growth rates of Western Rock Lobsters, *Panulirus cygnus*, reveal heterogeneous life-history parameters.

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Catch rate study. Left, fishers Brian Sloper, John Fitzhardinge and Paul Day setting pots in the low-catch zone; right, Masters student Ash Miller recording catches. Photographs Tim Langlois.

Abstract

The Western Rock Lobster fishery is recognised to be conservatively managed with breeding stock levels estimated to be at record levels over the last decade. Despite this, anecdotal reports from commercial fishers identified an area of unexpectedly low catches in the centre of the fishery and lobsters' biogeographic distribution.

To confirm the presence of this suspected "Low-catch" zone and examine the variability in catch and growth rates of lobsters if identified.

This study conducted an intensive mark-recapture survey over eight months to explore catch rate, density, movement and growth rates across this "Low-catch" zone and three comparable locations. A total of 9,318 lobsters were caught and 7,565 individuals were tagged during the study. Consistently low catch rates of undersized lobsters were observed in the "Low-catch" zone with catch rates increasing with distance from the zone. In contrast, similar catch rates of legal-sized lobsters were observed across all locations. The study confirmed low catch rates, for undersized lobsters, within an area of perceived low catch rates within the centre of the fishery. The lack of difference found in legal-sized catch rates between location is likely due to the low fishing pressure in the "Low-catch" zone resulting from hyperstability of fishers adapting to the historical perceived low catch rate. Modelled data demonstrated the "Low-catch" zone to be associated with faster growth rates and high fine-scale migration indicating a potential release from density-dependent processes. We anticipate these results will be a useful starting point for future research into the mechanisms responsible for the unexpectedly low catch of sub-legal lobsters within the "Low-catch" zone and the implications it may have on the wider population, both regionally and across the species distribution.

Introduction

Understanding the environmental drivers of demographic rates and the catchability of commercially targeted species underpins sustainable fisheries management. The Western Rock Lobster (WRL) (*Panulirus cygnus* George 1962) is found along the lower west coast of Western Australia and is exploited by both commercial and recreational fishers throughout its geographic range. The commercial fishery alone represents Australia’s most valuable wild-caught single-species fisheries, contributing a total revenue of $424 million in 2017 (Gaughan and Santoro 2018). Due to its high economic and social value, the Western Rock Lobster fishery has been the focus of over forty years of extensive research (de Lestang et al. 2016, Bellchambers et al. 2017). Much of this research relies upon stock assessments from pot-based surveys to derive size-structured abundance and demographic data. The fishery is currently managed using a strict quota-controlled system with individual transferable quotas (ITQ) and a Total Allowable Commercial (TAC) which is set annually (de Lestang 2014).

Despite the overall high catch rates currently reported within the West Coast Rock Lobster Managed Fishery (WCRLMF), a pre-study workshop with fishers from the Professional Fishermen’s Association (PFA) and perception surveys of fishers on changes in catch rates throughout the fishery identified an area of abnormally low legal-sized catch within the centre of the fishery (Brooker 2022). This “Low-catch” zone is centred on the shallow waters at ‘Cliff Head’ (Figure 11) with lower-than-expected catch rates since 1995 and a continued decline since. Additionally, a gradient of catch rates was identified within the fishery: a low to moderate catch area (“Boundary”), a moderate to high catch area (“Mid”), and a high-catch area (“High-catch”) commonly known as ‘Seven Mile Beach’ north of Dongara. Despite this variation in catch rate, all catch areas share broadly comparable environmental conditions and perceived historical (pre 1995) catch rates. The perceived low catch rates within this “Low-catch” zone has resulted in the relocation of almost all the commercial fishers that previously fished in this region to fish in adjacent locations. Interestingly, the identified “Low-catch” zone allegedly produced some of the highest catch rates in the fishery prior to 1995, supporting a large number of fishing vessels (> 60 boats, *Pers. Com.* John Fitzhardinge). Furthermore, the coastal waters within this region historically, and currently, receive some of the highest levels of recruitment within the fishery (Caputi et al. 2014, de Lestang et al. 2016). Moreover, the perceived “Low-catch” zone is situated in close proximity (< 40 km) to areas that are currently producing some of the highest catch rates in the fishery (de Lestang et al. 2016). Understanding the extent and the likely mechanisms driving these unexpected low-catch rates could be crucial for maintaining the sustainability of the fishery.

Palinurus cygnus (*P. cygnus*) have a relatively complex life cycle composed of a number of pelagic and benthic life stages that cover a large geographical extent, from deep offshore waters to shallow coastal reefs, where the majority of settlement is likely to occur (Chittleborough and Phillips 1975). Post-settlement *P. cygnus* are known to undergo a migration from shallow inshore waters (<40 m) between late November and January every year to deeper offshore waters (40-100 m) (Caputi et al. 2010). This migration occurs around 4 years of age before *P. cygnus* reach maturity. This process is known as the 'whites' migration due to the pale colouration of the lobsters after the moult prior to the migration event (Caputi et al. 2010). Given the lack of morphological age markers for crustaceans, there is no method to directly age decapods (Kilada et al. 2012), which results in an inability to obtain size-at-age data. Therefore, this 'whites' life stage provides an opportunity to compare individuals of likely comparable age.

Low catch rates within the near-shore "Low-catch" zone could be caused by a wide range of variables as both environmental and physiological factors have previously been demonstrated to influence the catchability and population density of *P. cygnus*. Water temperature (Chittleborough 1970), salinity (Morgan 1974), lunar phase (Morgan 1974, Srisurichan et al. 2005) and swell (Srisurichan et al. 2005) can influence the catchability of *P. cygnus*. Feeding activity, and therefore catch rate, has been shown to be significantly influenced during ecdysis or 'moulting', where the hard outer exoskeleton is shed to allow for growth (Needham 1946). For *P. cygnus*, feeding behaviours have been shown to vary with the stage of the moult cycle, in turn affecting the catchability of the individual (Morgan 1974). In addition, the presence of predators within a trap can affect the catch rate of *P. cygnus* (Morgan 1974). The main factors thought to influence population density are the levels of recruitment, which is thought to be highly influenced by a range of factors including environmental processes (de Lestang et al. 2015), post-larval survival, breeding stock abundance (de Lestang et al. 2015), natural mortality (MacArthur et al. 2007), and the degree of immigration/emigration (MacArthur et al. 2008). Disentangling whether the perceived low catch rates at Cliff Head ("Low-catch" zone) are attributable to certain factors influencing catchability or factors causing a decline in population abundance is a complex, yet vital task to investigate when exploring the potential implications of the reported low catches in this area and how these mechanisms may relate to the management of the fishery.

The current study conducted an intensive mark-recapture potting survey over eight successive months to firstly confirm the existence of low-catch rates within the "Low-catch" zone reported by fishers, relative to comparable adjacent areas. Specifically, we aimed to test the hypothesis that the "Low-catch" zone will be associated with lower standardised catch rates of legal-sized lobster compared to nearby locations with comparable environmental and catch rate histories, matching the fishers' perceptions.

Due to the design of the study the spatial extent of the “Low-catch” zone could be identified if evidence of low catch exists, and variations in growth rates between locations can be analysed. We investigated the role that environmental, behavioural, physiological and life-stage variables may be influencing the low catchability coefficient and/or low abundance within the perceived “Low-catch” zone. If the “Low-catch” zone is confirmed, a crucial component for future studies will be to explore the whether the identified low catch rates are due to a low population density for the area, or if it due to a low catchability of the lobster population within the “Low-catch” zone.

Methods

Study area

A preliminary workshop was conducted with 18 fishers from the Dongara PFA and a separate perception survey with 47 fishers was conducted as part of Study 1 in the current report. The surveys identified four locations with comparable historical catch rates and environmental variables, yet with contrasting current perceived catch rates (Figure 11). The “Low-catch” location centred on Cliff Head, was perceived to currently have the lowest catch and strongest contrast with fishers’ knowledge of historical catch averages, whereas the “Boundary” and “Mid” locations were perceived to have moderately low catch compared to historical catch averages. The “High-catch” location, commonly known as ‘Seven Mile Beach’, was perceived to currently have the highest and most comparable catch to historical (pre-1995) averages. Each location was chosen to capture this gradient in perceived change in catch-rate across locations representing otherwise comparable lobster habitat.

With the assistance of fishers and historical fishing records, representative and comparable potting sites (between 3-5 per location) were chosen. Due to the mandatory use of Sea Lion Exclusion Devices (SLEDs) on all recreational and commercial fishing activities south of 29°35.16'S it was not possible to find comparable sampling locations further to the south of the southernmost “Boundary” location.

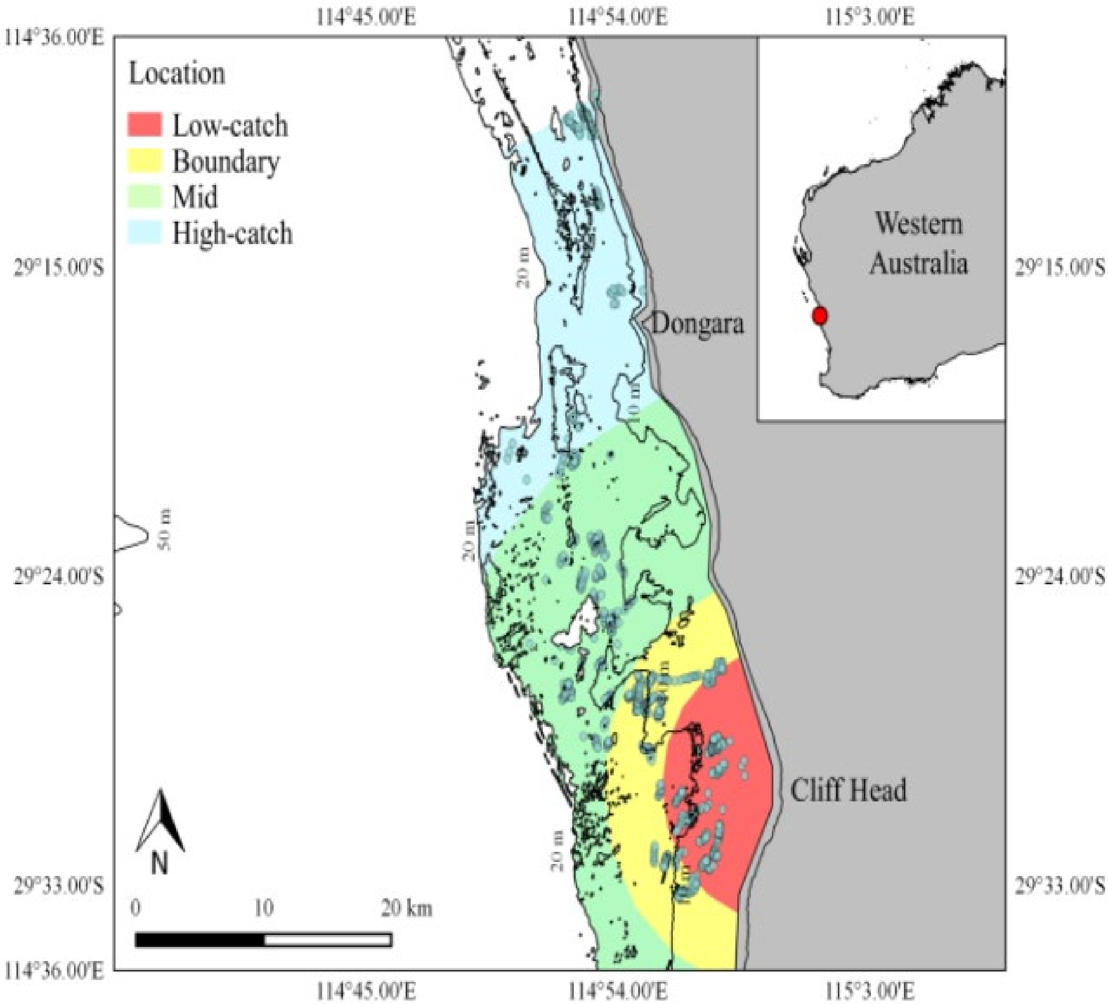

Figure 11 The mark-recapture potting locations; "Low-catch zone" (red, Cliff Head), "Boundary" (yellow), "Mid" (green) and "High-catch" (blue, Seven Mile Beach). Pot locations indicated by blue circles was restricted to a maximum depth of 20 m across all locations.

Catch-rate and mark-recapture experimental design

A catch and mark-recapture survey was conducted over four to six successive days, every month over an eight month study period between May and December in 2018. A minimum of 15 baited wooden pots, enclosed by mesh were used to capture individuals at each study location, with each pot site sampled twice on each trip. The pots were adapted from commercial wooden pots with a 1 cm wire mesh added to cover the interior of the pot (Supplementary Figure 17). This design of "mesh-enclosed" pot is used as a standard fisheries independent sampling method for sampling both legal size (>76 mm carapace length) and sub-legal size (<76 mm carapace length) lobsters across the fishery (Tuffley et al. 2018).

The fishing was conducted over reef habitats pre-identified as suitable fishing grounds and comparable habitats by fishers during the pre-study surveys. Potting was restricted to a maximum depth of 20 m across all locations. All pots were deployed and recovered the following day from a commercial fishing vessel. The bait was standardised across all sampling trips.

Data collection

On capture, lobsters were temporarily placed in a "chill tank" to stun the lobsters to reduce handling damage. Those individuals larger than >40 mm carapace length and in suitable condition (no more than four lost appendages and no visible damage) were tagged with a uniquely coded 50 mm plastic T-bar anchor tag (Hallprint®, Australia). Tags were inserted, with a tag applicator (Supplementary Figure 17), into the tail extensor muscle located between the first abdominal segment and the posterior edge of the carapace (Supplementary Figure 17). During each sampling month a unique pleopod was clipped to allow for estimates of tag loss; where any individual caught with a cut pleopod, but no tag was recorded as a tag loss. Biological data on each lobster included carapace length (CL: from the posterior edge of the cephalothorax to the rostral horns), sex, colour, reproductive state (presence/absence of ovigerous setae) and any external damage (lost or newly regenerated legs or antennae). The presence of predators and the type and number of by-catch in each trap was also recorded. All lobsters were placed in a holding tank prior to release to ensure they were in suitable condition before being released back into the water. Individuals were returned to the same GPS coordinates that the pot was pulled from. Sampling sites were left undisturbed for at least three weeks before potting was repeated. Water temperatures used in subsequent analyses was derived using the work of Chamberlain et al. (2012).

Additional mark-recapture data was obtained from a simultaneous and comparable on-going research program conducted by the DPIRD (Fisheries Research) at Seven Mile Beach between May 2017 and November 2018. This data extended the spatial coverage and number of recaptures in the study (Supplementary Table 6) and comprised a total of 534 tagged individuals with 213 (39.9%) total recaptures, 141 being unique (26.4%). Historical data from a previous tagging study between November 2017 and December 2017 conducted by the University of Western Australia (UWA), contributed an additional 1,682 tagged individuals with 102 (6%) total recaptures, 99 (5.8%) being unique. A further 206 recaptures of individuals marked during these studies were reported by commercial fishers fishing throughout the region between December 2017 and February 2019. Finally, 28 recaptures were obtained during a follow-up sampling trip in June 2019 which re-visited the 2018 study potting locations.

Quality control and validation

Due to the collaborative nature of the study an extensive amount of quality control and validation was required. All catch and mark-recapture data collected at the main locations and sites of interest was collected by a single observer (Lead author A. Miller), however, historical UWA data and that provided by commercial fishers and DPRID fisheries researchers was extensively checked prior to incorporation. Inaccurate, incomplete, and inconsistent data entries were either corrected, or removed prior to statistical analyses.

Statistical analysis

Contribution of location and environmental variables to catch rate and mean length

Differences between locations, perceived by fishers to be different, and the influence of environmental variables (Table 3) in catch rate and mean length per pot were assessed using generalised additive mixed models (GAMM) with a full subset model selection approach (as per Fisher et al. 2018). The full subset approach tests all possible combinations of a range of predictor variables, to a maximum of three, and then identifies the most parsimonious model (Fisher et al. 2018). Models containing variable combinations with correlations >0.28 were excluded, as suggested by Graham (2003), to eliminate potential problems with collinearity and overfitting, and model selection was based on Akaike's An Information Criterion optimised for small sample sizes (AICc) (Akaike 1973), and parsimony (Graham 2003, Fisher et al. 2018). Generalised Additive Mixed Models were chosen to standardise catch rates as they utilise smoothing techniques to accommodate for non-linear relationships with predictors and can be modified to suite the error distribution of the data and account for random effects (Hastie and Tibshirani 1986, Lin and Zhang 1999).

Table 3 Predictor variables used in generalised additive mixed effects models to investigate differences in catch rate and mean length of Panulirus cygnus.

Predictor variable	Reasoning to include as a predictor variable
Location The three study locations sampled each sampling trip	To assess the difference of catch and life-history parameters between locations of perceived contrasting catch rates.
Sea surface temperature (SST) Average sea surface temperature for sampling day for each study location	Water temperatures has been shown to influence the catchability (de Lestang et al. 2009) of Western Rock Lobsters (Srisurichan 2001). SST was derived from the work of Chamberlain et al. (2012).
Swell period (s) Average swell period (seconds) calculated for each day of sampling for each study location	The activity of Western Rock Lobsters has been shown to be influenced by swell from the previous day (Srisurichan et al. 2005).
Swell height (m) Average swell height (meters) calculated for each day of sampling for each study location	The activity of Western Rock Lobsters has been shown to be influenced by swell from the previous day (Srisurichan et al. 2005).

For catch data, the number of sub-legal and legal sized lobsters per pot was used as the response variable. The raw data had a high number of zeros (5.7% - 37% depending on the location), therefore a Tweedie error distribution was used (Tweedie 1984). The Tweedie distribution is an extension of a compound Poisson model and has the advantage of handling zero-inflated data in a unified way in contrast to delta or hurdle models (Tweedie 1984, Candy 2004, Shono 2008). Given that assessing temporal patterns in catch rate was not an objective of this study, and that broad temporal consistency of catch-rate was observed between sampling locations (Figure 12), the sampling date was considered as a random effect to account for fine-scale temporal variation within the study. In addition, the independent potting sites (3-5) nested within each location were also included as a random effect to account for small-scale spatial variation. All pots that had a predator present, or indication that one had visited, were removed from the catch rate analysis to reduce the impact of predator presence on variation in catchability and catch rate.

The mean length of the migratory 'white' and resident 'red' life stage of lobsters per pot was analysed in a similar fashion, however, data exploration found the residuals to be normally distributed for both analyses and therefore a Gaussian error distribution was used in modelling. The sampling date and the identity of each pot were used as random effects in these models to account for both spatial and temporal small-scale variation and account for the non-independence of length measures within each pot.

For all models, importance scores of every predictor variable were obtained by summing the AIC weights of each model for which each variable occurred within and these scores were then plotted to identify the relative importance of predictor variables across all possible models (Fisher et al. 2018). All data formatting, plotting, and statistical analyses were conducted in the R language for statistical computing (R Core Team 2018), using the following additional packages: tidyr (Wickham and Henry 2017), dplyr (Wickham et al. 2018), and ggplot2 (Wickham 2009).

Comparison of growth between locations

Growth curves were generated using Fabens (1965) modification of the traditional von Bertalanffy growth equation:

$\Delta L = (L\infty - L_1)\ (1- e^{-K\Delta t})$,

where L1, length at time of marking (tm); Lr, length at time of recapture (tr); ΔL is the change in length (Lr – L1); δt, time at liberty (tr-tm) and two deterministic growth parameters; K, Brody growth coefficient; and L∞, maximum length. The Brody growth coefficient (K) was allowed to vary between sexes and locations. To avoid potential overparameterization of the models, and given that our main objective was to compare growth rates (K) and that the majority of lobster tagged were immature and well below the maximum length for the species, the maximum size ($L\infty$) was kept constant across the groups being compared (i.e. it was estimated but could not vary between groups). Chi-squared maximum likelihood ratio tests were conducted to determine if growth varied significantly with sex or location. Recaptures obtained from commercial fishers and from the follow-up sampling trip conducted in June 2019 were incorporated to increase data abundance and accuracy of the model. Only recapture data from lobsters that were at liberty for more than 1 month were used, to ensure sufficient time for moulting (i.e. growth) to occur between recaptures. The data was standardised by seasons which resulted in the "High-catch" (Seven Mile) location being excluded due to the inconsistencies in the temporal coverage of the mark-recapture data from this location. Recaptures that had more than two damaged appendages were excluded since leg loss can affect growth of lobsters (Goosen and Cockcroft 1995). All analyses were again conducted using the R language for statistical computing (R Core Team 2018), using the mixed effects package lme4 (Bates et al. 2015).

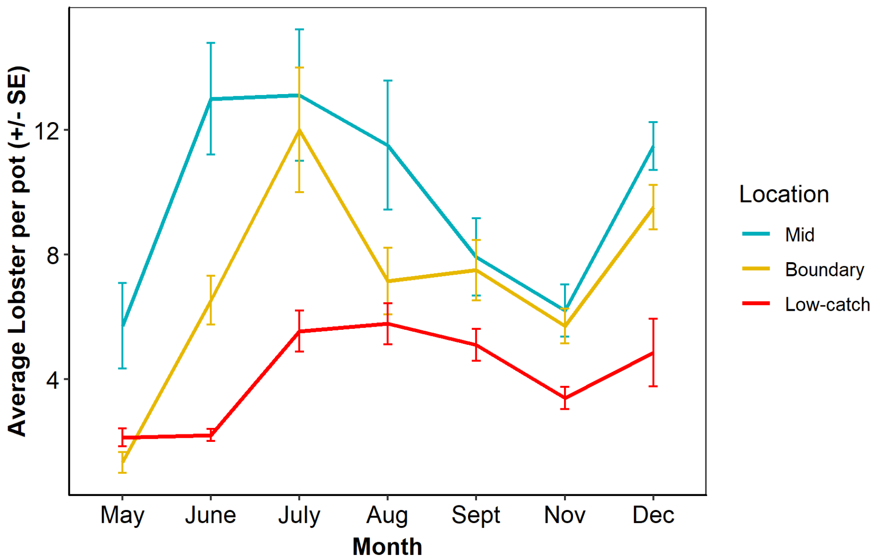

Figure 12 The raw temporal and spatial variation in the average number of lobsters caught per pot (+/- SE) over the eight separate sampling trips between May and December in 2018. The three study locations included: "Low-catch" (Cliff Head, red), "Boundary" (yellow) and "Mid" (blue). Date of sampling was included as a random effect in the formal statistical analysis.

Results

Catch and release data

In total, 9,318 lobsters were captured from 1,461 pot lifts across the eight sampling trips (May 2018 to December 2018). This resulted in 7,565 unique individuals suitable (> 40 mm CL and less than five missing appendages) for tagging. The raw catch rates varied temporally across the study but displayed broadly consistent differences between locations (Figure 12).

The influence of location and environmental variables on catch rate

The most parsimonious model for the legal-size class explained 23% of the deviance in the response variables and included the variables swell height, swell period and sea surface temperature (Table 4). Importance scores indicated that location had low importance for predicting the catch rate of legal-size individuals, but that all three environmental variables (swell height, period and sea surface temperature) were more important for predicting the catch rate across all possible models (Figure 13a). Catch rates were comparable across all four zones. However, the catch rates for the legal-sized class were anticipated to be strongly influenced fishing pressure within the study locations, as such, the trends across the four zones for this size class were not explored further.

Table 4 Best-fitting Generalised Additive Mixed Models for predicting the average catch rate of sub-legal size (<76 mm CL) and legal size (>76 mm CL) individuals per pot. Ordered by parsimony, including the difference between the lowest reported AIC (ΔAICc), AIC weights (ωAICc), explained variance (r^2), and the effective degrees of freedom (edf).

Size Class	Model	ΔAICc	ωAICc	R^2	edf
Sub-legal	Swell Height + Location + Sea surface temperature	0.035	0.307	0.317	47
	Swell Height + Sea surface temperature + Swell Period	0.451	0.25	0.317	47.41
Legal	Swell Height + Sea surface temperature + Swell Period	0	0.884	0.236	48.2

For sublegal individuals, importance scores indicated that swell period had low importance, but that location, swell height and sea surface temperature were more important for predicting the catch rate of sub-legal individuals (Figure 13). The most parsimonious model for the sub-legal-size class catch-rate included location, swell height, and sea surface temperature and explained 31% of the deviance (Table 4). There were lower catch rates in the “Low-catch” zone with a strong trend of increasing catch rate with increasing distance from the low catch zone, with the highest catch rate in the “High-catch” location (Figure 14).

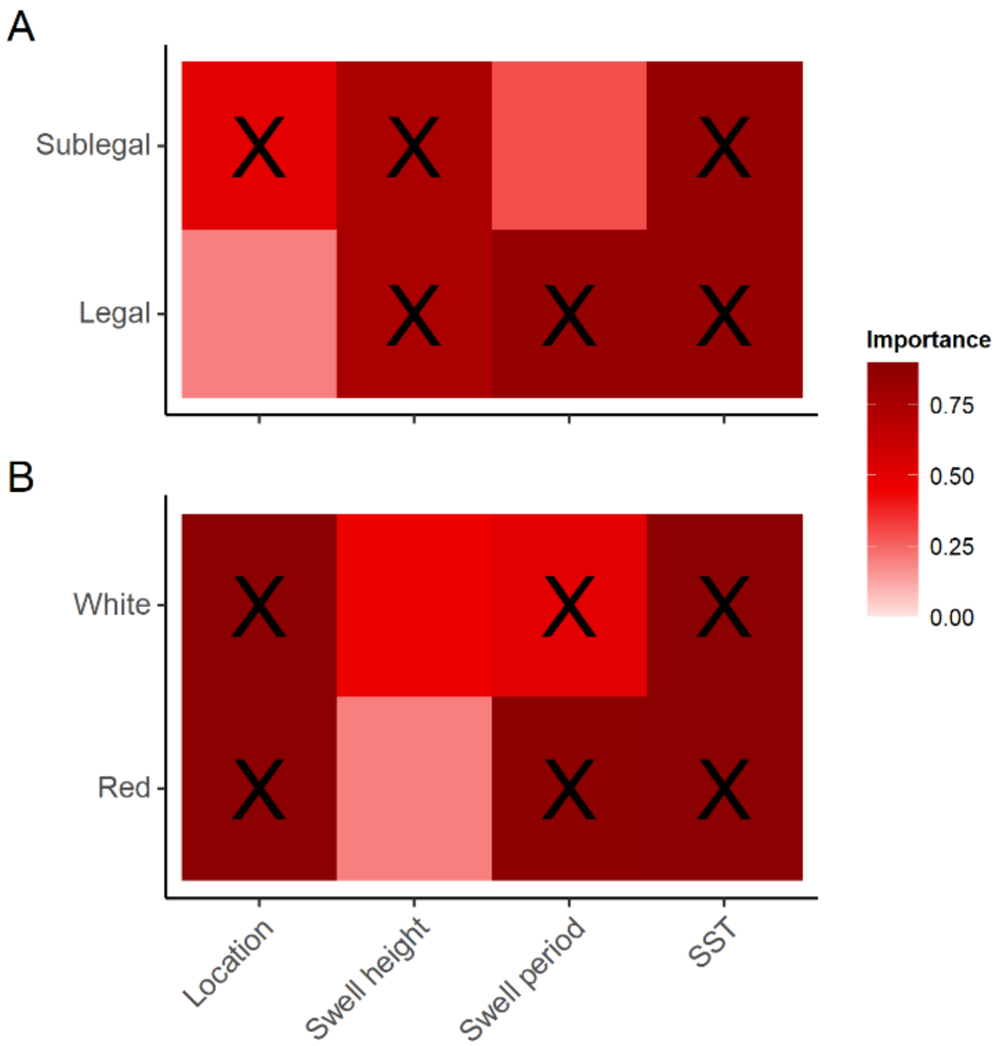

Figure 13 Relative variable importance scores from full-subsets Generalised Additive Mixed Model analyses investigating, a) the average catch rate per pot for legal size (>76 mm CL) and sub-legal size (<76 mm CL) size classes of P. cygnus individuals and b) the mean carapace length (mm) per pot for the resident “Red” and migratory “White” life stage of *P. cygnus* individuals. Variables included in the most parsimonious model indicated by an ‘X’.

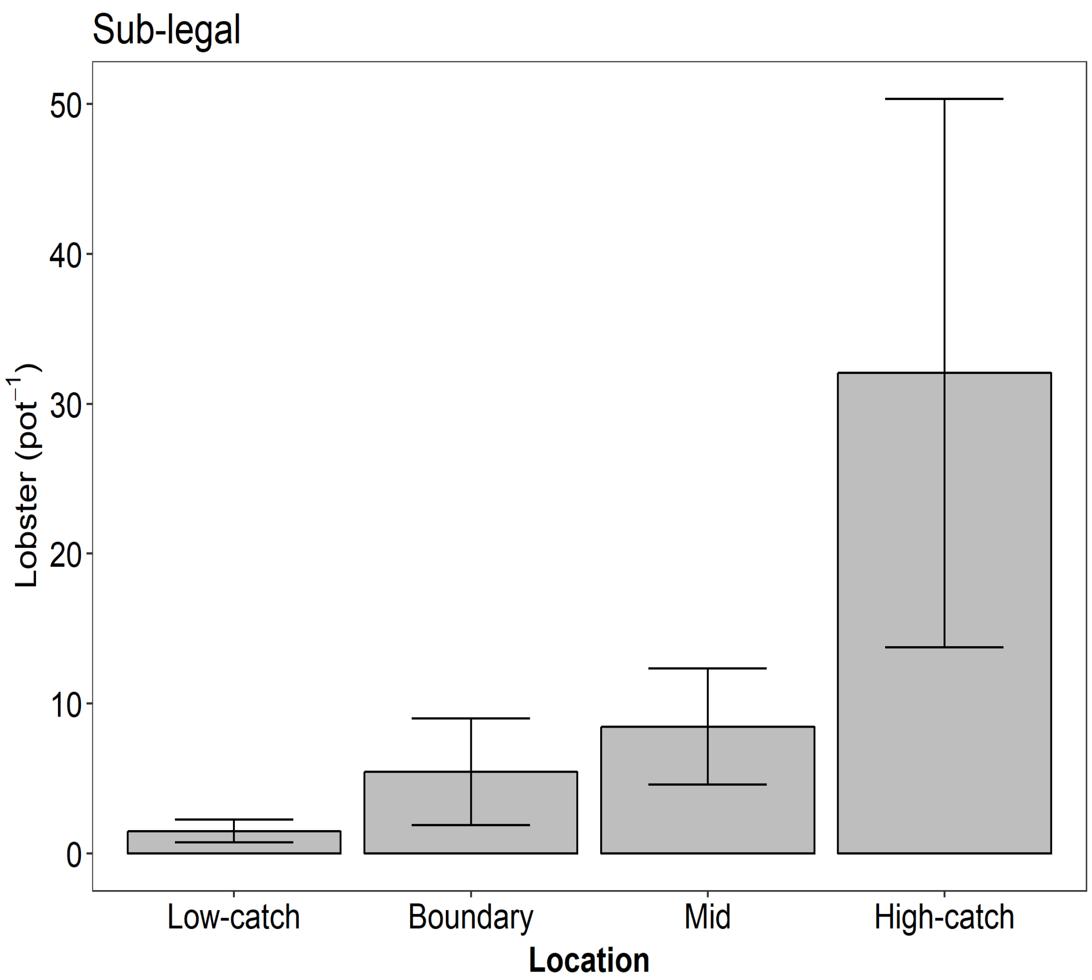

Figure 14 Predicted difference in the average and standard error of catch per pot of sub-legal-size individuals (<76 mm CL), standardised for month of sampling, swell height and sea surface temperature across the four reference study locations; "Low-catch" (Cliff Head), "Boundary", "Mid" and "High-catch" (Seven Mile).

Recapture rates

Of the 7565 unique individuals tagged with a uniquely coded T-bar anchor tag, a total of 1261 individuals (16.7%) were recaptured throughout the study (Supplementary Table 5). Of these recaptures, 992 (13.1%) were unique individuals, with more than three-quarters of the recaptured individuals caught on multiple occasions. A strong pattern was observed with the raw recapture rate of sub-legal-size lobsters in the "Low-catch" zone being approximately half of that within both the "Boundary" and "Mid" locations and a quarter of that found in the "Control" location (Supplementary Table 7). For the legal-size raw recapture rates a similar pattern was found, except for the "Mid" control location which displayed comparable recapture rates to the "Low-catch” zone. Unexpectedly, we found considerable along-shore movement of tagged sub-legal sized lobsters between study locations (up to 20 km), therefore the planned formal mark-recapture analyses were not attempted due to violation of the assumptions of closed, spatially explicit populations.

Mean length frequency

Migratory ‘white’ life stage

The most parsimonious model for the mean length of the ‘white’ life stage explained 20% of the deviance and included location, sea surface temperature and swell period (Table 5). The mean length of this migratory ‘white’ life stage was greater within the “Low-catch”, “Boundary” and “Mid” location compared to the “High-catch” location, with the majority of ‘white’ individuals greater than legal size (>76 mm, Figure 15). Importance scores indicated that swell height had a low importance for predicting the mean length per pot for the ‘white’ life stage, whereas, location, sea surface temperature and swell period were relatively more important (Figure 13b).

Table 5 Best-fitting Generalised Additive Mixed Models for the mean average length per pot for the resident ‘red’ and migratory ‘white’ life stages of P. cygnus. Ordered by parsimony, including the difference between the lowest reported AIC (ΔAICc), AIC weights (ωAICc), explained variance (r^2), and the effective degrees of freedom (edf).

Colour	Model	ΔAICc	ωAICc	r^2	edf
White	Location + Sea surface temperature + Swell period	0.000	0.562	0.201	28.58
	Swell Height + Location + Sea surface temperature	0.597	0.417	0.201	27.35
Red	Location + Sea surface temperature + Swell period	0.000	0.991	0.125	79.57

Resident 'red' life stage

The most parsimonious model for the 'red' life stage size class explained 12% of the deviance in the response variable and included the predictor variables; location, sea surface temperature and swell period (Table 5). For this resident 'red' life stage there was a higher mean carapace length found in the "Low-catch" and the "Boundary" location, with the "Mid" and "High-catch" locations demonstrating a comparably lower mean carapace length (Figure 15). Importance scores indicated that swell height had a very low importance for predicting the mean length per pot for the red life stage, whereas location, sea surface temperature and swell period were more important (Figure 13b).

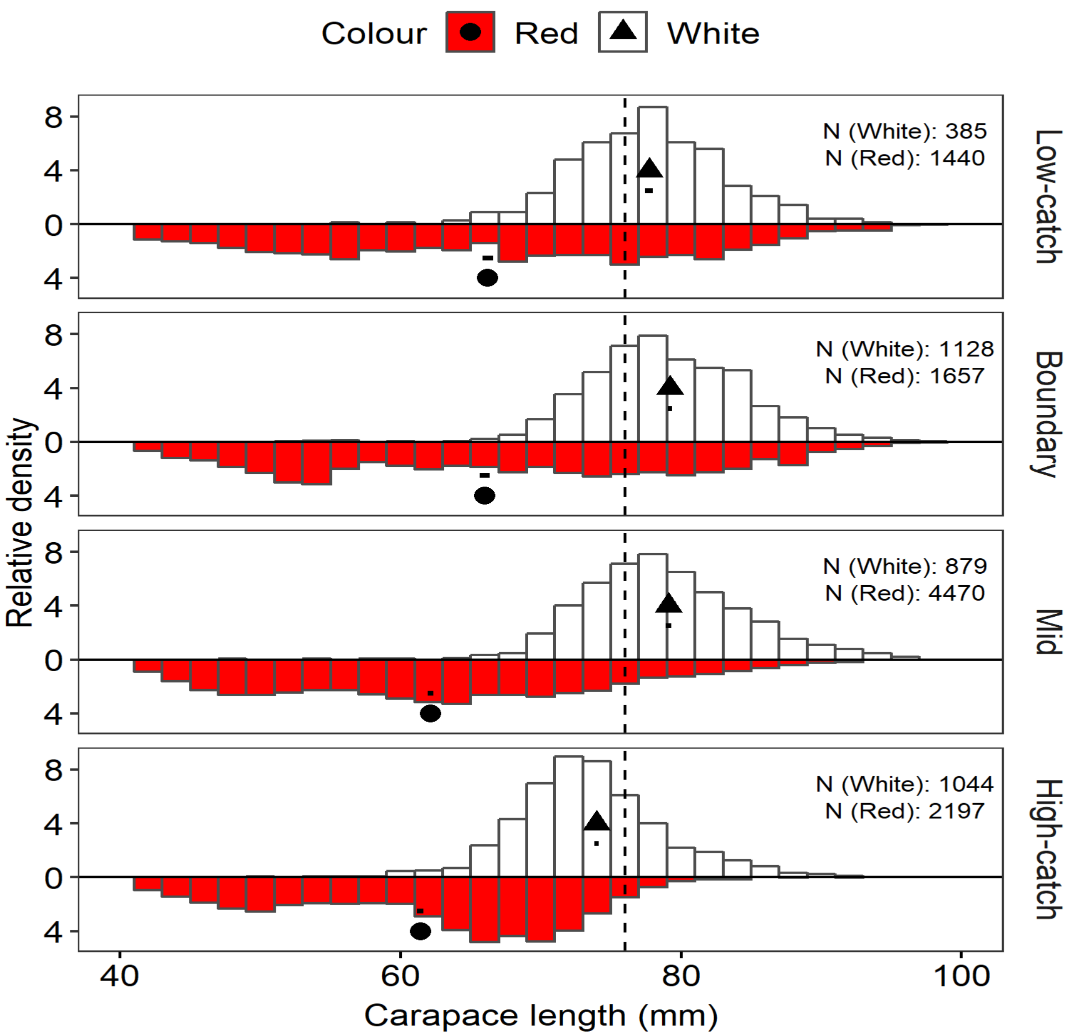

Figure 15 Relative density of P. cygnus by carapace length (mm) for the resident "red" (red) and migratory "white" (white) life stage for each of the four reference locations; "Low-catch" (Cliff Head), "Boundary", "Mid" and "High-catch" (Seven Mile). The mean (+/se) for the resident "red" life stage (black circle) and the migratory "white" life stage (black triangle) are displayed. The legal size (76 mm) is indicated by the dashed line.

Comparison of growth curves

The chi-squared maximum likelihood ratio tests on the growth coefficients obtained from the modified Fabens growth model found that growth rates varied significantly between locations ($p < 0.02$) but not between lobster sex ($p = 0.4$, Figure 16). Inspection of the residuals for each term in the Fabens found acceptable distribution of residuals supporting the model (Figure 18). Pairwise comparisons of growth rate between locations found that individuals in the "Low-catch" location grew significantly faster than the "Mid" ($p < 0.01$), but no significant differences were found between the "Low-catch" and the "Boundary", or the "Boundary" and "Mid" locations.

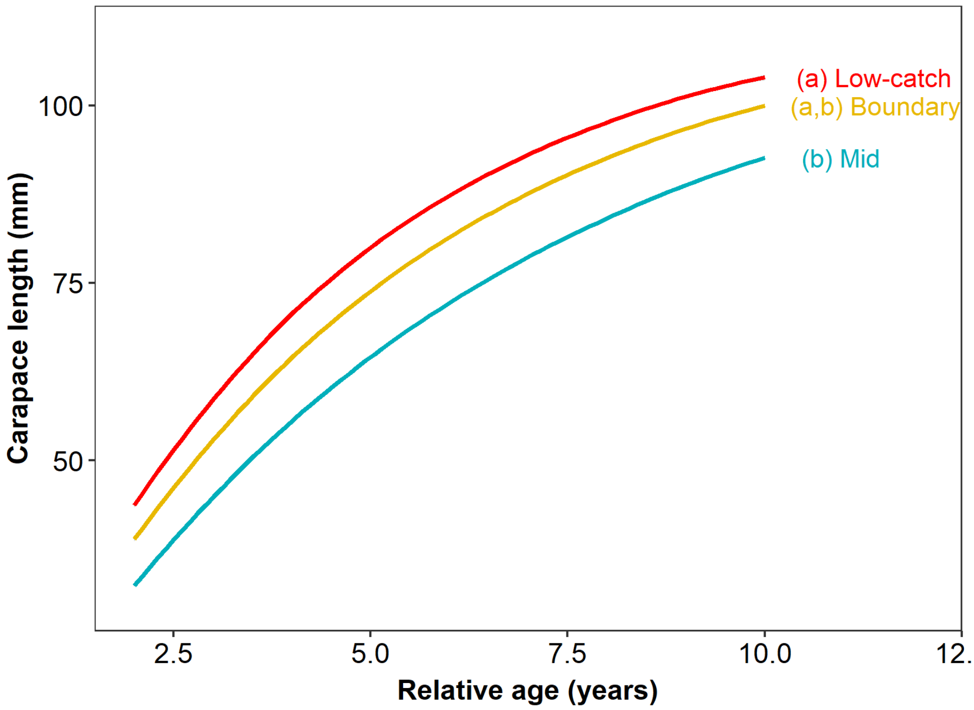

Figure 16 Comparisons of growth curves generated from parameter estimates using Fabens (1965) modification of the traditional von Bertalanffy growth equation model between three study locations; "Low-catch" (red line), "Boundary" (orange line), and "Mid" (blue line). Pairwise results are indicated by an alphabetic character.

Discussion

Our study confirmed the existence of an area of significantly lower standardised catch rates for sub-legal sized lobsters at the centre of Western Rock Lobster fishery. The area was identified to have previously supported high fishing activity and high catch rates between the 1970's and 1990's (*Pers. Com*. John Fitzhardinge). In contrast, the catch rates for legal sized lobsters were comparable across all perceived "Low", "Boundary", "Mid" and "High" catch areas. Additionally, recapture data revealed an unexpectedly high movement of individuals between our study locations (up to 20 km), particularly from the "Low-catch" area, for both sub-legal and legal-sized lobsters.

Movements of these distances have not previously been observed in comparable studies, and thus further research should be conducted to explore this pattern. Furthermore, recaptured lobsters in the “Low-catch” zone had the fastest growth rates relative to other areas. These results suggest fisher’s perceptions of catch rate could be more reflective of sub-legal size lobster populations or that these populations of sub-legal lobster represent the potential and sustained future legal catch rate of the area which fishers are perceiving through observation of low numbers of sub-legal lobsters.

In contrast to the fishers' perceptions, the current study found the catch rates of the legal-sized lobsters to be comparable between all four study locations. Previous studies have reported that flexibility and adaptation in fishing behaviours results in hyperstability in both fisheries dependent and independent data for a target population (Ward et al. 2013). Discussions with fishers at the pre-study workshop and during this current study indicated that hyperstability has occurred, with commercial fishing pressure lowest in the “Low-catch-zone” and highest in the “Mid” and “High-catch” locations for at least the last 20 years. Spatial data on commercial catches collected by DPIRD is unfortunately not of fine enough spatial resolution to demonstrate such small-scale changes in fishing effort (Gaughan and Santoro 2018). Regardless, given this apparent strong gradient in fishing pressure across the locations sampled, the comparable legal-sized catch rates between the locations support the perception that the “Low-catch” zone would have lower sustained catches of legal-sized lobsters if the fishing pressure was higher.

Comparison of raw-recapture rates indicate a strong contrast between the study locations. For both sub-legal- and legal-size lobsters the lowest recapture rate was found within the “Low-catch” zone at Cliff Head, with recapture rates generally increasing with increasing distance from the “Low-catch” zone. This trend was particularly evident in the sub-legal-size class, with the “Boundary” and “Mid” locations displaying a two-fold increase, and the “High-catch” location a four-fold increase in recapture rates compared to the “Low-catch zone”. Interestingly, the recapture rates for the legal-size class displayed a similar trend except for the “Mid” location, which had a recapture rate comparable to the “Low-catch” location. We suspect that the low recapture rate for legal size lobsters within the “Mid” location are due to the increased commercial fishing pressure that was observed over the study. Despite approaching and encouraging commercial fishers to submit recapture data via the DPIRD “tagging” app and release any tagged individuals caught, it was expected that not all will be consistently recorded or released which would contribute to a low rate of recapture.

Similarly, the mean carapace length of the migratory life stage, known colloquially as the “whites”, differed between locations. There was a greater mean carapace length in the “Low-catch”, “Boundary” and “Mid” location compared to the “High-catch” location. Interestingly, the majority of the size distribution for the “High-catch” location was below the legal-size cut-off (<76 mm), whereas for the other three locations it was above the legal size (>76mm). This greater mean length could indicate a faster growth rate of individuals within these areas of interest, allowing them to reach a larger size before they undergo the ‘whites’ migration. However, these results are likely to be confounded by the greater fishing pressure within the “High-catch” location, as commercial fishing would act to remove any individuals greater than 76 mm carapace length, which is evident by the truncated size distribution at legal size in this location. Additionally, swell period was shown to positively influence the mean carapace length of both the ‘white’ and the ‘red’ life stages. Increased swell activity has been shown to increase the activity of lobsters the following day, due to the stronger water movement disturbing the bottom habitat and increasing food availability (Srisurichan et al. 2005). It is therefore plausible the greater mean carapace length for the whites is due to (i) the greater likelihood of catching larger individuals at a certain locations due to greater swell increasing the activity of lobsters for the location, (ii) greater growth from increasing feeding and/or moulting events are resulting in a higher proportion of large lobsters within certain locations, or (iii) fewer larger individuals are located at areas that undergo higher fishing pressure resulting in a disproportionate population structure.

Comparison of the modelled growth curves derived from the recapture data should provide a comparison that is less confounded by fishing pressure compared to any analysis of mean length. Our study indicated that individuals from the ““Low-catch” zone had a significantly faster rate of growth over the sampling period compared to the “Mid” location. These growth results support the findings from a previous tagging study conducted by Chittleborough (1974), and a SCUBA diver survey conducted by Jernakoff et al. (1994), who both demonstrated faster growth rates of juvenile *P. cygnus* within the same location as the “Low-catch” zone (Cliff Head) compared to the more northern “High-catch” location used in the study (Seven Mile Beach). Unfortunately it was not possible to use the growth data from the “High-catch” location in our study due to seasonal differences in the survey times as temperature has been shown to significantly affect growth of *P. cygnus* (de Lestang and Melville-Smith 2006). Additionally, the growth rates recorded at Cliff Head in our current study are comparable to those recorded in aquaria-reared *P. cygnus* that were fed on a highly nutritional diet and reared in optimal conditions (Chittleborough 1974). Chittleborough (1976) suggested that the higher growth rates found at Cliff Head was attributed to the higher invertebrate component found in the Cliff Head population diet compared to the diet found at Seven Mile Beach. Regardless of the cause, our analysis found high growth rates that are comparable to those recorded in a study conducted over 40 years ago within the same “Low-catch” location (Cliff Head). Importantly, these current growth rates are comparable to a time when, according to fishers, the “Low-catch” location produced high catch rates, supported a large number of fishers, and had a much higher fishing pressure.

There are four main competing hypotheses which could explain the observed variations in catch rates across the study locations; the locations vary in (i) catchability, or the relative density of lobster populations at these locations differ due to (ii) recruitment limitation, (iii) post-recruitment movement patterns, or (iv) post-recruitment mortality. These hypotheses are discussed below.

The catchability of lobsters could confound catch rate estimates across the locations of interest as the ability to capture a lobster has been shown to be influenced by a wide range of environmental, behavioural and physiological factors, with each factor also shown to interact with each other in complex ways (Ziegler et al. 2002, 2003). The additional evidence of faster growth rates within the “Low-catch” zone, suggests that food availability is relatively higher and/or has a higher nutritional content, which in turn would decrease the likelihood of a lobster entering a pot (Ziegler et al. 2002). This could be attributed to a lower density of lobsters resulting in abundant food resources that are not found at the other locations. Conversely, research conducted in the 1970’s (Chittleborough 1976) both found the same high growth rates within the same location now known as the “Low-catch” zone, so other factors that influence catchability across the study locations cannot be ruled out. There are obvious limitations associated with utilising commercial fishing techniques as the only methodology to interpret the natural population structure of a species. The most recent study conducted within the area that utilised an alternative sampling technique was Jernakoff et al. (1994) over 20 years ago. The study used SCUBA surveys to explore the population densities of juvenile *P.cygnus*, and reported higher densities of juveniles at the Seven Mile Beach site compared to the Cliff Head site. Despite supporting our results, the study also acknowledged the methodology’s low accuracy and potential of underestimating the population size. This study recommends that future research utilises other technique, such as diver surveys and underwater cameras surveys, to limit deduce unconfounded data.

Recruitment limitation in the “Low-catch” zone may have resulted in the observed differences in catch rates within the fishery. Several environmental factors have historically been shown to strongly effect puerulus recruitment settlement within Western Australia. In particular, the strength of the Leeuwin Current, which brings warm waters southwards along the edge of the West Australian continental shelf, has been shown to be positively correlated with puerulus settlement (Caputi 2014).

However, ongoing studies using standard puerulus collection methods suggest that recruitment limitation is unlikely to be a factor in this region. This current ongoing research has recorded comparable recruitment levels between the “Low” and “High” catch locations (Brooker 2022).

Analysis of the recapture data revealed unexpectedly high levels of fine-scale movements of individuals between the study locations outside of the migratory time of year. Movements up to 20 km were recorded for some individuals, with the “Low-catch” area associated with the highest level of movement for both sub-legal and legal-sized lobsters. Previous fine-scale tracking studies have shown that *P. Cygnus* are typically sedentary species that display great retention within their home range, only traversing distances of <500m when foraging (MacArthur et al. 2008). These unusual movement patterns identified within our study are therefore unlikely to be related to normal foraging alone, and instead could be indicating unsuitable habitat or food abundance within the “Low-catch” location. These apparent high levels of emigration occurring from the “Low-catch” location could also be an attributing factor for the low catch rates and low recapture rates within the location. The contradictory findings of low recapture rates within the “Low-catch” zone, usually indicating high population density, could also be explained by the high levels of movement, as higher emigration from a location would subsequently result in low recapture rates.

High levels of post-recruitment mortality within the “Low-catch” location may explain the identified low catch rates of sublegal lobsters within the location. *P. cygnus* in their first-year post-settlement benthic stage have been shown to experience the highest levels of natural mortality (Phillips et al. 2003). Predation has been recorded as the main cause of natural mortality, with the smaller post-settlement stage particularly susceptible to predation. Evidence suggests up to 80% lobsters do not survive the first-year post-settlement stage, with majority of this due to predation. Various species have been identified to predate on small post-puerulus lobsters from historical studies of the diets of fish species at Seven Mile Beach (Howard 1988). There is a lack of data on fine-scale variations of predator density and activity between our study locations. However, it remains plausible that the “Low-catch” area may be associated with a higher level of predation and further research needs to be conducted.

Marine heat waves have been identified to impact the settlement survival and success of benthic invertebrate species. The extreme marine heatwave which occurred in the austral summer of 2010/2011, affecting approximately 2000km of W. A’s coastline, has been shown to indirectly effect the fishery (Caputi et al. 2019). Previous studies have utilised the abundance of the sublegal lobster population 3-4 years after the heatwave to evaluate the impacts to the puerulus and juvenile phase of the life cycle. Studies on the population abundance in Kalbarri, further north of our study area, have indicated long-term impacts with no sign of recovery evident after 7 years (Caputi et al. 2019). However, locations assessed closer to our study locations, such as the Jurien region, have demonstrated abundance levels to pre-marine heatwave conditions. Given that the low catch zone was identified prior to the marine heat wave, and no significant changes to the population was experienced within the life cycle since, it is unlikely that the marine heat wave has contributed to the existence of the low catch zone. There is potential that the shift in temperatures has impacted other aspects of the zone's ecosystem, which is indirectly impacts the lobster abundance there. However, more research is required to investigate this.

Conclusions

Overall, our study obtained strong, but clearly contrasting observations on the catch rate, growth, and raw recapture rates of sub-legal-size lobsters across the four study locations. The study confirmed that the "Low-catch" zone, within the near-shore shallow water habitat at Cliff Head, is characterised by populations with lower-than-expected catch rates of sub-legal lobsters, faster growth rates and higher levels of fine-scale movement patterns. This study investigated the main hypotheses which may be contributing to these fine-scale variations in catch rates within the centre of the fishery: low catchability, recruitment limitations, high post-recruitment movement patterns, or high post-recruitment mortality. A crucial component is distinguishing whether the lower catch rates of sub-legal lobsters are associated with a lower population density, from low recruitment or high post-recruitment movement and mortality, or simply due to a lower level of catchability. The latter being evidently difficult to disentangle for this study due to the reliance on commercial fishing methodologies. This study aimed to provide an insight into the biological and environmental factors which may be driving the catch and growth rates of *P. cygnus.* Furthermore, the study was designed to explore a trend that had only previously been anecdotally identified by commercial fishers within the region. Confirmation of the existence of the low catch rate within the "Low-catch" zone has emphasised the importance of transparent communication between researchers and relevant stakeholders when it comes to relevant management decisions. This study should be used as a starting point for further research to comprehensively understand the processes may be driving such patterns and whether these mechanisms pose any threat to the sustainability of the fishery in future.

Authorship contribution statement

Ash Miller: Writing – original draft, Formal analysis, Data collection, Data curation, Visualisation. **Emily Lester:** Writing- second draft, Writing- reviewing and editing. **Simon de Lestang:** Conceptualization, Formal analysis, Supervision, Writing -review and editing. **Jason How:** Writing- review and editing. **Brooke Gibbons:** Data collection, Data Curation, Formal Analysis. **Matt Navarro:** Formal Analysis, Writing- reviewing and editing. **Tim Langlois:** Conceptualisation, Formal Analysis, Supervision, Writing- reviewing and editing. **Michael Brooker:** Conceptualisation, Data collection, Data curation, Writing- reviewing, editing and final draft. **John Fitzhardinge:** Conceptualisation, Data collection, Writing- reviewing and editing.

Data Availability

Data used by this study is available here after registration by email.

Animal ethics approval

The work conducted for the study was undertaken under animal ethics protocol "RA/3/100/1550 Catch and release of Western Rock Lobster Panulirus cygnus in an area of unexpectedly low catch rates" approved by the University of Western Australia (UWA) Animal Ethics Committee (AEC) on 12 October 2017.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary Material

Figure 17 a) Wooden “mesh-enclosed” commercial pots used to capture Western Rock Lobsters, P. cygnus, in the study; b) The tag applicator used to tag individuals in the study and; c) a tagged male rock lobster with a unique 50 mm T-bar anchor tag inserted on the ventral side. Source: Hallprint™, Australia.

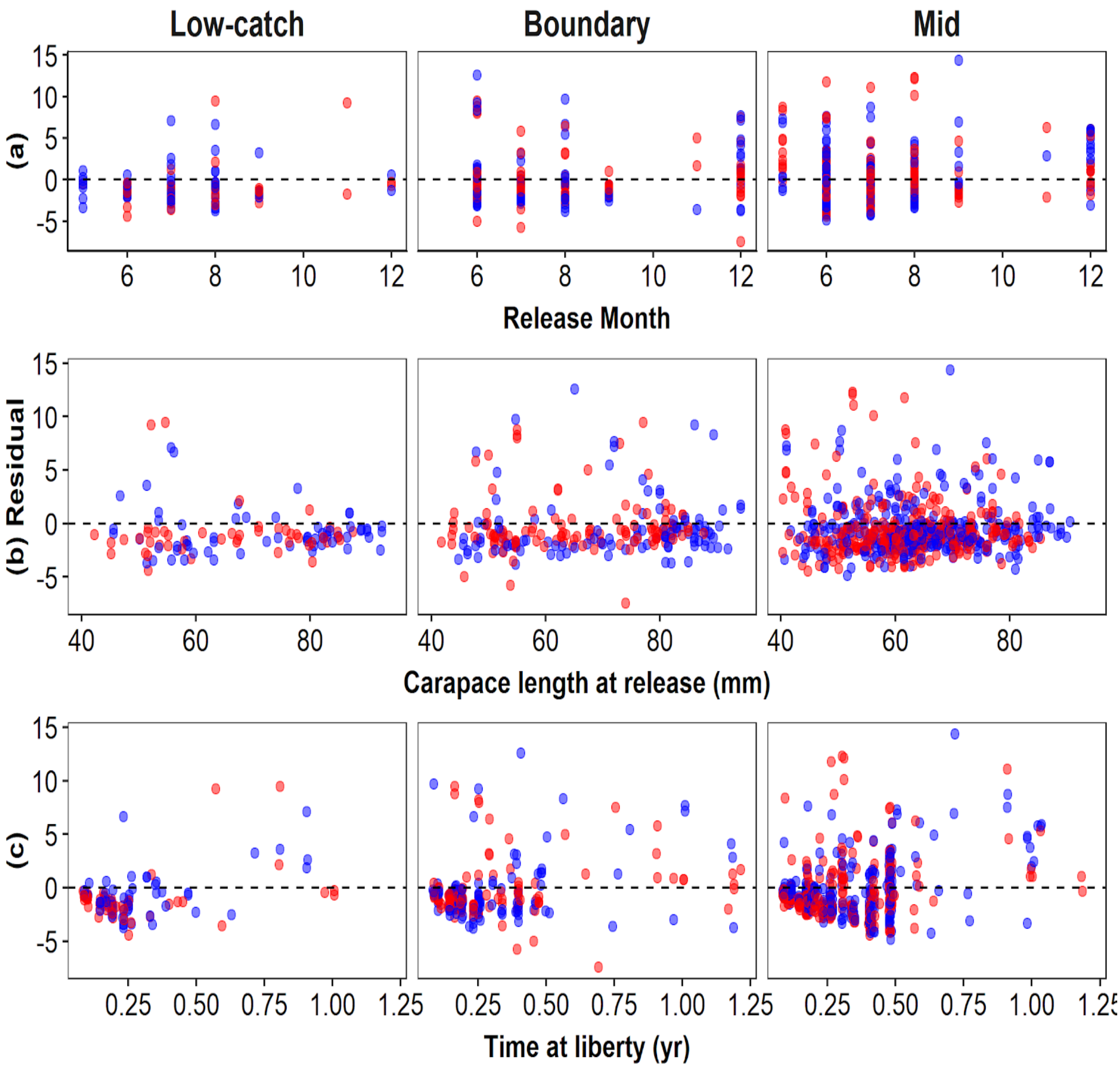

Figure 18 Residual plots for; (a) release month, (b) carapace length (CL mm) and (c) time at liberty (years) for both females (red circles) and male (blue circles) recaptures obtained from the three sampling locations; "Low-catch" (Cliff Head), "Boundary" and "Mid".

Table 6 Total numbers of tagged, recaptured and recapture rates for each study site from a) the current study conducted in 2018, b) a previous UWA tagging study from 2017 and c) a tagging study at Seven Mile site conducted by the Department of Fisheries throughout 2018.

Site	Total pot pulls	No. tagged & released	No. recaptured	% Recaptured
a) UWA 2018:				
Seven Mile	19	339	17	5.0
Rivermouth	5	74	0	0.0
Irwin Reef	269	2496	634	25.4
White Point	249	1169	176	15.1
Little Horseshoe	216	979	71	7.3
Cliff Head	555	1588	127	8.0
Golden Ridge	148	919	236	25.7
Total	1461	7564	1261	16.7
b) UWA 2017:				
Seven Mile	148	1062	53	5.09
Irwin Reef	5	9	0	0.0
White Point	86	217	11	5.1
Little Horseshoe	81	327	37	11.3
Cliff Head	147	67	1	1.5
Total	467	1682	102	6.1
c) Department of Fisheries 2018:				
Seven Mile	74	534	213	39.9
Total	2002	9780	1576	16.1

Table 7 Number of individuals tagged and released, number recaptured and the recapture rate (%) for (a) sub-legal and (b) legal size class sizes caught at the four reference locations; "High-catch", "Mid", "Boundary" and "Low-Catch" between May and November* in 2018. A two tone colour ramp indicates high (green) vs low (red) recapture rates (%).

Study site	No. tagged & released	No. recaptured	Recapture rate (%)
a) Sub-legal (<76 mm)			
High-catch	502	206	41.04
Mid	2453	506	20.63
Boundary	907	204	22.49
Low-catch	953	78	8.18
b) Legal (>76 mm)			
High-catch	27	7	25.93
Mid	475	46	9.68
Boundary	539	78	14.47
Low-Catch	501	46	9.18

*Recapture rates from the December sampling trip were excluded due to potential confounding results from the 'whites' migration.

Study 3 - Oceanographic processes influence the post-larval supply of Western Rock Lobster to an area of low abundance of juveniles

Submitted to Continental Shelf Research

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Abstract

A region of low abundance of juvenile sublegal Western Rock Lobster (*Panulirus cygnus*) has been described in the centre of their biogeographic distribution. *P.cygnus* has a long pelagic larval duration that ends with post-larvae (pueruli) crossing the continental shelf to reach nearshore settlement regions. Variability in the local surface currents suggested that flow patterns may impede the onshore movement of pueruli compared to adjacent Zones with a higher pueruli numbers and increased movement of water onshore. Therefore, it is possible that the supply of pueruli could have created this Low-catch Zone (LCZ). Our research focused on assessing pueruli supply to this region using puerulus collector data and larval dispersal modelling simulations of pueruli. According to the larval dispersal modelling results, the potential settlement of pueruli is significantly higher within the LCZ than adjacent high-catch Zones. Puerulus settlement was highly variable at small spatial scales in the field, although higher in the high-catch zone. This study suggests that settlement supply is unlikely to be the process that explained the LCZ but provides further evidence of variable puerulus settlement on small scales, highlighting that fine-scale flow dynamics in complex coastal features and ecological settlement cues may also have an important role.

Introduction

The distribution of marine species during their early larval stages can have varying consequences through high mortality due to current movements away from recruitment locations (Chiswell and Booth, 2008) or survival through retention in eddy systems (Cetina-Heredia et al., 2019; Hill et al., 1996) and connecting populations (Chiswell *et al.*, 2003; Cowen and Sponaugle, 2009; Nolasco *et al.*, 2018; Pires *et al.*, 2020). Lagrangian analysis of ocean circulation and pathways is an essential tool for understanding these dynamic environments including the nutrients, heat and biological matter within it (van Sebille *et al.*, 2018; Hawkins *et al.*, 2019; Jones *et al.*, 2020). From a practical and theoretical perspective, it forms the backbone of understanding dispersal throughout the ocean at local or vast spatial and temporal scales. Furthermore, understanding these mechanisms for a single species influences their spatial management scales and their likely responses to environmental disturbances or changes (Kvile *et al.*, 2018; Clavel-Henry *et al.*, 2020).

For the *Palinuridae*, or spiny lobster family, the pelagic larval stages greatly influence the ecology of juvenile and adult spiny lobsters. The length of this offshore journey varies between several months (*Palinurus elepha*s) and two years (*Jasus edwardsii*) (Booth and Phillips, 1994), making it vastly longer than other invertebrates (Meyer et al. 2021). Those with long pelagic larval durations can be transported up to thousands of kilometres offshore depending on their behavioural and vertical migration transformations over time (Rimmer and Phillips, 1979; Butler IV *et al.*, 2011). Throughout the stages of pelagic larval stages, spiny lobster larvae (phyllosoma) build up lipid reserves to undergo their final metamorphosis into a puerulus (Wilkin and Jeffs, 2011; Stanley *et al.*, 2015). At this stage, they have developed swimming abilities. Furthermore, they are non-feeding (Jeffs *et al.*, 2005; Espinosa-Magaña *et al.*, 2018), where their biochemical energy reserves help their transport across continental shelves and to reef or seagrass habitats (Phillips *et al.*, 1978).

For the spiny lobster species endemic to Western Australia, *Panulirus cygnus,* their pelagic early larval cycle begins at hatching between September to February each year in depths of 60 to 80 metres (de Lestang *et al.*, 2012). Western Rock Lobster phyllosoma are then transported hundreds of kilometres offshore, where they develop through a series of moults within the eastern boundary current, the Leeuwin Current (LC), and its associated eddy system (Figure 19) (Caputi, 2008; Wang *et al.*, 2015). They are offshore for 8 to 10 months and undergo nine stages of ontogenetic vertical migration before returning to the continental shelf (Feng *et al.*, 2011). The late-stage phyllosoma then metamorphose into nektonic non-feeding pueruli to swim towards the coast before settling into the fishery, gaining colour nearshore and becoming post-pueruli. The puerulus settlement season is between May and April, peaking in the middle of the austral summer (de Lestang *et al.*, 2016; Kolbusz *et al.*, 2021a).

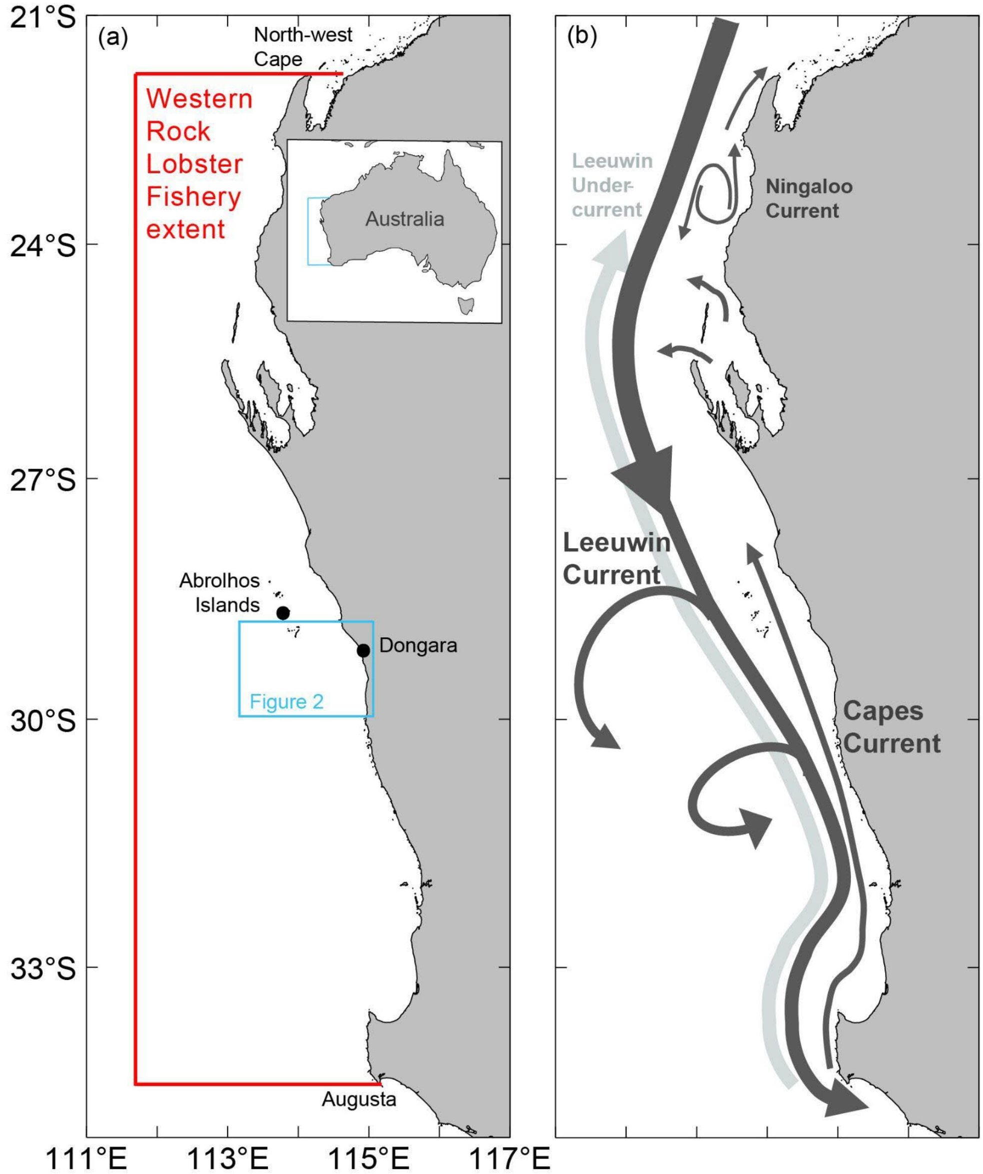

Figure 19 (a) The Western Rock Lobster fishery extent (WRFL) and key locations in the context of Australia, leading to the insert for Figure 20. (b) A schematic diagram of the major currents along the west coast of Australia and their approximate locations. Adapted from (Kolbusz et al. 2021). The extent of the figure is the extent of the larval dispersal model.

Summer oceanographic conditions along western Australia consist of a weaker southward flowing LC offshore and a wind-driven northward-flowing current, the Capes Current (Figure 19b), on the continental shelf at water depths generally < 50 m

(Woo and Pattiaratchi, 2008). As late stage phyllosoma reach the continental shelf, they undergo metamorphosis into swimming pueruli and can swim up to speeds of 0.5 ms^{-1} (Phillips and Olsen, 1975; Phillips *et al.*, 1978; Fitzpatrick *et al.*, 1989). Previous links have shown positive relationships between the strength of the LC and the puerulus settlement index (Pearce and Phillips, 1988; Caputi *et al.*, 2001). However, this relationship has broken down since the period of low settlement in the late 2000s (de Lestang *et al.*, 2015), but nevertheless demonstrates that future recruitment to the fishery is highly susceptible to changes in oceanographic conditions off western Australia (Caputi and Brown, 1993; Caputi *et al.*, 2010; Säwström *et al.*, 2014; Hood *et al.*, 2017).

Since 1968, monitoring the settlement of *P. cygnus* puerulus settlement has indicated subsequent recruitment three to four years later into the fishery when they reach the legal size for capture (de Lestang *et al.*, 2009). Therefore, the monitoring of puerulus settlement has been used to inform fishery management and set allowable total catch settings, helping to ensure the sustainability of this fishery. In particular, through a period of unusually low settlement in the late 2000s, this monitoring program indicated the need for reduced fishing effort, prompting the closure of key spawning ground locations to ensure the sustainability of the fishery (de Lestang *et al.*, 2012). The puerulus settlement monitoring program consists of artificial collectors located at eight sites (Figure 19) across the fishery extent, close to nearshore reef structures with seagrass to exploit their preferential habitat (Phillips, 1972; de Lestang and Rossbach, 2018).

Anecdotal reports of a low-catch zone within the centre of the fishery were confirmed in a fishery-wide survey of fisher perceptions (Brooker *et al.*, 2021) and a small-scale fishery-independent survey (Miller *et al.*, 2019). Miller (2019) found the zone was characterised by a very low abundance of juvenile and sub-legal lobster compared to adjacent relatively high catch areas, and that the area was infrequently fished commercially. The studies by Miller (2019) and (2021) suggested that the low catch rates within the region could be attributed to a reduced supply of settlement.

Specifically, the objective of this research was to determine the oceanographic processes that can contribute to high variability in puerulus settlement patterns within the centre of the biogeographic distribution of the species through field observations and numerical modelling. Three Zones of suspected contrasting settlement were defined based on the differences in the number of juvenile *P. cygnus* populations. Fieldwork consisted of deploying puerulus collectors to monitor spatial and temporal patterns in puerulus settlement. In addition, we conducted Lagrangian larval dispersal modelling, using a three-dimensional hydrodynamic hindcast dataset, to then understand the circulation patterns of the area and whether they constrain pueruli from specifically reaching the contrasting Zones. The combination of these methods provides a deeper understanding of the high spatial variability in Western Rock Lobster post-larval supply.

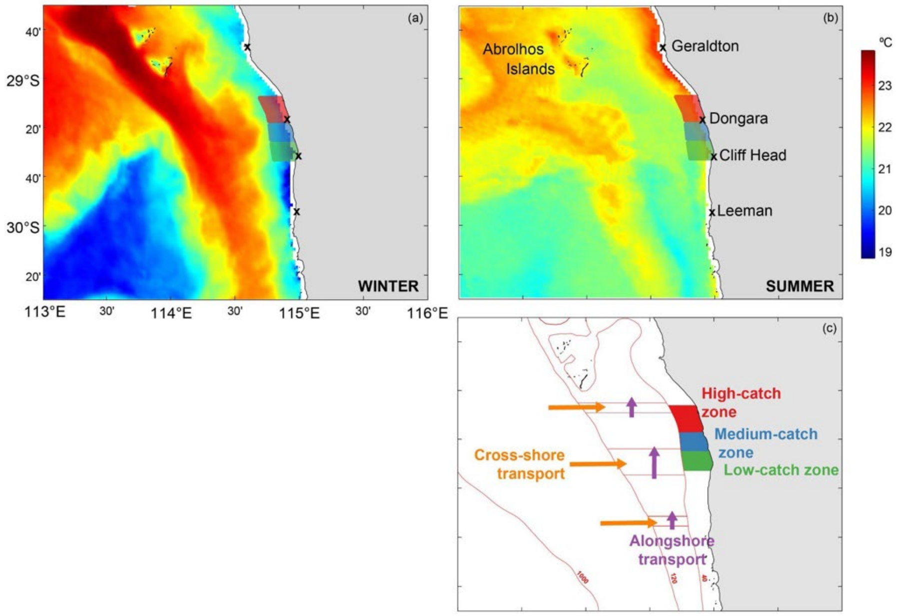

Figure 20 (a) IMOS Winter SST satellite image (30 May 2018, 6-day average) with the Zones b) IMOS Summer SST satellite image (20 January 2018, 6-day average) with Zones and key locations (c) High, medium and low-catch Zones including cross-shore and alongshore explanations and depth contours.

Methods

Zone Definition

The primary motivation for this research was due to satellite sea surface temperature data showing colder water trapped in the shallow areas of the perceived LCZ during both summer and winter (Figure 20). Given the lack of consistent upwelling in the region (Rossi et al. 2013), this suggested that the shallow areas of Cliff Head, 30 km south of Dongara, may be hydrodynamically disconnected from offshore, providing a possible mechanism for reduced puerulus settlement. In addition, from over 50 years of puerulus settlement monitoring by fisheries scientists, it was apparent that Seven Mile Beach, 10 km north of Dongara, and Jurien Bay, 130 km south of Dongara, had higher than mean puerulus settlement rates within the fishery (de Lestang *et al.*, 2012). These suspected strong gradients in puerulus settlement across a relatively small spatial scale provided an opportunity to assess the influence of small-scale (10 km) variation in oceanographic forcing on settlement patterns. This allowed us to define three different Zones of potential variation in puerulus settlement for investigation (Figure 20c). Three Zones of suspected contrasting settlement were defined as high, medium or low catch (HCZ, MCZ and LCZ) based on the likely differences in the number of juvenile lobster populations (Figure 20; Miller et al., 2023).

Puerulus collector data

Puerulus collectors were deployed in October 2017 to investigate spatial and temporal patterns in puerulus settlement. Collectors measured the abundance of pueruli settling within the LCZ relative to the adjacent areas with ongoing settlement monitoring programs. Collectors were checked on or around the full moon during the settlement season, between August and April, providing approximately monthly data. There were at least four collectors at each collector location, consisting of two designs. At the start of the 2018 season (August), additional collectors were added to investigate settlement at additional nearshore reef sites (northernmost site in the LCZ, Figure 21), potentially with more similar hydrodynamics to the HCZ. These data sets were reported as a mean monthly settlement and standard deviation for the collectors in the HCZ and LCZ collectors.

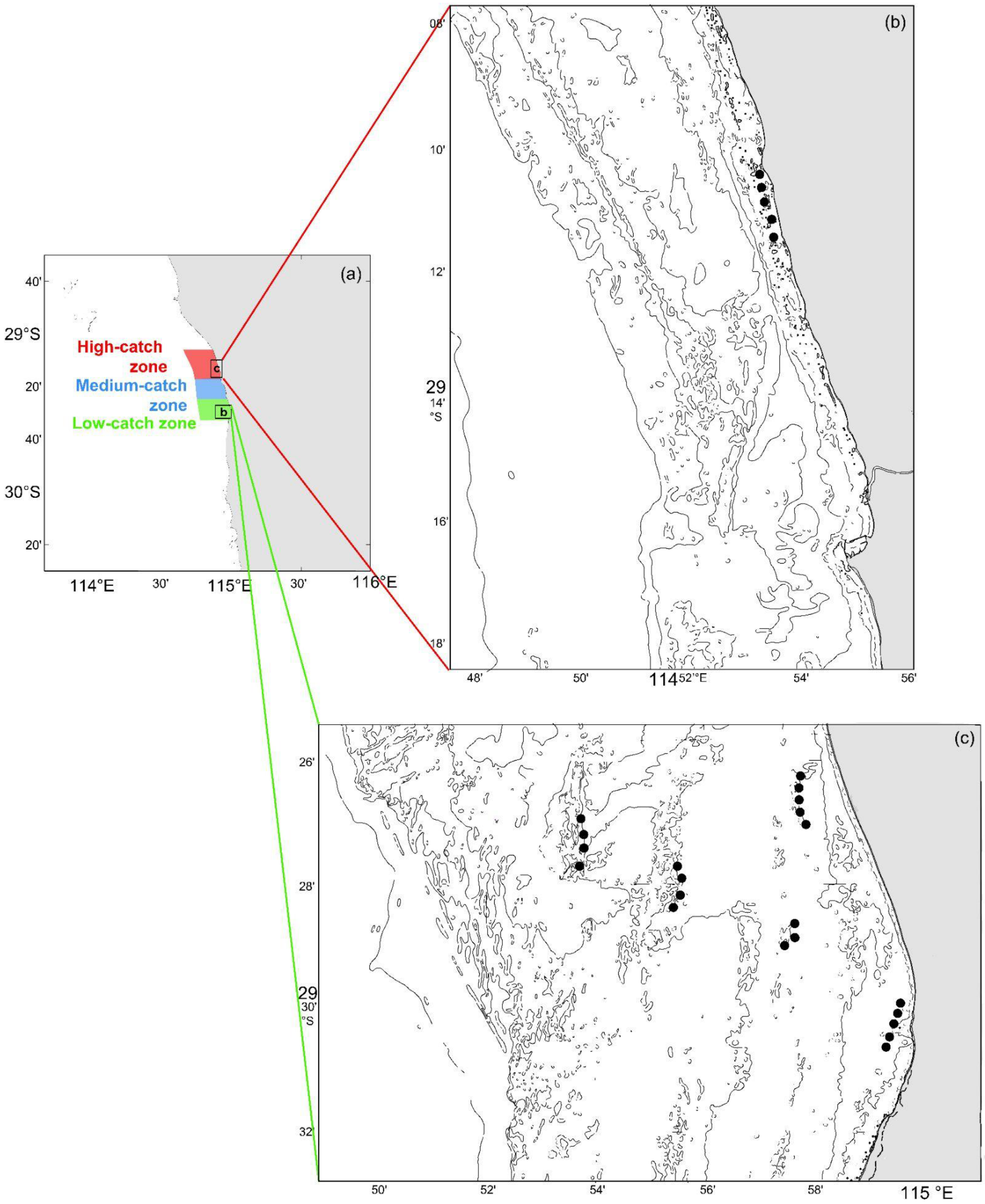

Figure 21 (a) Deployed puerulus collectors locations in the context of the high and low catch Zones between September 2017 to March 2019 (b) High-catch zone deployed collectors with the modified WA963 nautical chart (c) Low-catch zone deployed collectors with the modified WA979 nautical chart.

Hydrodynamic data set: ozROMS

The Regional Ocean Modelling System (ozROMS) has been used in hindcast mode (past time) for Australasian shelf and deep-water regions to resolve subsurface and surface currents and associated volume transports (Wijeratne *et al.*, 2018). This fully three-dimensional circulation model is designed to resolve processes along the continental shelf, including tide, wind, air-sea fluxes, and ocean forcing, setting it apart from other ocean models for the same region. The model grid used here was set at a horizontal spacing of 3 km, allowing for topographic variation to impact the predicted water movement. OzROMS model output, in three-dimensions at hourly intervals, was available for the period 2000-2018 for zonal (eastward) and meridional (northward) velocities, as well as temperature and salinity.

Cross-shelf and alongshore transport (in Sverdrupps (Sv) = 10^6 m^3s^{-1}) of water were calculated from ozROMS data. This was completed for each monthly time step between the depth contours of 120 to 40 meters over the latitudinal bins of the HCZ, the LCZ and south of the LCZ (Figure 21a). In addition, the south of the LCZ was included to understand the general transport conditions throughout the whole area. These were averaged, and the standard deviation was calculated for each month over the 18-year data set to obtain the mean conditions.

Larval dispersal model: Ichthyop

Lagrangian larval dispersal modelling was completed using the open-source larval transport model Ichthyop (Lett *et al.*, 2008). Pueruli data collection provides an instantaneous data set of pueruli existence in the Zones. In comparison, larval dispersal modelling provides transportation pathways from offshore to nearshore over multiple settlement seasons. Therefore, Ichthyop was used to determine whether particles reach the LCZ by tracking the particles' trajectories in three dimensions. This was completed using the hydrodynamic forcing (described above) in the u (east-west) and v (north-south) directions, with w (vertical) velocities calculated within Ichthyop, and simulated using the Runge-Kutta numerical advection scheme with a time step of 15 seconds. The small internal time step was chosen so that the Courant-Friedrichs-Lewy criterion did not occur, causing instabilities when calculating w (vertical) velocities (Lett *et al.*, 2008). The horizontal dispersion rate was set to $1x10^{-9}$ m^2 s^1, as suggested by Peliz et al. (2007) and within the Icthyop user interface (Lett *et al.*, 2008). The "particles", representing *P. cygnus* pueruli who had completed their offshore journey, were released on each ozROMS grid along the continental shelf (200 meter contour) at 40 meters depth between 26^oS and 32^oS. These latitudes and depth of release were chosen based on known distributions and their life-cycle (de Lestang et al. 2012; Feng et al. 2015). Particles were released from September to February, every five days, over the available years due to computational limitations. Available hourly advection data from ozROMS allowed the simulation of eight settlement seasons, 2000-2001 and 2007-12, to be modelled. We simulated only the last phase of the pelagic larval duration, the pueruli. This approach was adopted because the on-shelf variation in particle movement was the focal point alongside computational limits. The effects of the physical environment on the particle were tracked, including but not limited to horizontal advection and tracking of temperature.

Particles were transported with swimming capabilities of 0.05 ms^{-1} towards the coast, undergoing diurnal vertical migration (DVM) to 20 meters depth during the day and the surface at night (Feng *et al.*, 2011). Despite pueruli being able to swim up to speeds of 0.5 ms^{-1}, the model includes consistent swimming therefore a moderate average was chosen (Feng et al. 2011; Caputi et al. 2018). The recording frequency was set to output every 4 hours. If the particles had been moving for more than 21 days, they perished due to their non-feeding state (Feng *et al.*, 2011). Particles that moved outside the open ocean boundary (22^{o}S – 36^{o}S, 108^{o}E – 117^{o}E) were considered out of bounds and removed. The particles were also removed if the temperatures were outside survival limits of 10^{o}C to 26^{o}C.

Particle Flux

Given the horizontal resolution (3 km), we were unable to assess the successful settlement of particles at shallow depths confidently (< 15 m) due to the large number of shallow reefs (Figure 21). Furthermore, the size of each zone of interest (Figure 21) is at a minimum of six ozROMS grid cells. Therefore, we developed a post-processing particle flux algorithm to assess the number of chances that a particle has to settle within each zone along its trajectory. This method of assessing particle flux allows for the movement and potential settlement of pueruli instead of an instantaneous assumption of settlement.

A “chance” to settle or count was added if the particle trajectory went through a zone. Zones were spatially defined similarly to those of Miller (2019). Whether this was for one or several time steps, it was counted as one chance if the particle remained within the zone. If the particle left the zone and then went back into the zone, that was counted as two chances. Therefore, some trajectories may have two or more chances to settle in each zone (Figure 22) until they either beach or are no longer active (> 21 days). The algorithm was applied to all eight years’ simulation outputs, and a mean and standard deviation of the number of chances for each zone was calculated. The proportion of chances for particles to settle only in one zone was also calculated, and the associated standard deviation was calculated. Additionally, if the particle only went in one zone, it was within the proportion of particles entering that zone. Finally, a permutational analysis of variance (ANOVA) (Anderson, 2001) was undertaken to compare the mean number of settlement chances across each zone. This was also conducted for the proportions of the chances of only entering one zone. The ANOVA was completed using the adonis function within the vegan package in R (Oksanen *et al.*, 2020).

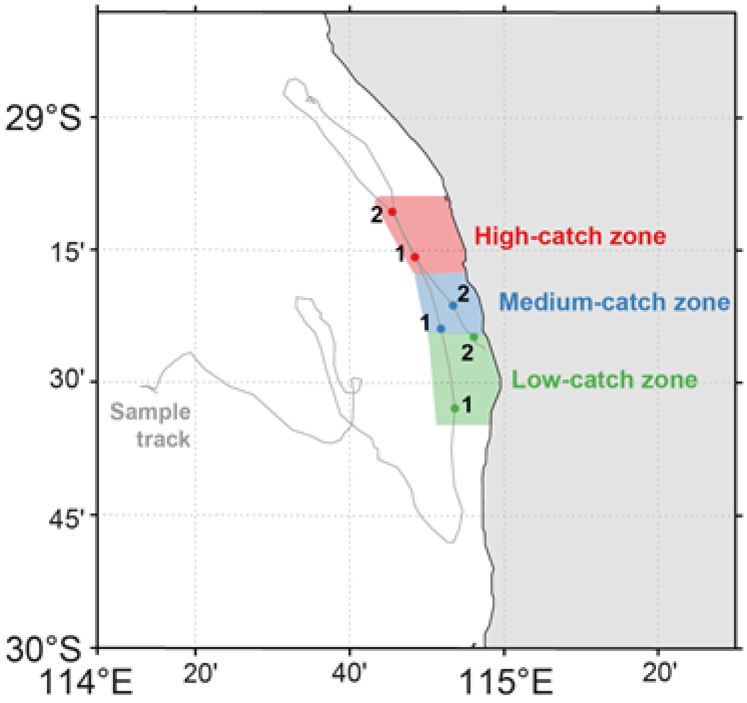

Figure 22 The particle flux method used. This shows an example of a particle trajectory that is transported to eventually being beached. Here, two chances are counted in each of the three Zones.

Results

We used particle zone fluxes to account for unresolved small-scale topographic features within the ozROMS forcing velocities. Particle zone flux was used to produce a “chance” to settle compared to definitively saying that a particle had settled in the zone. Interestingly, the settlement collector data (Figure 23) and the particle flux results (Figure 24-28) provide somewhat contrasting patterns. More puerulus settlement was observed in the high-catch zone (HCZ) in the field. In contrast, larval dispersal modelling results suggest more chances for pueruli to settle in the low-catch zone (LCZ).

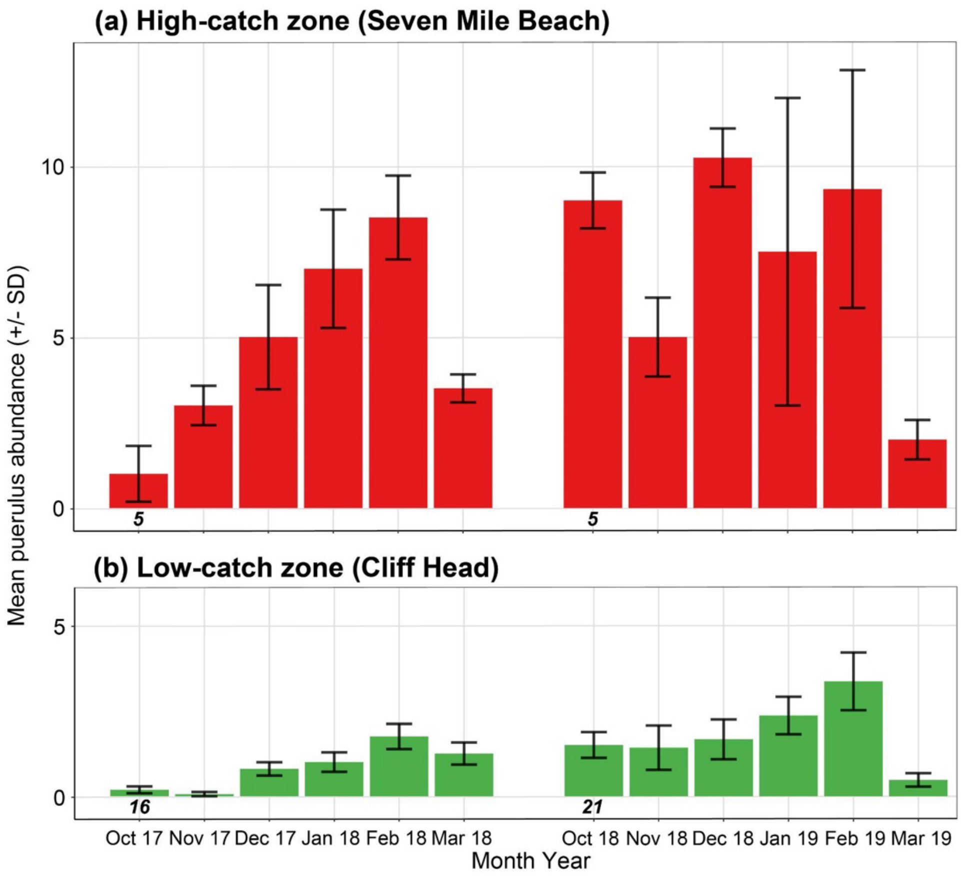

Figure 23 The mean monthly puerulus settlement data from the (a) high-catch zone and (b) low-catch zone. Error bars represent the standard deviation. The bold italicised value indicates the number of collectors used for the season. The northernmost set of collectors in the low-catch zone was only added in 2018.

Puerulus collector data

Puerulus collector data indicate that pueruli reach the LCZ, but these numbers are much greater on collectors in the HCZ, albeit with high levels of variance (Figure 23). After adding additional coastal collectors within the LCZ in the 2018-2019 season, the mean puerulus settlement recorded within the LCZ was greater, particularly in January and February 2019 (Figure 23).

Mean Transport Conditions

The meridional and zonal transport conditions in the Zones depict differing conditions of water transport across and along the shelf. Zonal, or cross-shelf transport, is different within each area (Figure 24), with little monthly variation according to seasonal conditions. For example, average values on the shelf adjacent to the HCZ are near net-zero, suggesting minimal onshore transport. Although the high standard deviation suggests over the winter months, this fluctuates between onshore (eastward) and offshore (westward) transport. In contrast, the shelf area adjacent to the LCZ exhibits predominantly offshore (westward) flow with no distinguishable monthly variation, as indicated by the small standard deviation. Whereas to the South of the LCZ, there is predominantly onshore (eastward) transport with a small increase over the summer months when puerulus settlement would be at its peak.

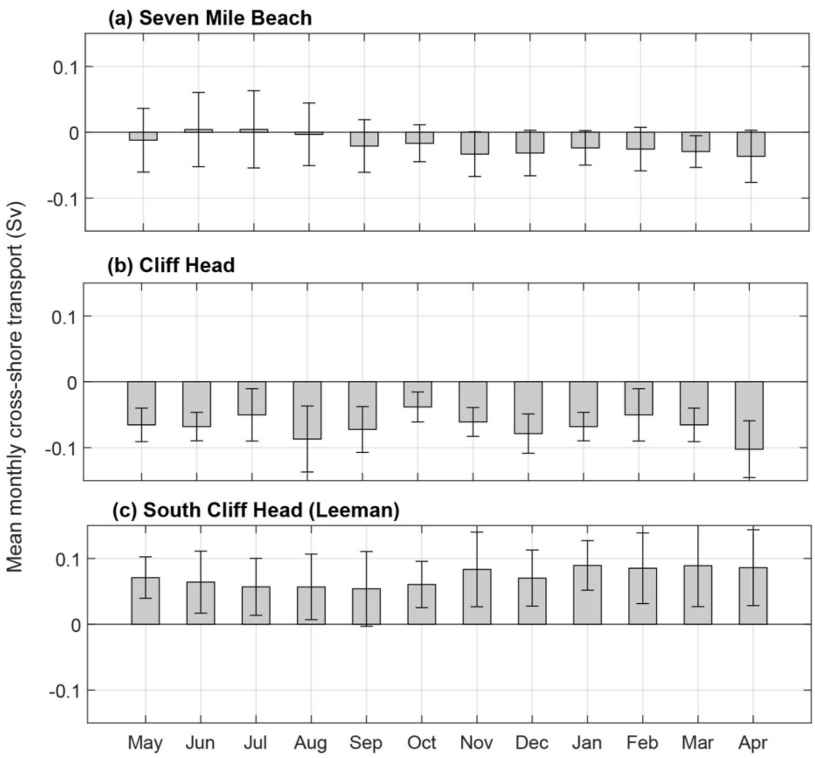

Figure 24 Mean monthly cross-shore transport between the 120 - 40 metre contour at (a) the High-catch zone latitude, (b) the low-catch zone latitude, and (c) south of the low-catch zone. These locations are shown in Figure 22a. Positive values denote eastward transport. They are calculated from monthly ozROMS hindcast data with error bars included as standard deviation.

Alongshore flows exhibit monthly variations consistent with the regional current and wind-driven systems (Figure 25). Across the HCZ and south LCZ latitudes on the shelf, there is a mean negative (southward) flux over the autumn and winter months, aligned with the southward flowing Leeuwin Current (Figure 25a and c). However, the LCZ, which is somewhat indented on the coast and potentially more isolated from the Leeuwin Current, has a mean northward flux during the winter months, presumably due to local wind conditions (Figure 25b). All three Zones exhibit a mean northward flux of water over the summer months, reflecting currents driven by the predominantly south-westerly winds that coincide with the peak period of puerulus settlement.

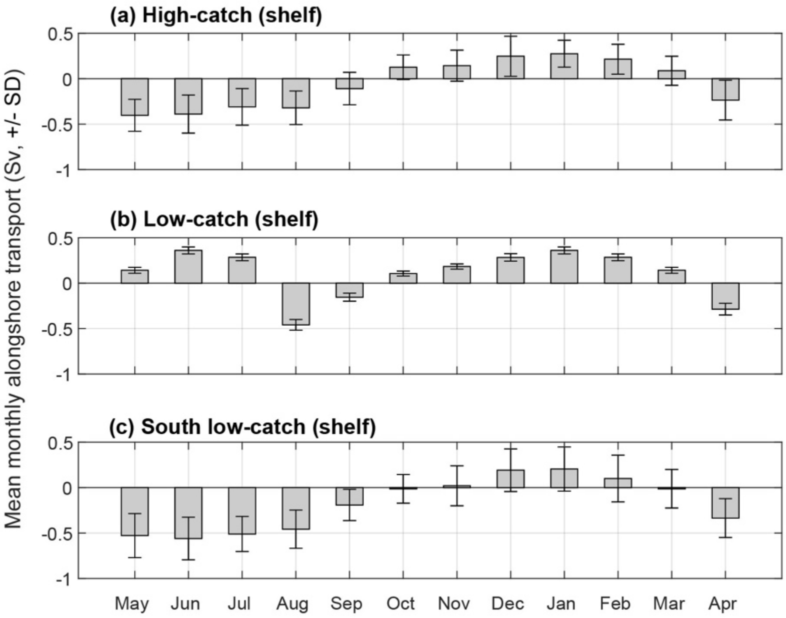

Figure 25 Mean monthly along-shore transport (Sv) between the 120 - 40 metre contour at (a) the High-catch zone latitude, (b) the low-catch zone latitude and (c) south of the low-catch zone. These locations are shown in Figure 22a. Positive values denote northward transport. They are calculated from monthly ozROMS hindcast data with error bars included as standard deviation.

Larval dispersal modelling outputs

The larval dispersal modelling output illustrated that circulation patterns provide substantially greater mean and proportional chances for pueruli to settle in the LCZ than the HCZ. Over the eight puerulus settlement seasons modelled, our particle flux method found that the number of chances particles have to settle within the LCZ is significantly higher ($p < 0.001$, 41%) than those being able to settle within either the medium or HCZ (Figure 26). Furthermore, particles that reach the LCZ are generally (90% of the time) transported from the south and through the LCZ and MCZ (Figure 26). Particles transported only to the MCZ is significantly lower than the LCZ or HCZ (Figure 26). When particles reach the LCZ, 38% of the time, the particle is only transported there. In contrast, only ~8% of particles reach the HCZ (Figure 27), reflecting the minimal onshore transport in that zone described in the mean transport conditions.

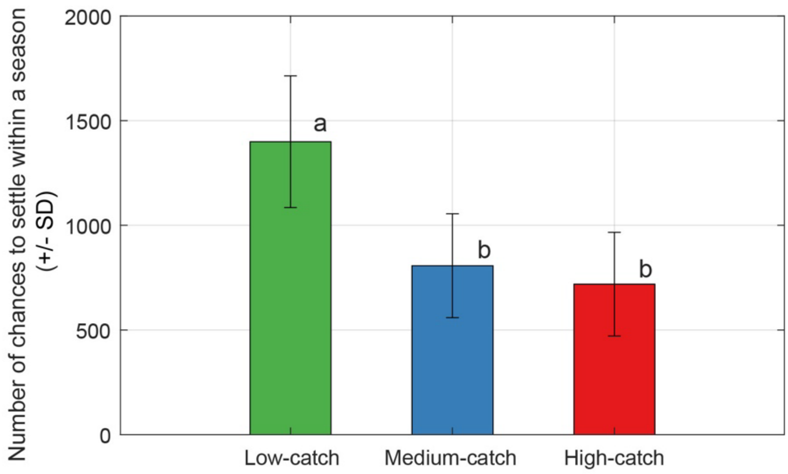

Figure 26 The mean number of chances for particles to settle within each zone (low-catch, medium-catch or high-catch) over the 8 sample settlement seasons. Error bars are the standard deviation. Results of pair-wise comparisons are indicated by alphabetic character ($p < 0.005$).

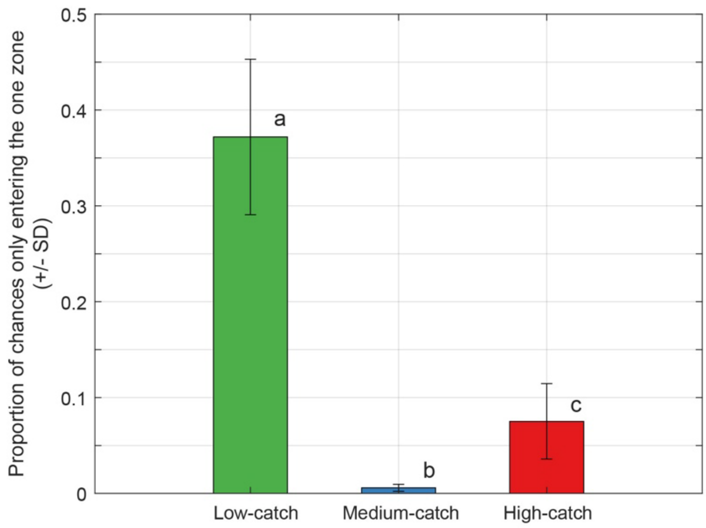

Figure 27 The proportion of the chances to particles settle only within the single zone (low-catch, medium-catch or high-catch) over the 8 sample settlement seasons. Error bars are the standard deviation. Results of pair-wise comparisons are indicated by alphabetic character ($p < 0.001$).

Tracking particle pathways shows that particles arriving within the LCZ usually originate from release points, as proxies for transport of offshore larvae, further north (Figure 28). Pathway analysis shows how particles typically travel southward, correlated with the flow of the Leeuwin Current. As they reach nearer to the coast, they shift to being transported northward, correlating with the wind-driven Capes Current on the shelf. In some years, this is near 30^{o}S (Figure 28 a, c, d, and f), whereas in others, there is movement north and south before eventual settlement in the area

(Figure 28 g and h).

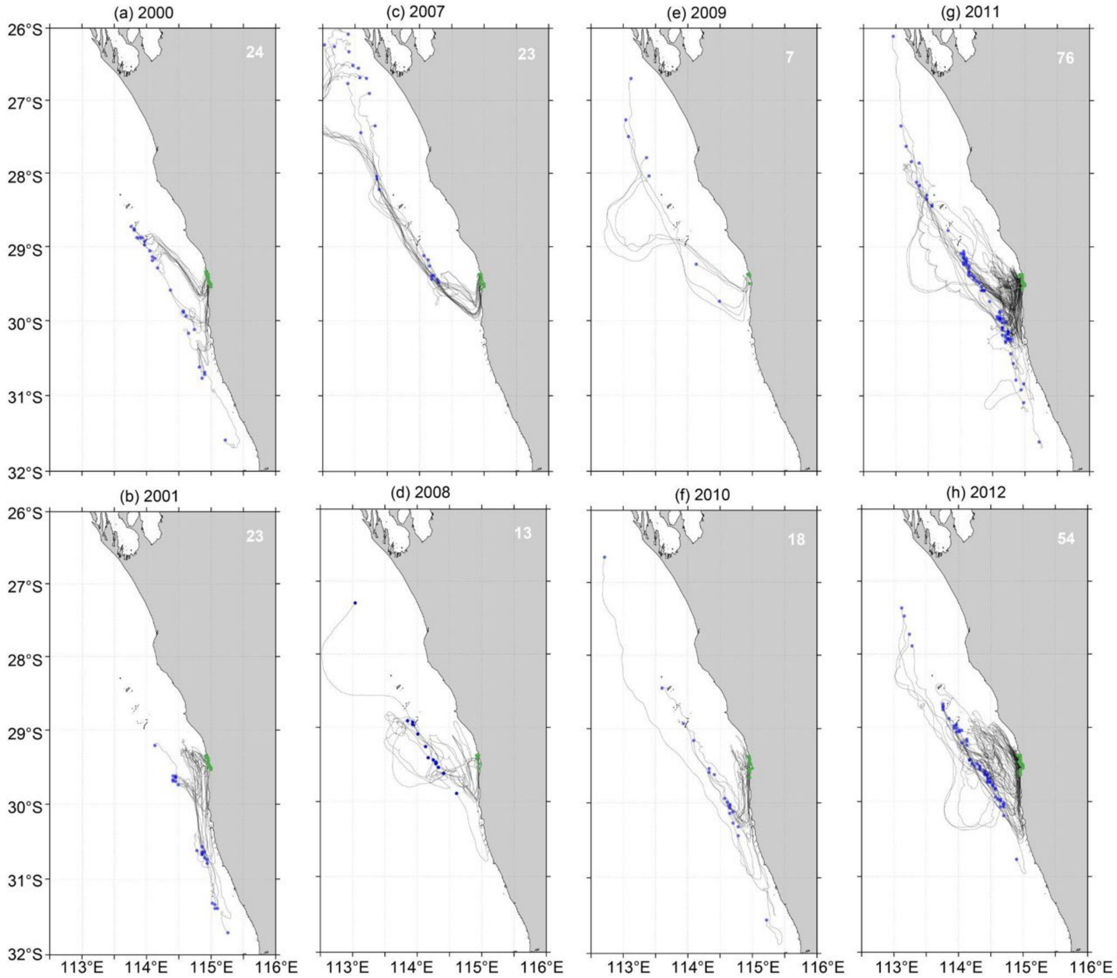

Figure 28 Trajectories of particles that end in the Low-catch zone over the 8 sample settlement seasons (a) 2000, (b) 2001, (c) 2007, (d) 2008, (e) 2009, (f) 2010, (g) 2011 and (h) 2012.

Discussion

Contrary to our expectations, the numerical simulations (larval dispersal modelling) in the current study found no evidence that post-larval supply contributes to the occurrence of a low-catch zone (LCZ) in the centre of the Western Rock Lobster biogeographic range and fishery. Whereas field observations encountered a high level of variability in settlement both between sites and within sites (between individual collectors) and was able to confirm that puerulus are settling over the LCZ albeit potentially at lower levels compared to areas immediately adjacent to the north (HCZ) and south. Despite the relative oceanographic isolation of the LCZ, this study has demonstrated that the area likely receives substantial post-larval supply and likely more than adjacent high catch areas. Therefore, the observations by Miller et al (2003) and documented in Study 2, which found unusually low numbers of sub-legal and juvenile lobster within this defined LCZ, in contrast to adjacent high catch areas, could be due to post-settlement mortality and growth processes (Meyer *et al.*, 2021).

The addition of five additional collectors to the LCZ in 2018 provides an insight into the spatial variability of the puerulus collectors. Although these additional collectors were only a few hundred meters north of an existing site, there was a substantial increase in the mean number of pueruli at the site. Similarly, with the Seven Mile location, where fisheries scientists have monitored pueruli since 1968, a single collector frequently collects a much greater number of pueruli than those nearby (de Lestang *et al.*, 2012). The numbers of puerulus collectors for spiny lobster species have been shown to increase where collectors are in direct influence of water flow (*P. argus)* (Ward, 1989; Gutierrez-Carbonell *et al.*, 1992), and lower water clarity (*J. edwardsii*) (Booth and Phillips, 1994). The fine spatial scale (order of 10m), but consistent variability in collector pueruli numbers observed including in other comparable studies (Eggleston *et al.*, 1998; Booth *et al.*, 2000; Booth, 2001; Phillips *et al.*, 2001), suggests that there are fine-scale oceanographic, or ecological cues which influence settlement at a localised scale within our study Zones.

There are inherent uncertainties regarding Lagrangian larval dispersal modelling, as it is forced by 3D hydrodynamic data (ozROMS) with its own assumptions, alongside assumed larval behaviour. However, the mean oceanographic conditions when pueruli reach the nearshore over the summer season corroborate the findings of the larval dispersal model (Figure 29). Generally, particles are transported from offshore waters, north of the Zones, before crossing the shelf at a more southern point, to be then driven northward by wind-driven flows to settle in these Zones. The Leeuwin Current (LC) is generally weaker in the summer (Wijeratne *et al.*, 2018) but continues to flow along the continental slope (~ 200 metres). As the LC becomes weaker further southward in the summer, the northward-flowing Capes Current (CC) and the swimming abilities of the pueruli assist its transport to the nearshore (Pearce and Pattiaratchi, 1999; Pearce and Phillips, 2011). This further emphasises nearshore wind-driven flows along the west coast and their potential role in puerulus settlement.

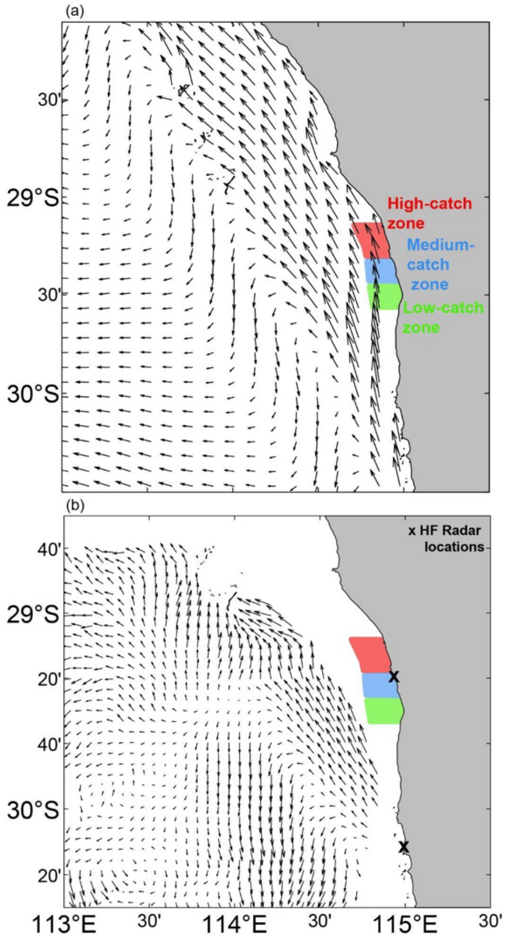

Figure 29 (a) The mean surface currents over October to February between 2000 and 2018 from ozROMS predicted hindcast data (Wijeratne et al., 2018) (b) The mean surface currents over October to February in 2019 and 2020 from HF Radar installed by IMOS *(Cosoli* et al.*, 2020)*. Both (a) and (b) include the High, Medium and Low-catch Zones indicated by the different colours.

Wind-driven surface currents on the continental shelf have previously been underestimated in larval dispersal models of the complete *P. cygnus* larval cycle (Feng *et al.*, 2011). This was due to the coarser-resolution models that did not adequately resolve the width of the continental shelf. Therefore, previous studies included Stoke's drift to ensure particles were not driven southward by the LC (Feng *et al.*, 2011; Caputi *et al.*, 2018). However, our results suggest that the cross-shelf flows at the specific latitudes of settlement are not indicative of local puerulus settlement (Pearce and Phillips, 1988; Fitzgibbon *et al.*, 2014). Instead, summer season wind-driven northward-flowing currents are likely to entrain post-larvae as they cross the shelf and transport them further north along the coast (Figure 29). This is evident in both predicted data (ozROMS) and measured surface currents (High-Frequency Radar) in the region (Wijeratne *et al.*, 2018; Cosoli *et al.*, 2020). There is also a year-round average onshore cross-shelf flux to the south of the LCZ, which aligns with some pathways of particles eventually reaching the LCZ and HCZ to the north. Releasing the particles along the continental shelf as model pueruli has shown that they can successfully reach nearshore areas from a range of latitudes along the continental shelf. The pathway of a pueruli to the nearshore is instantaneous and vary between larvae, as the larval dispersal modelling results attest. Therefore, average conditions can only provide an overview.

Consistent with the literature on other spiny lobster species, our research shows the influences of nearshore oceanographic processes on the settlement of pueruli. For *Jasus edwardsii*, southwest wind-driven surface currents also assist in transport to the South Australian coastline (Hinojosa *et al.*, 2017). Additionally, hurricanes and their associated sea-level changes have been correlated with the Caribbean spiny lobster, *Panulirus argus* (Briones-Fourzán *et al.*, 2008). The Yucatan Current has also been linked to *P. argus* dispersal (Munoz de Ceote-Hernandez *et al.*, 2021). A consistent decrease in the strength of the Capes Current alongside an unusual but steady increase in the strength of the Leeuwin Current in the summer coincided with a period of low puerulus settlement (Kolbusz *et al.*, 2021b). Throughout a period of unusually low settlement for *P. cygnus,* the LC was stronger over the summer, flooding the shelf and reducing the CC strength, which likely assists pueruli transport to the nearshore. The same occurs within the East Australia Current, where the jet-like stream can act as a barrier to the settlement of *Sagmariasus verreauxi* (Roughan *et al.*, 2011; Cetina-Heredia *et al.*, 2015). Therefore, successful settlement of *P. cygnus* can be considered a combination of offshore abundance and condition of larvae, followed by active swimming and oceanographic shelf processes (Yeung *et al.*, 2001; Goldsteins and Butler IV, 2009; Linnane *et al.*, 2010; Singh *et al.*, 2018).

Here, fieldwork monitoring of puerulus settlement has corroborated larval dispersal modelling efforts and provided evidence that post-larval supply is likely to be strong within the LCZ. The contrast between these results and the findings of Miller (2019), who found very low numbers of juvenile and sub-legal lobster within the LCZ, suggests other processes influencing post-settlement growth and mortality might be critical in the area, potentially related to habitat suitability or stability (Phillips *et al.*, 2003). The LCZ has high sediment instability and is potentially vulnerable to changes in regional sediment transport dynamics (Stul *et al.*, 2014). At the same time, the adjacent HCZ is characterised by higher relief topography and less vulnerable to changes in sediment transport. The higher number of pueruli collected within the HCZ than the LCZ, juxtaposed against the larval dispersal simulations, suggests that pueruli are able to settle in the zone but likely have more chances to settle in the LCZ. However, habitat unsuitability may cause movement away from the LCZ, possibly to the HCZ, or mortality.

Conclusion

Puerulus collectors were deployed, and larval dispersal modelling was conducted to investigate post-larval supply to an area of surprisingly low abundance of juvenile and sub-legal Western Rock Lobster. This is termed the “Low-catch zone” (LCZ) adjacent to areas of high sub-legal and legal lobster abundance, near the biogeographic centre of the Western Rock Lobster distribution and fishery. We found that a lack of supply of recruits is not a likely contributing factor to the strong gradient in the number of sub-legal and juvenile lobsters over the local region. From a physical oceanographic standpoint, three-dimensional hindcast data were used to calculate the region’s average cross-shore and along-shore flows. This highlighted that cross-shelf flows are on average offshore at the LCZ but onshore to the south of this area. However, the same data were implemented as the physical oceanographic forcing for a larval dispersal model, where trajectories detailed that pueruli arrive in the LCZ from further south, and their likely transport north along the coast, by wind-driven surface currents. Furthermore, high variability in pueruli numbers between collectors suggests that critical ecological and potentially physical processes are operating at very fine scales (e.g. 10-100 m’s). These processes have important implications for interpreting puerulus collector data and the future study of patterns in settlement across the range and fishery for this species.

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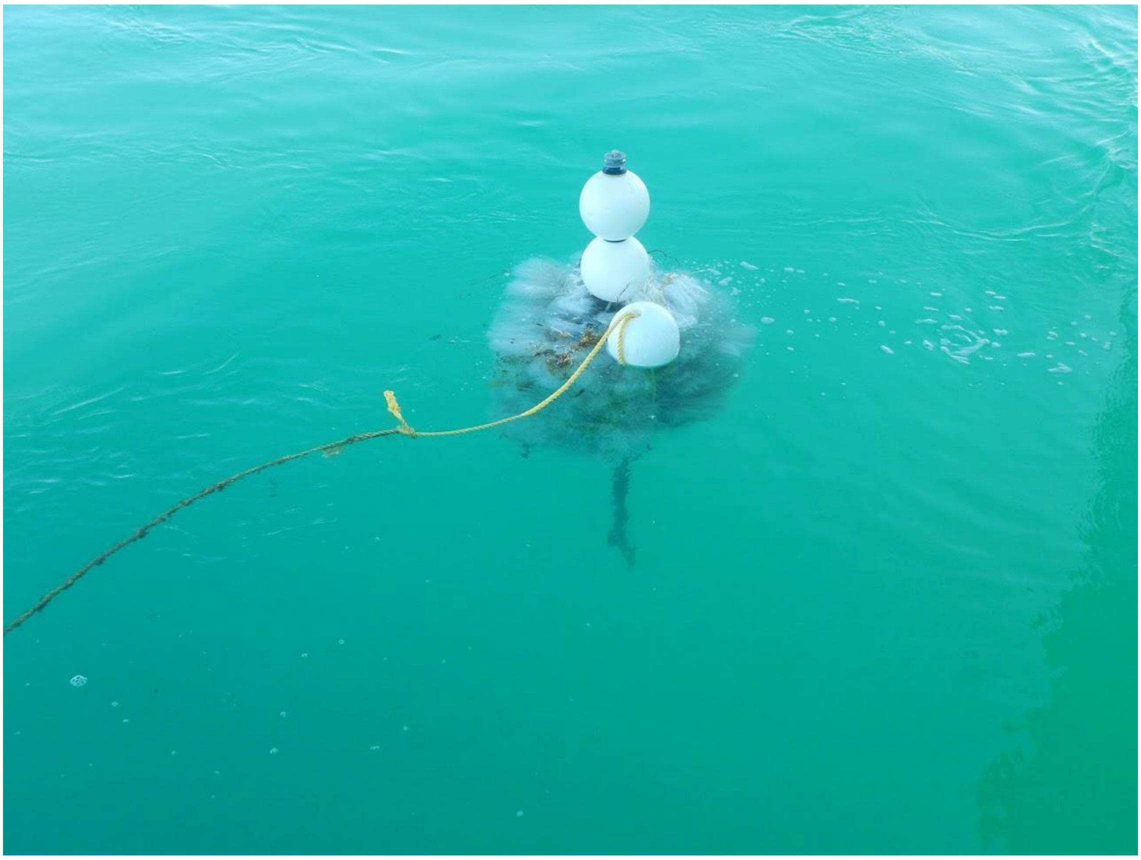
Study 4 - Examining the settlement of Western Rock Lobster larvae in an area of reduced catches



A recently deployed “Phillips” type Western Rock Lobster puerulus collector. Photograph by Michael Brooker.

Abstract

The management of wild species fisheries can be difficult and ideally needs to be responsive to changes in population dynamics and productivity for effective management to occur; if a fishery can identify a reliable indicator of current or future population productivity that can be a useful tool for management. The West Coast Rock Lobster Managed Fishery (WCRLMF) fishery has a long-established history of successful management actions informed by the “Puerulus Settlement Index'' which has been recorded since 1968, which has been found to reliably predict commercial catches in 3-4 years time and been the key to the sustainability of the fishery. However, despite the apparently healthy status of the fishery, commercial fishers of the WCRLMF have recently become increasingly concerned about an area of reduced productivity located near Cliff Head, Western Australia (29”31’S, 114”59’E). Previous work confirmed the existence of the Low-Catch Zone (LCZ) with a relatively low abundance of undersize lobsters which raises the question of whether lobster puerulus are settling in the area? The aim of the current study was to examine settlement patterns of Western Rock Lobster puerulus across LCZ using floating artificial puerulus collectors moored across the study area. This study encountered a high level of variability in settlement both between sites and within sites (between individual collectors) and was able to confirm that puerulus are settling over the LCZ albeit potentially at lower levels compared to areas immediately adjacent to the north and south. The levels of settlement found within the LCZ, were still at levels comparable to other locations in the fishery where substantial undersize and greater than legal size lobster populations have been reported. The results obtained by this study in addition simultaneous studies of oceanographic circulation in the region by others indicate that reduced settlement of puerulus in the study region is unlikely to be a process leading to the LCZ, therefore it will be important to further investigate other potential bottlenecks for the recruitment of lobster into the fishery, such as the habitat requirements for juvenile Western Rock Lobsters and how other factors, such as variation in habitat, may be limiting their survival and growth.

Introduction

The management of wild species fisheries can be challenging and needs to be responsive to changes in population dynamics and productivity for effective management to occur (Walters 1997). There are many factors that lead to difficulties in managing wild species ranging from disease, to habitat phase shifts, to variable stock-recruitment relationships and changing climates (Fenner 2012; Suuronen and Bartley 2014; Penn and Caputi 1986; Salayo et al. 2006; Gutberlet, Seixas, and Thé 2004). The nature of a species stock recruitment dynamics, or the importance of the size of the spawning biomass to production of recruits, can have a significant impact on a species ability to support a wild harvest fishery (Bruce et al. 2001; Briones-FourzÁn, Candela, and Lozano-Álvarez 2008).

Recruitment in marine ecosystems can be affected by an array of processes ranging from large scale oceanographic processes to species specific larval duration (Roughgarden et al. 1994; Menge 2000; Richardson and Schoeman 2004; Halpern, Cottenie, and Broitman 2006). The interaction of these influences can lead to the recruitment dynamics of marine organisms being governed by the biomass of reproducing individuals, environmental variability, dispersal of planktonic stage larvae or other factors governing the survival of new settled individuals prior to recruitment to a population. In the marine environment, there is a wide range of planktonic larval stage durations ranging from a matter of days to 22 months (Strathmann 1985; Doherty, Planes, and Mather 1995; Stanley Cobb and Phillips 2012) and this can impact not only dispersal but also the potential of environmental variables to impact settlement and therefore the successful recruitment to adult populations and the fishery.

Many wild harvested fish species have been documented to exhibit complicated biomass/stock driven recruitment (Daskalov 1999), as has been demonstrated with the cod fishery where recruitment was observed to be driven by spawning biomass when populations are above a certain level but become more vulnerable to environmental variation when spawning biomass is low (Marshall et al. 1998; Brander 2005). In contrast, the typically longer larval periods of many marine invertebrate fisheries species can result in a greater potential for dispersal but also a potential decoupling of stock-recruitment relationships and a greater role of environmental factors on successful settlement and recruitment to a fishery (Penn and Caputi 1986; Wilson et al. 2012; N. Caputi et al. 2014).

The ability of marine invertebrate larvae to swim vertically or to orient themselves in currents flowing in opposite and/or perpendicular directions depending on depth can lead to changes in dispersal and subsequently, this ability to direct their dispersal can influence settlement (Faillettaz, Paris, and Irisson 2018; Kolbusz, Langlois, et al. 2021). Even in the cases where larvae can direct their dispersal, oceanography and the large scale movements of water can have a major impact on this and may therefore dictate whether regional populations can be self-sustaining (Bruce et al. 2001), as is the case for the Caribbean spiny lobster which has sub-populations that rely solely upon recruitment from external populations (Briones-FourzÁn, Candela, and Lozano-Álvarez 2008). Similarly, recruitment in the Western Rock Lobster (*Palinurus cygnus* George 1962) is strongly influenced by the Leeuwin current which has been suggested to impact where and in what magnitude settlement occurs, with stronger current years typically leading to higher settlement and subsequent recruitment whereas weaker current years typically lead to lower settlement and weaker recruitment (A. F. Pearce and Phillips 1988; Kolbusz, Langlois, et al. 2021; Kolbusz, de Lestang, et al. 2021).

Indexes of recruitment, from settlement data, are very difficult to obtain for fin-fish species. Conversely, some invertebrate fisheries are fortunate to have indices derived from settlement including, the Western Rock Lobster fishery (B. F. Phillips 1972), Caribbean spiny lobster fishery (Panulirus argus; Briones-FourzÁn, Candela, and Lozano-Álvarez 2008), *Pecten alba* scallop fishery (Sause, Gwyther, and Burgess 1987) and Blue crab (*Callinectes sapidus*) fishery (Ogburn, Hall, and Forward 2012). The Western Rock Lobster fishery in particular has a long-established recruitment index known as the "Puerulus Index'' where settlement has been recorded continuously at various locations along the coast since 1968 (B. F. Phillips 1972; B. F. Phillips and Hall 1978). This index was developed using the counts derived from Phillips's (1972) puerulus collector design which was developed following numerous unsuccessful attempts to collect meaningful numbers of puerulus and post puerulus larvae of palinurid lobsters (Kensler 1967; Witham, Ingle, and Sims 1964; Lewis, Moore, and Babis 1952).

The Phillips collector (Phillips 1972), consists of a light aluminium frame that supports three grey PVC panels back-to-back around two floats. Each PVC panel contains 25 tassels of a Boral Kinnears Pty Ltd synthetic rope fibre (previously "Tanikalon" synthetic rope fibre from Taniyama Chemical Industries Ltd, Okayama, Japan) which imitates seagrass / seaweed and provides a habitat for the puerulus to settle in. Subsequent research looked to further refine and increase servicing efficiency of the Phillips collector which led to the development of the sandwich collectors which consist of two Phillips collector panels mounted back-to-back (Bruce F. Phillips et al. 2001). A variation of this collector, the 'sandwich' collector was found to be the most efficient design for efficiently harvesting Western Rock Lobster puerulus for proposed grow-out of early juveniles in aquaculture (Bruce Frank Phillips et al. 2002).

The West Coast Rock Lobster Managed Fishery (WCRLMF) is Australia's most valuable single species wild-caught commercial fishery, worth around AUD$300-500 million per annum (Nick Caputi et al. 2015; Nicolaou and Hammond 2017). Globally, the WCRLMF has been recognised as a leader in fisheries science, management, and sustainability. The fishery was the first to be awarded the Marine Stewardship Council (MSC) third party certification (Bellchambers et al. 2012) and subsequently recertified four times. Despite the overall healthy status of the fishery, commercial fishers of the WCRLMF had become increasingly concerned about an area of reduced productivity located near Cliff Head, Western Australia (29"31'S, 114"59'E; Fitzhardinge, J *pers comms*). Work conducted as part of Study 2 of this project and by Miller et al (2023) have confirmed the existence of the Low-Catch Zone (LCZ) through structured career history interviews and intensive mark-recapture and fisheries independent surveys. The outcomes of this research found there was a relatively low abundance of undersize lobster in the study area compared to nearby location (Miller et al. 2023); Figure 30) while oceanographic and particle tracking modelling work conducted by Kolbusz et. al. (2021) suggests that the LCZ should in fact receive greater larval supply than nearby areas and have ample pathways for puerulus settlement to occur.

Given there appears to be a reduced abundance of juvenile Western Rock Lobster in the LCZ near Cliff Head despite oceanographic modelling suggesting that there is ample supply of puerulus to the region, the aim of the current study was to examine the finer scale settlement patterns of Western Rock Lobster puerulus across this area. This examination was conducted through an intensive survey using floating artificial puerulus collectors moored across the study area.

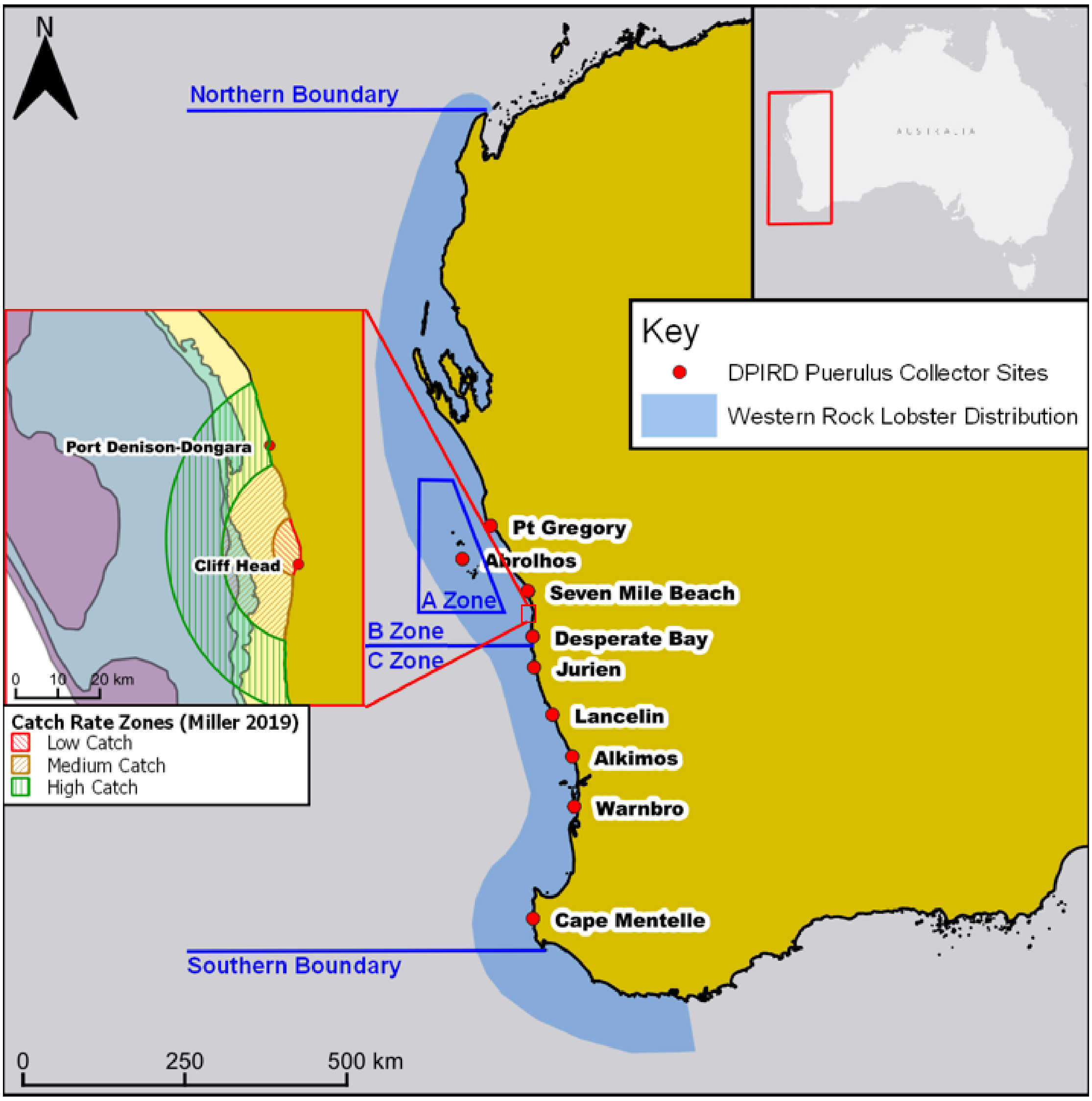


Figure 30 Locations of the "low", "medium" and "high" catch rate zones identified by Miller (2019) in reference to the DPIRD puerulus collector locations along the Western Australia coastline.

Methods and Materials

Study Location

Preliminary workshops held with 18 fishers from the Dongara Professional Fishermen's Association provided an overview of the likely extent of the LCZ and guided the sampling design for the deployment of the puerulus collectors. The study area ranged from Seven Mile Beach to the Beagle Islands with similar benthic habitats present across the area which broadly included limestone reef and seagrass habitats interspersed by sandy patches which is generally characteristic of the habitats across the species distribution (Figure 31). Each collector site had three sandwich collectors with select sites also including three Phillips collectors.

Puerulus Collector Design

Previous research conducted by Phillips et al (2001) found that both sandwich collectors and Phillips collectors had a similar effectiveness with the key difference being servicing time, where sandwich collectors can be serviced quicker. Given the comparative ease of servicing and the substantial area covered by the study it was decided the majority (up to 36) of collectors would be the sandwich type with some (up to 6) Phillips type collectors also included as a point of reference.

The Phillips collectors (Figure 32) consist of a light aluminium frame that supports three grey PVC panels back-to-back around two central floats. The PVC panels are 0.61 metres long and 0.30 metres wide and contain 25 tassels of a synthetic rope fibre (manufactured by Boral Kinnears Pty Ltd, Victoria, Australia; previously “Tanikalon” synthetic rope fibre from Taniyama Chemical Industries Ltd, Okayama, Japan). Each tassel is approximately 0.23 metre long and is bound to the PVC panel with flyscreen spline. The sheets slide into the aluminium frame from the top and are secured by rope.

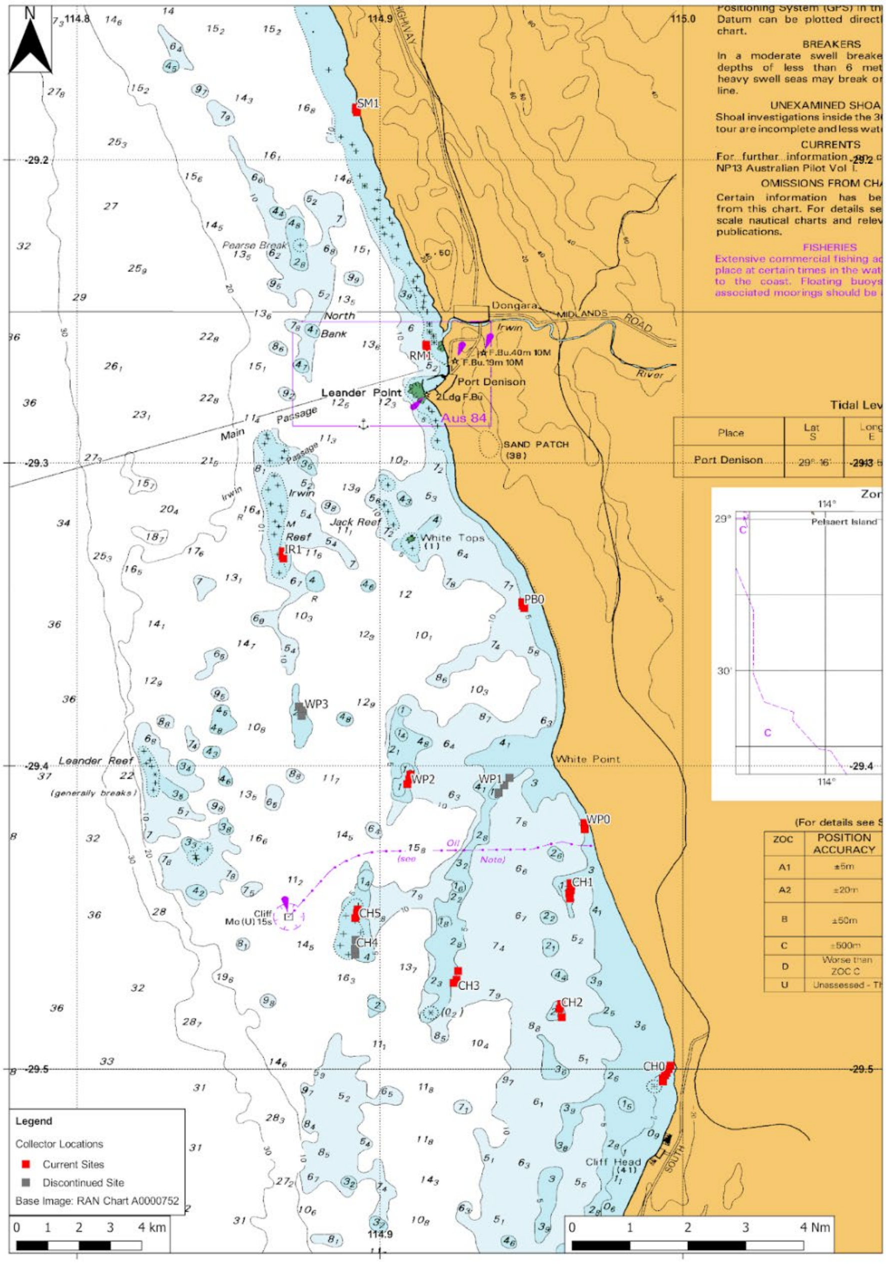


Figure 31 Puerulus collector sites for the Season 2018/19. Seven Mile Beach (SM), Irwin River Mouth (RM), Irwin Reef (IR), Pink Shell Bay (PB), White Point (WP), Cliff Head (CH). Desperate Bay collectors to the south are not shown.

The sandwich collectors (Figure 32d) consist of two of the PVC panels used for the Phillips collector which are mounted back to back with two Jarrah battens between the sheets (B. F. Phillips 1972; B. F. Phillips and Hall 1978; Bruce F. Phillips et al. 2001). The collector has a small amount of chain at the base for stability and two floats are attached to the top batten.

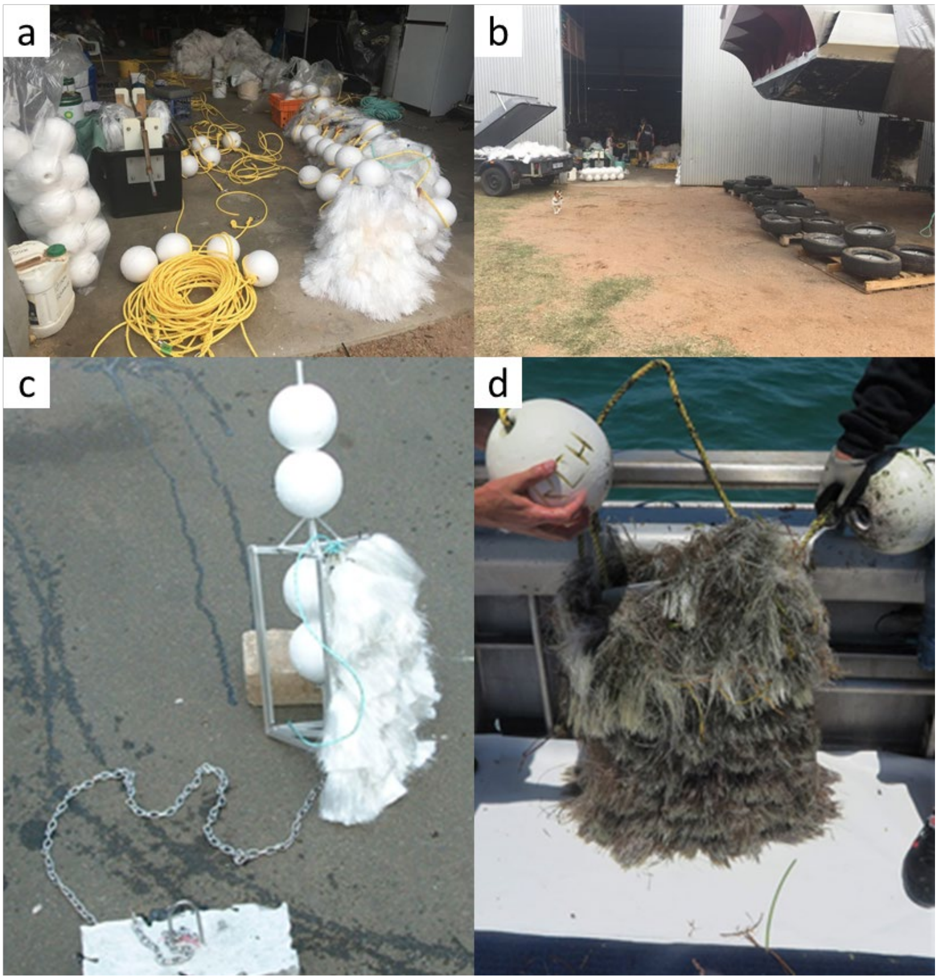


Figure 32 Construction and types of puerulus collectors. (a-b) Construction of the artificial puerulus collectors and moorings (c) "Phillips" type puerulus collector, (d) "sandwich" type puerulus collector.

Both types of collectors were deployed using the same mooring system whereby a mooring block was placed on the substrate with a rope attached to a float. The collectors were attached to the float via a removable bridle which allowed the collectors to remain vertical in the water column (Figure 32).

Puerulus Collector Servicing

Following standardised methods developed by Phillips and Hall (1978) which are still in use, puerulus collector servicing was undertaken every 28 days in conjunction with a full moon. For the sandwich collectors the collector was retrieved and kept in a tub, had the floats removed and a shaft inserted between the collector panels to allow the collector to be spun horizontally 20 revolutions in both a clockwise and anticlockwise direction. The number of puerulus that fell from the collector into the tub below was recorded. For the Phillips collectors, the collector was retrieved and kept in a tub while the collector sheets were removed one at a time and placed in a frame that was bashed 20 times over a collection tub. The number of puerulus that fell from the collector panels was counted for each collector and recorded. Following the "servicing," each collector was redeployed on the same mooring which remained anchored to the bottom in the same location.

Data Collection and Analysis

The number of puerulus at each site was recorded using three categories; puerulus (animal is still transparent), juvenile (animal is fully coloured), "*last monther*" (animal is much larger). For reporting, the three categories were combined as a total per collector and then the average was taken for the site as is done by the Department of Primary Industries and Regional Development (DPIRD) - Fisheries Research. The monthly averages were cumulatively tallied at each site to present an accumulation of puerulus for each season.

Results

During the 2017/2018 puerulus settlement season from August 2017 to April 2018, 36 sandwich collectors and 4 Phillips collectors were deployed at 12 sites (Seven Mile Beach [1 site], White Point [3 sites], Cliff Head [4 sites], Beagle Islands [4 sites]) and each serviced monthly across 8 months. The average total cumulative number of puerulus collected per collector for the season ranged from two at White Point to 50 at Seven Mile Beach (Figure 33).

During the 2018/2019 puerulus settlement season from August 2018 to April 2019, 33 sandwich collectors and 6 Phillips collectors were deployed at 11 sites (Seven Mile Beach [1 site], Irwin River Mouth [1 site], Irwin Reef [1 site], Pink Shell Beach [1 site], White Point [2 sites], Cliff Head [5 sites]]) and each serviced monthly across 8 months. The average total cumulative number of puerulus collected per collector for the season ranged from five at Cliff Head to 78 at Seven Mile Beach (Figure 33).

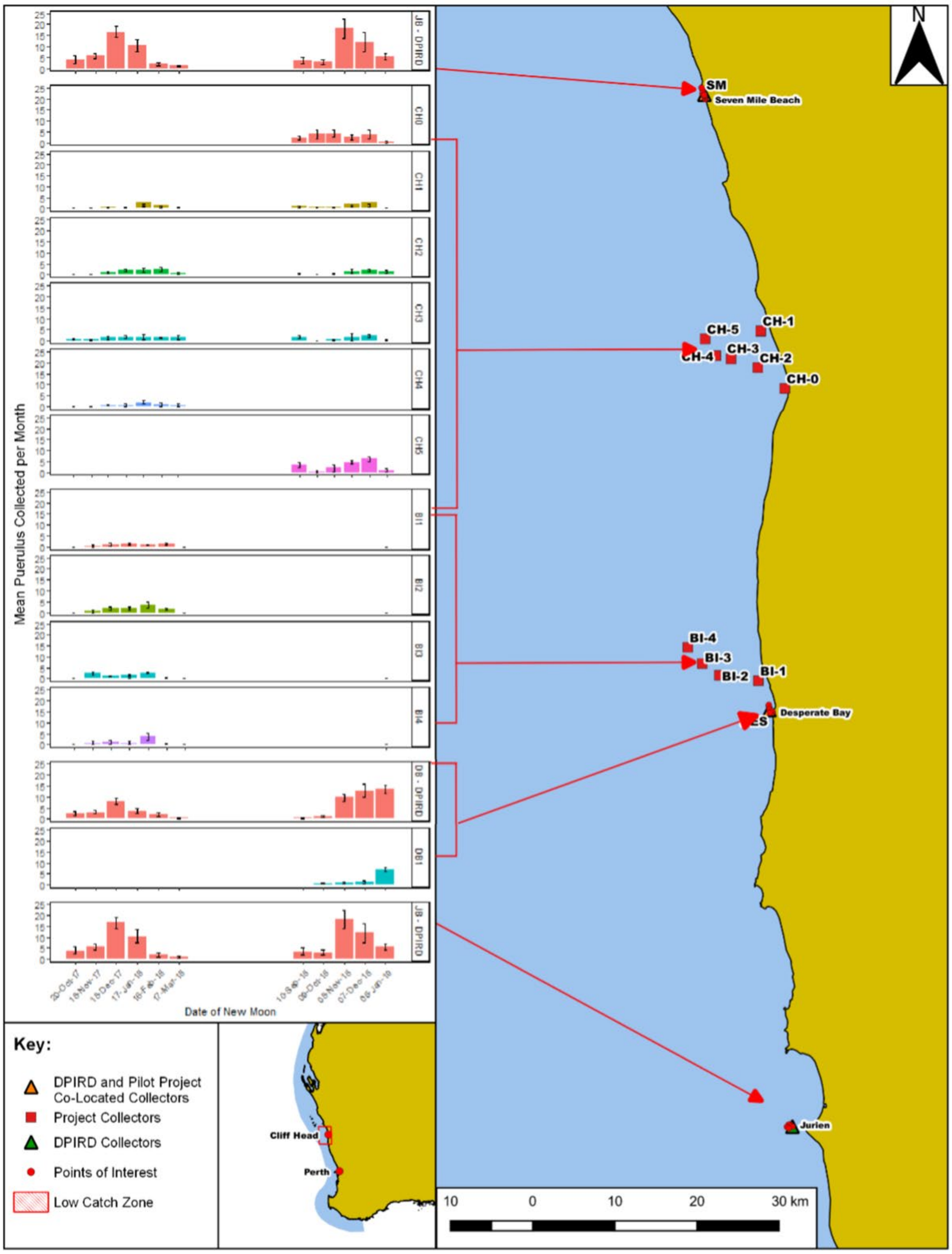


Figure 33 The deployment locations of the puerulus collectors presented with the mean count of puerulus per collector per month obtained from each site over the study period. Note, not all sites were studied in both seasons; CH-0 was only studied in the 2018-19 season, CH-4, BI-1,-2,-3,-4 were only studied in the 2017.

Discussion

This study encountered a high level of variability in settlement both between sites and within sites (between individual collectors). The high variability encountered by this study has previously been observed and commented on in the work of Phillips (1972) who also observed great variability between paired collectors positioned only metres apart. This study has been able to confirm that puerulus are settling over the LCZ albeit potentially at lower levels compared to areas immediately adjacent to the north and south but still at levels comparable to other locations in the fishery where substantial undersize and greater than legal size lobster populations have been reported (de Lestang, Caputi, and Melville-Smith 2009).

Observations made during this study suggest that the site-specific environmental conditions at the specific location of each collector could be the result of the high variability in puerulus numbers between adjacent collectors, including the immediately adjacent habitat and localised strength of water flow potentially explaining why there is such a large amount of between collection variation. Within the shallow and constrained inner reef channels at the Seven Mile site, where established and new collectors as part of this study were situated, water flow conditions were observed to be variable between collectors and could be part of an explanation for the high variability in puerulus numbers between individual collectors, which also mirror the high between collector variation first documented by Phillips (1972). This high level of fine scale variability in the catch rate of individual collectors suggests the importance of maintaining the consistency, and in particular the exact location of each collector, within the puerulus collector program operated by DPIRD.

An additional component of this study was the deployment of two different types of benthic puerulus/early juvenile collectors to provide an alternative method to investigate patterns in puerulus settlement or populations of early juvenile post-puerulus animals. The first of these designs used two of the PVC sheets and tassels used in the Phillips and sandwich collectors which were mounted in a modified lobster trap. The design of this collector was adapted from a benthic collector developed in Tasmania and south-east Australia that has been successfully used to sample the puerulus of *Jasus edwardsii* in deeper water (Ewing and Frusher 2015). The second benthic collector type was modelled on the successful wedge- collectors for post-puerulus animals used by Briones-Fourzn et al. (2008) for Caribbean lobster. This collector was also constructed within a commercial lobster pot frame and contained 10-15 wedge shaped crevices constructed from fibre cement or PVC sheets covered in scouring material. Initial pilot studies using single traps, suggested some potential of these methods, especially for the wedge style trap for post-puerulus animals but follow up studies with larger numbers of collectors found no consistent patterns or adequate numbers of animals for study and that the benthic collector was very vulnerable to becoming inundated with sediment in near shore locations.

Simultaneous studies of oceanographic circulation in the region by (Kolbusz et al. 2021) suggests that the LCZ near Cliff Head is likely to receive a greater or equal settlement than surrounding areas, including the higher catch zones to the north near Seven Mile Beach. In addition, Kolbusz et al. (2021) used an established oceanographic model of the region to simulate the path of both inert and actively swimming particles, simulating potential Western Rock Lobster puerulus distribution along the coast from 2000-2018. The study found that settlement in this region spanned the LCZ and north to Seven Mile Beach (which has the highest observed puerulus settlement rates in the fishery and is ~40 km north of the LCZ), all had a similar nearshore pathway, where particles entered the shallow water area offshore from the LCZ and travelled north along the coastline. This suggested that the LCZ likely has a greater chance of receiving settlement of Western Rock Lobster compared to areas further to the north including Seven Mile Beach, an area which is also characterised by a much higher abundances of undersize lobster as described by Miller et al. (2023) and documented in Study 2.

The results obtained by the current study in addition to the oceanographic modelling work by Kolbusz et al. (2021) and Study 3 indicate that the settlement of puerulus in the study region is unlikely to be a process leading to the LCZ, therefore it will be important to further investigate other potential bottlenecks for the recruitment of lobster into the fishery, such as the habitat requirements for juvenile Western Rock Lobsters and how this may be limiting their survival, growth and recruitment into the fishery.

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Study 5 - Tracking change in important recruitment habitats for Australia's most valuable fishery

In preparation for publication in Marine and Freshwater Research

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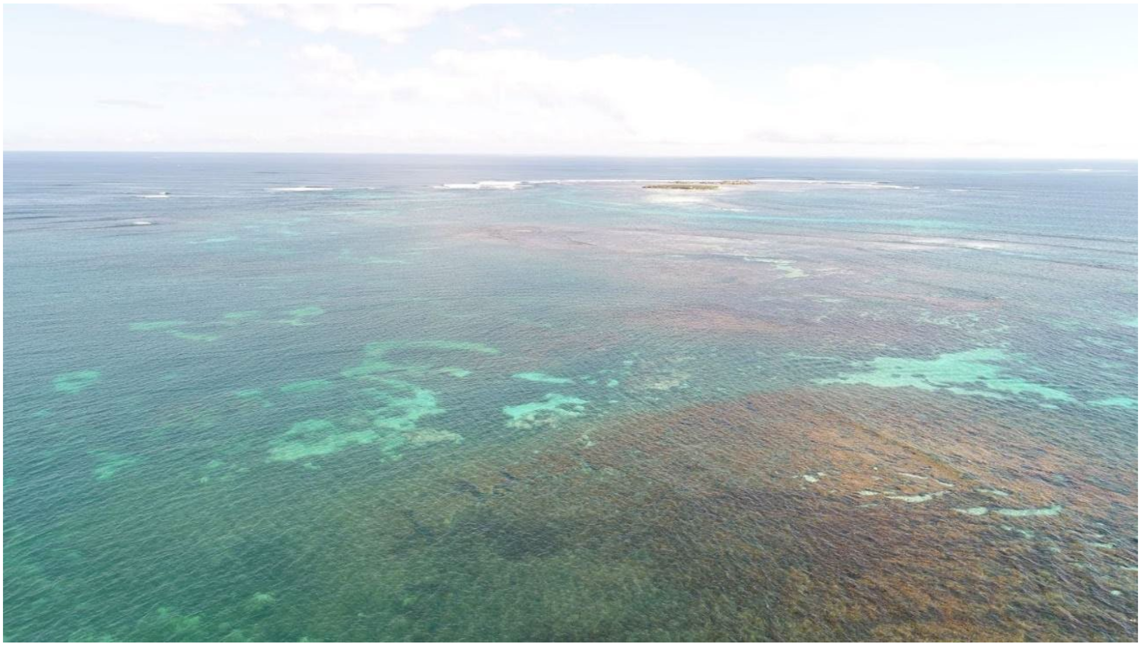

View west across the Beagle Islands. Photograph by Oscar Doncel Canon.

Abstract

Nearshore vegetated habitats can be important recruitment areas for valuable fisheries, including Australia's Western Rock Lobster. Anecdotal evidence derived during collaboration with commercial fishers suggests local catch rates in this area were less than expected, given the fisheries generally healthy status.

We used historical aerial imagery to generate a quantitative record of change in subtidal vegetation cover near Cliff Head, Western Australia over a decade and ground-truthed modern imagery using downward-facing towed video.

We revealed a pattern of thinning in nearshore vegetated habitats with a net loss/degradation of 52% of the study area. In-water imagery suggested some vegetation loss was associated with high sea urchin densities. We suspect this loss of vegetation is predominantly seagrass but cannot confirm due to a lack of historical data.

The specific cause of vegetation and concomitant lobster declines is unclear, there is evidence that a shift in hydrodynamics resulting in erosion/smothering of seagrasses and/or changes in herbivory levels .

Our findings highlight the need for consistent long-term monitoring of coastal nearshore vegetation, using remote and ground truthing imagery, alongside studies to improve our understanding of habitat use and recruitment processes.

Introduction

Shallow water coastal habitats can be important for the settlement and recruitment of many marine species of high economic and social value (Martínez et al. 2007; Seitz et al. 2014). These habitats are typically subjected to greater pressures from sources including fishing pressure (Worm and Branch 2012; Seitz et al. 2014) and land derived pollution (Worm et al. 2006), and are expected to suffer the greatest impacts from climate change (Sheaves et al. 2007; Bilkovic et al. 2009; Horton and McKenzie 2009; Altieri and Gedan 2015). Recent marine heat-waves on the western Australian coast have impacted shallow water coastal marine macrophytes, with substantial loss of both macroalgae and seagrass (Arias-Ortiz et al. 2018; N. Caputi et al. 2019; Wernberg et al. 2013; Smale and Wernberg 2013). These events are expected to become increasingly frequent as the climate warms (Oliver et al. 2018). The Western Rock Lobster *(Palinurus cygnus)* fishery is Australia's most valuable single species wild caught fishery, worth AUD$300-500 million per annum (Nick Caputi et al. 2015; Nicolaou and Hammond 2017). Settlement and recruitment of *P. cygnus* is thought to primarily occur in shallow coastal habitats along the central west coast of Australia (Edgar 1990c, 1990b; Jernakoff et al. 1994).

Despite the overall healthy status and sustainability of the Western Rock Lobster fishery (Lestang, Hoenig, and How 2022), over the last decades some experienced fishers had become increasingly concerned about an area of reduced catch near Cliff Head, Western Australia (29”31’S, 114”59’E). The West Coast Rock Lobster Managed Fishery (WCRLMF) was the first fishery in the world to gain Marine Stewardship Council (MSC) certification for sustainability in 2000 (Bellchambers et al. 2012) and has a long history of successful fisheries management (de Lestang, Caputi, and How 2016). Historical accounts from fishers document that from the 1970’s to 1990’s the area around Cliff Head (~ 80 km stretch of coastline) supported a large number of boats with annual lobster catches exceeding 1,000 t. Recent anecdotal reports from fishers suggested a trend of increasingly low lobster catch rates in the nearshore shallow water area near Cliff Head since the 1990’s (Figure 34). Commercial fishers also reported that this ‘low catch zone’ (LCZ) expanded along the coastline and into deeper waters (i.e. ~20 m depth) concurrent with a period of low settlement in the late 2000’s (Brown 2009; N. Caputi et al. 2014). Fishery independent surveys in the region demonstrated a significantly lower abundance of juvenile sub-legal lobster within the LCZ (Study 2, Miller et al. 2023)

Change in nearshore habitats, across the extensive coastline of western Australia, can both be challenging to detect and to attribute to particular factors. Previous observations of loss and change in marine vegetation have been attributed to a variety of factors ranging from land based runoff of excess nutrients, freshwater or sediment to physical disturbance from trawling, marine heatwaves, the movement of sand sheets or herbivory (Patriquin 1975; Thomas 1983; Cambridge and McComb 1984; Larkum and West 1990; G. P. Jones and Andrew 1990; Walker and McComb 1992; Frederick T. Short and Wyllie-Echeverria 1996; Duarte, Marbà, and Santos 2004; Bastyan and Cambridge 2008; Boudouresque et al. 2009; Zarco-Perello et al. 2020). Some of these processes can be more directly observed to cause vegetation loss than others but of these, herbivory, can be particularly hard to observe. In western Australia herbivory of seagrasses and macroalgae by fish (Zarco-Perello et al. 2020) and sea urchins (Azzarello et al. 2014) has been documented. In south eastern Australia, sea urchin grazing has caused the formation of significant seagrass habitat barrens (Carnell et al. 2020) with their extent determined through aerial imagery and in-water imaging to characterise the variation in seagrass cover and associated densities of sea urchins.

In the current study we tested the utility of time-series aerial imagery collected by Landgate, the Western Australian Land Information Authority (Landgate 2021). This imagery was collected to track shoreline change and plan coastal development (Stead 2018), and where this imagery fortuitously extends into nearshore environments it can be used to assess change in marine vegetation. A time-series of this imagery was found to have been fortuitously collected across the centre of the LCZ as described above (Miller et al. 2023). This study set out to evaluate the utility of this imagery for characterising vegetation change, complemented by in-water imagery for ground truthing, and to provide insight into the cause of the LCZ.

Methods and Materials

Study Location

Cliff Head, Western Australia (29”31’S, 114”59’E), nearshore habitats are less than 6 metres and extend up to approximately 4 km from shore (Figure 34). The shoreline in this region generally faces the west and the nearshore environment is relatively well protected, with wave heights rarely exceeding 0.5 metres, buffered by offshore limestone reefs and shoals (Edgar 1990c). The nearshore subtidal habitats near Cliff Head generally consist of scattered sand patches, dense seagrass meadows and limestone platform reef usually covered in mixed macroalgal assemblages. The dominant seagrasses include *Posidonia australis* [Hooker, 1858], *Posidonia sinuosa* [Cambridge & Kuo, 1979], *Amphibolis antarctica* [(Labill.) Sonder & Asch. ex Asch. 1868], *Amphibolis griffithii* [(J.M. Black) Hartog, 1970]), *Halophila ovalis* [(R. Brown) Hooker f., 1858] and *Zostera tasmanica* [G. Martens ex Ascherson, 1868] (Edgar 1990c, 1990a). In this region, *Posidonia* meadows are observed in the sandy substrates while the *Amphibolis* meadows are generally observed growing over the heavily dissected limestone reefs which run parallel to the coast. Areas of sand are also colonised by

H. ovalis and *Z. tasmanica* with remaining areas generally being unvegetated sand with some patches of mixed seaweed and macroalgal communities (Edgar 1990c, 1990a).

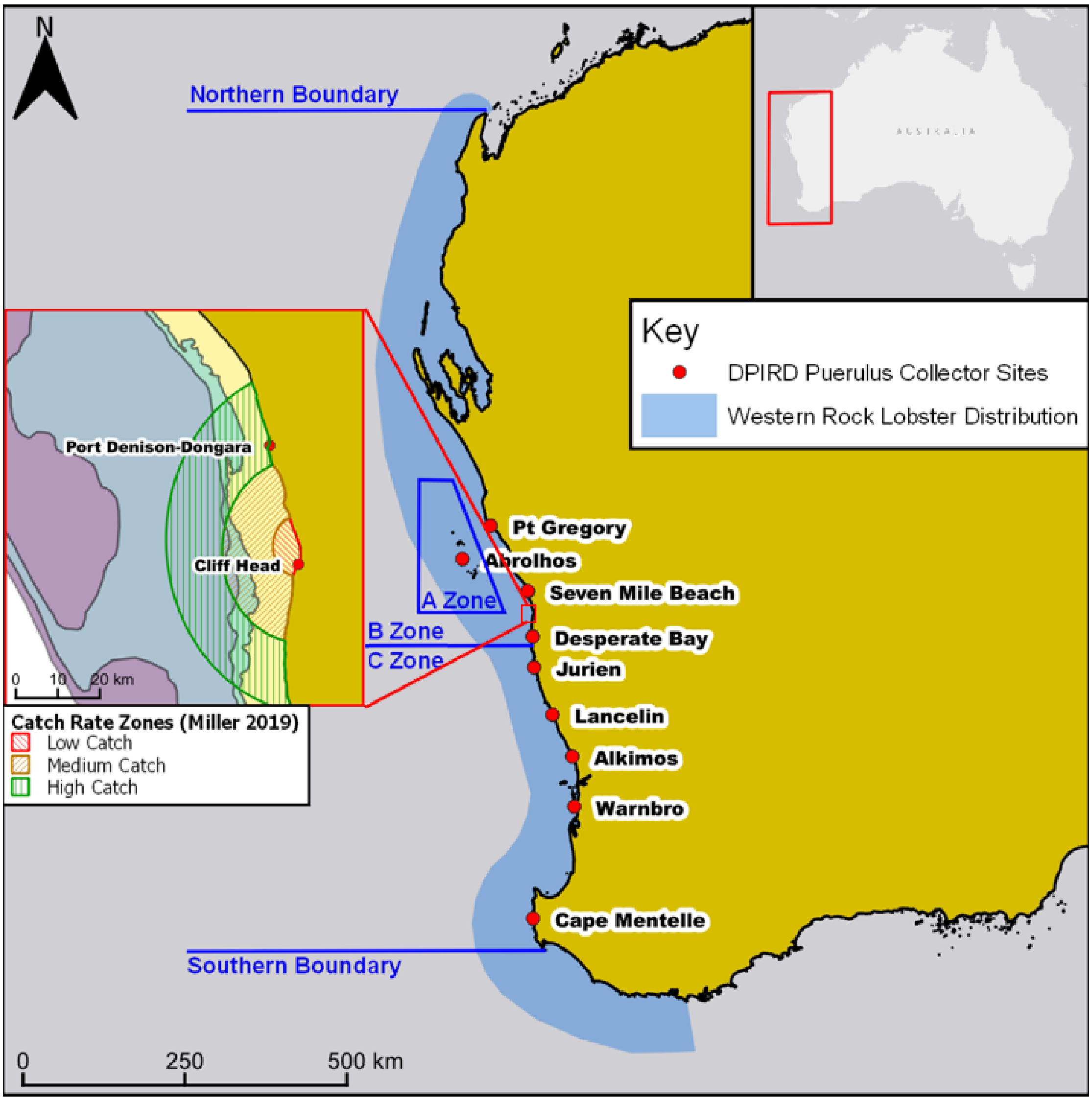

Figure 34 Study location (inset), focused on the Low-catch zone and distribution of the Wester Rock Lobster (blue shading) with the location of puerulus collector.

Aerial Image Collation and Selection

Aerial and satellite imagery present a valuable resource for tracking and investigating patterns of change in nearshore ecosystems. Various studies have used remote imagery from a variety of sources to assess the coverage of seagrasses and macroalgae (Larkum and West 1990; Walker and McComb 1992; Mumby et al. 1997; Kendrick et al. 2000; F. T. Short and Coles 2001; Phinn et al. 2008; Langdon, Paling, and Van Keulen 2011; Roelfsema et al. 2015; Moniruzzaman et al. 2019; Carnell et al. 2020). Satellite imagery and aerial imagery vary in the data that they collect, and the spatial scale collected, with aerial imagery potentially offering greater historical coverage. Freely available satellite imagery such as "Sentinel" and "LANDSAT" have nine different spectral bands while commonly available photographic aerial imagery possesses three bands (red, green, blue). A second key point of difference is spatial resolution, generally aerial imagery is of a higher spatial resolution and much finer scale (pixels can be 1 m or less) compared to satellite imagery that is often much coarser (LANDSAT pixel size is 30m but can be pan sharpened to 15m; Fensham and Fairfax 2002; Tuominen and Pekkarinen 2004, 2005).

The aerial imagery used in this study was captured by Landgate, or one of its preceding agencies. Landgate is the statutory authority responsible for property and land information in Western Australia and holds an extensive archive of aerial imagery to track land use change and inform planning. A total of 20 image mosaics were available across 10 years on the Landgate imagery portal (https://map-viewer-plus.app.landgate.wa.gov.au). Additional imagery was available dating back to 1998 but this imagery was either inadequate quality, black and white or low resolution. All mosaics were examined visually and via image metadata for their suitability using the following criteria: general image quality, water clarity, glare, camera angle and distortion. A total of four mosaics over three sampling periods were found to be of adequate coverage and visibility for use in the current study (Table 8). The remaining mosaics were deemed unsuitable for assessment due to turbid water conditions or only partial image coverage of the site.

The four viable image mosaics were downloaded using ArcGIS via the Landgate Web Mapping Server (WMS) on the Shared Landuse Information Platform (SLIP) which is managed by Landgate. The raster data was downloaded and saved with a pixel resolution of 0.5 x 0.5 m and saved as a Tagged Image File (.TIF) Format with GeoTIFF metadata encoding and density level information was stored in three bands for each pixel (red, green, blue).

Table 8 Aerial imagery details for the imagery used by this survey from Landgate (2021).

Year	Capture Date	Mosaic Name	Pixel Size	Comments
2010	07/07/2019	Dongara (1839)		Good image, slight underexposure
2016	27/11/2016	Arrowsmith (1938)	0.5 x 0.5 m	Exceptionally good image
2019	16/12/2019	Arrowsmith to Jurien Bay Coastline		Some swell patterning good benthos contrast
2019	16/12/2019	Drummond Cove to Arrowsmith Coastline		

Habitat Classification and Analysis

The study area used in subsequent analyses was set using the shoreline as the eastern boundary which was manually delineated from each individual scene to account for interannual variations in shoreline movements. The western boundary was determined by the western extent of the 2019 image mosaic as it had the least seaward coverage. The northern and southern boundaries remained the same for each year and were centred on Cliff Head (29”31’S, 114”59’E) giving the study site an area of approximately 7.5 km^2.

Table 9 Descriptions of the habitat classifications used in the aerial imagery classifications. Examples of each classification are provided in the supplementary material.

Classification	Description		Towed Video
	Aerial Imagery	Biological Description	
Vegetation	Darkest subtidal areas with a green colour.	Areas with dense vegetation.	75 - 100 % Veg. Cover
Partial Vegetation	Areas of subtidal habitat that are between the colour of the sand and vegetation categories.	Like the vegetation category except that some of the substrate is also visible indicating the vegetation is less dense and possibly broken up.	20 - 75 % Veg. Cover
Sand	Pale subtidal areas that are white with varying green blue tint further from shore.	Areas of bare substrate with little or no vegetation.	0 - 20 % Veg. Cover
Shallows/ Glare	White pixels.	White beach sand in the swash zone or dry on the beach and glare from the water surface.	-

Following an initial visual examination of the aerial imagery, four primary habitat classifications were identified (vegetation, partial vegetation, sand, and shallows/glare; Table 9). Following initial examination, a principal components analysis (PCA) was used to transform the multiband image and to remove potential correlations between the three (RGB) bands in the image allowing greater detail to be observed in the aerial imagery.

To automate the classification of habitats observed in the aerial imagery, this study made use of the “Supervised Image Classification” tool in the ArcGIS (10.5.1) Spatial Analyst Extension (ESRI 2011). The supervised image classification process allows the user to determine subsamples of each habitat classification and to tell the software which pixels should be grouped together for each classification. This process begins with the user producing a training data set using the “Training Sample Manager'' tool (ESRI 2011). The user selects areas of the same consistent habitat and classifies them according to the habitat classification scheme (Table 9). The software then develops a signature (range of pixel RGB values) for each of the habitat classifications based on the training data and presents these signatures as a scatter plot containing a point for each cell. The user can then adjust the training data in an iterative process to improve the distinction between the signatures by refining what data is included in the training data. Once a suitable training dataset has been produced the user can save a signature file which specifies the range and combination of RGB values that each signature includes.

Following the successful creation of the signature file, the “Interactive Supervised Image Classification” tool in the ArcGIS Spatial Analyst Extension (ESRI 2011) is used to perform an abbreviated maximum likelihood classification of the raster using the training sample data. The maximum likelihood classification considers both the variances and covariances of the class signatures when assigning each cell to one of the classes represented in the signature file (ESRI 2011). The results of this classification indicate the effectiveness of the signature data and whether the training data required further refinement. Once the training data was performing as expected the Maximum Likelihood Classification Tool was used to perform a classification of the aerial imagery raster file. The resulting classified raster file was then reclassified using the majority filter tool from the ArcGIS Spatial Analyst extension (ESRI 2011) to remove potentially misclassified cells and areas of error by reclassifying these cells with the values of cells immediately surrounding them to reduce the amount of overall noise (Kamusoko and Aniya 2009; Bartuś 2014).

Ground Truthing and Habitat Classification Accuracy Assessment

Ground-truthing data collection

Downward-facing towed video footage of the subtidal habitats in the study area was collected in August 2019 using a bottom tending towed video system (Figure 35) adapted from Sheehan et al. (2010) and designed and built in collaboration with Dongara Marine. The design of this system ensured it remained at a consistent height above the benthos as it was towed behind a vessel at approximately two knots (1 m/s). The system was fitted with GoPro Hero 3+ cameras recording in 1080p high-definition video. A Bad Elf GPS was mounted on the vessel to record the vessel track allowing for the towed video footage to be georeferenced at a later time using the video file metadata along with an appropriate set back. Prior to analysis individual frames were extracted from the video at 5 second intervals, giving a separation of approximately five metres between each image. The frames were analysed using BenthoBox (http://benthobox.com/), an online image annotation program produced by the Australian Institute of Marine Science (AIMS). BenthoBox was configured to place 25 random points across each frame for classification into habitat categories using the CATAMI classification methodology (Althaus et al. 2015). A side-by-side comparison for the habitat classifications are provided in the Supplementary Information (Supplementary Table 10). This method was also used to estimate the density of sea urchins on limestone reef at representative locations along transects.

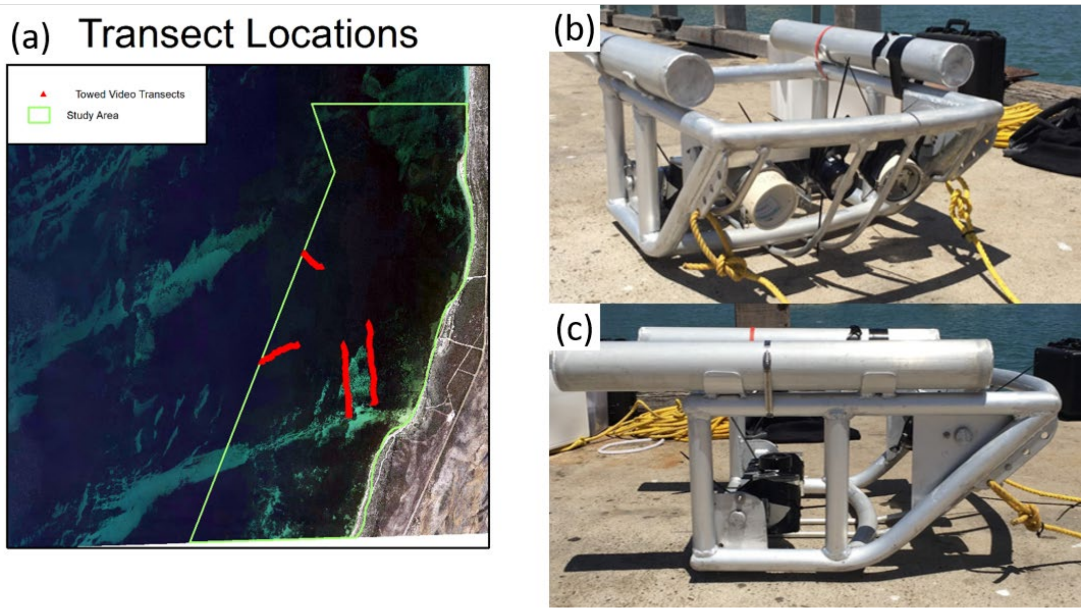

Figure 35 (a) The location of the towed video transects used by this study. (b) oblique and (c) side view of the bottom tending towed video system used by this study.

Ground-truthing accuracy assessment

Annotated benthic point data was exported from BenthoBox and converted to percent cover for each of the classification types (Table 8). This allowed for an accuracy assessment to be conducted on the February 2019 aerial imagery using the Accuracy Assessment Points tool and the Create Confusion Matrix tool in the ArcGIS Spatial Analyst extension (ESRI 2011). A side-by-side comparison for the benthic classifications along with the collected towed video imagery are provided in Appendix C.

An additional accuracy assessment was also performed on the classifications using the Compute Confusion Matrix and Accuracy Assessment Points tool in the ArcGIS Spatial Analyst Extension (ESRI 2011). In each assessment, 150 accuracy assessment points were randomly placed over the classified raster using an equalised stratified random sampling distribution (Niamir et al. 2019). Each of the accuracy assessment points were examined by a single user who classified each point using the same benthic classifications as the initial assessments. Once all of the accuracy assessment points were classified, a confusion matrix was produced to assess the agreement between the software classified and human classified data.

Habitat Changes Over Time

Changes in habitat over time were determined by re-coding each habitat classification and using the raster calculator in ArcGIS to compute a series of unique values that corresponded with changes in the value of each pixel from year to year. This process allowed for areas of gain, loss, no change, and noise to be mapped, assessed, and quantified at the same scale as the pixels. The R language for statistical computing (R Core Team 2021) was used for all data manipulation ("dplyr"; Wickham et al. 2020) prior to GIS analysis.

Results

Aerial Image Classification

The accuracy of the supervised image classification was acceptable, with kappa values for the classifications ranging from 0.792 - 0.912 (refer to Supplementary Table 10). The derived classifications are summarised below graphically (Figure 36) and tabulated with a summary of the area taken up by each of the classifications (Table 8). It should be noted that there was some noise present in the final classified raster which corresponds with glare on the water surface. These areas were classified accordingly.

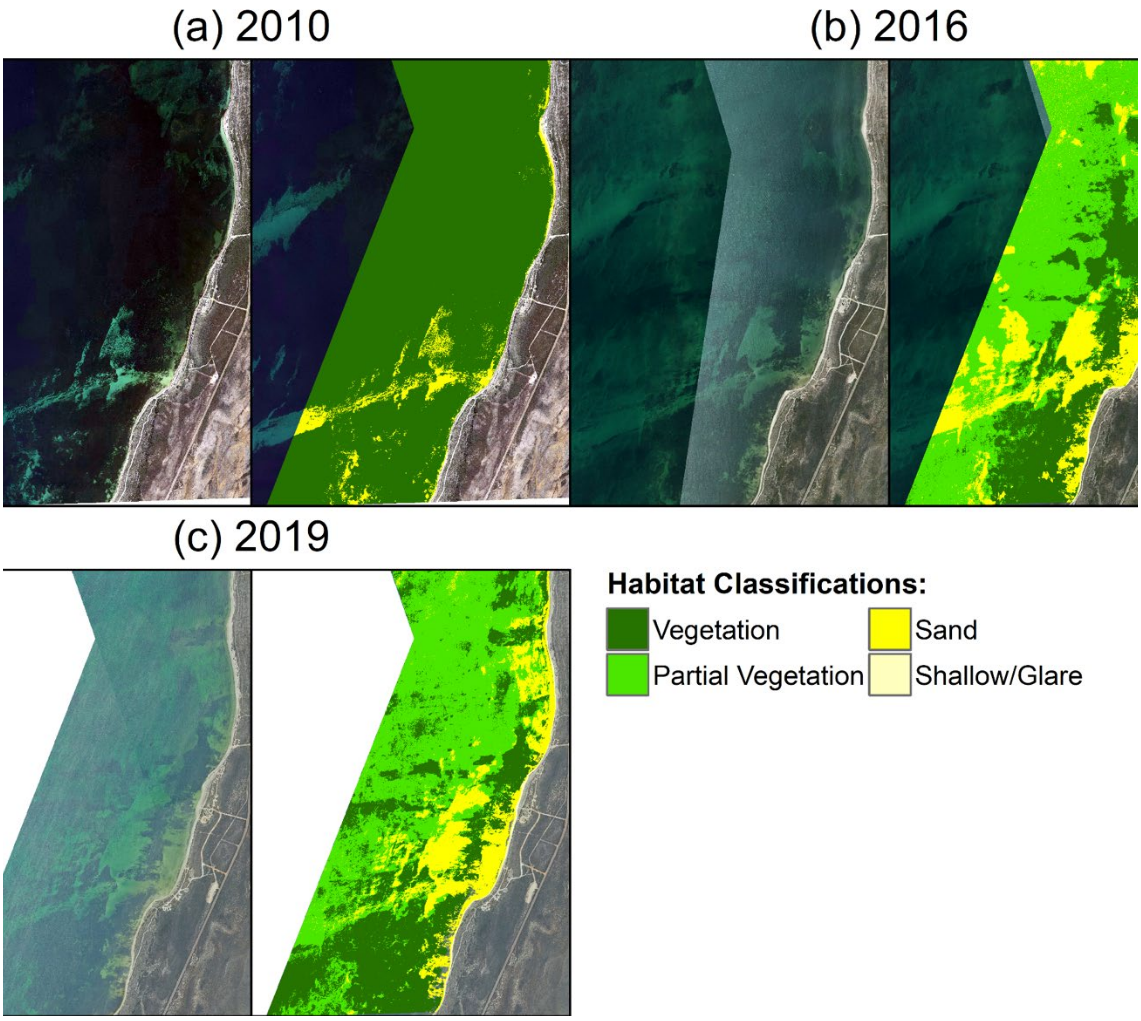

Figure 36 The image classification results for the aerial imagery from (a) 2010, (b) 2016, (c) 2019. Note the left panel of each pair presents the aerial image and the right panel presents the supervised maximum likelihood classification.

Habitat Changes Over Time

From 2010 to 2016 there was a loss of approximately 97 hectares (15%) of vegetation cover (Vegetated and Partially Vegetated; Table 8 and both Figure 36 and Figure 37). Following this initial net loss of vegetation, there was a slight increase of approximately 39 hectares (7%) of vegetation cover from 2016 to 2019 resulting in a net loss of 45 hectares (8%) vegetation over the study period (2010 - 2019). There was also evidence of a “thinning” of this vegetation through time. From 2010 to 2016, 337.6 hectares of vegetation changed from being classified as full to partial vegetation with an additional 12.5 hectares classified as partial vegetation from 2016 to 2019. The areas of vegetation thinning in 2016 to 2019 were generally different yet adjacent to that which experienced thinning in 2010 to 2016 indicating that the area of partial vegetation was expanding (Figure 36 and Figure 37). It should be noted that some of the changes between fully vegetated and partially vegetated may be due to image quality. Over the study numerous sandy features formed in 2010 and 2016 and became established with some spread on their eastern border along the coast in the subsequent surveys (2016 and 2019; Figure 36a-c).

Table 10 Coverage of each habitat classification for each year sampled.

Classification	Year 2010 Area (ha)	2016 Area (ha)	2019 Area (ha)
Total of all Vegetated	644.38	547.60	599.65
- Vegetated	644.38	210.00	249.53
- Partial Vegetation	0.00	337.59	350.13
Sand	69.99	162.49	109.73
Beach Sand/Glare	-	9.07	4.62
Noise/Other	-	-	5.26

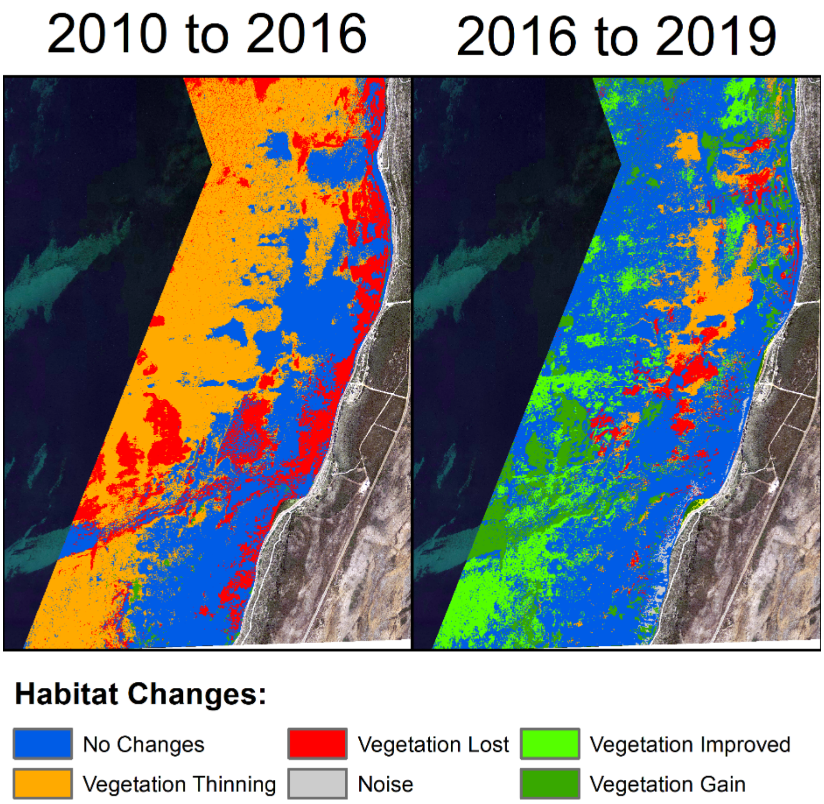

Figure 37 Changes in habitat composition between 2010 and 2016 and 2016 and 2019.

Estimates of sea urchin density

Sea urchin density estimates from in-water imagery revealed high variation in numbers per metre squared (Figure 38). The highest density of sea urchins was observed along the edge of sea grass patches (Figure 39) with an approximate density of 7.14 individual's m^{-2}.

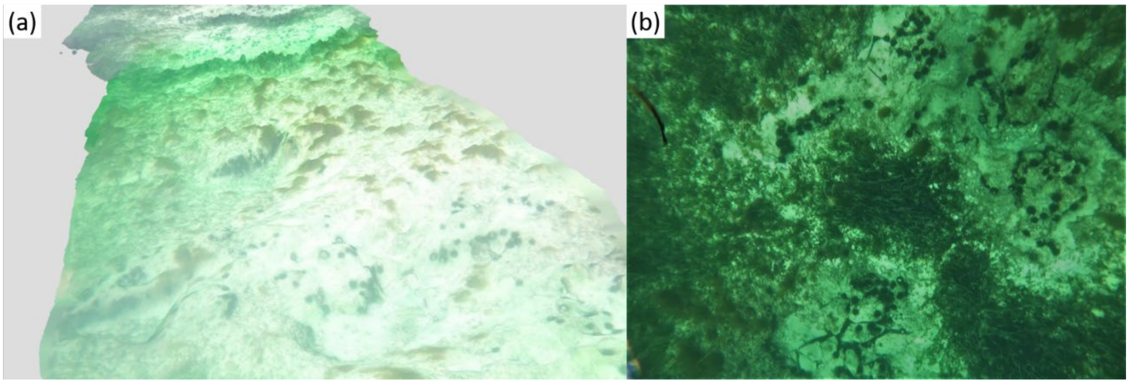

Figure 38 (a) Screenshot from a 3D image of the highest density of sea urchins on limestone reef, observed by the bottom tending towed video. The full 3D image that this image is taken from is located at the following link - seagrass to urchin barren (b) downward facing imagery from the towed video system showing the presence of sea urchins in the study area. Sea urchins can be seen around areas of relief.

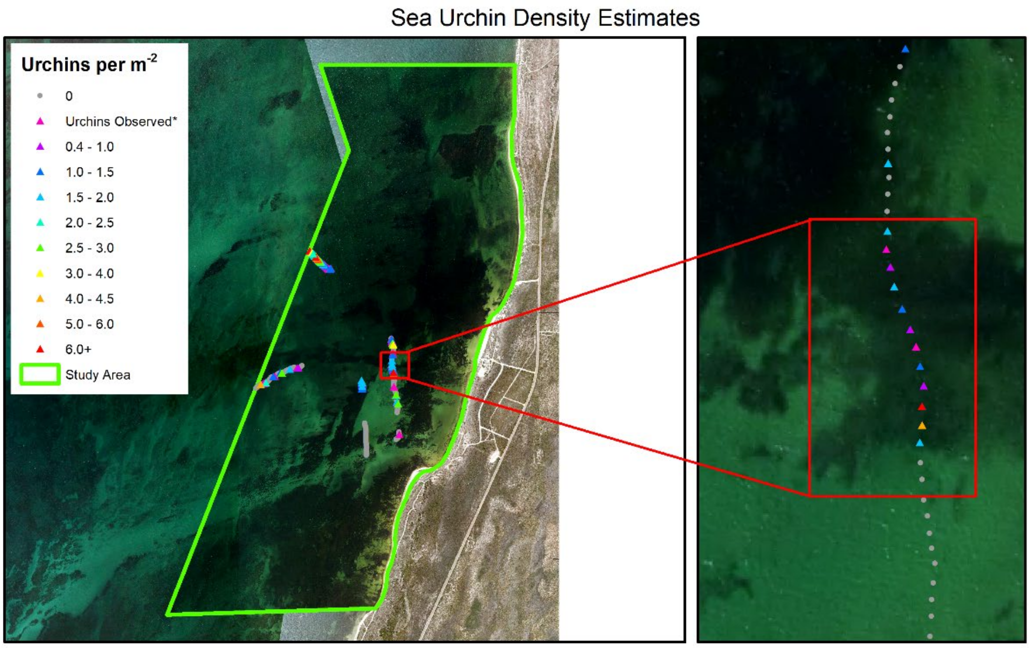

Figure 39 Estimates of sea urchin density from the in-water imagery. * In some cases, sea urchins were obscured by vegetation and reliable density estimates could not be made.

Discussion

This study has repurposed historical aerial imagery to document marine vegetation loss, over the period 2010 - 2019, within an area of interest in the centre of the West Coast Rock Lobster Managed Fishery. This localised area has been characterised by fishers and fishery independent surveys as a low catch area of concern, despite the apparent good condition of the surrounding fishery. In addition to vegetation loss, we also found evidence of decreasing vegetation condition with an increase in partially vegetated areas recorded in the most recent images in previously stable areas. This study provided insights into the spatial and temporal extent of changes occurring in vegetation and habitats within this localised area, that are broadly characteristic of the central western coast of Australia (Edgar 1990a). This study found a net decrease in vegetation cover of 86 hectares (14%) and up to 337 (52%) hectares of thinning or degraded vegetation since 2010 (Table 10), with in-water imagery confirming much of this vegetation to be seagrass assemblages dominated by both *Posidonia australis* and *Amphibolis antarctica* with macroalgae rarely recorded. We suspect that the historical losses of vegetation were seagrasses but could not confirm due to a lack of historical in-water ground truthing imagery. Historical information within a habitat map produced by Edgar (1990a) for this area was unable to be accurately georectified to allow for a direct comparison, due to change in coastal features. It is also important to acknowledge that, given the aerial imagery was not collected for marine vegetation mapping, some apparent changes in imagery could be influenced by sea conditions and image quality. Despite this we have taken great care to quality control the images used, and we are confident that our assessment of the expansion of degraded areas is accurate.

Walker and McComb (1992) reviewed Australian based studies on change in seagrass extent and found anthropogenic factors were often associated with seagrass bed degradation, including poor catchment and nutrient management, uncontrolled effluent disposal and dredging (Cambridge and McComb 1984; Larkum and West 1990; Walker and McComb 1992; Kendrick, Eckersley, and Walker 1999; Kendrick et al. 2000). In addition, physical disturbance through trawling, dredging, aquaculture, boating, anchoring and coastal developments have also been identified as causes for seagrass loss/degradation of a comparable scale to that described in the current study (Duarte, Marbà, and Santos 2004; Bastyan and Cambridge 2008; Boudouresque et al. 2009). However, given the low-level of human development and activity in this relatively remote study area it is unlikely that local anthropogenic factors are responsible for the losses observed.

There are multiple natural process that have been implicated in previously observed patterns of reduction in seagrass bed extent, including, marine heatwaves, freshwater inundation, sedimentation, movement of sand sheets and herbivory (Walker and McComb 1992; Kendrick et al. 2000; Duarte, Marbà, and Santos 2004; Boudouresque et al. 2009) that could impact a remote site such as Cliff Head. Studies conducted in various warm-temperate reef systems globally have established the importance of invertebrate and fish grazing patterns and their effects on local biodiversity (Dayton 1975; Ling and Johnson 2009; Norderhaug and Christie 2009; Azzarello et al. 2014). Many of these studies have highlighted sea urchins as having a particularly important role in structuring temperate benthic vegetation assemblages, this is because overgrazing by sea urchins can induce phase shifts from macroalgal canopies or seagrass beds to sea urchin 'barrens' (Breen and Mann 1976; G. P. Jones and Andrew 1990; Norderhaug and Christie 2009; Ling and Johnson 2009). However, in western Australia, herbivory of sea urchins on macroalgae has only been reported in a few localised regions of very high sea urchin density (6.5 individuals per meter squared; Azzarello et al. 2014).

Over grazing by sea urchins has previously been demonstrated to have large scale impacts on seagrass bed extent (Carnell et al. 2020; Langdon, Paling, and Van Keulen 2011). In western Australia, Langdon et al (2011) demonstrated that herbivory could drive seagrass decline at a medium to large scale within Luscombe Bay on Garden Island, Western Australia (c. 33,000 m^2 of seagrass was lost). The study investigated a sea urchin barren that began in 1985 and persisted until 2004 with the regrowth of seagrass occurring after 1993. The study highlighted the speed at which sea urchin driven herbivory can occur and the time taken for *Posidonia* seagrass assemblages to revegetate areas of loss.

Recent extreme climate events have also been found to impact seagrass bed extent along the west coast of Australia. Arias-Ortiz et al (2018) found large losses of seagrass and the associated stored organic carbon in Shark Bay after a marine heatwave that occurred in 2010/2011. Tropicalisation of herbivorous fish assemblages have also been documented in western Australia by Zarco-Perello et al. (2020) who found that the range expansion and increase in abundance of tropical herbivorous fish into higher latitudes after a marine heatwave. Zarco-Perello et al. (2020) found that there was a change in the functional redundancy with the herbivorous fish assemblage, with tropical species filling previously empty niches and as a result, seagrass and seaweed browsing and grazing increased by 15x and 2.5x, respectively. Examination of additional aerial imagery from other sources including Google Maps and LANDSAT indicates that the significant changes in seagrass coverage did not coincide with the 2010/11 marine heatwave at the study site. Despite there being a data gap from 2011 to 2013 for the current study area, the greatest vegetation losses appear to have occurred around 2016 and 2018 and are possibly still ongoing (refer to the videos in the supplementary material). Other studies have suggested the marine heatwave of

2010/2011 may have increased localised recruitment of fish (Bornt et al. 2015) and invertebrate species (N. Caputi et al. 2019), and it could also have led to localised increased recruitment of sea urchins within this region. While the greatest loss of seagrass does not appear to coincide with the marine heatwave, the heatwave may have resulted in ongoing physiological stress on the seagrasses in the study area or increased recruitment of herbivores, such as sea urchins, that could facilitate additional herbivory (e.g. Zarco-Perello et al. 2020).

In the current study, in-water ground truthing of the benthic assemblages revealed high density aggregations of the sea urchin, *Heliocidaris erythrogramma* [Valenciennes, 1846] (Figure 38), associated with areas of vegetation thinning and loss. In other locations this and related species of sea urchins, have been found to cause 'barren' areas, typically associated with a feeding front of sea urchins (Carnell et al. 2020). In the current study, in-water observations of aggregations of sea urchins along the edge of seagrass beds were made indicating feeding fronts (*pers. com.* Langlois, T.). The highest observed density of sea urchins in the current study was 7.14 individuals per m^2 and is comparable to the high densities (6.5 individuals m^2) previously observed by Azzarello et al. (2014), associated with barren areas in macroalgae.
Carnell et al. (2020) observed differing densities of sea urchins in relation to urchin barrens in seagrass beds on the south coast of Australia, with densities of 10.8 individual sea urchin per m^2 on the grazing front, 0.4 individuals per m^2 observed in seagrass and 3.8 individuals m^2 observed in one year old established barrens. In contrast sea urchins in the barren that formed in seagrass assemblages within Luscombe Bay, Western Australia reached densities of 65 individuals m^2 (Bancroft 1992; Langdon, Paling, and Van Keulen 2011), although this was a different and smaller-bodied species. Thus, to better understand the dynamics of the sea urchin herbivory in the study area additional studies should include observations of grazing rate and experimental manipulations of sea urchin density to better understand the potential of sea urchin grazing to impact seagrass assemblages in western Australia.

Within the current study, the areas of seagrass loss, particularly in the southern end of the study area, show signs of scouring and erosion of the underlying sediments. The observed seagrass loss may also be associated with such erosion processes as has been observed previously in other locations (Patriquin 1975). The direction of this scouring is consistent with the dominant wind and wave direction, namely from the south-west (BOM, 2021 2021), and movement of sand in the region could lead to a reduction in seagrass coverage. In addition to the movement of sand from scouring, storms and other severe weather have been documented to cause the erosion of sediments, rhizome and root matter (Patriquin 1975; Thomas 1983; Larkum and West 1990; Kirkman and Kuo 1990).

The vegetated habitats off Cliff Head study area, dominated by seagrass meadows, are likely to be a valuable nursery habitat for many species, in particular the Western Rock Lobster (Edgar 1990a). Aquaria studies have demonstrated a strong preference by early juvenile Western Rock Lobster to associate with *Amphibolis* and *Posidonia* seagrass assemblages (Brooker et al. 2022). Loss or change in density of these habitats, as indicated by this study, could have negative impacts on the survivorship of newly settling early juvenile lobster. Evidence of this was provided by the variable preference by early juvenile Western Rock Lobster Brooker et al. (2022) demonstrated, with the strength of choice for the seagrass assemblages decreasing as the density of these seagrass habitats decreases (Oh 2020; Brooker et al. 2022). The full implications of seagrass loss and change in density need to be assessed by further manipulative and aquaria studies to assess survivorship rates of early juvenile lobster within different habitats, including seagrass beds of varying density.

This study has demonstrated that opportunistic and historical remote sensing data can be used to determine broad scale changes in coastal marine vegetation and used to document a reduction in seagrass coverage. While the specific causes of this decline in vegetation since 2010 are unclear, there is evidence that a shift in hydrodynamics resulting in erosion/smothering of seagrasses and/or a change in herbivory levels (such as a possible pulse recruitment of sea urchins after the 2010/2011 marine heat wave) may account for this loss in habitat. If seagrass assemblages are a key recruitment habitat for Western Rock Lobster, these changes could impact populations of juvenile Western Rock Lobsters in the local region. We recommend that future research in the region increases the scales of observation by taking advantage of new developments in satellite remote sensing imagery and ground truthing using in water imagery collected by towed video or drop cameras, similar to that used in the current study. In addition, we recommend that focused studies should be conducted to ascertain if the aggregations of sea urchins observed are responsible for the observed loss and degradation of seagrass beds.

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Supplementary Material

Image Classification Performance and Accuracy Assessment

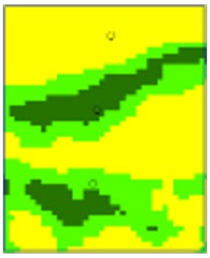
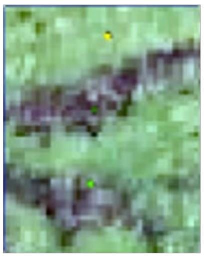
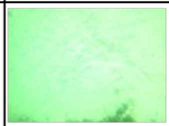
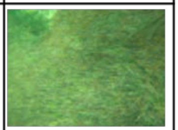
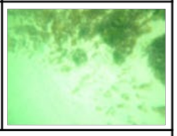
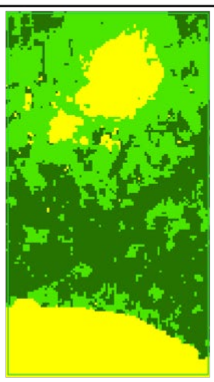
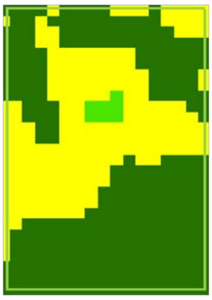
The results of the accuracy assessments indicated that the supervised image classification performed well, the kappa values derived for the classifications ranged from 0.792 - 0.912 (Table 11). It should be noted that the lower kappa values derived from the 2019 image classification can be attributed to the presence of glare and waves on the water's surface impacting the clarity of the imagery. The towed video was not used in accuracy assessments against the other years. Poor Kappa values were obtained by the towed video component of the ground truthing, and this was likely due to the errors with the setback and alignment of the towed video system and GPS receiver.

Table 11 Image Classification and Towed Video Ground Truthing Comparison. The kappa values derived from the accuracy assessment point confusion matrices. Note: * The "2019 - Towed Video" is the kappa derived from a confusion matrix using the towed video data in place of accuracy assessment points.

Classification	Year	Kappa Index of Agreement
Supervised Maximum Likelihood Classification	2010	0.9117
	2016	0.8684
	2019	0.7917
	2019 - Towed Video	0.2323

A detailed comparison between the supervised maximum likelihood classifications, the aerial imagery and the imagery collected using the towed video system is provided in Table 12 below. Towed video data was only available for the most recent sampling period and therefore only the 2019 aerial imagery was compared to the towed video data.

Table 12 A comparison of the results obtained by the supervised maximum likelihood classification, the aerial imagery and the imagery collected using the towed video system.

Imagery Year	Supervised Maximum Likelihood Classification	Aerial Imagery	Towed Video Classification	Towed Video Imagery
2019			100% Sand	
			100% Seagrass	
			24% Macroalgae 28% Seagrass 48% Sand	
2016				
2010				

Study 6 - Chemotaxis is important for fine scale habitat selection of early juvenile *Panulirus cygnus*

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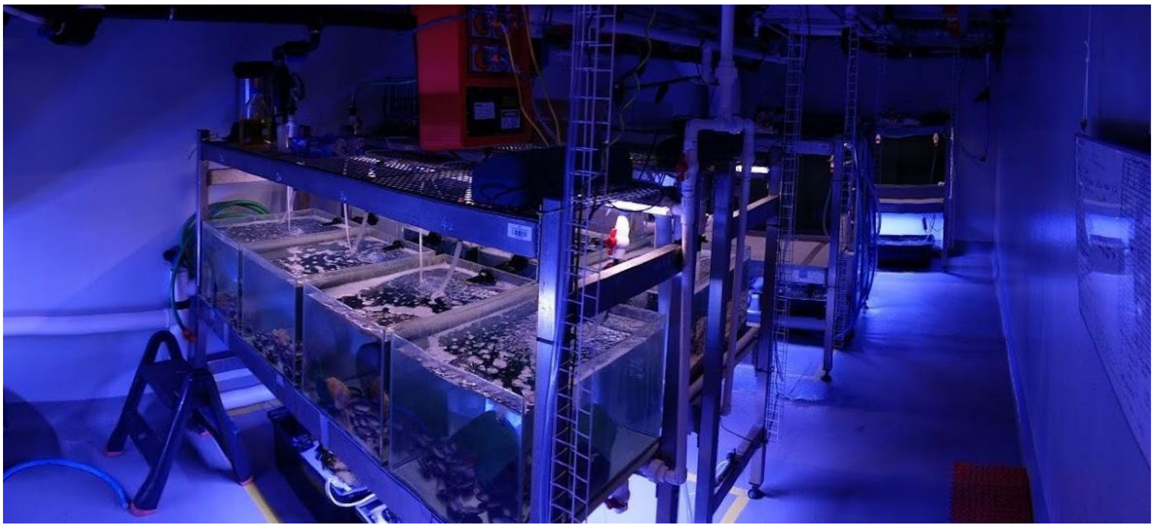

Photo: The controlled environment room where the Y-maze trials were conducted. Photograph Michael Brooker.

Abstract

The Western Rock Lobster (*Panulirus cygnus* [George 1962]) is the basis for Australia's most valuable single species wild caught fishery. The ability of early juvenile Western Rock Lobster to select and settle onto suitable habitats is critical for the recruitment of this commercially important species. Many marine organisms, including the Western Rock Lobster, have highly complex olfactory systems that allow for various behaviours including habitat selection and the location of food. We assessed the active habitat selection of early juvenile Western Rock Lobsters using only chemotaxis in scent-based trials. We used a Y-maze bioassay with which we were able to present individuals with several different natural scent stimuli. This study used three commonly observed broad habitat complexes followed by three fine scale seagrass assemblages to provide different scent stimuli. Seagrass habitats were chosen significantly more often by the juvenile lobsters in the broad habitat scale trials over bare sand and turf habitats. At a finer scale, lobsters showed a mixed response but tended to choose the canopy forming seagrass species, *Amphibolis antarctica* [(Labillardière) Sonder & Ascherson ex Ascherson, 1868] and Posidonia australis [Hooker, 1858] significantly more often than the other scents provided. This study developed a Y-maze chemotaxis assay for *P. cygnus* and confirmed that they respond to habitat related scent cues. These findings suggest the importance of seagrass habitats to early juvenile Western Rock Lobsters and the potential impacts that habitat change may have on the successful recruitment of this commercially important species.

Introduction

The West Coast Rock Lobster Managed Fishery (WCRLF; *Panulirus cygnus* [George 1962]) is Australia's most valuable wild caught single species fishery worth ~$450 million dollars per annum (Caputi et al. 2015; de Lestang, Caputi, and How 2016; Nicolaou and Hammond 2017). The management of the WCRLF has been recognised internationally and it was the first to receive Marine Stewardship Council certification in 2000 (Bellchambers et al. 2012). The management of this fishery has been aided, in part, by a settlement index using artificial seagrass collectors which has been sampled continuously at nine locations along the coast since 1964 (B. F. Phillips and Hall 1978). This index has been used to predict recruitment to the fishery with a 3 - 4 year lag (the time taken to grow to a legal size; B. F. Phillips and Hall 1978) and has been found to correlate strongly with the abundance of two to three year old juveniles in commercial catches (B. F. Phillips and Hall 1978). Despite the importance of this relationship there is currently little known about the intermediate early juvenile life stages of this lobster due to the highly cryptic nature of this life stage. For early juvenile lobster post-settlement, there is a lack of information on behaviour and habitat use in the period up until they appear in fisheries independent surveys at two to three years post settlement (B. F. Phillips and Hall 1978).

The ability of post-larvae to select and settle onto suitable habitats is critical for the recruitment of many marine organisms (R. K. Cowen, Paris, and Srinivasan 2006). Identifying the aspects of habitat required for successful recruitment of post larvae is equally important as it may explain the processes that underpin the structures of adult populations (Robert K. Cowen et al. 2007, Pineda et al. 2007). The Western Rock Lobster has a significant larval period that lasts for 9 - 11 months during which it is known as a phyllosoma which remains in the plankton during this life history stage (B. F. Phillips and Penrose 1985). At the conclusion of the larval period, the phyllosoma completes a final moult into the non-feeding puerulus life history stage which resembles the adult body form. The puerulus stage includes a long directional swim to shore and settlement on nearshore reefs (Macmillan, Phillips, and Coyne 1992). Work conducted by Phillips and Penrose (1985), Booth (1989) and observations presented in Jeffs et al. (2005) suggest that the pueruli of spiny lobsters in the family *Palinuridae* [Latreille, 1802] may respond to underwater sound as a settlement and direction finding cue. Thus, it can be hypothesised that underwater sound and other broad scale cues will guide *P. cygnus* pueruli towards the coast and settlement whereas the finer scale cues such as scent may help guide the lobsters to appropriate habitats during and post settlement.

Marine decapods have well developed chemosensory abilities through the use of their antennules which serve as olfactory organs capable of sensing particular chemical cues for a wide range of purposes including feeding, courtship and predator avoidance (Daniel, Shineman, and Fischetti 2001) Previous studies on the settlement cues for lobsters have also found chemotaxis and other chemosensory cues to be important, but to operate effectively at scales of less than 50 km (Jeffs, Montgomery, and Tindle 2005). Boudreau et al. (1993) found that post larvae of the clawed lobster *Homarus americanus* [Milne Edwards, 1837] swam toward the scent released by adult conspecifics and avoided the scent of predators while Atema and Engstrom (1971) examined the communications between *H. americanus* through the use of sex pheromones. Herrnkind and Butler (1986) conducted an experiment to assess the settlement choices of *Panulirus argus* and found that highly branching red algae and seagrasses are important settling habitats for post larval lobsters. Research on larger two to three year old sub adult *P. cygnus* have found them to be closely associated with the seagrasses *Amphibolis spp* (generally *Amphibolis antarctica* [(Labillardière) Sonder & Ascherson ex Ascherson, 1868] and *Amphibolis griffithii* [(Black) den Hartog, 1970]) characteristic of shallow-nearshore habitats throughout much of the species distribution (Jernakoff, Phillips, and Maller 1987; Edgar 1990c, 1990b; 1993) thus we hypothesise that post-settlement, early juvenile *P. cygnus* will be attracted to similar habitats. With marine ecosystems experiencing changes due to natural and anthropogenic impacts on climate (Jordà, Marbà, and Duarte 2012; Koch et al. 2013; Koenigstein et al. 2016), understanding the role of habitats in the settlement and recruitment of commercially important species has become important to inform fisheries science.

An extreme marine heatwave affected the western Australian coastline in the austral summer of 2010/2011 (N. Caputi et al. 2014; Alan F. Pearce and Feng 2013; Smale and Wernberg 2013). During this event, peak nearshore temperatures rose to approximately 5°C above the average temperatures along the central west coastal region over a period of one week at the end of February and early March 2011 (Alan F. Pearce and Feng 2013). This led to the significant loss of extensive areas of the previously dominant shallow-nearshore habitats, including seagrass (N. Caputi et al. 2019; A. Pearce et al. 2011; Thomson et al. 2015; Fraser et al. 2015) and macroalgae (Wernberg et al. 2016; Smale and Wernberg 2013; Wernberg et al. 2013). This change also led to an increase in turf dominated habitats across the centre and north of the fishery. Some mortalities of *P. cygnus* were reported in shallow water areas of the fishery along with many other species but these were not thought to be extensive (A. Pearce et al. 2011). Following the marine heatwave, fisheries scientists observed a disjoint between the puerulus settlement index and the expected index of juvenile abundance from fisheries dependent and independent surveys (N. Caputi et al. 2019; Kolbusz, de Lestang, et al. 2021) with the greatest disjoint being observed in the shallow water areas in the northern end of the fishery. The northern end of the fishery is where habitats were suspected to be most impacted by the marine heatwave

(Wernberg et al. 2013). This disjoint may be due to an increased mortality in early juvenile lobster due to either the loss or a reduction in the density of nearshore habitats or food assemblages after the marine heatwave. The marine climate of western Australia is warming at a rate of 0.02°C per year (Cheung et al, 2012) and the frequency of marine heatwaves has been predicted to increase (Smale and Wernberg, 2013). Therefore, a better understanding of the settlement and recruitment ecology of Western Rock Lobster will improve our understanding of the potential risks presented by these warming trends.

The current study used a series of Y-maze aquaria to examine habitat preference in early juvenile *P. cygnus* through chemotaxis and to assess if there is evidence of active selection between the different habitats, commonly found on the nearshore reefs throughout most of the species' range. Given the current knowledge on the distribution of early juvenile and sub adult *P. cygnus* it is predicted that seagrass habitats will be preferred. Y-mazes are a good tool for the assessment of the choices made by a wide range of animals (nautilus (Basil, Lazenby, and Nakanuku 2002), starfish (Dale 1999), reef fishes (Gerlach et al. 2007), and lobsters (Kenning et al. 2015) and generally consist of a mixing chamber that is fed by two or more different stimuli. Y-mazes have two choice chambers that are supplied with two different water sources containing different scents, water chemistry or other comparisons. To date there have been no habitat choice and preference experiments conducted with early juvenile *P. cygnus* due to the highly cryptic nature of these animals, however the current study found a novel source of recently settled animals from the established puerulus collectors to examine environmental cues such as habitat type and this study will provide a template for further investigations of spiny lobster habitat and food preferences.

Materials and Methods

Study Animals

Newly settled early juvenile *P. cygnus* (≤ 28 d post settlement; 224 animals with a 10 - 15 mm carapace length) were collected using 42 puerulus collectors (B. F. Phillips and Hall 1978; B. Phillips et al. 2003) at 10 sampling locations between Seven Mile Beach, Western Australia (29.171071°S, 114.888330°E) and Cliff Head, Western Australia (29.518153°S, 114.994436°E). The puerulus collectors used in the sampling of this study were those maintained by Department of Primary Industries and Regional Development – Fisheries to monitor the settlement across the fishery and were all located on the leeward side of shallow nearshore reefs, thus the localised habitat surrounding each collector consisted of seagrass meadow, reef habitats (including turfing algae), and unvegetated sand. Collectors were serviced monthly by shaking or spinning the collectors following protocols outlined in Phillips and Hall (1978; for Phillips type collectors) and Phillips et al. (2001; for Sandwich type collectors). Monthly servicing resulted in a series of monthly cohorts of lobster for trials.

Animal Transport and Housing

Early juvenile *P. cygnus* were transported to the Indian Ocean Marine Research Centre (IOMRC), Waterman's Bay, Western Australia in aerated transport canisters (25 L High Density Polyethylene [HDPE] water storage drums) each containing a sheet of green nylon scourer pad. On arrival at the IOMRC, animals were acclimated and housed in a controlled environment room (CER) in 110 L glass aquaria (600 mm L x 450 mm W x 450 mm H) with a flow through seawater system supplying fresh filtered (at ~ 90 µm) seawater at a rate of approximately 125 L hr^{-1} within approximately 1°C of ambient ocean water temperature. The aquaria contained a suitable number of artificial habitats made from limestone and green nylon scourer pads. These artificial habitats allowed the lobsters to hide and seek shelter without providing natural habitats that may bias habitat selection during the trials. The early juveniles were fed primarily crushed black mussels (*Mytilus spp*.). Early juveniles were graded into equivalent size groups (small [< ~ 12 mm carapace length] large [> ~ 12 mm carapace length] and oversize [> 15 mm carapace length]) as part of regular monitoring and cleaning to reduce the potential for cannibalism and to ensure an equivalent size class (10 - 15 mm carapace length) was used in all trials. Animals that were oversize (> 15 mm carapace length) were not included in the trials.

The lighting regime in the CER was controlled using a Phillips iPlayer® 3 DMX Lighting Controller connected to an eldoLED LINEARDrive 180 DC LED driver and PureLED SMD5050 RGB+W IP67 LED lighting strips (14 W m^{-1}) in 1 m lengths. A lighting program was designed to mimic a circadian lighting regime (fade in/out over a 24-hour period) using an astronomical clock that varied with the seasons. The lighting system allowed trials to be conducted under dark conditions using red lighting to minimise stress and disturbance to the animals (Weiss et al. 2006). The day-night cycle for the aquarium room was inverted to allow night trials to be conducted during normal working hours. The time shift occurred over approximately one week followed by one week at the new inverted time before trials commenced to minimise the impacts of the time change.

Scent Stimuli

Scent stimuli were selected from the dominant habitats which occur in the shallow water areas of the *P. cygnus* fishery as this is where the highest settlement rates typically occur (Meagher 1994). The habitats used by this study were classified into two different scales, "broad habitats" and "fine habitats." The broad habitat assemblages included a mixed seagrass meadow, mixed turf habitat and unvegetated sand while the fine habitat assemblages included three common types of seagrasses located at the sites: *Posidonia australis* [Hooker, 1858], *Amphibolis antarctica* and a mix of *Halophila ovalis* [Hooker, 1858] and *Zostera tasmanica* [(Martens ex Ascherson) den Hartog, 1970] (Table 13).

Table 13 The habitat assemblages used to provide scent stimuli.

Habitat Category	Primary Species	Description of habitat
Broad Scale		
Turf	Halophila ovalis and Heterozostera tasmanica	Mixture of algae including *Sargassum spp*., *Caulerpa spp*., Coralline algae and green filamentous algae. Seagrasses including *Halophila ovalis* and *Heterozostera tasmanica* with representative limestone reef. Turf habitats were sampled from the reef platform.
Mixed Seagrass	Posidonia australis and Amphibolis antarctica	Dense beds of *P. australis*, *P. sinuosa* and *A. antarctica* also including the associated epifaunal community. Sampling included both the leaf and rhizome material.
Unvegetated Sand	NIL	Bare sample of sand including the associated infauna.
Finer Scale		
Amphibolis	Amphibolis antarctica	*A. antarctica* including rhizome, canopy and all associated flora and fauna.
Posidonia	Posidonia australis	*P. australis* including rhizome, canopy and all associated flora and fauna.
Halophila	Halophila ovalis and Heterozostera tasmanica	*H. ovalis* and *H. tasmanica* including rhizome, canopy and all associated flora and fauna.
Control		
Control – ambient scent (from seawater intake)	NIL	Seawater from the aquarium facility intake, collected adjacent to sparse benthic habitats characteristics of the region and of similar composition to those presented as assays in the scent-based choice experiment[1].

Six representative samples for each of the stimuli were collected (one sample for each y-maze) following the sampling methods used by Edgar (1990a) and consisted of haphazardly placing a square plastic container (12.5 mm x 12.5 mm) over the habitat and cutting around the sample area with a knife to a depth of 100 mm or to the depth of rock if < 100 mm. Representative pieces of limestone bedrock were collected as part of the turf algae habitat but logistical issues prevented the removal of substantial pieces of rock. The contents of the plastic container were then transferred to a calico sample bag above the water to prevent the loss of epiphytes and epifauna. Where the container could not be used due to seagrass canopy, a bottomless container and calico sample bag was placed over the sample prior to cutting the substrate/rhizome. All samples were held in seawater and transported to the laboratory within 6 h. On arrival at the laboratory the scent stimuli samples were transferred to well-lit 150 L holding tubs supplied by 25 L/hr of filtered (90 µm) seawater. The water supply to the holding tubs was shut off for two hours prior to the commencement of the trials and water was transferred from the holding tubs to the reservoirs supplying the Y-mazes immediately prior to each trial to ensure freshness of the scent - this water was held in the reservoir for no longer than 20 minutes).

Trials

All laboratory trials were conducted within a single CER using six identical Y-mazes. The CER ensured the lighting regime for the aquaria was controlled and other potential external disruptions could be minimised and if occurred, would likely impact all trials in a similar manner. All trials were conducted at natural ambient ocean temperatures ranging from 22.6 °C to 24.1 °C. Seawater was supplied to the aquaria using a gravity fed system and all seawater was filtered to at least 90 µm but otherwise untreated (refer to Supplementary Figures for further details). Y-mazes were similar in design and dimensions to those used by Kenning et al. (2015), constructed of 4 mm thick grey coloured PALOPAQUE™ Flat Opaque PVC Sheet cut to size and welded using hot air and PVC welding rods. The PVC material provided an inert polished flat surface that was easily cleaned between trials. The Y-mazes had the following overall outside dimensions; 800 mm L x 200 mm W x 150 mm H, water volume of ~ 20.8 L when running (Figure 40).

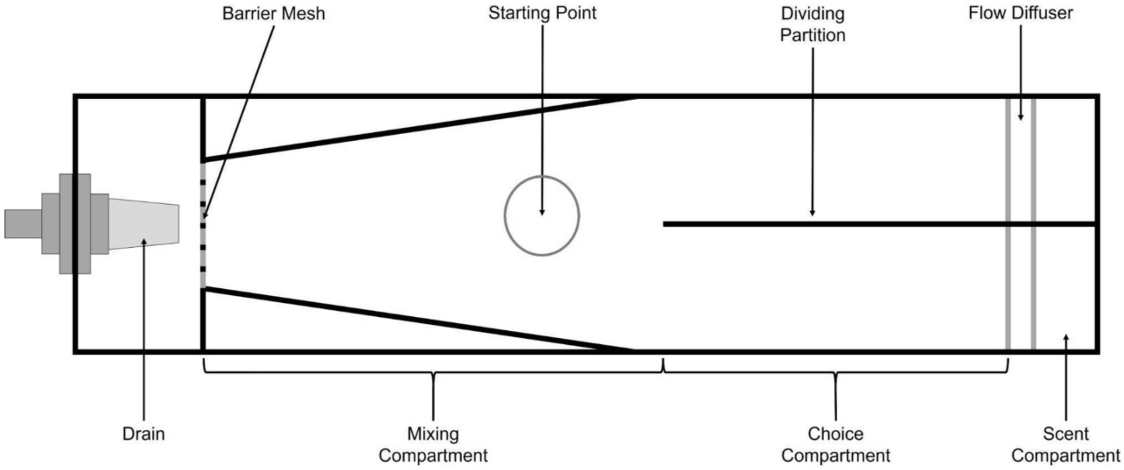

Figure 40 Top view of the Y-maze showing the various regions including the starting location.

The flow regime of each Y-maze was assessed using coloured dye to ensure a quasi-laminar flow with a stable water/odour speed of *ca*. 1.5 cm s^{-1}. The dye test also ensured that mixing of the two water supplies occurred beyond the mixing compartment with no backflow into the mixing compartments thus presenting the lobster with the contrasting smells at the beginning of the trial. Each mixing compartment on the Y-maze (two compartments per Y-maze) was supplied with filtered seawater and a single scent. Each of the scent stimuli were filtered to 90 µm and then held in a reservoir that was gravity fed to each Y-maze using dedicated lines (one dedicated line for each scent – these lines were only ever used for a single scent to avoid the potential for cross contamination). A summary of the flow rates is provided in Supplementary Table 14.

The trials conducted for this study were conducted in two rounds, the first round examined the broad habitat types (324 trials with 126 animals; 12 ± 2 mm CL) while the second round examined the specific seagrass species (288 trials with 98 animals; 12 ± 2 mm CL). All trials were conducted at simulated night (approximately 21:00 to 03:00 in simulated time and 09:00 to 15:00 actual time) and under low red light (620-630 nM). The seawater lines were thoroughly flushed, and all inline filters were cleaned prior to any trials commencing. Prior to the commencement of the trials, a stratified random allocation of scents was performed to ensure all scent combinations were presented in both sides of all y-mazes in a random order. The Y-mazes were filled and allowed to stabilise for approximately 90 s before the appropriate scent stimuli were introduced. A 90 mm PVC coupling was placed in the centre of Y-maze (refer to Figure 40) as a holding compartment with a randomly selected early juvenile lobster placed inside to acclimatise for 5 min following the handling and transfer. This allowed the lobster to be exposed to the scent prior to the commencement of the trial. After acclimatisation, the coupling was gently removed, and this signified the start of each trial. Each trial, which lasted at least 10 min, was filmed using a GoPro Hero 3+ mounted above each Y-maze. The 10 minute trial duration was established following a pilot study using crushed black mussels (*Mytilus spp*.) which obtained a strong consistent response and is comparable to the 5 minute duration used in the study conducted by Kenning et al. (2015). A successful trial was defined when the lobster moved from the starting point towards one of the stimuli and settled. For this experiment a lobster was deemed as having settled when it remained stationary in a location for at least 3 minutes. Following the conclusion of the trial, each lobster was placed in a different holding tank and the Y-mazes were drained and washed before another trial began. The early juvenile lobsters used in the Y-maze trials were each subjected to the trials three times, with a separation of ≥3 days.

Video Analysis

Each trial video was given a unique identifier and all trials were watched without knowledge of which stimulus was present in each side of the Y-maze to avoid observer bias. Trials were scored as either; lobster chooses side A (and settles), lobster chooses side B (and settles), lobster makes no obvious choice, and lobster does not move. The choice of a side of the Y-maze was based on the compartment that the lobster settled in and spent the most time in. Lobsters were deemed to have made no choice if they did not move from the starting location, did not enter either compartment or repeatedly swapped between compartments spending less than 60% of the time in any one of the compartments. During the majority of trials, the lobsters settled in one side of the Y-maze relatively quickly (114 sec average across all trials) and generally did not move after this point.

Data Analysis

A successful trial, where a lobster made an obvious choice, occurred in 88.6% of the broad habitat trials and 81.3% of the fine habitat trials. A total of 612 trials were conducted across all treatments, using 224 early juvenile lobsters, meaning each lobster was used either two or three times (average 2.7 times). For both broad and fine habitat scale trials, the estimates of tank/side preference did not indicate any bias from the side of any tank (P always > 0.05). To assess whether the early juvenile lobster showed a level of adaptation to the trials, the analysis for both broad and fine-scale trials was modified to include scaling parameters unique for consecutive trials. Since no significant change in behaviour was detected between subsequent exposures (presented in the supplementary material as Figure 45 & 46), these parameters were removed, and the model refitted to increase the power of the analysis and simplify the results.

A preference model was used to determine whether the early juvenile lobster's choice of the various scent stimuli differed significantly from random choice. The model assumed that each of the early juvenile lobsters preferred one scent over another and this preference would increase its likelihood to choose one water source over another. For the broad scale trials there were four preference parameters (P_w where $_w$ represents a water source) from seagrass, turf, control, or sand. There were three preference parameters for the fine scale trials; water sourced from either Amphibolis, Posidonia or Halophila ovalis / Zostera spp. The model also contained a number of "bias" parameters, which allowed it to assess the impact of puerulus accumulation and tank construction. Due to a lack of lobsters, each individual was subjected to the trials three times, with a break of ≥ 3 days in between rounds of trials. To assess for a change in behaviour, eight trial/water source-specific parameters (T_w), were included in the model which allowed for model to scale estimates from trial one for describing the early juvenile lobster's response in the two subsequent trials. If the trial scaling parameters were found not to differ significantly from one, thus indicating no significant change in behaviour, they were removed from the model to increase sample size and simplify the interpretation of results.

The impact of tank position and construction was examined using eight bias parameters; unique for each tank/side (βt, s where t represents tanks 1 – 6 and s represents either the left or right side of a tank. This permits any inherent preference for a specific side of a tank to be determined and, if present, to be removed from the estimates of P_w. Bias parameters were mean centred using the equation;

$$\beta_{t,s} = \beta_{t,s} \bigg/ \left(\sum_{i=1}^{8} \beta \Big/ 8 \right),$$

before being used in the model equation to calculate the relative likelihood of the *i*th early juvenile choosing a specific water source over another (α_i) given the tank and side of the water source:

$$\alpha_n = P_{a,t,s}\delta_s^T \Big/ \left(P_{a,t,c}\delta_c^T + P_{a,t,o}\delta_o^T\right) + \beta_{a_{t,c}}$$

where *a* is the water source on the side of the Y-maze chosen (*c*) and δ is the alternate water source provided on the side of the Y-maze not chosen (*o*). The negative loglikelihood of the choices made by all early juvenile (*n*) given the estimates of P_w and $\beta_{t,s}$ was:

$$\lambda = \sum_{i=1}^{n} -\ln\left(\alpha_n\right),$$

The model was built in R (R Core Team 2021), and solved using the nlminb function, with confidence intervals around the maximum likelihood estimate (MLE) being produced by bootstrapping the observed data 1000 times. The model was successfully validated prior to use through testing the model on an artificial data set.

Results

Broad Habitats

Between the broad habitat assemblages (Table 13), the mixed seagrass assemblage was the most frequently chosen habitat from the alternative habitats offered (all P < 0.05). Early juvenile lobsters chose the seagrass assemblage in 60% (±7%) of trials when offered against turf habitat (P = 0.020), in 66% (±10%) of cases when offered against the sand assemblage (P = 0.004) and in 70% (±8%) of cases when offered against the control (P < 0.001; Figure 41).

There was some evidence that the turf assemblage was more frequently chosen (60% ±9) than the control (P = 0.019) but there was no significant difference when offered against the sand assemblage (55% ±10, P = 0.121).

Fine Habitats

The *Amphibolis antarctica* assemblage was the most frequently chosen fine scale habitat assemblage (Table 13) overall when presented against the assemblages of *Posidonia australis* (60% ±11, P = 0.068), *Halophila ovalis* and *Zostera sp* (64% ±12, P = 0.015) and the control (77% ±12, P<0.001, Figure 42).

Posidonia australis was the marginally preferred habitat (56% ±12, P = 0.015, Figure 42) when offered against *Halophila ovalis* and *Zostera sp* but more strongly preferred than the control (70% ±11, P < 0.001). *Halophila ovalis* and *Zostera sp* was the preferred habitat assemblage (65% ±13, P < 0.001) when offered against the control.

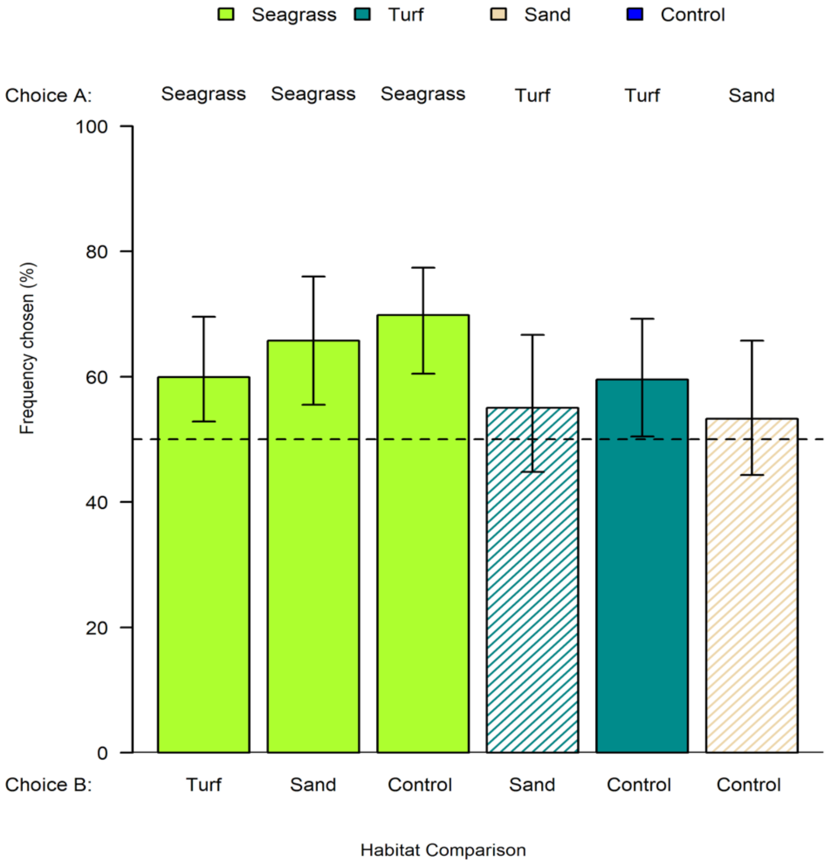

Figure 41 Broad habitat comparison trials showing the habitat chosen more often as indicated by the colour of the bars and the habitat listed at “Choice A”. The comparison habitat is listed at the bottom of each bar at “Choice B”. Solid fills indicate significance at the 95% confidence interval and hashed fill indicates non significance at this level. The error bars represent the 95% confidence intervals. Control was never chosen most often and so none of the bars are coloured blue.

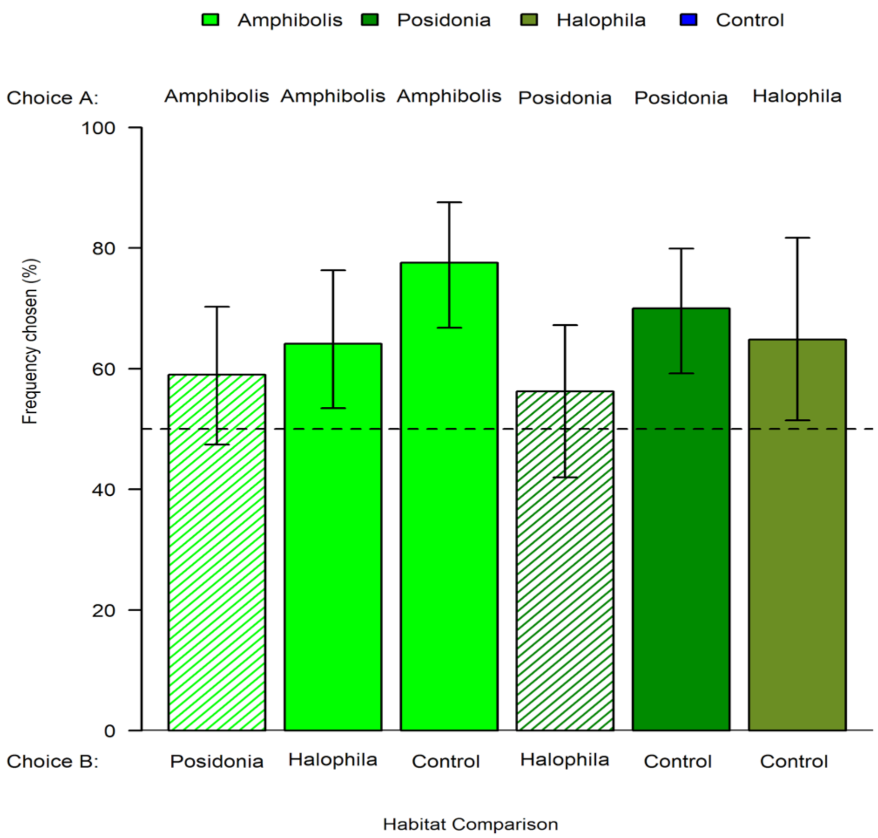

Figure 42 Fine habitat comparison trials showing the habitat chosen more often as indicated by the colour of the bars and the habitat listed at "Choice A". The comparison habitat is listed at the bottom of each bar at "Choice B". Solid fills indicate significance at the 95% confidence interval and hashed fill indicates non significance at this level. The error bars represent the 95% confidence intervals. Control was never chosen most often and so none of the bars are coloured blue.

Discussion

This study successfully demonstrated active habitat selection of early juvenile *P. cygnus* (< 30 days post settlement, 10 - 15 mm carapace length) using chemotaxis in scent-based trials. In laboratory-based Y-maze aquaria trials, early juvenile *P. cygnus* chose the mixed seagrass assemblage scent more frequently than any of the other broad habitat assemblages. When specific seagrass species assemblages were isolated in fine-habitat scale trials, *Amphibolis spp* and *Posidonia australis* assemblages were chosen most frequently. The *Amphibolis spp* assemblage was chosen significantly more than the *Halophila* assemblage and control treatment and there was a trend for *Amphibolis* to be chosen more frequently in a direct comparison to *Posidonia* which approached statistical significance ($P = 0.068$). These findings are highly novel as early juvenile *P. cygnus* are notoriously difficult to detect and study given their size and cryptic nature. Identifying the preferred habitats for this vulnerable life stage is important to inform the management of this valuable fishery, specifically given the suspected recent broad scale changes in nearshore habitats in this region subsequent to marine heatwaves and the predicted changes in climate and increased frequency of marine heatwaves that will likely alter nearshore assemblages and habitat further (Wernberg et al. 2013).

Amphibolis and *Posidonia* are two of the most common and dominant seagrass genera present along the lower west coast of Australia (Kilminster et al. 2018). These seagrasses cover a significant portion of the shallow water habitats along the lower west coast of Australia, particularly in the study area where these meadows can extend for several km from the coastline (Edgar 1990a). Both *Amphibolis* and *Posidonia* can be considered to be canopy forming seagrasses (Cambridge and McComb 1984) with the fronds and leaves extending to approximately 0.5 m from the substrate in the samples collected for this study. This canopy creates a greater habitat complexity and is likely to provide greater potential for camouflage and protection from predators whilst providing food of early juvenile lobsters, which includes epifauna and epiphytes. Edgar (1990a) investigated the invertebrate assemblages associated with these seagrass dominated habitats and found the highest densities of likely food items for early juvenile lobsters in the *Amphibolis* habitat, followed by Turf and *Halophila/Zostera* assemblages while the *Posidonia* assemblage had among the lowest densities of invertebrates observed. The contrasting canopy structure of the *Amphibolis*, *Posidonia* and *Halophila* likely explains this variation with the more complex branching structure of *Amphibolis* likely provides more interstitial habitat than within *Posidonia and Halophila* assemblages. The choice demonstrated by early juvenile *P. cygnus* for *Amphibolis* over the less complex *Halophila/Zostera* species and near significant choice for *Amphibolis* over *Posidonia* likely represents a preference for either the increased complexity of the habitat for shelter or the increased abundance of likely prey species which occur in *Amphibolis* meadows (Gartner et al., 2013). This relationship may not remain consistent for varying seagrass densities and should be a focus for future research. Although our research did not link habitat preferences to either survival or growth rates, the use of recently settled puerulus in our trials does suggest that these preferences are an inherited behaviour and that the biological basis behind preferring one habitat over another would be beneficial for the puerulus and early juvenile lobsters (*sensu* Putman, et al 2014). The possible benefits for choosing this habitat over others could be related to the greater availability of habitat providing shelter, the availability of food or other factors that increase their survival.

Marine benthic habitats can and often do change over time, through various natural and anthropogenic processes, and this may impact on the survival and growth of species that use these habitats (Cheung t al, 2012; Smale and Wernberg 2013). For example, a decline in coral cover caused a parallel decline in fish biodiversity both inside and outside reserves (Geoffrey P. Jones et al. 2004), which was likely due to decreased availability of food and habitat. For *P. cygnus*, the extent, coverage, and quality of seagrass meadows, particularly *Amphibolis*, and their associated assemblages along the coast are likely to be important for the successful recruitment of post-settlement lobsters as indicated by the work of Edgar (1990a, 1990b), Jernakoff et al (1987, 1993) and the current study. Therefore, understanding, and documenting habitat coverage and change could provide valuable information on the likely recruitment into the fishery which could complement existing indices of puerulus settlement. Historical and future trends in indices of sub-legal 2-3 year old and 3-4 year old lobster in fisheries catches across the fishery could be contrasted with habitat change information from sources such as satellite imagery (such as LANDSAT) and aerial photography surveys (such as those conducted by Landgate [West Australian Government]; Mumby et al. 1997; Phinn et al. 2008; Roelfsema et al. 2015). In addition to examining infield data, additional aquaria trials of habitat choice could examine the preference between physical habitats, potentially using mesocosms, to better understand the impact of change in seagrass density and coverage on the survival of early juvenile lobster. Future studies should consider further refinement of the y-mazes and trial procedures with a particular focus on the turbulent mixing zone and the use of ozonized or carbon filtered seawater with all scent components removed.

The economic value and sustainable management of the WCRLF is well recognised (Bellchambers et al. 2012; de Lestang, Caputi, and How 2016; Nicolaou and Hammond 2017). The puerulus settlement index has historically been a reliable predictor of sub-legal catches 2 to 3 years later and recruitment to the fishery 3 to 4 years later, contributing to the management of the fishery (de Lestang, Caputi, and Melville-Smith 2009). The 2010/2011 extreme marine heatwave (MHW) led to the loss of extensive areas and change in the density of previously dominant shallow-nearshore habitats, including seagrass and macroalgae, and an increase in turf dominated habitats across the centre and north of the fishery (Wernberg et al. 2016). In the years following the heatwave, fisheries scientists have begun to observe a disjoint between the puerulus settlement index and the undersized lobster recruitment index from fisheries independent surveys (N. Caputi et al. 2019). This disjoint was observed to be strongest in near-shore shallow water areas in the northern half of the fishery. Immediately following and during the MHW large amounts of detached and dead seagrass and macroalgae were reported along beaches or floating near the shoreline (A. Pearce et al. 2011; Alan F. Pearce and Feng 2013). In Shark Bay at the warm extent of the fishery, large amounts of *Amphibolis* were observed to die off during the same MHW (Arias-Ortiz et al. 2018). Work conducted by Butler et al (1995) observed a cascading disturbance where a cyanobacterial bloom caused mortality of sponges, a crucial habitat for *P. argus* which led to a shift in the distribution of juvenile lobsters to the remaining sponges and artificial habitats. This current study highlights the potential for habitat change to explain the observed decrease in recruitment in the warmer end of the fishery subsequent to the MHW (N. Caputi et al. 2019). Based purely on lobster species distribution data, Cheung et al. (2012) predicted that by 2055 with the Western Rock Lobster distribution shifting by 77km in this time period. Cheung et al. (2012) did not consider concomitant changes in habitat distribution, which could further compound and exacerbate changes in species distribution. The current olfactory preference study provides supporting evidence that seagrass habitats are preferred and therefore potentially critical habitats to the survival and successful recruitment of early juvenile *P. cygnus*.

This is the first study to examine the habitat preference of the cryptic post-settlement of early juvenile *P. cygnus* with a carapace length <25mm, and which cannot be reliably caught in traps until ~45 mm carapace length (~45 mm carapace length; Jernakoff 1990). Studies previously conducted on this life stage have been very time consuming and had a reliance on divers performing extensive searches in nearshore reef habitats (Jernakoff 1990). Studies conducted by Edgar (1990c; 25 to 85 mm carapace length animals) and Jernakoff et al. (1993; <25 mm carapace length animals) examined the diet and foraging of various larger size classes of *P. cygnus*. It was found that the larger, 45 - 80 mm carapace length lobsters generally foraged at night in the sparse *Zostera spp.* and *Halophila spp.* meadows away from the reefs at Seven Mile Beach (Joll and Phillips 1984; Jernakoff, Phillips, and Maller 1987; Edgar 1990c) while the smaller individuals of comparable size to this study (10 - 25 mm carapace length) tended to be observed in ledges and caves adjacent to *Amphibolis* and macroalgae during the day and forage at night amongst *Amphibolis spp.* and macroalgae on the reefs at Seven Mile Beach (Jernakoff 1990; Jernakoff, Phillips, and Fitzpatrick 1993), however these previous observations were based on very small numbers of observations (Pers. Com. Edgar). Given the limitations of studying these animals in their natural habitat, sourcing animals from collectors and conducting aquaria studies such as Y-mazes provide a valuable opportunity to improve our understanding of this life stage that represents an important but poorly known step between settlement and recruitment to the fishery.

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Supplementary Material

Y-maze Design and Installation

Six replicate aquarium systems were constructed and installed as per the design shown in Figure 43, below.

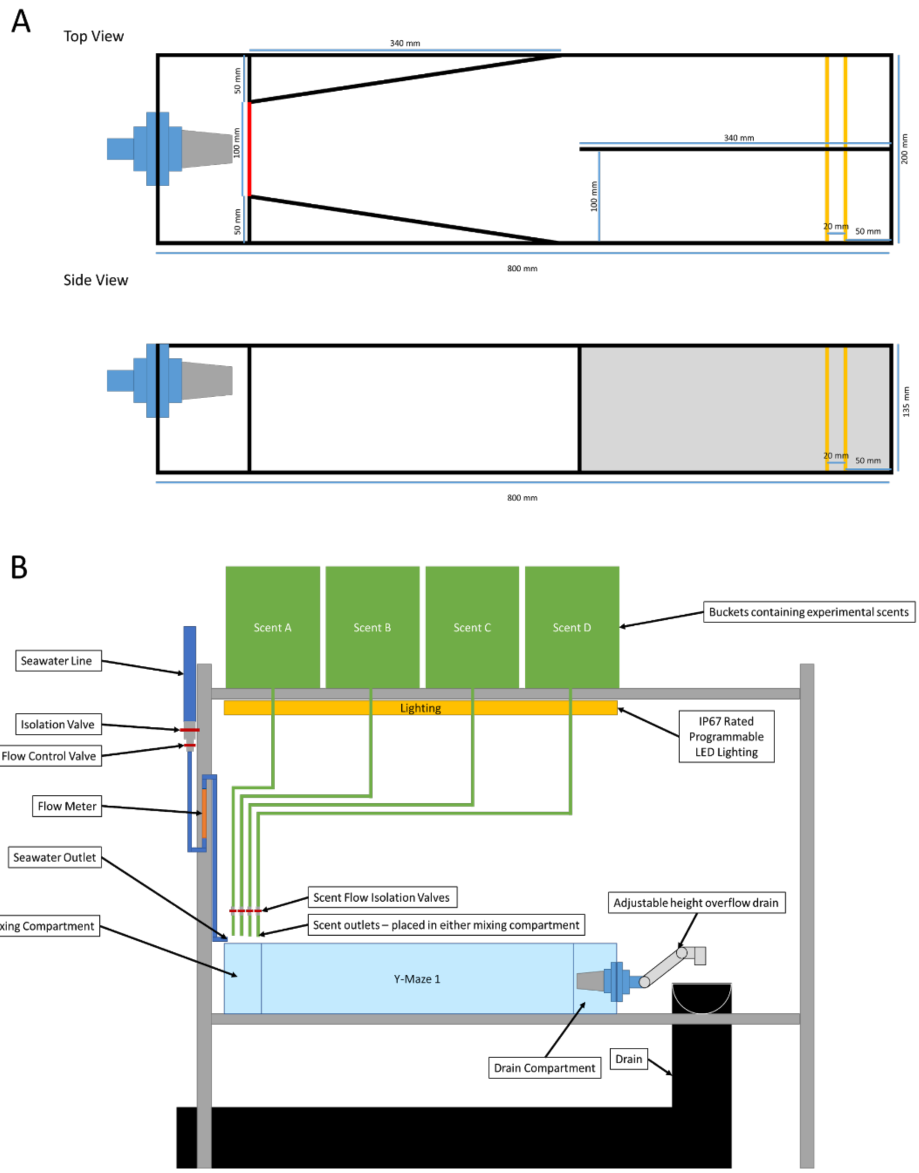

Figure 43 (A) Design of the Y-maze aquaria. (B) Installation schematic of the Y-maze and associated infrastructure (not to scale).

The design of each Y-maze consisted of five key components;

1 – The scent compartments - one compartment for each side of the Y-maze. This section allows for the scent and incoming water to mix prior to entering the Y-maze,

2 – The flow diffuser - two sheets of PVC with small holes drilled ensured that the flow of water diffused across the depth and width of each mixing compartment.

3 – The choice compartments - one compartment for each side of the Y-maze that the animal can access which contains only one scent.

4 – The mixing compartment - the section where both choice components flow to and allow the two scents to mix. This is where the animal is placed for the beginning of each trial.

5 – The drain compartment - located at the end of the Y-maze and drains from the centre of the end of the tank to ensure an equal drawdown of water across the width and depth of the Y-maze.

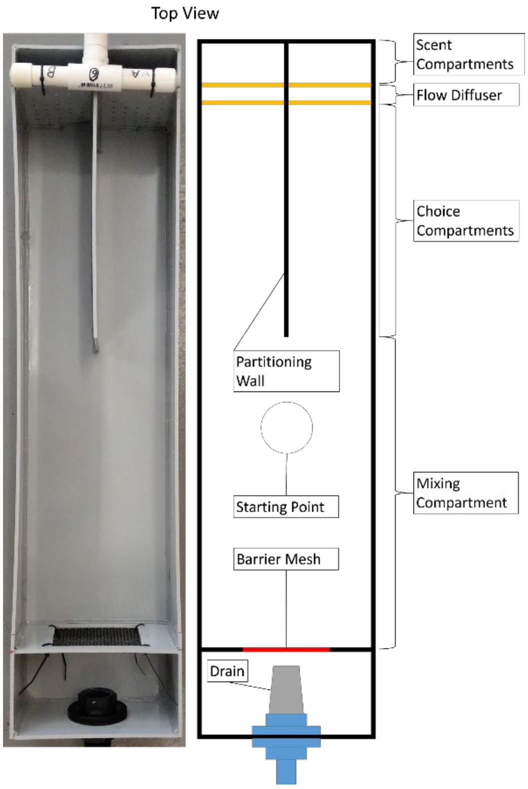

Figure 44 Top view of the Y-maze showing the various components including the scent compartments, choice compartments and the starting location.

Y-maze Operation

Water and scent containing water from the seagrass aquaria were both plumbed into the scent compartments to allow for sufficient mixing before entering the choice compartments (Figure 44). The flow rates for these water sources are details below in Table 14.

Table 14 Summary of flow rates and water sources for the Y-maze mixing compartments.

Mixing Compartment	Purpose	Supply	Flow Rates (approximate, ml min^{-1}) Supply	Compartment	Total
A	Fresh seawater supply to maintain flow.	Seawater Line	630	910	1820
	Scent stimuli	Gravity Fed Line A, B, C, D.	280		
B	Fresh seawater supply to maintain flow.	Seawater Line	630	910	
	Scent stimuli	Gravity Fed Line A, B, C, D.	280		

Assessment for Y-maze "tank effect"

The individual influence of a tank due to slight differences referred to as the "tank effect." This effect could have a confounding effect on the result of the trials and therefore must be examined to ensure there are no unintended biases in the results. The statistical analysis that was performed on this data in line with the methods section included an assessment for the effect of each tank on the outcome for the trials. The results of this analysis are presented below in Figure 45 and Figure 46 and indicate that there is no significant "tank effect".

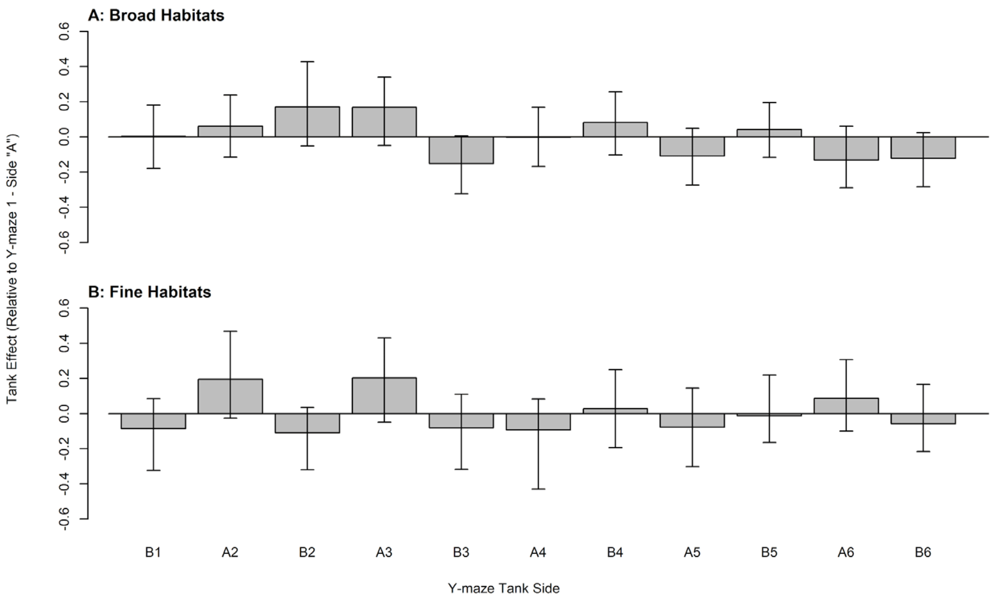

Figure 45 The results of the analysis for tank effect performed as part of the statistical analysis for (A) the broad habitat data and (B) the fine habitat data.

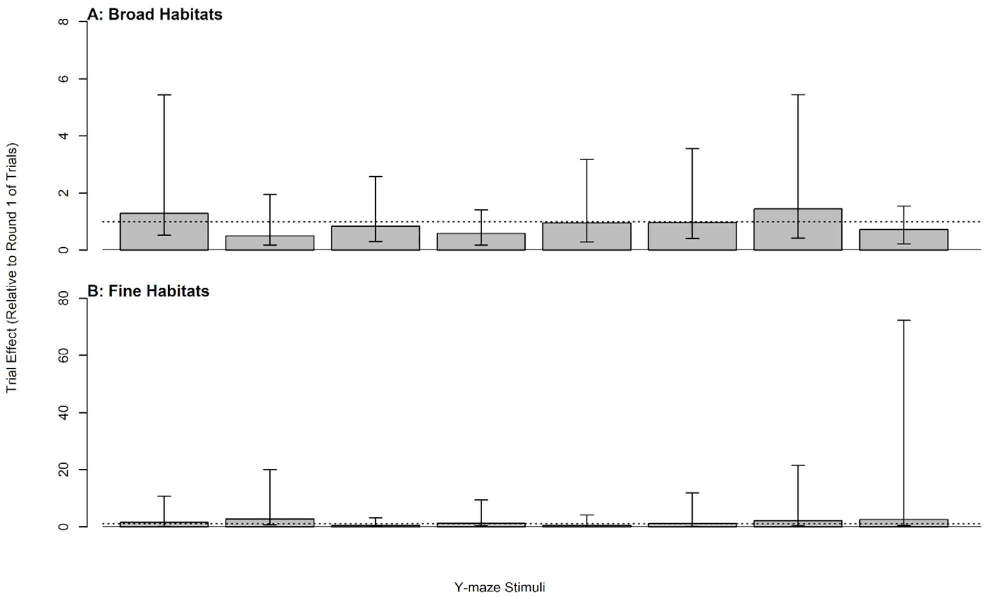

Figure 46 The results of the analysis for puerulus adaptation to the trials performed as part of the statistical analysis for (A) the broad habitat data and (B) the fine habitat data. Note, none of the stimuli are significantly different from the first round of trial.

Study 7 - Integrating expert fisher ecological knowledge into fisheries management: example of an area of unexpectedly low catch-rate and how its study informed fisheries ecology

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An early juvenile lobster hiding under seagrass in an aquarium planted with *Amphibolis antarctica*. Photograph Daphne Oh.

Abstract

Traditional fisheries science and management typically provides a delayed signal of change due to the time taken for data collection, analysis, and integration into management. In contrast, commercial fishers can potentially provide near real-time information, as local ecological knowledge (LEK), on immediate changes in catch rate to inform fisheries science and management. In this review, we use a case study examining a zone of unexpectedly low catch (LCZ) near Cliff Head, Western Australia to examine how LEK can be used to design a research program to investigate the affected area within the West Coast Rock Lobster Managed Fishery (WCRLMF) and in general provide insights for fisheries ecology. At the fine scale of the LCZ, fishers' perceptions of catch rates correlated better with density estimates of undersize lobster than those of legal sized lobster. This suggests the decreased abundance of sub-legal lobsters may be a contributing factor to the low catch zone and relate to fishers' perceptions about the productivity of an area. Subsequent and concurrent studies suggested that the region was not limited by the settlement of larvae however surveys of potentially important settlement habitats identified significant changes in the composition of the region with a net loss of seagrass and significant thinning of remaining seagrasses. Follow up work in aquaria experiments confirmed that newly settled Western Rock Lobster exhibited a strong chemo sensory preference for habitat assemblages dominated by *Amphibolis* and *Posidonia* seagrass species. Given the observed loss of these key habitats there may be a reduced likelihood for lobsters to settle or successfully recruit within the LCZ which could lead to the relatively low sub-adult lobster abundances observed. The multifaceted process that this study followed, has potential value and lessons for understanding the ecology of other similar trap-based fisheries.

Introduction

The management of wild species fisheries is typically very challenging and needs to be responsive to the natural dynamics of how populations vary over spatial and temporal scales (Gottret and White 2002; Davidson and Lockwood 2009; Coria and Sterner 2011; Fenner 2012; Suuronen and Bartley 2014). This difficulty is due to many factors which can influence populations of wild species in addition to our understanding of both settlement and recruitment dynamics, habitat interactions, fishery dynamics and the limitations and biases involved in collecting representative data. This project has shown that even in well researched and successfully managed fisheries, such as the WCRLMF there are knowledge gaps in the ecology of these species where multidisciplinary research informed by the local ecological knowledge (LEK) of commercial fishers can provide useful insights (Zukowski, Curtis, and Watts 2011).

Commercial fishers can be a valuable resource of LEK and other data for monitoring the status of fisheries and changes in the environment (Neis et al. 1999). Their regular engagement with their fishery species, focus on catch rates and other concomitant environmental variables, is the basis for their livelihoods (Cowx 2002). This provides a strong incentive for fishers to observe, 'understand' and predict these systems. Given their potential wealth of knowledge, and frequency of observation, commercial fishers' expert opinion can potentially provide a more immediate or alternate signal of change in a fishery or stock, than is typically possible through traditional fisheries science observation. Traditional fisheries science typically provides a delayed signal of change which can be delayed further before it is included in management (Evans, Cherrett, and Pemsl 2011). Given the observed, predicted and potentially rapid impacts of climate change and ocean acidification on marine ecosystems and fisheries populations (Cheung et al. 2012; Altieri and Gedan 2015; Koch et al. 2013; Koenigstein et al. 2016), case studies of commercial fishers providing real-time information to inform the management of a fishery provide a potentially important avenue of future fisheries management information.

In this review, we examine how expert commercial fisher perceptions and knowledge can be measured and used to design a research program to investigate processes potentially resulting in change within a fishery. We use a case study from the West Coast Rock Lobster Managed Fishery (WCRLMF) of Western Australia with a specific focus on an area near the centre of the fishery where, contrary to all expectations, commercial fishers had reported unexpectedly low catch rates.

Background

Species of spiny lobster from the family Palinuridae [Latreille, 1802] are frequently the subject of highly lucrative and valuable fisheries around the world (Radhakrishnan, Phillips, and Achamveetil 2019). Spiny lobster species are found in almost all oceans especially in warm and temperate seas such as those that surround Australia, New

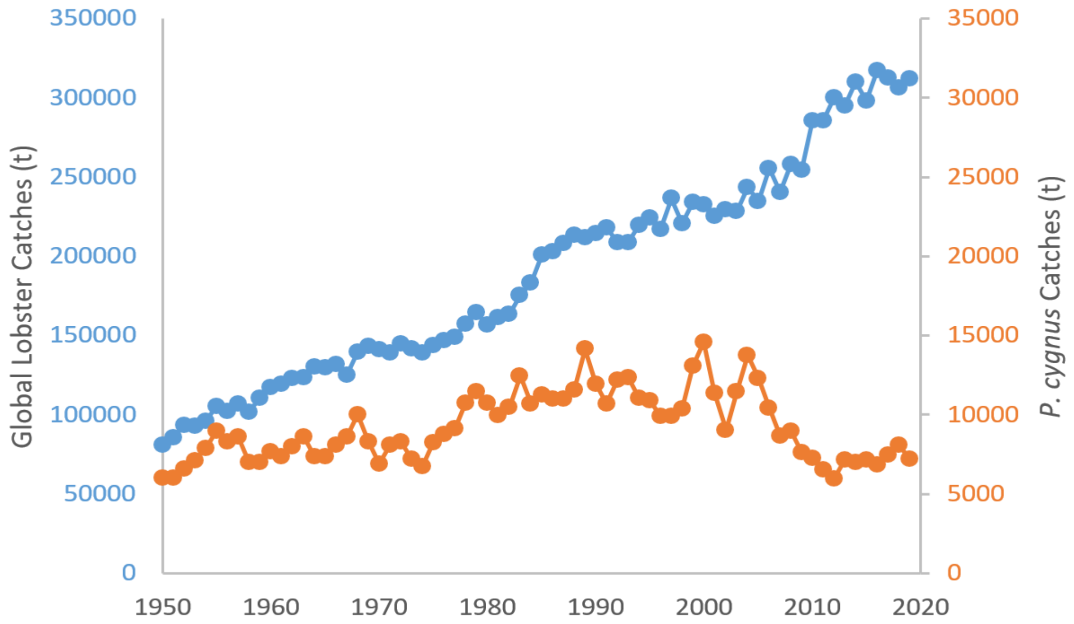

Figure 47 Global lobster catches and catches of Western Rock Lobster as reported by the FAO 1950 to 2019. Data: (FAO, 2021, 2020).

Zealand, and South Africa (Bruce F. Phillips et al. 2013). The fisheries that rely upon these species range from subsistence and recreational fisheries to commercial large scale industrialised fisheries (Bruce F. Phillips et al. 2013). The Food and Agriculture Organisation of the United Nations (FAO) reported global catches of lobster have increased almost 400% from 81,102 t in 1950 to 311,786 tons in 2019 (Figure 47).

Globally, the Australian West Coast Rock Lobster Managed Fishery (WCRLMF) has been recognised as a leader in fisheries science, management and sustainability, being the first fishery to be awarded the Marine Stewardship Council (MSC) third party certification (Bellchambers et al. 2012) and subsequently being recertified four times. In 1897, the nascent WCRLMF was among the first “managed fisheries'' in the world, when a minimum legal whole weight for landed lobster was set at 340g (Phillips and Melville-Smith 2005; de Lestang et al. 2012). Three years later in 1900 the fishery was also one of the first to introduce a minimum size limit, set to a 76 mm carapace length (Phillips and Melville-Smith 2005; de Lestang et al. 2012). This minimum size has remained to the current day (123 years later) with some minor short term variations, in the 1993/94 season when it was temporarily raised to 77 mm (de Lestang et al. 2012). The Department of Primary Industries and Regional Development (DPIRD; formerly Department of Fisheries), were one of the first agencies in the world to develop an index of settlement for a fishery (B. F. Phillips and Hall 1978), using artificial habitat puerulus collectors, they have been used to monitor Western Rock Lobster since August 1968 (B. F. Phillips 1972; B. F. Phillips and Hall 1978; Caputi & Brown et al. 1995). The number of puerulus settling on these collectors at multiple locations along the coast is recorded each month and the index had been demonstrated to provide a forecast on the likely catches in three to four years' time (Caputi 1995).

Catches in the WCRLMF have averaged approximately 11,000 t in the last decade with annual variations due fluctuations in puerulus settlement 3-4 years prior. Concerns over breeding stock saw increased effort control management measures introduced in 2010 which led to a decreased catches since the peak of the early 2000's (discussed below). A period of abnormally low puerulus settlement was encountered for six consecutive settlement seasons (2006/07 to 2011/12; N. Caputi et al. 2014). While puerulus settlement has improved since, puerulus settlement patterns have changed both temporally and spatially (Kolbusz, de Lestang, et al. 2021), potentially due to long-term changes in the oceanographic regimes off the west coast of Australia (Kolbusz, Langlois, et al. 2021). The start of the period of low puerulus settlement rates led to the government introducing a 50% decrease in catch with subsequent changes to the management of the fishery resulting in a change from input control to output control with the introduction of individual transferable quotas (ITQ's). The catch remained at this lower level with only small increases in TAC as set by in consultation with the industry peak body (Nick Caputi et al. 2015). The management changes and resulting reduced landings have resulted in increased spawning biomass within the fishery with a hindcasting biomass dynamics model (BDM) for the WCRLMF estimating the abundance of legal-sized (≥76mm CL) lobsters gradually declined to a low point of approximately 10,000 t in the early 2000's with a rapid increase after 2010 to around 20,000 t or approximately 80% of the estimated virgin biomass in 2016 (de Lestang, Caputi, and How 2016).

Case study: an area of unexpectedly low catch rates

Despite the estimated increased biomass of spawning biomass, legal sized lobsters and high catch rates across the fishery, commercial fishers in the centre of the WCRLMF have reported an area of reduced or unexpectedly low catch rate in nearshore shallow waters (Fitzhardinge, J *pers comms*; Figure 48). Historical accounts of this low-catch zone (LCZ) from the 1970's to 1990's suggested this area of coastline, from Dongara to Leeman (~ 80km), supported a large number of fishers with annual lobster catches exceeding 1,000 t. Fishers reported a trend of reducing catch rates in the shallows (<~15m depth) of the LCZ since the 1990's. Since the period of abnormally low puerulus settlement index, (2006 to 2012), fishers have perceived that catch rates have reduced further in this region. They also stated that the LCZ was expanding to deeper waters out to the edge of the shallows (~<20 m depth) and further north and south along the coastline (Brendan Crofts *Pers. Comms.*).

Since this time many Western Rock Lobster fishers considered this region to be relatively unproductive compared to other adjacent areas (Study 1) with the location being intermittently fished by only a few fishers (Miller et al. 2023). The concerns raised by these expert fishers present a challenge for fisheries science with all other modern indicators of the fishery suggesting stocks and catch rates should be high. This provides a challenge for “forensic” fisheries ecology to both validate fishers' concerns and elucidate the process/es potentially causing this low catch zone.

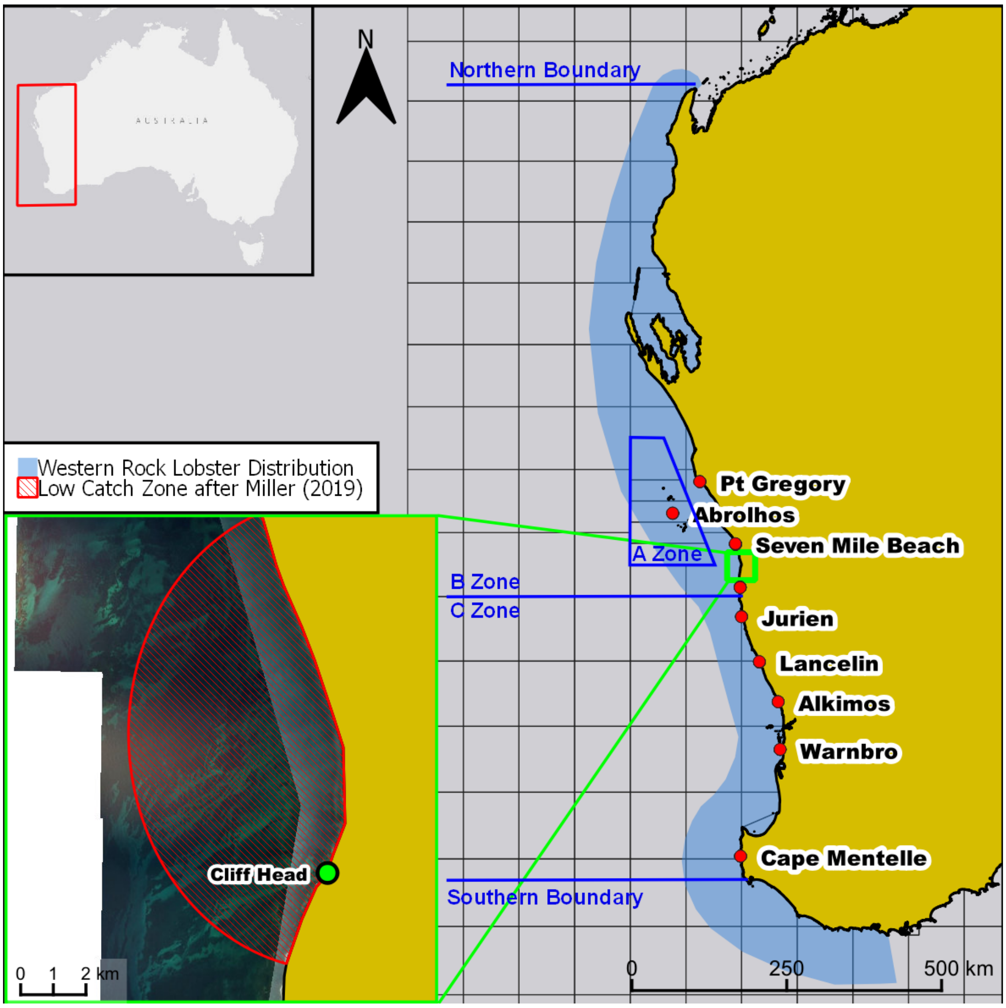

Figure 48 Management zones and “Catch and Effort System” (CAES) reporting blocks of the WCRLMF and locations of puerulus collector locations along the coast.

Ground truthing expert fisher perceptions

The research presented in Study 1 used a benchmark study across the WCRLMF to contrast perceptions of temporal and spatial trends in catch rates held by commercial fishers to standardised catch rate data collated by the Department of Primary Industries and Regional Development (DPIRD). This study used a series of structured career-history based interviews with fishers across the fishery using a consistent methodology and found a generally fishery-wide correlation between the two indexes. However, at a finer scale, perceptions and standardised catch rates were more closely aligned in the southern management zone ("C" Zone; Figure 48) but a recent and increasing divergence between the indexes in the northern half of the fishery, with commercial fishers perceiving the northern half of the fishery ("B" Zone; Figure 48) not to be performing as well as represented by standardised catch rate data in the region.

Studies of commercial fisher perceptions of temporal and spatial trends in catch rate have been conducted for many fisheries and for a wide range of species from seahorses (O'Donnell, Molloy, and Vincent 2012) to White Sharks (Taylor et al. 2017), and have the potential to be highly useful for data deficient fisheries where no formal catch returns data are available (Neis et al. 1999; J. P. G. Jones et al. 2008; O'Donnell, Molloy, and Vincent 2012). In contrast, the WCRLMF has some of the most extensive and detailed historical catch record data and accompanying fisheries science of any coastal fishery, demonstrated by its record with third-party Marine Stewardship Council (MSC) certification (Bellchambers et al. 2012). Within the WCRLMF catch data is currently collected using "Catch and Effort System'' (CAES) reporting blocks (1^{o}x1^{o},or approximately 60nM x 60nM; Figure 49). Additional sampling programs such as the Independent Breeding Stock Surveys (IBSS) provide data on the size structure of the Western Rock Lobster population (de Lestang et al. 2012). Despite this detailed data, the spatial extent of the LCZ fell within approximately one observation block and standardised DPRID catch rate data was not adequate to investigate the spatial and temporal extent of the anomalous catch rates reported by fishers. This may in part be due to the very limited commercial fishing occurring within the area, with on water observations suggesting the area is fished rarely and intermittently by only a few fishers (Miller et al. 2023; see also 2 Study 1). In addition, Study 1 was able to collect information on fisher perceptions at a much finer scale using a 10-minute grid (~10 nM; same scale as logbook data), rather than the 1-degree block used by the CAES reporting system. The finer scale data collected by Study 1 was designed to enable areas such as the LCZ to be better delineated.

A fisheries independent catch rate study in the LCZ and comparable adjacent high catch areas (Figure 49) was conducted using meshed commercial fishing traps designed to retain undersize animals (Miller et al. 2023). Unexpectedly it was found that catch rates of legal-size lobsters were not significantly different between the LCZ and adjacent comparable areas (Miller et al. 2023). However, there was a significant difference in the catch rate of sub-legal lobster. The strong delineation of the LCZ by catch rate of sub-legal juvenile lobster (Figure 49) provided evidence that the potential cause for the reduced catches was due to earlier life stages, potentially including the settlement of puerulus.

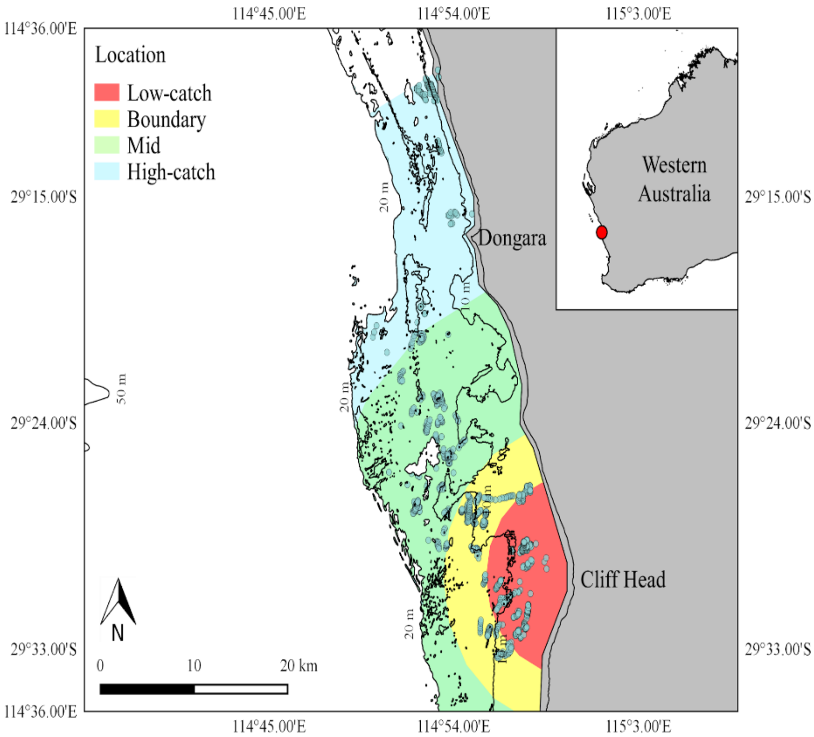

Figure 49 The monthly fisheries independent potting locations with fisher perceived catch levels; "Low-catch" (red, Cliff Head), "Boundary" (yellow), "Mid" (green) and "High-catch" (blue, Seven Mile Beach; Study 1, Miller et al. 2023).

Interestingly, fisher perceptions on catch rates did not correlate with Miller et al.'s (2023) standardised legal sized lobster catch rates. Instead, it was found that the fisher perceptions reported in Study 1 were representative of the standardised sub-legal sized lobster catch rates. These relatively low numbers of sub-legal lobsters in the LCZ and high numbers of sub-legal lobsters in the High Catch Zone (HCZ) suggest that the consistent catch rates of legal sized lobster found by Miller et al. (2023) would not have been maintained under a higher level of fishing pressure in the LCZ i.e., a level of fishing pressure concurrently occurring in the HCZ and comparable numbers of legal sized lobsters between locations are not necessarily representative of potential catch rates over a period of sustained fishing.

A plan to investigate the possible processes creating the low catch zone

The above studies confirmed both the presence of the low catch zone (LCZ) and the utility of commercial fisher local ecological knowledge to elucidate previously unknown patterns in fisheries ecology (Study 1; Miller et al. 2023). In this case-study, the lack of historical fisheries independent data, particularly on the abundance of sub-legal and juvenile lobster is a major limitation (prior to the work of Miller et al. [2023] which was conducted concurrently). The absence of this data restricts the ability of this or any future study to attribute the LCZ to temporal change in the abundance of sub-legal or juvenile lobster. However, with this major limitation in mind the current case study can start to investigate the processes that potentially could have caused the observed lower catch rate of sub-legal and juvenile lobster within the area.

The Western Rock Lobster exhibits a bi-phasic life cycle with pelagic and benthic early life history stages followed by benthic adult stages. This life history characteristic can present numerous potential bottlenecks that may account for the lower abundance of sub-legal and juvenile lobster within the LCZ. Two processes that could have resulted in potential bottlenecks leading to a reduced juvenile lobster abundance in the LCZ are the recruitment and survival of early juvenile lobster (B. F. Phillips and Hall 1978; N. Caputi, Brown, and Phillips 1995; N. Caputi et al. 2003; Bruce F. Phillips and Melville-Smith 2005; N. Caputi et al. 2014). With the presence of suitable benthic habitats as a good indicator of survival of early juvenile lobster (Edgar, 1990a, 1990b, 1990c) and the potential to use puerulus collectors to provide a useful indicator of recruitment (B. F. Phillips 1972; B. F. Phillips and Hall 1978). This study therefore set out to quantify and examine rates and patterns in lobsters' settlement and in addition to this both the spatial and temporal patterns in benthic assemblages likely to provide recruitment habitats across the study site.

Investigating lobster recruitment as an explanation for the LCZ

Artificial collectors have provided a useful index for recruitment to the WCRLMF (B. F. Phillips 1972) that have since become a key component of the fishery's management (Caputi et al. 1995; 2014). Extensive historical records exist from these settlement collectors throughout the fishery (N. Caputi et al. 2014), but unfortunately none of these collector locations are situated within or close to the LCZ. The closest collectors are located at Seven Mile Beach to the north of the LCZ and Jurien Bay to the south of the LCZ (Figure 50). To benchmark and start to quantify settlement within the LCZ the same settlement collector methodology that has been used by DPIRD and its predecessors since the 1960's was used.

A pilot study was conducted as part of Study 4 across two settlement seasons (2017/18 and 2018/19), to assess the rate and pattern of puerulus settlement across the LCZ and adjacent areas. That study found no evidence to suggest reduced puerulus settlement within the area (Figure 50). Characteristically, the cumulative counts derived from these collectors indicated a high level of variability both within and between sites (Figure 50), suggesting that the fine scale location of the collectors can have a considerable influence on the magnitude of settlement recorded. This high level of variability was also observed by Phillips (1972) who found high variability between paired adjacent collectors during the initial development of the method.

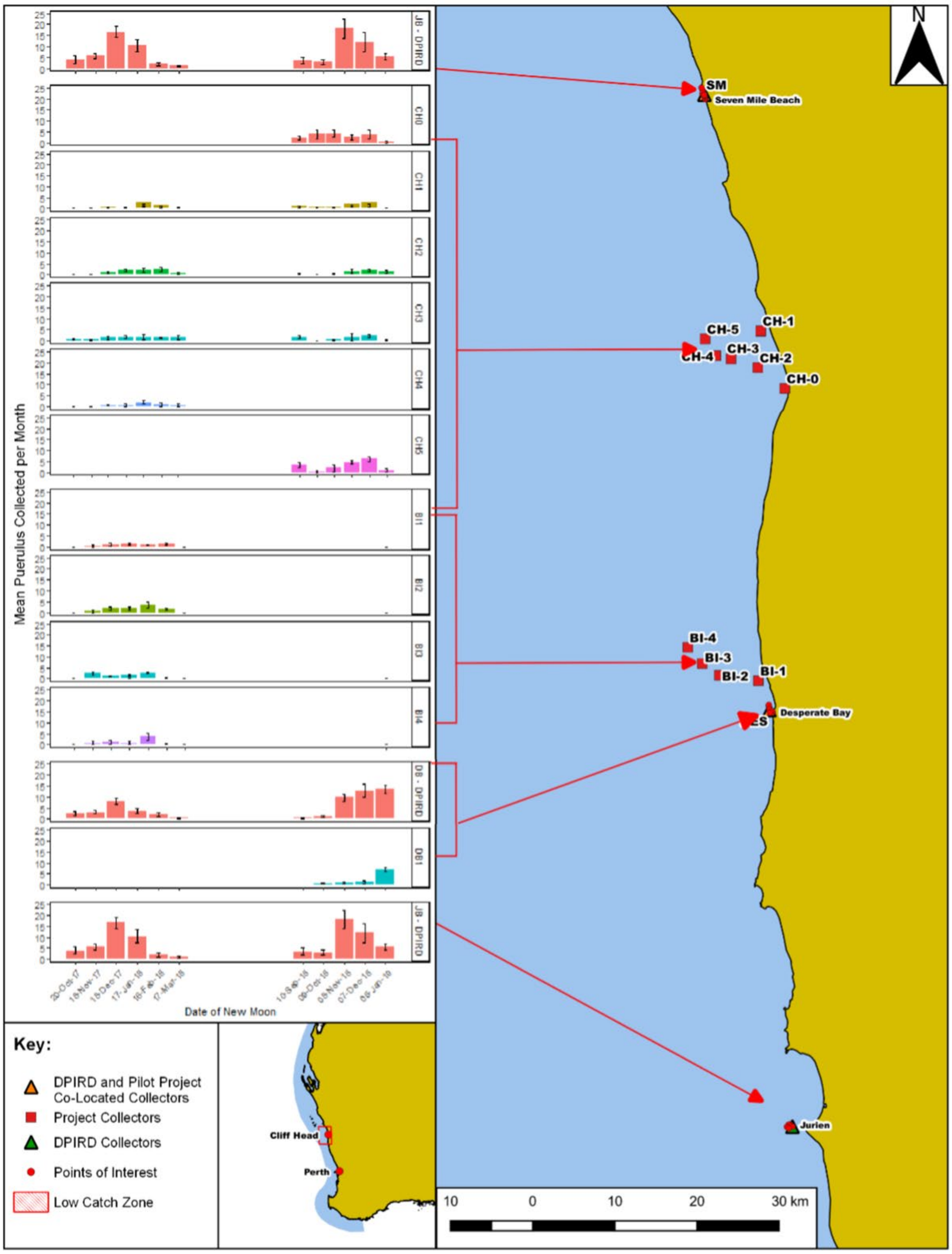

Figure 50 The deployment locations of the puerulus collectors presented with the mean count of puerulus per collector per month obtained from each site over the study period. Note, not all sites were studied in both seasons; CH-0 was only studied in the 2018-19 season, CH-4, BI-1,-2,-3,-4 were only studied in the 2017-18 season.

Subsequent work by Kolbusz, Langlois et al. (2021) and Study 3 also suggested the LCZ was likely to receive greater or equal settlement than surrounding areas, including the HCZ to its north. Study 3 used an established oceanographic model of the region to simulate the path of both inert and actively swimming particles, simulating potential Western Rock Lobster puerulus distribution from 2000-2018. The study found that settlement in this region spanned the LCZ and north to Seven Mile Beach (which has the highest puerulus collector settlement rates and is ~40 km north of the LCZ), all had a similar nearshore pathway, where particles entered the shallow water area offshore from the LCZ and travelled north along the coastline. This suggested that the LCZ had a greater chance of settlement compared to areas further to the north including Seven Mile Beach in the HCZ (Figure 51).

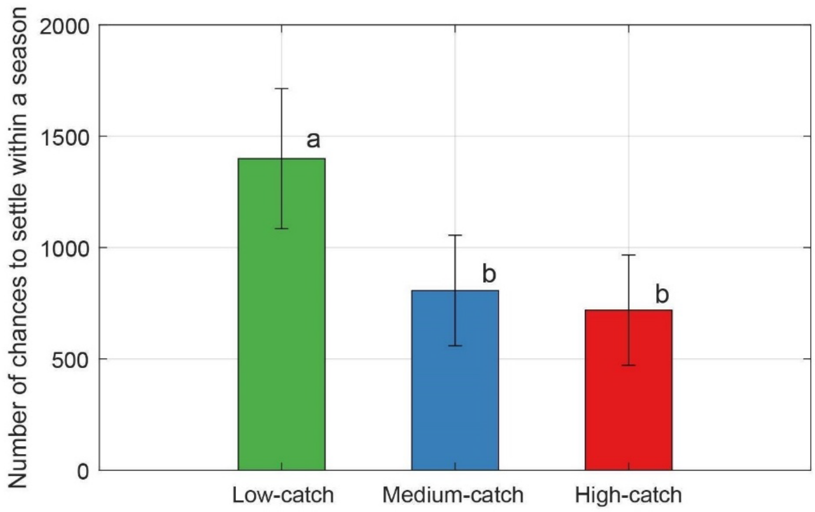

Figure 51 The mean number of chances for particles to settle within each zone (low-catch, medium-catch or high-catch) over the 8 sample settlement seasons. Error bars are the standard deviation. Results of pairwise comparisons are indicated by alphabetic character ($p < 0.005$). *After* Study 3 and Kolbusz *et al* (*in prep*).

The result obtained by Study 4 and the simulation study, covering 2000-2018, documented in Study 3 and by Kolbusz et al. (2021) both indicated that the settlement of puerulus in the study region is unlikely to be a process leading to the LCZ. Instead, these studies suggest that the low number of juvenile and sub-legal lobster within the LCZ are likely instead to be due to processes acting on the lobster during or post settlement.

Investigating change in benthic habitats as a possible mechanism for the origin of LCZ

The above studies indicate that processes acting on the settlement or post settlement phase of the lobsters' life history prior to retention in meshed pots (~35 mm carapace length; Miller 2023) could explain the occurrence of the LCZ. Previous studies of Caribbean spiny lobster have found the early juveniles of this species can be readily surveyed using artificial mini-casita habitats (Eggleston, Lipcius, and Miller 1992). Conversely, early juvenile post settlement, Western Rock Lobster has been previously found to be highly cryptic and difficult to find and study in the wild, with no historical information existing on their abundance. Nearshore shallow water benthic habitats are suspected to be a key habitat for early juvenile and larger sub-legal Western Rock Lobster (Edgar 1990a, 1990c).

There are many potential causes for a loss or change in vegetation cover in marine habitats, some of the factors that impact seagrass health and cover include; excess nutrients, trawling, dredging, aquaculture, boating, marine heatwaves, freshwater inundation, sedimentation, movement of sand sheets and herbivory (Cambridge and McComb 1984; Larkum and West 1990; Walker and McComb 1992; Duarte, Marbà, and Santos 2004; Bastyan and Cambridge 2008; Boudouresque et al. 2009). To assess the scale of these impacts, one of the more suitable methods for conducting surveys of seagrass at this scale is aerial imagery. This is because aerial imagery is much finer (1m or less) than other sources such as satellite imagery such as Landsat (generally 60 m pixels or pan sharpened to 30 m; Fensham and Fairfax 2002; Tuominen and Pekkarinen 2004, 2005). Landgate, the statutory authority responsible for property and land information in Western Australia, has conducted a campaign of regular aerial imagery capture along various sections of the coast to track land use change and inform planning, which is of sufficient resolution (~0.5m pixel size) to track changes in the coverage of marine aquatic vegetation through time.

Study 5 investigated the changes in vegetation coverage in the LCZ using aerial photography and augmented this data using towed underwater video as in-water ground truthing of the modern imagery. This study revealed significant changes in nearshore habitats including a net loss and thinning of nearshore subtidal vegetation consisting of seagrass and macroalgae over a period of 10 years (Figure 52). In-water imagery revealed the association of high densities of grazing sea urchins, *Heliocidaris erythrogramma* [Valenciennes, 1846] with areas of reduced vegetation cover. The occurrence of high-density aggregations of *H. erythrogramma* (up to 7.14 individuals m^2) or indeed other sea urchins is relatively uncommon in western Australia. In western Australia overgrazing of kelp has previously been reported in localised areas where *H. erythrogramma* reach densities of approximately 6.5 individuals m^2

(Azzarello et al. 2014) or on seagrass, with a much smaller bodied species at approximately 65 individuals m^2 (Langdon, Paling, and Van Keulen 2011; Bancroft 1992). Study 5 demonstrated how historical information on habitat change could be derived from incidentally collected aerial imagery, providing historical context to the study of the LCZ, which generally lacks any quantitative historical information at an appropriate scale to inform its study. Study 5 provided the strongest evidence so far of a potential mechanism for the origin of the LCZ.

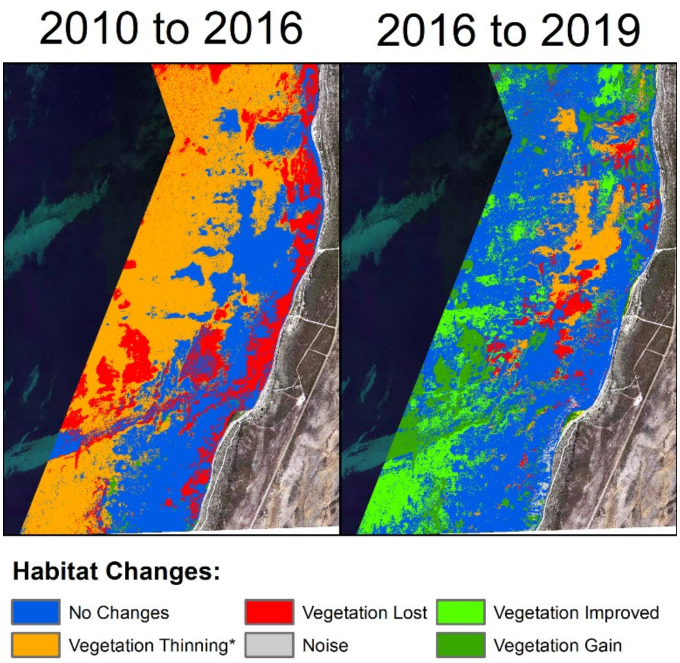

Figure 52 Changes in habitat composition between 2010 and 2016 and 2016 and 2019.

Implication of habitat change: Do early juvenile Western Rock Lobster have a strong preference for habitat type?

The current project has identified habitat change over time has emerged as being the most likely mechanism to account for the LCZ. Coarse changes in habitat were reported by experienced commercial fishers concomitant with reports of reduced catch rate in the low catch zone (Brendan Crofts *pers comms*) and has the potential to impact the growth and survival of early juvenile Western Rock Lobster (Study 6). As previously mentioned, little is known of the ecology and behaviour of early juvenile Western Rock Lobster given their highly cryptic nature and the difficulty of studying them in the field. Previous field studies on sub-adult 2-3 year old lobster found that these animals were closely associated with *Posidonia* and *Amphibolis* seagrasses and macroalgal assemblages that are characteristic of shallow-nearshore habitats in the LCZ (Joll and Phillips 1984; Jernakoff 1987; Edgar 1990c, 1990b; 1993) highly cryptic nature (Jernakoff 1990).

To overcome the difficulties in studying early juvenile Western Rock Lobster (<~30 mm), work conducted in Study 6 used aquaria-based trials on early juveniles sourced from puerulus collectors to observe their behaviour and habitat preferences. This approach provides a tractable alternative to studying these animals in the field, where they have only very rarely been discovered (Jernakoff 1990; Jernakoff et al. 1994), and the opportunity for experimental manipulation to investigate preferences for particular habitat types. In the absence of other data on natural populations and mortality rates of this potentially vulnerable life-stage of Western Rock Lobster, manipulative aquaria experiments can, by revealed choice and preference, provide an indication of the potential importance of these habitats to these animals. It is possible to then hypothesise that those habitats most frequently chosen or preferred are most likely to provide the greatest benefits (e.g. growth, survivorship) to the animal (Eggleston et al. 1990; Underwood, Chapman, and Crowe 2004). Study 6 used Y-mazes aquaria to assess the individual choices made by post-puerulus early juvenile Western Rock Lobster when presented with the scent of different habitat types. These included commonly encountered habitat complexes found in the nearshore areas of the LCZ, including mixed seagrass, turf algae, sand and followed this by presenting the scent of individual seagrass species along with their associated root matter. The scent only stimuli used in the Y-maze aquaria provided a clear test of habitat preferences, where the individual lobster can only rely on their chemosensory abilities. This provides a simultaneous test of the previously unknown but hypothesised chemosensory abilities of early juvenile animals (Jeffs, Montgomery, and Tindle 2005) and a clear test of preference for the habitat types without the confounding effect of different structural complexity within each habitat type (e.g. Oh 2020). The results of this study identified a strong preference of early juvenile Western Rock Lobster for *Posidonia* and *Amphibolis* seagrass assemblages (Figure 53) which form a significant portion of the benthic habitats in the LCZ (Edgar 1990a).

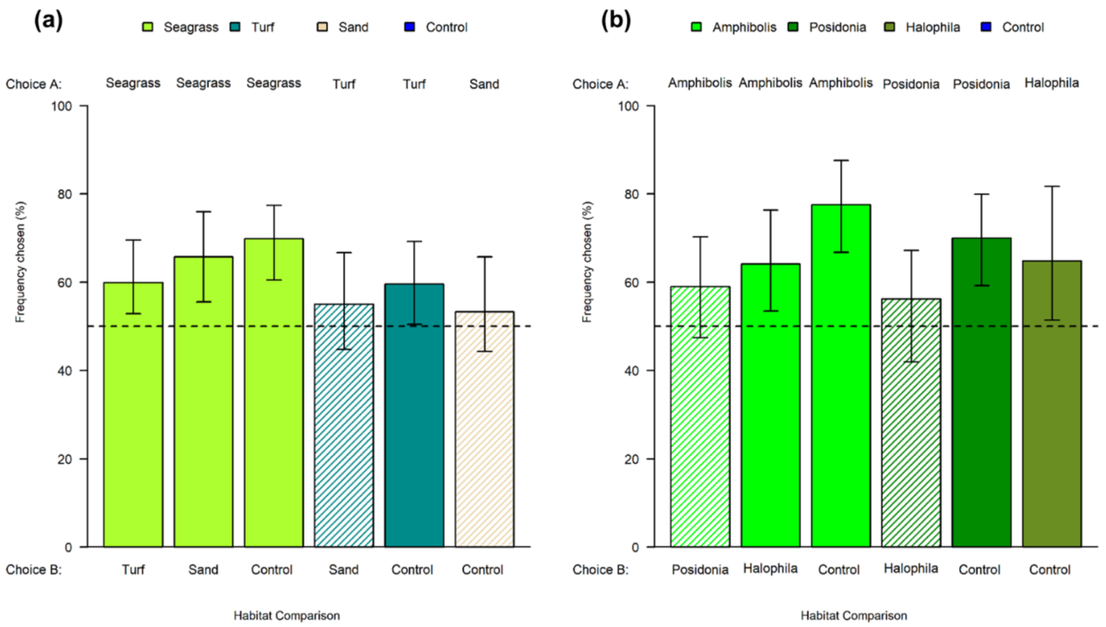

Figure 53 The choices made by early juvenile lobster in scent-based y-maze trials using (a) broad habitat categories and (b) specific seagrass habitats. The habitat chosen more often is indicated by the colour of the bars and the habitat listed at "Choice A". Solid fill indicates significance at the 95% confidence interval and hashed fill indicates non significance at this level. The error bars represent the 95% confidence intervals. Control was never chosen most often and so none of the bars are coloured blue.

Subsequent mesocosm aquaria studies by Oh (2020) found strong evidence of early juveniles choosing the densest patches of *Amphibolis* seagrass assemblages but displaying a tendency to bury in sand when *Amphibolis* assemblages became sparse.

Both Brooker *et al.* (2021; also Study 6; y-maze) and Oh (2020; mesocosm) provided strong evidence that post-puerulus early juvenile Western Rock Lobster will choose to associate with seagrass assemblages, and in particular those dominated by the *Amphibolis* species and in particular with patches of the highest density. *Amphibolis* species dominated seagrass assemblages are typical of the nearshore marine aquatic vegetation of the LCZ study area (Edgar 1990a), but is also the same assemblage that Study 5 documented had been thinning or lost from 2010 up to 2019. As discussed above, evidence of association or choice for a particular habitat, be it in field based or aquaria studies, provides some evidence that those habitats are important or likely to confer greater survival for individual animals (Eggleston et al. 1990; Underwood, Chapman, and Crowe 2004). In the absence of historical data on the abundance of under-size juvenile Western Rock Lobster within the LCZ, a likely hypothesis to why Miller (Miller et al. 2023) found their numbers to be lower is that the loss of a habitat (Study 5) that is strongly preferred by early juvenile lobsters (Study 6; Oh, 2020) has led to decreased survivorship of early juvenile Western Rock Lobster within this region.

Other Experiments

An early component of this project was the development of “mini-casitas” (after Birones et al. 2008) for the sampling of early juvenile Western Rock Lobsters. Our aim for this work was to design an artificial habitat and sampling unit for lobsters with a carapace length of approximately 30 mm. The primary driver behind this was to enable the ability to study juvenile lobsters that are 1-2 years post settlement because as previously discussed, this size class of lobster is notoriously difficult to study in the field or capture (Jernakoff 1990; Jernakoff et al. 1994). Early designs of these casitas included fencing materials such as lattice and cement sheeting along with concrete and was designed to be similar to the casitas used in the Gulf of Mexico by Eggleston et al (1992) and other researchers. A second early prototype included a benthic puerulus collector which consisted of two Phillips collector panels and tassels (B. F. Phillips and Hall 1978) mounted to a steel base. Despite initial success in single pilot collectors, once the number of collectors was increased we found neither design was able to collect adequate numbers of lobster. The benthic puerulus collector failed due to high sediment loads clogging the tassels rendering them ineffective (Figure 55). A third design developed, was based on crevice collectors that uses PVC sheeting covered in green nylon scrubber material mounted in a frame using a similar design to the crevice collectors designed by Priyambodo et al. (2017, Figure 54 and 55). Unfortunately, these collectors failed to “collect” useable numbers of lobster over a deployment of 6 months despite being situated at the location with the highest Western Rock Lobster puerulus settlement and known very high densities of early juvenile animals (Seven Mile Beach).

Figure 54 Two prototype early juvenile lobster collectors, the benthic puerulus collector (left) and crevice collector (right) trialled as part of a pilot study.

Figure 55 A crevice collector trial as part of a pilot study.

Conclusion

In summary, the local ecological knowledge (LEK) held by fishers had highlighted changes in a relatively restricted area of the WCRLMF, at a finer scale than typically able to be studied using standard interpretations of fisheries dependent data historically conducted for management purposes. Across the whole fishery, fishers' perception of temporal and spatial trends in catch rate can provide a certain level of comparative information to standardised fisheries dependent catch rates at the scale of the fishery, but these perceptions show a decreasing level of congruence with increased recall time and can be variable between locations (Study 1). We also found evidence of an interaction with the management zone, where perceptions and standardised catch rates were more closely aligned in the southern “C” management zone. Within the relatively small area of the perceived LCZ and adjacent HCZ areas, fisheries independent surveys found strong evidence of the lower numbers of juvenile and sub-legal Western Rock Lobster within the LCZ (Miller et al. 2023) suggesting that fishers LEK was potentially representing the numbers of undersize lobster that would be returned to the water in the area, as it is likely that the lower numbers of juvenile and sub-legal animals in the area (Study 2) would not have supported high catch rates of legal-sized animals under sustained fishing with similar intensity as the HCZ.

This work and the work of others (Raymond et al. 2010; Daw, Robinson, and Graham 2011; O’Donnell, Molloy, and Vincent 2012; Zukowski, Curtis, and Watts 2011) has found that different potentially conflicting or congruent information sources can be difficult to integrate at a single scale for the management of a fishery. At the broader scale, LEK information can be used in conjunction with more traditional fisheries management inputs to identify areas where there is a mismatch which may highlight potential “areas of interest” for fisheries scientists to consider. This can sometimes help to reveal population and ecological processes to better inform management. At a finer scale, LEK can also provide additional supporting information and alternative hypotheses for investigation (e.g. habitat change), given the knowledge gaps and necessary assumptions needed to create a stock level assessment to generate standard broad-scale fisheries data, and this is where the finer-scale LEK can potentially augment our understanding of fisheries ecology (Davis and Ruddle 2010).

In the current study, there was no evidence to suggest that puerulus settlement was a limitation in the region (Study 4), with oceanographic modelling finding that the LCZ should have been receiving at least equal if not greater settlement than adjacent HCZ over the last 10-20 years (Study 3). This oceanographic modelling also suggested that the puerulus settling in the HCZ would pass through the LCZ to arrive at HCZ areas to the north of the LCZ. Study 5 used available historical aerial imagery to track a large and extensive thinning and loss of vegetation over the LCZ over the last 10 years. Although the identity of the vegetation lost could not be confirmed, as there was no historical in-water imagery to use for ground truthing of previous images, however there was compelling evidence in the pattern and areas lost to imply the loss in vegetation was mostly seagrass assemblages dominated by *Posidonia* and *Amphibolis* species. The processes responsible for this loss of vegetation, and seagrass bed extent, is unknown due to a lack of historical information, but in-water ground truthing imagery revealed high densities of the sea urchin *H. erythrogramma* associated with areas of loss, in addition, some areas of imagery have some evidence of scouring which is another potential cause for seagrass loss.

Subsequent work in Study 6 and Oh (2020) demonstrated that early juvenile lobster exhibit a preference and chose to associate with seagrass, and in particular *Amphibolis* assemblages. This work was conducted under both controlled Y-maze conditions (only scent stimuli provided, Study 6) and mesocosms (scent and physical habitat presented, Oh (2020). Given that there was a loss of key habitats that are preferred by these early juvenile lobsters there may be a reduced likelihood for lobsters to settle in the LCZ as they pass through.

As a result, the most likely cause for the LCZ is a historical change in the subtidal benthic habitats leading to increased mortality of Western Rock Lobster early juveniles before recruitment to the fishery, resulting in reduced long-term catch rates in this area, that were not strictly obvious in standard fisheries returns due to the decreased effort in the LCZ and generally larger spatial scale of fisheries data reporting areas.

Given the socio-economic value of this fishery and the potential changes to oceanographic conditions and shifting of species distributions due to predicted changes in climate, and likely impacts on habitat, it is important that we continue to build upon our current understanding of the controlling factors of Western Rock Lobster populations. The multifaceted process that this review and broader study has followed, informed by commercial fishers LEK, could provide a template for studies of other similar trap-based fisheries, in particular where expert fishers can contribute observation at different spatial and temporal scales than that usually reported in standard fisheries monitoring.

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Project Conclusions

Assessment and the need for historical benchmarks

The iterative assessment process, used to guide this project (Figure 56), found that loss of essential habitat, relating to early juvenile lobster survival, was the most likely causative factor of the low-catch zone. However, this study and the assessment also highlighted that the lack of historical benchmarks of the extent and coverage of essential habitat, as well as a lack of information on spatial patterns in the abundance of juvenile and sub-legal lobster, limiting the ability of the current study to disentangle the multiple potential causes of the low catch zone.

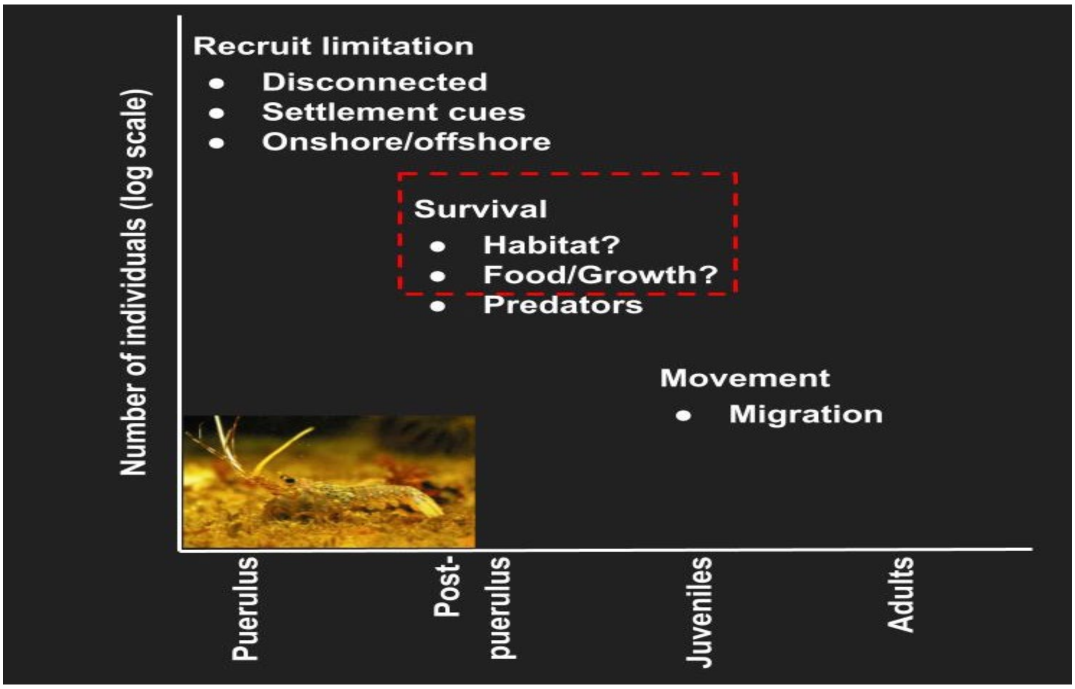


Figure 56 Iterative assessment process.

The first workshop held with fishers in Dongara (Figure 57) to establish the historical and spatial extent of the low-catch zone reported evidence of the low-catch zone from the mid 1990's and the expansion of this area of lower-than-expected catch through the 2000's.

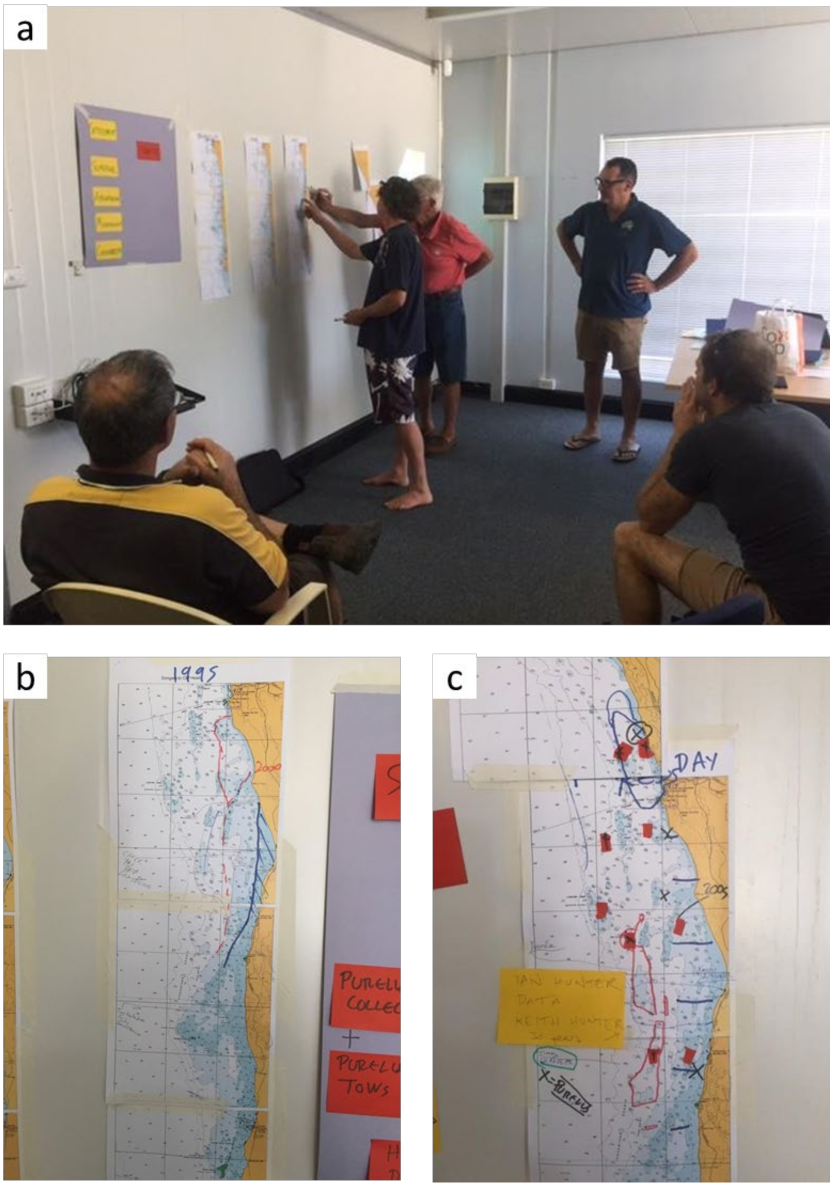


Figure 57 Preliminary workshop held in Port Denison, WA. Participants attending the workshop, (b-c) examples of the maps produced.

These reports were matched somewhat by temporal and spatial patterns in fishers' perceptions of catch rate and fisheries independent catch rate surveyed in subsequent studies in this project (Study 1 and 2). The current project found no support for the hypothesis that the low-catch zone was due to limited post-larval settlement (Study 3 and 4) and instead found that habitat change and preference (Study 5 and 6) are the most likely explanation and mechanisms behind the low-catch zone. However, the current study has only been able to source reliable remote sensing/aerial imagery of adequate quality back to 2010, documenting a potential large change in shallow water habitats, based on modern ground truthing with in-water imagery (Study 5). The lack of adequate historical remote sensing/aerial imagery before 2009, and lack of any suitable ground truthing information, prevents the current project from investigating any potential correlation of change in catch rate with change in the extent and coverage of potentially essential habitats in these nearshore areas.

Extension and Adoption

Extension of the project

This project has clearly demonstrated the need and value of historical benchmarks of juvenile and sub-legal lobster populations matched by benchmark information on the habitats potentially essential to early juvenile lobster survival. New FRDC WRL IPA funded projects have subsequently been created to further synthesis available information and collect new data for both early juvenile / pre-recruit lobster abundance (FRDC 2019-159 Independent Shallow Survey) and near shore habitats (FRDC 2019-099 Habitat as a limit to Western Rock Lobster recruitment) across the fishery, and we suggest that these will provide useful information in the future to investigate the likely causative factors of any low-catch areas or areas of concern to fishers.

The classification of aerial imagery presented in Study 5 presents a scalable framework that could be rolled out on a much larger scale across the fishery. The imagery used by this study is only a small portion of the imagery that is currently available with near continuous imagery, collected from Kalbarri to Esperance for the task of terrestrial coastal development planning (Stead 2018). Should this work be conducted at larger spatial scales it may be more suitable to use satellite imagery or other available imagery sources that are available. In addition to completing additional analyses on remote sensing imagery it will be valuable to improve the quality and quantity of ground truthing data to better understand the results obtained by the imagery.

Further development and implementation for fisher interviews

In the future, we suggest that it could be beneficial to further explore the utility of the structured collection of fisher perception of catch rates, as an additional data source for fisheries management and/or providing a form of early warning system whereby fishers are able to systematically collate their concerns about any area. We suggest there is value in investigating how to integrating perception surveys into instantaneous electronic reporting for fishers to fill out during fishing activities to expand the timescale of the current database and reduce the effects of recall time by focussing on immediate perception of catch (O'Donnell, Molloy, and Vincent 2012; Daw, Robinson, and Graham 2011).

Further suggestions for future studies

This project has further highlighted the importance of data on 1) the abundance of sub-legal lobster in near shore habitats and 2) change in near shore habitats as potential indicators for the stock assessment and management of the WRL fishery. In particular, the year-long catch-rate study conducted as part of this project provides a benchmark that can be used to test future trends in lobster populations within the low-catch zone area (Study 2). For future studies of any areas of suspected low catch, we recommend standardised surveys targeting sub-legal lobster, potentially using meshed pots.

The observed substantial change in habitat, including loss and degradation of seagrass, within an area central to the low catch zone demonstrated the use of combining remote imagery and in-water ground truthing (e.g. towed video surveys). Another area of new research could include using y-mazes aquaria to assess other influences on the settlement and recruitment of Western Rock Lobster puerulus of habitat change. Anecdotal evidence from some fishers have identified that localised submarine groundwater discharges may contribute to the attraction or deterrent of puerulus identifying suitable habitats for settlement. Y-maze aquaria provide an ideal methodology to test this hypothesis under controlled laboratory conditions. In addition to this the work conducted in Study 6 and by Oh (2020) can be expanded upon by constructing larger mesocosm aquaria where various aspects of the benthic assemblage and composition of predator and prey assemblage can be altered. This would allow for the effects of marine heatwaves and other broad scale impacts to be assessed and replicated under controlled conditions.

The co-occurrence of sea urchins, at densities over 50-100 times greater than those typically recorded along the WA coast (Smale and Wernberg 2013), with areas of substantial seagrass loss in Study 5 (Figure 58), should be investigated further. Other factors could be implicated in the loss of these seagrass habitats, including heat stress (Caputi et al., 2019) and or smothering by sand transport (Evans et al., 2019). The same species of sea urchin has been implicated in over grazing of seagrass and macroalgal beds in other parts of Australia, including Victoria and New South Wales and Tasmania (Wright et al., 2005). We recommend that focused studies should be conducted to ascertain if the aggregations of sea urchins observed are responsible for the observed loss and degradation of seagrass beds.

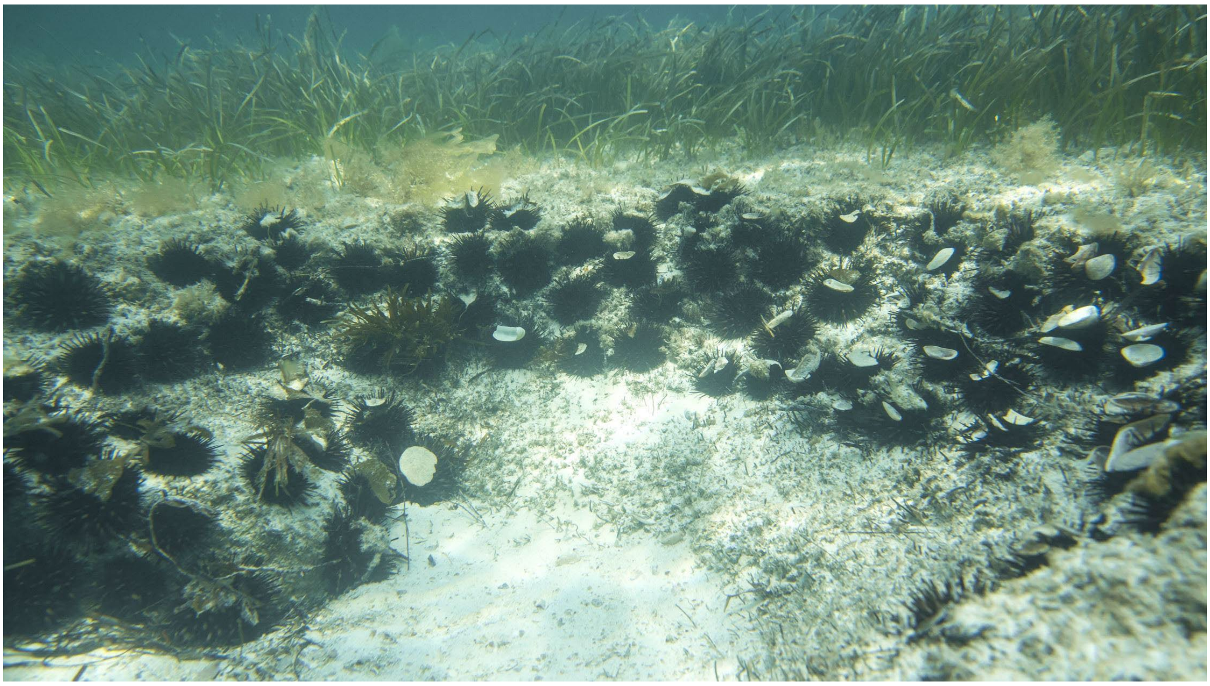


Figure 58 Sea urchin aggregations along the edge of degraded seagrass beds. Sea urchin *Heliocidaris erythrogramma* aggregations within the Cliff Head study area adjacent to areas of degraded seagrass (*Posidonia spp.*) beds.

Concluding remarks

It has been over 120 years since the first management actions were taken to sustain fishery catches of the Western Rock Lobster and in this time, we have learnt a substantial amount about this species and its dynamics as a fishery species, however this project demonstrates that there is still more to learn. This project provides the results of the first trials with Western Rock Lobster early juveniles in y-mazes to assess their habitat preferences and this has provided valuable insights into the chemosensory ability of early juvenile Western Rock Lobsters. The information gained by this project will assist in our understanding of this fishery and has provided valuable information on new parameters that have the potential to be included in the management of this highly valuable and socially important fishery. This work has shown that despite the wealth of knowledge about this fishery there is still much more work to be done on this important species and our fishery interactions with it.

Project Communication

Workshops, research updates and assessment

Workshop Summaries

Workshops were undertaken with fishers given the highly collaborative nature of the work. An initial workshop with fishers was undertaken to identify the suspected area of the low-catch zone and generate a list of potential causes for the abnormally low legal catch rates within this zone.

Regular workshops (Table 15) were used to update fishers throughout the project on present progress and obtain input from active and retired fishers to inform the scientific studies and recommendations provided by the project.

These regular workshops were also used to update fishers on the iterative assessment process used to identify the most likely causative factors of the low-catch zone (See Conclusion and Figure 56 above).

The first workshops were used to populate the assessment with processes both fishers and researchers thought could be likely causative factors of the low-catch zone (Figure 56 above). This assessment was then revisited and reviewed in each subsequent workshop where fishers and researchers presented and discussed recent findings and reassessed the likely causative factors in an iterative manner to guide the study and interpret the findings.

Table 15 Workshop summaries and research updates to fishers and WRL council.

Date	Location	Workshop/research update
December 2016	Port Denison	Preliminary workshop with 12 fishers and project team.
February 2017	Hillarys	Research update to the WRL Research Development Advisory Group by project team.
June 2017	Hillarys	Research update to the WRL Annual Management Meeting by project team.
July 2017	Hillarys	Research update to the WRL Research Development Advisory Group by project team.
May 2018	Hillarys	Research update to the WRL Fishery Peer Review and WRL council by project team.
June 2018	Port Denison	Research update and workshop with 10 fishers and project team.
June 2019	Port Denison	Research update and workshop with 22 fishers and project team. This included student presentations of the trapping, catch-rate and tag-recapture data and the presentation of an interactive web app to explore tag-recapture data.
September 2019	Port Denison	Research update and workshop with 32 fishers and project team. This included presentations of the findings of the trapping and catch-rate study that determined the northward extent of the low-catch zone.
August 2020	Port Denison	Workshop and final assessment presentation to 25 fishers at the Dongara Professional Fishers Association meeting. This included presentations by the project team on surveys of habitat change within the low-catch zone and studies of habitat preference by early juvenile lobster.

November 2021	Port Denison	Final synthesis workshop to 10 fishers at the Dongara Professional Fishers Association meeting. This included presentations by the project team on oceanographic studies suggesting potentially high settlement within the low catch zone and the further analysis of both habitat change data within the low-catch zone and further comparison of fisher perception of catch rate with fisheries catch records.

Workshop - December 2016

A preliminary workshop was held in Port Denison with 12 fishers and UWA and Department of Primary Industries and Regional Development (DPIRD) - Fisheries staff in December 2016 (Figure 57).

The workshop identified:

- The temporal and spatial extent of the zone of anomalous low catch rates (Figure 57).
- Perception of the factors likely to be responsible for the low catch zone (Figure 57).
- A recommended sampling design for puerulus and catch rate studies both inside and outside the zone of anomalous low catch rates.

Suggested factors likely to be responsible for the low catch zone were grouped into three types; recruitment limitation, survival and movement, as presented in the Assessment (See Conclusion and Figure 58 above). These included:

- Recruit limitation
    - Greater oceanographic isolation
    - Reduced settlement cues
    - Greater on onshore/offshore variation in recruitment
- Survival
    - Reduced habitat
    - Reduced food and growth
    - Increased predation
- Movement
    - Increased migration.

Research update - February 2017

Tim Langlois presented a research update to the WRL Research Development Advisory Group.

Research update - June 2017

Jason How presented a research update to the WRL Annual Management Meeting.

Research update - July 2017

Tim Langlois presented a research update to the WRL Research Development Advisory Group.

Workshops - March/April 2018

A series of six workshops were held across the fishery in conjunction with the Western Rock Lobster Councils' April Coastal Tour at meetings in Fremantle, Lancelin, Jurien, Dongara, Geraldton, Kalbarri. During these workshops UWA students and staff interviewed fishers and recorded their spatial and temporal accounts of change in catch rate (Figure 59) which were presented in Study 1.

Figure 59 Workshop and interviews with fishers. Interviews to record their spatial and temporal accounts of change in catch rates.

Workshop and research update - May/June 2018

As part of the Western Rock Lobster Fishery Peer Review, a project update was presented to representatives of DPIRD, reviewers participating in the fishery model and fishers of the Western Rock Lobster Fishery. The issue of the low-catch zone was discussed by reviewers and draft results from the fishery wide perceptions of change in catch rate survey were presented.

Workshop and research update - June/July 2018

A workshop and research update was held in Port Denison with 10 fishers and the project team on 27 June 2018 (Figure 60). The current research and results to date were presented by Tim Langlois, Michael Brooker, Jessica Kolbusz and John Fitzhardinge. Following the presentation there was discussion with fishers on the current and planned research, and additional areas of interest were identified to be sampled in the upcoming tag and recapture study.

Figure 60 Workshop held in Port Denison, WA on 27 June 2018.

Workshop and research update - June 2019

Research update and workshop with 22 fishers and project team (Figure 61). This included student presentations of the trapping, catch-rate and tag-recapture data (Figure 62) and the presentation of an interactive web app to explore tag-recapture data (Figure 63).

Figure 61 Workshop held in Port Denison, WA on 27 June 2019.

Figure 62 Student presentations on potting, tag-recapture and catchability study.

Figure 63 Presentation of interactive web app to explore tag-recapture data.

Workshop and research update - September 2019

Research update and workshop with 32 fishers and project team (Figure 64). This included presentations of the findings of the trapping and catch-rate study that determined the northward extent of the low-catch zone (Figure 65).

Figure 64 Workshop held in Port Denison, WA September 2019.

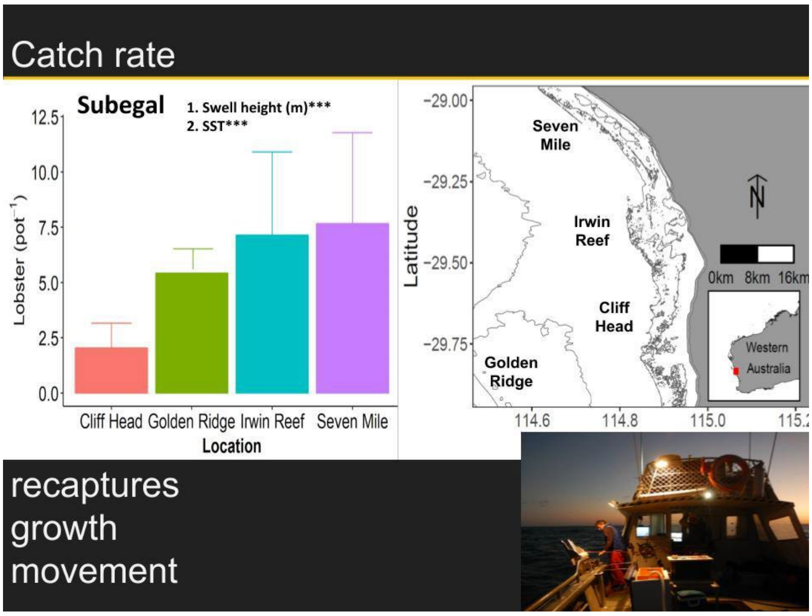


Figure 65 Catch rate of sub-legal lobster indicated the northward extent of the low-catch zone.

Workshop and research update - August 2020

Workshop and final assessment presentation to 25 fishers at the Dongara Professional Fishers Association meeting (Figure 68). This included presentations by the project team on surveys of habitat change within the low-catch zone and studies of habitat preference by early juvenile lobster. The final assessment was presented to fishers and discussed, where the loss of essential habitat, relating to early juvenile lobster survival, was presented as the most likely causative factor of the low-catch zone.

Figure 66 Workshop held in Port Denison, WA Aug 2020.

Final synthesis workshop - November 2021

Final synthesis workshop to 10 fishers at the Dongara Professional Fishers Association meeting (Figures 67). This included presentations by the project team on oceanographic studies suggesting potentially high settlement within the low catch zone and the further analysis of both habitat change data within the low-catch zone and further comparison of fisher perception of catch rate with fisheries catch records. The final assessment was updated and discussed, where the loss of essential habitat, relating to early juvenile lobster survival, was indicated as the most likely causative factor of the low-catch zone (See Conclusion section above).

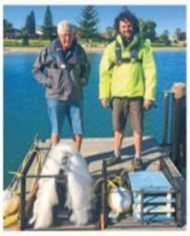
Figure 67 Workshop held in Port Denison, WA November 2021. Photography Linda Cole

Project media coverage

Midwest Times article 1 Nov 2017

Study looks at decline in catches

Midwest Times 1 Nov 2017 John Fitzhardinge and Tim Langlois (UWA) with two of the experimental pots, a demersal post-larval collector on the left and a juvenile collector on the right



Rock lobster fishermen say they are spending less time working the shallow waters from Cliff Head to Leeman.

Dongara boatbuilder John Fitzhardinge said more than 60 commercial lobster boats had seasonally worked there in what had been a very productive fishing ground before the turn of the century.

"Currently very little of the catch comes from these shallows but instead (it) now comes from deeper water," Mr Fitzhardinge said.

Mr Fitzhardinge has had a close involvement with the fishery for more than 50 years.

He has obtained a grant for a three-year project to investigate the low-lobster catches in these waters with three scientists.

They are UWA's Tim Langlois and Simon de Lestang and Jason How from the departments of Primary Industries and Regional Development.

Dr Langlois has previously worked on the ecology of southern rock lobster in New Zealand and in WA and has investigated the feeding preferences and fertilisation rates of western rock lobster.

"The project aims to quantify whether a decline in lobsters has occurred in this region and, if so, to investigate what could be the cause," Dr Langlois said.

"We will use a range of methods to collect various life stages of lobsters from post-larvae to adults.

"This includes lobster pots, demersal and pelagic post-larval collectors, juvenile hides, diver-operated surveys and habitat mapping."

Dr Langlois said the project would also use historical information to detect long-term trends in lobster abundance.

This includes factors such as commercial catch data, private catch logs and photos.

He said the team was keen to hear from anyone with experience in those waters and any information on changes in habitat or local rock lobster population.

People are encouraged to email him via timothy.langlois@uwa.edu.au.

Mr Fitzhardinge asked people to respect the gear that would be set in the shallows from just to the north of Cliff Head out to Big Horseshoe Reef, and inside Beagle Islands.

It is to be clearly marked "FWA Research" on the top floats.

The project is jointly funded by the Western Rock Lobster Council and the Fisheries Research and Development Corporation and will be led by Dr Langlois from the University of WA's Oceans Institute and School of Biological Sciences, Mr Fitzhardinge of Dongara Marine, Dr de Lestang and Dr How of the Department of Primary Industries and Regional Development, Fisheries Division and the Western Rock Lobster Council.

Appendices and Project materials developed

Materials from Study 1 - Contrasting fisher perceptions of spatial and temporal changes in lobster catch rate with detailed fishery dependent catch data: a case study of an area with unexpectedly low catches

Survey Instrument

Following pages provide a copy of the standardised survey used in Study 1.

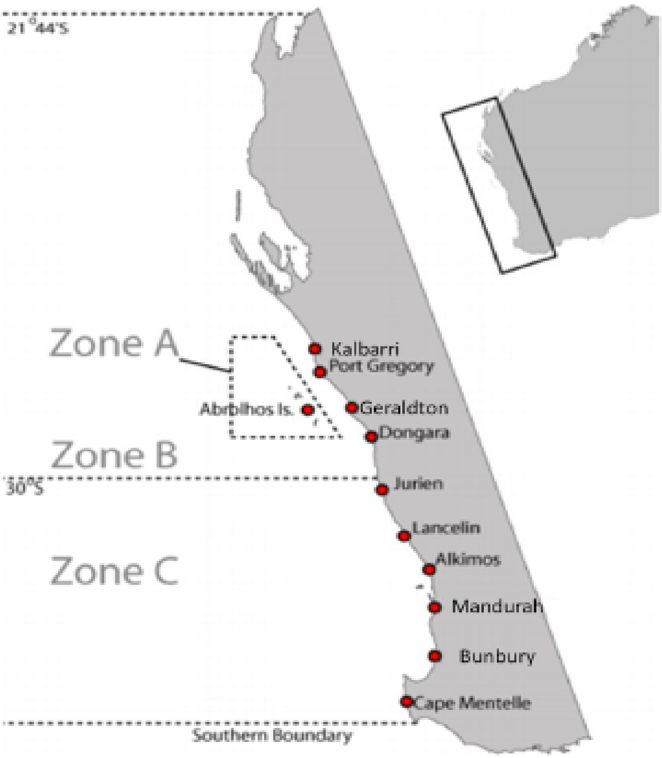
Factors influencing catchability and long-term catch rate in the Western Rock Lobster fishery

Background

The aim of this Fisheries Research Development Corporation (FRDC) funded project study is to collect information from past and current commercial western rock lobster fishers on two aspects on the Western Rock Lobster Fishery; lobster catchability and long term catch rate trends.

Interviews for this study will be conducted along the coast from Kalbarri to Mandurah at the following locations;

- Kalbarri,
- Geraldton,
- Dongara,
- Jurien Bay,
- Lancelin,
- Fremantle, and
- Mandurah.



You will be interviewed by two PhD students. One student will interview you regarding your perception of what factors affect your catch rates, while the other student will interview you about your long term catch rate trends. Interviews will take between 20 and 40 minutes. Audio recordings will be made of all interviews to ensure accurate transcription of the data to be collected. (Please see overleaf for privacy information).

ID#___________

Reds Specific Fisher Survey — March-April 2018.

Interview Metadata:

Participant Details:

Name: ____

Email Address: ____

Today's Date: ___ / ___ / 2018 Interview Location: ______________________

Fishing Experience:

Licenced Fishing Boat (LFB) Number(s): ______________________

Years fished (range):______________________________

Quota:

Approximately how many pots did you generally fish with pre / post quota?

Pre:__________________; Post:__________________

How many of your pots are now the larger 1 m x 1m pots (as opposed to the traditional sized batten pots)?______________________________

What tonnage are you fishing this year?______________________

Temporal Fishing Effort - Post Quota:

What months do you generally fish now? (*Circle all that apply.*)

Jan. Feb. Mar. Apr. May Jun. Jul. Aug. Sep. Oct. Nov. Dec.

Year Round Year Round - Market Dependent

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Trends in the catch rate of Western Rock Lobster:

For the purpose of this survey we are looking at shallow (<10 fathoms), mid (10-20 fathoms) and deep (20-40 fathoms) catches for "Reds" (not "Whites" fishing).

Q1. What has happened to your long term catch rate of 'reds'?

Inner Shallows (<10 Fathoms)	Increase	□	Decrease	□	No Change	□	Unsure	□
Shallows (10-15 Fathoms)	Increase	□	Decrease	□	No Change	□	Unsure	□
Edge of Shallows (15-20 Fathoms)	Increase	□	Decrease	□	No Change	□	Unsure	□
Mid-Deep Water (20 - 35 Fathoms)	Increase	□	Decrease	□	No Change	□	Unsure	□

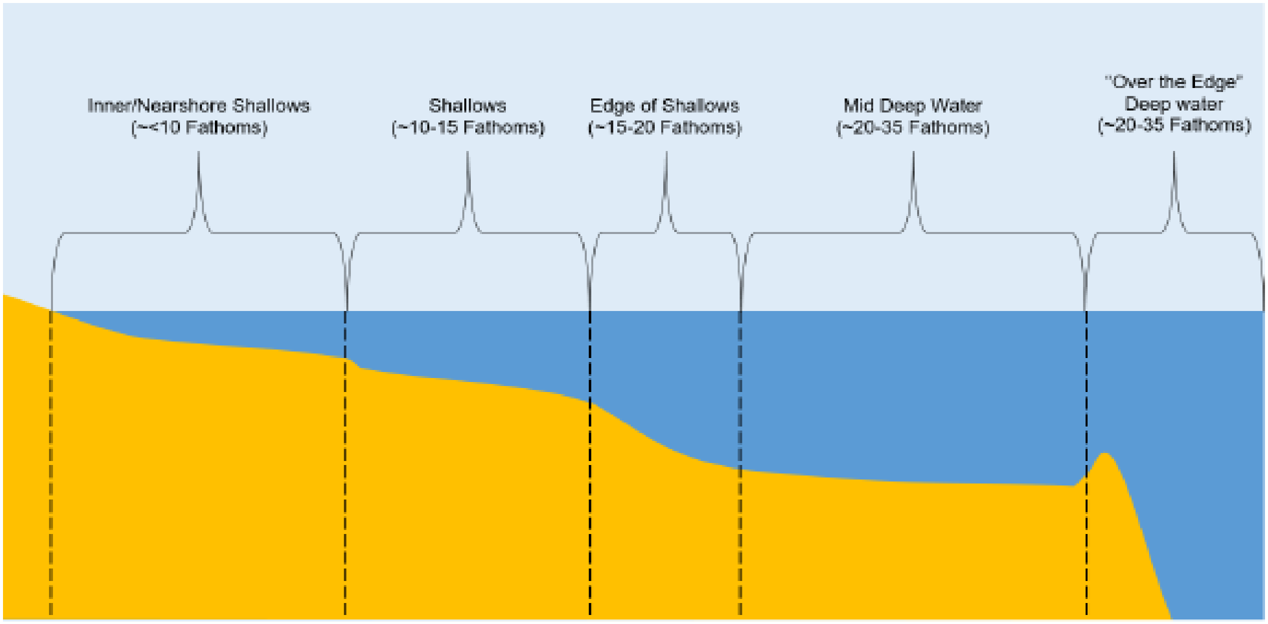
Q2. Have the catch rates in the four zones mentioned above changed the same, or has one performed better/worse than the other?

Inner Shallow Performed Better.	□	Shallows Performed Better.	□	Edge of Shallows Performed Better.	□	Mid-Deep Performed Better.	□	Equal Performance	□	Unsure	□

Q3. Please draw a graphical representation of your catch rates over time. Please complete this for the time you have been fishing and scale the vertical axis from your best catches to your worst catches providing estimates for these catch rates along with you average catch rate. Please complete this for the following zones:

- Inner Shallows **(<10 Fathoms)**
- **Shallows (10-15 Fathoms)**
- Edge of the Shallows **(15 to 20 Fathoms)**
- **Mid Deep Water (20-35 Fathoms)**

Below is a graphical representation of these zones from information provided by fishers:



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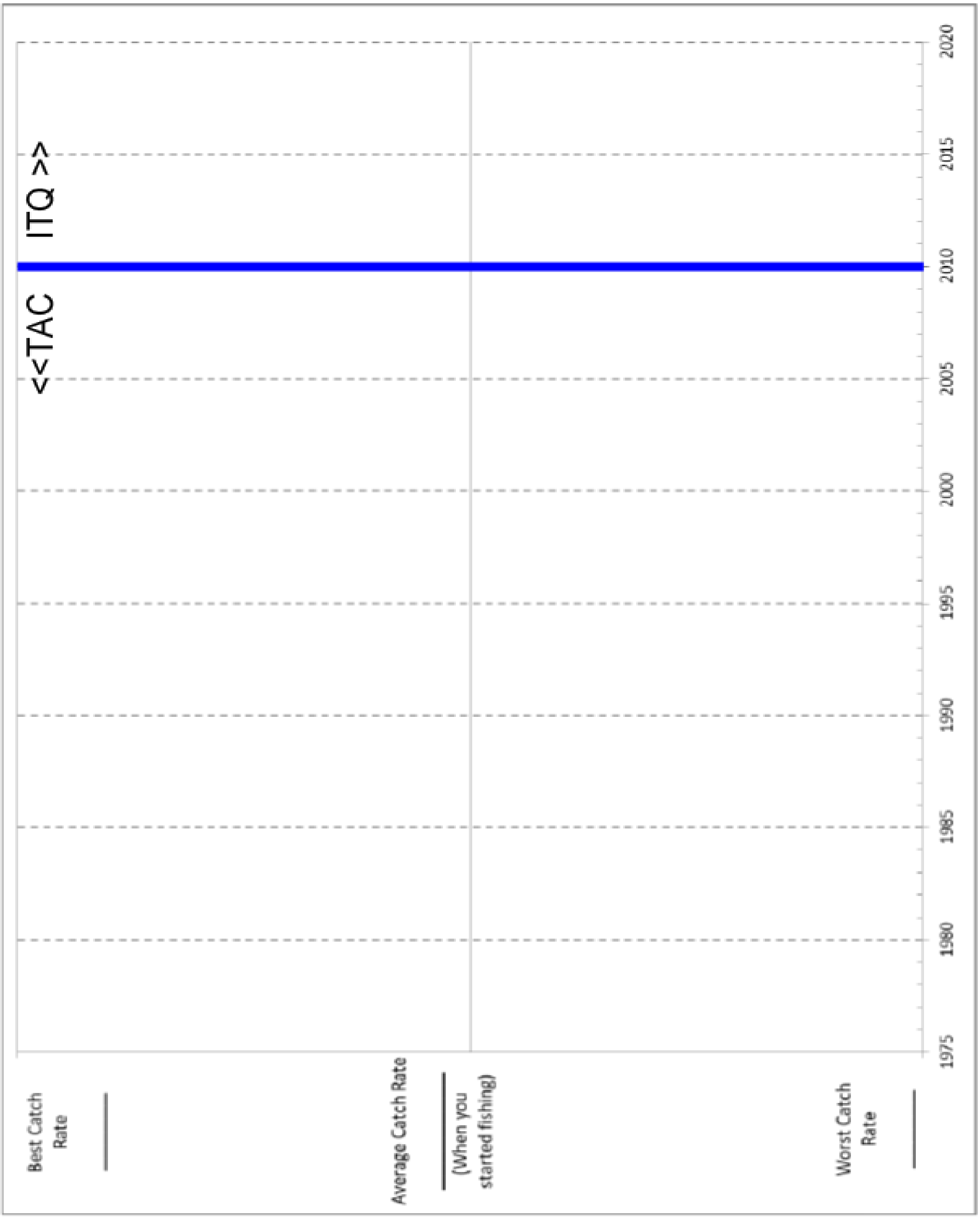
<<TAC
ITQ >>
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Best Catch Rate
Average Catch Rate
(When you started fishing)
Worst Catch Rate

ID#____________

Q4. Where and when have your catches been better, worse or as expected?

Use the maps provided and note whether you perceive catches to be different from expected. Greater than expected (⇧), worse than expected (⇩), or as expected (⇔) including when (year) the change occured for each block and depth combination. Please split observations into the following depth ranges used previously Inner Shallows (<10 Fathoms), Shallows (10-15 Fathoms), Edge of the Shallows (15 to 20 Fathoms), Mid Deep Water (20-35 Fathoms). Only complete block you have regularly fished in.

Q5. What factors do you think could be causing the **positive** changes in observed catch rates?

Puerulus (<20 mm CL)	**Juvenile (20 - 40 mm CL)**	**Sublegal (40 - 70 mm CL)**	**Legal (>70 mm CL)**

Q6. What factors do you think could be causing the **negative** changes in observed catch rates?

Puerulus (<20 mm CL)	**Juvenile (20 - 40 mm CL)**	**Sublegal (40 - 70 mm CL)**	**Legal (>70 mm CL)**

Q7. If you noticed a reduction in catch rates what were the strategies you used to overcome the reduction? (Select up to 5 options and circle the most important strategy pre and post quota).

Strategy:	Pre-Quota	Post-Quota
Fisher Remains Actively Fishing		
Increase time spent fishing	☐	☐
Change bait type	☐	☐
Move latitudinally to another shallow water area (<20 fathoms)	☐	☐
Move longitudinally offshore to deeper water	☐	☐
Move to latitudinally + longitudinally to offshore area of deeper water	☐	☐
Lease in	☐	☐
Change time of year of fishing	☐	☐
Other...	☐	☐
Fisher Stops Actively Fishing / Leaves Fishery		
Lease quota	☐	☐
Sell quota	☐	☐
Other...	☐	☐

Additional Information:

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Materials from Study 4 - Examining the settlement of Western Rock Lobster in an area of reduced catches

Puerulus collector description and deployment details

After numerous unsuccessful attempts to collect significant numbers of puerulus and post puerulus larvae of palinurid lobsters (Kensler 1967; Witham, Ingle, and Sims 1964; Lewis, Moore, and Babis 1952), Phillips (1972) was able to develop a collector that was able to successfully continuously sample puerulus and post puerulus WRL. The collector, known as the Phillips Collector (B. F. Phillips 1972), consists of a light aluminium frame that supports three grey PVC panels back to back around two floats. The PVC panels are 0.61 meters long and 0.30 meters wide and contain 25 tassels of a synthetic rope fibre. Each tassel is approximately 0.23 meter long and is bound to the PVC panel with flyscreen spline. The sheets slide into the aluminium frame from the top and are secured by rope. The collectors are “serviced” monthly which consists of the collector being lifted from the water, the panels removed and shaken using a knock box. The animals shaken from the tassels are counted, the panels are replaced in the collector, the collector is redeployed and the animals that were collected are released some distance from the collector to reduce the likelihood of resettlement on the collectors. Since its initial development the Phillips Collectors (B. F. Phillips 1972) have remained largely unchanged with the only major changes being the material used for the tassels and seagrass matting on the collectors. Subsequent comparison studies found that the original “Tanikalon” fibre was significantly more efficient (18%) than the current Boral Kinnears split fibre and that there was no effect of the seagrass matting, it was also noted that the rate of efficiency would be revised following further work (De Lestang et al. 2012).

A Fisheries Research Development Corporation (FRDC) funded project 1998/302 investigated techniques for the large-scale harvesting of pueruli for aquaculture grow-out. This project investigated several different harvesting methods for puerulus including pump nets, fixed nets, trawl nets, Mills collectors (Bruce F. Phillips et al. 2001), Witham collectors (Witham, Ingle, and Joyce 1968), purse type collectors with tubes (Serfling and Ford 1975), sandwich collectors (Bruce F. Phillips et al. 2001) and Rossbach collectors (Bruce F. Phillips et al. 2001). The study found the sandwich collectors to have an overall effectiveness with significantly better catch rates and ease of servicing compared to the other methods trialled.

Sandwich collectors consist of two Phillips collector panels mounted back to back with two Jarrah battens between the sheets (Bruce F. Phillips et al. 2001). The collector has a small amount of chain at the base for stability and two floats are tied to the top batten. The collector is attached to the mooring using a bridle to assist in the recovery of the collector. The sandwich collectors are also “serviced” monthly which consists of the collector being lifted from the water, the floats are then removed, and the collector is placed on a shaft which is placed over a large tub and spun. The collector is covered and spun 20 times in each direction. The total number of puerulus are counted and released a distance from the collector much like the Phillip’s collector. The floats are reattached to the collector, and it is reattached to the mooring and redeployed.

Both types of collectors were deployed on the leeward side of emergent reefs at varying distances from shore (refer to the manuscript). The collectors were moored to the seafloor using a bridle and float to ensure easy recovery and resilience against swell and currents (Figure 68).

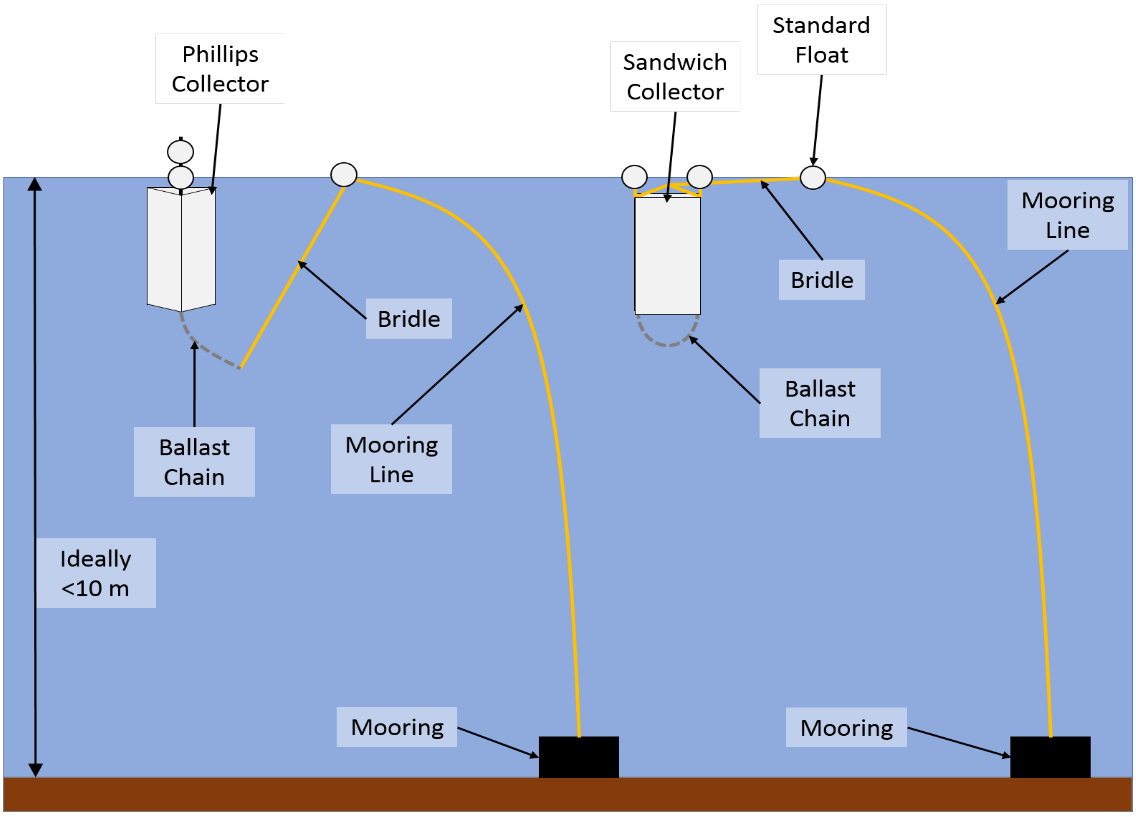

Figure 68 Typical puerulus collector deployment design for the "Phillips" type collector (shown left) and "sandwich" type collector (shown right).

Protocols for settlement collector servicing

Phillips Type Collectors

The method of checking the collectors needs to be as standardised as possible. A routine for handling the collector should be determined, written down, and adhered to.

With the Phillips collector the instructions to the boat crew for checking collectors are as follows:

a) Round up to the collector and attach a hook to the centre of the aluminium frame. Secure the hook with a rope to the side of the boat so that the top float sits on the gunwale.
b) Reach below collector to snap hook and release collector from mooring chain, attach mooring chain to a bow line to anchor your boat.
c) Then either using a derrick and pulley lift the whole collector on board and untie 6.0 mm rope holding sheets into frame or with the collector still in water untie sheets one at a time and lift on board by hand.
d) Pull the sheet out of the frame and put it into the shaking tray, fibre side down.

e) Slide the aluminium shaker over the PVC. backing board so that the PVC. board slides into the channels in the aluminium shaker.
f) Hold the shaker by the handles and give the sheet 20 "bangs" and then drop the whole device on the deck, fibre side down.
g) Pour the contents in the tray of the shaker through the sieve, pick up the shaker with a sheet attached and bang it another 10 times over the tray. If any more puerulus appear in the tray, "bang" the sheet another 10 times and repeat this process until no more puerulus appear.
h) Slide the PVC. sheet out of the shaker and stand the sheet against the inside of the side of the boat so that the fibres inwards to air out.
i) Repeat this process for the remaining two sheets still in the frame.
j) When all three sheets have been shaken, hold the collector on the gunwale and slide the three sheets into the channels in the frame. Retie the sheets onto the frame and then pull on the bow line and retrieve mooring chain, reattach collector and push over the side and back into the water.
k) Count the number of puerulus on each collector. Take care that any specimens are larger than the others, and might have settled at the previous moon phase, are clearly identified.
l) If there is no other need for the puerulus from the collectors, they should be returned to the sea, taking care that they are released at some distance from the collectors to prevent contamination.
m) Each month it is essential that the sheets of tassels be examined for tangling, loss of tassels, etc. Sheets with missing tassels can be repaired hence it is necessary to carry a few spare tassels on each trip. After about six to eight months (sometimes earlier in coral areas or in areas of heavy siltation) the end of the tassels may become too matted or the sheet too heavy to make the sheet useful. These sheets should be replaced. As a working plan it is best to replace one sheet in each collector every third or fourth month.

Sandwich Type Collectors

The method of checking the collectors needs to be as standardised as possible. A routine for handling the collector should be determined, written down, and adhered to.

With the Sandwich collector the instructions to the boat crew for checking collectors are as follows:

a) Round up to the collector and attach a grappling hook to the bridle connecting the collector to the mooring. Haul the collector to the side of the vessel. Then either using a derrick and pulley lift the whole collector on board placing it into a tub to prevent the loss of puerulus. Untie the bridle from the collector. Throw the bridle over the side and ensure it remains clear of the propellers.

b) Untie the two surface floats and clean the floats if required.
c) Clear the tassels from the top end of the collector and insert the spinning shaft through the collector. If the collector is equipped with a Bluetooth temperature logger ensure the data is downloaded.
d) Place the collector on the spinning tub and place the "spacer" on the end of the shaft to stop the collector coming out of the "catch".
e) Pull the blue tarp over the collector and ensure it is held down.
f) Spin the collector 20 revolution clockwise and 20 revolutions anti clockwise at a moderate to fast pace.
g) Remove the collector from the tub and pull the shaft from the collector.
h) Tie the surface floats back onto the collector.
i) Tie the collector back to the bridle and redeploy the collector over the side ensuring that it is sitting correctly in the water and is not tangled.
j) Pour the contents of the spinner tub and hold the tub through the sieve. Collect any other samples as necessary.
k) Count the number of puerulus on each collector. Take care that any specimens are larger than the others, and might have settled at the previous moon phase, are clearly identified. Complete the ArcCollector data entry form.
l) If there is no other need for the puerulus from the collectors, they should be returned to the sea, taking care that they are released at some distance from the collectors to prevent contamination.
m) Each month it is essential that the sheets of tassels be examined for tangling, loss of tassels, etc. Sheets with missing tassels can be repaired hence it is necessary to carry a few spare tassels on each trip. After about six to eight months (sometimes earlier in coral areas or in areas of heavy siltation) the end of the tassels may become too matted or the sheet too heavy to make the sheet useful. These sheets should be replaced. As a working plan it is best to replace one sheet in each collector every third or fourth month.