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An industry-based mark recapture program to provide stock assessment inputs for the Western Rock Lobster Fishery following introduction of quota management

FRDC Project No. 2014/023

Simon de Lestang, Matthew Pember, John Hoenig, Jason How

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Enquiries:

WA Fisheries and Marine Research Laboratories,
PO Box 20,
North Beach, WA 6920

Tel: +61 8 9203 0111
Email: library@fish.wa.gov.au
Website: fish.wa.gov.au

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Department of Primary Industries and Regional Development
Gordon Stephenson House
140 William Street
PERTH WA 6000
Telephone: (08) 6551 4444
Website: dpird.wa.gov.au
ABN: 18 951 343 745

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1.0 Executive Summary

The West Coast Lobster Managed Fishery (WCRLMF) moved from input to output controls in 2010. This change directly affected the relativity of a number of fishery-based data sources, making assessment of the fishery more problematic. A novel examination of the stock dynamics was required to help ensure the stock assessment and associated management outcomes for this valuable resource were maintained. This study derived estimates of current biomass levels and harvest rates throughout the WCRLMF based on the release (over 40,000) of tagged Western Rock Lobsters (*Panulirus cygnus*) and the recapture of tagged lobsters, using a multi-stage modelling process. Components of this study, such as tag loss and reporting rates, were initially independently examined, before a generalised “Brownie” tag-recapture (BTR) model was implemented that provided an assessment on a fishery-wide basis. Finally a novel purpose-built individual-based model (IBM) was developed that was capable of producing estimates of biomass and harvest rates on finer spatial and temporal scale, as well as providing estimates of migration and growth.

The two tag-recapture models (BTR and IBM) used in this study both produced very similar estimates for the fishery-wide exploitation rate (ER ~0.3 vs 0.29 – 0.33) and legal (≥76 mm) biomass (~18,500 vs 19,000 – 23,000 t). These estimates indicate that the Western Rock Lobster resource is currently in a very sustainable condition, and is being fished at a rate below that considered to represent maximum economic yield (ER ~ 0.39). These findings are in concert with estimates derived for this fishery during recent annual stock assessments, based on two separate population models, an integrated population model and a biomass-dynamics model. Such strong agreement between all models provides a greater certainty in the current assessment and management of this important fish resource.

In addition to examining biomass and exploitation rates, the IBM estimated movement patterns and growth rates. This added to our understanding of migration rates, migration size and growth of *P. cygnus* under lower exploitation rates than they have experienced previously. These estimates showed that movement rates were greatest in the southern end of the fishery, declining in a northward direction, especially in deep-water locations. Further work is planned to better understand the management implications of these differential movement patterns.

The IBM also predicted offshore movement (from shallow locations to deeper waters) was conducted by lobsters with a slightly larger mean size than those in their adjacent deep-water areas. This was contrary to our current understanding but may be explained by recent environmental perturbation which may have impacted WRL growth differently in shallow and deep water. The study also found that the growth of *P. cygnus* is relatively plastic, varying in response to changes in water temperature, habitat and population density. Based on future projections of a warming climate and the harvest rate objective to maintain the fishery at MEY, these factors are likely to result in a reduced growth rate and smaller size at maturity than has been recorded historically for this species. This has implications for the productivity and management of this resource and need to be incorporated in future stock assessment modelling.

The IBM model developed during this study was capable of deriving estimates of exploitation rate and biomass on a fine spatial and temporal scale without using standard fishery-derived data sets (e.g. catch and catch rates). Its incorporation into the new integrated population model would only increase the robustness of this new model, thus increasing the accuracy of the annual stock assessments and the ability to best manage this important resource.

KEYWORDS: Western Rock Lobster; Tag; Recapture; Exploitation; Biomass; Sustainability; Modelling

2.0 Acknowledgments

Our thanks go to the FRDC for providing the funds for this study. Very important contributions were provided by all the fishers who returned tags, including the Geraldton Fishermen's Cooperative who also provided tags when found in the factory. We would also like to thank Nick Caputi and Lachlan Strain for reviewing this report.

3.0 Abbreviations

AIC:	Akaike Information Criterion
bGAM:	binomial Generalised Additive Model
bGLM:	binomial Generalised Linear Model
BTR:	Brownie Tag-Recapture model
CDR:	Catch Disposal Record
CL:	Carapace Length
CSIRO:	Commonwealth Scientific and Industrial Research Organisation
DPIRD:	Department of Primary Industries and Regional Development
IBM:	Individual Based Model
IBSS:	Independent Breeding Stock Surveys
TP:	Tag-Pleopod
TT:	Tag-Tag
WCRLMF:	West Coast Rock Lobster Managed Fishery
WRL:	Western Rock Lobster

4.0 Introduction

The West Coast Rock Lobster Managed Fishery (WCRLMF) has been managed for over 40 years by ensuring breeding stock levels remain above threshold reference points using a range of effort controls such as limited pot numbers, closed seasons and biological controls (e.g. protection of breeding females and minimum and maximum size limits) (de Lestang et al. 2016). The effectiveness of this harvest control system relied heavily on the consistency between fishery-dependent catch rates and lobster abundance. Between 2009 and 2013 the fishery progressively altered its management regime to one controlled through individual-transferable quotas. This change in management dramatically altered the behaviour of the catching sector, as they moved away from competing with each other for catch during a limited season, to maximizing profits through fishing in high beach price periods and reducing their costs. Fishers have now increased pot soak times, are using less bait and are not moving great distances in search of small increases in catch, all of which have affected their catch rates.

These changes in fishing behaviour affected the relativity of the long standing empirical fishery-dependent catch rate indices that have been a major component of the assessment of lobster stocks (e.g. catch rates of legal, undersize and breeding lobsters). A recent FRDC funded study (2009-019: Evaluating the potential use of change-in-ratio and index removal techniques for determining harvest rates and efficiency increases in the Western Rock Lobster Fishery) examined the possibility of using alternative data sources unbiased by effort to monitor biomass levels and exploitation rates using change-in-ratio techniques (de Lestang et al. 2012). The project concluded that: 1. The current data sources available to the fishery had too many unknowns including size and sex specific timing of growth and movement to enable the assessment of exploitation rates using these techniques. 2. A robust tag-recapture study with multiple releases across different fishing seasons could generate independent assessments of legal biomass and exploitation rates. These data would provide an additional baseline improving the interpretation of post quota catch rate indices. A comprehensive tag-recapture study would also provide increased resolution of the movement dynamics of lobsters, especially the rate of migration between management zones. Such information is considered vital by industry in their discussions of the potential benefits of voluntarily reducing quotas to generate increased localised catch rates (de Lestang et al. 2012).

In 2008 the Department of Primary Industries and Regional Development (DPIRD) began to develop a stock assessment model that integrated fishery-independent data into the assessment process. With the recent breakdown in the relativity of fishery-dependent catch rates between years, this stock assessment process has been forced to rely heavily on fishery-independent data. Fishery-independent data however, is currently limited both spatially and temporally and to increase these surveys to collect additional data is both very expensive and time consuming. Tagging studies have proven to be a good alternative to additional fishery-independent surveys, as they utilise fishing fleets for capture, tagging, release and re-capture which reduces costs dramatically, while their results can still remain unaffected by fishers' behaviour. The Brownie tag-recapture tagging design is especially valuable in this circumstance. This technique utilises multiple releases of animals separated by relatively short temporal periods (months - years), with the contrast in recaptures between releases shown to provide accurate and timely estimates of catchability, mortality and stock size (Hoenig et al. 1998a,b; Ley-Cooper et al. 2013).

This study aims to derive estimates of current biomass levels and harvest rates throughout the WCRLMF based on the use the multiple release and recapture of tagged lobsters. A multi-stage modelling process will be applied, whereby components of a tag-recapture study, such as tag loss and reporting rates, will be examined individually. A generalised "Brownie" model will then be applied, utilising information from the initial analysis, to assess the tag-recaptures on a fishery-wide basis. This will produce global estimates of harvest rate and biomass levels for the fishery, independent of biases associated with fisher behavior. This form of model has been thoroughly tested in the literature and is well suited to such a study (Hoenig et al. 1998b; Ley-Cooper et al. 2013; Lauretta and Goethel 2017). Finally, a novel purpose-built individual-based tag-recapture model (IBM) will be developed. This IBM will produce estimates of biomass and harvest rates on a finer spatial and temporal scale, as well as estimates of migration and growth. This model will be developed using the same framework (spatial and temporal scale and on the TMB platform) as the new WRL population model being developed in conjunction with CSIRO. As such, if successful, components of the tag-recapture model can be integrated into the new population model for this fishery.

4.1 Objectives

1. Determine spatially specific exploitation rates and legal biomass levels
2. Increase precision of estimates for movement rates between management zones
3. Improve understanding of the variability of growth throughout the range of the fishery

5.0 Methods

The objectives of the study were achieved using a combination of four statistical models, a tag-loss model, a reporting rate model, a Brownie Tag-Recapture model (BTR; Brownie et al. 1985) and a novel individual-based population model (IBM). The latter two models were capable of producing estimates of harvest rate and legal biomass (Objective 1). In addition, the IBM was capable of producing estimates of movement and growth rates throughout the fishery (Objectives 2 and 3) as well as rates of tag loss and tag reporting. Data inputs differed for the four models (Table 1). When estimates were required as an input (e.g. tag-loss rate in the BTR), these estimates and their associated variances, were determined by stand-alone preliminary models developed in R (R Core Team 2019). The BTR was also developed in R, whereas the IBM was developed in the R/TMB combination due to its greater number of estimable parameters (13 vs 53 parameters, respectively).

Table 1. Data or estimate input requirements of the two preliminary analyses (tag loss and reporting) and the two models (BTR and IBM).

Data / Estimate inputs	Tag-loss	Tag-reporting	BTR	IBM
Tag release and recapture data		Y	Y	Y
Double tag release and recapture data	Y			Y
Commercial catch and effort data		Y	Y	Y
Commercial monitoring data		Y		Y
Independent Survey Data (IBSS)				Y
Tag loss rate estimate			Y	
Reporting rate estimate			Y	

5.1 Tag Release

Tagging of lobsters was conducted by Government (DPIRD) staff using a standard version of the Hallprint^{TM} T-Bar anchor tags (TBA – 46 mm streamer length, 14 mm exposed filament and 8 mm T-bar width and TBF – 25 mm streamer length, 10 mm exposed filament and 6 mm T-bar width; http://www.hallprint.com; accessed 27 Nov. 2019). Tags were inserted ventrally (either the left or right side of the lateral line into the abdominal muscle between the posterior margin of the cephalothorax and the first abdominal somite (Figure) using an Avery Dennison ™ Mark III Swiftach Tool tagging gun. This location of tagging was chosen as it has the lowest rate of tag loss and tag mutilation (Melville-Smith and Chubb 1997). Some lobsters released as part of the Tag Reporting trial [see Tag Reporting (preliminary model)] were dorsally tagged at the posterior margin of the cephalothorax. The size (carapace length; CL), sex, reproductive state, colour, tag number and release location were recorded and entered into an SQL database. Only lobsters without obvious damage (e.g. missing appendages) were tagged. If a tagged lobster dropped a leg or antennae prior to being released, this damage was recorded. A number of tagged lobsters were double tagged (see Tag-Tag) or were additionally marked by the clipping of one of their pleopods (see Tag-Pleopod). Both additional tagging methods were applied to aid in determining the rate of T-bar tag loss. These are further described below under “Tag Loss”.

Figure 1. Tagged Western Rock Lobster showing the Hallprint ™ spaghetti tag inserted between the posterior margin of the cephalothorax and first abdominal somite.

Tagged lobsters were released using one of two techniques. The majority of lobsters (~99%) were released using the traditional method of being returned individually, immediately post tagging to the water at the site of capture. Alternatively, ~1% of tagged lobsters were returned using a novel release cage designed to reduce potential mid-water predation as the lobster transverse the water column on their way to the sea floor. This cage consisted of a 66 L Lug box (https://www.silverlock.com.au/m-lb001-lug-box-66lt-various-colours; accessed 27 Nov. 2019) with a steel lobster pot base (650 mm long x 450 mm wide) that would pop open upon landing on the sea bed (Figure). When opened the positively buoyant lug box would float off the steel base to a height of one meter (length of a tether between the two objects) and the lobsters contained within would be free to move off towards a safe habitat. Any remaining lobsters would be flushed out of the box upon its retrieval approximately five minutes later. On average the cage contained 30 lobsters for release. Trials of release techniques were conducted between 2014 and 2015. Analysis of proportions returned and distance moved for lobster released using the two techniques (see Results; Impact of release cage) were used to inform the release method for all subsequent tagging activities.

Figure 2. Release cage constructed of a steel base spring-clamped to a lug box (orange). Lobsters are loaded into the lug box and the base added to the top and the clamps closed. Upon deployment the box rolls over so that the base is facing the seafloor. Upon reaching the substrate, the two clamps are forced away from, and thus releasing, the lug box by the movement of the two hinge arms in towards the base.

Lobster-tagging occurred in pulses from July 2014 to September 2017 off both commercial and research vessels throughout the fishery (Figure 3). Releases from commercial vessels were limited to non-retained lobsters (e.g. those high-graded or protected), whereas those from research vessels consisted of all captured lobster. This limitation on lobsters available for tagging on commercial vessels was not considered too restrictive as, due to rapid changes in the relationship between lobster size and value (beach price), those lobsters high graded one week became the targeted lobsters the following, thus generally allowing a range of lobster to be tagged. For the purpose of estimating fishing mortality, the data has been limited to only those lobsters released with carapace lengths (CL) ≥76 mm (lobsters below this have a substantially reduced catchability due to the use of escape gaps in lobster pots). This removed 12% of records from the analysis of fishing mortality. All lobsters tagged (irrespective of release size) were used in the determination of growth and movement.

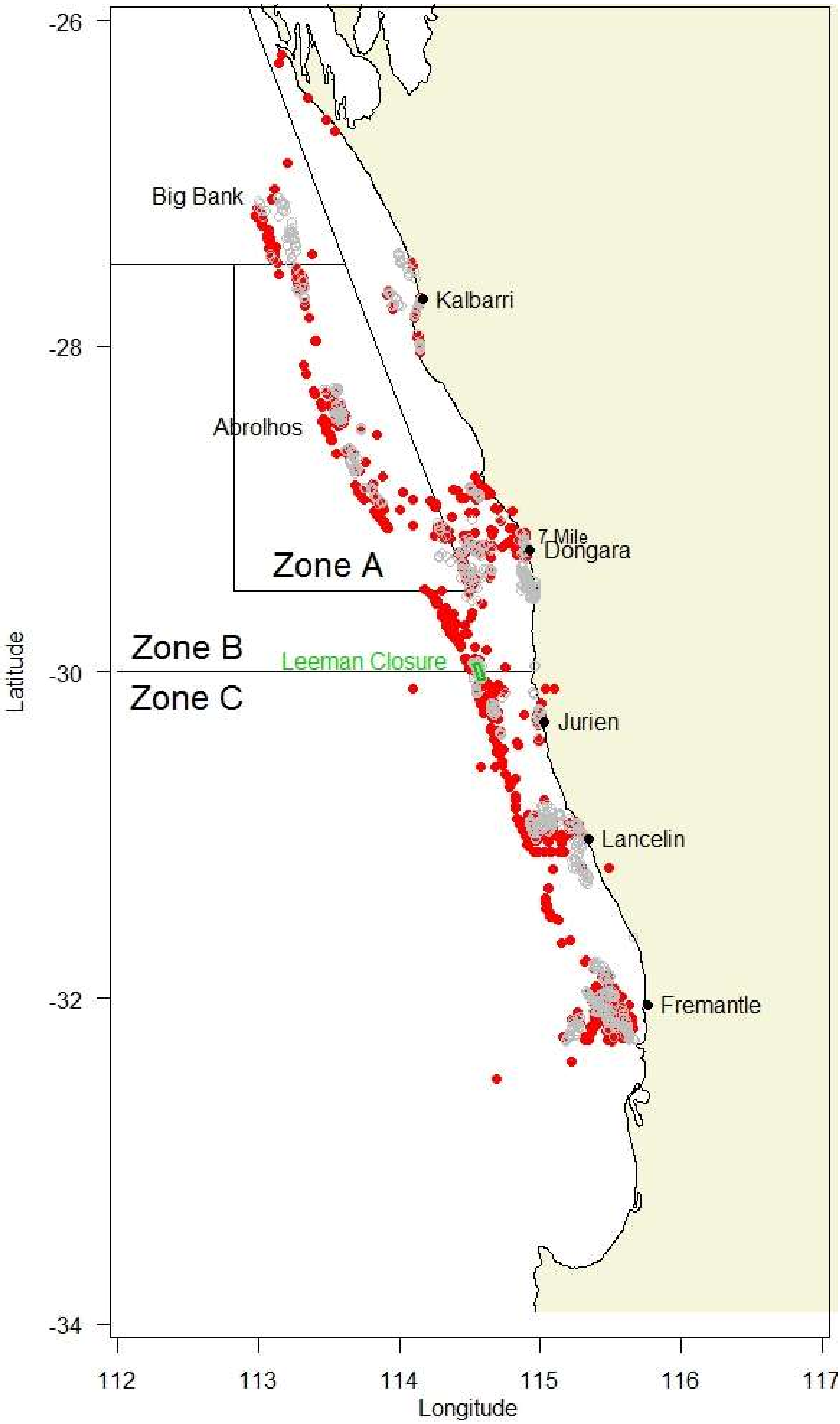

Figure 3. Release (grey) and recapture (red) location of lobsters tagged as part of FRDC

2014-023.

5.2 Tag Recaptures

Information from recaptured lobsters was provided by commercial and recreational fishers as well as research staff during research trips. Information requested included recapture location (GPS), recapture date, sex, size and condition (colour, maturity state and appendage damage). All tag-release and recapture data was stored on a DPIRD-owned SQL database. Prior to analysis, the tagging database was examined for obvious erroneous information. Records were excluded from analysis if the tagged lobster was reported to have changed sex between release and recapture or was reported to have been released or recaptured on land.

5.2.1 *Recapture Reporting Options*

A range of options to submit tag returns were provided in an attempt to accommodate the preferences of different fishers within the commercial and recreational sectors, thus maximising tag returns.

1. Tags return card: These cards, which have reply-paid postage, and have been used within the industry for 50 years (Appendix 1 Tag Return Card). Many fishers have these tags on board and provide a ready means by which to record the necessary information which can be posted back to the Department free of charge.
2. Catch Disposal Record: Fishers are required to submit a catch disposal record (CDR), either electronically or as part of a logbook, at the conclusion of a fishing trip. Tag-recapture information was entered into the comments section of the CDR. (Appendix 2 Catch Disposal Record; CDR). Once entries are compiled into the CDR database, all CDRs are scanned electronically for the presence of three sequential numbers within a sentence in the comments. All identified CDRs are then examined by a DPIRD technician to determine if they represent a tag return. In ambiguous cases the skipper is contacted for clarification.
3. Electronic App (FishtagWA): A purpose-built tag-recapture app available for IOS devices on the App store[1] was developed to facilitate tag returns. The app simplified data submission automatically populating the recapture location (using the device's GPS system) and date, while also directing the user to include the appropriate information (such as sex, CL and reproductive state). It also allows for the addition of photographic evidence of the recapture.
4. Email: A purpose built email address (lobster.tag@fish.wa.gov.au) was developed, such that fishers could email in tag recapture information.

[1] https://itunes.apple.com/au/app/fishtagwa/id785910062?mt=8

5. Phone: The Research Section's main phone number was also provided to fishers such that they could call up and provide the details of a tag return over the phone.

All of the aforementioned tag return methods were communicated to fishers at industry meetings which occurred annually throughout the fishery.

5.2.2 *Recapture Reporting Incentives*

All fishers, commercial and recreational, who returned tags were provided with an information letter (**Error! Reference source not found.**). This letter detailed the tagging history of their recaptured lobster including information on its release size and location, which coupled with the recapture information they provided permitted the growth and movement of the lobster whilst at liberty to be determined and supplied to the fisher. The letter also included a $5 instant win lottery ticket by way of reward for returning the tag.

Throughout the three-years of the study, an annual lottery was also run for all fishers who returned tagged lobster recapture information. The lottery (run by the Western Rock Lobster Council), was based on the number of tags returned that year, with a first prize of $3000 with 20 lots of $100 prizes. The prizes were drawn at annual management meetings between the Department and industry, which coupled with presentation of preliminary data, was aimed at further raising the profile of the study and hence return rates.

5.3 Commercial Catch and Effort Data

Catch and effort data are required to be completed by all fishers at the conclusion of each fishing trip via a Catch Disposal Record (CDR) (Appendix 2 Catch Disposal Record). This mandatory reporting ensures 100% of all fishing effort is captured; reported as the number of pot lifts per session within a 10x10 nm block. Catch is recorded as weight (kg) and the number of lobsters high-graded is also recorded. For further information see de Lestang et al. (2016). This data was used in determining tag reporting rate (Methods: Tag Reporting) and as an input into the BTR and IBM.

5.4 Commercial Monitoring Data

Research staff undertake fishery-dependent monitoring of size, sex, reproductive state and colour (indicative of migratory phase) at six locations (Fremantle, Lancelin, Jurien, Dongara, Kalbarri and Abrolhos Islands) throughout the fishery (Figure 4). Monitoring aims to cover each of the four depth categories (<10, 10-20, 20-30 and >30 fathom) each month and measure at least 300 lobsters per depth per site, per month. This can't always be achieved and is dependent on the effort distribution of fishers. Where all the lobsters on a fishing trip are not measured, a record is kept of the number of pots sampled and the total number pots pulled along with total catch. When all lobsters are measured during a fishing trip, the total number is divided by the total catch to provide an average lobster weight for the trip. For more details on the catch monitoring program see de Lestang et. al. (2016).

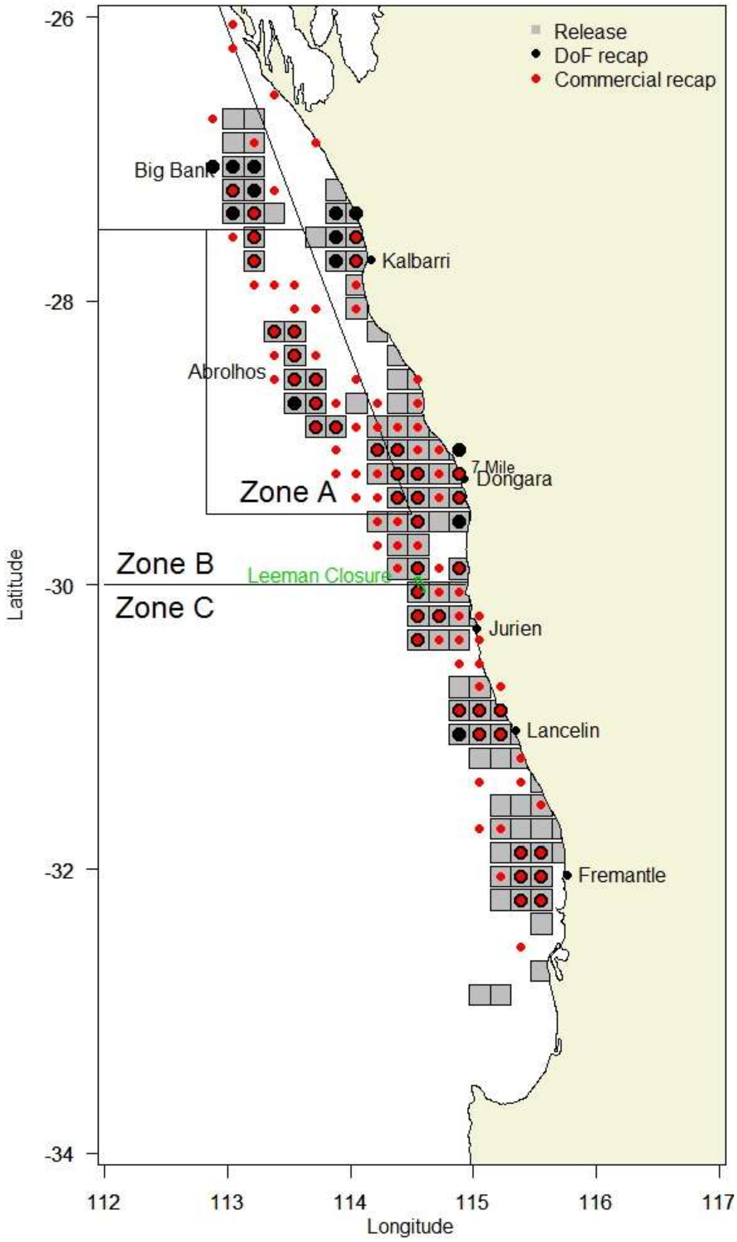

Figure 4. Blocks (10x10nm) indicating research monitoring (grey square), research tag returns (black dot) and commercial tag returns (red dot) within the West Coast Rock Lobster Managed Fishery. Ports from where monitoring are conducted are denoted by small black dot and associated location.

5.5 Independent Survey Data

DPIRD conducts annual independent breeding stock surveys (IBSS) at a number of deep-water locations throughout the fishery in September/October/November each year. These surveys are standardised for changes in fishing behaviour and are staffed by DPIRD staff. Every lobster captured during these trips is examined closely, therefore all those with a tag would be expected to be discovered (expected to have a reporting rate of 100%). For more details on the IBSS see de Lestang et al. (2016).

5.6 Tag Loss (preliminary model)

Tagged lobsters can disappear from the population by capture, tag shedding, tag-induced mortality or via natural mortality. Tag-recapture models are capable of determining tag loss due to fishing and natural mortality if it has prior estimates of tag shedding and tagging-induced mortality. It is not necessary to separate these two forms of tag loss, only a measure of their combined effect is required (this is collectively referred to as tag loss). A common method to determining tag loss is to use animals released with two identical tags and then compare the relative recapture rates of animals with either both or only one tag (Tag-Tag (TT)). Improved estimates can be produced by combining TT methods with a second trial of tag loss whereby only one tag is used (for which tag loss needs to be determined) and an additional mark with a known shedding rate (e.g. a permanent mark such as a snipped pleopod, Tag-Pleopod (TP)) which does not cause mortality. Estimates of tag loss for this project were achieved through combining TT and TP estimates.

5.6.1 *Tag-Tag (TT)*

The double tag trial (TT) consisted of releasing lobsters tagged with two standard T-Bar anchor tags inserted ventrally either side of the lateral line into the abdominal muscle between the posterior margin of the cephalothorax and the first abdominal somite (Figure). A total of 1,032 TT lobsters were released mainly in 2014 and 2016. All releases occurred in water depths > 40 m with most lobsters being mature and larger than 76 mm CL. Since these lobsters were released within the general fishing grounds, the majority of returns were reported by commercial fishers.

Figure 5*.* Image of a Western Rock Lobster tagged ventrally with two standard T-Bar anchor tags (TT).

5.6.2 *Tag-Pleopod (TP)*

The double mark trial (TP) consisted of the release of a number of lobsters tagged with a single T-Bar tag and the marking of a month-specific pleopod via snipping with scissors (Figure). This trial was conducted at two locations, one closed to fishing (Leeman closed area; 30°00’00”S, 114°10’37.00”E sampled in 2017; Table 2) and one not closed to fishing (Seven Mile Beach; 29°10’18.07”S, 114° 53’19.67”E, sampled from 2014 – 2018; Table 2) (Figure). Another difference between the two locations were the water depth and average size composition of the stock. The Leeman survey was conducted in waters ranging from 40 – 60 m and the majority of lobsters in this area were mature and larger than 70 mm CL (Figure 5 left). At Seven Mile Beach, the depth was always < 4 m, with very few mature lobsters and most CL’s being < 80 mm (Figure 5 right).

Lobster measuring <60 mm CL were tagged with small spaghetti tags (Hallprint™ TBF; see Tag Release**Error! Reference source not found.**) while individuals larger than 60 mm CL were tagged using standard spaghetti tags (Hallprint™ TBA; see Tag Release). Those lobster which were not tagged with a spaghetti tag had pleopod 7 or 8 snipped (Figure). If a lobster was tagged with a spaghetti tag the pleopod was marked by snipping, with scissors, to remove the distal half of the specific pleopod. Each month a different pleopod was marked allowing its release month to be determined upon recapture (Table 2).

For these trials all recaptures were conducted via research surveys. This had the advantage that every lobster was examined for the presence of both a tag and a marked pleopod. If a lobster was recaptured with either a spaghetti tag and/or a marked pleopod, the pleopod for the current month was snipped. All pleopods which have been previously marked were recorded and re-snipped to ensure they remained obvious.

Figure 6. (left) Ventral side of a Western Rock Lobster and the numbers assigned to each pleopod for marking and (right) image of a Western Rock Lobster tagged ventrally with a standard T-Bar anchor tag and removed (marked) pleopod (TP) demonstrating clean marked pleopds 5 and 6 with a partially regenerated pleopod 3 indicating a moult.

Table 2. Year and month of sampling trips at Seven Mile and Leeman and the number of the pleopod which was marked for that trip.

Year	2014				2015			2016	2017					2018							
Month	2	5	8	12	3	8	11	3	3	8	9	10	11	2	3	4	5	6	7	8	11
Seven Mile	6	3	1	4	5	6	2	3	4					1	2	3	4	5	6		
Leeman										2	1	4	3							6	

5.6.3 *Analysis*

Prior to estimating the rate of tag loss from each of the two tagging trials (TT and TP), the data from each trial was first examined with a binomial Generalised Additive Model (bGAM), to see if any of covariates (e.g. sex, carapace length) affected tag loss. Any covariates that were found to significantly impact the rate of tag loss would need to be taken into account when determining overall tag loss (e.g. determine a unique rate for each sex or size class) and the tag-recapture model would need to be constructed accordingly (e.g. design the model to have a unique tag loss for each sex). A bGAM was used for this initial analysis since preliminary examination showed that the response of tag loss to carapace length and time at liberty were not linear. The model which was applied to each location and trial separately was;

$$P \sim M + S + D + s(L) + s(C),$$

where the probability of retaining a tag (*P*) was a function of the month of release (treated as a factor; *M*), lobster sex (female or male; *S*), in water depth (below or above 40 m depth; *D*), for a time at liberty (covariate with spline [*s*] fitted; *L*) and carapace length (covariate with spline [*s*] fitted; *C*).

Based on results from the above analysis, the tag-loss data from the two trials (*TT* and *TP*, including the two locations; Leeman and Seven Mile Beach) were each grouped by all non-significant factors. For example, sexes were grouped if sex was not found to impact tag loss prior to the rate of tag loss being modelled using the methodology of Barrowman and Myers (1996). This methodology breaks tag loss down into two separate components, initial tag shedding (ρ; instant loss due to poor technique or mortality) and chronic tag loss (ϕ), which is a constant rate of loss over time (*t*). The likelihood of tag (*T*) retention at a point in time ($R_T[t]$) is:

$$R_T[t] = \rho \, \mathrm{e}^{(-\phi t)}.$$

Since the TT and TP trials differed in the number of unique tags/marks (e.g. 1 and 2, respectively), the model needed to be designed with two separate components: one for fitting the TT dataset, where P_{TT} and P_T represent the probability of a lobster being recaptured with both or only one of the same tag, respectively. The other component was for the TP datasets, where P_{TP}, P_T and P_P represent the probability of recapture with either both a tag and a pleopod marked, only a tag or only a pleopod marked, respectively. The equations used for the TT model were:

$$P_{TT}^{TT}[t] = R_T[t]^2,$$
$$P_T^{TT}[t] = 2R_T[t](1 - R_T[t]),$$

and for the TP model were:

$$P_{TP}^{TP}[t] = R_T[t]R_P[t],$$
$$P_T^{TP}[t] = R_T[t](1 - R_P[t]),$$
$$P_P^{TP}[t] = R_P[t](1 - R_T[t]).$$

For each model there were two (TT, *I* = 2) or three (TP, *I* = 3) states for recaptured lobsters, and for a recapture that occurs at time *t*, the probability that this occurs for observation *i* was;

$$P[t] = P_i\,[t] \Big/ \sum_{k=1}^{I} P_k[t],$$

and the negative log likelihood was; $\lambda = -\sum_{i=1}^{i} N_i \ln(P_i[t])$ where N_i is the number of lobsters returned in state *i*. The negative log-likelihood was minimized using the nlimb function in R (R core team, 2019). The model was capable of fitting to either a single tag-loss experiment (e.g. TT or TP) or both simultaneously (both TT and TP) by combining the negative log-likelihoods from each component (e.g. $\lambda = \lambda_{TT} + \lambda_{TP}$). Bootstrapping (*n*=5000) was used to estimate the precision of all parameters. For more details see Barrowman and Myers (1996) and the implementation R code and data sets can be found to the GitHub site https://github.com/sdelestang/FRDC-Project-No-2014-023. To ensure the methodology of Barrowman and Myers (1996) had been properly replicated, a set of simulated data, with known levels of tag loss, was developed and analysed. The accurate replication of known tag loss parameters indicated that the model was functioning appropriately (Appendix 4 Model Simulation of Tag Loss Parameters).

5.7 Tag Reporting (preliminary model)

Estimation of tag reporting (return rates) was assessed through the use of planted tags. Four trips to plant tagged lobsters in fishers' pots were undertaken throughout the fishery with trips 1 (March/April 2015) and 2 (April 2016) being more coastally focused, while the third (May 2016) and fourth (January/February 2018) encompassed more offshore areas of the fishery (Figure). Two to four pots in a line of a fisher's gear were retrieved after being set by the commercial fisher and tagged lobsters planted into the pot. The process of planting tagged lobsters into the pot used a technique developed by the Regional Services branch of the Department that ensured the planted lobsters could not exit a pot prior to the pots retrieval. This technique was covert and therefore fishers were unaware that their pot had a planted tagged lobster placed in it.

The tag number, tag location (dorsal or ventral) and associated biological data of the planted lobster was recorded along with the location and identity of the fisher's gear. The fisher details were combined with commercial catch returns (see Methods: Commercial Catch and Effort t) to derive details on the fishers' activities from the first fishing trip to occur post seeding. These data were used to examine the impact of fisher's behaviour (Table 3). In addition to fisher's behaviour, return rates can be impacted by lobster predation (e.g. from an octopus or fish within the pot), and thus the lobster is absent from the pot when it is retrieved. The likelihood of predation was considered relative to the time the salted pot remained deployed prior to retrieval and hence retrieval time was also incorporated into the model. Finally, tagging trip was analysed as presentation of preliminary results after the first year's trial (2015) to industry, may have potentially made fishers more aware of tagged lobsters in their pots. These factors and covariates (Table 3) were analysed using a binomial Generalised Additive Model (bGAM) in R (R Core Team 2019), with the bGAM reduced in complexity through a step-wise reduction based on AIC. Only the most parsimonious model is presented.

Table 3. Levels and types (f: factor, cv: covariate; s: spline) of variables examined with regard to their impact on return rates of planted tags.

Variable	Type	Levels / Description
Zone	f	A, B and C Zones
Catch Rate	cv	CPUE of landed lobsters from subsequent trip
Potlifts	cv	Effort from subsequent trip
High Grading	f	0: None, 1: ≤200 lobster, 2: >200 lobster
Trip	f	Number of salting trip (1, 2, 3, or 4)
Tag Location	f	Dorsal or ventrally tagged
History	f	Prior history of fisher returning tags (Yes / No)
Retrieval Time	s	Number of days after salting when pot was pulled

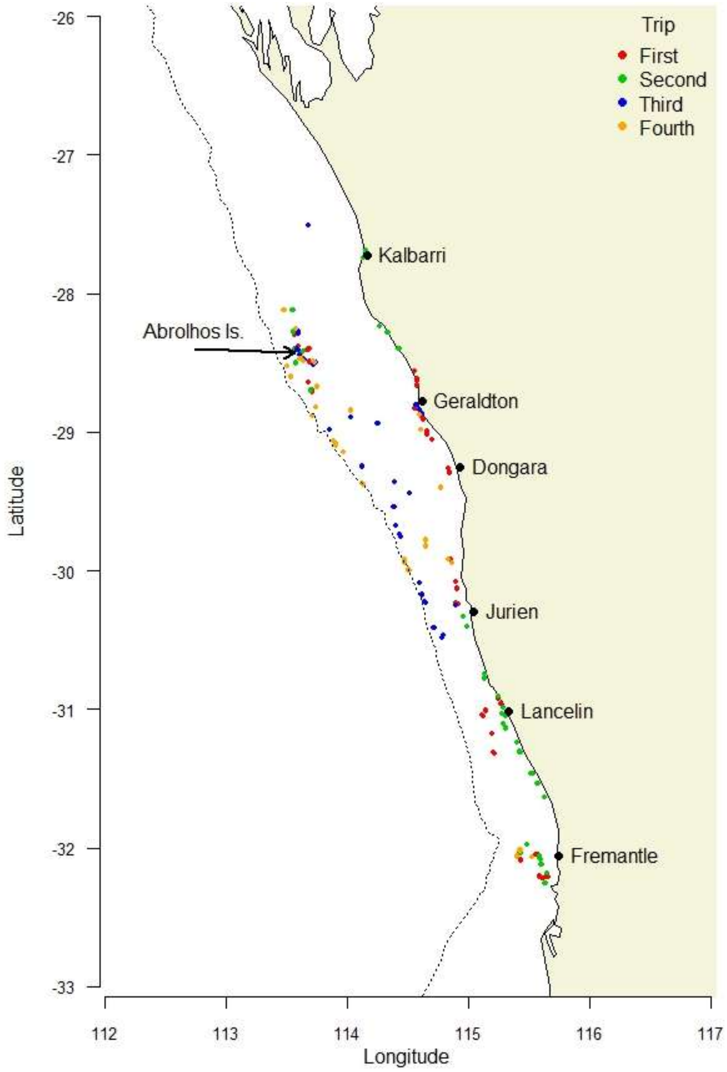

Figure 7. Locations of salted pots by trip (Trip 1 (March/April 2015; red), Trip 2 (April 2016; green), Trip 3 (May 2016; blue) and Trip 4 (January/February 2018; orange).

5.8 Brownie Tag-Recapture Model (primary model)

A fishery-wide exploitation rate and legal biomass estimate was determined using a modified Brownie Tag-Recapture model (BTR), which required lobster tag and recapture data, commercial catch and effort data and estimates of tag loss and tag reporting (Table 1).

The BTR estimates the catchability of an average lobster (*q*), i.e. the probability of capturing a lobster with one unit of effort (Brownie et al. 1985). For this project the BTR was built on a monthly time scale spanning August 2014 to July 2017 (36 months) and treated the entire WCRLMF (Fremantle to Kalbarri; Figure) as a single stock unit. The BTR fitted to all tagged lobster (CL ≥ 76 mm) released during this period (37,837) of which a total of 6,642 tagged lobsters were reported to the Department that fitted the requirements of use in this model. For example, a recaptured lobster could still be used in the model if it had an unknown recapture carapace length, or unknown recapture location. The size composition of tagged lobsters was assumed to be proportional to lobster sizes within the commercially caught population (as tagged lobsters were randomly sampled from commercial catches). Released lobsters were also assumed to have mixed within the population within the first month at liberty (i.e. there was not a period of concentrated tags in any area). The model equation was;

$$\lambda_1 = O_{l,r} \ln\left(T_{r-l} R_r \left(\frac{F_r}{(F_r + M)} \right) (1 - \exp(-F_r - M)) \exp\left(-\sum_{t=l}^{r-1} F_t - (r - l - 1) M \right) \right),$$

where λ_1 is the log-likelihood associated with observed reported lobsters ($O_{l,r}$) that were released in month/year (l), recaptured in month/year (r) and t is a specific month/year. T_{r-l} is the proportion of lobsters still retaining their tag after a specific time at liberty (recapture month - release month), R_r is the estimated reporting rate in a month/year combination and M is the instantaneous rate of natural mortality (estimated parameter). F_r is the fishing mortality in a specific month of a year based on the equation;

$$F_r = E_r q_m ,$$

where E_r is the observed effort in pot lifts in the recapture month/year combination and q_m is the estimated catchability of lobsters in that recapture month (*m*; q_m does not differ between years, only months).

A second log-likelihood component (λ_2) was derived using the lobsters that were not reported and a similar equation as to that above used to calculate λ_1 except that the observed lobsters ($O_{l,r}$) were substituted with "not observed" lobsters ($N_{l,r}$) and a "1-" was included immediately within the first bracket. The sum of the two log-likelihood components was then maximised in R using the "nlminb" routine to estimate the 13 parameters (R core team 2019).

Estimates produced by the model included the annual harvest rate (*HR*) and legal biomass. The equation used to derive these estimates was;

$$HR = \left[1 - e^{\left(-\sum_{m=1}^{12} F_m / N_m \right)} \right] \kappa ,$$

where the estimates of monthly fishing mortality (F_m) are averaged based on the number of estimates (N_m) of F_m for each month and then summed across a fishing season. κ is the proportion of the legal catch retained (not high graded, currently set to 0.75; based on the average level of high grading recorded over the study period [see de Lestang et al., 2016 for further details on high grading]). The legal biomass estimate is based on the average landed commercial catch (6200 t) from the 2015, 2016 and 2017 fishing seasons divided by the *HR*.

Estimates of uncertainty were derived from 20,000 bootstrap runs of the model whereby the observations used in the log-likelihood functions were randomly sampled.

5.9 Individual-Based Model (primary model)

Fishery-wide exploitation rates and legal biomass estimates for each fishing season 2014 – 2018 were determined using a novel individually-based population model (IBM). Inputs to the model were lobster tag and recapture data, double-tagging data, commercial catch and effort data, fishery-dependent monitoring data, high-grading and discard (return of protected lobster) data and fishery-independent survey data (**Table 1.** Data or estimate input requirements of the two preliminary analyses (tag loss and reporting) and the two models (BTR and IBM).

The model did not require the input of any previously determined parameter estimates except for an estimate of natural mortality. This was assumed to be 0.15 year^{-1} based on the estimate produced by the BTR model (see Brownie Tag-Recapture model; Outputs).

The IBM tracks each released lobster through its biological processes (growth and movement) and exposes it to commercial and survey exploitation for its period at liberty if it was reported to have been caught, or for the time-span of the model if it had not been recaptured (until the end of the 2018 fishing season). For this project the IBM was built on the same time and spatial scale as that used by a stock assessment model currently being built for this fishery (Table 4; Figure). The IBM fitted to all tags released during the 2014 – 2018 fishing seasons (38 555) that had a known sex, a carapace length > 40 mm and were at liberty for at least two months. Of these tagged lobsters 35 898 were used in the model to determine catchability of the commercial sector with 2697 discarded as they were recaptured during the IBSS (and therefore do not represent exploitative fishing) or by recreational fishers. Furthermore, only a subset of all tagged lobsters could be used for estimating growth (4233) and movement patterns (4481). Released lobsters were assumed to have mixed within the population within the first month at liberty. The model contained two main components, a tag loss (produced one likelihood value) and a population component (produced three likelihood values, one for each growth, migration and catchability). The likelihood values from the two components were summed to allow the model to fit each aspect of the observed data simultaneously.

5.9.1 *Tag loss component*

The tag loss component of the model had the same formulation as described above under Tag Loss (preliminary model). It included both TT and TP data sets and produced a log-likelihood component (λ_L).

5.9.2 *Population component*

The population component of the model tracked each tagged lobster over the time-steps corresponding to that lobster's liberty, and if the lobster was not recaptured, the model tracked them until the end of the 2018 fishing season. Within each time-step a lobster was subjected to the processes outlined for that time-step (Table 4), which included migration (1/2 probability), growth, mortality (natural and fishing) and migration (1/2 probability), in that order. The timing of the various processes was based on previously reported *P. cygnus* biology (de Lestang et al. 2016).

5.9.2.1 *Migration*

For the WRL, migration begins in shallow water areas in late November/early December each year, with a movement directly offshore, which then changes to a northward deep water migration in January/February (de Lestang 2014). Since the first IBM time-step spans 15 January – 28 February 2014, migration occurs northwards during this time-step, with the subsequent year's migration starting in shallow water and moving offshore in the last model time-step of each fishing season (15 December 2014 – 14 January 2015). The probability (P) of a lobster migrating from one area to another is determined by four factors; the lobster's estimated carapace length for that time-step; a normal distribution, scaled to a maximum of 1.0 with an area-specific mean (α_f: where α is the mean carapace length of migration from area *f* [seven parameters for areas 1-7]) and one of two standard deviation parameters common for all shallow or deep water areas (σ_g^m, where *g* indicates depth); a second area-specific parameter (β_f, [seven parameters for areas 1-7]) representing the proportion of the scaled normal distribution that migrates; and a pre-defined movement matrix (K_{dft}:**Table 5**) that identifies during which time-step (*t*) from each source area (*f*) lobsters move to area (*d*). The movement equation was;

$$P_d = P_f K_{tfd} N\left(\alpha_f, \sigma_d^m\right)\beta_f .$$

The log-likelihood (λ_m) of a lobster being in the area within which is was reported to have been caught in based on the model parameters was determined using the equation;

$$\lambda_m = \sum_{i=1}^{n} -\ln\left(P_{r_i}\right),$$

where P_r is the model estimated probability of the *i*th lobster being present in the area where the observed *i*th lobster was recaptured (r_i).

5.9.2.2 *Growth*

In WRL, growth declines with increasing size/age, and although it is fairly continuous in small/younger lobsters, it becomes intermittent and synchronous throughout that sex of the population in later life (de Lestang et al. 2016). Although this is the general pattern of growth, pervious work has shown that growth can be well replicated by growing individuals intermittently either on a short time scale (monthly) or longer time scale (bi-annually) (Punt et al. 2013; de Lestang 2018). The IBM applied growth on a time-step scale, i.e. increasing the length of a lobster during every time-step based on the temporal length of that time step (**Table 4**). The IBM used a four parameter inverse logistic equation to describe the relationship between body size and increase in body size over a period of one month. If two months of growth was needed to be applied to a lobster, the equation was applied twice. The equation used was:

$$L_{a,s,n+1} = L_{a,s,n} + \left(\delta_{a,s} + \eta_{a,s}\right) / (1 + e^{((L_{a,s,n} - \gamma_{a,s})/\kappa_{a,s})}) + \eta_{a,s},$$

where the carapace length ($L_{a,s,n+1}$) of a lobster after one month (n) is based on the area (a) and sex (s) specific parameters for maximum growth rate ($\delta_{a,s}$), minimum growth rate ($\eta_{a,s}$), an inflection point ($\gamma_{a,s}$) and a rate of change in growth ($\kappa_{a,s}$). The log-likelihood (λ_g) of a lobster having been grown to the length of a recaptured lobster was determined using the equation;

$$\lambda_g = \sum_{i=1}^{n} -\ln\left(\frac{1}{\sigma_g\sqrt{2\pi}} e^{\frac{(O_i - L_i)}{2\sigma_g^2}}\right),$$

where O_i and L_i are the observed and model estimated lengths of the *i*th lobster, and σ_g is a sd. parameter, common for all areas and sexes.

5.9.2.3 *Capture*

Commercial fishing effort data was divided into two groups based on the presence of government staff on the fishing trip as part of the commercial monitoring program (see de Lestang et al. 2016). Data was split to account for differential tag reporting rate. During commercial monitoring government staff examine every lobster carefully and are assumed to detect and report all tag-recaptured lobsters. Commercial operators have a different focus and have been found to miss tagged lobsters as they do not always examine the underside of every animal landed (see Tag Reporting). The IBM uses the contrast between tag recaptures from these two groups in each model region and time-step to estimate commercial tag reporting rate (see below).

After applying ½ migration and the time-steps' growth, the estimated probability of being caught ($\tilde{\Gamma}^g$) by each commercial group (*g*) based on their level of fishing mortality (F^g) in that model area (*a*) and time-step (*t*) was determined using the equations;

$$F_{a,t}^g = q_t \sum_{i=1}^{g} E_{a,t}^i,$$

$$Z_{a,t} = \tau_t T + \tau_t M + \sum_{i=1}^{g} F_{a,t}^i$$

and

$$\tilde{\Gamma}^{c}_{a,t} = P_{a,t}\frac{F^{g}_{a,t}}{Z_{a,t}}\left(1-e^{\left(-Z_{a,t}\right)}\right),$$

with catchability (q) being unique for each time-step (common across years), T is the monthly rate of tag loss, M representing monthly natural mortality (set at 0.0125 month^{-1}), τ is the temporal length of the time-step in months and $E^{g}_{a,t}$ being the effort in pot lifts for each commercial group. If a lobster was recaptured by a vessel without a government observer, its probability of being caught was further adjusted by the model estimated reporting rate (ς, common across all areas and time-steps).

If a lobster remained at liberty in a time-step its probability of being in that model area was reduced by the product of the probability of being caught and not reported, natural mortality and tag loss using the equation;

$$P_{a,t+1} = P_{a,t}e^{\left(-Z_{a,t}\right)}.$$

The log-likelihood (λ_c) of a lobster having been caught in a model area and time-step and not caught in other model areas and time-steps was determined using the equation;

$$\lambda_c = \sum_{i=1}^{h} -\ln\left(\varsigma\tilde{\Gamma}_h\right) + \sum_{i=1}^{l} -\ln\left(1-\tilde{\Gamma}_l\right),$$

where h and l represent all captured and non-recaptured lobsters, respectively, in each area and time-step and ς is set to 1 if government staff are on-board (otherwise it is estimated and constrained to be between 0 and 1).

The total log-likelihood of the observations given the model parameters was therefore:

$$\lambda_T = \lambda_L + \lambda_m + \lambda_g + \lambda_c.$$

5.9.3 *Model outputs*

The primary objective of the model is to produce estimates of commercial harvest rates (*HR:* proportion of available (legal) lobsters extracted from the fishery, i.e. retained after discards/high-grading has occurred), and legal biomass (*LB*: all lobster ≥ 76 mm CL) in the fishery. These were estimated on a fishery-wide seasonal basis (2014 – 2018) using the following equations;

$$F^{o}_{y,a,t} = \left(1-H_{y,a,t}\right)\sum_{i=1}^{g} F^{i}_{y,a,t},$$

where the total fishing mortality (F^{o}) is derived from the fishing mortality estimates of the two commercial fishing groups (g), i.e. with or without departmental monitoring staff, adjusted for discards/high-grading (H). The harvest rate was then determined by the equation;

$$HR_y = \frac{\sum_{j=1}^{t}\sum_{i=1}^{a} F_{y,i,j}^{t}}{\sum_{j=1}^{t}\sum_{i=1}^{a} Z_{y,i,j}} \left(1 - e^{\left(-\sum_{j=1}^{t}\sum_{i=1}^{a} F_{y,i,j}^{t} - 12M\right)}\right),$$

and legal biomass by the equation;

$$LB_y = \frac{C_y}{HR_y},$$

where *C* represents the commercial catch in year *y*.

Table 4. Temporal scale of the IBM and associated processes

Time Step	Time Step (months of growth)	Model Activity
1	15 Jan – Feb (One month)	½ Migration North Growth Mature females protected M and F mortality and Tag Loss ½ Migration North
2	Mar – Apr (Two months)	Growth M and F mortality and Tag Loss
3	May – June (Two months)	Growth M and F mortality and Tag Loss
4	Jul – 14 Sep (Three months)	Growth M and F mortality and Tag Loss
5	15 Sep – 14 Nov (Two months)	Growth Mature females protected M and F mortality and Tag Loss
6	15 Nov – 14 Dec (One month)	Growth Mature females protected M and F mortality and Tag Loss
7	15 Dec – 14 Jan (One month)	½ Migration Offshore Growth Mature females protected M and F mortality and Tag Loss ½ Migration Offshore

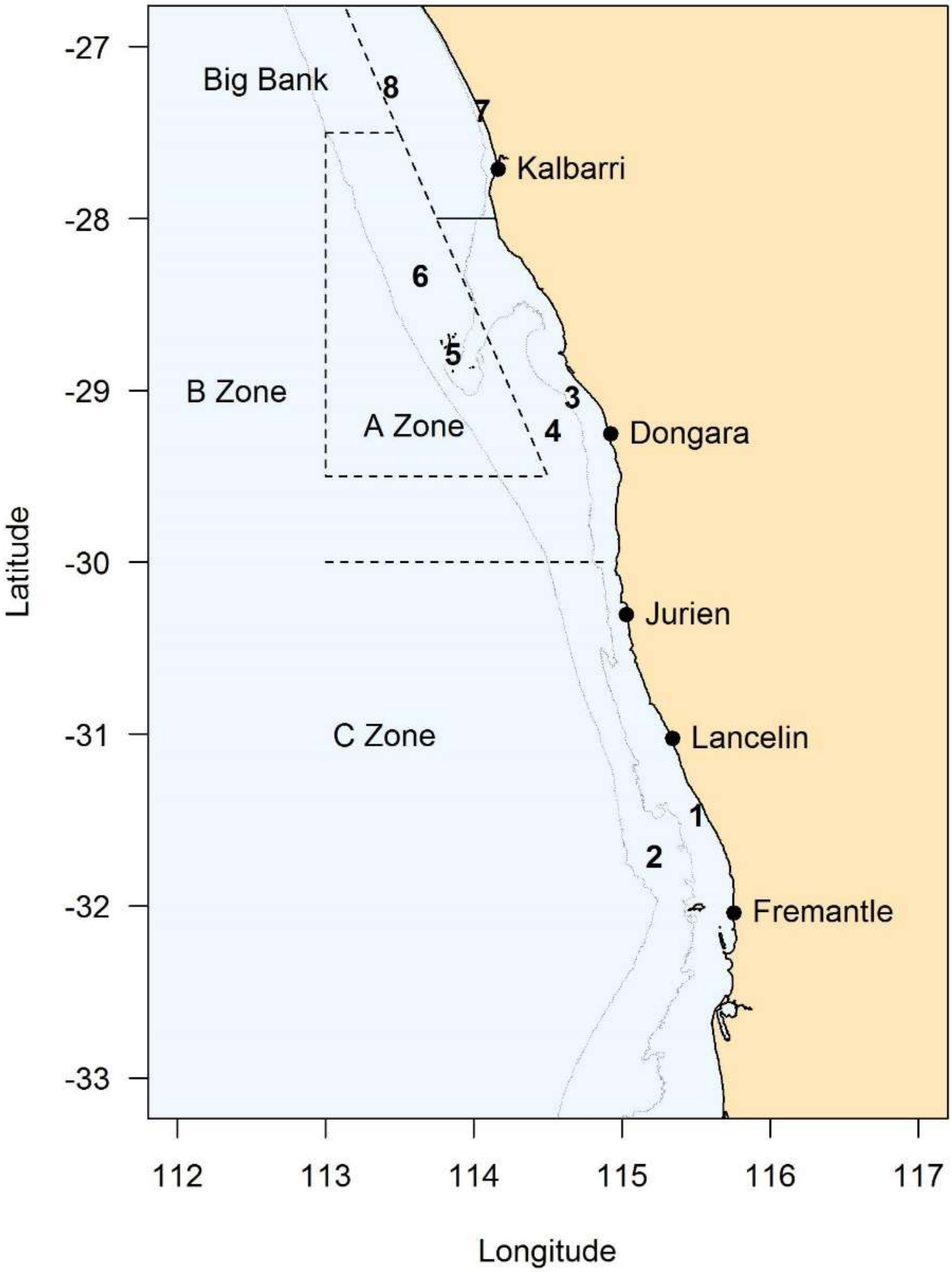

Figure 8. Spatial scale of the IBM model showing the area codes (1-8).

Table 5. Pre-determined movement matrix identifying which model areas lobster can move between. O denotes offshore movement (in time-step 7) and N denotes northwards movement (in time-step 1).

		From							
		A1	A2	A3	A4	A5	A6	A7	A8
To	A1								
	A2	O							
	A3								
	A4		N	O					
	A5								
	A6		N		N	O			
	A7								
	A8		N		N		N	O	

6.0 Results

A total of 42,999 lobsters ranging in size from 29 – 158 mm CL were released between 2014 and 2017 (Figure ; Table 6). For estimating harvest rates and legal biomass, the data was limited to lobsters that had a CL ≥76 mm (Figure) as the likelihood of commercial fishers re-capturing a lobster <76 mm CL is far lower. This reduced the total number of lobsters for this analysis to 37,837 (Table 7).

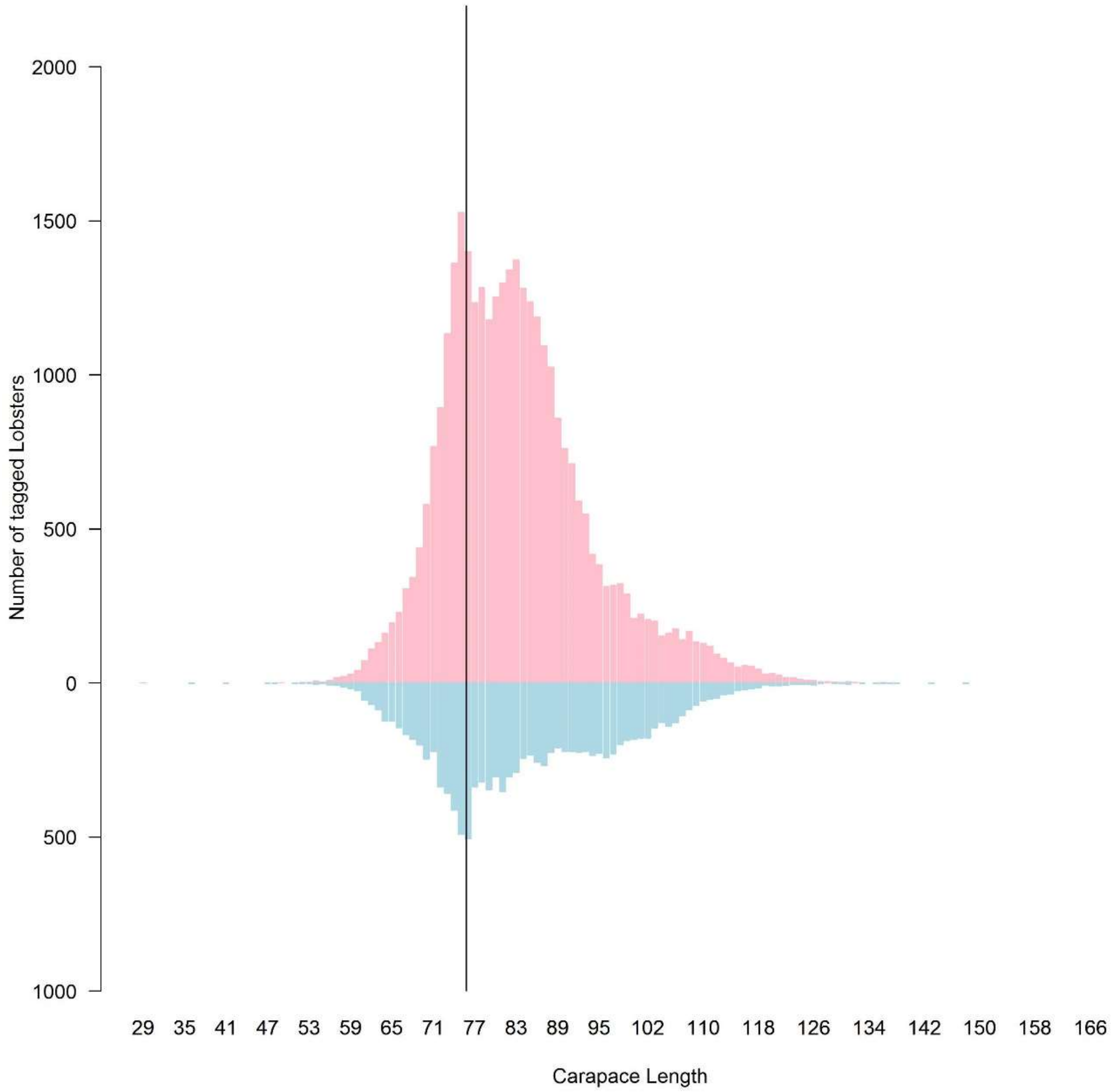

Figure 9. Size composition of female (pink) and male (blue) Western Rock Lobsters tagged and released during the study.

Table 6. Number of all tagged lobsters released with a T-bar tag by month and year.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2014	52	435			79		998	23	1875	4029		3106	10,615
2015		1645	102		28	662		941		5699	5726		14,350
2016	1495	899	2203					734	1712	4776	2857		14,676
2017	473		87					1569	1129				3,358
Total	2020	2684	2444	0	79	659	998	3206	4716	14,504	8583	3106	42,999

Table 7. Number of tagged lobsters ≥ 76 mm CL released with a T-bar tag by area (<30°, 30-31°,>31° S) and time period.

	Months												
Year	Jan-Mar			Apr-Jun			Jul-Sep			Oct-Dec			Total
	<30	30-31	>31	<30	30-31	>31	<30°	30-31	>31	<30	30-31	>31	
2014		233	18	310	210	455	1158	423	606	2817	1551	838	8619
2015	117	1433	364	118	362	109	556	1230	601	5824	2196	1098	14,008
2016	525	716	1605				1184	1699	1280	4203	1018		12,230
2017	76		454				1386	1064					2980
Total		5541			1564			11,187			19,545		37,837

6.1.1 *Impact of release cage*

A comparison of the impact of releasing tagged lobster using either one of two techniques, traditional method of singularly and immediately returning lobsters straight back into the water over the capture location or using a release cage for a safer transit to the sea floor, was examined using two response variables, proportion recaptured and distance moved.

6.1.1.1 *Proportion recaptured*

Based on the outputs of the bGLM, the proportion of lobsters recaptured from either release method (traditional or cage) differed significantly at one location only (27° latitudinal band), as identified by the interaction between latitude and release (**Table 8**). Since this only occurred in deeper waters, there was also a significant interaction with latitude and depth zone (Table 8, Figure). In shallow water locations there was no difference in the proportion being reported using either method, however there was quite a difference across the various latitudes sampled, with lobsters released in latitude 29° having a much greater chance of being reported than those in latitudes 27° or 32° (Figure). In deeper waters, only in latitude 27° was there a significant difference in the proportion of lobsters being returned by the two release methods. Of those released in the traditional method, ~27% were reported, whereas only ~16% of those released using the cage were reported.

Table 8. Analysis of deviance summary for a binomial GLM examining the relationship between the recapture rate of lobsters released by the two different methods across six latitude bands (27 – 32°) and two depth zones (≤40 m, > 40m). Significant interactions are highlighted in bold.

Factor	X^2	df	p
Latitude	436.99	5	**<0.001**
Depth zone	5.48	1	**0.0193**
Release method	44.03	1	**<0.001**
Latitude x Depth	91.13	3	**<0.001**
Latitude x Release	47.68	5	**<0.001**
Depth x Release	0.35	1	0.555

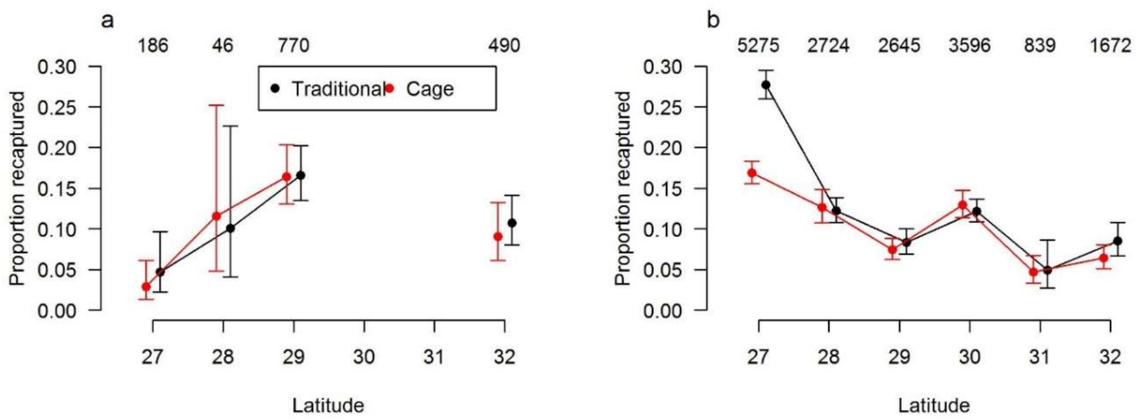

Figure 10. Proportion (± 95% CI) of lobsters recaptured from either traditional (black) and cage (red) release protocols, across different latitude bands for a) shallow water (≤40 m)

and b) deeper water (> 40m) depth zones. Number above indicate the number of lobsters released in each latitude band/depth zone.

6.1.1.2 *Distance moved*

The distance moved by lobsters recaptured from either release method (traditional or cage) differed significantly in all three interactions examined (Table 9). There was generally a greater movement of lobsters released in shallow vs deep water areas, and in the 32° latitude band in shallow water lobsters moved significantly greater distances if released by traditional method (Figure 1a). In deeper water areas there was a consistent pattern of greater lobster movement in the more southern locations, with lobsters moving significantly further if released using the cage technique in all latitudes except 27° and 32° (Figure 1b).

Table 9. Analysis of deviance summary for a log-normal GLM examining the relationship between the distance moved by lobsters released using two different methods across six latitude bands (27 – 32°) and two depth zones (≤40 m, > 40m). Significant interactions are highlighted in bold.

Factor	X^2	Figure 1	p
Latitude	663.76	5	**<0.001**
Depth zone	175.44	1	**<0.001**
Release method	8.31	1	**0.004**
Latitude x Depth	15.17	3	**0.002**
Latitude x Release	35.5	5	**<0.001**
Depth x Release	6.53	1	**0.0106**

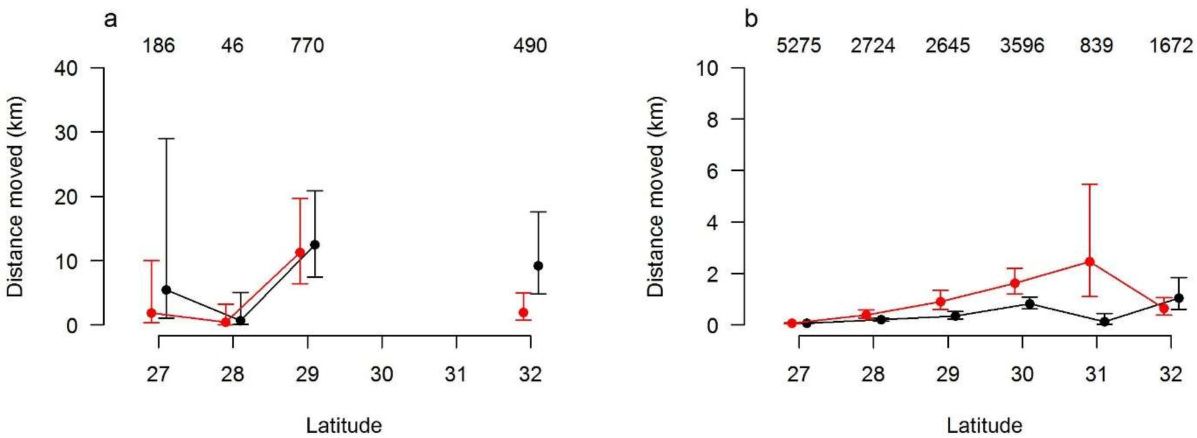

Figure 1. Distance (± 95% CI) between release and recapture locations of lobsters recaptured from either traditional and cage release protocols, across different latitude bands for a) shallow water (≤40 m) and b) deeper water (> 40m) depth zones. Number above indicate the number of lobsters released in each latitude band/depth zone. Note different y-axis scales for plots a and b.

The cage release resulted in a decline in lobster recaptures in latitude 27° (Figure) and a general increase in lobster movement in deep-water when compared to the traditional release method (Figure 1). Cage release required additional gear and was more demanding on staff, coupled with the slightly lower recapture rate and increased movement, it was considered better to release all remaining lobster for the remainder of the study using traditional methods. A total of 9073 lobsters were released using the cage and 33,926 were released using the traditional method. For consistency only lobsters released using the traditional method were used to estimate movement and catchability (all lobsters released were used to estimate growth).

6.1.2 *Tag Loss*

6.1.2.1 *Tag-Tag (TT)*

A wide size range of both sexes of lobsters were released (♀ 40.4 – 124.5 and ♂ 54.0 – 130.1 Figure 2) with two ventral T-Bar spaghetti tags. The numbers of lobsters and the timing of release as well as the numbers recaptured with one or both tags are shown in Table 10. The majority of recaptures were performed by commercial fishers and reported to the Department via the various reporting methods (see Methods: Tag Recaptures).

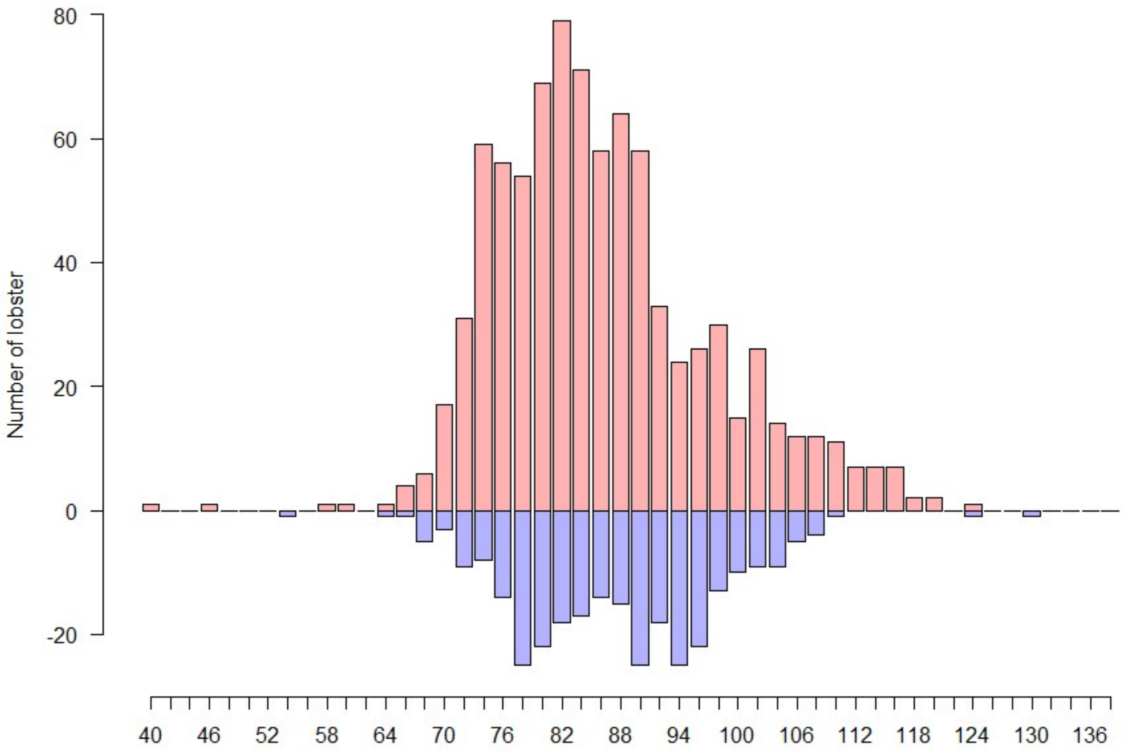

Figure 2. Size composition of all females (pink) and males (blue) double-tagged Western Rock Lobsters.

Table 10. Number of lobsters released in the West Coast Rock Lobster Fishery with two T-bar tags (TT). Recapture numbers represent lobsters caught with both tags

present with recapture numbers of a single tag present (i.e. single tag lost) in parentheses.

Date Number released	Release Dec 14 201	Dec 15 20	Mar 16 33	Sep 16 509	Dec 16 259	Sep 17 10	**Total** **1 032**
Liberty (months)				Recapture			
1		1 (1)	6 (4)	5 (3)	5 (0)	0 (1)	
2				5 (0)			
3				2 (0)			
4				5 (3)			
5				2 (0)	2 (0)		
6				1 (0)	3 (0)		
7				4 (4)			
8				6 (6)			
9				2 (4)			
10	1 (0)			6 (0)			
11				2 (0)	2 (0)		
12	1 (0)			2 (0)	1 (0)		
13	1 (0)				1 (0)		
14	1 (2)			1 (0)			
15	2 (0)		2 (0)				
18	1 (0)			1 (0)			
20	1 (1)			4 (0)			
21				5 (2)			
22				1 (0)			
28				1 (0)			
31				1 (0)			
33				3 (1)			
34				1 (1)			
35				3 (0)			
36				1 (0)			
37	1 (0)			0 (1)			
44	0 (1)						
Total	**13**	**2**	**12**	**89**	**14**	**1**	**134**

Of the 1032 lobsters released with two T-Bar tags (TT), 134 were recaptured with either both tags present (96) or only one tag present (38). The bGAM indicated that the probability of recapture in either of these two states did not differ significantly (all $P > 0.2$) among lobsters of different sex, release month, release water depth, carapace length or time at liberty (Table 11; Figure 3). The data were therefore pooled by all non significant factors prior to the application of the tag-loss model (TT component).

Table 11. ANOVA summary of a binomial GAM examining the relationship between a number of covariates and the probability of retaining either one or both T-bar tags.

Coefficient	X^2		df	p
		Parametric terms		
Sex	0.016		1	0.898
Water depth	0.003		1	0.960
Release Month	4.652		4	0.325
		Smooth terms		
		Effective df	Ref. df	Approx. p
Carapace length	1.513	1.878	2.194	0.251
Liberty (months)	3.381	1.188	7.782	0.120

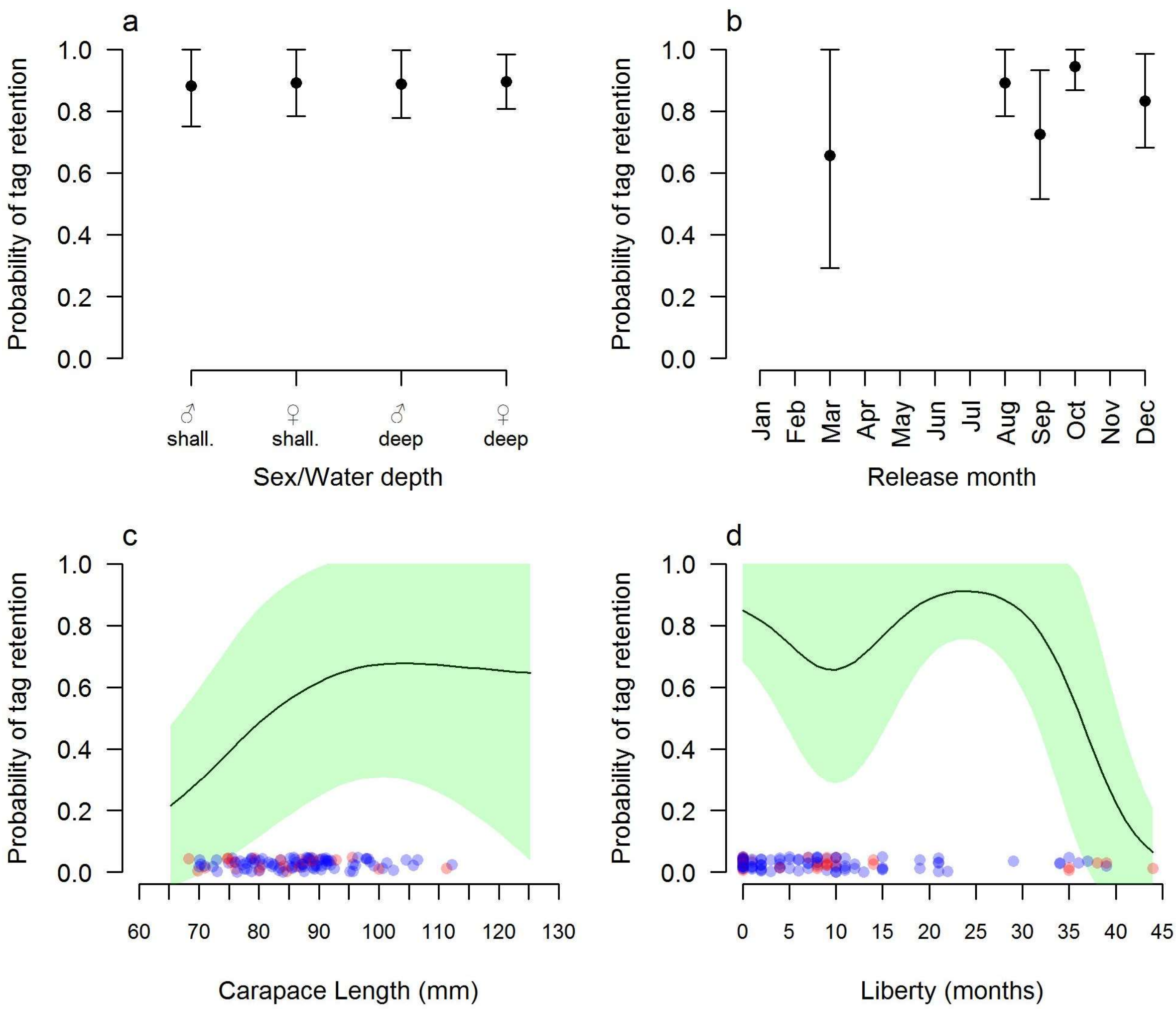

Figure 3. Estimates from a binomial GAM examining the relationship between a number of covariates and the probability of retaining either one or both T-bar tags.

The TT tag-loss model successfully converged and replicated the observed dataset well, with the residuals from the model (observed – estimated) showing no progressive patterns across the time at liberty (Figure 4a). The model estimated that for the TT dataset the proportion of a lobster retaining a tag following release (i.e. 1-instantaneous tag loss) was 0.85 (0.79 – 0.91 95% CI) whereas the rate of constant monthly tag loss (i.e. chronic tag loss) was 0.004 (0 – 0.01 95% CI) (Figure 4b). The residual plot highlighted a rapid reduction in sample size (observations) after a liberty of 10 months, although there were still multiple recaptures per liberty between 30 and 40 months liberty (Figure 4a).

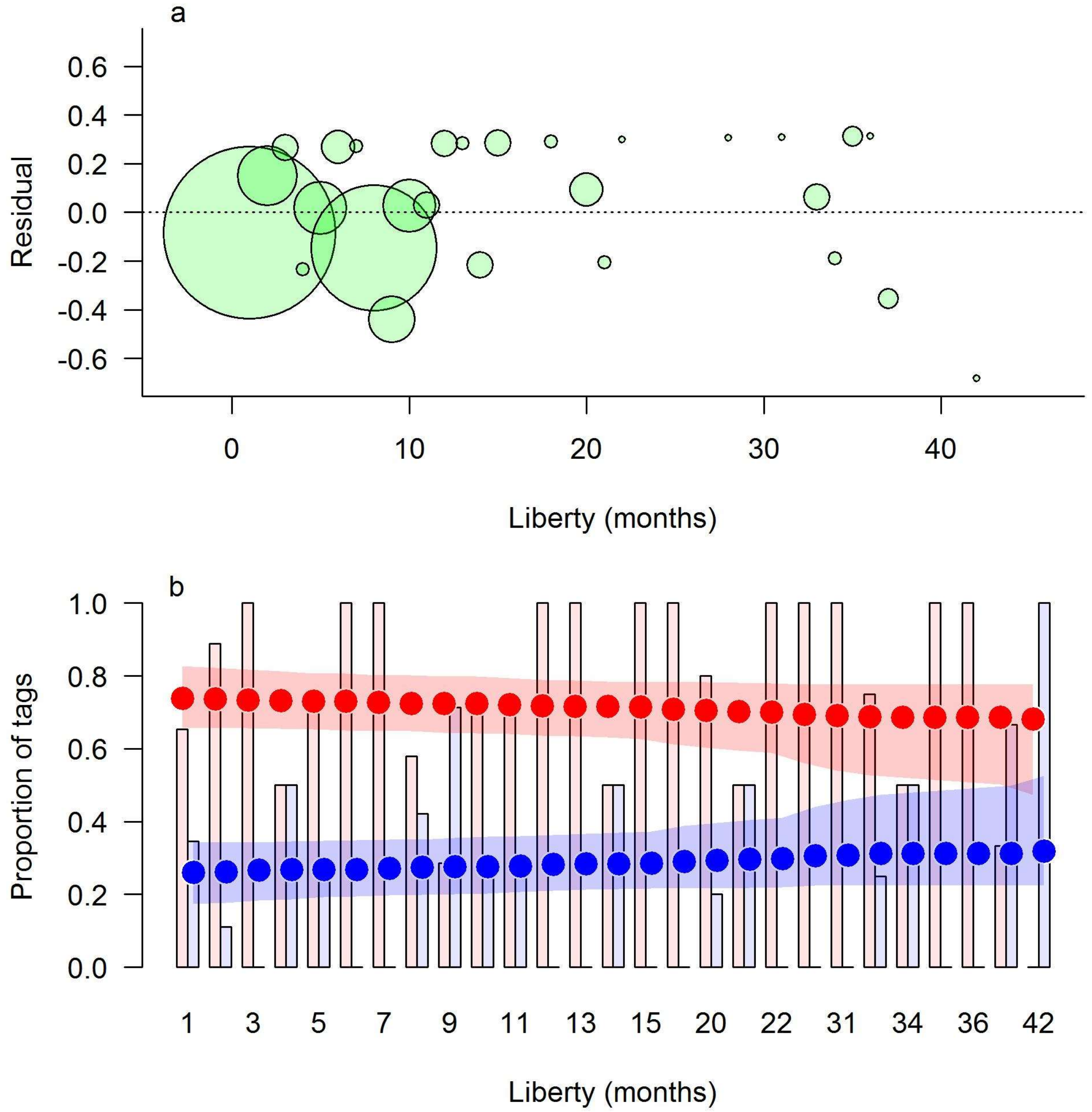

Figure 4. *a*. Residual plot from the TT model with the diameter of the green circles representing the relative number of lobsters for that observation, with the largest diameter representing 26 lobsters and the smallest 1 lobster. *b.* Observed (bars) proportion of lobsters caught with two T-bar tags (red) or only a single tag (blue) across the range and liberties with model estimated proportions shown as solid points with associated 95% CI (translucent zones).

6.1.2.2 *Tag-Pleopod (TP)*

6.1.2.2.1 *Leeman TP trial*

Tag loss through TP marking was assessed in lobsters which ranged in size from 63.1 to 123.8 at Leeman, with males contributing more to the larger sizes (Figure 5).

Of the 7060 lobsters released at Leeman 354 were recaptured with one T-bar tag and one marked pleopod, while only 47 lobsters were caught with a missing T-Bar tag (Table 12), identified by the marking of their month-specific pleopod (Table 2). The maximum time at liberty (12 months;Table 12) was far shorter than in the TT (42 months) trial. The size composition of lobsters release at Leeman was much larger than those released at Seven Mile Beach, ranging from ~ 65 – 105 mm CL vs 35 – 80 mm CL, respectively (Figure 5).

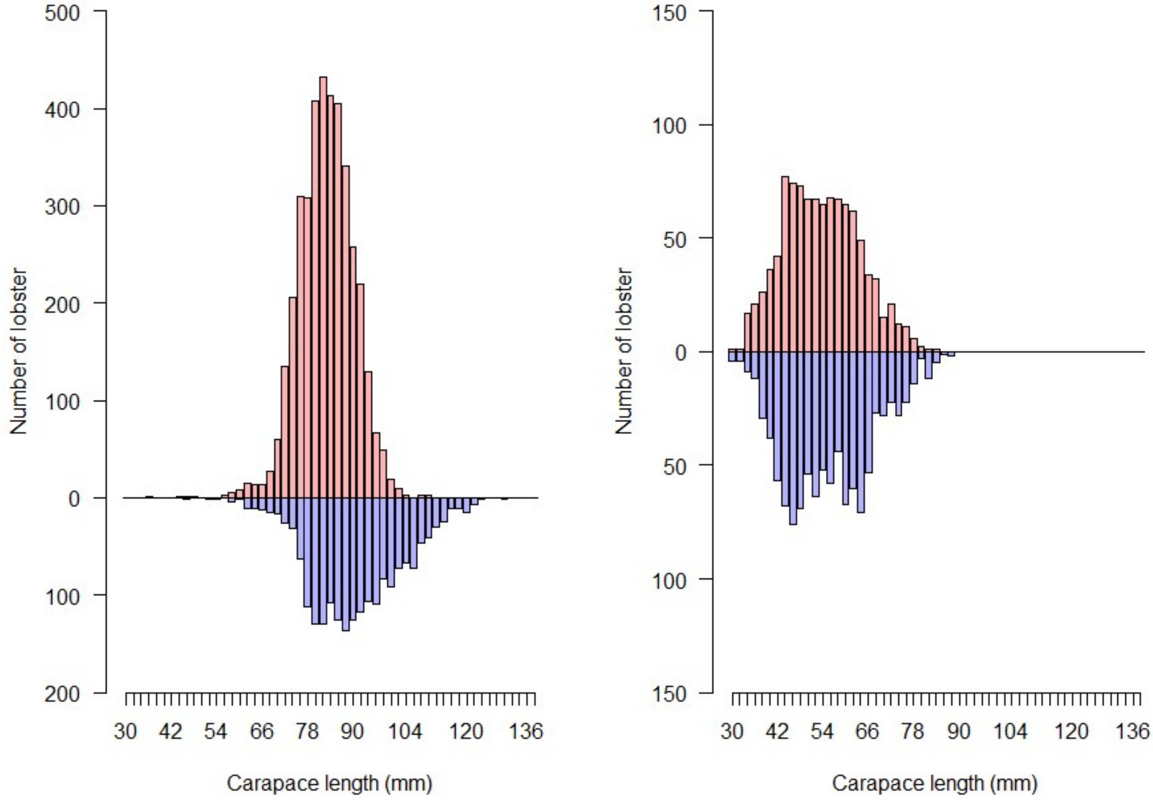

Figure 5. Size composition of all double-marked (TP) lobsters at Leeman (left) and Seven Mile Beach (right) with females (pink) and males (blue) above and below, respectively.

Table 12. Number of lobsters released in the Leeman closed area with a tag-pleopod combination (TP). Recapture numbers represent lobsters caught with both marks present with recapture numbers where only a pleopod mark present (i.e. tag lost) in parentheses.

	Release					
Date	8/17	9/17	10/17	11/17	8/18	9/18
Number released	1647	1216	780	559	1761	1097
Liberty (months)	Recapture					
1	41 (0)	21 (1)	27 (1)		9 (0)	
2	27 (7)	23 (3)				
3	19 (1)					
8						
9				9 (1)		
10			25 (5)	3 (0)		
11		44 (5)	11 (0)			
12	15 (8)	17 (7)				

A bGAM indicated that the likelihood of being recaptured with either a T-Bar tag and a snipped pleopod, or just a snipped pleopod did not differ significantly (all $p > 0.34$) among lobsters of different sex or carapace length or release month, however it did differ significantly across time at liberty (P=0.001) (Table 13; Figure 6). All data was therefore pooled across sex, carapace length and release month prior to the application of the tag-loss model (TP component).

Table 13. Summary of a binomial GAM examining the relationship between a number of covariates and the probability of retaining both the T-Bar tag and a snipped pleopod at Leeman.

Coefficient	X^2		d.f.	Probability
Parametric terms				
Sex	2.29		1	0.421
Release Month	5.24		4	0.325
Smooth terms		Effective d.f.	Ref. d.f.	Approximate *P*
Carapace length	8.78	6.36	7.52	0.344
Liberty (months)	10.79	1	1	0.001

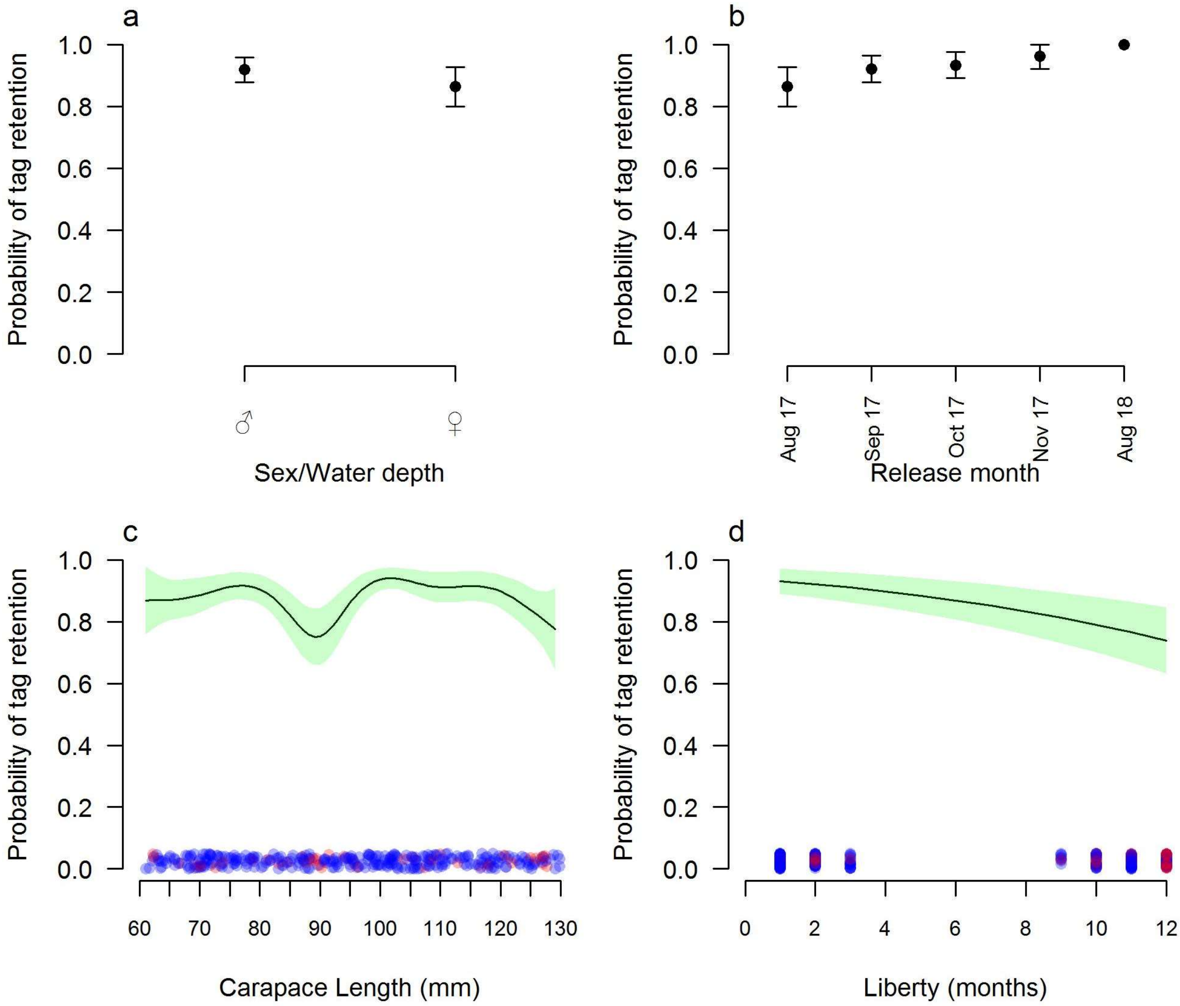

Figure 6. Estimates from a binomial GAM examining the relationship between a number of covariates and the probability of retaining a T-bar tag in the TP trials at Leeman.

The TP tag-loss model fitted to Leeman data successfully converged and replicated the observed dataset well, with the residuals from the model (observed – estimated) showing no progressive patterns across liberties (Figure 7a). The model estimated that for the TP dataset the proportion of a lobster retaining a tag following release (i.e. 1- instantaneous tag loss) was 0.96 (0.91 – 1 95% CI) whereas the rate of constant monthly tag loss (i.e. chronic tag loss) was 0.014 (0.005 – 0.024 95% CI) (Figure 7b; Table 16). The residual plot showed a maintenance of good sample sizes across most liberties (Figure 7a).

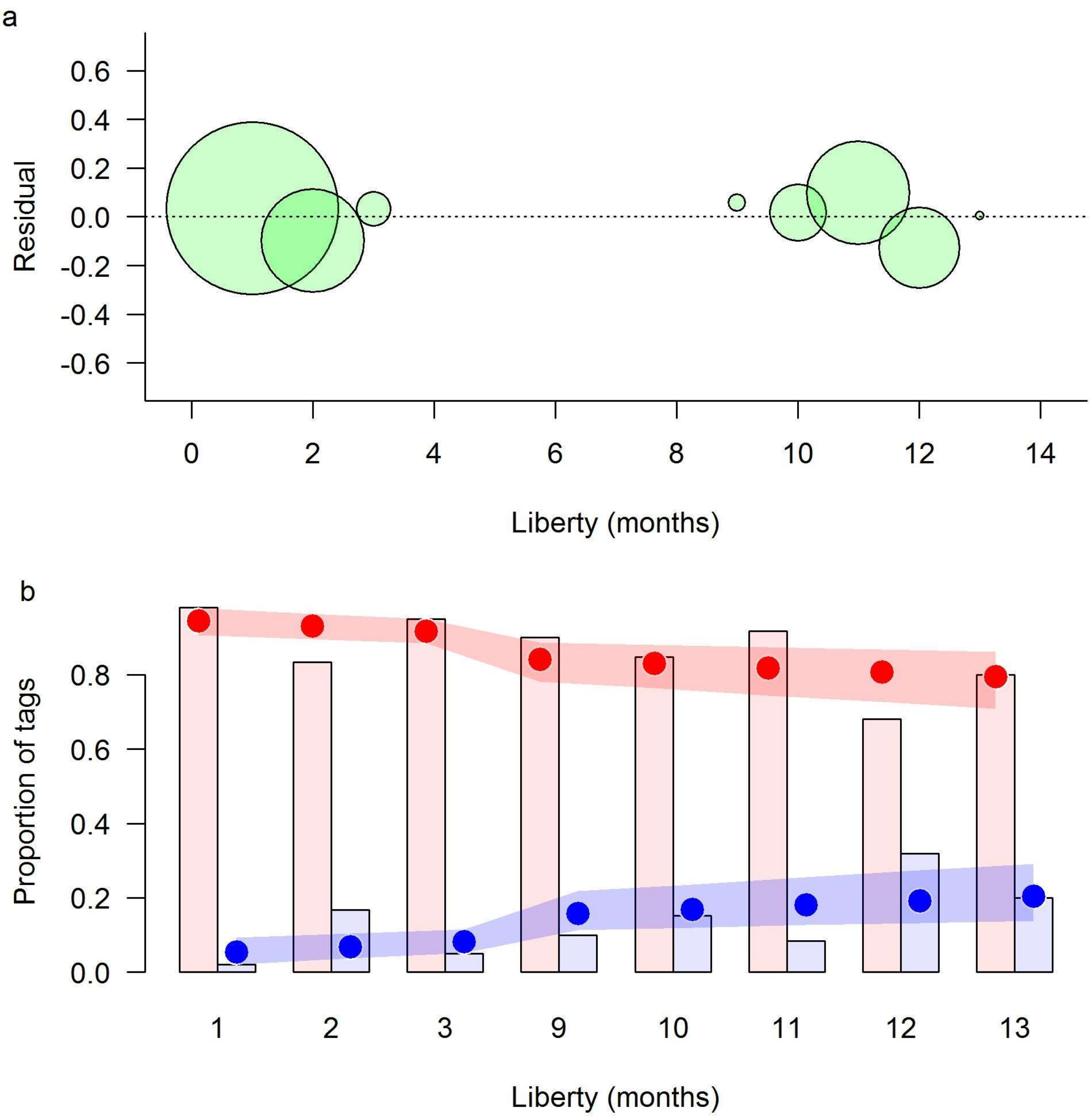

Figure 7. *a*. Residual plot from the TP model applied to Leeman data with the diameter of the green circles representing the relative number of lobsters for that observation, with the largest diameter representing 100 lobsters and the smallest 5 lobsters. *b*. Observed (bars) proportion of lobsters caught with a T-Bar tag and snipped pleopod (red) or only a snipped pleopod (blue) across the range and

liberties with model estimated proportions shown as solid points with associated 95% CI (translucent zones).

6.1.2.2.2 *Seven Mile Beach TP trial*

Tag loss through TP marking was assessed in lobsters which ranged in size from 31.7 to 86.3 mm at Seven Mile Beach, with an even spread of lobster between the two sexes (Figure 5). Of the 886 lobsters released at Seven Mile Beach 487 were recaptured with one T-bar tag and one marked pleopod, while only 19 lobsters were caught with a missing T-Bar tag (Table 14), identified by the marking of their month-specific pleopod (Table 2). The maximum time at liberty (five months; Table 14) was relatively short when compared to that in the TT (42 months) and TP trial at Leeman (12 months).

Table 14. Number of lobsters released in Seven Mile Beach with a tag-pleopod combination (TP). Recapture numbers represent lobsters caught with both marks present with recapture numbers where only a pleopod mark present (i.e.tag lost) in parentheses.

	Release					
Date	2/18	3/18	4/18	5/18	6/18	7/18
Number released	233	220	150	147	117	19
Liberty (months)	Recapture					
1	92 (2)	54 (4)	23 (1)	26 (1)	4 (1)	
2	58 (1)	22 (1)	20 (0)	2 (0)		
3	77 (7)	40 (0)	7 (0)			
4	41 (0)	11 (1)				
5	10 (0)					
9						

A bGAM indicated that the likelihood of being recaptured with either a T-Bar tag and a snipped pleopod, or just a snipped pleopod did not differ significantly (all $p > 0.08$) among lobsters of different sex, release month, or time at liberty (Table 15). Carapace length was found to have a significant (P=0.04) effect on the probably of retaining a tag, with lobsters the probability of retention dropping off markedly in lobsters with a carapace length < 40 mm (Figure 8). All lobsters with a carapace length <40 mm were removed before all remaining data was pooled across sex, carapace length and release month prior to the application of the tag-loss model (TP component).

Table 15. Summary of a binomial GAM examining the relationship between a number of covariates and the probability of retaining both the T-Bar tag and a snipped pleopod at Seven Mile Beach.

Coefficient	X^2		df	p
	Parametric terms			
Sex	2.60		1	0.125
Release Month	8.34		4	0.080
	Smooth terms			
		Effective df	Ref. df	Approx p
Carapace length	8.53	2.60	2.89	0.041
Liberty (months)	0.89	1.35	1.58	0.641

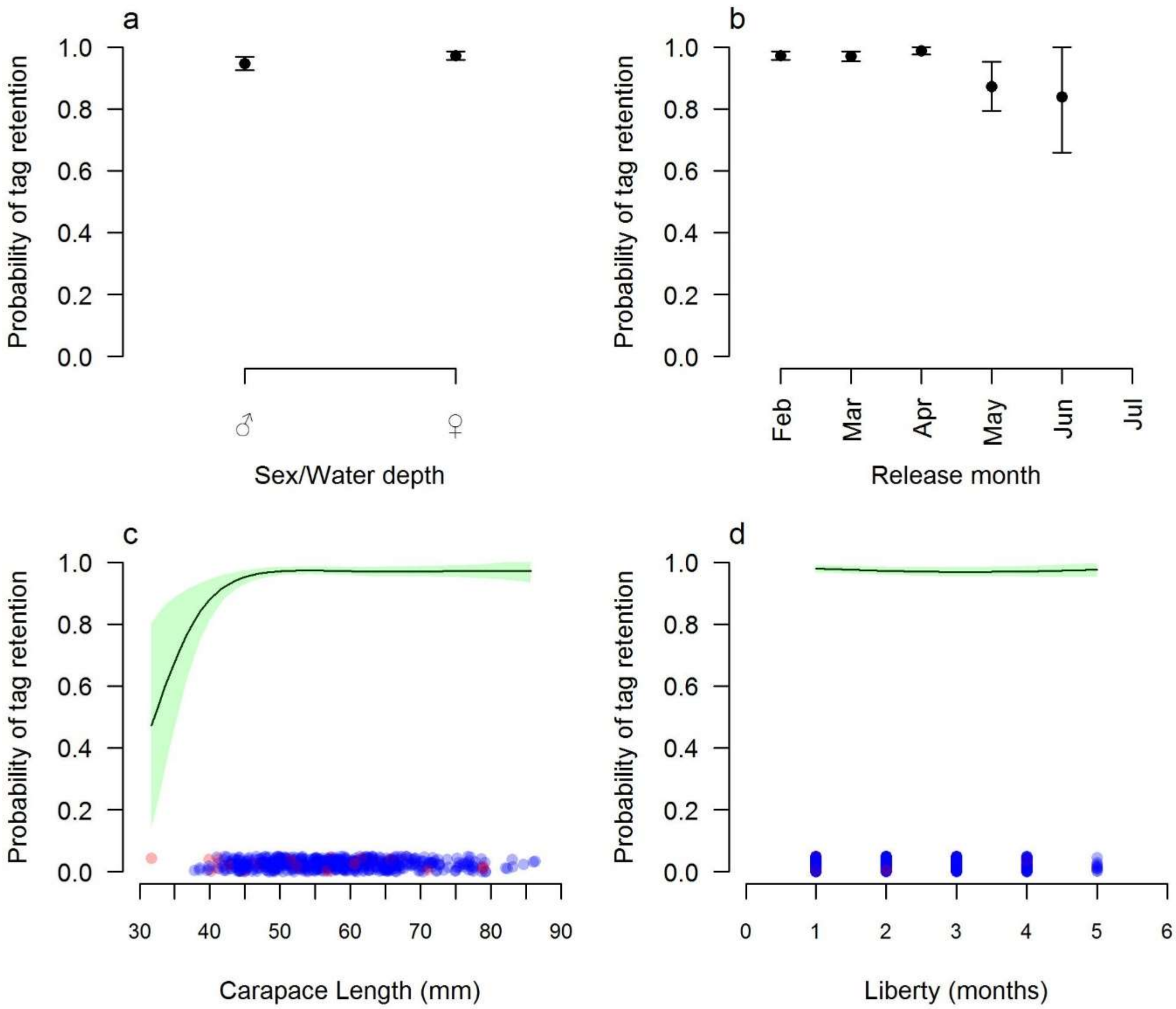

Figure 8. Estimates from a binomial GAM examining the relationship between a number of covariates and the probability of retaining a T-bar tag in the TP trials at Seven Mile Beach.

The TP tag-loss model fitted to Seven Mile Beach data successfully converged and replicated the observed dataset well, with the residuals from the model (observed – estimated) showing no progressive patterns across liberties (Figure 9a). The model estimated that for the TP dataset the proportion of a lobster retaining a tag following release (i.e. 1- instantaneous tag loss) was 0.96 (0.95 – 0.99 95% CI) whereas the rate of constant monthly tag loss (i.e. chronic tag loss) was 0 (0 – 0.001 95% CI) (Figure 9b; Table 16). The residual plot showed a progressive decline in sample sizes across the time at liberty (Figure 9. a. Residual plot from the TP model applied to Seven Mile Beach data with the diameter of the green circles representing the relative number of lobsters for that observation, with the largest diameter representing 208 lobsters and the smallest 10 lobsters. *b*. Observed (bars) proportion of lobsters caught with one T-Bar tag and one snipped pleopod (red) or only a snipped pleopod (blue) across the range and liberties with model estimated proportions shown as solid points with associated 95% CI (translucent zones).a).

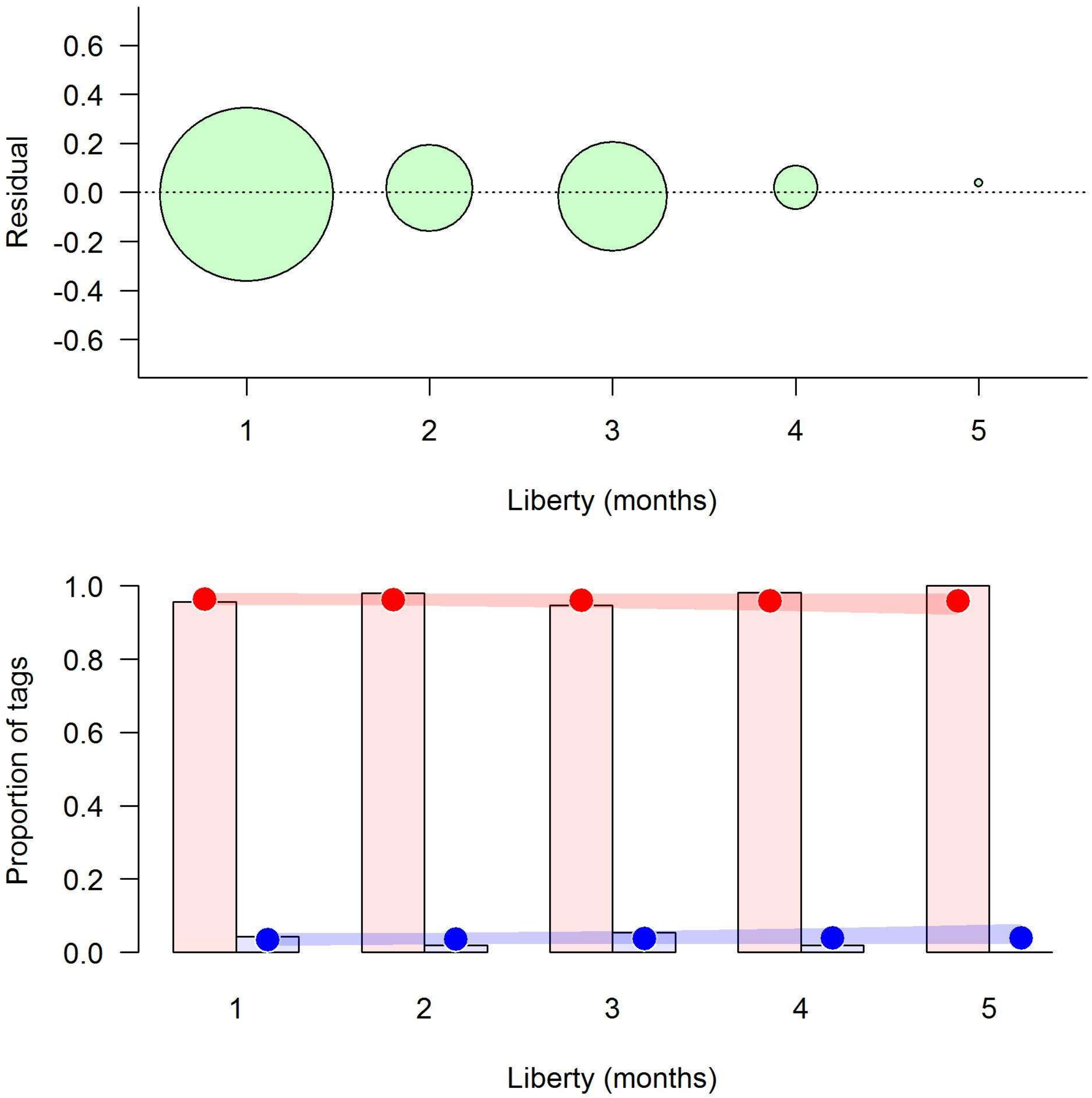

Figure 9. a. Residual plot from the TP model applied to Seven Mile Beach data with the diameter of the green circles representing the relative number of lobsters for that observation, with the largest diameter representing 208 lobsters and the smallest 10 lobsters. *b*. Observed (bars) proportion of lobsters caught with one T-Bar tag and one snipped pleopod (red) or only a snipped pleopod (blue) across the range and liberties with model estimated proportions shown as solid points with associated 95% CI (translucent zones).

6.1.2.2.3 *Combined TT, TP Leeman and TP SMB model*

Model estimates from the three tag-loss models (TT, TP Leeman and TP SMB) produced slightly inconsistent estimates for instantaneous and chronic tag loss (Table 16), due in part to the three models consisting of data with very different dynamics (longevity and sample sizes). As such the entire data set, from all three trials was analysed in the same, multi-likelihood model to produce a single set of parameter estimates that would be balanced for longevity and sample size from each data set. This model successfully converged and replicated the observed datasets well, with the residuals from the model (observed – estimated) showing no progressive patterns across liberties (Figure a). Observations with large sample sizes all displayed smaller residuals (better fit) than those with smaller sample sizes. The model estimated that the proportion of lobster retaining a tag following release (i.e. 1- instantaneous tag loss) was 0.96 (0.89 – 0.98 95% CI) whereas the rate of constant monthly tag loss (i.e. chronic tag loss) was 0.01 (0.002 – 0.018 95% CI) (Figure b; Table 16). The residual plot highlighted the large differential in sample sizes and longevity of liberty between the two tagging forms (TT vs TP) (Figure a).

Table 16. Parameter estimates (%) from four tag loss models, TT, TP Leeman, TP Seven Mile Beach and TT/TP combined (95% CI are shown in brackets).

	Model			
Parameter	TT	TP - Leeman	TP – SMB	Combined
Instantaneous (%)	15.4 (8.8-21.3)	4.2 (0.1-9.1)	3.6 (1.0-5.4)	4.4 (1-6-10.0)
Chronic (% month^{-1})	0.04 (0-0.8)	1.4 (0.7-2.4)	0 (0-1.1)	0.9 (0.2-1.8)

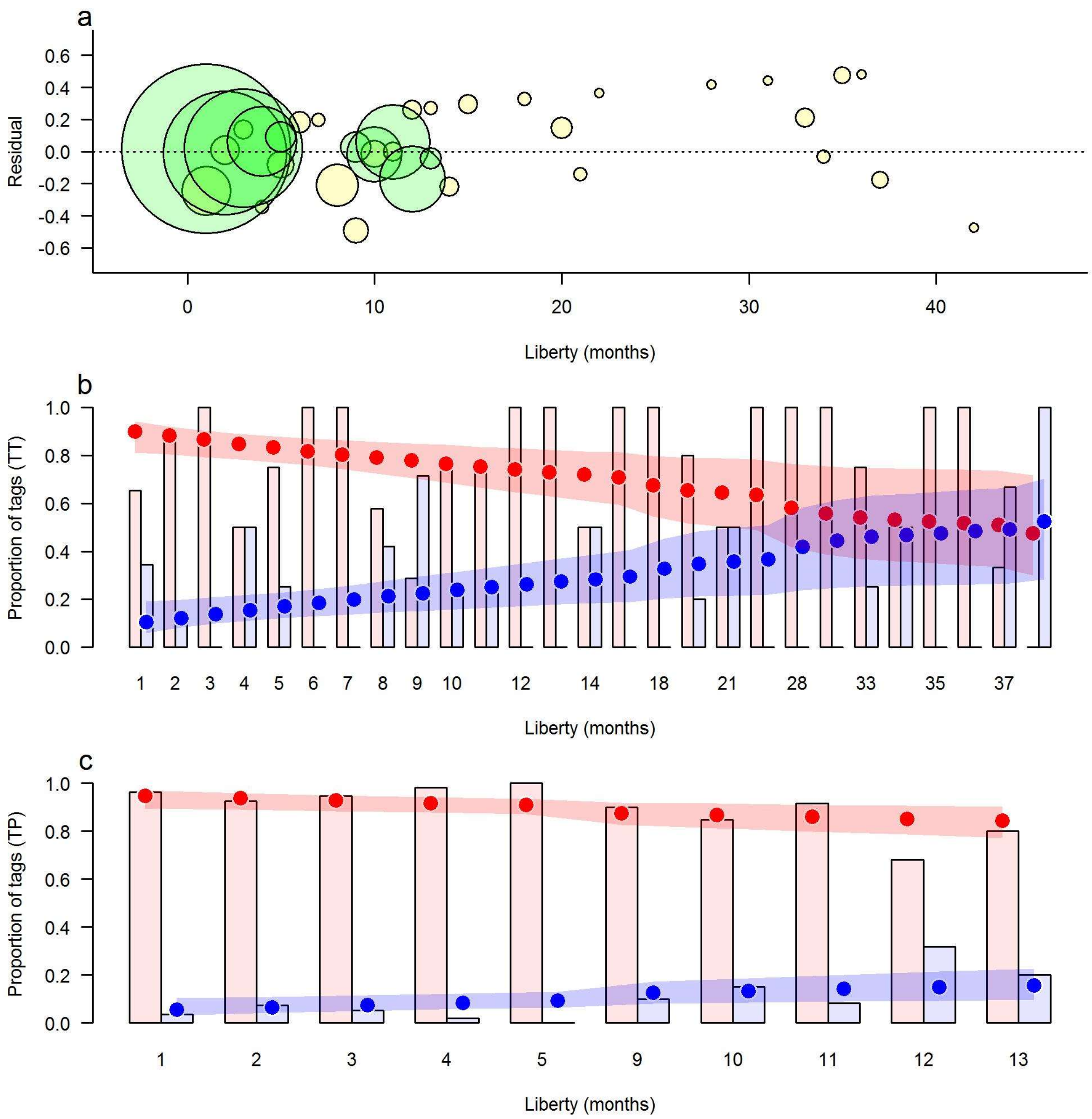

Figure 20. *a.* Residual plot from the combined TT/TP model with the diameter of the yellow and green circles representing the relative square root number of lobsters for that observation from the TT and TP datasets, respectively. The largest diameter represents 308 lobsters and the smallest 1 lobster. *b.* Observed (bars) proportion of lobsters caught with two T-Bar tags (red) or only one T-Bar tag (blue) across the range and liberties with model estimated proportions shown as solid points with associated 95% CI (translucent zones). *c*. Observed (bars) proportion of lobsters caught with one T-Bar tag and one snipped pleopod (red) or only a snipped pleopod (blue) across the range and liberties with model estimated proportions shown as solid points with associated 95% CI (translucent zones).

6.1.3 *Tag Reporting*

6.1.3.1 *Planted Tags*

Across the four trips, 121 fishers had a total of 308 tagged lobsters planted into their pots (Table 17). Four lobsters were omitted from analysis owing to Departmental research monitoring staff being on board when the pots were pulled, one pot may have been lost/stray as it was not in a line of other pots from that fisher and the final pot was from a recreational fisher. Of the remaining planted tagged lobsters, 32 lobsters were reported back to the Department while 272 were not reported.

Table 17. Number of planted lobsters, fishers and the number returning zero, one or both of the planted tags, by trip.

Trip	Planted Lobsters	Unique Fishers	Tags Returned		
			0	1	2
1	106	44	38	4	2
2	81	42	35	5	2
3	58	30	28	0	2
4	59	33	26	3	4

The initial bGAM model used to examine the likelihood of a tag being returned was reduced based on AIC to the most parsimonious model of;

$$P \sim H + Z + DV + HG + U + E + s(T),$$

where the probability of retaining a tag (P) was a function of fisher history of reporting tags (H), fishing zone (Z), ventral or dorsal tagging location (DV), level of high grading during that fishing trip (HG), catch rate during that fishing trip (U), effort during that fishing trip (E) and the time (T) until pot was retrieved. The final model indicated that the probability of a tag being reported varied significantly with history of returning tags (P<0.001) and the time until the pot was retrieved both as two significant components explaining tag returns (

Table **18**).

Table 18. Model output from bGAM on return rates of planted tags.

Variable	Estimate	SE	p	
History	1.6198	0.5028	0.00128	**
		Smoothed Term		
	X^2			
Retrieval	4.317		0.378	*

The significance of retrieval (days between planting of lobster and retrieval;

Table 18) was due to a declining trend in reporting rate with increasing days between planting the lobster and the pots retrieval regardless of a fishers tag returning history (Figure 10). Fishers who had a prior history of returning tags were significantly more likely to report the planted tags. After accounting for possible predation effects, fishers with a history of returning tags had a reporting rate of 0.24 (0.14-0.35 95%CI) compared to those fishers who hadn't previously returned tags 0.06 (0.0-0.12 95%CI).

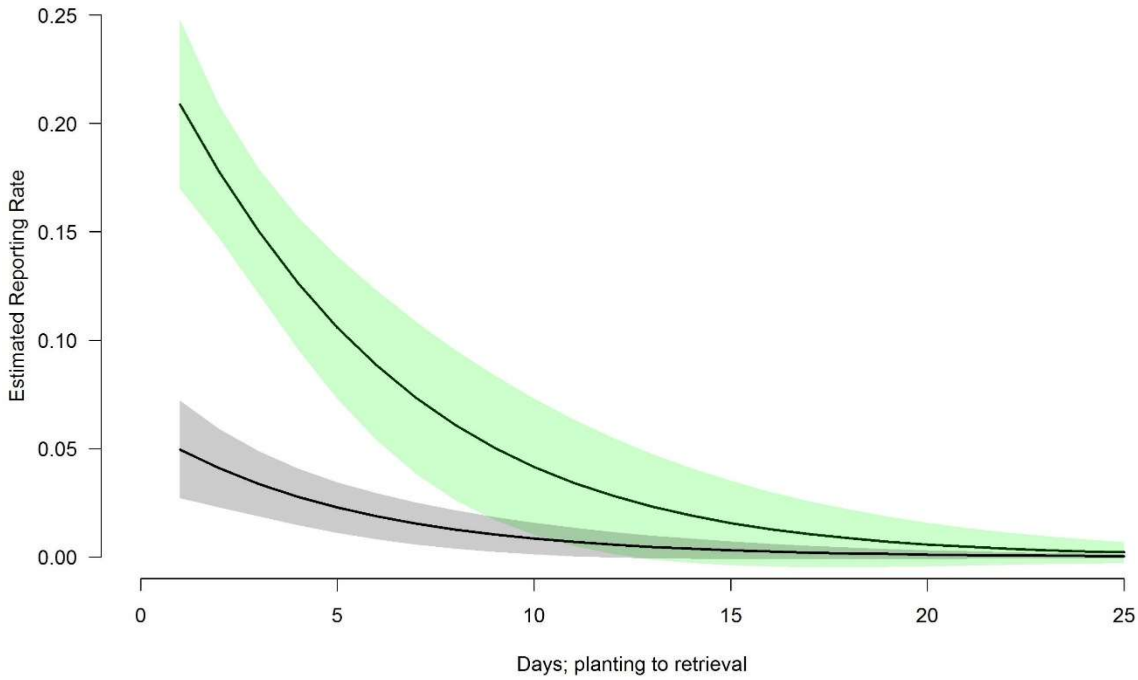

Figure 10. Model estimated reporting rate for fishers who hadn't (grey) had (green) a history of returning tags depending on number of days since the pot was retrieved after planting the lobster.

6.2 Objective 1: Determine spatially specific exploitation rates and legal biomass levels

6.2.1 *Brownie Tag-Recapture model*

6.2.1.1 *Diagnostics*

Two diagnostics were produced to assess the fit of the Brownie Tag-Recapture (BTR) model to the observed data, the residuals associated with reported lobsters and those with un-reported lobsters (Figure 11). Although the model failed to replicate some of the high recaptures rates, there were no obvious patterns across the residual plot that would have indicated a missing component in the model (Figure 11). There were three areas of increased residual size (late 2014/early 2015, late 2015/early 2016 and late 2016/early 2017), and these were relatively well split between positive and negative residuals. The increased size of the residuals in these three time periods are likely related to the increased number of tags released during these periods. The annual Independent Breeding Stock Surveys (IBSS) occurs at the end of each year (surveys are conducted annually in October / November).and are a vehicle for releasing and recapturing large numbers of tags.

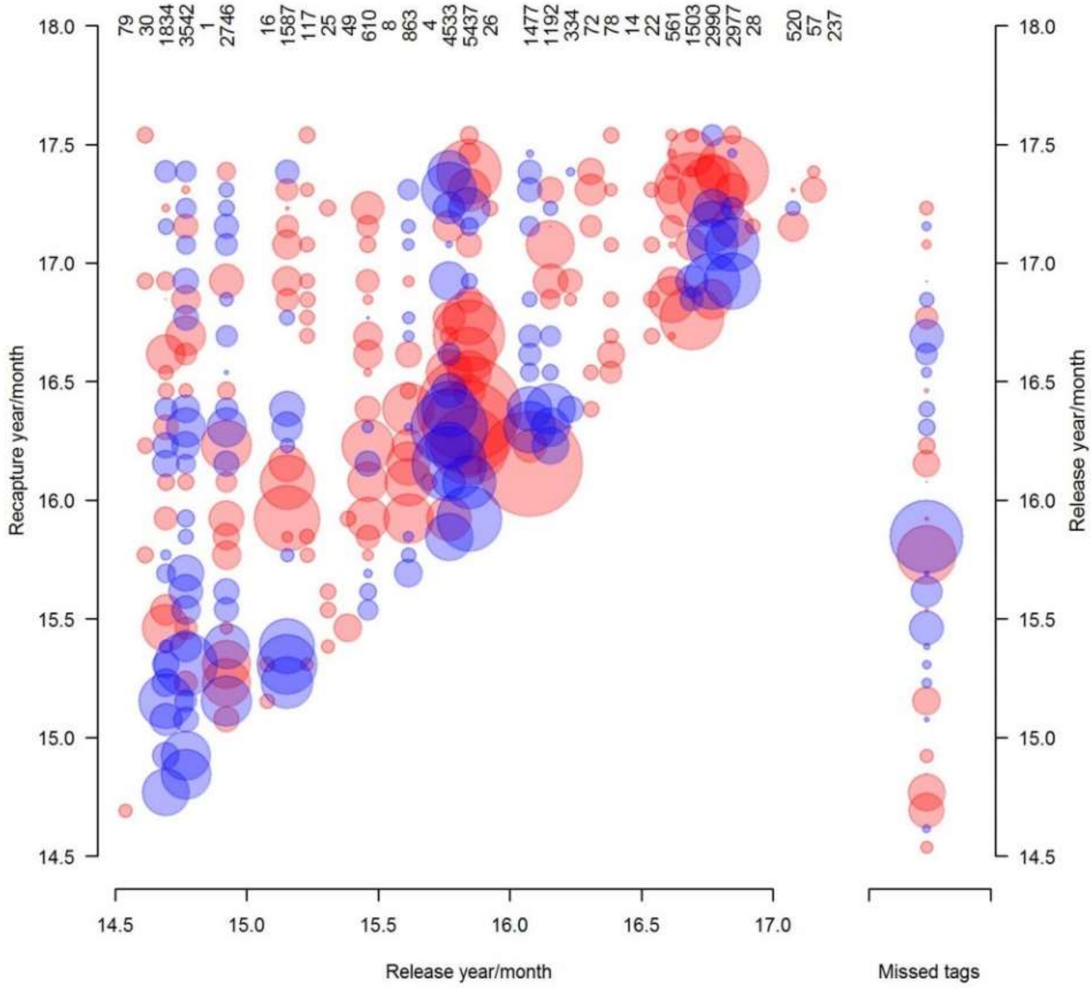

Figure 11. Residual plot between observed and estimated tag returns from each release pulse in each recapture year/month in decimal form (e.g. 15.0 = January 2015 and 15.5 = July 2015). Positive and negative residuals are identified by red and blue colouration respectively, with the symbols size indicating the relative magnitude of the residual. Numbers at the top indicate the number of tags released during that month. Missed tags represents the tags that were not reported and are presented on a different scale to the reported tags (symbol size is not comparable between groups (recaptured vs missed), only within groups).

6.2.1.2 *Outputs*

The BTR model estimated the average harvest rate (HR) for tagged lobsters during the period 2014 to 2017 (time span of the model) to have been ~40% ± 15% (95% CI). This estimate is based on all captured lobsters over legal size and hence includes those, which are protected from capture (e.g. reproductively active females), as well as those high-graded (currently ~ 25% of the legal catch is high graded). As a result it does not represent the true harvest rate, i.e. the proportion of the legal catch landed. This was estimated by adjusting the harvest rate by the high grading rate (25%), resulting in a harvest rate estimate of 30% ± 12%. Based on this harvest rate estimate and the average landings of ~ 6200 t over the past three fishing seasons, the estimated average biomass of legal lobsters over these three seasons is 18 500 t ± 7500 t. The model also estimated the annual natural mortality rate to be 0.14 ± 0.22.

6.2.2 *Individual-Based Model*

6.2.2.1 *Diagnostics*

6.2.2.1.1 *Tag Loss*

Residuals between observed and estimated tag loss component of the IBM showed no progressive patterns across liberties or between the two tag loss trials (TT or TP) (Figure 12a). Observations with large sample sizes generally displayed smaller residuals (better fit) than those with much smaller sample sizes. As such overall the model fits better to the TP (Figure 12c) data than TT data Figure 12b), as the TT data has a greater variability between successive temporal observations. The confidence limits produced by the IBM around estimated tag loss were relatively small when compared to those from the stand alone tag-loss combined model (Figure).

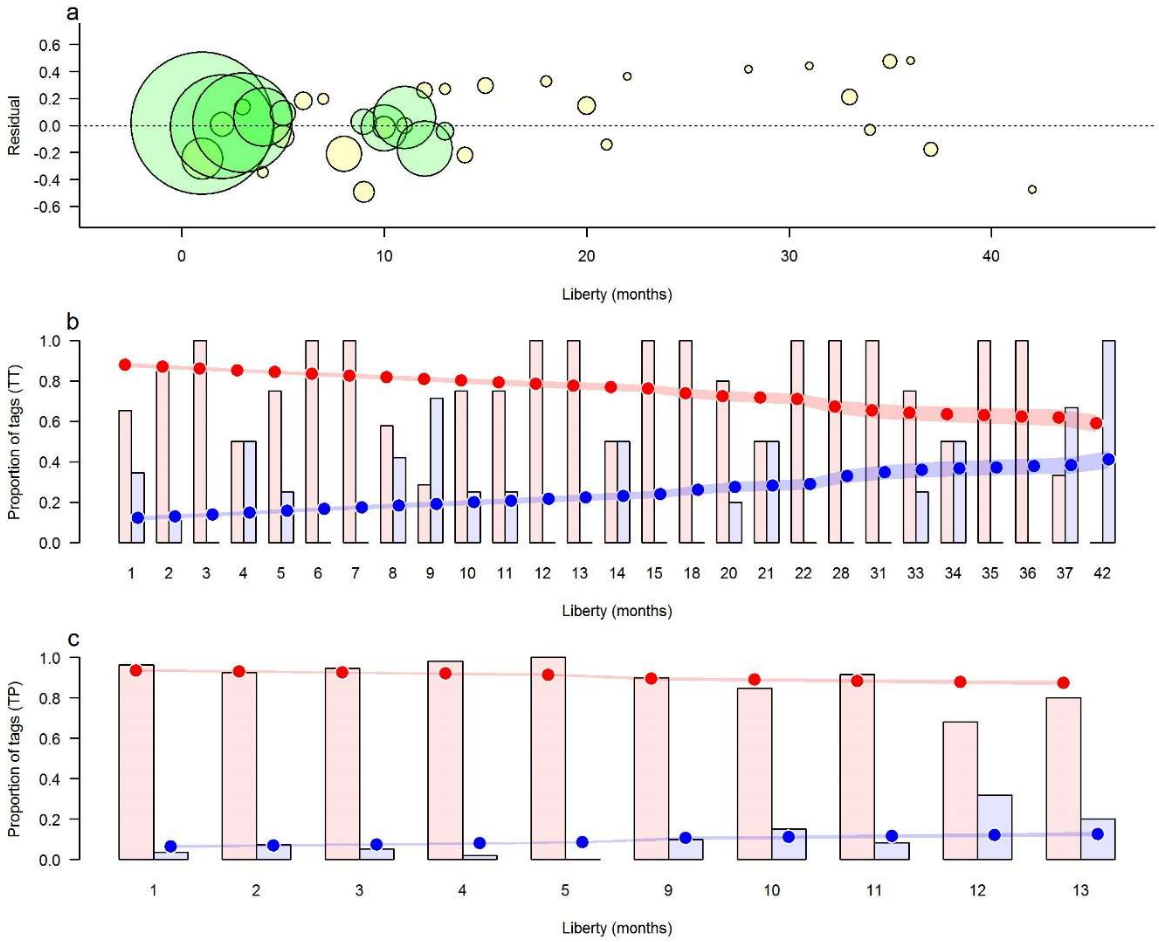

Figure 12. *a*. Residual plot from the IMB combined TT/TP component with the diameter of the yellow and green circles representing the relative square root number of lobsters for that observation from the TT and TP datasets, respectively. The largest diameter represents 308 lobsters and the smallest 1 lobster. *b*. Observed (bars) proportion of lobsters caught with two T-Bar tags (red) or only one T-Bar tag (blue) across the range and liberties with model estimated proportions shown as solid points with associated 95% CI (translucent zones). *c*. Observed (bars) proportion of lobsters caught with one T-Bar tag and one snipped pleopod (red) or only a snipped pleopod (blue) across the range and liberties with model estimated proportions shown as solid points with associated 95% CI (translucent zones).

6.2.2.1.2 *Growth*

Residuals between observed and estimated carapace length of recaptured lobsters showed no progressive trends or patterns when plotted against a number of different characteristics that existed in the data, namely release carapace length, recapture source (who reported the lobster), sex of lobster, release location or the time at liberty (Figure 13). This indicates that the model was sufficiently capable of replicating the tag-recapture growth of lobsters. The residual plots also highlighted low samples for lobsters released with a carapace length > 120 mm, returned by commercial monitoring, females and males in area 7 and at liberty for more than 24 months (although a good sample size does exist for lobsters at liberty for 36 months).

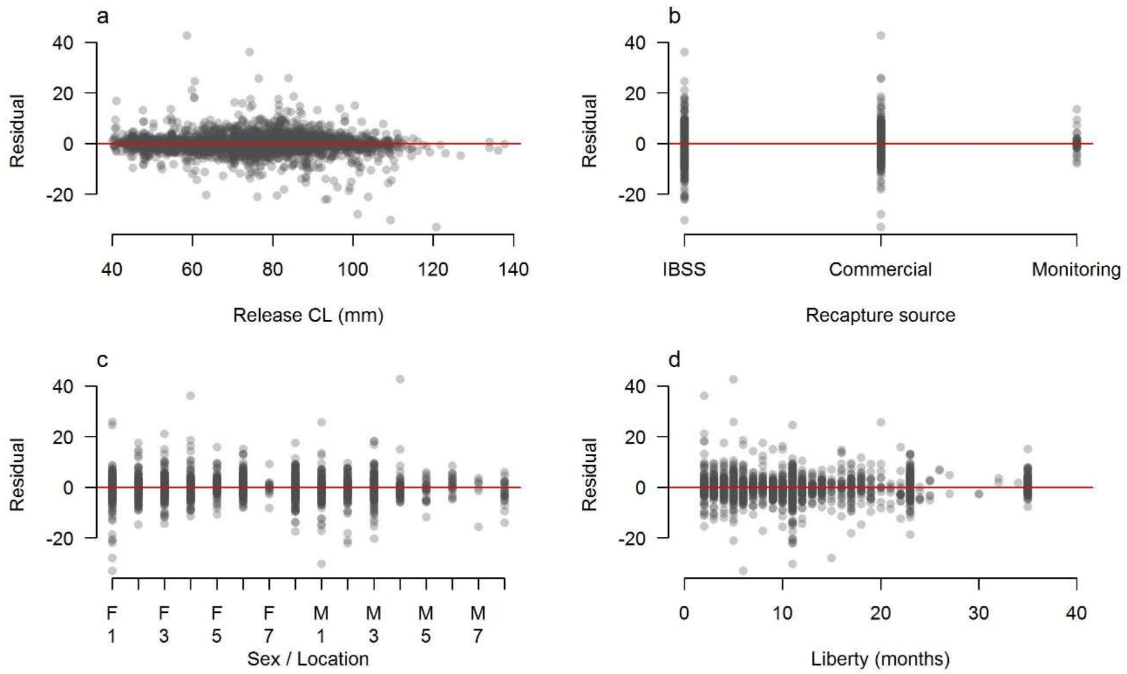

Figure 13. Residuals plots between observed and estimated carapace length of recaptured lobsters against release carapace length (*a*), recapture source (*b*), lobster sex and release location (*c*) and time at liberty (*d*). The horizontal red line represents 0, a perfect fit.

6.2.2.1.3 *Movement*

Migration was well replicated by the model as indicated by the high concordance correlation coefficient (ρc) in each release location (Figure 14a-h). These plots also highlight a lack of recaptures that occurred of tagged lobsters released in locations five and seven in their directly offshore model location (six and eight, respectively). This is partly explained by the small release sample sizes within these two areas, but also indicates a relatively lower rate of migration from these areas.

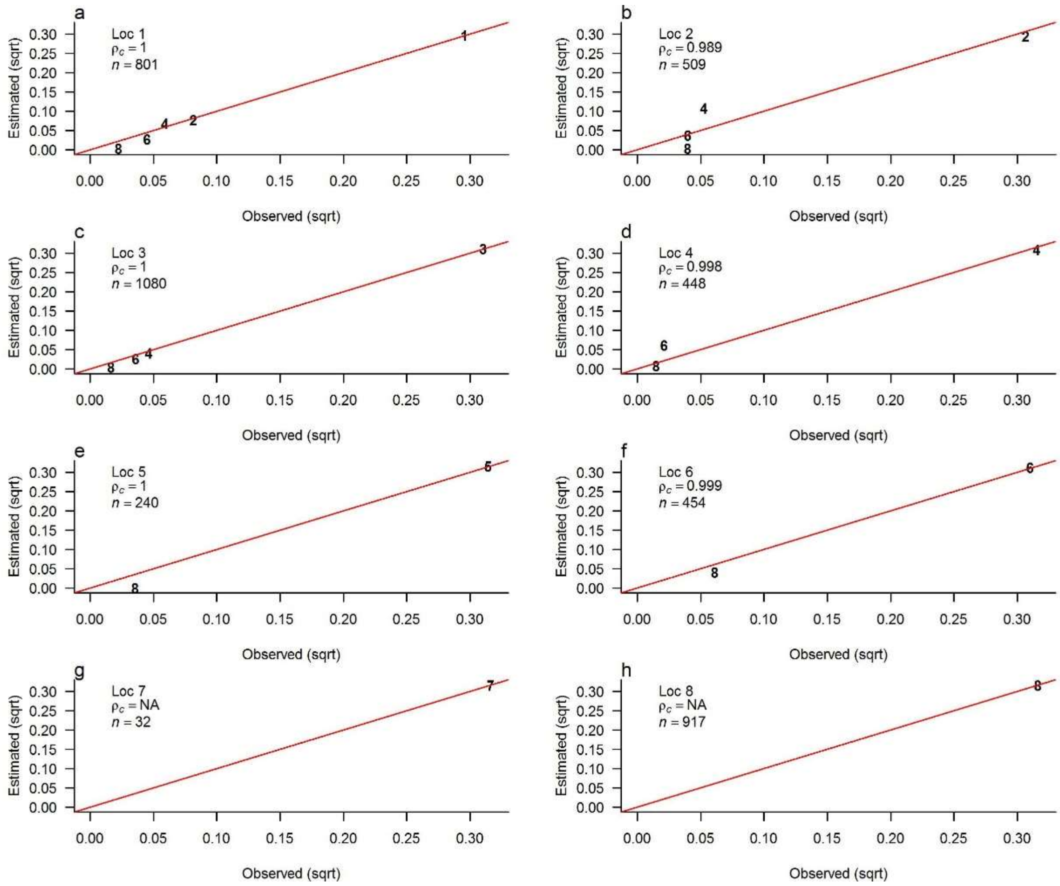

Figure 14. Proportion of lobsters released in each model location ("Loc" a-h) showing the square root of the observed and estimated proportions recaptured in each model location (identified by the numeric). The red line shows the line of concordance, "ρ_c" the concordance correlation coefficient and "n" the sample size.

6.2.2.2 *Outputs (Harvest Rate and Biomass)*

The IBM model estimated tag loss to be very similar to that produced by the combined tag-loss model (**Table 16**) but with much greater confidence (small confidence intervals); the IBM estimated the proportion of lobster retaining a tag following release (i.e. 1- instantaneous tag loss) was 0.94 (0.93 – 0.95 95% CI) however it estimated a considerably smaller constant monthly tag loss (i.e. chronic tag loss) of 0.006 (0.005 – 0.007 95% CI) compared with 0.9 (0.2-1.8) for the combined tag loss model. Based on the contrast in return rate between commercial vessels with and without observers onboard, the model estimated the average tag reporting rate across the study period (e.g. throughout the fishery and across the four years) to be 47.9% (36.7 – 59.1 95% CI).

Tagged lobster catchability was estimated to have increased slightly from late January/February period to peak in March /April before progressively declining to a catchability half of the maximum in late November/early December (Figure 15a). Catchability then started to increase again in late December/early January. The harvest rate of tagged lobsters estimated by the model declined marginally from 0.34 (0.28 – 0.40 95% CL) in 2015 to 0.29 (0.24 – 0.35 95% CL) in 2017 and then increased slightly in 2018 (0.31; 0.25 – 0.36 95% CL) (Figure 15b). Lobster biomass, as represented by the tagged lobsters (which were considered representative of all lobsters > 76 mm carapace length), was estimated to have increased over the study period from ~ 19 000 t in 2015 to ~ 23 000 t in 2017 and 2018 (**Figure 15**c).

On a finer spatial-scale the model estimated markedly different biomass levels in the various model regions (Figure 16). The southern model locations (representing the entire management Zone C) were estimated to have the largest legal (≥76 mm) biomass levels (4000 – 8000 t, depending on fishing season). In contrast the most northern model locations (areas 7 and 8), which represent part of management zone B, had the lowest legal biomass levels (250 – 600 t, depending on fishing season). All deep water locations showed a progressive increase in biomass levels over the study period (locations 2, 4, 6 and 8), whereas shallow water locations generally remained constant (Figure 16).

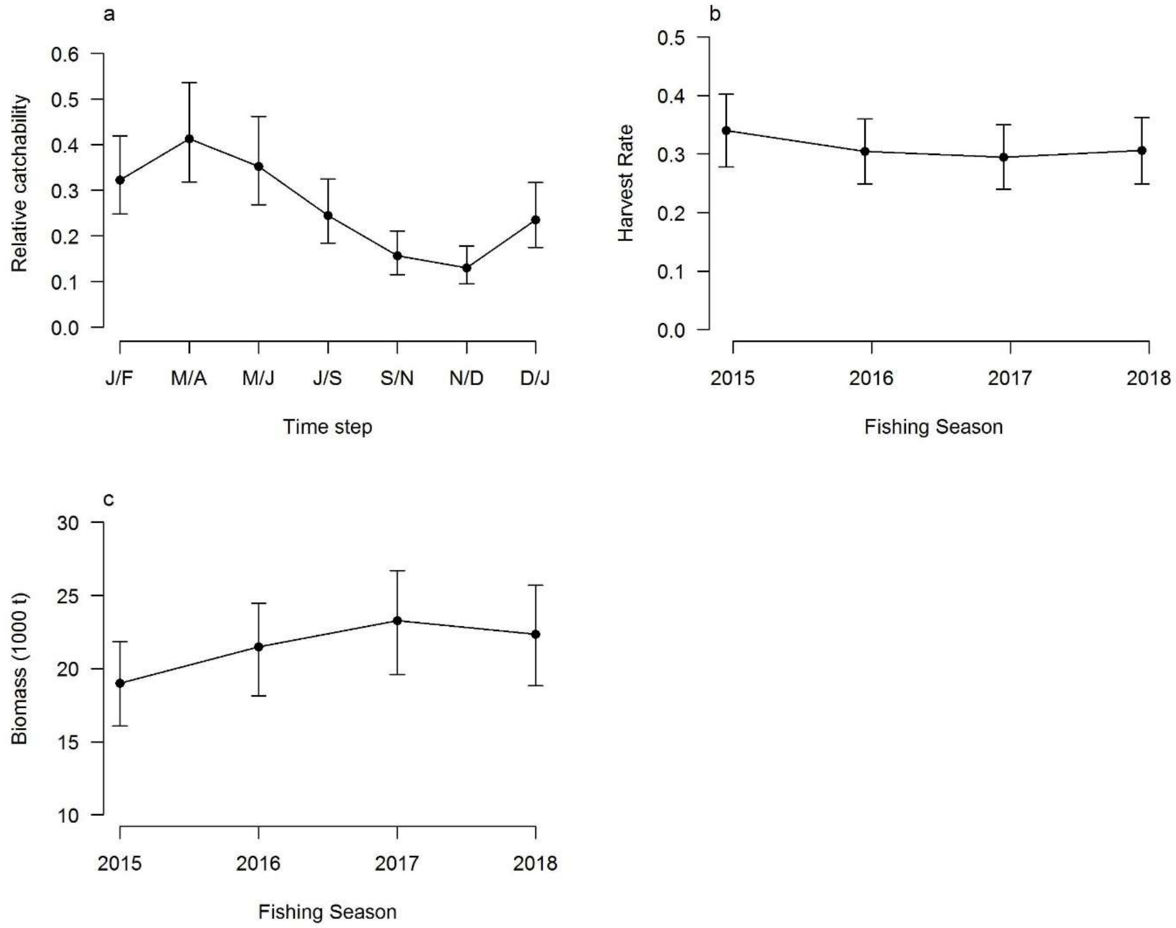

Figure 15. Model estimated (± 95% CI) (a) relative catchability of tagged lobsters, (b) commercial harvest rate and (c) biomass of all legal-sized lobsters (carapace length > 76 mm).

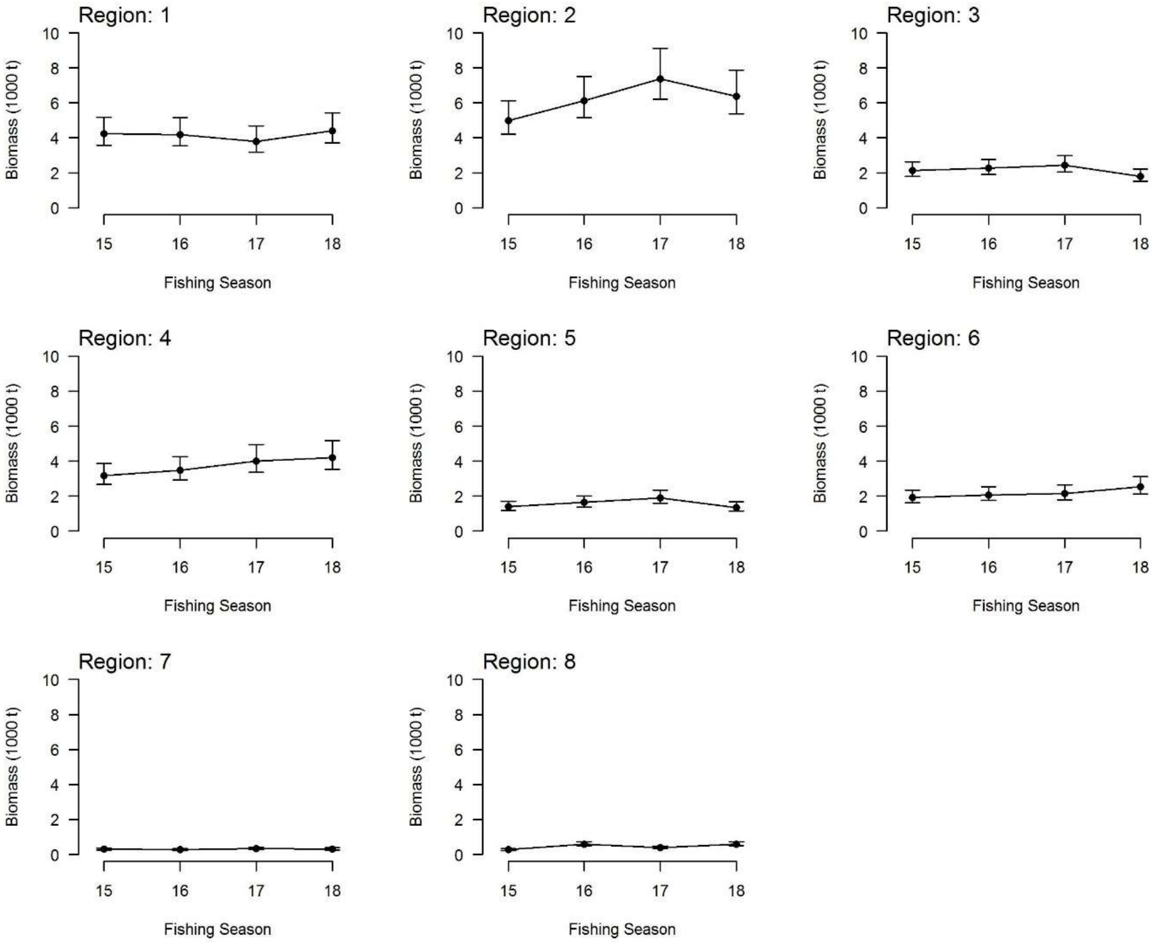

Figure 16. Model estimated (±95% CI) spatial-specific biomasses of all legal-sized lobsters (carapace length > 76 mm).

6.3 Objective 2: Increase precision of estimates for movement rates between management zones

This study has increased the amount of data suitable for examining Western Rock Lobster movement throughout the fishery (data requires release and recapture dates and locations as well as release carapace length) by almost 300%, from 4162 observations before the study to now 12 149 observations.

One benefit of this additional movement data was highlighted in the IBM as it allowed this model to move lobsters throughout the model areas with greater accuracy. This resulted in exposing them to the appropriate, location specific, levels of fishing mortality, which in turn increased the accuracy of harvest rate and biomass estimates. Additionally, it allowed more accurate measures of movement to be determined. The IBM estimated the proportion of lobsters migrating from one area of the model to another differed markedly across release depths and with latitude along the coast (Figure 17a). Of the lobsters that were of the size to migrate (model estimated; Figure 17b) in each latitude, lobsters in the offshore area (areas 2, 4, 6) consistently showed a much greater propensity to move to an adjacent area (move northward), than did those released in corresponding shallow areas (1, 3, 5; move westward). For example, in the most southern areas (1 and 2), ~ 25% of lobsters at the mean size of migration (see below) were estimated to move westward into area 2, whereas almost all of those lobsters of mean migration size in area 2 were estimated to move further northward into area 4 (Figure 17a). The magnitudes of migration rates, in both shallow and deep areas, progressively declined with decreasing latitude (i.e. towards the north), to where very few lobsters were estimated to migrate offshore from areas 5 and 7. Furthermore, the rate of movement from area 6 to 8 (i.e. northward movement) was only a fraction of that estimated for the more southern regions, e.g. ~ 10% (Figure 17a).

The size at which lobsters migrated was estimated to be smaller in offshore areas than inshore, 71.0 (68.2 – 74.0 mm 95% CI) vs 77.4 (74.2 – 80.8 mm 95% CI) (Figure 17b). The normal distributions representing these cohorts of lobsters migrating was estimated by the model to have a fairly similar standard deviations for offshore and inshore (8.3 vs 7.6 mm respectively) model locations. These relatively wide distributions allowed small proportions of lobsters to migrate at carapace lengths < 60 mm and > 90 mm (Figure 17b).

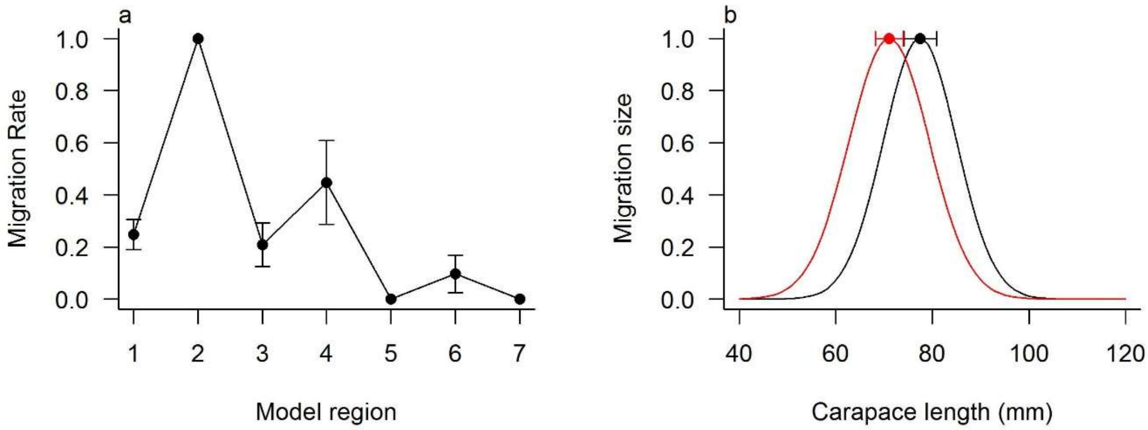

Figure 17. Model estimated (*a*) proportion (± 95% CI) of lobsters at the mean migration size migrating from each area in the model, (*b*) mean migration size (± 95% CI) and associated normal distributions describing the size cohort of lobsters migrating from shallow (black) and deep (red) model regions.

6.4 Objective 3: Improve understanding of the variability of growth throughout the range of the fishery

This study has increased the amount of data suitable for examining Western Rock Lobster growth (data requires release and recapture dates, release location, as well as release and recapture carapace length) by almost 18%, from 30,821 samples before the study to now 35,054 samples. However, a large amount of the historical data (all tagged and recaptured lobsters released prior to 2000 = 28,271), have been found to be contaminated with lobsters used to examine poor handling practices. These lobsters were exposed to higher than normal stressors when caught, such as time out of water in windy and hot conditions (Brown and Caputi, 1983). These studies showed that poor handling can lead to lost limbs, weak release behaviour and higher than average mortality. Furthermore, many of these lobsters showed little to no growth over the first two years post release, which was attributed to their experiences during these trials (Brown and Caputi, 1983). As it is unclear which of these lobsters experienced the various treatments, all tagged and recaptured lobsters released before 2000 should not be used for growth analysis. Following this subsetting of the dataset, this study increased the usable data set for growth analysis by over 200%, from 2550 to now 6783. The historical lobster growth dataset (i.e. that collected after 1999) consists mainly of lobsters released in shallow water regions south of Geraldton and the deep-water Abrolhos Islands. The additional growth data added by this study has increased data in these areas, but more importantly has increased the data that can be used to examine growth in the most northern nearshore and offshore areas (Kalbarri and Big Bank) as well as the offshore areas throughout the rest of the fishery.

This increase in the temporal and spatial coverage of the growth data has allowed the examination of variability in growth between sexes, locations as well as in response to changes in lobster density and water temperatures (Figure 18). By compounding monthly growth rates from an initial carapace length of a puerulus (8.7 mm CL) the effects of these factors on the size at age of lobsters is highlighted. Young lobsters (i.e. < 5 years post settlement [yps]) were of a similar size at the two locations, whereas those in lower density (areas with lower catch rates) and warmer water temperature scenarios were predicted to have grown significantly larger by the age of 3 – 4 yps. Between the two water temperature scenarios (Figure 18d) the length of lobsters were predicted to become similar for ages 5 – 11 yps before those in cooler waters became progressively larger than those in warmer waters. In the other scenarios (between sexes, locations and lobster density) the length-at-age of lobsters started to deviate, with males (after seven yps), lobsters on the coast (after eight yps) and those in less densely populated areas (after five yps) becoming much larger than females, lobsters at the islands or those in highly populated areas, respectively (Figure 18a-c). This work has recently been published (de Lestang 2018).

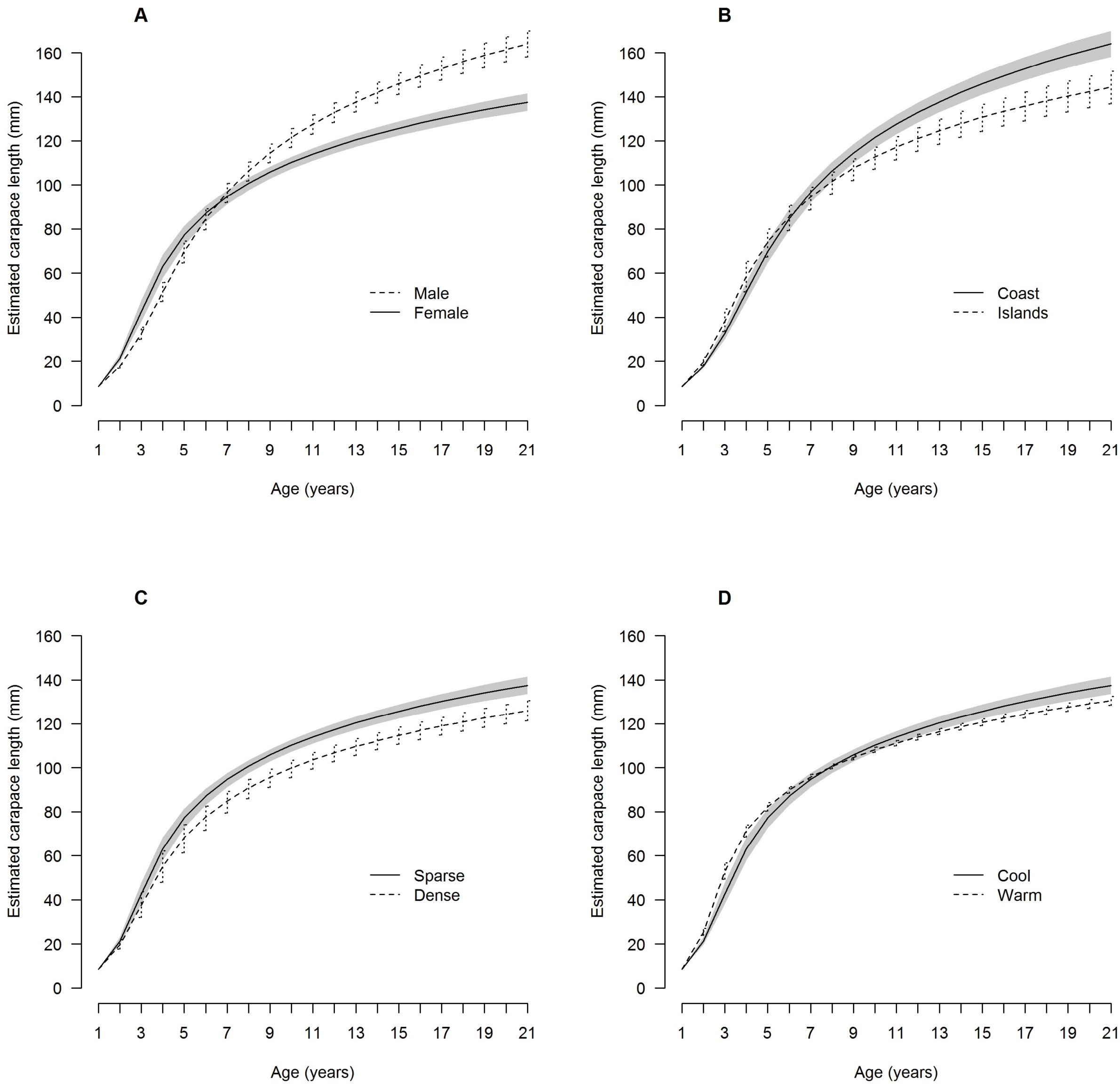

Figure 18. Model derived growth curves (median and 95% credible regions) constructed by compounding estimated monthly growth from an initial carapace length of 8.7 mm (mean puerulus CL). A: Sex scenario (coast, sparsely populated and cool waters). B: Location scenario (males, sparsely populated and cool waters). C: Lobster density scenario (females, coast and cool waters). D: Water temperature scenario (females, coast and sparsely populated).

7.0 Discussion

This study has successfully achieved its three main objectives: (i) determine spatially specific exploitation rates and legal biomass levels, (ii) increase precision of estimates for movement rates between management zones and (iii) improve understanding of the variability of growth throughout the range of the fishery, through the robust collection of data that was applicable to a novel purpose-built individual based model.

The two tag-recapture models (BTR and IBM) used in this study both produced very similar estimates for fishery-wide exploitation rate (~0.3 vs 0.29 – 0.33) and legal (≥76 mm) biomass (~18,500 vs 19,000 – 23,000 t). These estimates indicate that the Western Rock Lobster resource is currently in a very sustainable condition, and is being fished at a rate below that considered to represent maximum economic yield (MEY~ 0.39; Caputi et al. 2018) and well below that representing maximum sustainable yield (MSY~ 0.6; Caputi et al. 2018). These findings are in concert with estimates derived for this fishery during recent annual stock assessments, based on two separate population models, Integrated Population Model (IPM) and Biomass-Dynamics model (BDM) (de Lestang et al. 2019). Such strong agreement between all models provides a greater certainty in the current assessment and management of this important fish resource.

The BTR model was used in this study as it has a proven formulation and is considered robust and appropriate for estimating exploitation rates and biomass levels from tag-recapture animals (Hoenig et al. 1998b; Ley-Cooper et al. 2013). However, it is not easily adaptable to a highly dynamic system where-by animals move and experience different levels of catchability and retention depending on their size, sex and position within the fishery. Since an objective of this study was to examine variation in lobster dynamics within the fishery (e.g. on a finer-spatial scale), results from the BTR have been used to cross check estimates produced by the purpose built Individual-Based Model (IBM) that has the capability to examine stock dynamics on a finer scale. The similarity between broad fishery-wide estimates produced by the two models provides greater confidence in the outputs produced by the IBM.

The IBM highlights the value of tag-recapture data for examining exploitation and biomass in a wild capture fishery. However, due to the complex nature of tag-recapture data and the requirement to have a good understanding of tag loss and reporting rate it is rarely incorporated into integrated population models for any purpose other than estimating movement or growth (de Lestang et al. 2019). The formulation of the IBM in this study was based on the same structure used in DPIRD's new IPM being developed for WRL. This was with a view that tag-recapture data can be utilised in this new model for the estimation of fishing mortality, increasing the new model's comprehensiveness and robustness for appropriate management advice.

Legal (≥76 mm) biomass levels estimated in this study showed a gradual increase over the course of the study. When examined on a fine spatial scale, the increase was driven by the offshore deep-water locations. Juvenile WRL settle in the nearshore environment, but move offshore to deeper areas at the age of ~ 4 years post settlement (de Lestang 2014). With relatively low fishing levels (i.e. below those at MEY) and a stock that has an ontogenetic offshore migration, any stock build-up would be expected to occur in the offshore areas.

Of the model locations, the two southern locations were estimated to have the largest biomass levels, while those in the very north of the fishery, the lowest. These estimates need to be considered in the context of their relative size, with the two southern locations being far bigger spatially than any other locations within the model and as such they would have the greatest habitat for lobsters (**Figure**). Furthermore, this study commenced three years following the 2011 extreme marine heat wave, an event that significantly affected the habitat and stock levels of a number of fisheries in the northern half of the WRL fishery (Caputi et al. 2019). There is anecdotal evidence that this heat wave event also impacted the survival of juvenile lobster in northern model locations (3 and 7), with this impact only starting to dissipate almost 10 years later. As such, it is possible that biomass levels within this part of the fishery would have been negatively affected to a much greater extent than those in more southern areas of the fishery.

This study examined tag loss and reporting rate both as stand-alone investigations and collectively in the IBM, the latter of which had the advantage that the variances associated with the estimates were taken through into the target estimates of exploitation rate and biomass levels. Tag loss was found to be relatively low in WRL (6% and 0.5%, for instantaneous and chronic tag loss, respectively), which has the advantage that a large number of marked animals remain in the system for many years and are thus able to provide robust estimates of a number of population dynamics such as movement and growth. This finding is supported by the fact that some tagged lobsters have been returned in recent years (not only during this study) that have been at liberty for over 15 years. This level of tag loss was lower than that reported for a similar lobster (*Panulirus argus*) with a similar tag type (T-bar), although they only reported the combination of instantaneous and chronic tag loss at ~4% month^{-1}. A much closer estimate was produced by Gonzalez-Vicente et al. (2012), who showed an instantaneous tag loss almost identical to this study for the spiny lobster *Palinurus elephas* based on a double tagging trial (7% year^{-1} for males and 5% year^{-1} for females).

The release of double tags proved to be a very efficient method for examining tag loss, namely because it did not matter who re-captured the tagged lobster. By contrast the TP trials required DPIRD staff to examine the all captured lobster for a marked pleopod. The TP trials also had a finite duration due to pleopods regrowing over two successive moults. It is therefore not surprising that the TT method has been used in a number of other fisheries previously (e.g. Frusher and Hoenig 2001; Gonzalez-Vicente et al. 2012), whereas the TP trial was unique to this study. In most cases when a fisher noticed a tag they also saw and reported the second tag if it was present (one lobster was reported as having one tag and the photo supplied with this submission clearly showed two). The ability to have double and single tags reported by all fishers allowed for a greater range of lobsters in more areas to be examined for tag loss, thus allowing for any biases to be discovered and accounted for in the analysis.

Combining the data from the two studies (TT and TP) allowed the advantages from each method to be incorporated into the overall estimate of tag loss, producing a more robust estimate. The TP trial was staff intensive but provided a large number of samples over a relatively short liberty of release, enabling the combined model to produce a good estimate of instantaneous tag loss. The TT trial by contrast, produced a smaller sample size in the short term, but provided data on tag loss up to 44 months after release, which was considerably longer than the TP trial (~12 months). This long time series was invaluable for examining the rate of chronic tag loss.

Estimates of reporting rate varied between the two methods used to examine this factor, with the direct salting of pots indicating that ~25% of fishers who had a history of previous tag reporting were likely to report a planted tag, whereas the IBM estimated an overall tag reporting rate between 36.7 and 59.1%. These two estimates are however not directly comparable as they refer to slightly different concepts. The salting trials examined the proportion of fishers reporting tags and did not account for lobster predation that may have occurred between salting and subsequent fishing. Even relatively low predation rates would have reduced the observed reporting rate in this study. The IBM on the other hand produced estimates of the proportion of tagged lobster recaptured that were reported and, as such, this estimate can be considered independent of lobster predation rates in pots. Furthermore, this estimate is not a proportion of fishers, rather it is a proportion of pots pulled and is therefore more equivalent to the proportion of fishers reporting tags, weighted by the relative number of pots fished by each fisher over the fishing season.

Irrespective of the method use to assess reporting rate, it was surprising that both estimates indicated that it was well below optimal. Adding to this was the fact that the only factors examined that partly explained variation in reporting from the salting trials, was the reporting rate history of that fisher and time taken to collect the pot. Collectively this indicates that a number of fishers with the WCRLMF simply do not return tags. This study provided five methods for fishers to report tags, many of which required very little effort on behalf of the fisher. In addition, the importance of the study and benefits associated with a high reporting rate were publicised *ad nauseam* in flyers to fishers and at industry meetings (see Extension and Adoption). Even the use of a high value lottery of $3000 did not alter some fisher’s behaviour, an incentive that has been beneficial in other fisheries (Green et al. 1983). There may be advantages for future studies to first conduct a survey of fishers to ascertain what drives participation in such a trial and what activities may be undertaken to increase tag reporting.

One potential driver which may have previously reduced participation was the introduction of a particular management arrangement in 1993. This arrangement prohibited the retention of lobsters <77 mm CL until the 1st February each season. The intent of the arrangement was to reduced effort on migrating lobsters (migration starts as early as late November). This led to a theory that increased numbers of lobsters were moving from one management zone (Zone B) into another (Zone A). As such, many fishers within Zone A were concerned that reporting tagged lobsters would add credence to this perception of in-equitability and force authorities into changing this management arrangement. This led to a marked bias in tag reporting between fishers in different fishing zones and to some interesting movement patterns being displayed by tagged lobsters, as they appeared to stop at the boundary between Zone A and B (de Lestang 2014). In 2014, one year before this study was to commence, the managements arrangements surrounding 76 mm lobster were reversed, and the perceived in-equitability between zones was no longer issue. The salting trials did not find a significant difference in return rates between any of the fishing zones.

The trial of a release cage in this study was in response to concerns (based on studies in other fisheries) that lobsters may be experiencing significant mortality from fish on their decent to the sea floor post release. Similar release techniques have been used in other species (e.g. Beyers 1994; O'Malley 2008; Courtney et al. 2001; William et al. 2015; Melville-Smith et al. 2007) to reduce release mortality and/or to place animals back in a certain location. This study found that lobsters released with a cage in deep water, on average, displayed greater movement than those released traditionally (thrown straight over the side after tagging), but no significant increase in recapture rate was recorded. The lack of detectable difference in return rate suggests that, within the WCRLMF there is very little release mortality of lobster after tagging. This is supported by *in situ* observations of fishers and departmental staff who have reported not seeing any of the predatory species that typically follow lobster vessels, such as sharks and dolphins, feeding on returned lobster. Since there were no discernible benefits to releasing lobsters with the release cage, combined with the increase requirement of cage transportation, deployment and retrieval, its use was not deemed worthwhile in the case of *P. cygnus.* In a number of other studies that have used release cages, very few examined their impact, i.e. did not compare either recapture rates or movement patterns, rather they just assumed it would benefit survival. Where recapture rates were examined between traditional vs cage releases, results were inconclusive (Courtney et al. 2001). In slipper lobsters *Thenus* spp, the release cage resulted in an increase in recapture rates of large or stressed lobster, but also a reduction in recapture rates, which they attributed to over-crowding of the cage, or increased exposure during the filling up of the cage (Courtney et al. 2001).

The greater distance moved by lobsters released using the cage in deep water may be associated with low levels of nomadism as described by Brown and Caputi (1983). They found that lobsters, if not returned to their place of capture often did not return to the reef of their capture, rather they wandered "aimlessly". It is possible that when filling up the cage from lobsters caught from multiple pots, not all lobsters were returned close enough to their reef of capture and some moved off in search of a new reef system.

In addition to examining biomass and exploitation rates, the IBM replicated recapture location and size of tagged lobster. This added to our understanding of movement rates, movement size and growth of *P. cygnus* under lower exploitation rates than they have experienced previously. These estimates showed that movement rates were greatest in the southern end of the fishery, declining in a northward direction, especially in deep-water locations. Previous work on WRL migration showed that the strength of the Leeuwin Current had a negative relationship with deep-water migration, with the longest northward movements occurring when the current was relatively weak (de Lestang and Caputi 2015). Since the strength of the Leeuwin Current is generally stronger in the north of the fishery (e.g. off Kalbarri) than it is in the south (e.g. off Fremantle) this may partially explain why there is greater rates of movement in the south of the fishery.

The model also predicted that offshore movement (from shallow locations to deeper waters) was conducted by lobsters with a slightly larger mean size than those in their adjacent deep-water areas. This was surprising since previous work has shown that a number of lobsters in deep water regions that had moved there during a previous migration (at about age four) can remain in an immature state and migrate a second time the following year (at about age five), after growing for an additional year (de Lestang 2014). This infers that lobsters migrating in deep-water consist of lobsters undertaking either their first or second migration (four and five year old lobsters) and would therefore be larger on average than their conspecifics undergoing their first migration from the shallows (as these are all undertaking their first migration at about age four). The IBM was limited to lobsters with carapace lengths ≥76 mm and tracks the movement of lobsters over the entire time period of the model, i.e. over a period of four years which allows many of the smaller lobsters being tracked to grow into size well above 80 mm. As such it should be resilient to changes in selectivity around the minimum legal size. However it is possible that, with the greater catch rates during the whites, migration in deep-water and the fact that in fuller lobster pots the escape gaps are less efficient, that a greater proportion of 76 mm migrating whites would be retained by fishers in these areas, thus biasing the mean size at migration to lower estimate.

Data collected during this study found that the growth of *P. cygnus* is relatively plastic, varying in response to changes in water temperature, habitat and population density. This has been demonstrated previously for this species (Morgan 1977; Edgar 1990), which showed similar plasticity in response to food availability and lobster biomass. Since the WRL fishery has recently (~2010) undergone a marked increase in legal biomass (de Lestang 2018) and a marine heat wave in 2011, which impacted both water temperature and marine habitats (Caputi et al. 2019) growth rates of this species are likely to have varied markedly over the past decade (de Lestang 2018), including during this study. Based on future projections of a warming climate and the harvest rate objective to maintain the fishery at MEY, these factors are likely to result in a reduced growth rate and smaller size at maturity than has been recorded historically for this species. This has implications for the productivity and management of this resource and need to be incorporated in future stock assessment modelling for this resource. The additional growth data produced by this study has been incorporated into a stand-alone growth model used to develop inputs that vary on a decadal scale, for the integrated population stock assessment model currently being developed for this fishery. This will allow, for the first time, variation in growth of this species to be incorporated into the annual stock assessment process.

8.0 Conclusion

This project addressed a serious issue resulting from the change in the management system of the fishery through producing a robust estimate of the current biomass of Western Rock Lobster against which future assessments can be benchmarked. In addition it increased our understanding of exploitation rates across the fishery and markedly increased the amount of data and understanding of variability in growth and movement of this species throughout the fishery. These results confirm those produced during the annual stock assessment of this resource, which are based on a different set of data being analysed by a population level integrated model. This concordance re-affirms the appropriateness of this study and it inherent assumption as well as increasing the confidence of the current stock assessment and ensures that the current management of this important resource is appropriate.

Outcomes from this project have shown that this fishery is currently in a sustainable condition, with a large legal biomass being harvested at a relatively low rate of ~ 30%, that is considered below that associated with MEY. This low level of exploitation allows large numbers of lobsters to move from shallow nursery areas to offshore breeding grounds ensuring that the complete range of habitats and areas throughout the fishery are populated with *P. cygnus*.

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10.0 Implications

This project provided an update on key data sources used in the stock assessment of the WRL resource as well as confirm the current annual WRL stock assessment. This concordance increases the confidence of the current stock assessment and ensures that the current management of this important resource is appropriate.

Additionally, WRL fishers have commented that they can better relate to the results from a tag-recapture study, as against a traditional catch and effort based assessment. Through the release of tags on commercial vessels and the supply or recapture data back to the fisher it has increased industry's engagement with research and they have requested that a similar study be conducted at intervals in the future

11.0 Recommendations

Data developed by this study has already been incorporated into the stock assessment process for this resource. In addition, leaders in the commercial WRL industry have raised the possibility of re-running a similar tag-recapture project at 5 – 10 year intervals in the future. DPIRD supports this suggestion.

11.1 Further development

The model developed during this study was capable of deriving estimates of exploitation rate and biomass on a fine spatial and temporal scale without using standard fishery derived data sets (e.g. catch and catch rates). Its incorporation into the new integrated population model would only increase the robustness of this new model, thus increasing the accuracy of the annual stock assessments and the ability to best manage this important resource.

12.0 Extension and Adoption

The outputs from the project have been provided to WRL stakeholders at annual management meetings and information sessions throughout the fishery over the life of the project. These outcomes will again form a major component of the Annual Management Meetings for the WRL resource in October 2020. Data from the project has already been incorporated into the current stock assessment process. Up to three journal articles are planned from this work.

While the current study has concluded, there are still significant numbers of tags that remain at large. The dissemination of these results and the continued engagement with fishers throughout the study will markedly increase future tag returns, increasing our knowledge of movement and growth of this critically important marine resource.

13.0 Appendices

13.1 Appendix 1 Tag Return Card

TAG RECAPTURE CARD

DATA REQUIRED FOR EACH TAGGED LOBSTER

Please fill in all details and place card in mail (no postage stamp required).

If the rock lobster is an undersize, spawner, setose or oversize animal (or a legal lobster that you choose to return to sea) do not remove the tag.

Tag No. ____________________ Date caught: ____________________

GPS Lat: ____________________ Long: ____________________

(☐ decimal degrees OR ☐ degrees and minutes)

Depth (fms.): ____________________ Size: ____________________ (0.1mm)

Please circle the appropriate conditions below:

Sex: M / F

Spawner: Orange / Orange Brown / Brown / Egg cases (hatched)

Setose: Yes / No

Tar spot: New / Eroded (scratched)

Please ensure reward information is filled out below:

Boat name and No.: ____________________

Skipper's name: ____________________

Skipper's address: ____________________

Contact phone No.: ____________________

13.2 Appendix 2 Catch Disposal Record.

Government of **Western Australia**
Department of **Fisheries**

WEST COAST ROCK LOBSTER FISHERY

Use a black or blue pen – print legibly

RLA 103001

PART 1A PRE FISHING NOMINATION (CALL 1300 340 135) → **Pre Fishing Confirmation Number:**

PART 1B DETAILS OF FISHING TRIP – Complete once per landing and prior to completing Part 1C

Zone fished (circle one): A B C
Main block number (refer to map):
Total number of pots pulled:
Pull period (days):
Depth range of pots (fathoms): to

Retained Species (not WRL)	Number	Weight (kg)
Octopus (Headed Wt)		
Southern Rock Lobster		

Protected species interactions (Tick if none):

Protected species	№ Alive	№ Dead

PART 1C PRE LANDING NOMINATION (CALL 1300 340 135) – Complete before entering an approved landing area

Pre Landing Confirmation Number:
Landing Area Number:
Number of Containers:
or
Number of Lobsters on board:

PART 1D POST LANDING NOMINATION AND DECLARATION (CALL 1300 340 135) – Complete after weighing last consignment

CDR Numbers related to this landing:
From: to
Registered Receiver Number:
MFL Number:
Registered Receiver Name:
Boat LFB:
Boat Name:

Tag Numbers: e.g. A A 0 0 0 1 to A A 0 0 1 0
to
to

№ of Containers:
Gross Weight: . kg
Total Weight of Containers: . kg
Net Weight: . kg
Time Weighed: : am / pm (circle one)

Personal Consumption (circle one): Yes / No → **If Yes, full name of crew member receiving lobsters (please print):**
Residential address where lobster will be delivered:

I declare that the information I have provided is true and correct
Master's Full Name:
Master's Contact Phone Number:
Master's Signature:
Date: / /
Post Landing Confirmation Number:

PART 1E VOLUNTARY RESEARCH LOG BOOK – Although optional this information helps guarantee the future of the industry – Tick if completing an electronic research log book

Date	Block №	Berried above minimum size	Setose above minimum size	Not setose above maximum size	Undersize	Dead	High Graded	Live	Comments
/ /									
/ /									
/ /									

NOTE: It is a major offence to make false or misleading statements, or to fail to fully complete this form.When completed, the top **(WHITE)** form must immediately be sent to: **Catch Monitoring Section,** Department of Fisheries, Locked Bag 43, Cloisters Square WA 6850. The second **(YELLOW)** form is to be kept in the book. The third **(GREEN)** form must be provided by the **MASTER** to the REGISTERED **RECEIVER**. When completed the third **(GREEN)** form must immediately be sent by the **REGISTERED RECEIVER** to: **Catch Monitoring Section,** Department of Fisheries, Locked Bag 43, Cloisters Square WA 6850. ***PROTECT YOUR FISHERY – REPORT ILLEGAL FISHING ACTIVITIES TO FISHWATCH – 1800 815 507 – ALL CALLS ARE CONFIDENTIAL***

13.3 Appendix 3 Example Tag Return Information Letter

GOVERNMENT OF WESTERN AUSTRALIA

Department of
Primary Industries and Regional Development

Tagged Rock Lobster Information Sheet

Dear: [redacted]

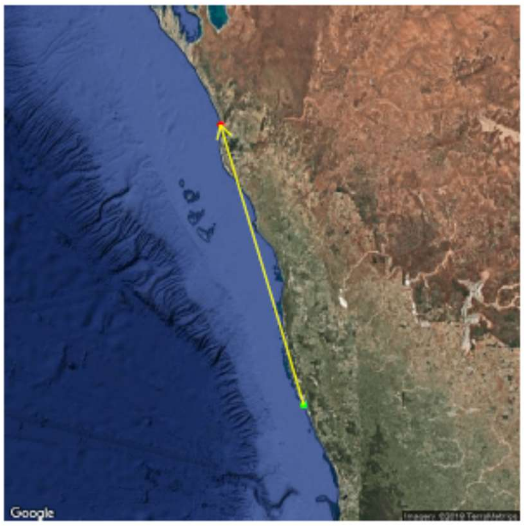
Thank you for taking the time to report information on the tagged female rock lobster: B9281 which you re-captured on Tuesday 18 December 2018. Information from our tagging program serves an important role in the management of your fishery.

It is great to see that you have used our tag return "app". If you have any ideas how we may make this "app" easier to use please let me know. As we have your email address, we have provided your tag-recapture information back to you using an automated process. Unfortunately this does not include your "Scratch-n-Win" reward. So if you would like to receive this reward, please reply to the email with your postal address.

Your Lobster:

The lobster you caught was tagged and released on Tuesday 11 August 2015. When released this lobster had a carapace length of 80.4 mm and was at liberty for 40.8 months. Since this time the lobster has grown 17.6 mm and has moved 386.5 km along a bearing of 343 degrees.

Below is a map showing the initial tagging (green point) and recapture location (red point) of the lobster and its possible movement. If you have any queries please feel free to contact Ben Hebiton at `lobster.tag@fish.wa.gov.au`



Ben Hebiton
Technical Officer – Rock Lobster/Deep Sea Crab Research
Sustainability and Biosecurity
Department of Primary Industries and regional development
Email: ben.hebiton@dpird.wa.gov.au
Phone: +618 9203 0172

The *FishTagWA* app can be downloaded from:
https://itunes.apple.com/au/app/fishtagwa/id785910062?mt=8

Please note the tag submission web form is currently offline

13.4 Appendix 4 Model Simulation of Tag Loss Parameters

The tag loss model was first tested on data derived from known parameters (dummy data) to see if it could accurately reproduce the parameters used to make the dummy data and to fit to the resultant patterns. Two sets of dummy data were developed with small amounts of random noise, one with two of the same tags to mimic the TT dataset and one with two different tags to mimic the TP dataset. In both cases the model was accurately able to fit the dummy data sets (Figures A4.1 and A4.2) and recreate the initial parameters used to make each data set (Table A4.1).

Table A4.1. Model estimates of the known parameters used to make the TT and TP dummy datasets.

Model	Model / Parameter	Known value	Estimate	95% CI
TT	Initial tag shedding (ρ)	0.7	0.71	0.64 - 0.78
TT	Chronic tag loss (ϕ)	0.05	0.03	0.01 – 0.05
TP	T_1 / ρ	0.5	0.54	0.46 – 0.63
TP	T_1 / ϕ	0.05	0.05	0.02 – 0.08
TP	T_2 / ρ	1	0.97	0.93 – 1
TP	T_2 / ϕ	0	0	0 – 0.01

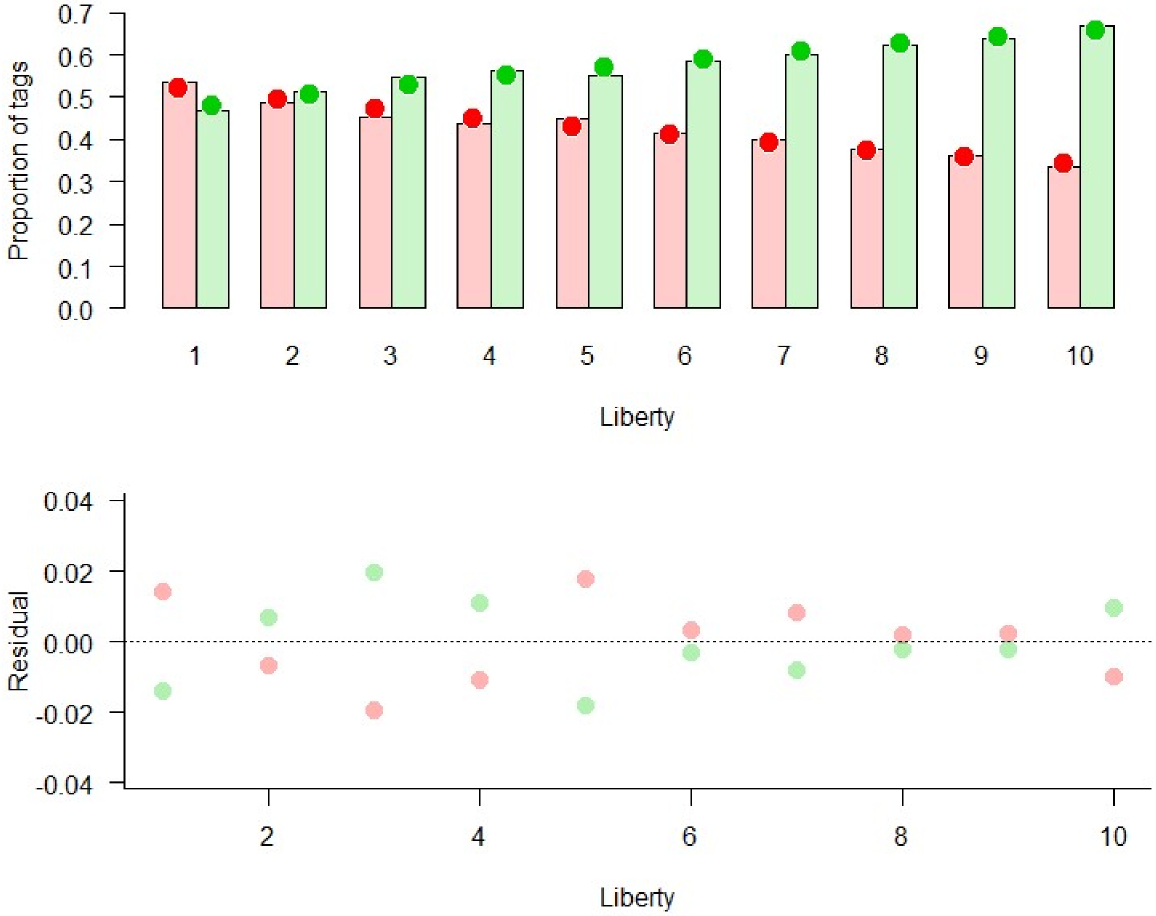


Figure A4.1. (top) Observed (bars) proportion of lobsters caught with both marks (red) or only one tag (green) across a range of liberties with model estimated proportions shown as solid points. (bottom) Residual plot from the TT model.

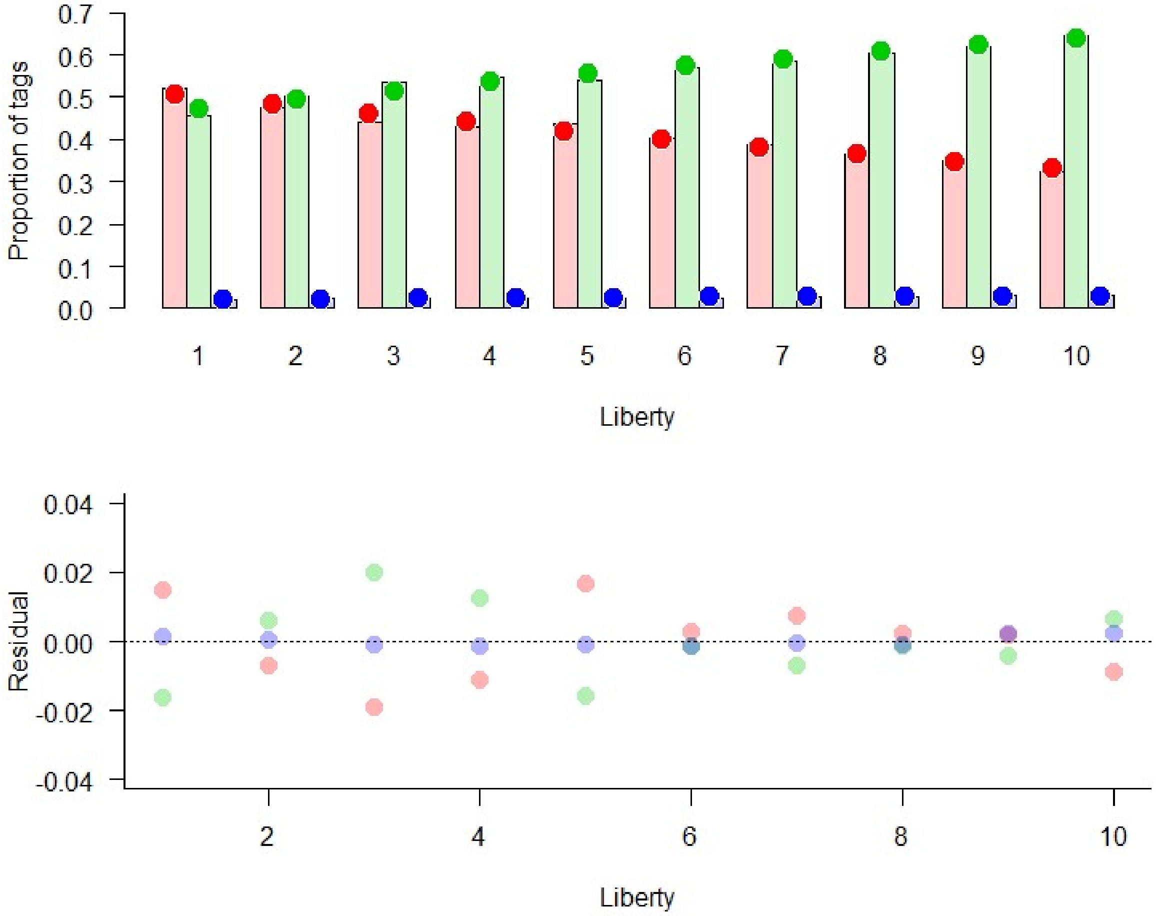


Figure A4.2. (top) Observed (bars) proportion of lobsters caught with both marks (tag 1 and tag 2) (red), only tag 1 (green) or only tag 2 (blue) across a range of liberties with model estimated proportions shown as solid points. (bottom) Residual plot from the TP model.