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Tini a Tangaroa

Characterisation, catch-per-unit-effort, and stock assessment of packhorse rock lobsters (*Sagmariasus verreauxi*) in New Zealand

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J. Roberts,
D.N. Webber

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EXECUTIVE SUMMARY

Roberts, J.[1]; Webber, D.N.[2] (2021). Characterisation, catch-per-unit-effort, and stock assessment of packhorse rock lobster (*Sagmariasus verreauxi*) in New Zealand.

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The aims of this research were to characterise the packhorse rock lobster (*Sagmariasus verreauxi*) (PHC) fishery in New Zealand, update and improve a standardised catch-per-unit-effort (CPUE) time series, and to then do a stock assessment.

Packhorse rock lobsters are captured by a targeted fishery operated by a small number of vessels, and as bycatch in the red rock lobster (*Jasus edwardsii*) (CRA) fishery. Nearly all the PHC catches are taken in Quota Management Areas (QMAs) CRA 1 and CRA 2, along the north coast of the North Island. Following the introduction of this species into the Quota Management System (QMS) in 1990, commercial landings were initially low relative to the Total Allowable Commercial Catch (TACC), which has been set at 40.3 tonnes since 1992–93. Commercial landings steadily increased since the early-2000s, and the TACC has effectively been taken in every fishing year since 2013–14. The annual landings of this fishery were estimated by a separate study to have been much higher in the 1960s and 1970s, although records of PHC landings are unreliable from this period.

The available data are informative for estimating maturity. However, there were very few tag recaptures for informing the estimation of size-specific growth. Previous research on the New Zealand and Australian stocks suggested that this species is highly migratory compared to red rock lobsters, with ontogenetic up-current movement towards warm-water breeding grounds. Tentative support for this hypothesis was obtained from a characterisation of the tag and size composition data, although both sources of information are too sparse to confirm this for the New Zealand packhorse rock lobster stock.

An existing standardised CPUE time series was updated and improved for the fishing years 1991–92 to 2018–19 by a model fitted to Catch Effort Landing Return (CELR) records of packhorse rock lobster catch by the CRA-target fishery. The resulting CPUE time series indicated a continual increase in relative abundance since the beginning of the early 1990s, consistent with a similar trend for the New South Wales stock in Australia. The PHC-target fishery, which took slightly more than half of the recent packhorse rock lobster catch, appears to target mature lobsters in rock lobster statistical areas 901 and 902 (both in CRA 1). The target fishery was excluded from the CPUE analysis because of concerns that the CPUE from this fishery would be hyperstable, as well as recognising that only a few vessels operated in this fishery.

The size composition and tag recapture data are too sparse to inform the development of size-based stock assessment models. Instead, a biomass dynamics stock assessment model was developed based on estimates of historical catch and CPUE. This model suggested a stock that was initially heavily fished to a low level in the 1980s, then increased rapidly during the 1990s, and has plateaued at levels well above B_{MSY} since the mid-2000s.

Future assessments of this species would benefit from improved information for estimating packhorse rock lobster growth, movement patterns, size composition of the catch, and CPUE across the range of exploited sizes and maturity stages.

[1] Anemone, New Zealand.
[2] Quantifish Ltd., New Zealand.

1. INTRODUCTION

1.1 Biology, distribution, and movements

The packhorse rock lobster or pawharu (*Sagmariasus verreauxi*, previously *Jasus verreauxi*; Fisheries New Zealand species code 'PHC') is distributed around New Zealand. The species is primarily found around the North Cape and in the Bay of Plenty, with only sporadic and relatively rare presence around the remainder of New Zealand. Packhorse rock lobster are also found around the south-eastern mainland of Australia and Tasmania (where they are called 'eastern rock lobster'). Packhorse rock lobster are the largest of all Palinuridae, reported to reach at least 8 kg, 400 mm carapace length (CL) (measured from the tip of the rostrum to the posterior edge of the carapace), and almost 1 m total body length (from the supra-orbital spines to the end of the telson) (Fisheries Research and Development Corporation 2020).

Packhorse rock lobsters are found on rocky reefs, sand, or mud substrates ranging from the surface to 200 m depth. This species is best-studied along the coast of New South Wales (NSW), Australia, where the commercial catch has exceeded 100 tonnes in every fishing year since 1905–06, occasionally exceeding 300 tonnes (Montgomery & Liggins 2013), compared with an annual catch around New Zealand of 40 tonnes or less since the late-1980s (Webber 2013). The biology and population dynamics of packhorse rock lobster in New Zealand was reviewed by Booth (2011), including a summary of the New Zealand fishery for this species. The New Zealand PHC fishery was characterised by Webber (2013). Prior to this, various studies have characterised the larval dispersal and development, recruitment, reproductive biology, and movements of the New Zealand population (e.g., Booth 1984a, Booth 1984b, Booth 1986, Booth 1997, Kittaka et al. 1997, Chiswell et al. 2003).

The main New Zealand breeding grounds are centred around North Cape, in the Far North. The dominant early life stage of rock lobster species is the phyllosoma larvae, which, in the case of packhorse rock lobsters, are thought to survive for up to one year post-spawning, before metamorphosing into puerulii that settle on the seafloor (Kittaka et al. 1997). Puerulii moult into their first instar after 3–4 weeks (Kittaka et al. 1997). Juveniles tend to be more abundant than mature lobsters at depths shallower than 10 m (New South Wales Department of Primary Industries 2017) and, around New Zealand, are predominantly found along the north and east coasts of the North Island, down-current of the Far North spawning grounds (Booth 2011).

As they approach maturity, individuals are hypothesised to march counter-current up the east coast of the North Island, eventually returning to their main spawning grounds around the Far North of New Zealand (Booth 1984b, Booth 2011). Then, as with other rock lobster species, packhorse rock lobsters of both sexes move seasonally inshore and offshore as they moult and then reproduce. Large lobsters accumulate over shallow seafloor (less than 60 m depth) by October. Berried females (which must have moulted) are first found in late September and most are in berry by December (Kensler 1967). Packhorse rock lobster are considered the most fecund of all rock lobster species, producing up to two million eggs in the case of very large females (Kensler 1967). In December and January, the lobsters then move into deeper waters (up to at least 100 m), where the eggs hatch and larvae are dispersed by strong currents (Booth 2011). Their movements after this are poorly understood, although it has been suggested that they remain over deep seafloor (up to 200 m depth) until subsequent inward migration for moulting and breeding (Booth 2011).

Information on the stock structure of packhorse rock lobsters is available from studies of genetic composition and the oceanographic modelling of phyllosomae dispersal. A recent genetic analysis, based on single nucleotide polymorphisms (SNPs), concluded that the New Zealand and Australian populations are genetically homogenous despite physical separation by the Tasman Sea (Woodings et al. 2018). This contradicted an earlier preliminary analysis based on mitochondrial DNA, which indicated a genetic sub-division of Australian and New Zealand stocks, although this was based on a comparatively small sample (Brasher et al. 1992). A study using satellite-derived surface currents simulated the dispersal of phyllosomae across the Tasman Sea from Australia and concluded that only about 2% of their larvae would reach New Zealand alive (Chiswell et al. 2003). These larvae mostly arrived at the northern tip of the North Island where the New Zealand fishery is most active (Chiswell et al. 2003).

1.2 New Zealand fishery

The New Zealand PHC fishery is minor compared with the red rock lobster or koura (*Jasus edwardsii*, Fisheries New Zealand species code 'CRA') fishery, which is the most valuable inshore fishery in New Zealand. Only a few fishers actively target packhorse rock lobster, which are almost entirely taken along the north and east coasts of the North Island, overlapping with the CRA fishery in the Quota Management Areas (QMAs) CRA 1 and CRA 2 (Webber 2013) (Figure 1).

The PHC fishery entered into the Quota Management System (QMS) on 1 April 1990 and the fishery is currently managed as a single QMA (PHC 1) by Fisheries New Zealand. Initially, the Total Allowable Commercial Catch (TACC) was set at 27 tonnes. This was raised in the same year to 30.5 tonnes due to quota appeals. The TACC remained at 30.5 tonnes for just two years and was increased to 40.3 tonnes during the 1992–93 fishing year, where it has remained. Packhorse rock lobster catches have ranged from 6 to 40 tonnes per fishing year since introduction into the QMS and have been close to the TACC since 2013–14 (see Figure 2 and Table A.2). Historical landings have been estimated to be much higher (Kensler & Skrzynski 1970, Booth, 2011) (Figure 2 and Table A.1). One of the reasons the PHC TACC has remained low is that this species has never been formally assessed.

Prior to the introduction to the QMS, the PHC 1 fishery was managed using input controls, including: minimum legal size (MLS) regulations, a prohibition on taking berried females and soft-shell lobsters, making it illegal to commercially dive for or spear the species, requiring specific modification to pots to allow small lobsters to escape, requiring that lobsters are landed ashore alive, and some local area closures. All these input controls are still in place, including a tail length (TL, the straight line measurement along the underside of the tail, between the rear of the calcified bar on the first tail segment to the tip of the middle fan of the tail) MLS of 216 mm for both females and males, which is applied to both commercial and recreational catches.

Recreational fishers may gather packhorse rock lobsters by pot or hand (freediving or scuba), although these are subject to all the other input controls in place for commercial fishers. Recreational fishers may not take soft shell individuals or berried females, and it is illegal to spear them. Additionally, a daily bag limit of six rock lobsters (CRA and PHC combined) applies to recreational fishers in most QMAs (CRA 2 is the exception where the daily bag limit is three rock lobsters since 1 July 2020). The total recreational and customary catches of packhorse rock lobster are unknown but are thought to be low.

The New Zealand PHC 1 fishery was characterised by Webber (2013), who also developed a standardised catch-per-unit-effort (CPUE) time series. This analysis estimated an increasing trend in catch rate between 1991–92 and 2012–13, which was comparable to the increase in CPUE estimated for the Australian stock along the coast of NSW (New South Wales Department of Primary Industries 2017). However, there has been no formal stock assessment for the New Zealand PHC fishery, and there are no management procedures in place. Furthermore, the characterisation by Webber (2013) identified a need for more basic biological information, including: morphometric data for obtaining relationships between TL, tail width (TW) (the straight line measurement between the tips of the two primary spines on the second tail segment), CL, and weight; and tagging data for estimating growth.

1.3 Research objectives

The aims of this research were to:

- update the characterisation of the New Zealand PHC 1 fishery, including the generation of catch summaries, length frequencies (LFs), and summaries of tag-recapture observations;
- estimate morphometric relationships;
- provide the basis for a TW-based MLS for PHC by converting from the TL-based MLS;

- update and improve the existing standardised CPUE time series indexing relative abundance; and
- develop a stock assessment model for the PHC 1 fishery.

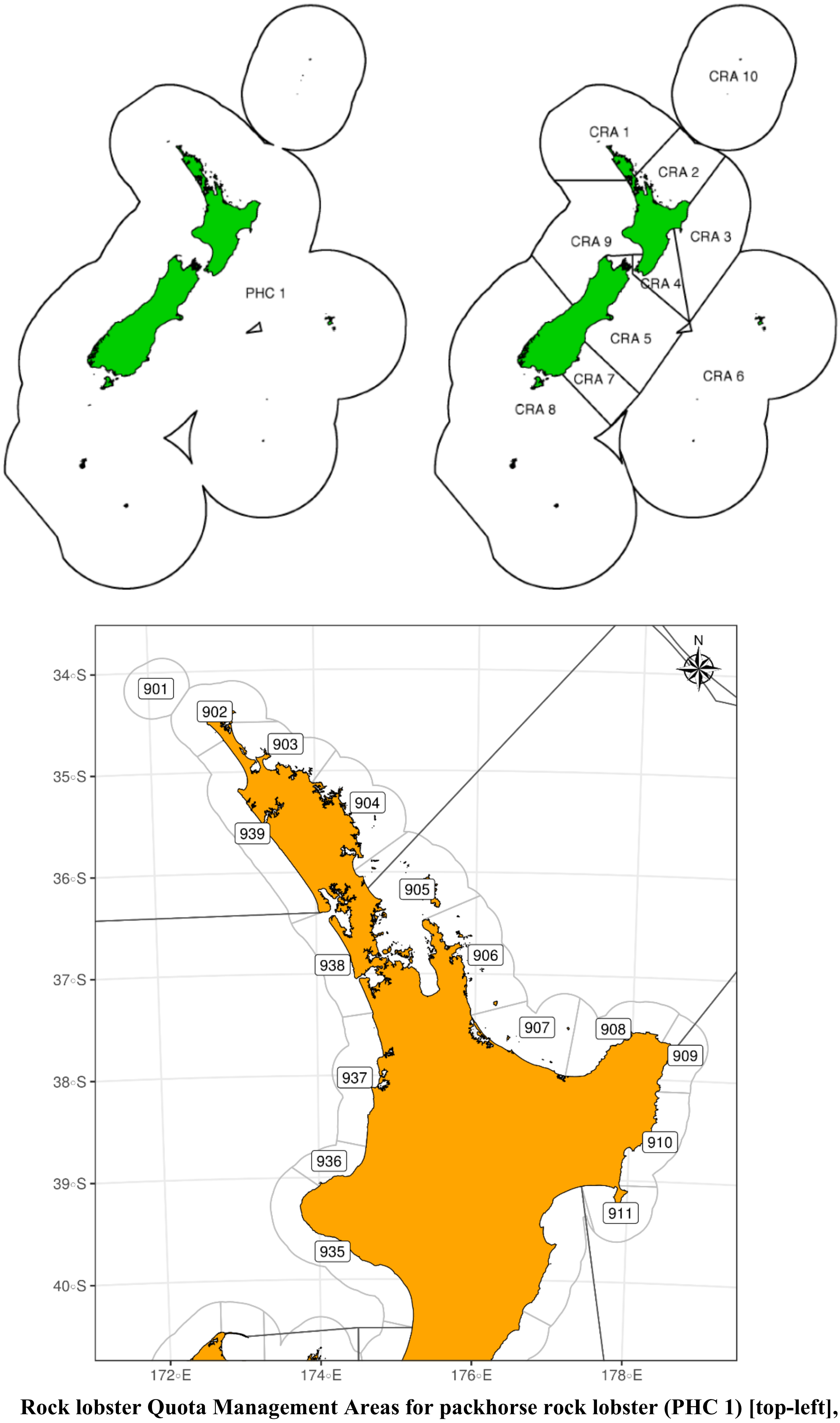

Figure 1: Rock lobster Quota Management Areas for packhorse rock lobster (PHC 1) [top-left], red rock lobster (CRA) [top-right], and rock lobster statistical areas within CRA 1 and CRA 2, which overlap with the PHC fishery [bottom].

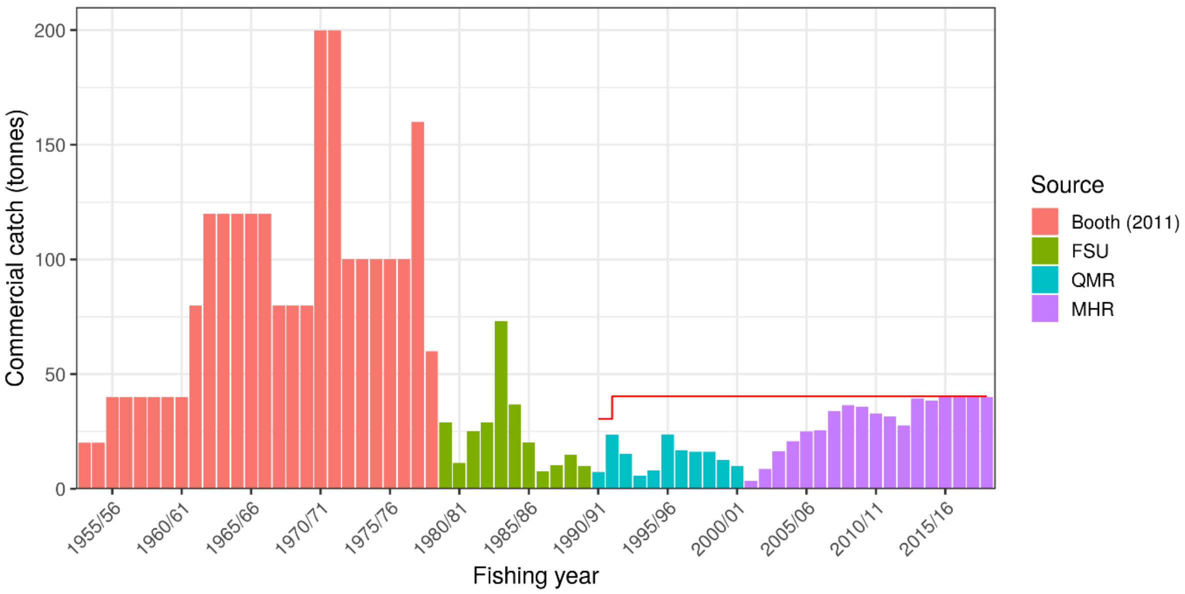

Figure 2: Packhorse rock lobster landings (tonnes) and Total Allowable Commercial Catch (TACC, tonnes) around New Zealand from 1953–54 to 2018–19. The landings for 1953–54 to 1978–79 are estimates from Booth (2011), from 1979–80 to 1989–90 are FSU data, and from 1990–91 onwards are QMR/MHR data. The annual TACC for the PHC 1 fishery is indicated by the red line.

2. MORPHOMETRICS

Morphometric data were collected by commercial fishers Nat Davey and Rochele Potter in statistical area 902 during February and November 2017 and March and April 2018. They recorded the date, sex, tail length (TL), tail width (TW), and weight of over 1700 individual packhorse rock lobsters (Table 1). Weight was measured using gyroscopically stabilised scales onboard their fishing vessel. These data were stored in a database held by FishServe. The *rlcs* observer catch sampling database also included paired measurements of carapace length (CL) and TW and these data were received August 2019 (Table 2).

This section describes morphometric relationships between TL and TW, and TW and weight. These two relationships were modelled using the data collected by Nat Davey and Rochele Potter. The relationship between TW and CL was modelled using the *rlcs* data. The units of all measurements are millimetres (mm) and weight is in kilograms (kg).

Table 1: Number of individual packhorse rock lobsters sampled in statistical area 902 by Nat Davey and Rochele Potter measured for tail length, tail width, and weight by sex and date.

Date	Female	Male	Total
11-02-2017	234	154	388
12-02-2017	236	129	365
06-03-2018	237	97	334
03-04-2018	27	11	38
06-11-2018	453	166	619
Total	1 187	5 57	1 744

Table 2: Number of individual packhorse rock lobsters measured by observer catch sampling for both tail width and carapace length, by sex and fishing year.

Fishing year	Female	Male	Total	Fishing year	Female	Male	Total
1988–89	303	358	661	2004–05	87	60	147
1989–90	2	1	3	2005–06	54	52	106
1990–91	170	320	490	2006–07	138	102	240
1991–92	380	403	783	2007–08	123	126	249
1992–93	12	16	28	2008–09	301	272	573
1993–94	21	8	29	2009–10	108	103	211
1994–95	45	52	97	2010–11	181	147	328
1995–96	37	22	59	2011–12	61	46	107
1996–97	2	4	6	2012–13	167	159	326
1997–98	5	1	6	2013–14	112	82	194
1998–99	9	4	13	2014–15	670	494	1 164
1999–00	4	0	4	2015–16	287	256	543
2000–01	19	12	31	2016–17	136	124	260
2001–02	12	10	22	2017–18	114	65	179
2002–03	36	38	74	2018–19	186	197	383
2003–04	94	68	162	2019–20	16	15	31
Total					3 892	3 617	7 509

2.1 Relationship between tail length and tail width

The relationship between TL and TW was modelled with measurement error in both TL and TW as

$$\log(TW_i) = \log(\alpha) + \beta \log\left(\mu_i^{TL}\right) + \varepsilon_i$$

where μ_i^{TL} is the expected TL from the measurement error component of the model

$$\log\left(\mu_i^{TL}\right) \sim N(\log(TL_i),\ 0.02^2)$$

and

$$\varepsilon_s \sim \text{student}(\nu, 0,\ \sigma^2)$$

or any other suitable distribution (e.g., the normal distribution). The student-t distribution was used to minimise the impacts of outliers. This approach meant that records where the wrong sex may have been recorded did not need to be removed, hence eliminating the need for a subjective decision. A log-log relationship was used to better model the variance such that variance is higher at larger sizes, a pattern that seems apparent in the data (Figure 3). The choice of 0.02 as the standard deviation for the measurement error model was somewhat subjective (but was thought to be reasonable) which equates to a standard deviation of approximately 5 mm about the TL in natural space. Bayesian inference was done using the *R* package *brms* (Bürkner 2017, R Core Team 2019) (Table 3, Figure 3).

The current MLS used for packhorse rock lobster is 216 mm TL for both sexes. The model predicted that this equates to a median estimate of the MLS of 89.1 mm TW for females and 83.5 mm TW for males (Figure 4). In practice, any TW-based MLS close to these values would be suitable (e.g., 90 mm for females and 84 mm for males, which gives the same absolute difference between the sexes as the current 60 mm and 54 mm TW MLS for male and female red rock lobsters).

Table 3: Parameter summary for the packhorse rock lobster tail length to tail width model. The parameter α is the intercept, β is the slope, σ is the standard deviation, and ν is the degrees of freedom of the student-t distribution.

Parameter	Sex	Mean	SD	2.5%	Median	97.5%
$\log(\alpha)$	Female	-1.560	0.066	-1.690	-1.560	-1.428
$\log(\alpha)$ offset	Male	0.622	0.102	0.420	0.622	0.821
β	Female	1.126	0.012	1.102	1.126	1.150
β offset	Male	-0.128	0.019	-0.165	-0.128	-0.091
σ	Female	-3.407	0.030	-3.467	-3.407	-3.348
σ offset	Male	-0.360	0.061	-0.379	-0.359	-0.242
ν	–	4.285	0.631	3.243	4.212	5.682

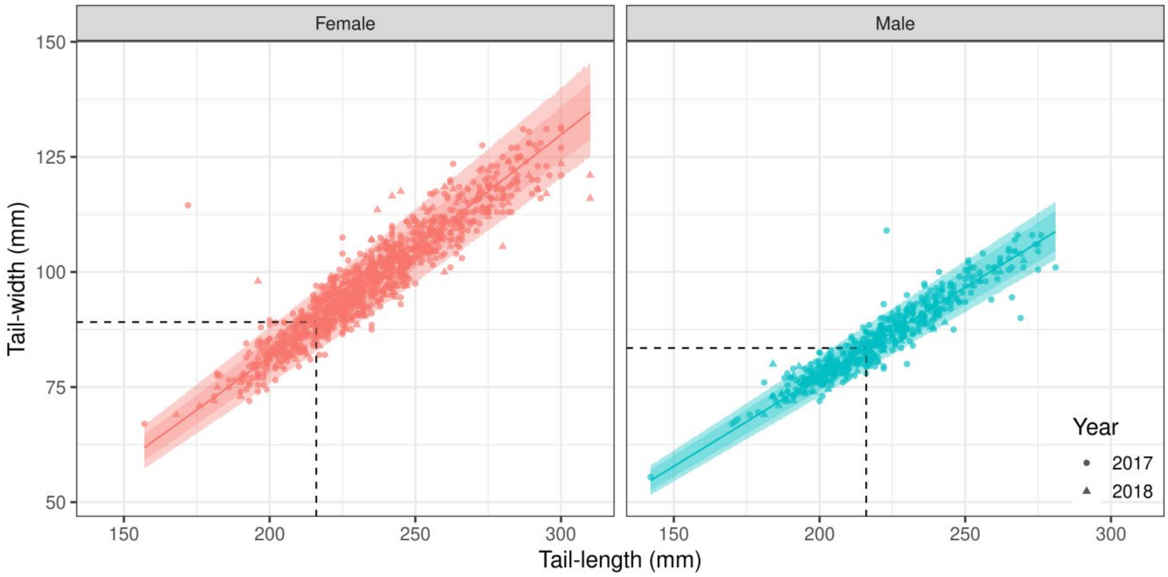

Figure 3: Relationship between tail length and tail width for packhorse rock lobster showing: the observations (points), the posterior mean (solid line), posterior distribution (inner darker shaded region), and posterior predictive distribution (outer lighter shaded region), by sex. The dashed vertical line is the current MLS of 216 mm tail length and the dashed horizontal lines are the predictions of MLS in tail width.

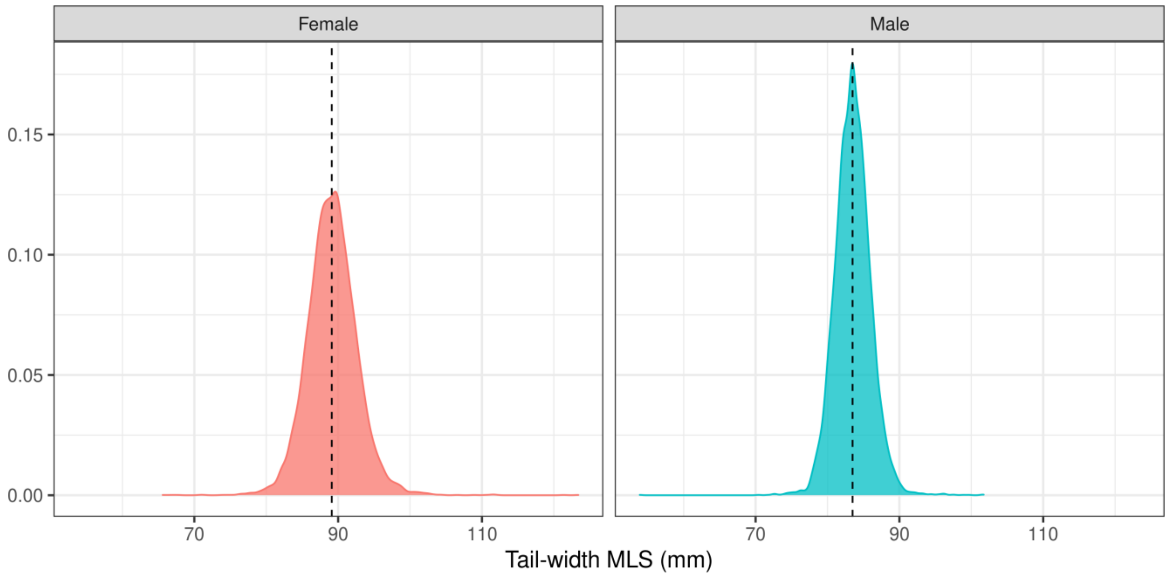

Figure 4: Prediction of the tail width minimum legal size (MLS) for packhorse rock lobster showing the variability about this prediction.

2.2 Relationship between tail width and weight

The relationship between length (or in this case *TW*) and weight (W) is commonly modelled using the simple length-weight relationship, usually written as

$$W_i = \alpha TW_i^{\beta}$$

or in log-space

$$\log(W_i) = \log(\alpha) + \beta \log(TW_i)$$

Here, the relationships between TW and weight is modelled with measurement error as

$$\log(W_i) = \log(\alpha) + \beta \log(\mu_i^{TW}) + \varepsilon_i$$

where

$$\log(\mu_i^{TW}) \sim N(\log(TW_i),\ 0.02^2)$$

and

$$\varepsilon_i \sim \text{student}(\nu, 0,\ \sigma^2)$$

Because the student-t distribution was used, records where the wrong sex may have been recorded did not need to be removed. Bayesian inference was implemented using the *R* package *brms*. The estimated parameter values are shown in Table 4, and the posterior relationships between TW and weight are shown in Figure 5.

Table 4: Parameter summary for the length-weight model for packhorse rock lobster. The parameter α is the intercept, β is the slope, σ is the standard deviation, and ν is the degrees of freedom of the student-t distribution.

Parameter	Sex	Mean	SD	2.5%	Median	97.5%
α	Female	0.03933	0.0039	0.03235	0.03912	0.04741
α	Male	0.00023	0.0005	0.00015	0.00023	0.00034
β	Female	2.340	0.0213	2.298	2.340	2.382
β	Male	3.577	0.0460	3.487	3.577	3.667
σ	Female	0.0520	0.0028	0.0466	0.0520	0.0575
σ	Male	0.0491	0.0046	0.0403	0.0491	0.0583
ν	–	3.175	0.337	2.572	3.151	3.893

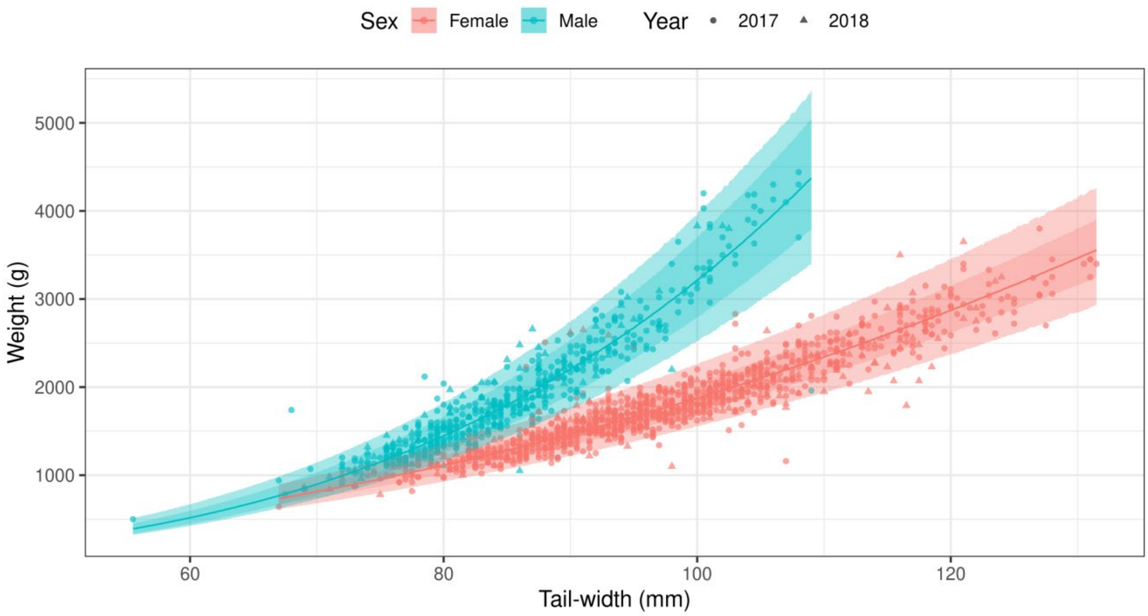

Figure 5: Relationship between tail width (mm) and weight (g) for packhorse rock, showing: the observations by sex and survey year (points), the posterior mean by sex (solid line), posterior distribution by sex (inner darker shaded region), and posterior predictive distribution by sex (outer lighter shaded region).

2.3 Relationship between tail width and carapace length

Carapace length was the standard measurement recorded at the beginning of the commercial sampling programme for both PHC and CRA (see Section 3.2). Since 1993–94, paired TW and CL measurements were taken from most individuals. Because TW is the standard measurement used for the CRA stock assessments, it was decided to adopt the same standard for PHC. This decision necessitated converting historical CL measurements to TW using a morphometric relationship.

An initial exploration indicated that females generally had a greater TW for a given CL, and that this relationship was non-linear for both sexes (Figure 6). This was confirmed by comparison of model Akaike Information Criterion (AIC; Akaike 1974) obtained when fitting linear or non-linear models to the CL-TW relationship by sex (AIC for the non-linear model was 111 and 71 units lower for females and males, respectively).

The relationship between TW and CL was modelled as

$$TW \sim N(\mu^{TW}, \sigma^2)$$

where

$$\mu^{TW} = \alpha\, CL^{\beta}$$

Model fits to observations were reasonably good for both sexes, with minimal evidence for a trend in residuals with increasing CL (Figure 7). The parameter estimates for the male and female models are shown in Table 5.

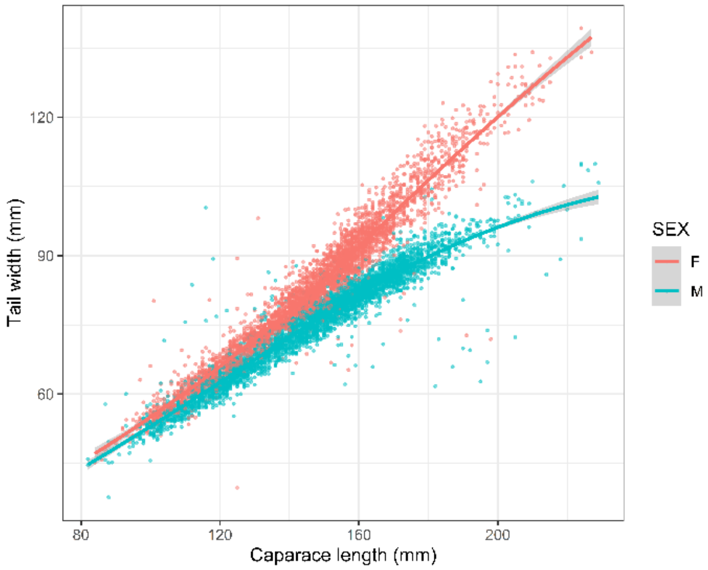

Figure 6: Relationship between carapace length and tail width for packhorse rock lobsters by sex (source: *rlcs* database). The lines are loess smoothers for males and females, and the associated shaded area is within 1 standard error of this smoother.

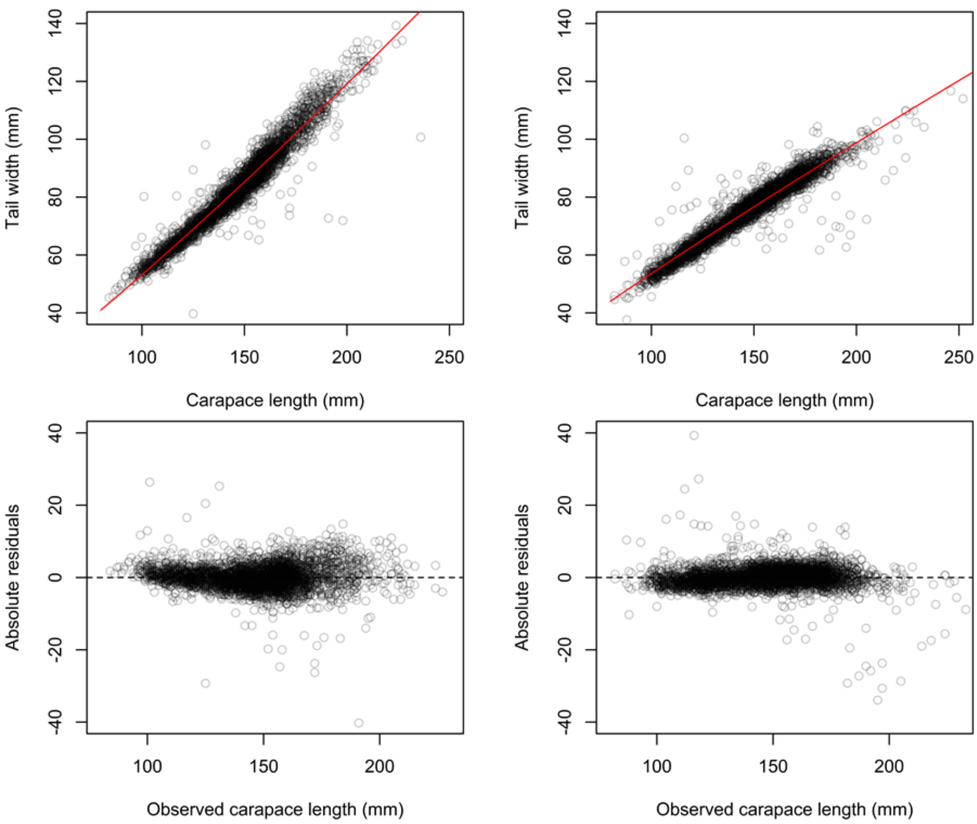

Figure 7: Fits of non-linear models (red lines) for predicting tail width from carapace length (top) and model residuals with increasing observed carapace length (bottom) for female (left) and male (right) packhorse rock lobsters.

Table 5: Parameter summary for the packhorse rock lobster carapace length to tail width model. The parameter α is the intercept, and β is the slope.

Parameter	Sex	Mean	Standard Error
α	Female	0.250	0.00645
α	Male	0.922	0.01929
β	Female	1.164	0.00512
β	Male	0.882	0.00416

3. CHARACTERISATION

Commercial catch and effort data, observer catch sampling data, and tag-recapture data were analysed. Catch and effort data were obtained from Fisheries New Zealand in August 2019 (report log 12695). Fisher logbook data were provided by FishServe in September 2019.

3.1 Distribution of catches

Since the introduction of the QMS, the annual commercial landings of packhorse rock lobster have been low (no more than about 40 tonnes per fishing year) compared with published landings in the 1960s and 1970s (annual estimates range from 40 to 200 tonnes) (Booth 2011), but have been close to the current TACC of 40.3 tonnes in all years since 2013–14 (Figure 2, Table A.1 and Table A.2). There was a reasonable correspondence between the catch reported to the Quota Management Report (QMR) / Monthly |Harvest Return (MHR) system and the sum of the 'L' landings from the bottom section of the Catch Effort and Landing Return (CELR) form, except during the 1990–91 fishing year where the sum of the landings is much lower than the QMR value (Table A.3).

The monthly distribution of packhorse rock lobster landings is shown in Figure 8. This species was mainly landed during the last half of the April–March fishing year (except for April in some fishing years), with a distinct drop in catches during winter months (May–August). Increased catch during April in some years does not appear to be from holding pots carried over from the previous year, since the landings to destination codes 'Q' and 'P' are not high enough at the end of the previous fishing years (Figure 9 and Table 6).

Fisheries New Zealand defines 43 rock lobster statistical areas to which fishers allocate their catch to during a fishing event (statistical areas 901 to 943, Figure 1). In the past, packhorse rock lobster was mainly caught in statistical areas 901 and 902, but catches have increased in statistical areas 904 to 905 in recent years, primarily driven by the CRA-target fishery (Figure 10). The number of pots lifted (i.e., fishing effort) tended to be higher in statistical areas within CRA 2 compared with CRA 1, particularly during the most recent years (Table A.6), implying lower CPUE for CRA bycatch, which predominates in CRA 2.

Since 1990–91, approximately half of the packhorse rock lobster catch was bycatch of the CRA fishery, with the other half taken by the PHC-target fishery (Table A.4). The total fishing effort and number of vessels catching packhorse rock lobster have remained relatively constant within CRA 1 (Table A.5 and Table A.6) but have gradually increased in CRA 2 since 1990–91.

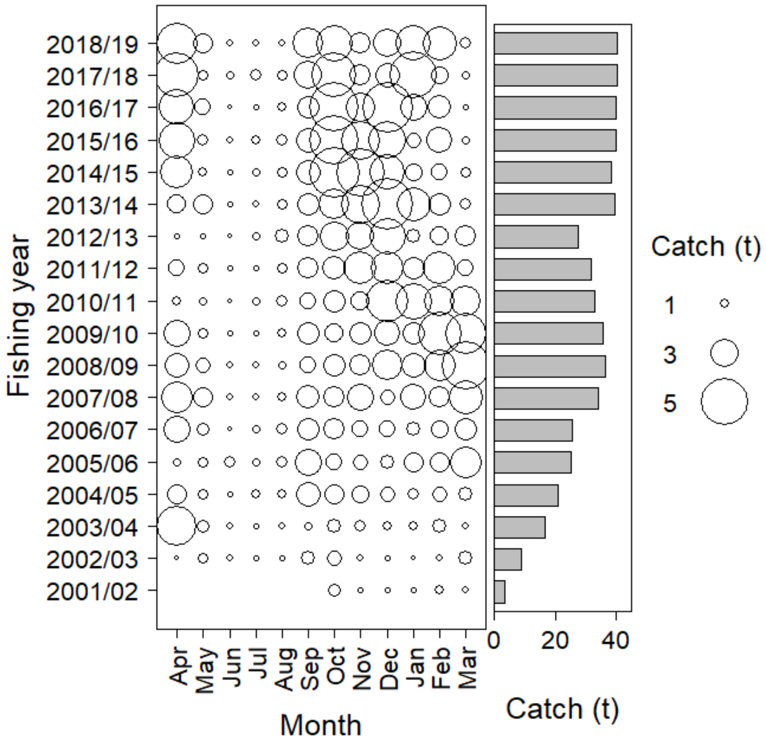

Figure 8: Monthly distribution of packhorse rock lobster (PHC 1) catches (tonnes) by fishing year (source: MHR). Circle areas [left] are proportional to the total catch across all fishing years; horizontal bars [right] show the total catch of a particular fishing year.

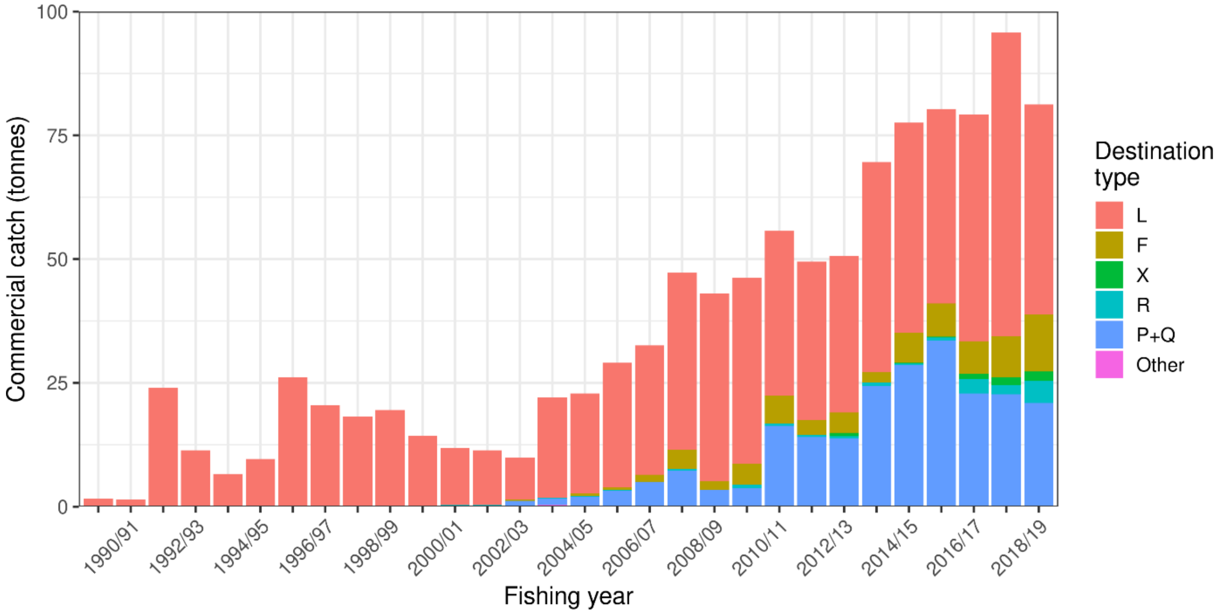

Figure 9: Packhorse rock lobster (PHC 1) tonnages by destination type from 1990–91 to 2018–19. The destination types are: L = landed in New Zealand (to LFR), F = section 111 recreational catch, X = QMS returned to sea (except Schedule 6A), P = holding receptacle in water, Q = holding receptacle on land, R = retained on board, and Other = a destination type other than those specified.

Table 6: Packhorse rock lobster (PHC 1) tonnages for the destination types P, Q, and R by month from 1997–98 to 2018–19 for all pot lifts targeting PHC (source: CELR). The table begins in 1996–97, since this was the first year that destination types P (holding receptacle in water), Q (holding receptacle on land), or R (retained on board) were reported.

Fishing												Month	
year	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Total
1996–97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.04
1997–98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.04
1998–99	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.00	0.19
1999–00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2000–01	0.00	0.00	0.00	0.05	0.18	0.10	0.00	0.00	0.00	0.01	0.01	0.01	0.35
2001–02	0.00	0.01	0.04	0.01	0.00	0.00	0.00	0.01	0.01	0.03	0.13	0.07	0.32
2002–03	0.00	0.00	0.00	0.01	0.02	0.08	0.04	0.00	0.01	0.00	0.10	0.11	0.38
2003–04	0.83	0.00	0.02	0.02	0.07	0.02	0.18	0.43	0.23	0.10	0.01	0.00	1.91
2004–05	0.01	0.01	0.01	0.15	0.15	0.31	0.15	0.21	0.11	0.17	0.03	0.01	1.32
2005–06	0.11	0.02	0.01	0.12	0.33	0.56	0.90	0.46	0.08	0.04	0.25	0.05	2.93
2006–07	0.00	0.02	0.06	0.20	0.37	0.83	0.61	0.65	0.46	0.64	0.58	0.29	4.73
2007–08	0.39	0.20	0.07	0.15	0.33	0.67	1.14	1.31	0.96	0.49	0.50	0.42	6.63
2008–09	0.36	0.15	0.02	0.07	0.11	0.48	0.69	0.34	0.20	0.27	0.12	0.14	2.95
2009–10	0.03	0.03	0.01	0.05	0.16	0.79	0.83	0.61	0.73	0.54	0.10	0.23	4.10
2010–11	0.51	0.05	0.03	0.08	0.26	0.62	0.88	1.53	4.87	3.41	2.23	2.20	16.64
2011–12	0.36	0.18	0.04	0.04	0.32	0.95	1.52	2.93	2.51	1.37	2.53	1.05	13.80
2012–13	0.08	0.09	0.04	0.14	0.29	0.85	1.16	1.76	3.83	0.88	1.61	1.59	12.31
2013–14	0.43	1.61	0.10	0.18	0.21	1.04	3.30	4.49	4.77	3.73	3.15	0.97	23.98
2014–15	2.47	0.06	0.05	0.19	0.51	1.61	5.03	5.79	5.43	1.48	1.12	4.02	27.75
2015–16	1.36	0.83	0.04	0.47	0.29	1.42	6.89	4.40	6.17	1.74	3.85	5.01	32.47
2016–17	0.40	0.03	0.00	0.08	0.22	1.52	5.64	3.14	6.65	1.20	4.82	0.52	24.22
2017–18	0.91	0.58	0.10	0.14	0.45	2.42	3.23	1.62	3.79	5.13	1.65	3.11	23.11
2018–19	2.57	1.14	0.06	0.04	0.12	2.41	3.12	2.05	3.25	5.46	1.44	3.01	24.66
Total	10.82	5.11	0.70	2.19	4.37	16.69	35.32	31.74	44.11	26.74	24.26	22.78	224.81

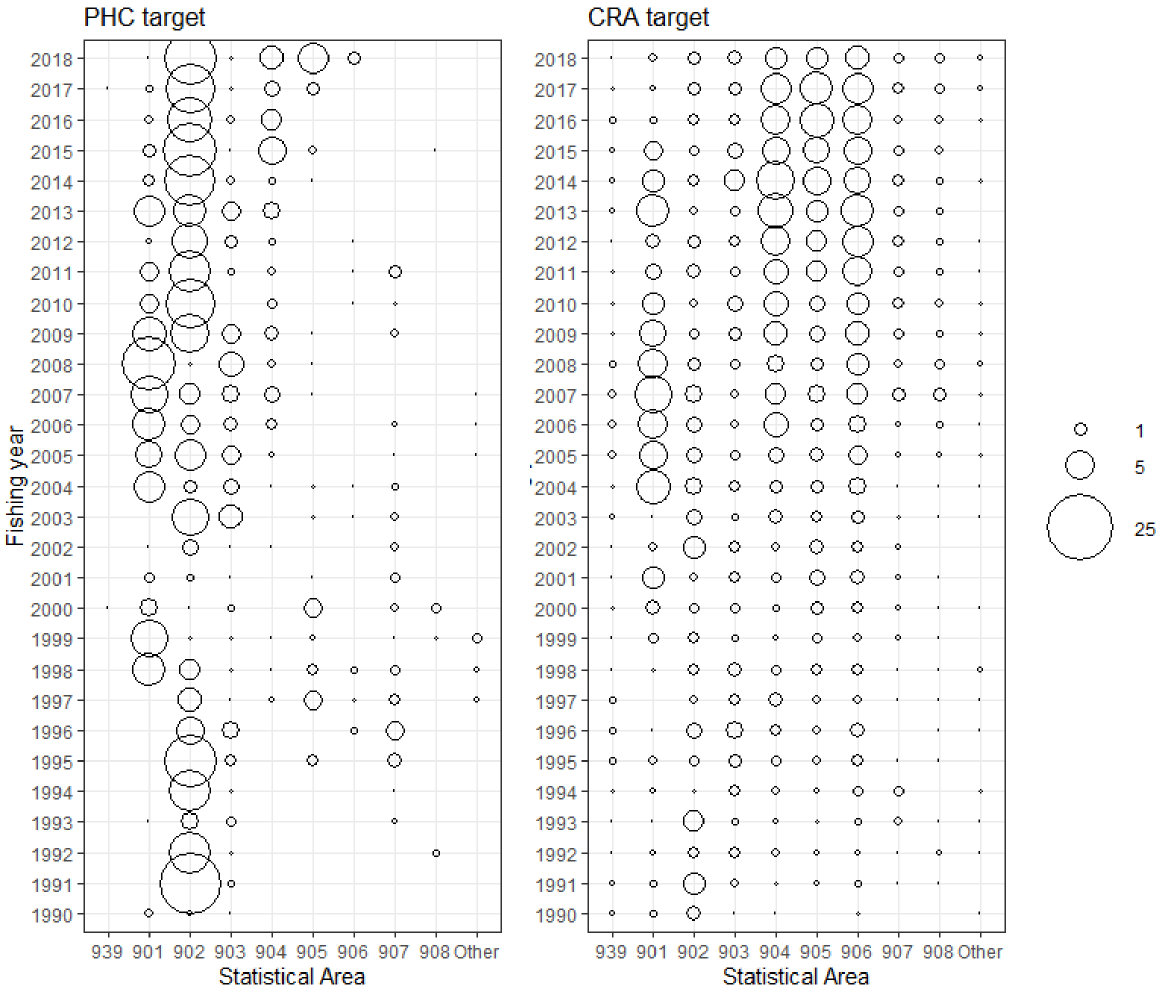

Figure 10: Distribution of packhorse rock lobster (PHC 1) catch by statistical area, fishing year (labelled with first year of the pair) and target species (PHC = packhorse rock lobster, CRA = red rock lobster) (source: estimated catch from CELR). Circle areas are proportional to the catch in tonnes.

3.2 Size composition and maturity

From 1990–91 to 1992–93, a special permit was granted for a commercial fisher to run an exploratory survey for packhorse rock lobsters in deep water off Cape Reinga. During this survey, observers carried out a catch sampling programme. To obtain these data and any other LF data collected by observers since (or prior), all data from pot lifts targeting PHC were requested from the *rlcs* database between 1973–74 and 2018–19 (received from Fisheries New Zealand in August 2019). Length-frequency data were summarised as LF plots by year and statistical area for all sample types. Note that almost all (over 99%) PHC measurements from 1990–91 to 1992–93 were obtained from the dedicated packhorse rock lobster exploratory catch sampling programme, and measurements in all other years were from the red rock lobster catch sampling programme only, which were most likely taken from vessels targeting CRA.

The numbers and mean lengths of packhorse rock lobsters recorded in the *rlcs* database are summarised in Table 7. Approximately equal numbers of males and females were sampled throughout the time series. The resulting LFs using TW measurements and estimates (with all records converted from CL measurements if TW was missing) combined are shown separately for males and females in Figure B.1 to Figure B.8. Relatively large numbers were sampled during the 1990–91 to 1992–93 exploratory surveys in statistical areas 901 and 902. For both sexes, a greater proportion of larger individuals (over 90 mm TW for males and over 100 mm TW for females) were sampled in 1992–93 relative to the two preceding years (Figure B.1 and Figure B.2). However, these larger individuals were almost entirely captured in statistical area 902 (Figure B.3 and Figure B.4), indicating that this may have resulted from changes in the spatial distribution of catch sampling by fishing year. Note that under 1% of measurements in those years were by the CRA-targeted catch sampling programme.

Table 7: Numbers of measured packhorse rock lobsters by measurement type, sex, year, and statistical area (source: *rlcs*). This table excludes individuals for which the carapace length measurement was anomalously small (under 40 mm) and individuals obtained using non-standard sampling methods. Note the gap in the time series of fishing years in which no measurements were recorded (grey shading).

Fishing year	Carapace length measurements		Tail width measurements	
	Female	Male	Female	Male
1975–76	81	49	0	0
1976–77	3	1	0	0
1989–90	1	2	1	2
1990–91	1 584	1 493	397	380
1991–92	2 016	2 011	12	11
1992–93	984	904	15	15
1993–94	10	21	10	21
1994–95	52	41	49	41
1995–96	24	37	22	37
1996–97	4	2	4	2
1997–98	1	5	11	14
1998–99	4	9	9	10
1999–00	4	4	25	20
2000–01	12	19	41	43
2001–02	10	12	53	61
2002–03	39	38	46	43
2003–04	68	92	69	95
2004–05	67	96	66	116
2005–06	62	76	62	76
2006–07	88	111	94	112
2007–08	242	250	255	264
2008–09	169	189	168	189
2009–10	167	172	167	172
2010–11	74	106	73	105
2011–12	83	94	84	94
2012–13	124	130	125	132
2013–14	80	116	80	116
2014–15	491	666	492	667
2015–16	251	283	252	285
2016–17	134	149	134	150
2017–18	94	133	95	133
2018–19	172	168	172	167
Total	7 191	7 479	3 083	3 573

Statistical area	Carapace length measurements		Tail width measurements	
	Female	Male	Female	Male
901	3 608	3 522	419	409
902	1 916	1 936	882	1 006
903	126	144	130	146
904	179	193	191	206
905	28	27	34	30
906	418	463	459	516
907	93	95	96	96
908	203	250	232	270
909	242	349	238	369
910	260	352	260	354
911	53	69	54	73
912	12	23	15	23
913	3	2	3	2
914	1	1	1	1
915	4	9	5	10
927	1	1	1	1
928	1	1	1	1
934	1	3	2	3
939	43	39	61	57
Total	7 191	7 479	3 083	3 573

Length-frequency plots are also shown for males and females from 2005–06 to 2018–19, the next period with consistent sampling after 1992–93 (all samples from CRA catch sampling programme). The size distribution of lobsters sampled in these years decreased with increasing distance from the main breeding grounds in the Far North. Few males exceeded 70 mm TW in statistical areas 909 to 912, whereas approximately half of males were greater than 70 mm in statistical areas 903 to 908, and hardly any were smaller than this in statistical areas 901 and 902 (Figure B.5). A similar pattern was observed for females, although some relatively large individuals were also observed in statistical area 904 (Figure B.6). Based on a visual inspection of Figure B.6, the relative proportion of females with setae also decreased with increasing distance from the main breeding grounds, and these were almost entirely absent in statistical areas 909 to 912.

Taken together, these observations are consistent with the movement of individuals towards the main breeding grounds in the Far North with advancing size and maturity stage, as previously hypothesised by Booth (2011). The LF sample size was too small for assessing potential changes in size composition through time (Figure B.7 and Figure B.8), as required by length-based stock assessment. The 2014–15 fishing year had the greatest sample size in recent years, and the LF plots for both sexes in this year suggest the presence of some relatively strong cohorts (two LF modes for males and three for females), however potential confounding with spatial effects on size composition was not explored.

The percentage of sampled females with setae decreased from a high of 63% in statistical area 902 to below 10% in combined statistical areas 908 to 912 (Table 8). Very few berried females were sampled outside of statistical area 902 (17.5% in statistical area 902, 5.6% in statistical area 905, and 2.1% or less in all other areas). The percentage of females in berry was between 25 and 30% in November and December, and much lower in all other months (Table 9).

Table 8: Numbers of female packhorse rock lobsters by reproductive status and statistical area (source: *rlcs*).

Statistical	Female reproductive status					
area	No setae	With setae	Berried	Total	% with setae	% berried
901	1 956	1 649	19	3 624	45.5	0.5
902	454	1 478	410	2 342	63.1	17.5
903	94	36	1	131	27.5	0.8
904	87	104	4	195	53.3	2.1
905	22	12	2	36	33.3	5.6
906	330	129	4	463	27.9	0.9
907	77	19	0	96	19.8	0.0
908	209	23	1	233	9.9	0.4
909	236	2	0	238	0.8	0.0
910	258	2	0	260	0.8	0.0
911	53	1	1	55	1.8	1.8
912	14	1	0	15	6.7	0.0
913	3	0	0	3	–	–
914	0	1	0	1	–	–
915	4	1	0	5	–	–
928	1	0	0	1	–	–
934	0	2	0	2	–	–
939	51	13	1	65	20.0	1.5

Table 9: Numbers of female packhorse rock lobsters by reproductive status and fishing month (source: *rlcs*).

	Female reproductive status					
Month	No setae	With setae	Berried	Total	% with setae	% berried
Apr	1 035	1 093	0	2 128	51.4	0.0
May	489	446	0	935	47.7	0.0
Jun	121	1	0	122	0.8	0.0
Jul	204	25	1	230	10.9	0.4
Aug	258	67	1	326	20.6	0.3
Sep	100	101	0	201	50.2	0.0
Oct	211	139	10	360	38.6	2.8
Nov	227	532	319	1078	49.4	29.6
Dec	147	115	87	349	33.0	24.9
Jan	74	18	0	92	19.6	0.0
Feb	53	112	8	173	64.7	4.6
Mar	930	824	17	1 771	46.5	1.0

Using a subset of females captured in statistical area 902 in November and December (the area and months in which females were more likely to be in berry), the size at which 50% of female PHCs had setae and were in berry was approximately 85 mm TW and around 93–95 mm TW, respectively (Figure 11). This is consistent with previous research by Booth (1984a), which concluded that female packhorse rock lobster start breeding at about 10 mm CL larger than the size at which setae develop.

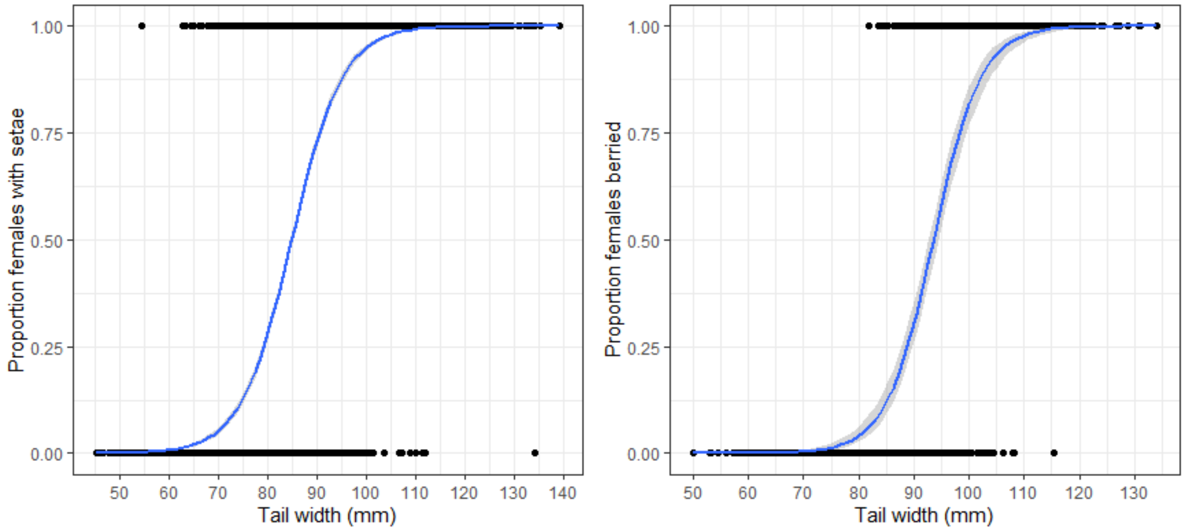

Figure 11: Proportion of female packhorse rock lobsters (PHC) in statistical area 902 during November or December with setae [left], and proportion of females in berry [right] (source: *rlcs*).

3.3 Tag recapture growth information

Tag release and recapture information were extracted from the Fisheries New Zealand *tag* database in August 2019 (report log 12518) and supplemented with additional recaptures provided by the New Zealand Rock Lobster Industry Council (NZ RLIC) up until 28/09/2019. Of the 2795 PHC lobsters tagged from 1976–77 to 2018–19, 97% were released from 2014–15 (Table 10), and only 62 have subsequently been recaptured. This number excludes two recaptures in 2019 for which no TW measurement was recorded, and six recaptures in 1979 for which implausible sizes were reported relative to release given the short time periods at liberty (e.g., 25 mm carapace length increment after a single day).

All packhorse rock lobster recaptures were released in fishing years 2014–15 or 2015–16, of which seven out of 62 were recaptured within the year of release (Table 11). Approximately half of the recaptures (32 out of 60 for which a statistical area was assigned, Table 12) were in a different statistical area to the location of release. Notably, all movements between statistical areas were in the direction of North Cape, consistent with the hypothesised counter-current migration up to the Far North as these lobsters grow (Booth 2011). Of the areas with more than 10 releases, recapture rates appear to be greater from statistical areas 906 to 909, compared with statistical areas 902 and 903 (compare Table 10 and Table 12).

There are too few tag recaptures to be useful for informing growth increment-at-size and the available recovery size range does not include fully mature individuals. The information from the small number of available recaptures is consistent with annualised TW growth of 5 mm or greater across the range of vulnerable sizes (Figure 12). However, the range of TW available to inform growth (60–85 mm for males and 55–105 mm for females) is below the maximum TW typically captured in the statistical area 902 spawning fishery (100 mm TW for males and 120 mm TW for females).

Table 10: Numbers of packhorse rock lobster tag releases by fishing year [left] and statistical area [right]. Note gaps in the time series of fishing years in which there were no tag releases (grey shading).

Fishing year	Tag releases
1976–77	4
1977–78	0
1978–79	2
1979–80	27
1980–81	6
1997–98	2
1998–99	0
1999–00	0
2000–01	11
2001–02	3
2002–03	24
2014–15	858
2015–16	1 138
2016–17	0
2017–18	0
2018–19	720

Statistical area	Tag releases
901	3
902	1 550
903	38
904	4
905	23
906	79
907	32
908	59
909	539
910	35
911	4
928	2
935	1
938	3
939	33

Table 11: Matrix of packhorse rock lobster tag recaptures by fishing year of release and recapture. Recaptures in the same fishing year of release are shaded grey.

	Tag recaptures by fishing year				
Fishing year of tag release	2014–15	2015–16	2016–17	2017–18	2018–19
2014–15	7	33	9	2	3
2015–16	–	0	4	0	4

Table 12: Matrix of packhorse rock lobster tag recaptures by statistical area of release and recapture. This table excludes two recaptures that were located outside the bounds of statistical areas based on the reported coordinates. Recaptures in the same statistical area of release are shaded grey.

Statistical	Tag recaptures by statistical area of recapture											
area of tag release	939	901	902	903	904	905	906	907	908	909	910	All
939	0	0	0	0	0	0	0	0	0	0	0	0
901	0	0	0	0	0	0	0	0	0	0	0	0
902	0	0	8	0	0	0	0	0	0	0	0	8
903	0	0	0	0	0	0	0	0	0	0	0	0
904	0	0	0	0	0	0	0	0	0	0	0	0
905	0	0	0	0	0	0	0	0	0	0	0	0
906	0	0	0	0	0	0	8	0	0	0	0	8
907	0	0	0	0	0	0	1	11	0	0	0	12
908	0	0	0	0	0	0	0	0	0	0	0	0
909	0	0	0	0	0	0	3	2	26	1	0	32
910	0	0	0	0	0	0	0	0	0	0	0	0
All	0	0	8	0	0	0	12	13	26	1	0	–

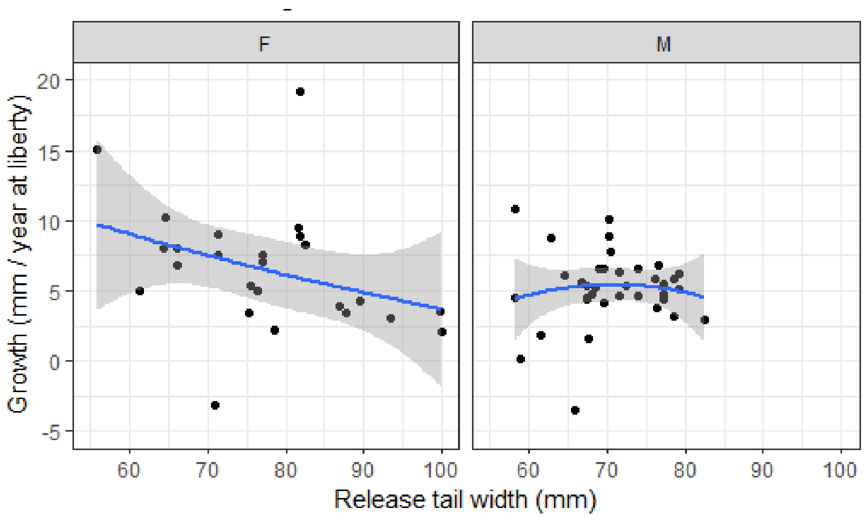

Figure 12: Annualised tail width growth increment (mm/year at liberty) of packhorse rock lobsters by tail width at release and sex, in all fishing years until 2018–19.

4. CPUE ANALYSIS

4.1 Data preparation

In the previous packhorse rock lobster characterisation by Webber (2013), catch and effort data from 1 April 1979 to 30 June 1989 were obtained from the Fisheries Statistics Unit (FSU) database. FSU data were not used at that time for the calculation of CPUE indices because this data set appeared to be deficient in records where the catch is zero (biasing the catch rates upwards). This issue is discussed further by Bentley et al. (2005). For this reason, there was no attempt to use the FSU data to develop CPUE indices for this report.

Catch and effort information for the rock lobster potting method was, up to the end of 2018–19, reported on the Catch Effort Landing Return (CELR) form, which reports daily totals of the number of pots lifted and the estimated catch of the top species unless the fisher has changed statistical area or target species (in which case a single record may represent only part of a day). The verified landed green weight that is obtained at the end of the trip is also reported on the bottom part of the form. CELR data from 1 July 1989 to 31 March 2019 were obtained from the Electronic Data Warehouse (EDW) (report log 12695). Electronic reporting of lobster catch/effort data commenced in the 2019–20 fishing year.

The CELR data used for the standardised CPUE estimates were subjected to error screening (Bentley et al. 2005). Records with error rating of at least 2 for the field's statistical area, pots lifted, estimated catch, and landings were excluded from this analysis. These error ratings were first described by Bentley et al. (2005).

Legally captured lobsters specified as recreational catch from commercial vessels or high grading practices during fishing are included in the catches used in the CPUE calculation. This is done to ensure comparability with the period before these practices became widespread. Consequently, landings to the destination codes 'F' (section 111 recreational catch) and 'X' (QMS returned to sea) were added to the catches used in the CPUE analysis. Furthermore, the use of holding pots and onshore holding facilities breaks the link between the landing information at the bottom of the form with the estimated catches recorded in the effort section of the form. Therefore, the 'B4' algorithm (Bentley et al. 2005) which relies on linking the two parts of the form, was not considered appropriate; a lot of the PHC landings were to destination codes 'P' (holding receptacle in water), 'Q' (holding receptacle on land), or 'R' (retained on board), particularly in the more recent years (Table 13, Figure 9). The 'F' algorithm (documented by Starr 2021), which calculates an annual factor used to scale estimated catches to landings for every vessel, was developed to address this issue. The 'F2-LFX' algorithm (Starr 2021) was therefore used to convert the PHC estimated catches into landings to give the corrected catch for each year/month/area/vessel/target stratum.

Table 13: Packhorse rock lobster (PHC 1) tonnages by destination type from 1990–91 to 2018–19. The destination types are: L = landed in New Zealand (to LFR), F = section 111 recreational catch, X = QMS returned to sea (except 6A), P = holding receptacle in water, Q = holding receptacle on land, R = retained on board, and Other = a destination type other than those specified.

	Destination type							
Fishing year	L	F	X	P	Q	R	Other	Total
1989–90	1.36	–	–	–	–	–	0.00	1.36
1990–91	1.39	–	–	–	–	–	0.00	1.39
1991–92	24.06	–	–	–	–	0.00	0.00	24.06
1992–93	11.08	–	–	–	–	0.00	0.00	11.08
1993–94	5.90	–	–	–	–	0.00	0.00	5.90
1994–95	7.80	–	–	–	–	0.00	0.00	7.80
1995–96	24.35	–	–	–	–	0.00	0.04	24.40
1996–97	19.00	–	–	0.03	–	0.01	0.00	19.03
1997–98	14.60	–	–	–	–	0.00	0.10	14.70
1998–99	15.97	–	–	–	–	0.19	0.05	16.20
1999–00	12.70	–	–	–	–	0.00	0.01	12.72
2000–01	9.88	–	–	–	–	0.35	0.02	10.24
2001–02	8.82	0.00	–	–	0.01	0.32	0.00	9.15
2002–03	8.57	0.24	–	0.25	0.14	–	0.26	9.46
2003–04	16.43	0.20	–	1.78	0.09	0.05	0.48	19.02
2004–05	21.40	0.42	–	1.08	0.10	0.14	0.46	23.59
2005–06	25.49	0.48	–	2.03	0.74	0.16	0.50	29.40
2006–07	26.05	0.61	–	4.53	0.10	0.09	0.61	31.99
2007–08	34.80	0.90	–	6.04	0.26	0.33	0.91	43.23
2008–09	36.65	0.61	–	2.85	0.06	0.04	0.64	40.83
2009–10	36.51	0.82	–	3.35	0.09	0.66	0.84	42.26
2010–11	33.16	1.04	0.03	16.04	0.20	0.40	1.05	51.92
2011–12	31.67	0.86	0.01	13.13	0.24	0.44	0.86	47.21
2012–13	27.89	0.93	0.06	10.98	0.86	0.47	0.94	42.12
2013–14	39.38	0.61	0.02	15.34	8.04	0.60	0.67	64.67
2014–15	39.19	1.46	0.09	21.45	6.02	0.28	1.49	69.99
2015–16	39.65	2.08	0.06	25.39	6.36	0.72	2.19	76.43
2016–17	39.94	2.08	1.10	20.21	1.06	2.95	2.11	69.45
2017–18	40.14	2.79	1.39	20.27	0.93	1.91	2.88	70.31
2018–19	39.36	2.31	1.80	19.88	0.27	4.50	2.35	70.48
Total	731.54	18.42	4.56	184.63	25.55	14.64	19.47	998.80

Core statistical areas were identified in the characterisation as areas which could be used to monitor the abundance of packhorse rock lobster, given that these areas accounted for a significant proportion of the landed lobsters. Only small amounts of packhorse rock lobster were caught outside statistical areas 901 to 907 (CRA 1 and CRA 2, Figure 10, Table A.4), so the data used in the CPUE analysis were restricted to these areas (Figure 13).

Records without a vessel key were dropped, as were records for vessel 4548 (a coded value) because of a high number of outliers from this vessel. The data used in the CPUE analysis were further restricted to those vessels that participated with some consistency in the PHC fishery. These core vessels were identified by specifying two variables: the number of trips that determined a qualifying year, and the number of qualifying years that each vessel participated in the fishery. The core fleet was selected by choosing the variable values that resulted in the fewest vessels, while maintaining the highest proportion of the landed catch (bottom of the CELR form). The variables were set at three trips per qualifying year for three years. This reduced the number of vessels in the dataset by over 70% while reducing the amount of landed catch by 14% (Figure 14).

Much of the effort that caught PHC targeted CRA (Figure 15). However, catch rates tended to be higher when targeting PHC than when targeting CRA (Figure 16). This is because fishers tend to use larger pots and longer soak times when targeting packhorse rock lobsters (D. Sykes, pers. comm.), requiring the use of a target species variable in the CPUE models.

Zero catches are rare in a target fishery as well as being implicitly included in CPUE standardisation models when the data are aggregated. However, in bycatch fisheries, zero catches are frequent and, even when data are aggregated, there may still be strata with zero catch but with positive effort (i.e., a vessel targeting CRA may be fishing in a fishing year/month/statistical area stratum but not catch any PHC). Not including zero catches will positively bias catch rates and may result in a CPUE index that is not proportional to the abundance of the fish stock. For this reason, all qualifying effort, including unsuccessful effort, was included into this CPUE standardisation analysis.

Due to a lack of estimated and landed catch (caused by dropping data that were flagged with an error, not from a core vessel, or not within one of the core statistical areas), the data for the 1990–91 fishing year were dropped from this analysis. Qualifying records for use in the CPUE analysis were defined as those fishing events by core vessels, in the core statistical areas during the fishing years 1991–92 to 2018–19, in all months (Figure 17). These data were aggregated into strata by year, month, vessel, statistical area, and target species. Only lobster caught using the rock lobster potting method were included in this analysis. Figure 18 shows the corrected catch after removing records during error checking, the application of the F algorithm, and restricting the analysis to the core statistical areas and the core vessels.

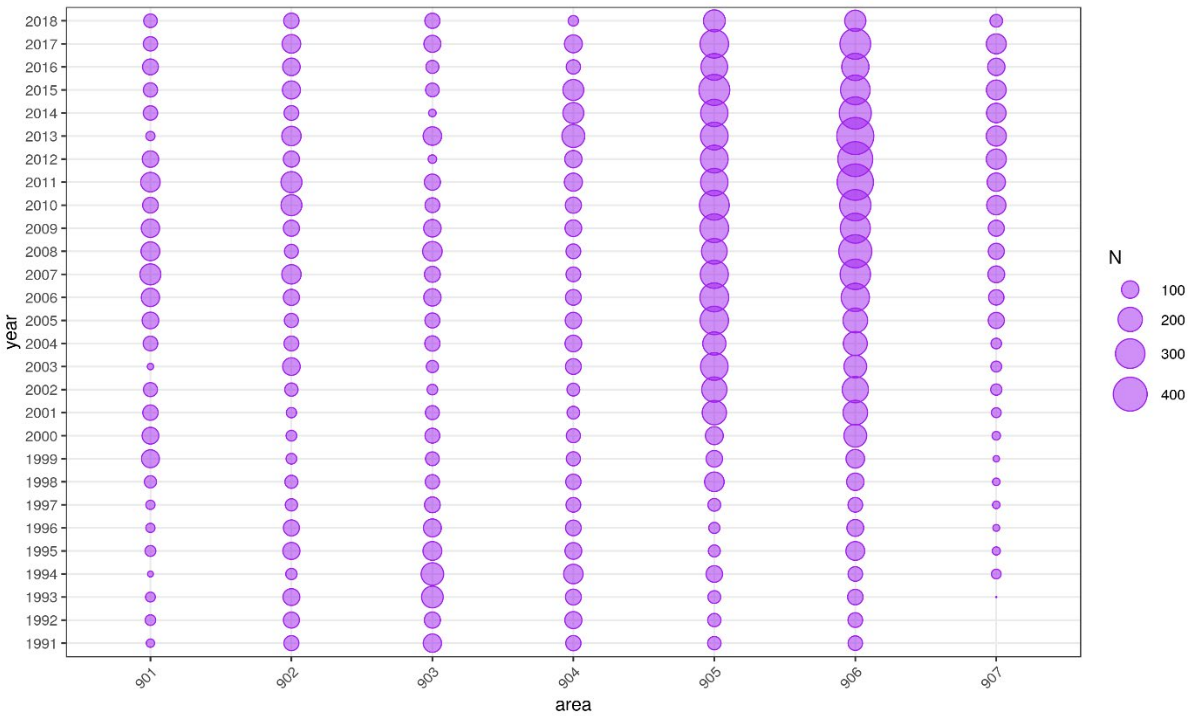

Figure 13: Distribution of packhorse rock lobster records by statistical area and fishing year (labelled with first year of the pair). Circle areas are proportional to the total number of records across all fishing years. Source: corrected catch of core vessels/areas from CELR.

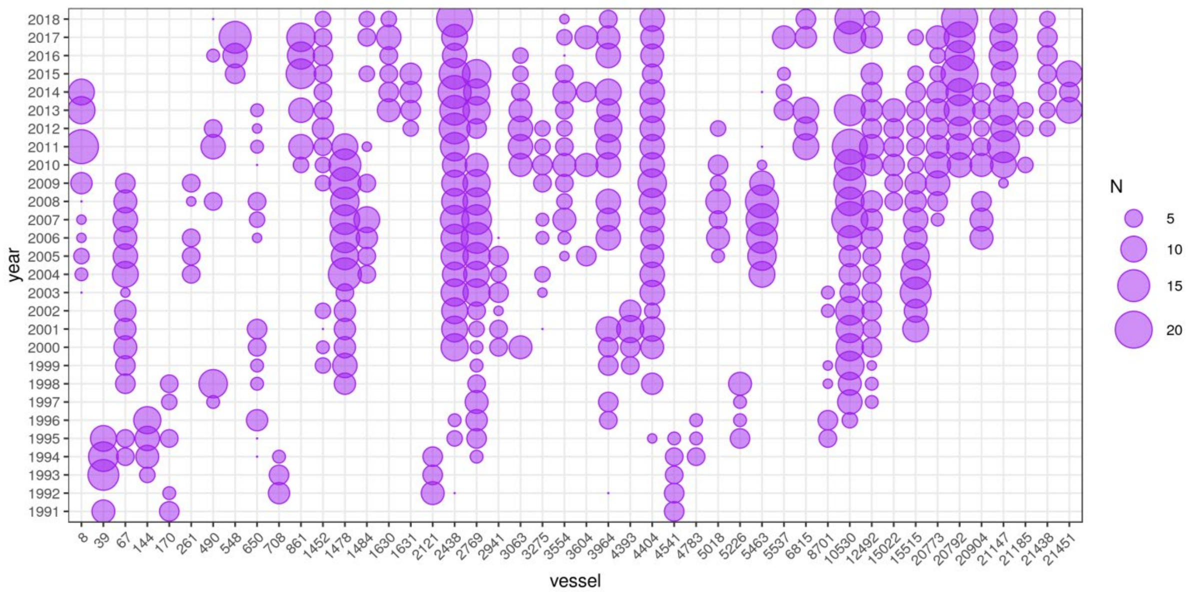

Figure 14: Distribution of packhorse rock lobster records by core vessels and fishing year (labelled with first year of the pair). Circle areas are proportional to the total number of records across all fishing years. Source: corrected catch of core vessels and areas from CELR.

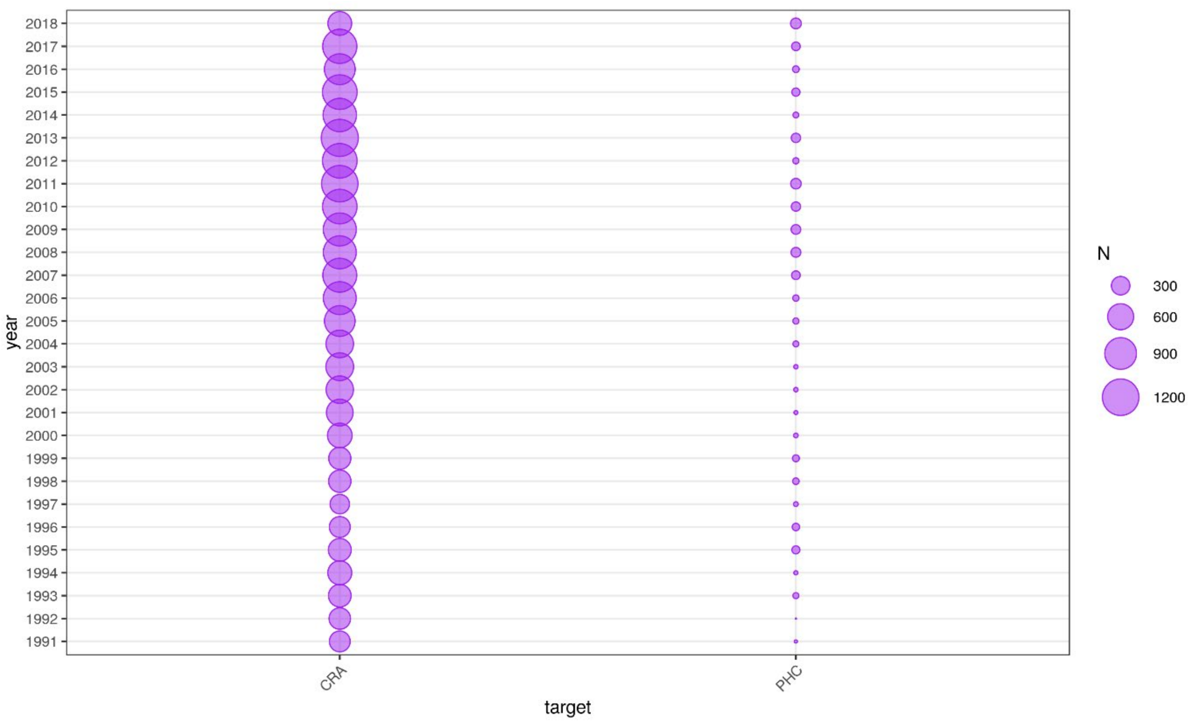

Figure 15: Distribution of packhorse rock lobster records by target species and fishing year (labelled with first year of the pair). Circle areas are proportional to the total number of records across all fishing years. Source: corrected catch of core vessels and areas from CELR.

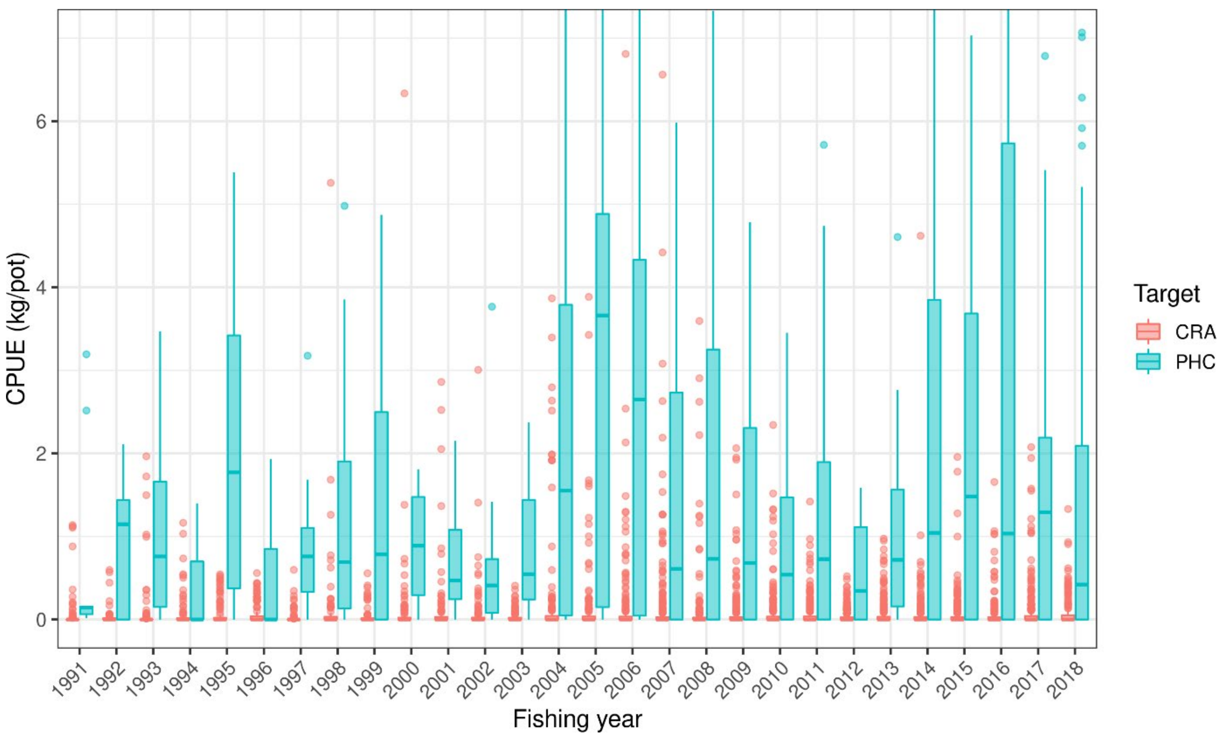

Figure 16: Raw catch rate of packhorse rock lobster by target species and fishing year (labelled with first year of the pair). Source: corrected catch of core vessels and areas from CELR.

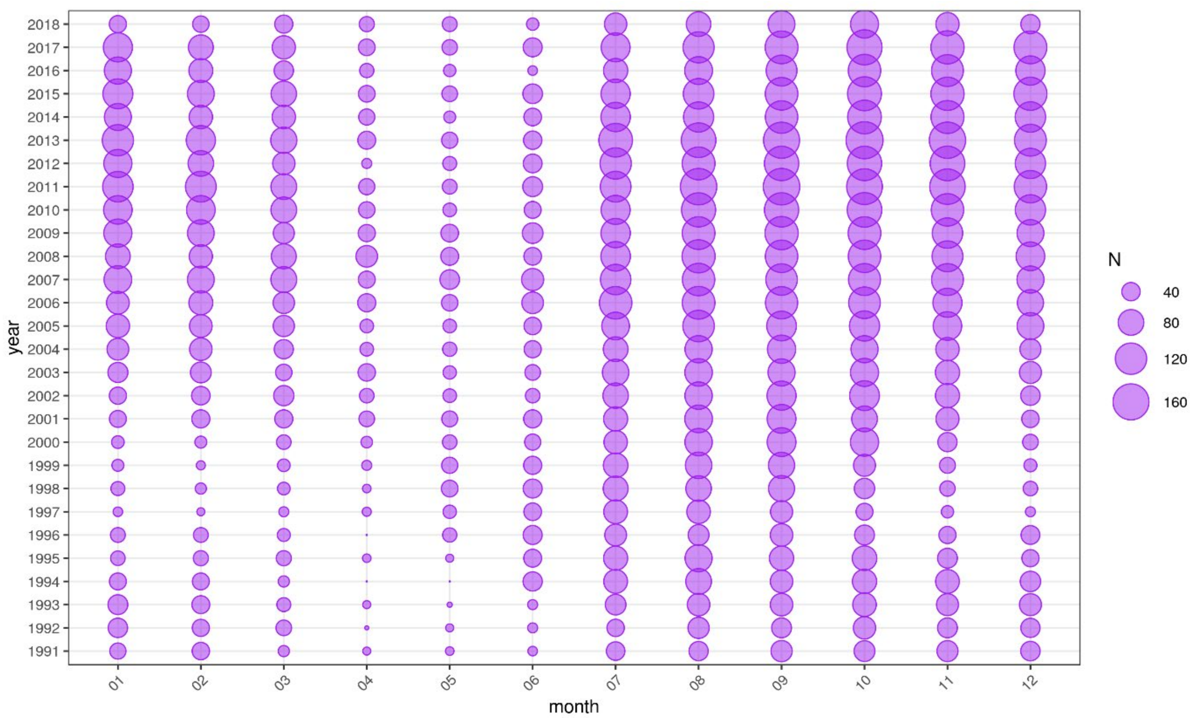

Figure 17: Distribution of packhorse rock lobster records by month and fishing year (labelled with first year of the pair). Circle areas are proportional to the total number of records across all fishing years. Source: corrected catch of core vessels and areas from CELR.

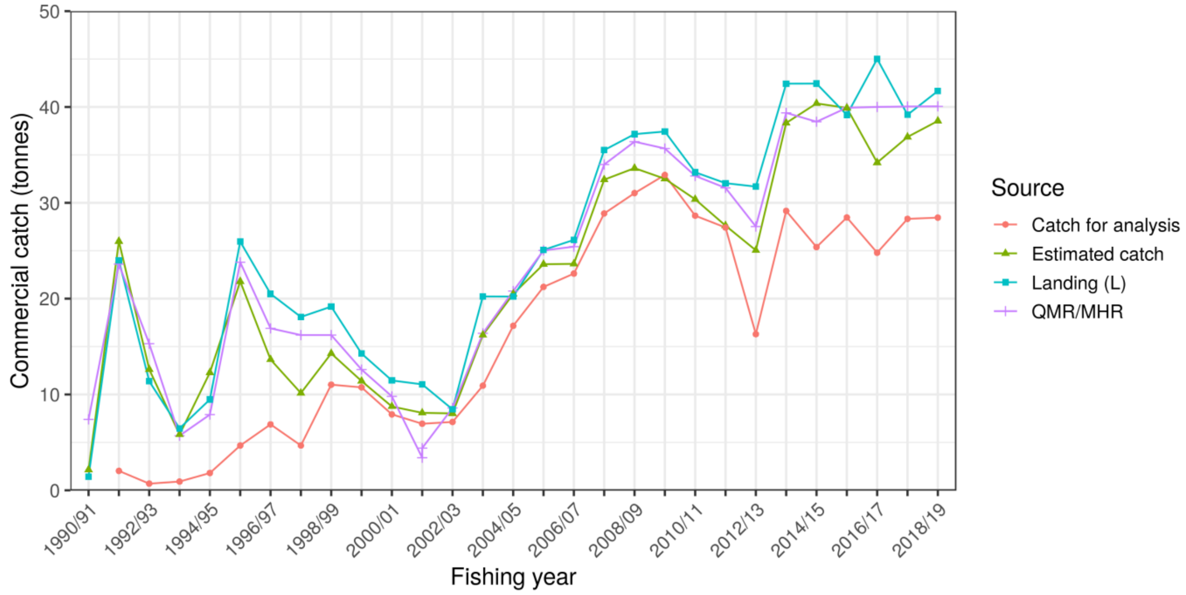

Figure 18: Packhorse rock lobster catch (tonnes) by fishing year including the QMR/MHR reported catches (QMR/MHR), the landings from the bottom of CELR forms aggregated by fishing year (Landing (L)), the estimated catch of PHC from the CELR forms (Estimated catch), and the catch used in the CPUE analysis (Catch for analysis, after filtering for core vessels in core statistical areas).

4.2 Analysis

Unstandardised and standardised indices of annual CPUE were calculated. The unstandardised CPUE (G_y, kg/potlift) in year y is the geometric mean of the ratio of catch (C_i, kg) to number of pots lifted (E_i) for each month-area-vessel-target combination (i):

$$G_y = \exp\left(\frac{\sum_{i=1}^{n_y} \log(Y_i)}{n_y}\right)$$

where

$$Y_i = \frac{C_i}{E_i}$$

and n_y is the number of month-area-vessel-target combinations i in year y. The geometric mean has the same lognormal distributional assumptions as the standardised CPUE but does not take into account changes in the seasonal and spatial distribution of fishing effort or any other explanatory variables.

The standardised CPUE is derived from a generalised linear model (GLM). CPUE was modelled as the estimated catch weight (kg) of PHC per potlift ($\boldsymbol{Y}$):

$$\boldsymbol{Y} = \boldsymbol{X\beta} + \boldsymbol{\varepsilon}$$

where $\boldsymbol{X\beta}$ is the linear predictor composed of a matrix of independent variables ($\boldsymbol{X}$) and vector of estimated coefficients ($\boldsymbol{\beta}$), and $\boldsymbol{\varepsilon}$ is the error term vector. Fishing year was always forced as the first explanatory variable. Other variables offered included: month, vessel, target species, and statistical area. Early exploratory models trialled moon phase (as a four or eight phase factor or continuous variable) and the average sea surface temperature (SST) associated with each statistical area for each year and month, but these were dropped because they did not have sufficient explanatory power.

Initially, separate binomial and lognormal frequentist GLMs were developed (i.e., using the *glm* function in R software). For the binomial models, the dependent variable was a binary set to 1 for records which had associated packhorse rock lobster catch and 0 for records with no reported catch of this species. The lognormal models excluded strata where the dependent variable (CPUE) was zero because the logarithm of zero is undefined. Models were developed using the full data set or a subset of the data set containing only fishing events that targeted CRA (i.e., fishing events targeting PHC were dropped). The GLMs were applied using a stepwise multiple regression procedure, selecting explanatory variables until the improvement in model r^2 was less than 0.01.

Vessel was always selected as the most important explanatory variable, followed by target species (in those model runs that included PHC-target fishing events), and then month. When vessel was offered, statistical area did not meet our criteria to enter the model. However, when vessel was not offered, statistical area took its place as the second most important explanatory variable, followed by month. The order of importance of explanatory variables was the same in all binomial (Table 14) and lognormal (Table 15) model runs.

Table 14: Summary of the final binomial model for packhorse rock lobsters using corrected catch (restricted to core vessels) divided by the number of pots lifted (i.e., catch per pot) as the dependent variable. Explanatory variables (terms) are listed in order of their acceptance into the model (fishing year was forced as the first variable). DF is the degrees of freedom, r^2 is the proportion of the deviance explained at each step, and Final indicates whether each term was included in the final model.

		Events targeting PHC or CRA		Events targeting CRA only	
Term	DF	r^2	Final	r^2	Final
None	0	0.000	*	0.000	*
Fishing year	27	0.011	*	0.013	*
Vessel	45	0.064	*	0.070	*
Target species	1	0.091	*	–	–
Month	11	0.102	*	0.081	*
Statistical area	6	0.104		0.084	

Table 15: Summary of the final lognormal model for packhorse rock lobsters using corrected catch (restricted to core vessels) divided by the number of pots lifted (i.e., catch per pot) as the dependent variable. Explanatory variables (terms) are listed in order of their acceptance into the model (fishing year was forced as the first variable). DF is the degrees of freedom, r^2 is the proportion of the deviance explained at each step, and Final indicates whether each term was included in the final model.

		Events targeting PHC or CRA		Events targeting CRA only	
Term	DF	r^2	Final	r^2	Final
None	0	0.000	*	0.000	*
Fishing year	27	0.045	*	0.035	*
Vessel	45	0.620	*	0.597	*
Target species	1	0.724	*	–	–
Month	11	0.750	*	0.643	*
Statistical area	6	0.755		0.651	

Following the advice of the Rock Lobster Working Group (RLWG), the CPUE analysis that only included fishing events targeting red rock lobster was chosen for further model development, which included approximately half of the reported catch of packhorse rock lobster since the introduction of the QMS (Figure 10). This was justified by the targeted packhorse rock lobster fishery being operated by few vessels compared to that part of the CRA-target fishery which regularly reported packhorse rock lobster catches. Furthermore, vessels targeting packhorse rock lobster tended to focus on spawning aggregations making their catch rates more likely to exhibit hyperstability.

A Bayesian generalised linear model (GLM) was used to estimate the CPUE series using the *R* package *brms*. Compared with standardisations done using maximum likelihood, Bayesian GLMs better represent parameter uncertainty. The CPUE model assumed a hurdle-lognormal distribution and included fishing year, month, and vessel coefficients for both the hurdle and lognormal components. Doing it this way avoids the post-hoc processing required when using the delta-lognormal method to combine binomial and lognormal indices (Vignaux 1994).

A lognormal hurdle model (i.e., the combination of a binomial and lognormal distribution) was used. Alternative positive catch distributions were also tested, including the gamma, Frechet, and Weibull, but the leave one out information criterion (LOO IC; Vehtari et al. 2017) identified the lognormal as providing the best fit to the data (Table 16). The Frechet distribution, also known as the inverse Weibull, was a close second (the Frechet distribution is a special case of the extreme value distribution and worth considering in future CPUE modelling).

Table 16: Comparison of the LOO IC for different distributional assumptions. LOO IC is analogous to AIC in that a lower value is better.

Distribution	ELPD difference	SE difference	LOO IC	SE LOO IC
Lognormal	0	0	-6118	222
Frechet	-105	30	-5908	228
Gamma	-307	45	-5504	249
Weibull	-375	43	-5368	239

The updated CPUE standardisation estimated an increasing trend in catch rate for PHC 1 from 1991–92 to 2018–19 (Table 17, Figure 19). The recent rate of increase in CPUE is comparable in scale to the increase in catch rate of the New South Wales fishery in Australia over a similar time period. For example, a fishery-independent index of spawner abundance increased by approximately 5 times between 2004–05 and 2016–17 (see figure A3.5 of New South Wales Department of Primary Industries 2017), and there was an approximate 3-fold increase in raw CPUE since a nadir in catch rate in the early-1990s (see figure A3.2 of New South Wales Department of Primary Industries 2017).

Two Bayesian CPUE standardisations were done as sensitivities to this model. These included (1) a model where statistical area was used as an explanatory variable instead of vessel; and (2) another model where the full data set was used (i.e., including data for the vessels targeting PHC), with target species included as an explanatory variable. The model that included PHC-target fishing events produced a very similar CPUE index to the CRA-target only run (Figure 20). The leave one out information criterion can only be used to compare models when the data set is the same in both models. However, choosing either model would not influence stock assessment outcomes in any meaningful way. The model that included statistical area rather than vessel has the same general trend as the chosen model, but the CPUE was lower from 2010–11 to 2018–19 (Figure 21). However, the LOO IC preferred the model that included vessel as an explanatory variable, as was the case for the AIC in the frequentist models.

Table 17: Unstandardised (geometric mean) CPUE and standardised CPUE (kg/potlift) for packhorse rock lobster (PHC) from 1991–92 to 2018–19. CELR data held by Fisheries New Zealand were used in this analysis, using the 'F2' algorithm corrected for 'LFX' destination code landings (see text for definition), constrained to vessels with at least five years in the fishery and events targeting CRA only (i.e., events targeting PHC were excluded). This series was estimated using a vessel explanatory variable.

Fishing year	Unstandardised	Standardised	SE
1991–92	0.0130	0.0029	0.0015
1992–93	0.0086	0.0050	0.0022
1993–94	0.0074	0.0039	0.0017
1994–95	0.0156	0.0071	0.0026
1995–96	0.0264	0.0107	0.0035
1996–97	0.0432	0.0217	0.0073
1997–98	0.0160	0.0161	0.0057
1998–99	0.0287	0.0223	0.0066
1999–00	0.0144	0.0188	0.0060
2000–01	0.0230	0.0276	0.0073
2001–02	0.0229	0.0304	0.0080
2002–03	0.0193	0.0192	0.0055
2003–04	0.0164	0.0199	0.0053
2004–05	0.0371	0.0337	0.0082
2005–06	0.0265	0.0255	0.0062
2006–07	0.0275	0.0303	0.0073
2007–08	0.0336	0.0367	0.0088
2008–09	0.0200	0.0251	0.0062
2009–10	0.0284	0.0267	0.0065
2010–11	0.0255	0.0440	0.0101
2011–12	0.0269	0.0359	0.0080
2012–13	0.0176	0.0342	0.0082
2013–14	0.0237	0.0427	0.0095
2014–15	0.0211	0.0383	0.0089
2015–16	0.0227	0.0316	0.0080
2016–17	0.0234	0.0330	0.0088
2017–18	0.0316	0.0511	0.0123
2018–19	0.0410	0.0559	0.0155

Figure 19: Unstandardised (geometric mean) CPUE and standardised CPUE for packhorse rock lobster (PHC 1) from 1991–92 to 2018–19. Note both series in this plot have been rescaled to have a geometric mean of 1. The shaded region represents the 25 and 75% credible intervals.

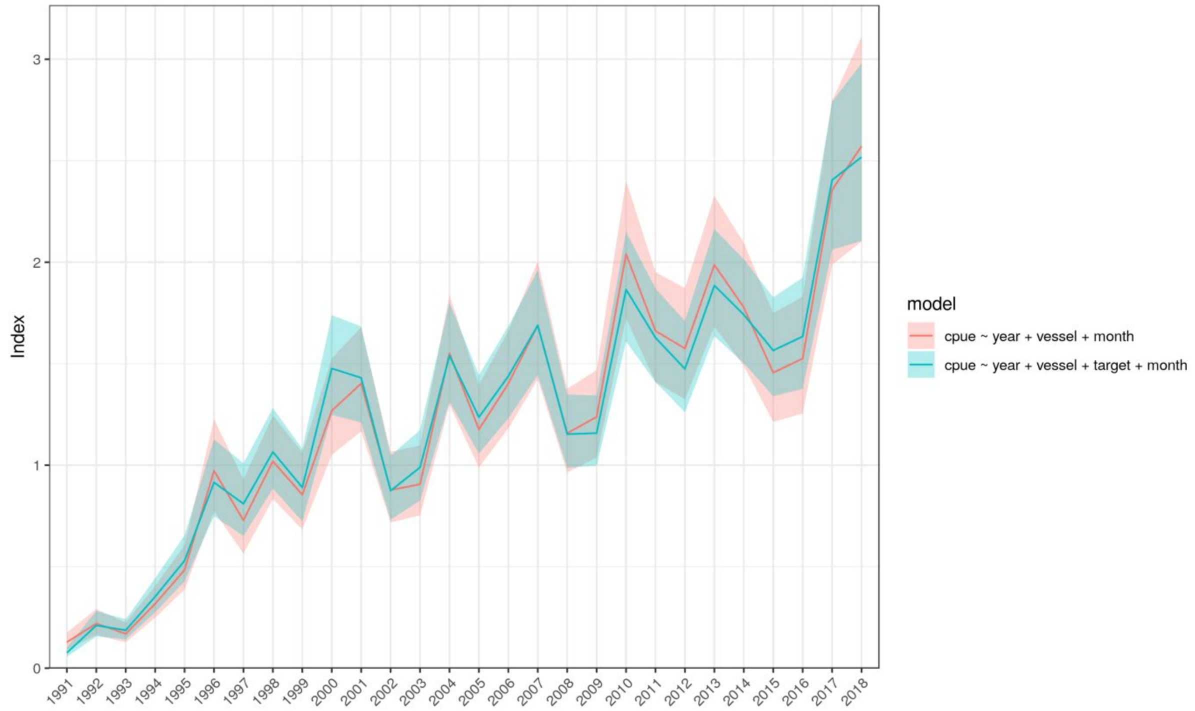

Figure 20: Standardised CPUE (kg/potlift) of packhorse rock lobster (PHC 1) from 1991–92 to 2018–19 for the chosen model structure (year + vessel + month) including only CRA-target events and the model that includes fishing events that target PHC and includes a target species explanatory variable (year + vessel + target + month).

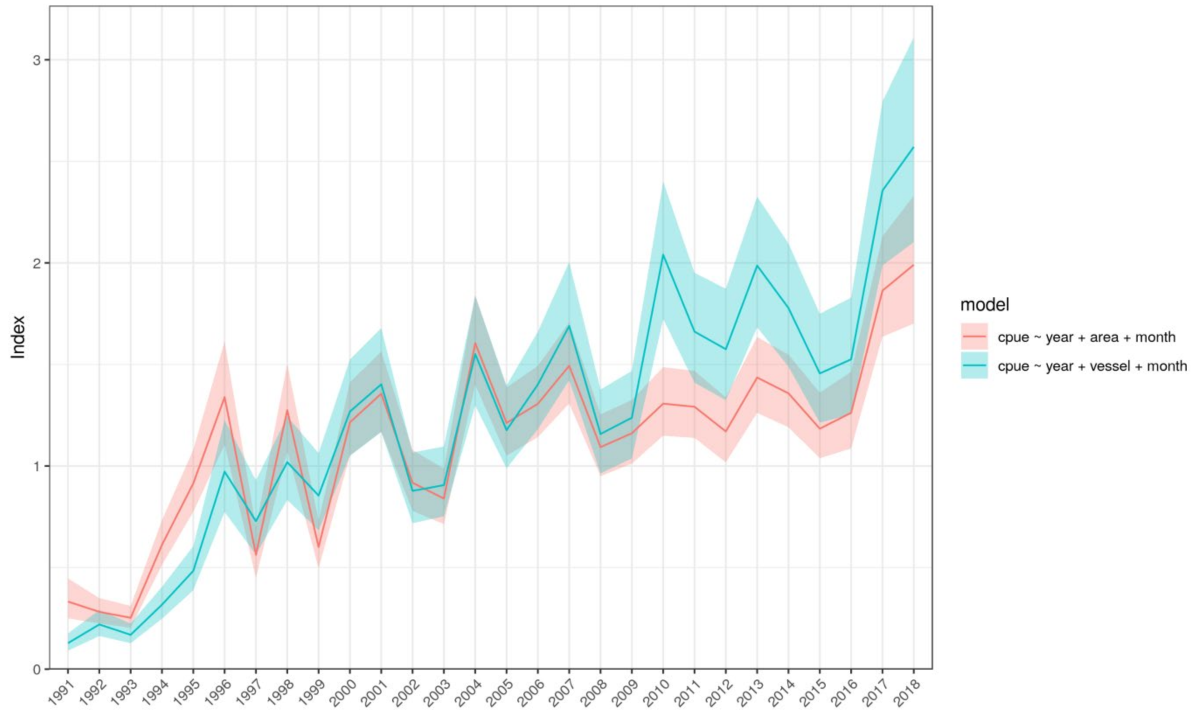

Figure 21: Standardised CPUE (kg/potlift) of packhorse rock lobster (PHC 1) from 1991–92 to 2018–19 for the chosen model structure (year + vessel + month) and the model that includes a statistical area explanatory variable rather than vessel (year + area + month). Both models include CRA-target events only.

5. STOCK ASSESSMENT

This section reports the first completed stock assessment for packhorse rock lobster (PHC 1). Based on the characterisation of potential input data (see Section 3), it was decided that a length-structured stock assessment using the lobster stock dynamics (LSD) model would not be possible. This was primarily due to the lack of sufficient length-frequency and tag-recapture data. A delay-difference model was also considered and tested, but reasonable fits to the CPUE series could not be obtained. Instead, a simple biomass dynamics model was used.

5.1 Catch history

The annual recreational catch history is highly uncertain. However, there were three estimates of recreational catch for packhorse rock lobster that could be used to help derive a recreational catch time series: the 2011–12 national panel survey (NPS) (Wynne-Jones et al. 2014), an east Northland survey conducted by John Holdsworth in 2013 (Holdsworth 2014), and the 2017–18 NPS survey (Wynne-Jones et al. 2019). The 2011–12 NPS survey estimated the recreational take in 2011 to be 4 080 individual lobsters (CV = 0.33) based on 19 events from 15 fishers. Using the average size of 2.412 kg reported by Holdsworth (2014) this equates to 9.84 tonnes. The Holdsworth (2014) estimate for 2013 was 5 tonnes. However, this estimate applied to Northland only, so this estimate was doubled. The 2017–18 NPS survey estimated the recreational take to be 11 833 individual lobsters (CV = 0.78) based on 33 events from 17 fishers. Again, using the average size of 2.412 kg reported by Holdsworth (2014) this equates to 28.66 tonnes. Given that the commercial fishery took 40.1 tonnes in the same year, and also noting the very high CV, this quantity does not appear to be credible. These catch estimates are summarised in Table 18. Based on this information, recreational fishing catch in the stock assessment was assumed to increase from 2 tonnes to 10 tonnes from 1953−1979 and to remain at 10 tonnes thereafter.

Table 18: Information used to estimate recreational catch of packhorse rock lobster. The mean weight is from Holdsworth (2014). The two national panel surveys attempt to estimate PHC catch for all of New Zealand while the Holdsworth survey applies to Northland.

Category	Numbers	Mean weight	Weight (kg)	CV
2011–12 (Wynne-Jones et al. 2014)	4 080	2.412	9 841	0.33
2013 (Holdsworth 2014)	–	–	5 000	–
2017–18 (Wynne-Jones et al. 2019)	11 883	2.412	28 662	0.78

The catch history used in this stock assessment is provided in Figure 22. This stock assessment included both the commercial catch and recreational catch series but ignored customary and illegal catches, because no information exists about these catches. It is likely that these catch categories are small, and previous experience has shown that adding a small but constant catch to the commercial/recreational catch vector will not change stock assessment outcomes. The commercial catch from 1953–54 to 1978–79 was set to 65% of the catch presented by Booth (2011), because, upon review, the RLWG deemed that these catch estimates were too high to be credible. For example: catch estimates presented by Kensler & Skrzynski (1970) from 1962 to 1966 were, on average, 30% of the Booth (2011) catches for the same period; and the catch estimates presented by Annala & King (1983) from 1967 to1973 were, on average, 10% of the Booth (2011) catches. However, the Kensler & Skrzynski (1970) and Annala & King (1983) catches probably represent a realistic lower bound on the catch, since the anecdotal evidence summarised by Booth (2011) suggests a high proportion of catch went unreported.

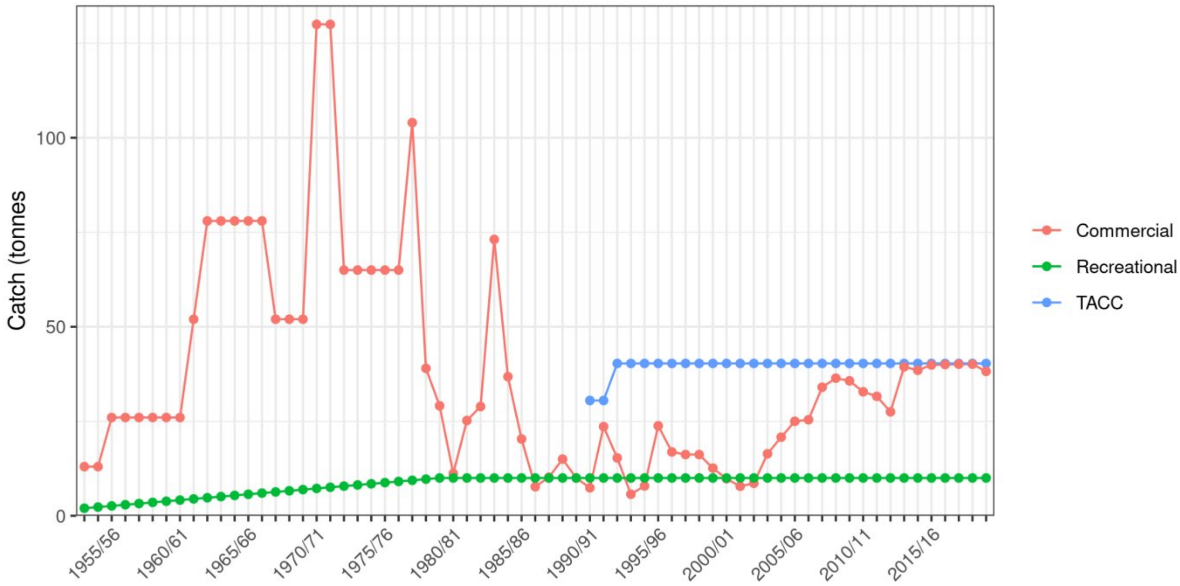

Figure 22: Commercial and recreational catch of packhorse rock lobster (PHC 1) from 1953–54 to 2018–19 used in this stock assessment. Commercial catch from 1953–54 to 1978–79 is 65% of the catches reported by Booth (2011), from 1979–80 to 1989–90 comes from the FSU database, and from 1990–91 onwards from the QMR/MHR. Also shown is the Total Allowable Commercial Catch (TACC) from 1990–91 to 2018–19.

5.2 Model structure

The stock assessment assumed Pella-Tomlinson production (P_t) (Pella & Tomlinson 1969) in each fishing year (t)

$$P_t = \frac{r}{z} B_t \left(1 - \left(\frac{B_t}{K}\right)^z\right)$$

where r is the intrinsic rate of population increase, z is the Pella-Tomlinson shape parameter, K is the carrying capacity, and B_t is the biomass (tonnes) each year. The shape parameter defines a Schaefer (1954) model if $z = 1$, and as z tends towards zero it becomes the modified Fox (1970) model. The initial biomass is assumed to be near the carrying capacity

$$B_{t=1} = K e^{\varepsilon_{t=1}^p}.$$

Otherwise, the biomass is defined as

$$B_t = (B_{t-1} + P_{t-1} - C_{t-1}) e^{\varepsilon_t^p}$$

where C_t is the catch (tonnes) which includes commercial and recreational catch added together each fishing year. The process error each fishing year is

$$\varepsilon_t^p \sim N(0, \sigma_p^2)$$

where σ_p is the process error standard deviation. The CPUE series is assumed to be directly proportional to biomass such that

$$I_t = q B_t e^{\varepsilon_t^o}$$

where q is the catchability coefficient. The observation error (ε_t^o) is defined as

$$\varepsilon_t^o \sim N(0, \sigma_t^2)$$

and

$$\sigma_t = \frac{1}{\tau}\sqrt{\left(\sigma_t^{\mathrm{GLM}}\right)^2 + \left(\sigma_t^{\mathrm{add}}\right)^2}$$

where σ_t^{GLM} is the SD from the GLM, σ_t^{add} is additive process error, and τ is the CPUE data set weight. A prior was used for the parameter z which has an expected value of 1 (i.e., a Schaefer model)

$$z \sim \mathrm{lognormal}(\log(1) + 0.5^2, 0.5^2).$$

A prior was also used for the parameter σ_p that resulted in a sensible level of process error

$$\sigma_p \sim \mathrm{lognormal}(\log(0.05), 0.01^2).$$

The derived quantities B_{MSY} and maximum sustainable yield (*MSY*) were calculated as

$$B_{\mathrm{MSY}} = K\left(\frac{1}{z+1}\right)^{\frac{1}{z}}$$

and

$$\mathrm{MSY} = \frac{r}{z}B_{\mathrm{MSY}}\left(1 - \left(\frac{B_{\mathrm{MSY}}}{K}\right)^z\right)$$

This model was coded in *Stan*, specifically for the packhorse lobster stock assessment (Stan Development Team 2021). A full list of prior specifications and parameter bounds is provided in Table 19. Early exploratory model runs trialled an initial depletion parameter and a CPUE power parameter (to allow for hyperstability/hyperdepletion), but these were both dropped because their parameter estimates were close to 1 and they did not change the model fits/outcomes in a meaningful way.

Table 19: Specifications for estimated parameters in the packhorse rock lobster (PHC 1) stock assessment models including the upper and lower bounds, prior type, and prior parameters.

Parameter	Lower bound	Upper bound	Prior type	μ	σ
r	0	3	uniform	–	–
z	0.001	5	lognormal	log(1) + 0.5^2 = 0.25	0.5
K	1	1e5	uniform	–	–
q	0	1	uniform	–	–
σ_p	0	–	lognormal	log(0.05) = -3	0.01
B_t	0	–	lognormal	–	σ_p

5.3 Model inference

The assessment model was fit to the standardised CPUE obtained from fitting to the CRA-target data, assuming a lognormal distribution. Additive process error was used and was set to 0.1 from 1991 to 2016 and 0.05 in 2017 and 2018 to help fit the last two years better. The CPUE data set weight (τ) was tuned (set to 0.3) so that the standard deviation of normalised residuals was 1 (Figure D.3).

Bayesian inference was done using Stan's Hamiltonian Monte Carlo (HMC) Markov chain Monte Carlo (MCMC) algorithm. Four chains, each with a burn-in period of 4000 samples and length of 4000 samples, were run retaining every second sample, for a total of 2000 samples in the posterior distribution. The median and 90% credible interval (CI) for estimated parameters and derived quantities of interest are reported.

5.4 Projections

Projections were done using the current commercial catch (40.3 tonnes) or a range of alternative catch levels, specified in Table 20. In all projection years, the recreational catch of 10 tonnes was added to the commercial catch. Projections ran for 20 years, from 2020–21 to 2039–40. The process error during each projected year was drawn from a normal distribution with mean and standard deviation calculated from the last 10 years of process errors estimated by the model. An alternative projection run was also done in which forward projections had a process error mean of 0 and SD of σ_p (**proj_low**), otherwise this model run is the same as the **base** run.

Table 20: Commercial catch (tonnes) of the packhorse rock lobster specified for each projected fishing year (2020–21 to 2039–40).

		Commercial catch						
Fishing year	Recreational catch	0	40.3	47	53	67	80	Phased
2020–21	10	0	40.3	47	53	67	80	53
2021–22	10	0	40.3	47	53	67	80	67
2022–23	10	0	40.3	47	53	67	80	80
2024–25	10	0	40.3	47	53	67	80	80
2025–26 onwards	10	0	40.3	47	53	67	80	80

5.5 Performance indicators and results

The base case model fit to CPUE was adequate (Figure 23) with the standardised residuals falling within -2 and 2 in almost all years (Figure 24). This model however failed to capture the high observed CPUE in the final two years even with the reduced process error.

The production curve suggested that peak production in the base model was just below 50% of the carrying capacity (Figure 25). This is also reflected in the estimate of B_{MSY} (median of 309.6 tonnes, 90% CI 221.8–418.7) which was approximately half of the carrying capacity (median of 650.9 tonnes, 90% CI 449.1–868.4) (Table 21).

Biomass in the assessment model is the annual biomass vulnerable to the fishery because it is scaled to the CPUE, which is based on the vulnerable population. Figure 26 shows the posterior distribution of the estimated packhorse rock lobster vulnerable biomass by fishing year for the base case stock assessment. The stock is predicted to have declined rapidly from the start of the model to the late-1980s, then increased rapidly back to near unfished levels by the late 2000s.

The exploitation rate (U) in the base case has been increasing since 2001 but is well below U_{MSY} (Figure 27).

Projections for the base case model suggest that the current TACC could be increased from 40.3 to 67 tonnes per year without any probability of going below B_{MSY} (Table 21, Figure 28). The predicted *MSY* (median of 68.4 tonnes, 90% CI 60.3–77.5) further supports the conclusion that this level of catch is sustainable (Table 21). Even the highest projected catch (80 tonnes per year) only has a low (0.09) probability of declining below B_{MSY}. The proj_low model run produced a slightly lower projected biomass (B_{2024}) compared with the base model run; however, this difference is minimal (Table 21).

5.6 Sensitivity runs

A single MCMC sensitivity was done. This involved changing the informative prior on the Pella-Tomlinson shape parameter to

$$z \sim \text{lognormal}(\log(1) + 5^2, 5^2).$$

This model run is referred to as the **flat_z** run and the prior is illustrated in Figure D.5.

Results from the base case and the sensitivity are compared in Table 21. The sensitivity did not differ much from the **base** run. The **flat_z** run produced a lower estimate of the population increase parameter (r) and the shape parameter (z) and a higher carrying capacity (K); however, this alternative combination of parameters produced a very similar fit to the CPUE series and a very similar stock status to the **base** model run. This inverse correlation of the two key model parameters is typical of simple production models, resulting from a trade-off between stock size and productivity. Because the only data provided to the model are catch and a biomass trend, in the absence of biological data specific to the stock, the model cannot reconcile these two hypotheses.

Peak production in the flat_z model run was slightly left shifted (Figure 25), B_{MSY} was slightly lower (median of 298.4 tonnes, 90% CI 230.2–395.6), and the carrying capacity was a bit higher (median of 711.7 tonnes, 90% CI 524.1–921.2) (Table 21). However, the relative probability indicators (e.g., P($B_{2024} < B_{MSY}$) are very close to the equivalent base case probabilities.

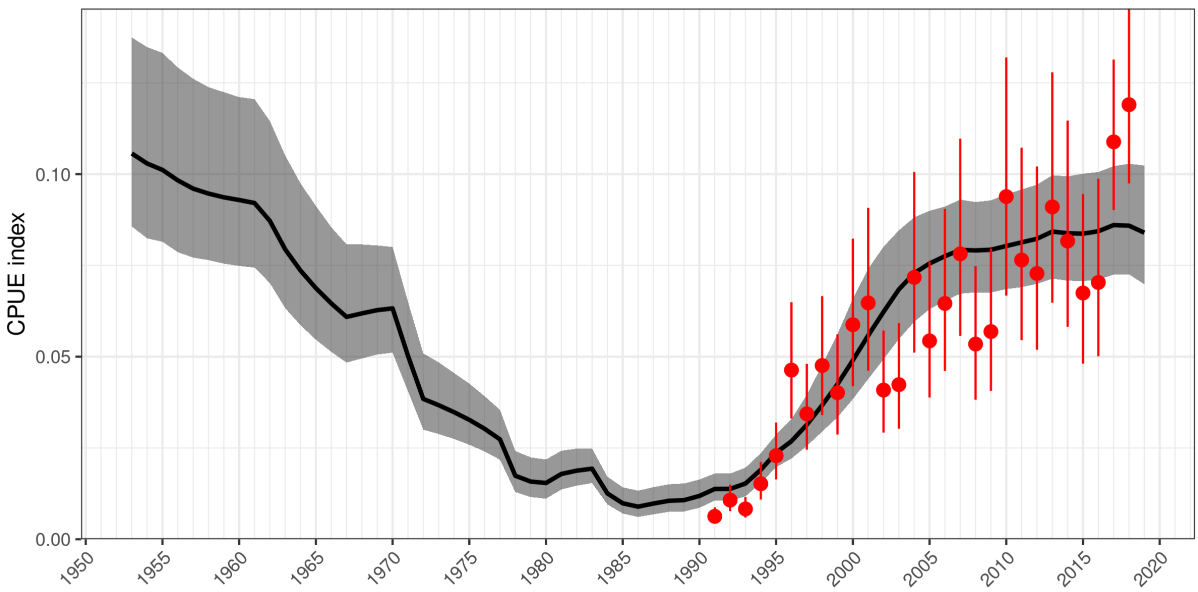

Figure 23: Posterior distribution of the packhorse rock lobster (PHC 1) CPUE for the base case stock assessment model by fishing year (labelled with first year of the pair). The black line and grey-shaded area are the median and 90% credible interval of the model prediction. Red points and whiskers are the median and 90% of the credible interval of the CPUE index being fitted to.

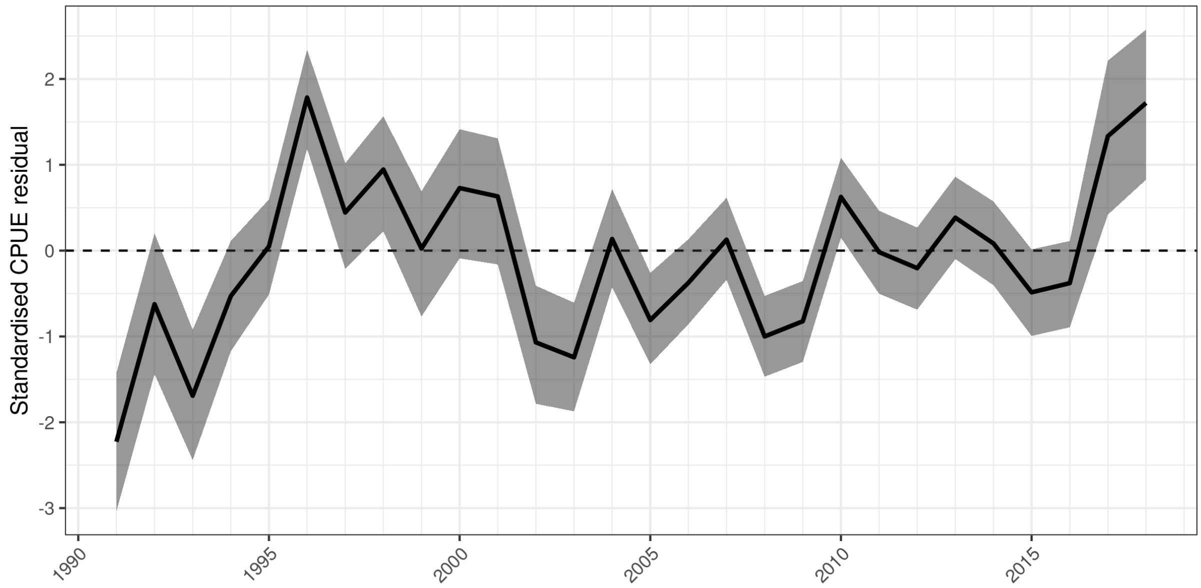

Figure 24: Posterior distribution of the packhorse rock lobster (PHC 1) standardised CPUE residual for the base case stock assessment model by fishing year (labelled with first year of the pair). The black line is the median residual and the grey-shaded area is the 90% credible interval.

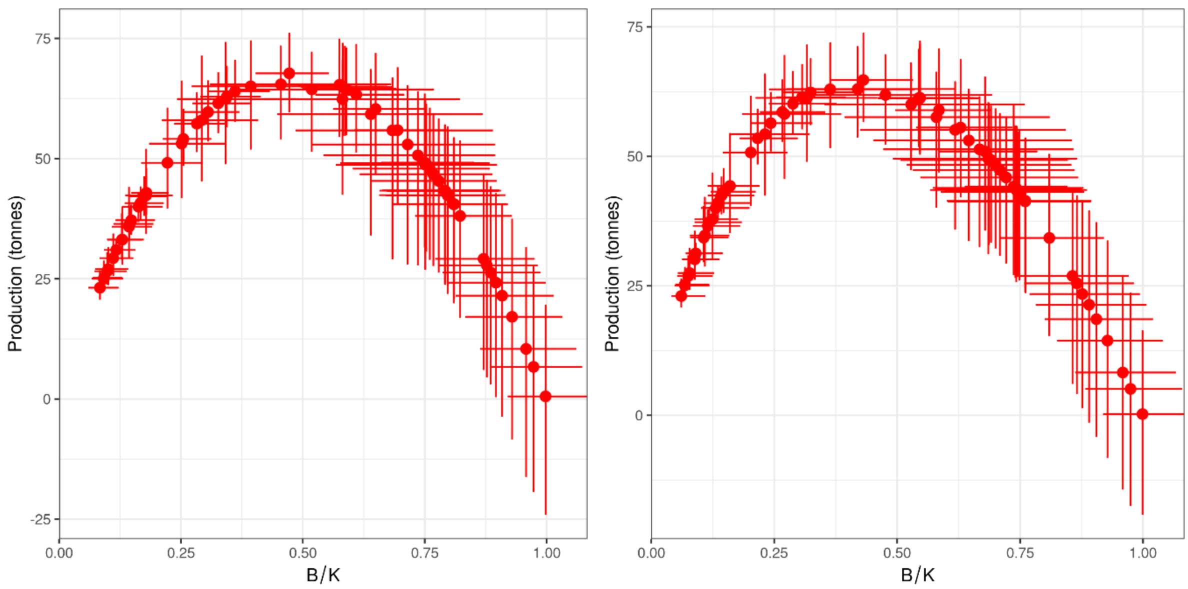

Figure 25: Posterior distribution of the production curve for the base (left) and flat_z (right) model runs.

Table 21: Packhorse rock lobster stock (PHC 1) base case and sensitivity stock assessment model runs, reporting the 5th, 50th (median – grey shading), and 95th quantiles of the posterior distributions. SDNR = the standard deviation of the normalised residuals. (Continued on next page)

		base			proj_low			flat_z	
	5%	50%	95%	5%	50%	95%	5%	50%	95%
τ	–	0.3	–	–	0.3	–	–	0.3	–
SDNR	0.875	0.997	1.139	0.877	0.998	1.140	0.815	0.942	1.105
proj_mu	-0.012	0.012	0.037	–	–	–	-0.012	0.012	0.037
proj_sd	0.031	0.048	0.068	–	–	–	0.030	0.048	0.069
proj_rho	-0.002	0.000	0.001	–	–	–	-0.002	0.000	0.001
K	449.1	650.9	868.4	483.2	662.9	879.7	524.1	711.7	921.2
r	0.252	0.391	0.719	0.250	0.381	0.650	0.189	0.282	0.558
z	0.376	0.776	1.646	0.377	0.771	1.556	0.024	0.270	1.321
σ_p	0.049	0.050	0.051	0.049	0.050	0.051	0.049	0.050	0.051
B_0	444.8	648.9	875.9	475.4	661.3	887.5	517.0	710.3	933.2
B_{min}	31.7	53.8	91.2	33.2	55.5	91.6	26.2	43.8	79.0
B_{2019}	359.9	510.1	693.3	381.8	520.7	695.8	395.3	520.0	683.5
B_{MSY}	221.8	309.6	418.7	233.8	315.9	423.0	230.2	298.4	395.6
MSY	60.3	68.4	77.5	60.1	68.0	76.5	57.2	64.9	74.3
B_{2019} / B_0	0.660	0.793	0.928	0.660	0.792	0.926	0.592	0.743	0.894
P(B_{2019} > B_{min})	–	1.000	–	–	1.000	–	–	1.000	–
P(B_{2019} > B_{MSY})	–	1.000	–	–	1.000	–	–	1.000	–
P(B_{2019} > B_0)	–	0.007	–	–	0.006	–	–	0.003	–
B_{2024} - 0 t	430.0	610.2	825.8	448.2	603.7	791.4	478.3	634.3	845.4
B_{2024} - 40.3 t	351.4	502.9	703.2	361.5	494.4	668.1	375.4	514.5	714.3
B_{2024} - 47 t	335.4	483.5	682.2	344.5	475.0	647.5	357.6	493.5	691.9
B_{2024} - 53 t	320.4	465.9	662.6	328.8	457.1	628.8	340.8	474.9	671.5
B_{2024} - 67 t	282.8	423.3	617.1	290.0	413.7	583.5	299.2	429.4	624.1
B_{2024} - 80 t	243.9	381.7	573.7	250.2	371.8	541.7	256.9	385.6	577.6
B_{2024} - phased	266.0	406.9	600.7	273.1	397.5	568.6	283.6	413.8	608.6
B_{2024} / B_0 - 0 t	0.792	0.950	1.106	0.779	0.917	1.061	0.723	0.910	1.087
B_{2024} / B_0 - 40.3 t	0.634	0.788	0.941	0.625	0.754	0.890	0.564	0.741	0.916
B_{2024} / B_0 - 47 t	0.606	0.758	0.912	0.597	0.725	0.860	0.537	0.711	0.886
B_{2024} / B_0 - 53 t	0.579	0.731	0.886	0.570	0.698	0.832	0.511	0.684	0.858
B_{2024} / B_0 - 67 t	0.513	0.663	0.821	0.508	0.632	0.766	0.450	0.618	0.794
B_{2024} / $\mathrm{B_0}$ - 80 t	0.448	0.597	0.758	0.444	0.567	0.703	0.390	0.554	0.731
B_{2024} / B_0 - phased	0.491	0.636	0.792	0.486	0.607	0.740	0.431	0.595	0.767
B_{2024} / B_{2019} - 0 t	1.051	1.198	1.362	0.991	1.161	1.353	1.060	1.222	1.406
B_{2024} / B_{2019} - 40.3 t	0.865	0.994	1.132	0.809	0.956	1.117	0.855	0.994	1.152
B_{2024} / B_{2019} - 47 t	0.828	0.956	1.094	0.775	0.918	1.075	0.817	0.955	1.111
B_{2024} / B_{2019} - 53 t	0.794	0.922	1.059	0.742	0.884	1.039	0.781	0.918	1.073
B_{2024} / B_{2019} - 67 t	0.707	0.837	0.974	0.666	0.800	0.949	0.691	0.829	0.987
B_{2024} / B_{2019} - 80 t	0.617	0.753	0.898	0.583	0.718	0.865	0.599	0.745	0.906
B_{2024} / B_{2019} - phased	0.674	0.803	0.943	0.634	0.767	0.917	0.660	0.798	0.956
B_{2024} / B_{MSY} - 0 t	1.649	1.964	2.324	1.639	1.909	2.203	1.690	2.132	2.610
B_{2024} / B_{MSY} - 40.3 t	1.347	1.628	1.949	1.332	1.570	1.823	1.365	1.728	2.159
$\mathrm{B_{2024}}$ / B_{MSY} - 47 t	1.289	1.567	1.883	1.275	1.509	1.760	1.299	1.658	2.083
B_{2024} / B_{MSY} - 53 t	1.233	1.510	1.823	1.222	1.452	1.701	1.240	1.593	2.017
B_{2024} / B_{MSY} - 67 t	1.095	1.374	1.683	1.088	1.315	1.563	1.099	1.441	1.856
B_{2024} / B_{MSY} - 80 t	0.952	1.237	1.556	0.950	1.181	1.430	0.951	1.294	1.707
B_{2024} / B_{MSY} - phased	1.043	1.316	1.629	1.039	1.262	1.509	1.050	1.387	1.803
P(B_{2024} > B_{2019}) - 0 t	–	0.986	–	–	0.941	–	–	0.989	–
P(B_{2024} > B_{2019}) - 40.3 t	–	0.467	–	–	0.319	–	–	0.475	–
P(B_{2024} > B_{2019}) - 47 t	–	0.285	–	–	0.185	–	–	0.293	–
P(B_{2024} > B_{2019}) - 53 t	–	0.162	–	–	0.106	–	–	0.173	–
P(B_{2024} > B_{2019}) - 67 t	–	0.030	–	–	0.014	–	–	0.038	–
P(B_{2024} > B_{2019}) - 80 t	–	0.005	–	–	0.001	–	–	0.007	–
P(B_{2024} < B_{2019}) - phased	–	0.014	–	–	0.006	–	–	0.024	–
P(B_{2024} < 20% B_0) - 0 t	–	0.000	–	–	0.000	–	–	0.000	–
P(B_{2024} < 20% B_0) - 40.3 t	–	0.000	–	–	0.000	–	–	0.000	–
P(B_{2024} < 20% B_0) - 47 t	–	0.000	–	–	0.000	–	–	0.000	–

	base			proj_low			flat_z		
	5%	50%	95%	5%	50%	95%	5%	50%	95%
P(B_{2024} < 20% B_0) - 53 t	–	0.000	–	–	0.000	–	–	0.000	–
P(B_{2024} < 20% B_0) - 67 t	–	0.000	–	–	0.000	–	–	0.000	–
P(B_{2024} < 20% B_0) - 80 t	–	0.000	–	–	0.000	–	–	0.000	–
P(B_{2024} < 20% B_0) - phased	–	0.000	–	–	0.000	–	–	0.000	–
P(B_{2024} > B_{MSY}) - 0 t	–	1.000	–	–	1.000	–	–	1.000	–
P(B_{2024} > B_{MSY}) - 40.3 t	–	1.000	–	–	1.000	–	–	0.999	–
P(B_{2024} > B_{MSY}) - 47 t	–	0.999	–	–	1.000	–	–	0.999	–
P(B_{2024} > B_{MSY}) - 53 t	–	0.999	–	–	1.000	–	–	0.998	–
P(B_{2024} > B_{MSY}) - 67 t	–	0.985	–	–	0.990	–	–	0.981	–
P(B_{2024} > B_{MSY}) - 80 t	–	0.912	–	–	0.898	–	–	0.923	–
P(B_{2024} < B_{MSY}) - phased	–	0.971	–	–	0.975	–	–	0.970	–

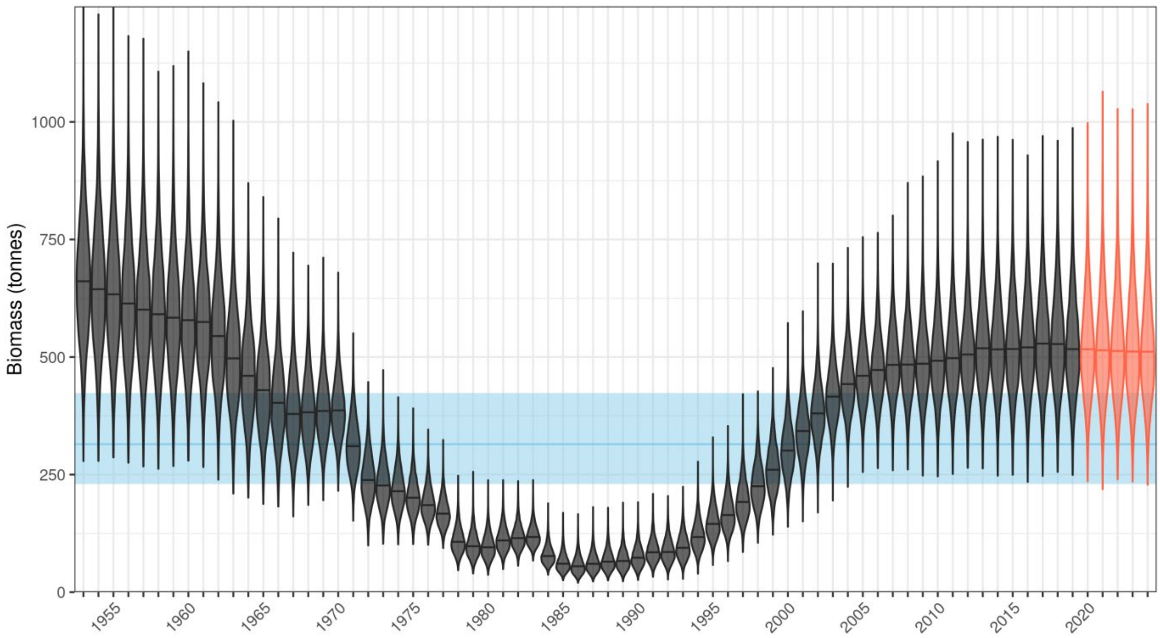

Figure 26: Posterior distribution of the packhorse rock lobster biomass (tonnes) for the base case stock assessment model by fishing year. The horizontal line within each violin represents the median, the red violins represent projection years 2020–21 to 2024–25, the horizontal blue line represents the median of B_{MSY}, and the blue shaded region represents the 90% credible interval of B_{MSY}.

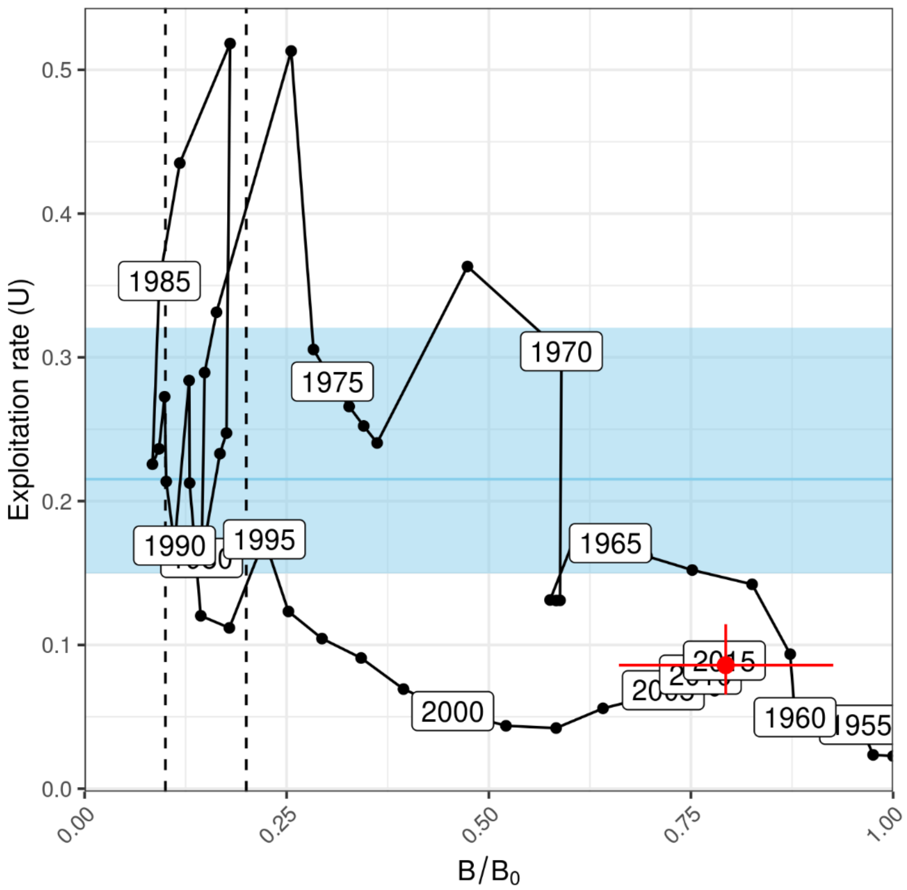

Figure 27: Packhorse rock lobster (PHC 1) base case model. The line tracks the median of the posterior for each axis and the red point with error bars represents the 90% credible interval for the final model year (2019). The dashed vertical lines are 20% B_0 (soft limit) and 10% B_0 (hard limit), the horizontal blue line represents the median of U_{MSY}, and the blue shaded region represents the 90% credible interval of U_{MSY}.

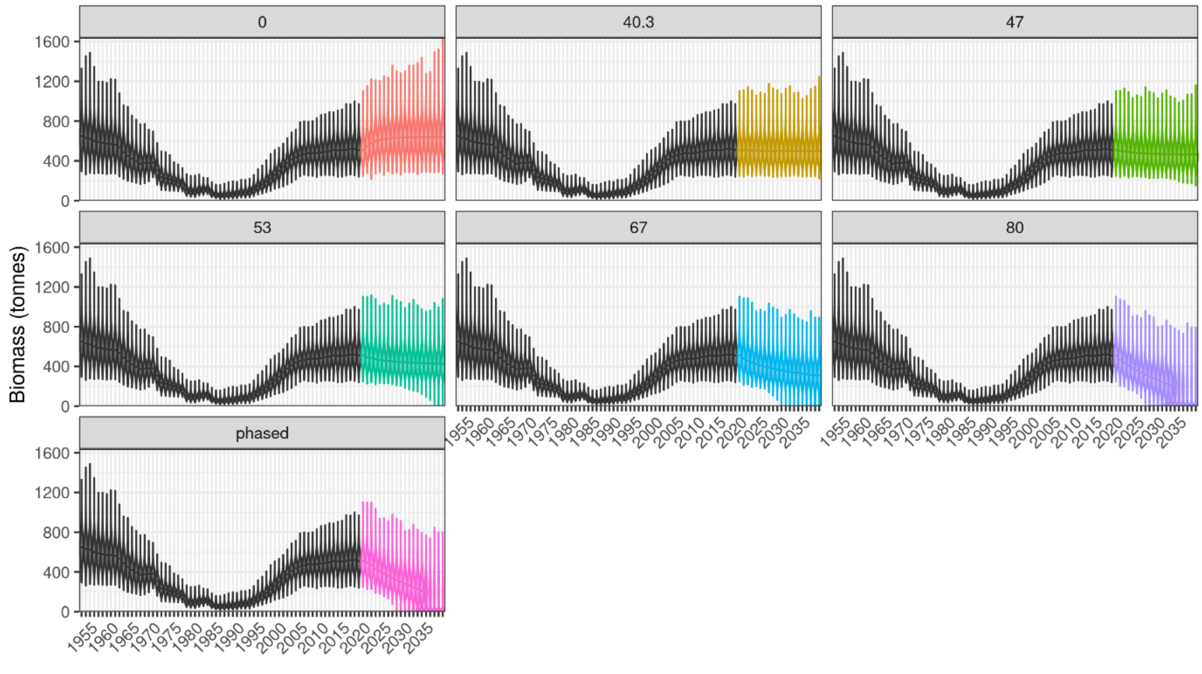

Figure 28: Posterior distribution of the packhorse rock lobster biomass (tonnes) for the base case stock assessment model by fishing year for each of the catch levels specified in Table 20. The horizontal line within each violin represents the median, the coloured violins represent projection years 2020–21 to 2039–40.

6. DISCUSSION

6.1 Life history

Size-specific growth is a key input for size-based stock assessment models and can be difficult to estimate without bias. From the published information, it is known that packhorse rock lobsters are capable of reaching very large body size relative to other spiny lobster (*Palinurid*) species (Wahle & Fogarty 2007). Their early growth can be rapid relative to other palinurids and they also reach maturity at a relatively large size (Montgomery 1992).

Unfortunately, the available tag-based growth information is too sparse for estimating growth for New Zealand packhorse rock lobsters. Further, the sizes of the few tag recaptures obtained to date were small relative to the typical size range captured across the fishery (compare Figure B.7 and Figure B.8 with Figure 12). The use of growth increment data and estimates from the Australian stock (e.g., Montgomery et al. 2009) may be complicated by differences in temperature in New Zealand and Australia waters and other environmental factors known to affect rock lobster growth rate, such as food availability and quality. Other options could include the development of methods for direct ageing of lobsters (e.g., Gnanalingam et al. 2018), which have previously been trialled on this species (Leland & Bucher 2017).

Size at maturity of the New Zealand population appears to be much better informed by the available data. The estimated size at 50% maturity was based on the presence of eggs and the resulting estimate (93–95 mm TW) is comparable with the previous estimate of Booth (1984a). The size at which 50% of female packhorse rock lobsters had setae (about 85 mm TW) was below this value (Figure 11), indicating that the presence of eggs (rather than setae) should be used to determine individual maturity stage of this species, consistent with the findings of Booth (1984a).

6.2 Dispersal and stock structure

The area covered by the PHC 1 stock is large compared with CRA QMAs, although most of the catch occurs along the north coast of the North Island, roughly corresponding to the sum of CRA 1 and CRA 2. Furthermore, it has been hypothesised, based on research on the New Zealand and Australian populations, that this species is highly migratory (compared to red rock lobsters) (Booth 1984b), such that the relative vulnerability of different life stages will vary spatially around New Zealand. The available tag-recapture and size-composition data tentatively support this hypothesis, although they are too sparse to confirm this at present.

Based on the most recent genetic analysis, the Australian and New Zealand populations of packhorse rock lobster cannot be separated on the basis of genetic composition (Woodings et al. 2018). Furthermore, there is a plausible oceanographic mechanism for transporting phyllosomae from the main NSW breeding ground to New Zealand (Chiswell et al. 2003). There are other parallels between these stocks, e.g., with respect to increasing catch rate since the early 1990s (which could also plausibly be the result of parallel shifts in climate), and similar putative life cycles (Booth 2011, New South Wales Department of Primary Industries 2017). However, information to assess the extent to which the New Zealand stock is supported by the dispersal of larvae from Australia is currently lacking. In any case, the stock assessment approach used here to project the New Zealand stock does not require the assumption of a stock-recruitment relationship, such that projected recruitment would not be affected by estimated changes in spawning stock biomass in Australia or New Zealand. However, the potential connections between these stocks deserve future consideration.

6.3 Characterisation

This characterisation summarised the data sets that would typically be used to produce the inputs for a rock lobster stock assessment, including:

- catch histories by fishery area, season, and target species (i.e., PHC or CRA);

- catch LFs by fishing year;
- tag-recapture observations;
- information for estimating size at maturation;
- various morphometric relationships; and
- a CPUE-based index of relative abundance.

The voluntary logbook database operating in CRA 2, CRA 5 and CRA 8 is presently not designed to capture packhorse rock lobster data. As such, catch sampling data for packhorse rock lobster size, sex, and maturity were obtained only from the Fisheries New Zealand *rlcs* database. LF catch sampling has been comparatively sparse for packhorse rock lobster, and patchy through time. For example, fewer than 100 packhorse rock lobsters were measured each year from 1993–94 to 2000–01 (Table 7). A relatively large number of packhorse rock lobsters were measured in statistical areas 901 and 902 under a dedicated catch sampling programme for this species in years 1990–91 to 1992–93. In subsequent years, all packhorse rock lobster measurements in the *rlcs* database were recorded as being collected under the red rock lobster catch sampling programme and were assumed to be collected from CRA-target fishing events.

6.4 Analysis of catch and effort data

The packhorse rock lobster fishery is managed as a single stock (PHC 1), covering the entire EEZ of New Zealand, although the targeted fishery almost entirely operates along the north coast of the North Island. Since the introduction of the QMS, total packhorse rock lobster landings were initially low relative to the TACC, but gradually increased over time. The TACC has been effectively taken in every fishing year since 2013–14 (Figure 2). The CRA 1 and CRA 2 QMAs account for most of this catch (Figure 10). Catches in statistical areas within CRA 2 have increased in recent years, likely due to the increased abundance and range expansion of packhorse rock lobster. Just under half of the recent packhorse rock lobster catch was bycatch of the CRA fishery (Table A.4).

In consultation with the RLWG, the base case CPUE standardisation model was derived from events targeting CRA only, for which catch rates of packhorse rock lobster were generally low (Figure 16), although effort was high. This approach was used because of the small number of vessels which target PHC in any year. There was also concern that a small-scale target fishery had the potential for hyperstability of catch rates, given that this is primarily a spawning fishery. Although moving to bycatch fishery data has likely resulted in a more robust index of relative abundance, it may not necessarily reflect relative abundance at the spawning grounds. This situation may change if there is a future expansion of the PHC-target fishery in response to increasing abundance and increased TACC.

6.5 Stock assessment

The biomass dynamics stock assessment model was informed by estimates of historical catch and CPUE only. This model suggested a stock that was initially heavily fished to a low level in the 1980s, then increased rapidly during the 1990s, and has plateaued to near unfished levels since the mid-2000s.

The stock assessment and projections suggest that, at the current levels of catch, the stock is being under-utilised. The TACC could be sustainably increased from 40.3 to 68 tonnes as evidenced by the long-term projections (Figure 28) and based on the model estimated *MSY* (Table 20). All of the catch projections showed a high probability of remaining above B_{MSY} in 2024, with the probability only dropping below 1.0 at catch levels above 67 tonnes per year.

The catch estimates for PHC from the 1960s and 1970s are highly uncertain (e.g., there are blocks of years where the catch is estimated to be the same) (Figure 2, Table A.1) and are consistently higher than estimates from an earlier study (Kensler & Skrzynski 1970), which did not exceed 67 tonnes for any calendar year from 1962 to 1966, and were typically closer to half that value. However, there is no way to confirm historical catch levels and the catches for this period used in this stock assessment are based on the best available information and on reasonable assumptions.

6.6 Input controls

Typically, an MLS restriction is designed to allow most females to breed at least once before becoming legal to harvest. However, the current MLS in the PHC fishery (216 mm TL) coincides with the mean size at which setae first appear on the females' pleopods, which is smaller than the size at first breeding (Booth 1984a). This implies that, under the current management framework, packhorse rock lobsters can be harvested prior to breeding.

The current MLS is based on TL, which is difficult to measure in a standard and repeatable way and requires pressure to be put on the tail of the lobster when measuring which could result in injury and associated handling mortality in lobsters being returned (Breen et al. 1987). Changing to an MLS based on TW (as used by the CRA fishery) should help to increase the precision of measurements and to enhance post-release survival.

6.7 Recommendations

The use of a MLS defined in terms of TL (rather than TW or CL) in this fishery is not consistent with the MLS used for CRA in New Zealand. Moving to an MLS measured by TW should make it easier for commercial and recreational fishers to measure lobsters and help reduce handling mortality.

Moreover, there are a number of measures which could improve future stock assessments, including the collection of new information, the development of alternative stock assessment inputs, and additional data analysis.

Collection of new information

- Due to the lack of target species information in the *rlcs* database, it was not possible to separate out *rlcs* catch sampling data of PHC collected since 1993–94 by fishery target (all were assumed to be from CRA-target fishing events). Furthermore, the voluntary logbook database is presently not designed to hold PHC information (the *lobsters* table does not currently have a species field). Remedying these issues should increase the number of PHC measurements and provide clearer information for the estimation of selectivities for the PHC- and CRA-target fisheries.
- Multiple modes were observed in the most recent fishing year with a reasonably large LF sample (over 1000 observations in 2014–15), possibly indicative of variable recruitment through time. This appears to be a good target sample size for monitoring changes in PHC catch size structure through time.

Development of inputs for future stock assessments

- The CPUE index developed here was primarily informed by the catch rate of core vessels, in core statistical areas, targeting CRA. Because of differences in the spatial distribution of each fishery, the CPUE index may be more representative of pre-breeders than of the breeding-age lobsters dominating the catch of the PHC-target fishery. Future research could explore the development of separate packhorse rock lobster CPUE series for the CRA- and PHC-target fisheries, indexing the abundance of different life stages.
- Future CPUE standardisations could consider area × year or month × year interaction terms.
- Sampling of catch size composition and growth information should be increased to inform future size-based stock assessment models. Growth information is particularly lacking for maturing and mature lobsters. In addition to increasing the tagging information around New Zealand or using growth information from the Australian stock, consideration could be given to developing methods for direct ageing and, also, to better informing the estimation of maturation, to properly define spawning stock biomass. Future research could explore the use of existing logbook catch records of PHC to estimate a CPUE index of relative abundance (see Webber 2013 for a summary of these data).

- Increase recreational catch estimates in recent years, e.g., by assuming they are proportional to the recent increase in CPUE and investigate other means of improving estimates of non-commercial catch.

Additional data analysis

- The impact of alternative historical catch series on stock assessment conclusions could be investigated.
- Annual data for evidence of fishers avoiding PHC could be investigated by, for example, comparing catch data in each half of a respective quota year, to determine whether there is evidence of the TAC constraining CPUE and areas fished in recent years.

Finally, collaboration with groups researching the Australian stock should be sought. The Australian fishery is more developed and has better information for elucidating the life history and lifecycle of this species.

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APPENDIX A. CATCH AND EFFORT SUMMARY TABLES

Table A.1: Commercial catch (tonnes) of packhorse rock lobsters from 1953–54 to 1978–79 (Booth 2011).

Fishing year	Estimated catch (tonnes)	Fishing year	Estimated catch (tonnes)
1953–54	20	1966–67	120
1954–55	20	1967–68	80
1955–56	40	1968–69	80
1956–57	40	1969–70	80
1957–58	40	1970–71	200
1958–59	40	1971–72	200
1959–60	40	1972–73	100
1960–61	40	1973–74	100
1961–62	80	1974–75	100
1962–63	120	1975–76	100
1963–64	120	1976–77	100
1964–65	120	1977–78	160
1965–66	120	1978–79	60

Table A.2: Reported commercial catch and TACC (tonnes) of packhorse rock lobsters from 1979–80 to 2018–19. Data from FSU for 1979–80 to 1987–88, consultation with industry for 1988–89 and 1989–90 (see table 17 of Booth et al. 1994), QMR for 1990–91 to 2000–01 and MHR for 2001–02 to 2018–19.

	FSU		QMR/MHR			MHR	
Fishing year	Catch	Fishing year	Catch	TACC	Fishing year	Catch	TACC
1979–80	29.1	1990–91	7.4	30.5	2005–06	25.0	40.3
1980–81	11.2	1991–92	23.6	30.5	2006–07	25.4	40.3
1981–82	25.2	1992–93	15.3	40.3	2007–08	34.0	40.3
1982–83	28.9	1993–94	5.7	40.3	2008–09	36.4	40.3
1983–84	73.1	1994–95	7.9	40.3	2009–10	35.7	40.3
1984–85	36.8	1995–96	23.8	40.3	2010–11	32.8	40.3
1985–86	20.3	1996–97	16.9	40.3	2011–12	31.6	40.3
1986–87	7.7	1997–98	16.2	40.3	2012–13	27.5	40.3
1987–88	10.2	1998–99	16.2	40.3	2013–14	39.4	40.3
1988–89	15.0	1999–00	12.6	40.3	2014–15	38.5	40.3
1989–90	10.0	2000–01	9.8	40.3	2015–16	39.9	40.3
		2001–02	7.8	40.3	2016–17	40.0	40.3
		2002–03	8.6	40.3	2017–18	40.1	40.3
		2003–04	16.4	40.3	2018–19	40.1	40.3
		2004–05	20.8	40.3			

Table A.3: Catch data sets for packhorse rock lobster, including: total allowable commercial catch (TACC); QMR/MHR reported catches (QMR/MHR); landings from the bottom of CELR forms aggregated by fishing year (Landings); estimated sub-catch from the CELR forms (Estimated catch); and the corrected catch after the core vessel selection procedure (see Section 4.1) is applied and limiting to statistical areas 901, 902, 903, 904, 905, 906, 907, and 939 (Corrected catch for analysis). All catches are in tonnes.

Fishing year	TACC	QMR/MHR	Landings	Estimated catch	Catch for analysis
1990–91	30.5	7.4	1.43	2.15	–
1991–92	30.5	23.6	24.00	25.99	1.71
1992–93	40.3	15.3	11.38	12.63	0.70
1993–94	40.3	5.7	6.46	5.82	0.43
1994–95	40.3	7.9	9.48	12.29	1.72
1995–96	40.3	23.8	25.95	21.80	2.67
1996–97	40.3	16.9	20.50	13.65	3.35
1997–98	40.3	16.2	18.09	10.15	2.24
1998–99	40.3	16.2	19.17	14.28	2.78
1999–00	40.3	12.6	14.27	11.40	1.73
2000–01	40.3	9.8	11.46	8.75	3.37
2001–02	40.3	7.8	11.06	8.08	5.87
2002–03	40.3	8.6	8.45	8.02	5.37
2003–04	40.3	16.4	20.23	16.21	2.84
2004–05	40.3	20.8	20.22	20.49	10.19
2005–06	40.3	25.0	25.09	23.59	9.11
2006–07	40.3	25.4	26.13	23.63	12.49
2007–08	40.3	34.0	35.50	32.42	15.91
2008–09	40.3	36.4	37.17	33.62	10.32
2009–10	40.3	35.7	37.44	32.51	11.69
2010–11	40.3	32.8	33.19	30.37	11.26
2011–12	40.3	31.6	32.05	27.62	12.12
2012–13	40.3	27.5	31.69	25.04	8.56
2013–14	40.3	39.4	42.43	38.33	15.05
2014–15	40.3	38.5	42.44	40.37	13.03
2015–16	40.3	39.9	39.17	39.90	9.83
2016–17	40.3	40.0	45.02	34.20	6.64
2017–18	40.3	40.1	39.19	36.87	11.86
2018–19	40.3	40.1	41.67	38.54	7.00

Table A.4: **Estimated sub-catch of packhorse rock lobster by target species (PHC = packhorse rock lobster, CRA = red rock lobster) and fishing year or statistical area, from the CELR forms (Estimated catch). All catches are in tonnes for the period from 1990–91 to 2018–19.**

	Target species	
Fishing year	**CRA**	**PHC**
1990–91	1.70	0.45
1991–92	3.72	22.27
1992–93	2.42	10.2
1993–94	3.46	2.35
1994–95	2.38	9.91
1995–96	3.83	17.97
1996–97	5.35	8.24
1997–98	3.17	6.97
1998–99	4.02	10.13
1999–00	2.58	8.82
2000–01	4.04	4.71
2001–02	6.91	1.17
2002–03	6.14	1.89
2003–04	4.78	11.42
2004–05	12.84	7.65
2005–06	11.69	11.9
2006–07	13.40	10.23
2007–08	18.79	13.62
2008–09	12.69	20.93
2009–10	13.52	18.99
2010–11	13.41	16.96
2011–12	14.63	12.99
2012–13	16.41	8.63
2013–14	23.35	14.98
2014–15	23.73	16.64
2015–16	17.55	22.35
2016–17	19.49	14.71
2017–18	20.25	16.62
2018–19	12.22	26.23
All years	298.45	349.97

	Target species	
Statistical area	**CRA**	**PHC**
901	56.09	75.52
902	29.67	210.14
903	22.18	22.08
904	63.17	17.93
905	45.92	12.6
906	63.15	1.44
907	8.23	7.35
908	5.21	0.85
909	0.04	–
910	0.00	0.42
911	0.17	0.03
912	0.05	–
913	0.00	–
914	0.01	–
915	0.25	–
917	0.01	–
925	0.03	0.01
926	0.03	–
930	0.00	–
934	0.03	–
935	0.10	–
936	0.01	0.01
937	0.03	–
938	0.00	–
939	3.51	0.01

Table A.5: Number of vessels by statistical area and fishing year that caught packhorse rock lobster (PHC) within a fishing year from 1990–91 to 2018–19. The "Other" column is the number of vessels fishing a statistical area other than those shown. The "All" column is the number of vessels from all statistical areas that landed PHC during that fishing year.

Fishing						CRA 1					CRA 2		
year	901	902	903	904	939	All	905	906	907	908	All	Other	All
1990–91	5	5	2	2	3	11	0	1	0	0	1	2	13
1991–92	8	13	9	5	3	20	1	5	2	2	8	3	26
1992–93	1	8	9	7	3	19	3	11	3	4	16	8	35
1993–94	5	7	6	7	2	18	3	11	3	5	18	5	37
1994–95	2	8	7	6	4	20	2	10	1	3	13	4	33
1995–96	3	5	4	4	4	17	7	12	2	4	18	2	33
1996–97	1	3	9	5	4	16	7	7	2	2	15	2	31
1997–98	0	6	7	5	5	19	5	7	3	3	13	8	31
1998–99	3	5	5	4	5	18	7	8	2	2	17	5	34
1999–00	4	1	6	3	4	16	4	12	2	4	17	6	30
2000–01	3	2	2	4	5	12	4	11	3	3	15	4	26
2001–02	3	4	2	5	1	11	9	10	3	3	19	4	27
2002–03	5	6	3	4	2	11	8	9	3	0	18	2	26
2003–04	2	5	4	2	3	12	10	11	3	2	23	4	38
2004–05	2	5	5	3	4	17	8	14	4	3	24	5	39
2005–06	3	5	5	3	3	14	14	12	7	5	28	13	47
2006–07	3	4	5	2	3	13	10	12	4	5	27	11	45
2007–08	4	6	8	2	2	17	9	14	6	4	29	16	52
2008–09	5	4	7	2	2	17	11	12	4	8	29	15	55
2009–10	2	5	7	2	2	16	11	12	6	6	31	16	54
2010–11	5	6	8	6	3	19	15	13	4	6	34	17	59
2011–12	4	6	10	3	3	20	18	15	4	10	36	7	55
2012–13	2	5	9	5	2	19	16	15	4	7	38	4	54
2013–14	2	5	7	4	3	17	12	16	5	8	35	3	50
2014–15	3	5	5	5	3	16	10	15	5	6	32	6	48
2015–16	5	6	3	4	3	16	16	16	4	8	36	5	48
2016–17	6	4	2	5	3	16	14	16	5	8	35	3	48
2017–18	2	3	5	4	4	16	11	13	4	7	31	12	47
2018–19	3	5	2	4	3	14	10	11	5	8	32	9	48

Table A.6: Number of potlifts ('000s) by statistical area and fishing year of vessels that caught packhorse rock lobster (PHC) within a fishing year from 1990–91 to 2018–19. The "Other" column is the number of vessels fishing a statistical area other than those shown. The "All" column is the number of pot lifts from all statistical areas that landed PHC during that fishing year.

Fishing	CRA 1						CRA 2						
year	901	902	903	904	939	All	905	906	907	908	All	Other	All
1990–91	11.0	20.6	18.3	4.1	21.2	75.1	0.0	10.9	0.0	0.0	10.9	13.6	99.6
1991–92	5.9	34.6	38.3	22.4	23.9	125.1	12.8	50.7	10.3	0.4	74.2	0.7	200.0
1992–93	6.1	22.1	29.8	41.5	20.5	119.9	20.7	133.4	31.6	7.2	192.9	34.6	347.4
1993–94	8.9	20.3	37.8	27.6	19.4	114.0	16.7	112.0	10.8	6.4	145.8	38.0	297.9
1994–95	9.4	13.3	29.8	34.4	24.0	110.9	12.8	111.3	9.3	0.4	133.8	10.2	254.8
1995–96	7.6	14.6	25.6	44.8	25.9	118.5	26.8	96.5	7.2	0.4	130.9	0.2	249.5
1996–97	1.0	19.3	34.3	27.6	22.8	104.9	23.4	60.2	4.5	0.3	88.4	8.2	201.5
1997–98	0.0	9.7	30.0	35.1	35.2	109.9	18.6	57.4	5.0	0.2	81.2	1.0	192.1
1998–99	8.5	12.0	23.3	17.9	23.2	84.8	38.8	71.3	5.7	10.9	126.8	0.6	212.1
1999–00	15.8	5.6	18.4	24.0	26.8	90.7	19.9	91.1	14.8	16.8	142.6	2.7	236.0
2000–01	8.4	4.3	13.6	15.0	29.2	70.5	25.6	107.4	15.9	0.5	149.4	5.2	225.1
2001–02	13.3	4.4	13.2	12.1	10.6	53.6	36.1	133.9	21.3	0.2	191.6	0.5	245.6
2002–03	11.2	8.9	11.1	12.9	12.2	56.3	37.5	137.6	24.8	0.0	199.9	0.2	256.5
2003–04	7.2	17.9	9.4	28.6	27.4	90.6	50.7	119.7	27.5	18.0	215.9	23.8	330.3
2004–05	5.6	19.3	12.7	25.0	20.3	82.9	42.5	161.4	39.5	20.5	263.9	18.9	365.7
2005–06	13.3	13.4	14.0	24.1	18.1	82.9	66.6	133.5	50.2	31.0	281.2	72.3	436.4
2006–07	8.4	12.1	20.1	27.8	23.3	91.7	59.8	149.8	54.7	22.9	287.1	48.9	427.7
2007–08	9.6	10.8	16.1	26.6	13.8	77.0	51.4	143.0	58.2	63.4	316.0	83.7	476.8
2008–09	11.1	13.8	18.0	27.3	16.1	86.4	55.5	160.5	65.8	98.0	379.7	90.1	556.2
2009–10	9.2	10.9	14.6	24.4	12.2	71.2	68.2	170.1	63.1	96.7	398.0	64.3	533.6
2010–11	8.8	21.6	16.2	28.7	15.3	90.5	97.6	146.8	68.0	94.5	406.9	54.5	551.9
2011–12	10.7	27.4	11.2	29.2	10.9	89.4	91.8	188.3	72.5	84.7	437.3	25.1	551.7
2012–13	9.2	22.0	12.6	30.0	6.4	80.3	93.1	226.1	79.4	93.2	491.9	6.3	578.4
2013–14	8.7	19.6	14.9	36.2	12.6	92.1	110.4	225.6	73.8	88.1	497.8	1.5	591.4
2014–15	18.0	16.1	12.2	38.8	14.7	99.8	92.2	221.1	69.1	89.7	472.2	10.7	582.7
2015–16	18.7	17.9	13.4	37.9	14.5	102.3	103.7	188.8	63.2	104.1	459.8	12.2	574.3
2016–17	10.0	13.9	10.1	33.8	16.9	84.6	103.0	169.5	69.2	109.0	450.6	18.9	554.2
2017–18	4.7	13.7	10.3	35.4	14.2	78.2	84.8	161.6	65.7	90.1	402.3	44.0	524.5
2018–19	11.9	18.3	6.8	33.4	6.3	76.7	60.2	94.9	29.5	33.1	217.8	53.6	348.1

Table A.7: Number of records by statistical area from 1991–92 to 2018–19 within the CPUE analysis (source: corrected catch data set, core vessels and core statistical areas only). A "–" indicates no records for that year-area strata.

Fishing	CRA 1				CRA 2			Total
year	901	902	903	904	905	906	907	
1991–92	5	15	26	24	9	20	–	99
1992–93	1	16	26	30	9	22	–	104
1993–94	–	10	41	30	18	26	1	126
1994–95	4	8	58	43	22	22	11	168
1995–96	8	18	40	28	15	36	5	150
1996–97	2	24	27	27	10	25	3	118
1997–98	3	14	27	24	10	16	4	98
1998–99	1	17	19	24	37	31	4	133
1999–00	10	11	20	21	21	31	4	118
2000–01	16	11	25	23	33	55	5	168
2001–02	13	11	24	16	66	58	9	197
2002–03	12	16	12	15	62	66	11	194
2003–04	–	23	17	25	87	46	11	209
2004–05	18	16	26	26	58	56	11	211
2005–06	19	19	22	24	89	59	24	256
2006–07	26	24	34	23	88	92	23	310
2007–08	39	36	32	21	86	99	29	342
2008–09	26	18	36	19	71	115	26	311
2009–10	25	27	29	26	97	88	26	318
2010–11	19	36	26	24	105	95	35	340
2011–12	33	33	31	34	94	122	31	378
2012–13	21	18	11	33	94	126	37	340
2013–14	3	34	32	49	89	153	42	402
2014–15	21	16	8	41	89	116	41	332
2015–16	9	27	19	39	117	98	40	349
2016–17	20	26	16	15	75	79	32	263
2017–18	9	33	27	23	96	108	43	339
2018–19	11	20	22	9	40	57	17	176

Table A.8: Number of records with positive packhorse rock lobster catch by statistical area from 1991–92 to 2018–19 within the CPUE analysis (source: corrected catch data set, core vessels and core statistical areas only). A "-" indicates no records for that year-area strata.

Fishing	CRA 1				CRA 2			Total
year	901	902	903	904	905	906	907	
1991–92	1	5	1	–	–	6	–	13
1992–93	–	3	2	14	–	7	–	26
1993–94	–	–	13	9	–	5	–	27
1994–95	–	1	21	10	–	10	4	46
1995–96	3	7	16	6	7	12	1	52
1996–97	1	5	14	7	3	7	–	37
1997–98	–	4	7	8	–	6	1	26
1998–99	1	7	9	5	12	15	1	50
1999–00	2	4	10	4	–	17	–	37
2000–01	5	4	10	5	12	37	2	75
2001–02	4	2	11	4	22	39	4	86
2002–03	3	8	7	3	14	23	6	64
2003–04	–	5	7	10	21	21	4	68
2004–05	9	7	9	13	22	31	4	95
2005–06	9	6	9	13	30	31	5	103
2006–07	13	8	10	12	25	49	7	124
2007–08	15	11	11	12	23	48	11	131
2008–09	9	1	12	9	20	54	12	117
2009–10	10	12	9	13	26	31	9	110
2010–11	9	10	8	10	52	43	18	150
2011–12	11	12	9	18	38	55	15	158
2012–13	–	7	5	7	35	60	17	131
2013–14	1	7	13	24	42	75	19	181
2014–15	–	5	3	17	44	51	19	139
2015–16	1	9	3	17	50	30	16	126
2016–17	3	6	–	7	28	32	10	86
2017–18	1	12	10	13	36	50	21	143
2018–19	3	9	9	–	15	24	8	68

APPENDIX B. LENGTH-FREQUENCY PLOTS

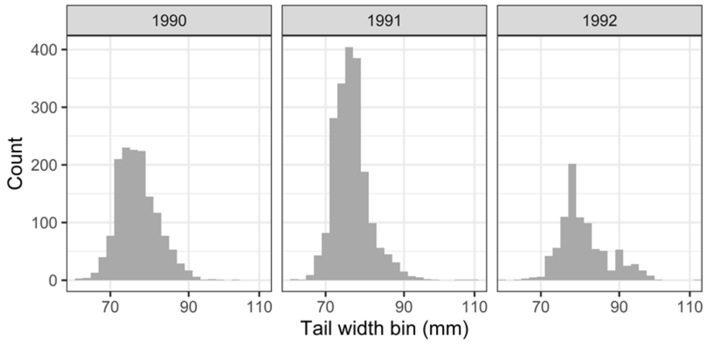

Figure B.1: Length-frequency plots (2 mm tail width length bins) of male packhorse rock lobsters (PHC) from the PHC exploratory catch sampling programme by fishing year, from 1990–91 to 1992–93 (labelled with first year of the pair).

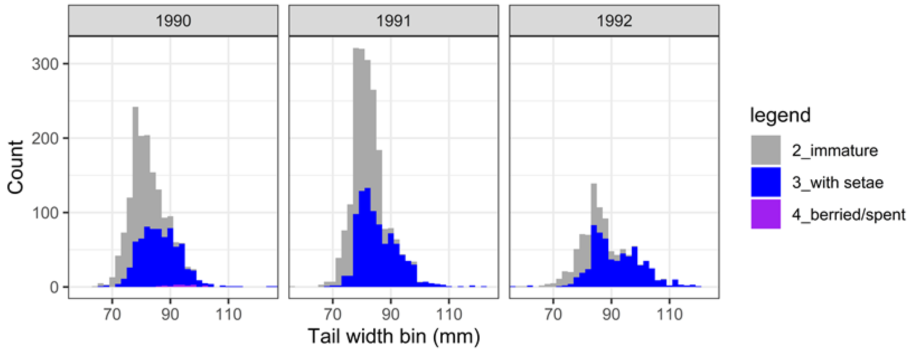

Figure B.2: Length-frequency plots (2 mm tail width length bins) of female packhorse rock lobsters (PHC) from the PHC exploratory catch sampling programme by fishing year, from 1990–91 to 1992–93 (labelled with first year of the pair).

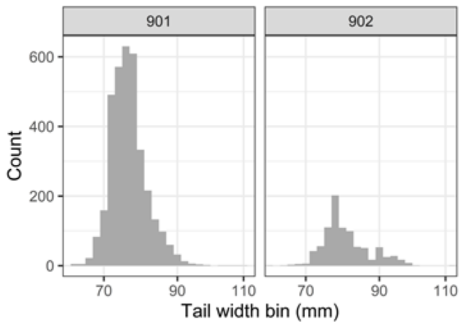

Figure B.3: Length-frequency plots (2 mm tail width length bins) of male packhorse rock lobsters (PHC) from the PHC exploratory catch sampling programme by statistical area, from 1990–91 to 1992–93.

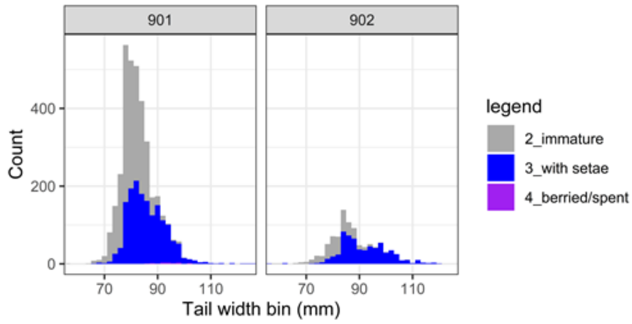

Figure B.4: Length-frequency plots (2 mm tail width length bins) of female packhorse rock lobsters (PHC) from the PHC exploratory catch sampling programme by statistical area, from 1990–91 to 1992–93.

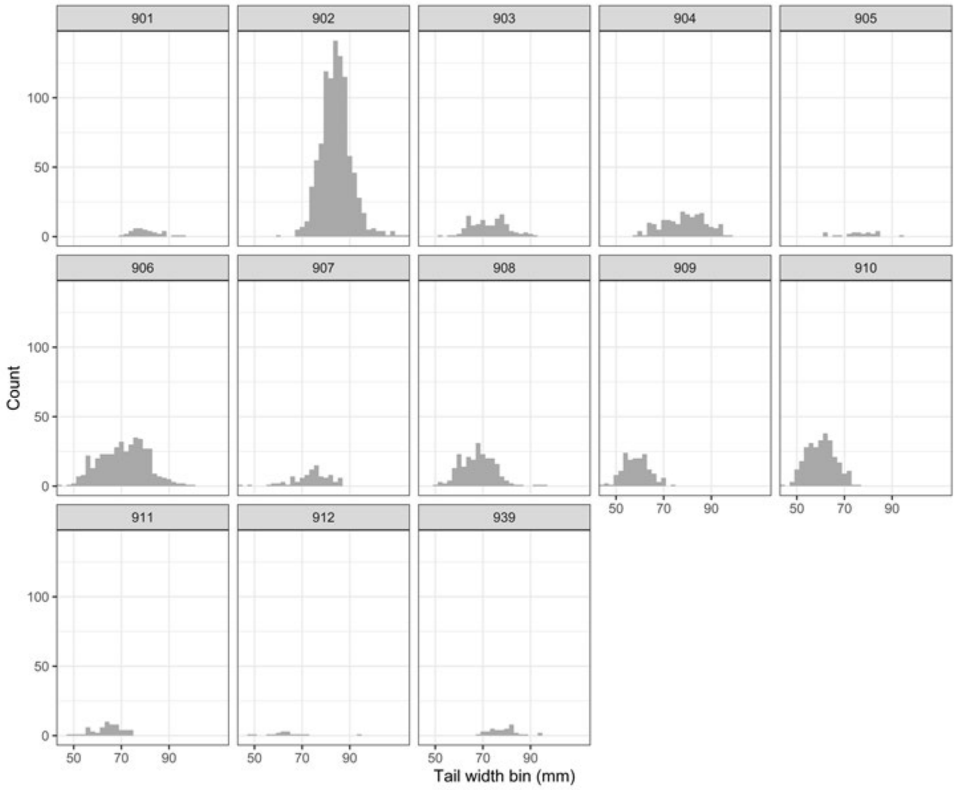

Figure B.5: Length-frequency plots (2 mm tail width length bins) of male packhorse rock lobsters (PHC) from the CRA catch sampling programme by statistical area, from 2005–06 to 2018–19.

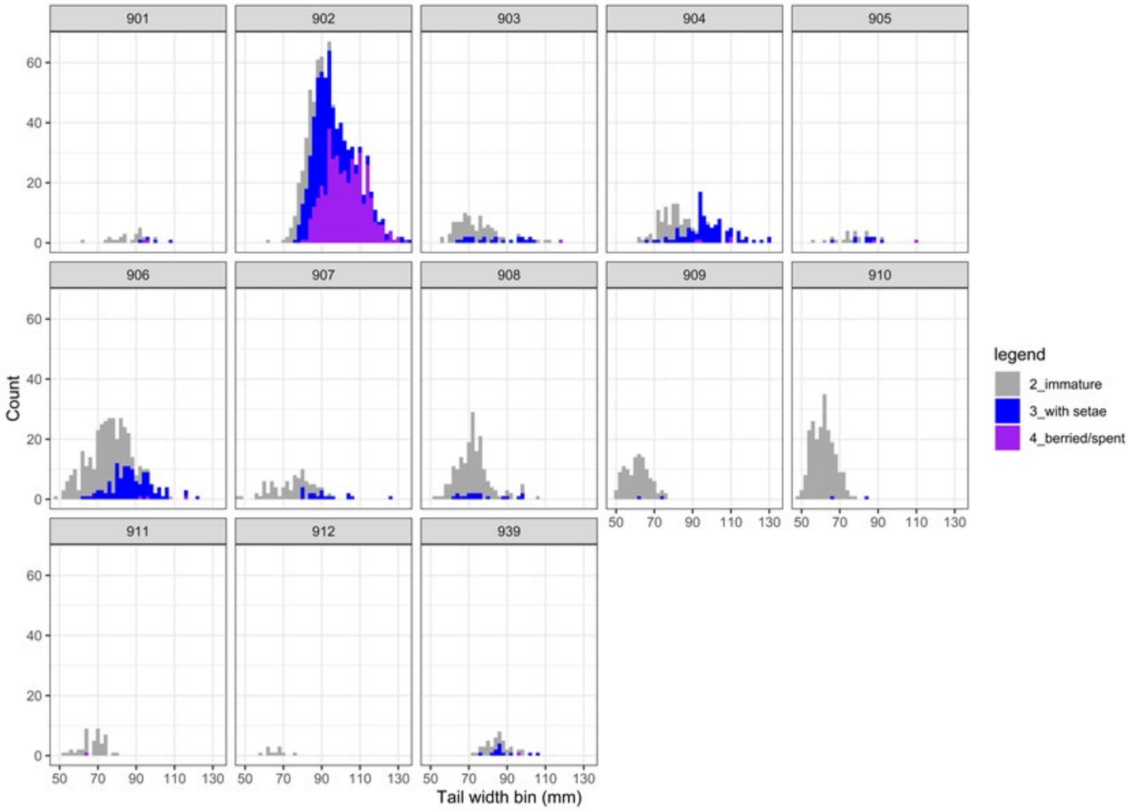

Figure B.6: Length-frequency plots (2 mm tail width length bins) of <u>female</u> packhorse rock lobsters (PHC) from the <u>CRA catch sampling programme</u> by statistical area, from 2005–06 to 2018–19.

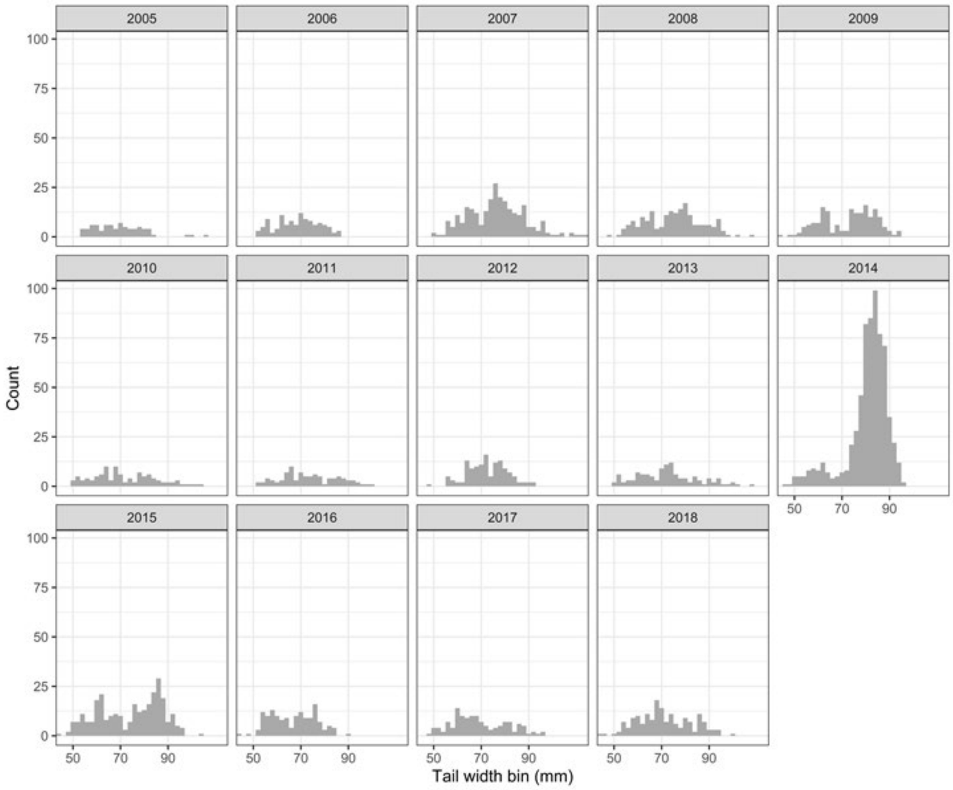

Figure B.7: Length-frequency plots (2 mm tail width length bins) of <u>male</u> packhorse rock lobsters (PHC) from the <u>CRA catch sampling programme</u> by fishing year, from 2005–06 to 2018–19 (labelled with first year of the pair).

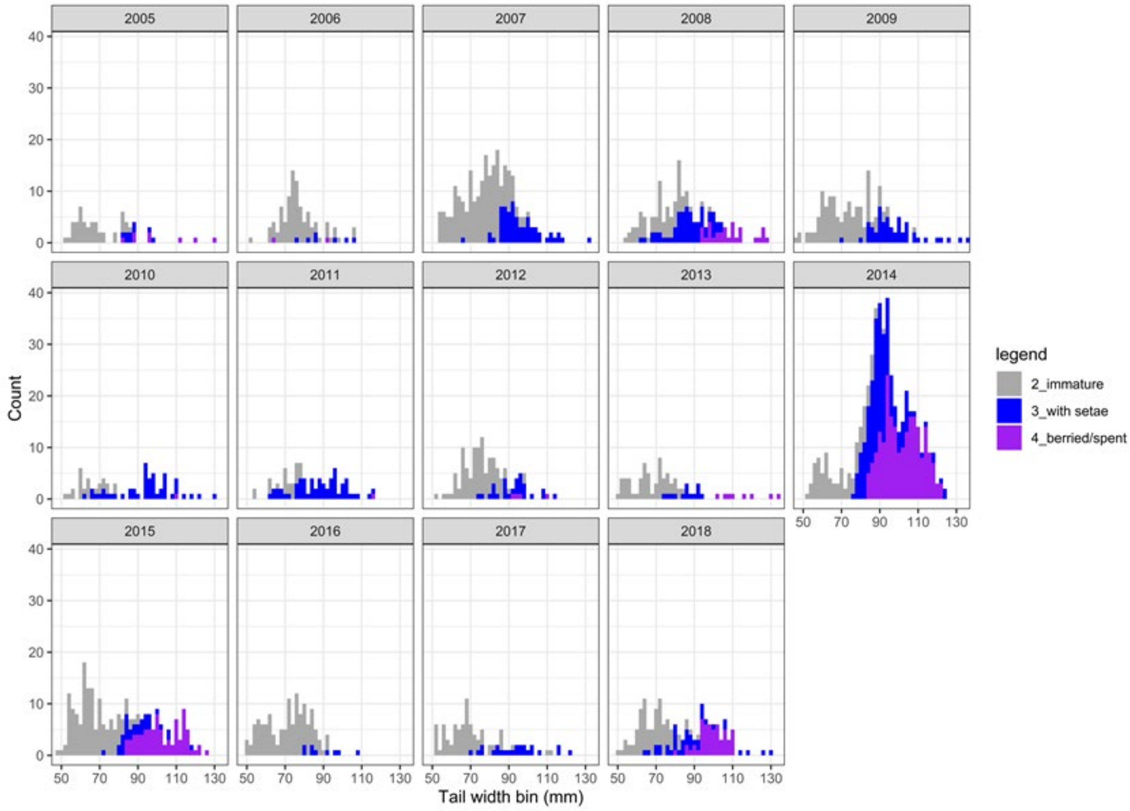

Figure B.8: Length-frequency plots (2 mm tail width length bins) of female packhorse rock lobsters (PHC) from the CRA catch sampling programme by fishing year, from 2005–06 to 2018–19 (labelled with first year of the pair).

APPENDIX C. DIAGNOSTIC PLOTS FOR THE CPUE STANDARDISATION

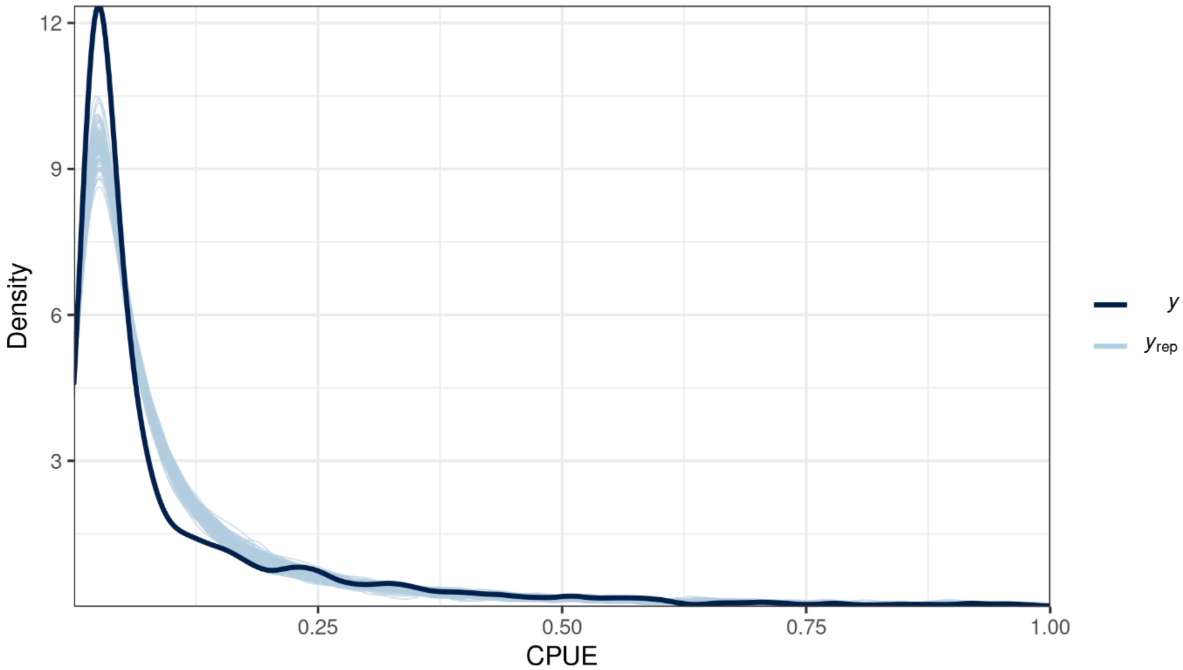

Figure C.1: Comparison of the empirical distribution of the data (*y*) to the distributions of simulated/replicated data (*y_{rep}*) from the posterior predictive distribution.

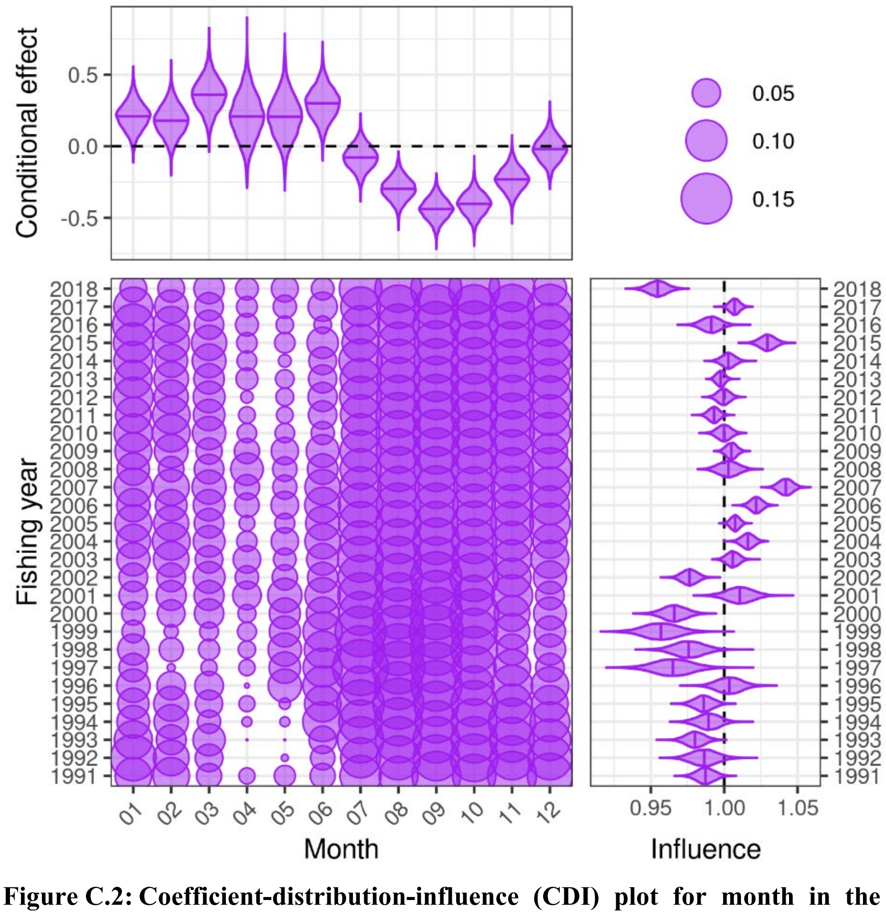

Figure C.2: Coefficient-distribution-influence (CDI) plot for month in the hurdle sub-model. Months (January to December) are labelled from '01' to '12', inclusive.

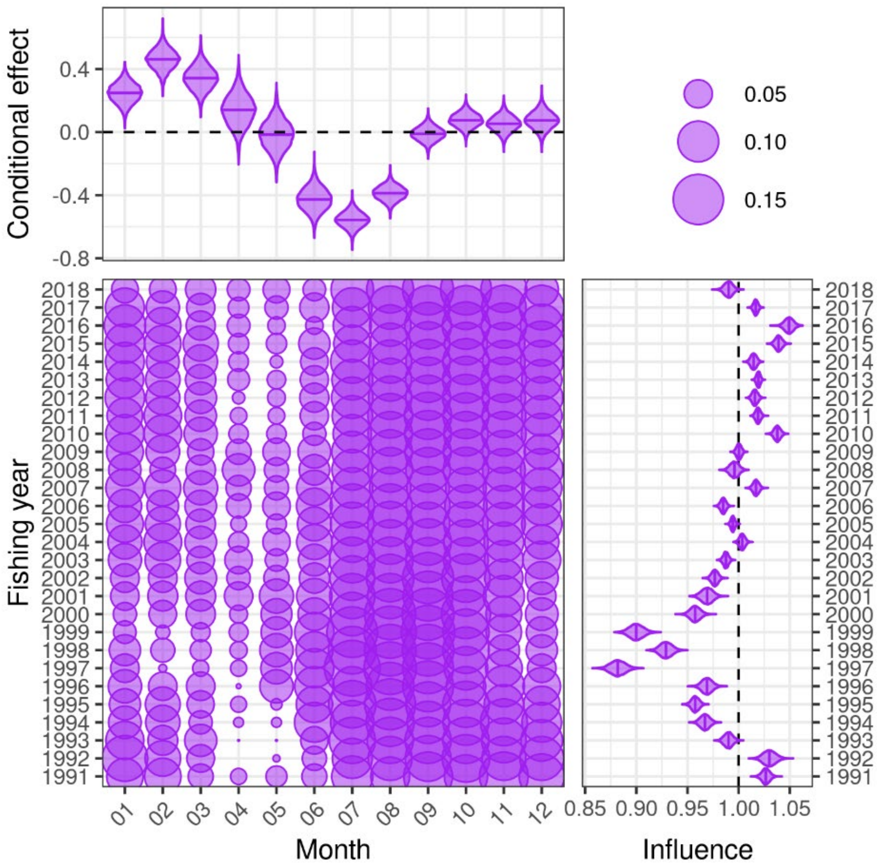

Figure C.3: Coefficient-distribution-influence (CDI) plot for month in the lognormal sub-model. Months (January to December) are labelled from '01' to '12', inclusive.

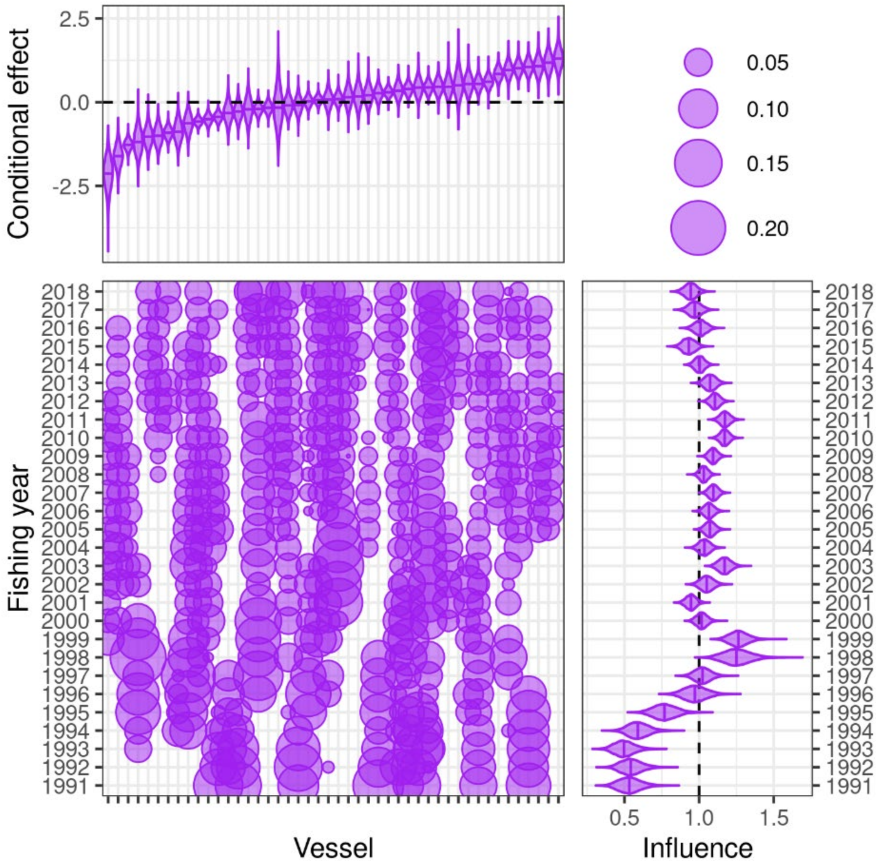

Figure C.4: Coefficient-distribution-influence (CDI) plot for vessel in the hurdle sub-model.

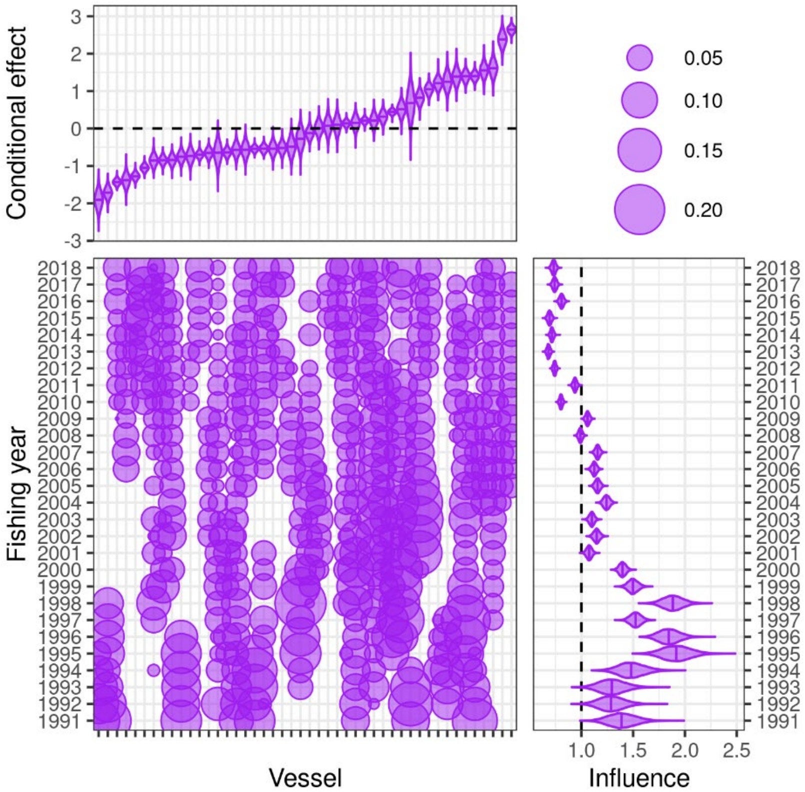

Figure C.5: Coefficient-distribution-influence (CDI) plot for vessel in the lognormal sub-model.

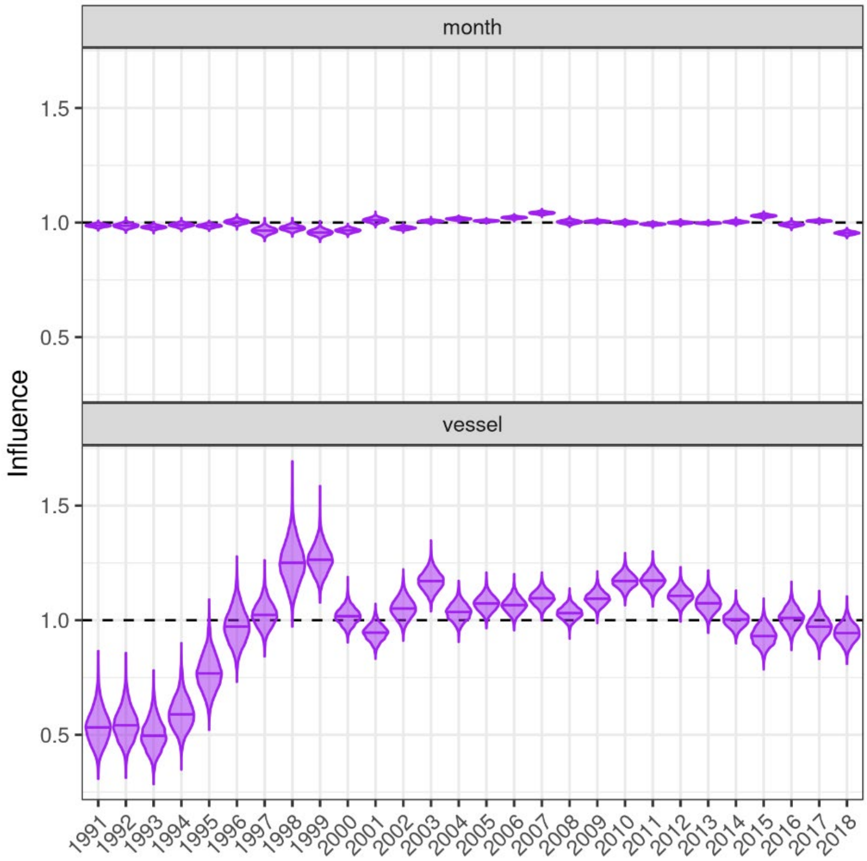

Figure C.6: Influence of month and vessel in the hurdle sub-model.

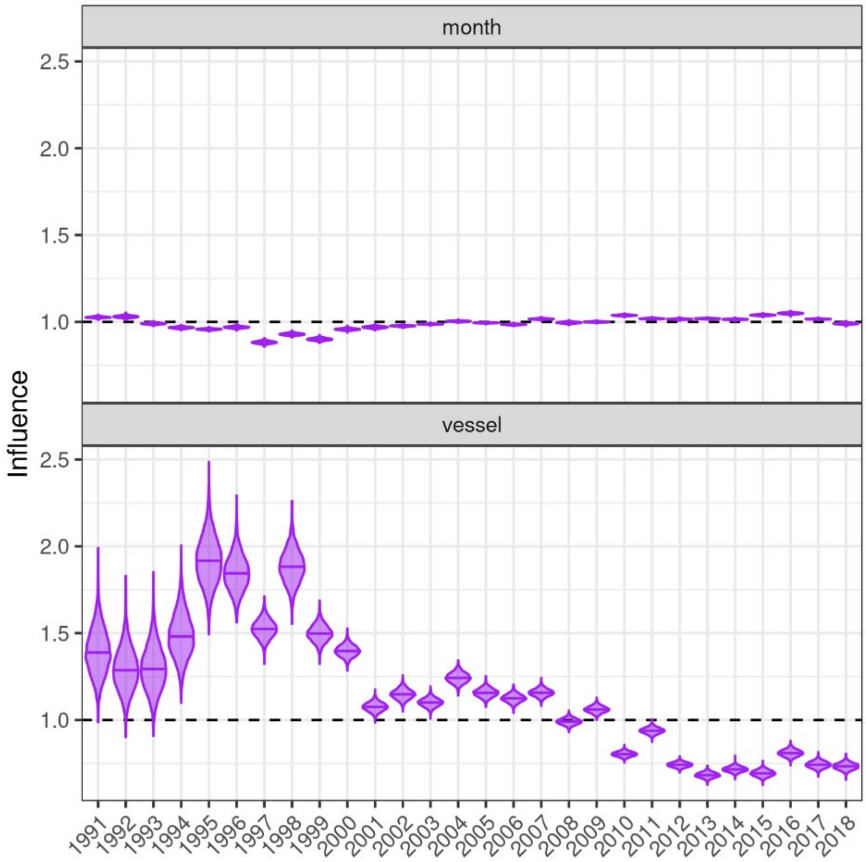

Figure C.7: Influence of month and vessel in the lognormal sub-model.

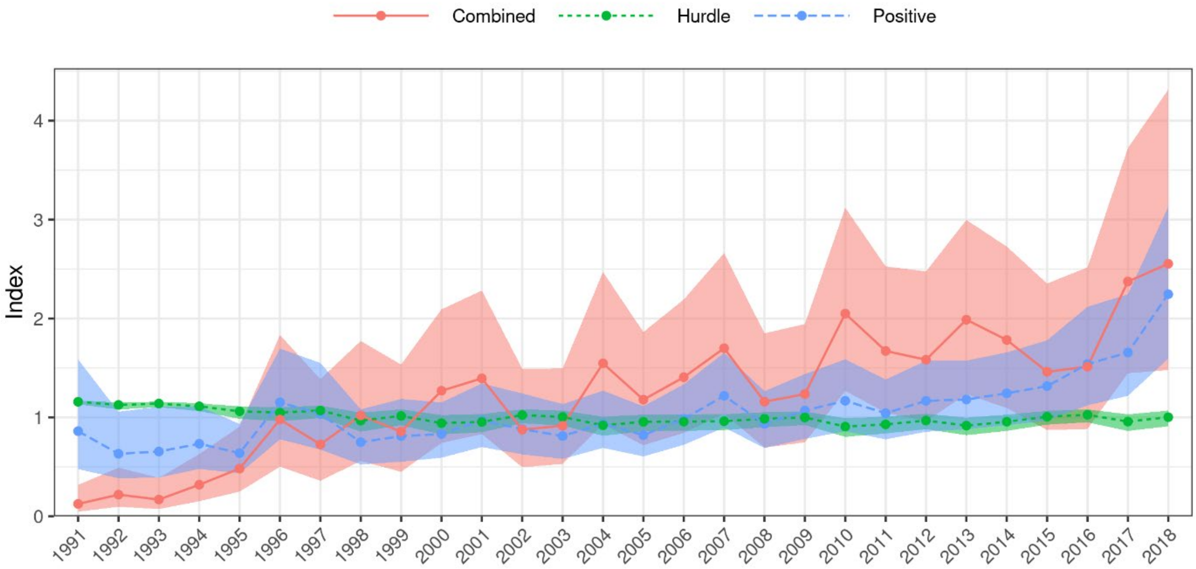

Figure C.8: The series for the hurdle model, the lognormal (positive) model, and the combined model. The shaded regions represent the 25% and 75% credible intervals.

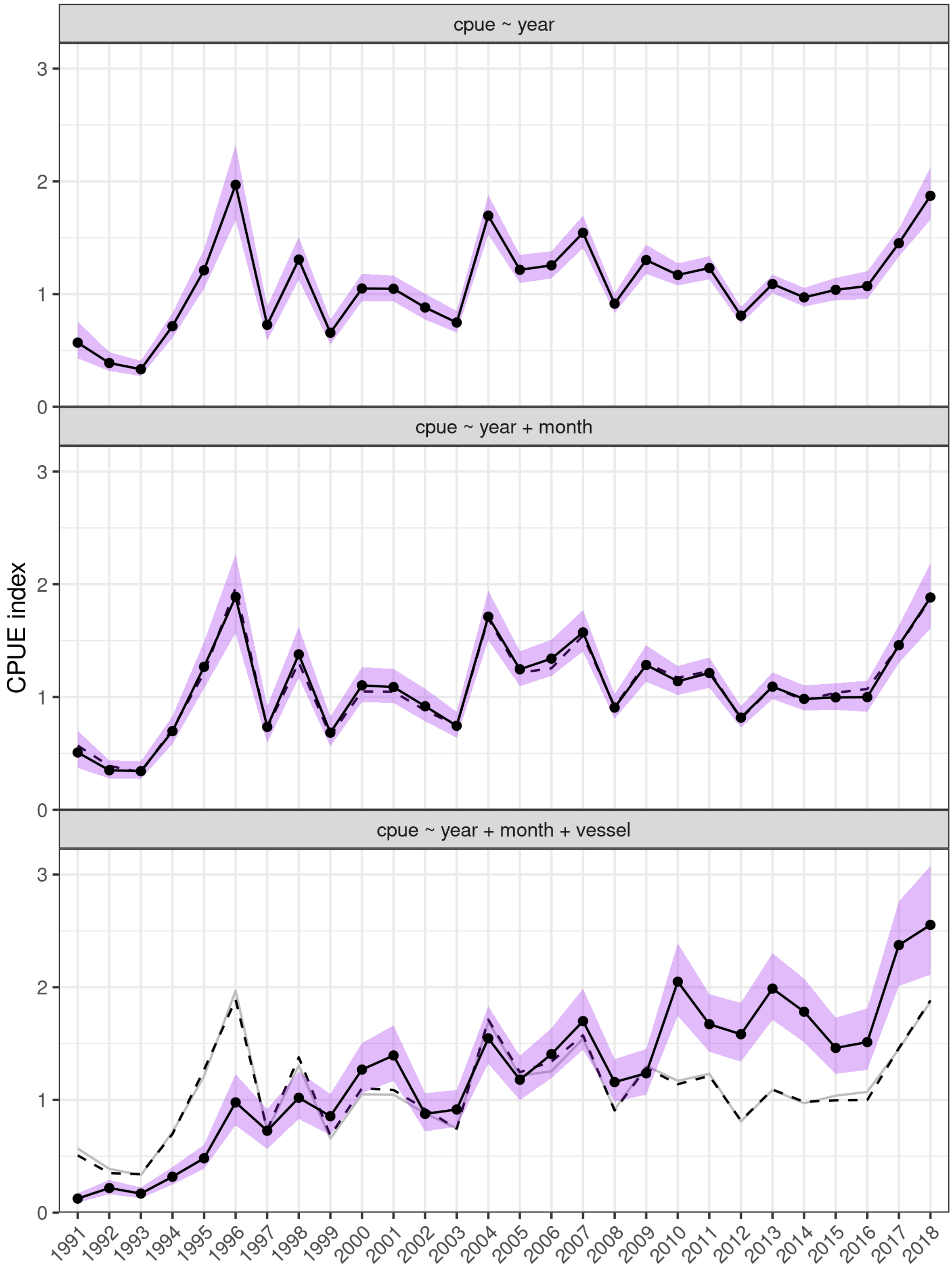

Figure C.9: Step plot for the full model (i.e., hurdle and lognormal). Dashed line shows the previous series and the grey line shows the initial series. Black points and purple shaded areas are the median and 90% of the credible interval of the model prediction.

APPENDIX D. DIAGNOSTIC PLOTS FOR THE STOCK ASSESSMENT

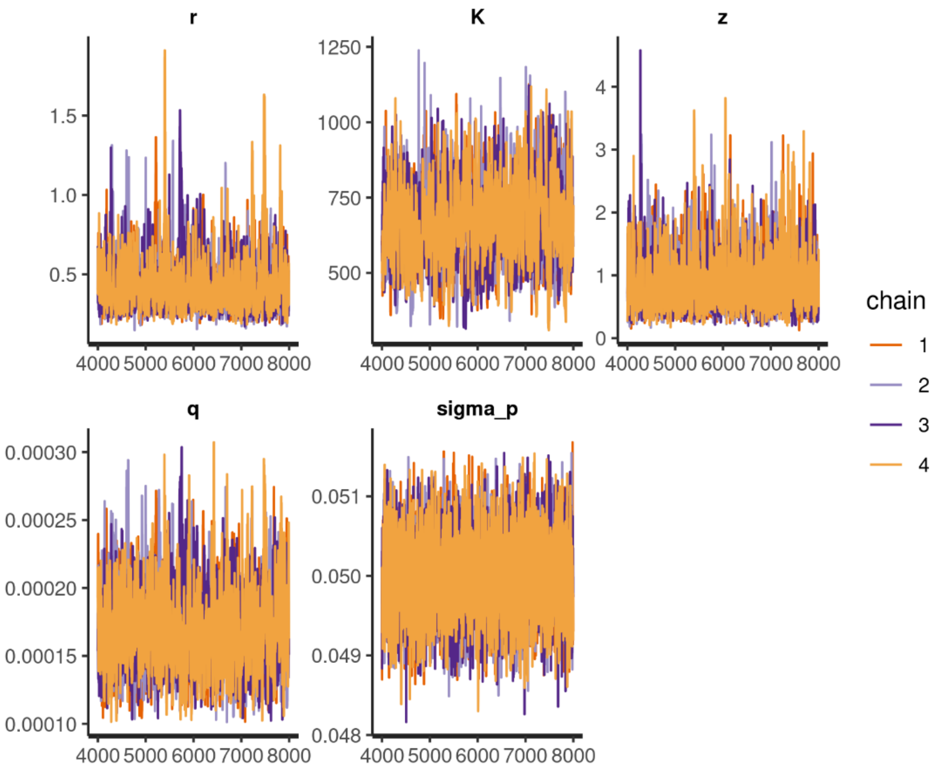

Figure D.1: MCMC trace plots for the base model run.

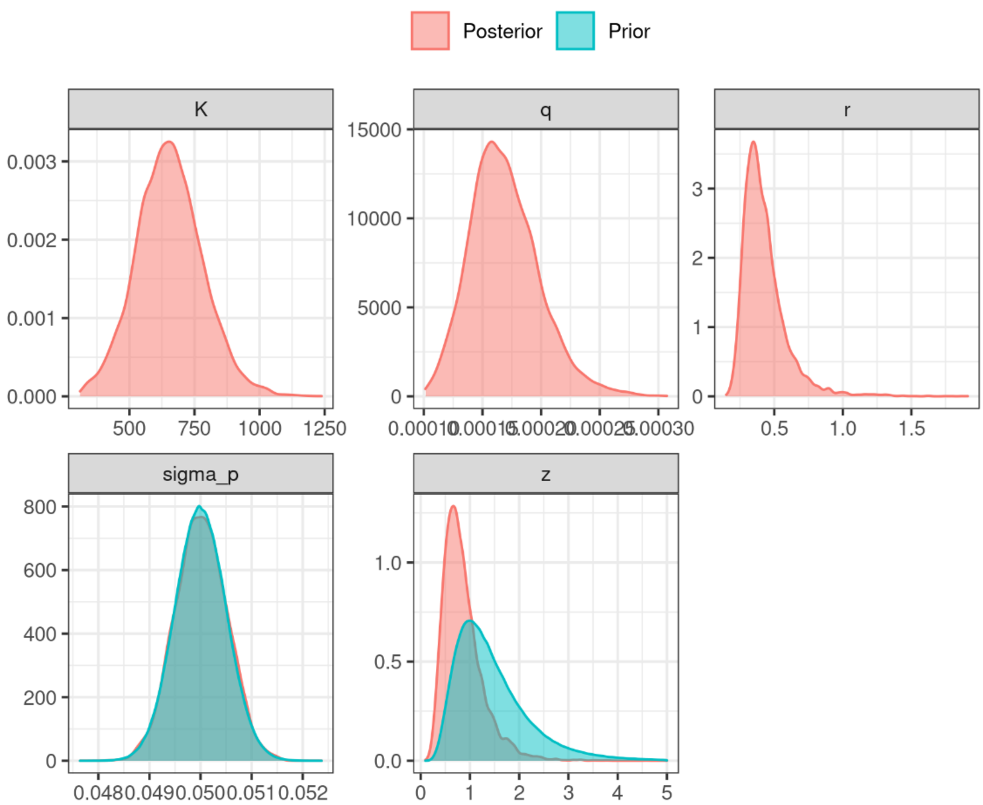

Figure D.2: Prior and posterior distributions for the base model run.

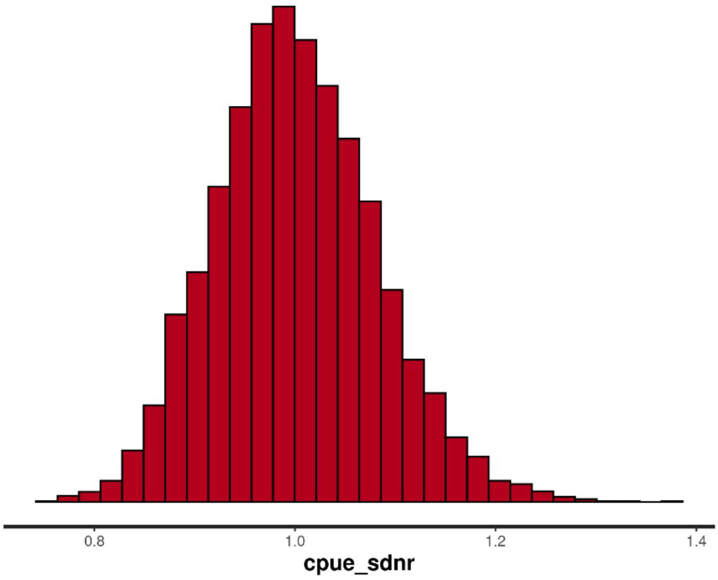

Figure D.3: SDNR for the base model run.

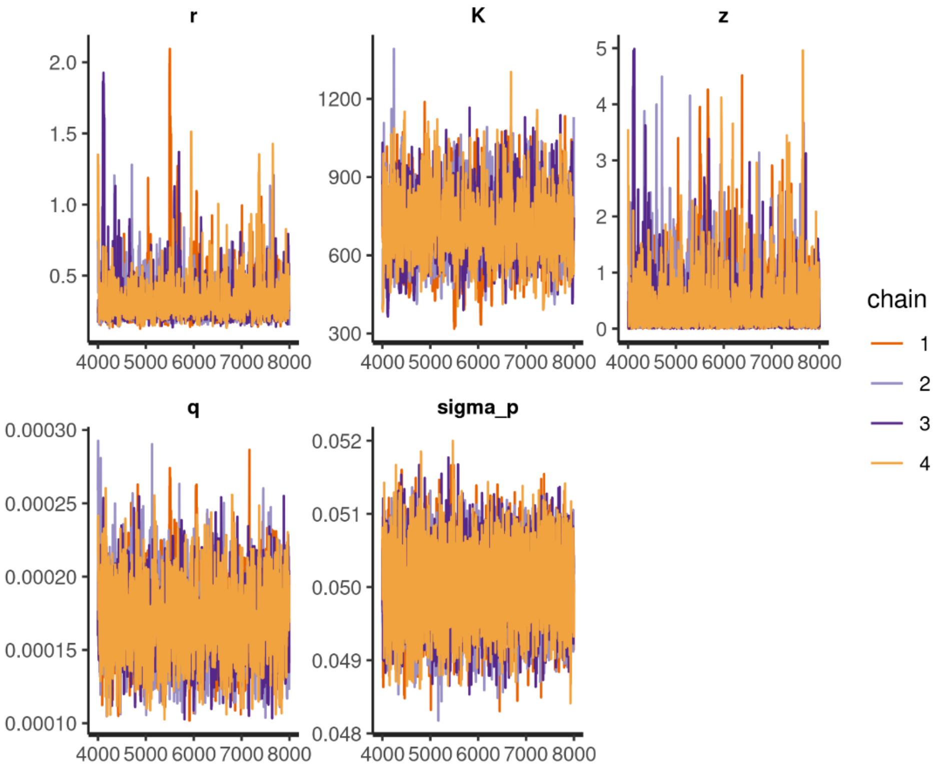

Figure D.4: MCMC trace plots for the flat_z model run.

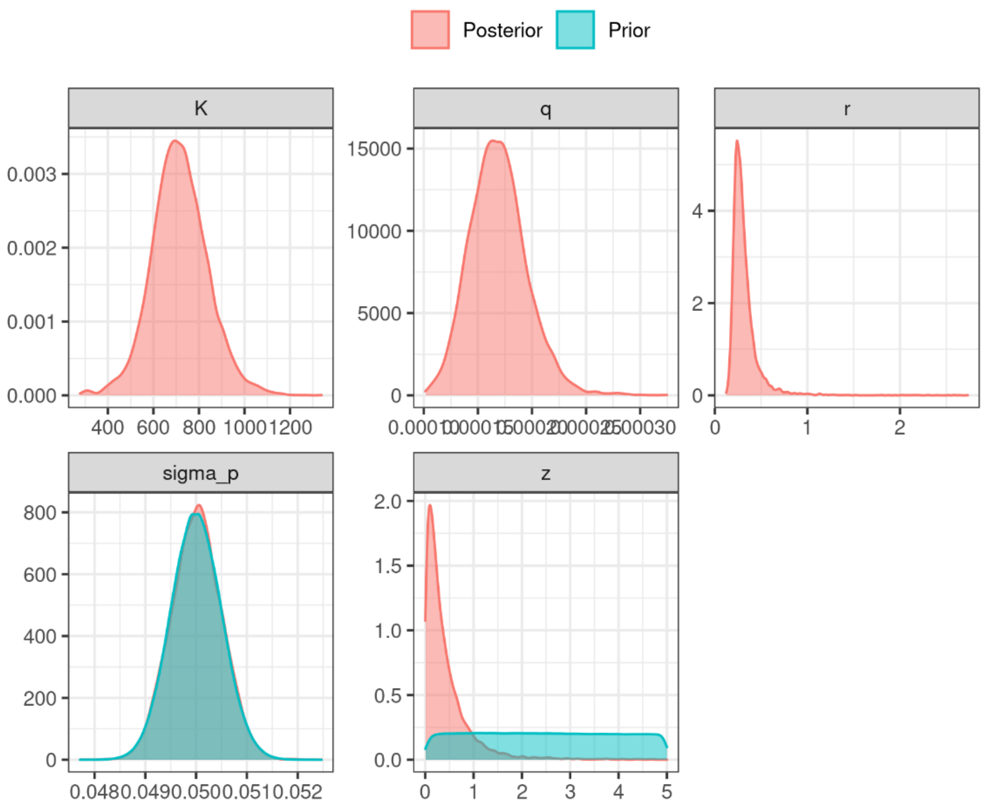

Figure D.5: Prior and posterior distributions for the flat_z model run.