Fisheries

Northern Zone Rock Lobster (*Jasus edwardsii*) Fishery Stock Assessment 2020/21

A. Linnane, R. McGarvey, J. Feenstra and D. Graske

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Government of South Australia
Department of Primary Industries and Regions

SARDI
SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

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EXECUTIVE SUMMARY

This stock assessment determined the status of South Australia's Northern Zone Rock Lobster Fishery (NZRLF) and provides the latest estimates of the biological performance indicators (PIs) in context of the reference points (RPs) and stock status classification described in the Management Plan for the fishery (PIRSA 2021). Stock status was determined using the harvest strategy for the fishery that was developed in alignment with the National Fishery Status Reporting Framework (NFSRF) classification system that is used to determine the status of all South Australian fish stocks (Piddocke et al. 2021).

Assessment of the NZRLF relies heavily on data from the commercial fishing sector through mandatory catch and effort logbook reporting. Catch per unit effort (CPUE) of legal and undersized (pre-recruit) lobsters are the main indicators of legal and pre-recruit abundance, respectively. Fishery model outputs also contribute to the assessment.

The 2020 season (i.e. 2020/21) was the second consecutive year the NZRLF was impacted by overseas market disruptions. Therefore, to allow for greater fishing flexibility, the 2020 season was extended from 1 November to 30 October (normally 1 November to 31 May).

In 2020, the total allowable commercial catch (TACC) in the NZRLF was 324 t (263 t Inner sub-region, 61 t Outer sub-region). This reflected a regular TACC of 296 t plus 28 t of carry-over from the 2019 season. The reported logbook catch (1 November 2020 to 31 October 2021) was 249.00 t (77% of the TACC). By sub-region, the catch was 225.69 t and 23.31 t from the Inner and Outer sub-regions, respectively.

Effort required to take the catch was 249,293 potlifts, reflecting the fifth consecutive season that effort has decreased and the lowest estimate on record (but noting that the TACC was under-caught in both 2019 and 2020).

Nominal catch per unit effort (CPUE) of legal-sized lobsters (kg/potlift) is the primary biological performance indicator for the fishery. In 2020, the zonal CPUE was 1.05 kg/potlift, reflecting a 36% increase from 2016 (0.77 kg/potlift) and the highest CPUE since 2011. This estimate is above the Trigger Reference Point (TrRP) (0.60 kg/potlift) for the fishery. CPUE increases were evident in both inner and outer sub-regions in 2020.

The secondary biological performance indicator is the pre-recruit index (PRI; no. of undersized lobsters/potlift). In 2020, the PRI was 0.22 undersized/potlift reflecting a 10% increase from 2019 (0.20 undersized/potlift) and remaining above the TrRP of 0.16 undersized/potlift. In the NZRLF, the time taken for pre-recruits to enter the fishable biomass is estimated to be approximately one year.

Model outputs show long-term declines in lobster biomass from 1999 to 2008. While overall biomass remains low in 2020, levels have increased over the last four seasons, which, combined with reduced TACCs and under-catch in 2020, have reduced the exploitation rate to 19%, the lowest on record. Despite improvements at the zonal level,

the performance of the Outer sub-region of the fishery remains uncertain due to the low levels of catch in recent seasons (17 t in 2019 and 23 t in 2020).

The stock status classification for the NZRLF is defined in the Management Plan for the fishery (PIRSA 2021). In 2020, the CPUE of 1.05 kg/potlift was above the TrRP of 0.60 kg/potlift. As a result, the NZRLF stock is classified as "**sustainable**". This means that the current fishing mortality is being adequately controlled to avoid the stock becoming recruitment impaired.

Table 1. Key statistics for the NZRLF.

Statistic	2020/21	2019/20
TACC	324 t	296 t
Total commercial catch (Nov-Oct)	249.0	219.6 t
Total effort (Nov-Oct)	249,293 poltifts	254,563 potlifts
Commercial CPUE (Nov-Apr)	1.05 kg/potlift	0.89 kg/potift
Pre-recruit index (Nov-Mar)	0.22 undersized/potlift	0.20 undersized/potlift
Biomass estimate	1,388 t	1,255 t
Exploitation rate	19%	19%
Status	**Sustainable**	**Sustainable**

Keywords: Southern Rock Lobster, *Jasus edwardsii*, stock assessment, harvest strategy, total allowable commercial catch.

1 INTRODUCTION

1.1 Overview

Stock assessments for the South Australian Northern Zone Rock Lobster (*Jasus edwardsii*) Fishery (NZRLF) have been produced annually since 1996 (McGarvey et al. 1997). The current report presents information on the fishery and biology of the species and provides a current assessment of the status of the NZRLF in relation to the performance indicators provided in the Management Plan for the fishery (PIRSA 2021).

1.2 Description of the Fishery

1.2.1 Access

Southern Rock Lobster is a highly valued fishery species across the States of South Australia, Victoria and Tasmania for both commercial and recreational fishing sectors. Within South Australia, the commercial fishery is divided into two zones: Northern and Southern, with an approximate NZRLF value of $25.5 million in 2018/19 (Econsearch 2020). The NZRLF includes all South Australian marine waters between the mouth of the Murray River and the Western Australian border and covers an area of 207,000 km^2 (Figure 1-1). It is comprised of 50 Marine Fishing Areas (MFAs), but most of the fishing is conducted in ten MFAs (7, 8, 15, 27, 28, 39, 40, 48, 49 and 50).There are 63 commercial licences with lobsters caught using steel-framed pots (Figure 1-2) that are set overnight and hauled at first light.

1.2.2 Management arrangements

The NZRLF is managed by the South Australian State Government's Primary Industries and Regions South Australia (PIRSA), Fisheries and Aquaculture Division, in accordance with the legislative framework provided within the *Fisheries Management (General) Regulations 2017* while specific regulations are established in the *Fisheries Management (Rock Lobster Fisheries) Regulations 2017*. The policy, objectives and strategies to be employed for the sustainable management of the NZRLF are described in the *Management Plan for the South Australian Commercial Northern Zone Rock Lobster Fishery* (PIRSA 2014). Recreational fishers are regulated under the *Fisheries Management (General) Regulations 2017.*

The commercial NZRLF has undergone considerable management changes over the past 50 years that has seen the fishery restructured and limited through gear restrictions, spatial and temporal closures, size limits and the implementation of a total allowable commercial catch (TACC) in 2003 (Table 1-1). The TACC is set annually and divided proportionally between licence holders owning individual transferable quota (ITQ) units. The daily catch of individual vessels is monitored via catch and disposal records and mandatory commercial logbooks. In 2015/16, based on the outcomes from Linnane et al. (2016), spatial management of the zone was implemented and individual quotas for "Inner" and "Outer" sub-regions were introduced. In addition, the annual fishing closure (1 June to 31 October) in the Outer sub-region was removed, resulting in a 12-month fishing season (1 November to 31 October). The fishing season for the Inner sub-region remained unchanged (1 November to 31 May) up to 2018/19. In 2019/20 and 2020/21, the annual fishing closure was also removed from the Inner sub-region on a temporary basis. Details of all management arrangements for the 2020/21 season are provided in Table 1-2.

1.2.3 Recreational Fishery

Recreational fishers are allowed to use drop-nets, pots or diving to take lobsters during the same season as commercial fishers. All recreational lobster pots must be registered. The recreational season extends from 1 November to 31 May.

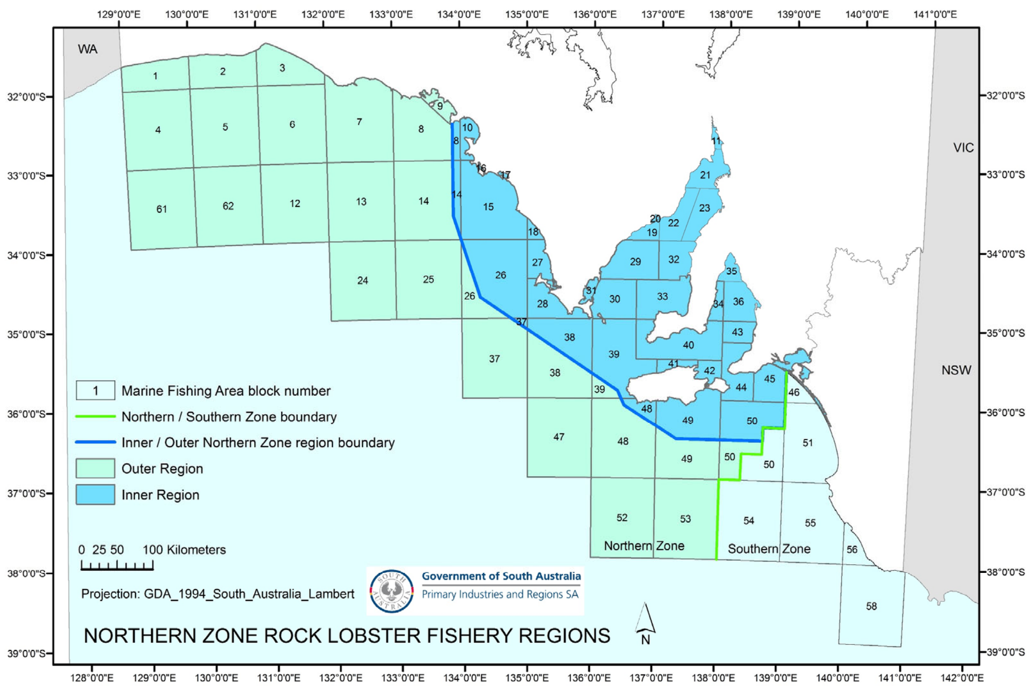

Figure 1-1 MFAs in the Northern and Southern Zones of the South Australian Rock Lobster Fishery. Blue line represents Northern Zone Inner and Outer region boundary.

Figure 1-2 A commercial Southern Rock Lobster fishing pot

Table 1-1 Major management milestones for the NZRLF.

Year	Management milestone
1968	Limited entry declared
1985	10% pot reduction; max number of pots set at 65
1992	10% pot reduction; max number of pots decreased to 60
1993	1 week closure during season
1994	Minimum legal size (MLS) increased from 98.5 to 102 mm carapace length (CL); further "1-week" closure
1995	Further "1-week" closure added
1997	Flexible closures introduced; first Management Plan published (Zacharin 1997)
1999	Extra 3 days of fixed closure added
2000	MLS increased from 102 to 105 mm CL
2001	7% effort reduction
2002	8% effort reduction; max number of pots increased to 70
2003	TACC implemented for the 2003 season at 625 t; VMS and escape gaps introduced
2004	TACC reduced to 520 t; Vessel length and power restrictions removed
2005	Max number of pots increased to 100
2007	Second Management Plan published (Sloan and Crosthwaite 2007)
2008	TACC reduced to 470 t
2009	TACC reduced to 310 t
2011	New Harvest Strategy developed
2012	TACC increased to 345 t
2013	Four licences removed from fishery through marine parks voluntary commercial fisheries catch and effort reduction program. SLEDs introduced.
2014	Third (current) Management Plan published (PIRSA 2014). TACC reduced to 323.2 t
2015	Spatial management implemented. TACC set at 300 t for Inner sub-region and 60 t for Outer sub-regions.
2016	Annual fishing closure (1 June to 31 October) in Outer sub-region removed.
2017	Inner sub-region TACC reduced to 250 t. Outer sub-region TACC retained at 60 t.
2018	Outer sub-region TACC reduced to 46 t. Inner sub-region TACC retained at 250 t.
2019	Annual fishing closure (1 June to 31 October) in Inner sub-region removed temporarily.

Table 1-2 Management arrangements for the NZRLF in 2020/21. *Includes 28 t carry-over from 2019/20.

Management tool	Current restriction
Total Allowable Commercial Catch (TACC)	*324 t (263 t Inner sub-region and 61 t Outer sub-region)
Closed season	1 June to 31 October (Inner sub-region only but temporarily removed in 2019/20 and 2020/21)
Limited entry	63 licences
Total number of pots	3,694
Minimum size limit	105 mm CL
Maximum number of pots/licence	100 pots
Minimum number of pots/licence	20 pots
Maximum quota unit holding	Unlimited
Minimum quota unit holding	320 quota units
Spawning females	No retention
Maximum vessel length	None
Maximum vessel power	None
Closed areas	Gleeson Landing Reserve
Catch and effort data	Daily logbook submitted monthly
Catch and Disposal Records (CDRs)	Daily records submitted upon landing
Landing times	Landings permitted at any time during the season
Prior landing reports to PIRSA	1 hour before removing lobster from vessel
Escape gaps	2 gaps per pot
Vessel Monitoring System (VMS)	Operational VMS units required on all vessels during the season
Bin tags	All bins must be sealed with a lid and an approved tag prior to lobster being unloaded from the vessel. Tags are sequentially numbered.
Sea Lion Exclusion Device (SLED)	Mandatory in all pots used in water <100 m

1.3 Biology of Southern Rock Lobster

Southern Rock Lobster are distributed around southern mainland Australia, Tasmania and New Zealand. In Australia, the northern limits of distribution are Geraldton in Western Australia and Coffs Harbour in northern New South Wales, but the bulk of the population is found in South Australia, Victoria, and Tasmania where they occur on algal-dominated reef habitat to depths of approximately 200 m.

Detailed reviews on the reproductive biology and life history of *J. edwardsii* are provided in Phillips (2013). In brief, *J. edwardsii* mate from April to July followed by a brooding period of 3–4 months over the Austral winter (June to August) (MacDiarmid 1989). Larvae hatch in early spring and pass through a brief (10-14 days) nauplius period before entering into a planktonic, leaf-like phase called a phyllosoma. These develop through a series of 11 stages over 12–23 months before metamorphosing into the puerulus stage (Booth et al. 1991; Bruce et al. 1999). Puerulus can actively swim thereby aiding settlement onto suitable reef habitat (Booth et al. 1991; Phillips and McWilliam 2009).

In South Australia, the strength of westerly winds during late winter and early spring, plays an important role in inter-annual settlement variation (McGarvey and Matthews 2001; Linnane et al. 2010). After inshore settlement, early juveniles (<20 mm carapace length, CL) are solitary and normally found in isolated holes and crevices. As they develop, juvenile lobsters become increasingly communal with larger juveniles and sub-adults residing in large aggregations inside rocky dens within structurally complex reef habitat.

Based on morphological and mitochondrial DNA analysis, historical research provided little evidence of population sub-structuring across mainland Australia, Tasmania and New Zealand (Smith et al. 1980; Brasher et al. 1992; Ovenden et al. 1992). The long larval phase and widespread occurrence of larvae across the central and south Tasman Sea, in conjunction with known current flows, pointed to the likely transport of phyllosoma from south-eastern Australia to New Zealand, providing genetic mixing between the two populations (Booth et al. 1990; Bruce et al. 2007). More recent and powerful genetic techniques however have rejected the concept of panmixia and revealed significant population structure in both Tasmanian (Morgan et al. 2013) and New Zealand (Thomas 2012) stocks.

1.4 Research program

SARDI Aquatic Sciences maintains an on-going stock assessment and monitoring program for both the Northern and Southern Zone rock lobster fisheries of South Australia. Outputs from the program are provided to the Primary Industries and Regions of South Australia (PIRSA) Fisheries and Aquaculture, through a series of annual status and stock assessment reports. Dedicated research projects are also undertaken periodically to address key knowledge gaps or improve ongoing stock assessments (McGarvey et al. 2014; Linnane et al. 2016).

1.5 Information sources for assessment

1.5.1 Commercial catch and effort data

All licenced commercial fishers are required to complete a daily logbook of fishing activity. This includes information such as MFA fished, species targeted, species caught, weight of legal–sized catch, number of legal–sized lobsters landed and fishing effort as potlifts. In addition to mandatory details, a number of voluntary fields may also be completed such as number of undersized individuals, lobster mortalities and levels of high-grading (weight of lobsters returned to the water due to low market value). Records are submitted monthly to SARDI Aquatic Sciences where they are entered into the South Australian Rock Lobster (SARL) database. The catch and effort time series used in this assessment extends from 1 November 1970 to 31 October 2021.

1.5.2 Recreational catch and effort data

Four recreational fishing surveys have been carried out in South Australia over the past 15 years. These were primarily telephone/diary surveys in nature and were undertaken in 2000/01 (Henry and Lyle 2003), 2004/05 (Currie et al. 2006), 2007/08 (Jones 2009) and 2013/14 (Giri and Hall 2015).

1.5.3 Voluntary catch sampling

Since 1991, commercial fishers and researchers have collaborated in a voluntary catch sampling program. Fishers contribute by recording data from up to three pots per day (with escape gaps closed when used) while researchers generally record data from all pots during on-board observer trips. The program collects catch and effort data at finer spatial scales to that recorded in commercial logbooks in addition to supplementary data such as sex ratios, reproductive condition of females and bycatch. An important contribution from the program is lobster size data which are used to generate size frequency distributions as well as provide input data for the length-based LenMod fishery model.

1.5.4 Puerulus monitoring program

Rates of puerulus and post-puerulus settlement have been monitored in the NZRLF since 1996/97. This program was initiated based on the settlement-recruitment relationship observed in Western Australia where future commercial catches of *Panulirus cygnus* were predicted from settlement indices using a 3–4 year time-lag (Caputi et al. 1995). Though not as explicit, similar relationships are now also evident in specific regions of some *J. edwardsii* fisheries in both Australia and New Zealand (Gardner et al. 2001; Booth and McKenzie, 2009; Linnane et al. 2013; 2014).

1.5.5 "qR" and "LenMod" stock assessment models

Two computer-based fishery stock assessment models have been developed for the South Australian Rock Lobster Fishery, referred to as "qR" and "LenMod" models. Each model provides outputs for both the Northern and Southern Zone fisheries that take into account known biological information specific to each region.

The primary data input to the qR model is catch by weight and catch by number. Model outputs have been presented in stock assessment reports for the fishery since 1997 (McGarvey et al.1997; McGarvey and Matthews 2001) with a review in 2002 (Breen and McKoy 2002) concluding that the qR model was an appropriate tool for assessing rock lobster stocks. The model has been refined over time, most notably during the peer review process for publication of McGarvey and Matthews (2001) and with changes to biomass definitions in 2008.

The basic structure of the second model, LenMod, was developed in the 1990s (Punt and Kennedy 1997). Variants of this length-based lobster model are now used for management and quota setting in most *J. edwardsii* fisheries, notably in New Zealand, Victoria and Tasmania. LenMod fits to monthly catch by number and catch per unit effort (CPUE), while conditioning on catch by weight. In addition, it also incorporates length-frequency data from voluntary catch sampling, where the lobster population is broken down into size categories of differing CL.

The primary outputs from both models are: (i) legal-sized biomass; (ii) egg production; (iii) % unfished egg production (%UEP); (iv) exploitation rate (fraction of legal-sized biomass harvested); and (v) recruitment. In addition, both models have been extensively used in bio-economic analyses and harvest strategy evaluations (McGarvey et al. 2014; 2015; 2016; 2017).

1.6 Harvest strategy

1.6.1 Management Plan

A new Management Plan for the NZRLF was adopted in July 2021 (PIRSA 2021). The harvest strategy in this management plan provides a structured framework for decision-making that aims to ensure that the ecologically sustainable development objectives of the *Fisheries Management Act 2007* are achieved. The aim of this harvest strategy is to improve the stock towards levels that give long-term optimum utilisation and to avoid stock over-exploitation.

1.6.2 Performance indicators

The Harvest Control Rule (HCR) uses multiple performance indicators to monitor the performance of the fishery (PIRSA 2021). Details of the HCR and its associated testing are provided in McGarvey et al. (2016). Broadly, the HCR aims to target a constant exploitation rate based on historical fishery performance and uses two fishery-dependent indicators.

The primary indicator is commercial CPUE (kg of legal-sized lobster/potlift) based on data from November to April, inclusive. The secondary indicator is a commercial logbook pre-recruit index (PRI; number of undersized lobsters/potlift) based on data from November to March, inclusive. Additional indicators not explicitly used to set a TACC, but which contribute to the overall assessment, include the puerulus settlement index (PSI), length-frequency data and model outputs such as % unfished egg production (%UEP), exploitable biomass, exploitation rates and model-estimated recruitment.

CPUE bands, which equate to target exploitation rates, have been developed for both the inner (Table 1-3) and outer (Table 1-4) regions. To set a TACC for the upcoming season, the CPUE from the previous season is applied. A Trigger Reference Point (TrRP) of 0.60 kg/plotift is used, below which, exploitation rates (and corresponding TACCs) are reduced, while a Limit Reference Point (LRP) of 0.40 kg/potlift reflects the point at which the fishery is closed. TACCs can only be increased if the PRI is above a TrRP of 0.16 undersized/potlift. TRPs and LRPs are not applied to additional indicators.

Table 1-3 CPUE bands and associated TACCs for the NZRLF inner region harvest control rule.

CPUE (kg/potlift)	TACC (t)
<0.40	0
0.40-0.44	17
0.45-0.49	52
0.50-0.54	90
0.55-0.59	129
0.60-0.64	150
0.65-0.69	170
0.70-0.75	215
0.76-0.79	235
0.80-1.19	250
1.20-1.99	275
2.0+	300

Table 1-4 CPUE bands and associated TACCs for the NZRLF outer region harvest control rule.

CPUE (kg/potlift)	TACC (t)
<0.40	0
0.40-0.44	3
0.45-0.49	10
0.50-0.54	19
0.55-0.59	29
0.60-0.69	38
0.70-0.79	44
≥0.80	46

1.7 Stock status classification

The status of the NZRLF was classified using the National Fishery Status Reporting Framework (NFSRF) (Flood et al. 2014) the terminology of which was recently refined and amended (Piddocke et al. 2021) (Table 1-5). It considers whether the current level of fishing pressure is adequately controlled to ensure that the stock abundance is not reduced to a point where the production of juveniles is significantly compromised. The system combines information on both the current stock size and the level of exploitation into a single classification for each stock against defined biological reference points. Each stock is then classified as 'sustainable', 'depleting', 'recovering', 'depleted', 'undefined' or 'negligible'. PIRSA has adopted this classification system to determine the status of all key South Australian fish stocks.

The CPUE performance indicator in the current harvest strategy for the NZRLF is directly linked to a definition of stock status based on data across the entire zone (Table 1-6).

Table 1-5 Stock status terminology (Piddocke et al. 2021).

	Stock status	Description	Potential implications for management of the stock
	Sustainable	Biomass (or proxy) is at a level sufficient to ensure that, on average, future levels of recruitment are adequate (recruitment is not impaired) and for which fishing mortality (or proxy) is adequately controlled to avoid the stock becoming recruitment impaired (overfishing is not occurring).	Appropriate management is in place.
	Depleting	Biomass (or proxy) is not yet depleted and recruitment is not yet impaired, but fishing mortality (or proxy) is too high (overfishing is occurring) and moving the stock in the direction of becoming recruitment impaired.	Management is needed to reduce fishing mortality and ensure that the biomass does not become depleted.
	Recovering	Biomass (or proxy) is depleted and recruitment is impaired, but management measures are in place to promote stock recovery, and recovery is occurring.	Appropriate management is in place, and there is evidence that the biomass is recovering.
	Depleted	Biomass (or proxy) has been reduced through catch and/or non-fishing effects, such that recruitment is impaired. Current management is not adequate to recover the stock, or adequate management measures have been put in place but have not yet resulted in measurable improvements.	Management is needed to recover this stock; if adequate management measures are already in place, more time may be required for them to take effect.
	Undefined	Not enough information exists to determine stock status.	Data required to assess stock status are needed.
	Negligible	Catches are so low as to be considered negligible and inadequate information exists to determine stock status.	Assessment will not be conducted unless catches and information increase.

Table 1-6 Stock status classification for the NZRLF (PIRSA 2021).

Commercial Catch Rate (kg/potlift)	Status
≥ 0.6	Sustainable
< 0.6	Depleting or Recovering
≤ 0.4	Depleted

2 METHODS

2.1 Commercial catch and effort data

Commercial logbook catch and effort data are compulsorily recorded by licensed fishers in the NZRLF. Detailed analyses of these data are provided for the period between 1 January 1970 and 31 October 2020. For ease of reference, figures and text refer to the starting year of each season (e.g. “2020” refers to the 2020/21 fishing season starting 1 November of 2020).

Important commercial data such as catch (t), effort (potlifts), CPUE (kg/potlift), PRI (number of undersized/potlift) and mean weight (kg) were analysed both spatially and temporally. Spatially, data are presented by zone, MFA and in some cases, depth range. Temporally, data are presented by month and year.

In addition to the above, other data sources recorded in the voluntary component of the logbook are presented at a reduced spatial or temporal scale. While these are not directly linked to setting the TACC, they are either deemed to contribute to the overall understanding of the fishery or have been specifically requested by stakeholder groups. These include catch rates of: (i) ovigerous (spawning) females and predation mortality as estimated through catch rates of: (ii) dead lobsters and (iii) octopus, which are responsible for the depredation of lobsters caught in pots. The average numbers of days fished per licence holder (as a proxy for fishing effort) and estimated levels of fishery high-grading were also analysed.

2.2 Recreational catch and effort data

The specific details of the methodology used in the four recreational surveys considered in this assessment can be found in their respective reports (2000/01: Henry and Lyle 2003; 2004/05: Currie et al. 2006; 2007/08: Jones 2009; 2013/14: Giri and Hall 2015). A detailed description of the telephone-diary design philosophy and method is provided in Henry and Lyle (2003).

2.3 Voluntary catch sampling

Voluntary catch sampling datasheets are completed daily and submitted monthly to SARDI Aquatic Sciences. Fishers and observers count, measure (mm CL), and determine the sex of lobsters from all pots sampled and, for females, record the reproductive condition. In addition, all bycatch are identified and counted. The latitude and longitude of each pot sampled is recorded, thereby providing information at a finer spatial resolution than that of commercial logbooks.

2.4 Puerulus monitoring program

Four puerulus collector sites are located in the NZRLF, two at Port Lincoln (one each at McLaren Point and Taylor Island) and two at Yorke Peninsula (one each at Marion Bay and Stenhouse Bay) with the collectors set in groups of 5 or 10 at each site. The collectors are similar in design to those described by Booth and Tarring (1986) and consist of angled wooden slats that mimic natural crevice habitat. The design has remained unchanged throughout the sampling period. Sampling is undertaken monthly from July to October, whereby collector heads are detached from a base by a diver, covered with a mesh bag and hauled to the surface for counting of pueruli.

The annual PSI is calculated as the mean monthly settlement on all collectors combined. This index is correlated against future recruitment indices based on previously established time lags.

2.5 "qR" and "LenMod" stock assessment models

Two models are used to assess the NZRLF. The qR model is yearly and uses the three logbook time series of catch by weight, catch by number, and fishing effort as potlifts. LenMod is monthly, and integrates catch-sampling length-frequencies, in addition to the logbook data used by the qR model. Growth in the two models differs; the qR model uses a vector of mean lengths-at-age while LenMod uses length-transition matrices. Both models estimate yearly independent recruitment. LenMod is conditioned on monthly catch-in-weight totals, while the qR model is conditioned on yearly (scaled) effort.

LenMod estimates a separate catchability for years under quota (2003+). From 1983 to 2000, when the adoption of GPS and sounder technology is known to have substantially improved fishing power, both models assume a steadily rising effective effort, as 3% per year linear increases in catchability. The total increase in effective effort over this period is 51%.

A number of changes were introduced to the two models in 2017. In both models, the method of computing unfished egg production (UEP) was modified by adopting 1990-2011 as the reference period for computing mean unfished recruitment. This reference period is also used in other jurisdictions (e.g. Tasmania) and therefore permits State-wide consistent reporting at the stock level under the Status of Key Australian Fish Stocks (SAFS) system. Also, this reference period covers years of both higher-than-average (pre-2002) and lower-than-average (2002+) historical recruitment. For LenMod, the method of estimating monthly and sex-specific selectivity has been improved to allow separate length selectivity by grouped months through each season. For the qR model, weights-at-age have been raised to yield better agreement with LenMod in absolute levels of estimated stock biomass, as recommended in the 2017 review of these stock assessments (Smith, 2017). Most recently for the qR model, weights-at-age were derived that assume first-year recruits have a mean length obtained by one-half-year's growth above the LML of 105 mm CL, and a separate catchability parameter for years since quota (2003+) is now estimated.

With winter fishing now fully adopted in the NZRLF, the yearly effort values inputted into the qR model have been corrected to remove the effect of consistently lower winter catch rates. Inputted yearly effort values since 2015 were proportionally adjusted to produce a yearly CPUE that equals what is given by the 7-month regular-season (Nov-May), preventing winter fishing from biasing downward this index of relative abundance. Due to COVID-19 market impacts on fishing practices in the 2019/20 season, for both models, the catch rate index of abundance used reported catch and effort up to January 2020 only. Similarly, for the 2020/21 season, LenMod was fitted to monthly catch rate and catch in number only over December 2020 to May 2021 inclusive, with no fitting to data from winter months for any season.

2.5.1 qR model

The qR model (McGarvey and Matthews 2001) fits to: (i) annual catch in weight and (ii) annual catch in number of lobsters landed. The model is effort conditioned and runs on a yearly time step. It incorporates a Baranov survival model and conditions on effort by assuming that yearly instantaneous fishing mortality rate varies in proportion to yearly reported fishing effort. The likelihood that is maximised numerically to estimate parameters is the sum of the likelihood terms for fitting to catch in weight and number. These normally distributed data provide a shared estimated parameter for the residual error as a likelihood coefficient of variation. Yearly recruitment is estimated for the start of each fishing season. Annual stock biomass is reported as an integrated average over the 12 months of each model year.

Both stock assessment models rely on catch rate as a measure of relative fishable biomass. The addition of landed catches in number to the fitted logbook data set, unavailable in most fisheries, provides important yearly information about the size of lobsters in the legal catch. Information on mean size in crustacean fisheries is normally available only from length-frequency samples, which can show high sample variation and are subject to additional variation in the specific locations or times during the season when length samples are taken. Catch in weight divided by catch in number gives the yearly mean weight of a landed lobster. Because reported catches in weight and number constitute a 100% sample, the quality of information obtained regarding changes in mean size from catch-log data is far more precise than that obtained from length frequencies, which typically constitute a 0.1% to 1% sample. Thus, the data informing the qR model provide relative indices of abundance as yearly catch rates (in both weight and number) and yearly mean landed weight. McGarvey et. al. (2005) demonstrated, using independent individual-based simulated data, that adding catch in number dramatically improves the accuracy and precision of stock assessment estimates in species that cannot be aged. Further details of the qR model specifications including its equations, assumptions and parameters are provided in Appendix 2.

For 2019/20, the method used to exclude qR catch rate data after January 2020 differed from that of LenMod, because the qR model time step is yearly. This COVID correction extends the rescaling of qR model inputs implemented since the implementation of NZ winter fishing in 2014 that uses catch rate only from the 7 months of the regular season i.e. November–May. The qR model is now accounting for recreational catch. Details of these model updates are given in Appendix 2.

2.5.2 LenMod

LenMod is a length-based assessment model running on a monthly time step. Lobster population numbers are broken down and estimated in 4-mm carapace length bins. Catchability is estimated separately for each month. LenMod infers stock dynamics and abundance levels using maximum likelihood by fitting to three data sources, and conditioning on a fourth: (i) nominal monthly logbook CPUE (in weight) to which fishable biomass is assumed to vary in direct proportion; (ii) monthly logbook catch in number; and (iii) frequency proportions by length sex bin fitted by a multinomial likelihood. CPUE data provide LenMod with information on trend in relative abundance, while data sources (ii) and (iii) both provide information on size of lobsters in the catch which, interpreted in combination with length-transition matrices, yield estimates of total mortality. The model is conditioned on catch in weight landed that is sourced from commercial and recreational landed lobsters, plus dead lobsters. The aforementioned, together with lobsters dying naturally (10% per year), are directly removed from the model population in each time step.

Moulting growth occurring in semi-yearly moulting times is modelled, for each sex, by length-transition matrices that specify the proportion of lobsters in each length class that grow into larger length classes, or remain in that length class, during each summer and autumn moulting season. These length-transition probabilities were estimated using extensive tag-recovery data mainly from the 1990s. The length-transition estimation method of McGarvey and Feenstra (2001) was applied, which infers widely flexible growth curves to be inferred by modelling the parameters predicting mean and variance of observed tag-recovery growth increments as polynomial functions of (starting) CL. Growth matrices were estimated for each combination of sex and moulting season. As growth rates of female lobsters are known to slow substantially once they reach maturity, this flexible polynomial estimation method, which accommodates non-linear growth rate versus starting length, provides a more accurate estimation of female adult growth than a traditional von Bertalanffy model of mean growth increment. Full details of LenMod specifications including its equations, assumptions and parameters are provided in Appendix 3.

Since 2018/19, the method of estimating monthly and sex-specific selectivity has been improved to allow separate length selectivity by grouped months through each season. Full details of LenMod specifications including its equations, assumptions and parameters are provided in Appendix 3.

2.6 Quality assurance of data

All logbook and catch sampling data were entered and validated according to the quality assurance protocols identified for the NZRLF in the SARDI Information Systems quality assurance and data integrity report (Vainickis 2010). The data were stored in an Oracle database, backed up daily, with access restricted to SARDI Information Systems staff. All puerulus data were entered into Excel spreadsheets and stored on a SARDI network drive.

3 RESULTS

3.1 Commercial catch and effort statistics

The 2020 season (i.e. 2020/21) was the second consecutive year the NZRLF was impacted by overseas market disruptions. This was particularly evident in November 2020 to January of 2021 but should be taken into consideration when interpreting fishery trends throughout the entire 2020/21 season.

3.1.1 Zone

In 2020, the total allowable commercial catch (TACC) in the NZRLF was 324 t (263 t Inner sub-region and 61 t Outer sub-region) which reflected a regular TACC of 296 t plus 28 t carry-over from 2019. The reported logbook catch (1 November 2020 to 31 October 2021) was 249.00 t (77% of the 324 t TACC) (Figure 3-1a; Table 6-1). By sub-region, the catch was 225.69 t and 23.31 t from the Inner and Outer sub-regions, respectively (Table 3-1). Long-term trends show a consistent decline in zonal catch from 1999 to 2008, with the TACC being under-caught until catch levels were constrained in 2009 (Table 3-2). Current catch levels are low in a historical context and have remained relatively stable over the last twelve fishing seasons.

Effort in 2020 was 249,293 potlifts, reflecting an 18% decrease from 2019 (304,040 potlifts) (Figure 3-1a; Table 6-1). In 2009, effort decreased considerably from 600,000 to 350,000 potlifts, before decreasing further to 287,000 potlifts in 2011. After increases to 438,000 potlifts in 2015, the 2020 estimate reflects the fifth consecutive season that effort has decreased and is the lowest on record (but noting that the TACC was under-caught by 23% in 2020).

In 2020, the legal-sized CPUE was 1.05 kg/potlift, reflecting a 36% increase from 2016 (0.77 kg/potlift) and the highest CPUE since 2011 (Figure 3-1b; Table 6-1). Following a period of consistent decline between 1999 and 2008, when CPUE decreased to a historical low of 0.68 kg/potlift, CPUE briefly increased to 1.1 kg/potlift in 2011, before again declining to 0.77 kg/potlift in 2016. By sub-region, 2020 reflected the first season since spatial management was introduced in 2015 that Inner sub-region catch rates exceeded 1 kg/potlift. For the Outer-region, CPUE increased by 18% from 0.78 kg/potlift in 2019 to 0.92 kg/potlift in 2020 (Table 3-1).

Pre-recruit Index (PRI) estimates are now based on logbook data (previously catch sampling) from November to March inclusive. Following a long-term decline from 1999 to 2015, PRI has increased by 69% (Figure 3-1c). In 2020, the PRI was 0.22

undersized/potlift reflecting a 10% increase from 2019 (0.20 undersized/potlift) and remaining above the trigger reference point (TrRP) of 0.16 undersized/potlift. In the NZRLF, the time taken for pre-recruits to enter the fishable biomass is approximately one year. The legal-sized mean weight of lobsters has remained relatively stable since 1983 (Figure 3-1d). Between 2010 (0.97 kg) and 2016 (1.20 kg) mean weight increased before decreasing over the next four seasons to 1.02 kg in 2020.

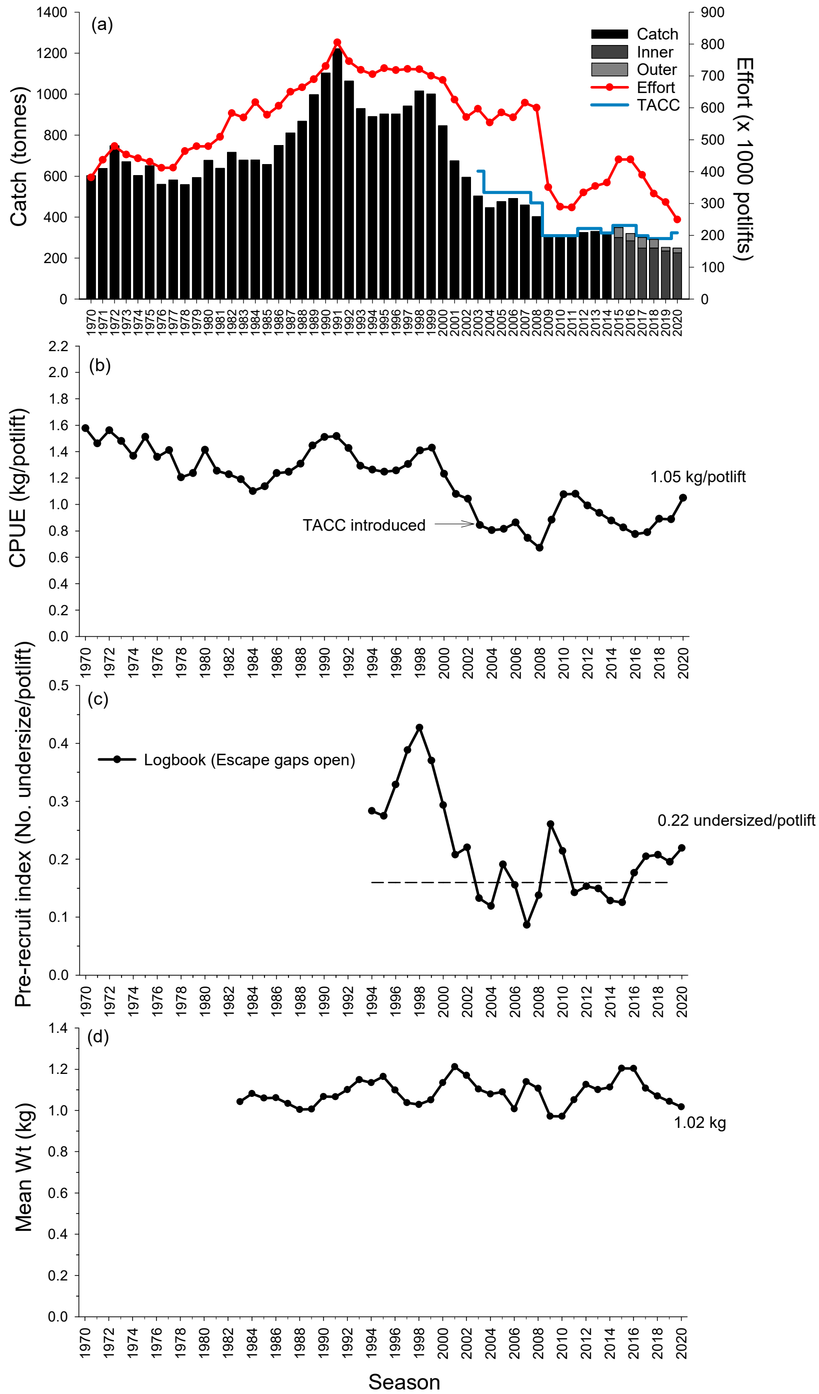

Figure 3-1 Fishery dependent outputs for the NZRLF. (a) Catch and effort including total allowable commercial catch (TACC) limit; (b) catch per unit effort (CPUE; (c) pre-recruit index (PRI) including trigger reference point (dashed line); and (d) mean weight.

Table 3-1 Commercial catch and effort statistics for the NZRLF sub-regions. Inner sub-region data are from Nov-May* while Outer sub-region data are from Nov-Oct. *Except 2019 and 2020 (Nov-October). CPUE estimates in both sub-regions based on Nov-May data.

Inner sub-region					
Season	Catch (t)	Effort (potlifts)	CPUE (kg/potlift)	TACC (t)	TACC Uncaught (t)
2015	301.18	378,667	0.80	300	0
2016	284.58	382,007	0.74	300	15.47
2017	249.17	319,290	0.78	250	0.83
2018	249.65	277,843	0.90	250	0.35
2019	235.78	281,005	0.87	250	14.22
2020	225.69	223,531	1.03	263	37.37
Outer sub-region					
Season	Catch (t)	Effort (potlifts)	CPUE (kg/potlift)	TACC (t)	TACC Uncaught (t)
2015	32.74	34,705	0.94	60	27.26
2016	20.94	20,576	1.01	60	39.06
2017	46.83	58,889	0.80	60	13.17
2018	40.13	48,592	0.83	46	5.87
2019	17.01	23,045	0.78	46	28.99
2020	23.31	25,762	0.92	61	37.69

Table 3-2 Chronology of TACC versus landed catch in the NZRLF.

Season	TACC (t)	Landed catch (t)	Shortfall (t)	% TACC taken
2003	625	503	122	80
2004	520	446	74	86
2005	520	476	44	92
2006	520	491	29	94
2007	520	459	61	88
2008	470	403	67	86
2009	310	310	0	100
2010	310	312	0	100
2011	310	307	3	99
2012	345	325	20	94
2013	345	331	14	96
2014	323.2	321	2.2	99
2015	360	349	11	97
2016	360	321	39	89
2017	310	301	9	97
2018	296	291	5	98
2019	296	253	43	85
2020	324	249	75	77

3.1.2 Within-season trends

Within-season commercial catch trends presented here are based on data from 2018 to 2020. Results from earlier seasons are accessible in previously published stock assessment reports (http://pir.sa.gov.au/research/publications/research_reports). In general, within-season trends in catch, effort, CPUE, PRI and mean weight within the

NZRLF are consistent through time (Figure 3-2). The highest catches are taken during spring/summer from November to February before declining thereafter (Figure 3-2a).

The market closures occurred in late January and November of the 2019/20 and 2020/21 seasons, respectively. Consequently, the catch in February of the 2019/20 seasons decreased to 6 t, where normally up to 60 t are landed (Figure 3-2a). In the 2020/21 season, the overall impact was lower catches, particularly from November to January, compared to previous seasons. In 2020/21, the highest catch was taken in December (53 t), and the lowest catch in May (13 t).

Within-season effort levels are largely consistent with those of catch (Figure 3-2a). In 2020/21, effort was highest in December (49,713 potlifts) and lowest in May (18,324 potlifts).

Legal-sized CPUE generally tends to be highest in spring/summer at the start of the season and declines thereafter (Figure 3-2b). In 2020/21, monthly catch rates were consistently higher across all months of the season compared to 2019/20. In 2020/21, CPUE was highest in January (1.17 kg/potlift) and lowest in May (0.69 kg/potlift).

Monthly trends in catch rate of pre-recruits (i.e. PRI) tend to follow those of legal-sized CPUE, being highest at the start of the season before decreasing thereafter (Figure 3-2c). Compared to 2019/20, the monthly PRI in 2020/21 was higher across most months. In 2020/21, the PRI was highest in February (0.25 undersized/potlift) and lowest in May (0.10 undersized/potlift).

Monthly legal-sized mean weight generally increases as the season progresses (Figure 3-2d). In 2020/21, with the exception of November and April, monthly mean weight was consistently lower across most months compared to the 2019/20 season, being highest in April (1.18 kg) and lowest in November (0.90 kg).

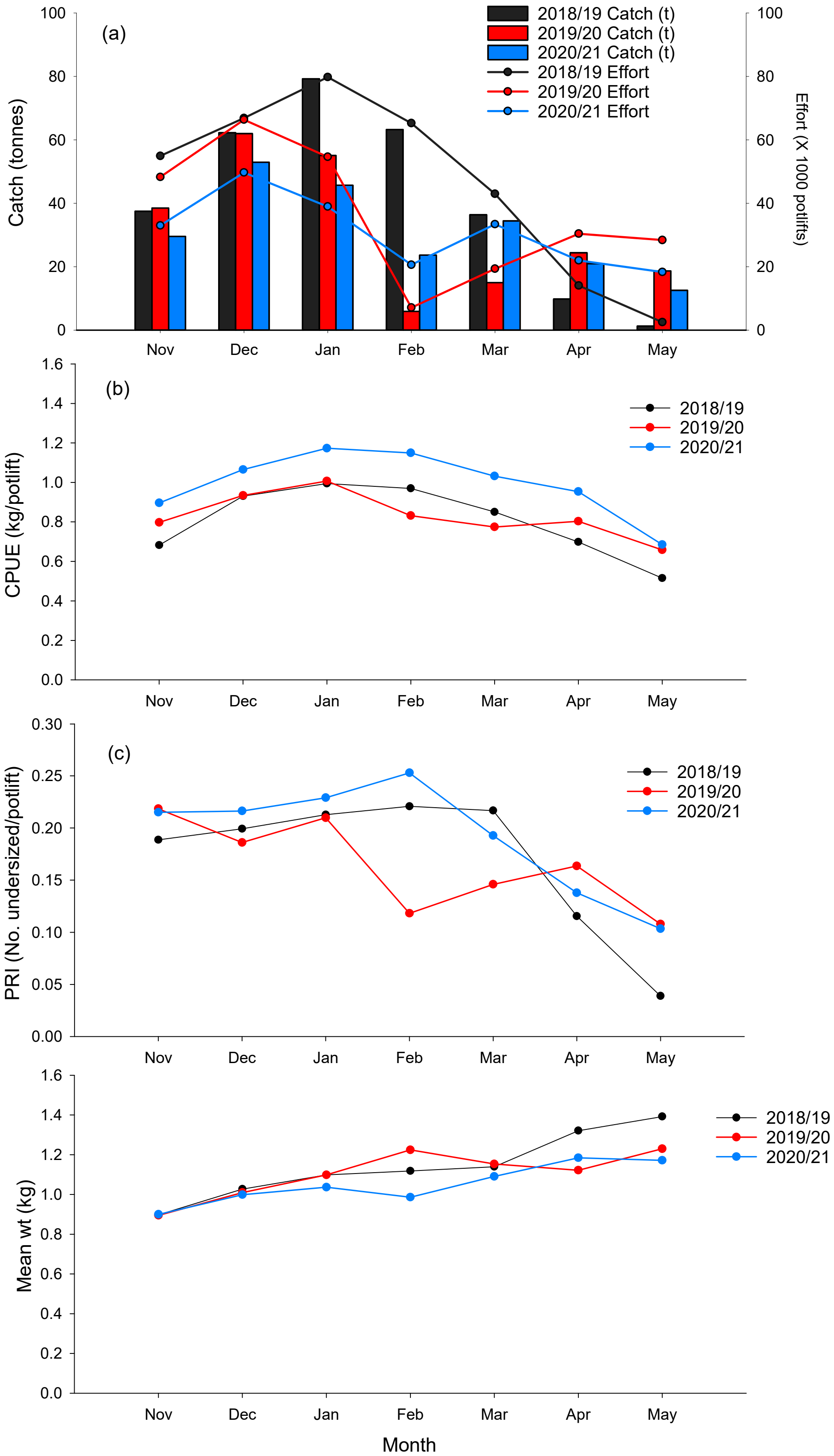

Figure 3-2 Within-season fishery dependent trends in the NZRLF. (a) Catch and effort; (b) catch per unit effort (CPUE); (c) pre-recruit index (PRI); and (d) mean weight.

3.1.3 Spatial trends

3.1.3.1 Marine Fishing Areas (MFAs)

In 2020, 96% of the catch (240 t) came from ten MFAs: MFAs 7, 8, 15, 27, 28, 39, 40, 48, 49 and 50 (Figure 3-3 and Figure 3-4). Current catch levels are now low in a historical context but have remained relatively stable across most MFAs over the last nine seasons. The exception is MFA 28 where catch decreased from 74 t in 2014 to 41 t in 2020 (Figure 3-3e). In 2020, within the primary MFAs, the highest catch was taken in MFA 39 (49 t) (Figure 3-4a) and the lowest in MFA 7 (<2 t) (Figure 3-3a).

Effort levels largely reflect trends in catch (Figure 3-3 and Figure 3-4). In recent seasons, the highest effort has been in MFA 39 (approximately 50,000-91,000 potlifts annually over the last five seasons (Figure 3-4a). In 2020, effort decreased in MFAs 15, 28, 39, 40, 49 and 50 and increased in MFAs 7, 8, 27 and 48.

Trends in annual legal-sized CPUE are temporally consistent among the MFAs, with higher values occurring in the 1970s through to the late 1990s, and lower values in the 2000s (Figure 3-3 and Figure 3-4). From 1999 to 2008 CPUE generally declined in most regions with the estimates in MFAs 7, 28, 39, 40, 48 and 49 the lowest on record in 2008. More recently, following six seasons of successive decline from 2010 to 2016, catch rates have increased in almost all MFAs over the last 3–4 seasons.

Spatial estimates of the logbook based PRI indicate that the number of undersized/potlift is consistently lower in the north-western MFAs of 7, 8, 15, 27 and 28 (Figure 3-3) and higher in the south-eastern MFAs of 39, 40, 48, 49 and 50 (Figure 3-4). The zonal increase in PRI in 2020 was largely driven by MFAs, 28, 39, and 40.

Rock lobster mean weights are highest in MFAs located in the north-west of the NZRLF (e.g. MFA 7, 8, 15, 27) (Figure 3-3), and lowest in MFAs located further to the south-east (e.g. MFA 48, 49, 50) (Figure 3-4). In 2020, the zonal decrease in mean weight was observed in all of the primary MFAs with the exception of MFA 49 (Figure 3-4s) and MFA 50 (Figure 3-4t).

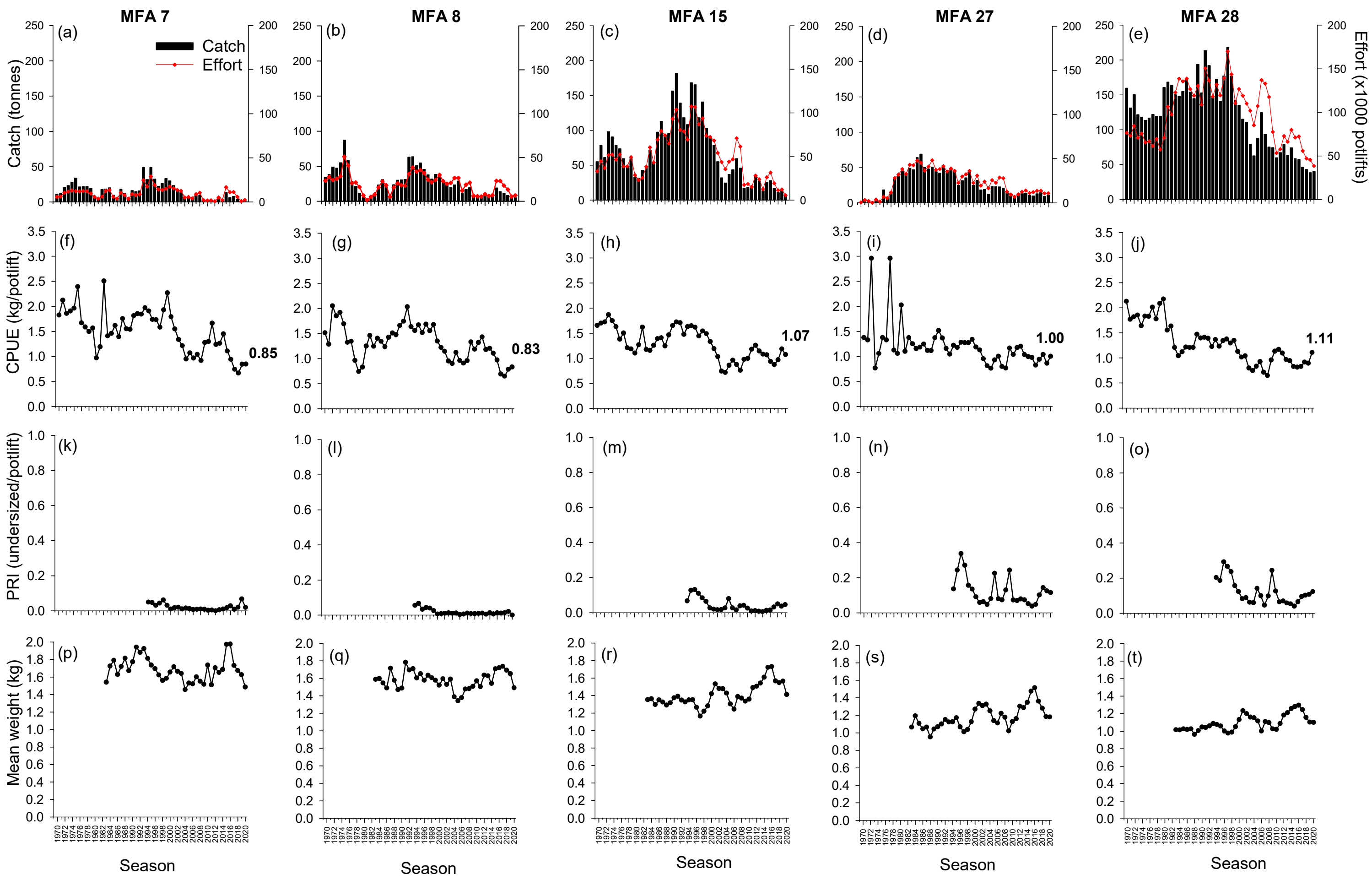

Figure 3-3 Spatial fishery dependent trends in the NZRLF for MFAs 7-28. (a-e) Catch and effort; (f-j) catch per unit effort (CPUE); (k-o) pre-recruit index (PRI); and (p-t) mean weight.

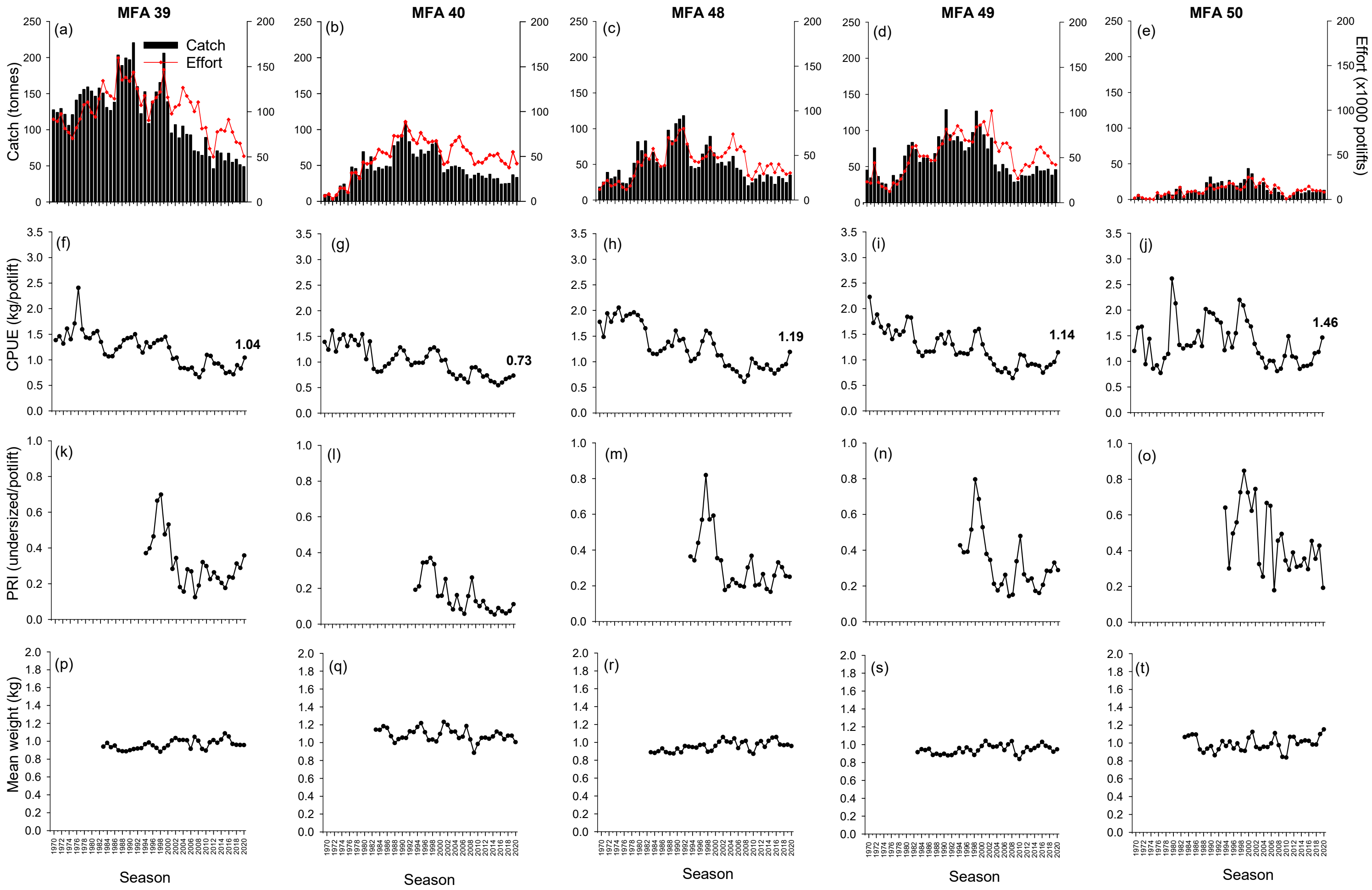

Figure 3-4 Spatial fishery dependent trends in the NZRLF for MFAs 39-50. (a-e) Catch and effort; (f-j) catch per unit effort (CPUE); (k-o) pre-recruit index (PRI); and (p-t) mean weight.

3.1.3.2 Depth

To assess spatial trends by depth, logbook derived catch from four depth range categories of 0–30, 31–60, 61–90 and >90 m were analysed. Since 2003, there has been a consistent distribution of the total catch by depth, with more than 80% taken from inshore waters at depths ≤60 m within the zone (Figure 3-5) and each of the main MFAs (Figure 3-6).

Despite reflecting the majority of the annual catch, CPUE (November-April) in depths of 0-30 m and 31-60 m is consistently lower than that for offshore areas of 61–90 m and >90 m depth (Figure 3-7). Over the last eight seasons, trends for different depth ranges largely reflected those at the zonal level, with decreases in all depth ranges from 2011 to 2016 before gradual increases over the next four seasons. In 2020, estimates were 0.97, 1.08, 1.32 and 1.04 kg/potlift in 0–30, 31–60, 61–90 and >90 m, respectively.

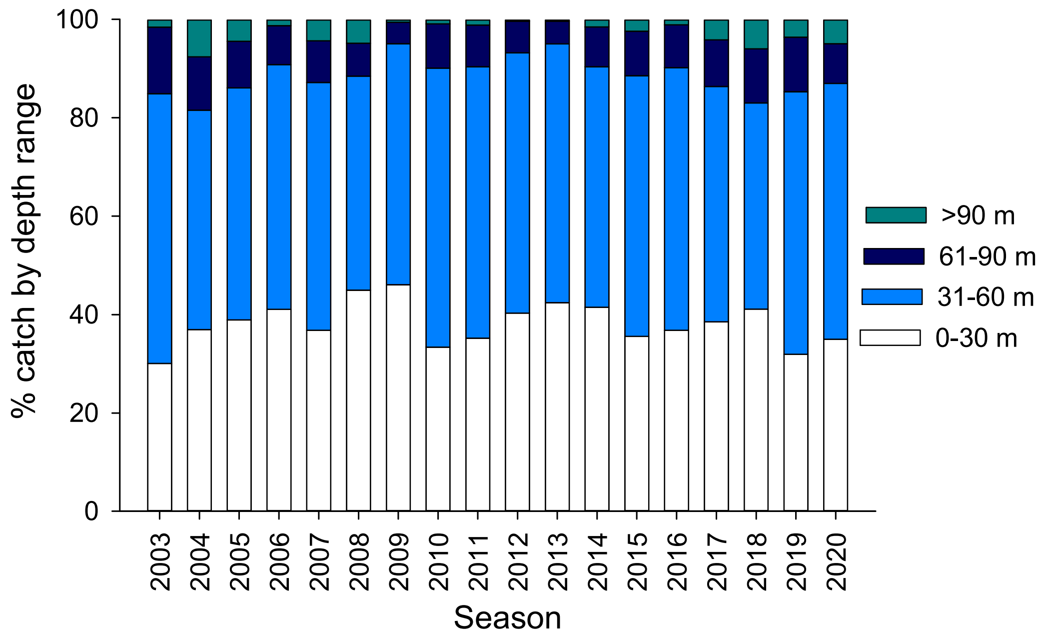

Figure 3-5 Percentage of catch taken from four depth classes in the NZRLF from 2003 to 2020.

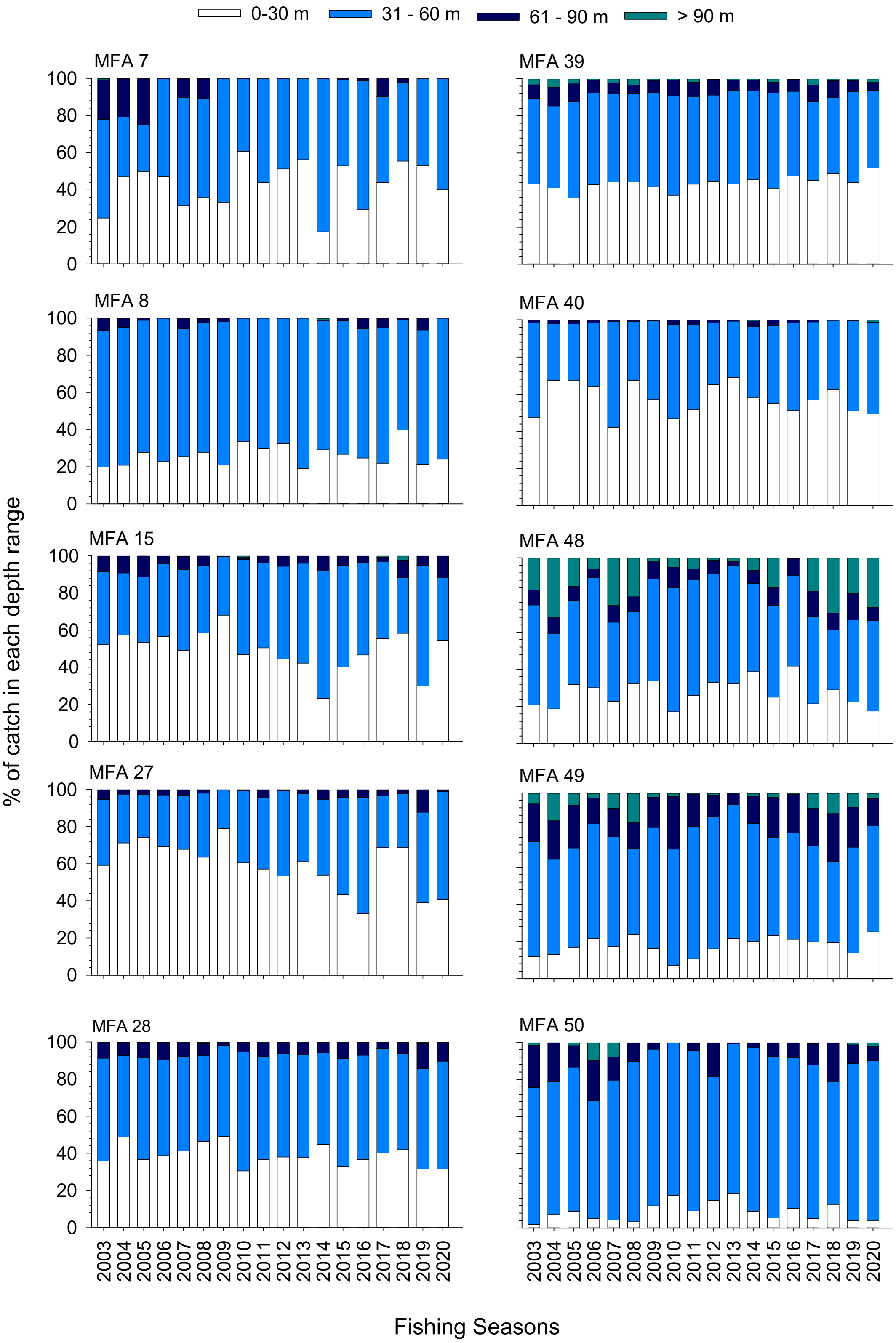

Figure 3-6 Percentage of catch taken in four depth ranges from 2003 to 2020 across the primary MFAs of the NZRLF.

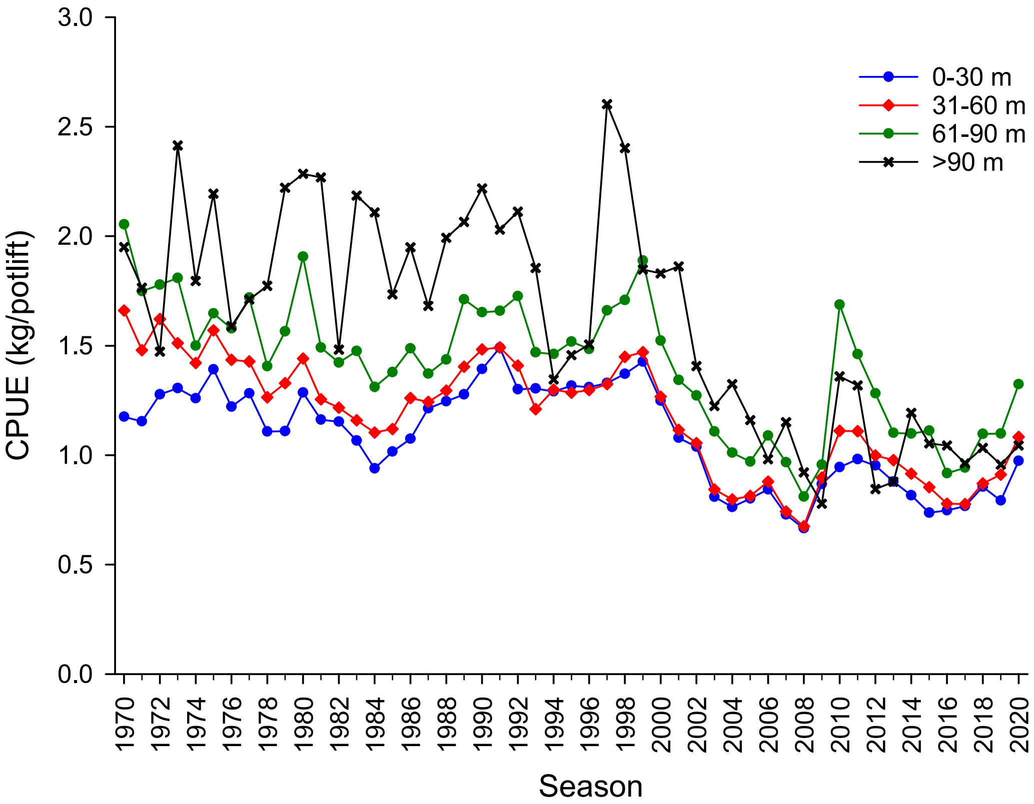

Figure 3-7 CPUE by depth in the NZRLF from 1970 to 2020.

3.1.4 Additional indices

To ensure consistency with previous reports, additional indices for 2020 are based on data from the agreed assessment period of November to May inclusive.

3.1.4.1 Ovigerous (spawning) females

In 2020, the catch rate of ovigerous (spawning) female lobsters was 0.02 spawners/potlift (Figure 3-8a). Consistent with overall declines in legal-sized lobster catch rates (Figure 3-1b), the CPUE of spawners decreased from 1997 (0.09 spawners/potlift) to 2001 (0.02 spawners/potlift). Since then, the index has remained below 0.04 spawners/potlift.

3.1.4.2 Predation mortality

The maori octopus (*Pinnoctopus cordiformis*) is the primary predator of Southern Rock Lobster within commercial fishing pots (Brock and Ward 2004). As a result, both the catch rate of octopus and dead lobsters are highly correlated (Figure 3-8b; R^2 = 0.79).

The number of dead lobsters/potlift decreased from 1998 (0.08 dead/potlift) to 2002 (0.04 dead/potlift) and with the exception of 2010 (0.06 dead/potlift) and 2020, has remained below 0.05 dead/potlift (Figure 3-8b). In 2020, the catch rate was 0.06 dead lobsters/potlift.

Similarly, octopus catch rates decreased from 0.02 octopus/potlift in 1998 to 0.003 octopus/potlift in 2005 (Figure 3-8b). Since then (except for 2015), the annual estimate has remained below 0.005 octopus/potlift and in 2020 was 0.003 octopus/potlift.

3.1.4.3 Average days fished

In 2020, the average number of days fished per licence holder in the NZRLF was 76 days, reflecting the fifth consecutive season that this index has decreased and the lowest recorded (Figure 3-8c). Overall, this index is a proxy for fishing effort and largely reflects trends in annual potlifts within the fishery (Figure 3-1a). From 2003 to 2008, the estimate ranged from 152 to 163 days, even though the fishery changed to output controls in the form of a TACC quota system in 2003. These data indicate that during this period, the TACC (introduced in 2003 at 625 t and subsequently reduced to 470 t in 2008) had minimal impact in constraining effort in the fishery, highlighted by the 2008 estimate of 156 days fished being only 15% less than that recorded in 1997 (184 days), when the fishery was still managed under input controls. In 2009, the TACC was reduced to 310 t, which resulted in the average numbers of days fished decreasing to 100 days. In 2010, it decreased further to 84 days, the lowest estimate on record. Over the next five seasons, the estimate increased to 134 days which in part reflects the increase in TACC to 345 t in 2012 and 360 t in 2015. Since 2018, the TACC has been retained at 296 t in the fishery.

3.1.4.4 High-grading

Current estimates of high-grading (total weight of all lobsters returned to the water due to low market value) in the NZRLF are low and in 2020 was 1.2 t (Figure 3-8d). Since the introduction of a TACC in 2003, estimates have not exceeded 3 t. While the overall reported values in logbooks are likely to be conservative, since high-grading is recorded on a voluntary basis, the estimates are still considered to be indicative of an overall trend.

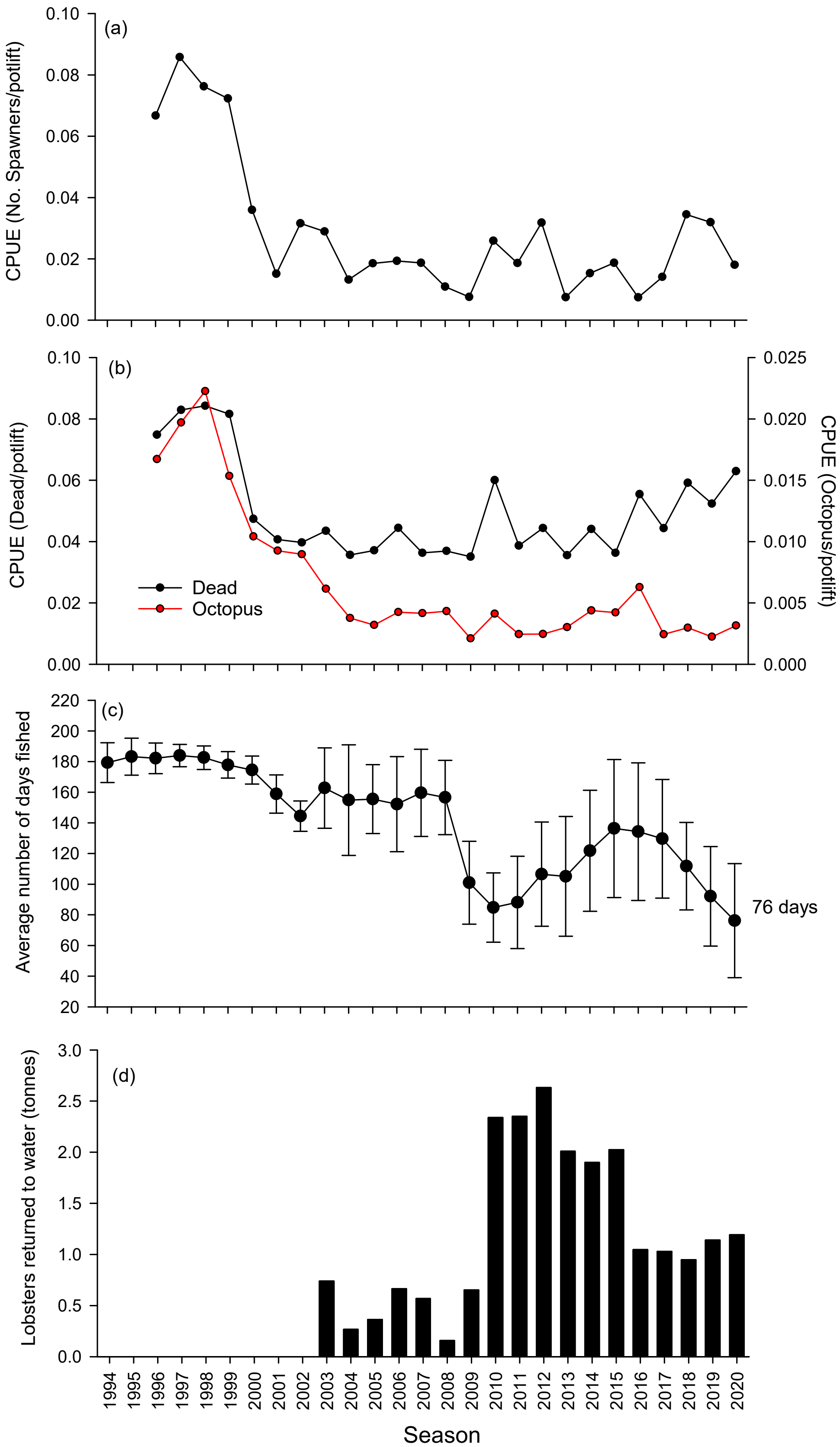

Figure 3-8 Additional fishery dependent indices in the NZRLF. (a) Catch rate of spawning lobsters; (b) predation mortality and predatory octopuses; (c) average number of days fished (with S.D.); and (d) levels of high-grading.

3.2 Recreational catch and effort

The most recent report on recreational rock lobster fishers was undertaken during the 2013/14 South Australian Recreational Fishing Survey (Giri and Hall 2015). An estimated 102,931 (± 58,763) lobsters were caught by South Australian residents with 62,346 (± 39,085) of these harvested and 40,585 (± 25,202) released representing a release rate of 39.4%. In total, the harvested catch equated to approximately 75 t of which one-third were caught in the NZRLF. Pots and nets accounted for 83% of all lobsters caught with dive and fishing line being the other capture methods.

These results can be compared with 106,483 lobsters caught in 2007/08 with 47,875 harvested (equating to 60 t with approximately 5 t caught in the NZRLF) and 58,608 released representing a release rate of 55% (Jones 2009). A 2021-22 recreational fishing survey will provide State-wide estimates of rock lobster catch from 1 March 2021 to 28 February 2022, with results due to be released by the end of 2022. Recreational catches are accounted for within the LenMod fishery outputs.

3.3 Voluntary catch sampling

Since 1991, up to 32,000 lobsters have been measured annually in the NZRLF as part of the voluntary catch sampling program. The number measured is proportional to the level of participation in the program with data presented as number of lobsters/100 potlifts. In this report, annual length frequency data are presented for the period from 2011–2020. Earlier length frequency distributions are presented in published stock assessment reports (http://pir.sa.gov.au/research/publications/research_reports).

Male lobsters, which generally grow faster and reach larger sizes than females, range between 70 and 200 mm carapace length (CL). In contrast, few females are larger than 150 mm CL. In 2020, a total of 2,048 lobsters were sampled. Of these, 50% were within the 105 to 130 mm CL range with 22% of lobsters in 2020 below the minimum legal size (MLS; 105 mm CL) (Figure 3-9).

Length-frequency data obtained through the voluntary catch sampling program over the last two seasons support recent trends in pre-recruit indices from commercial logbook samples. Notably, the percentage of lobsters measured below the MLS increased from 19% to 22% between 2019 and 2020, reflecting the increase in undersized catch rate over the same period (Figure 3-1c).

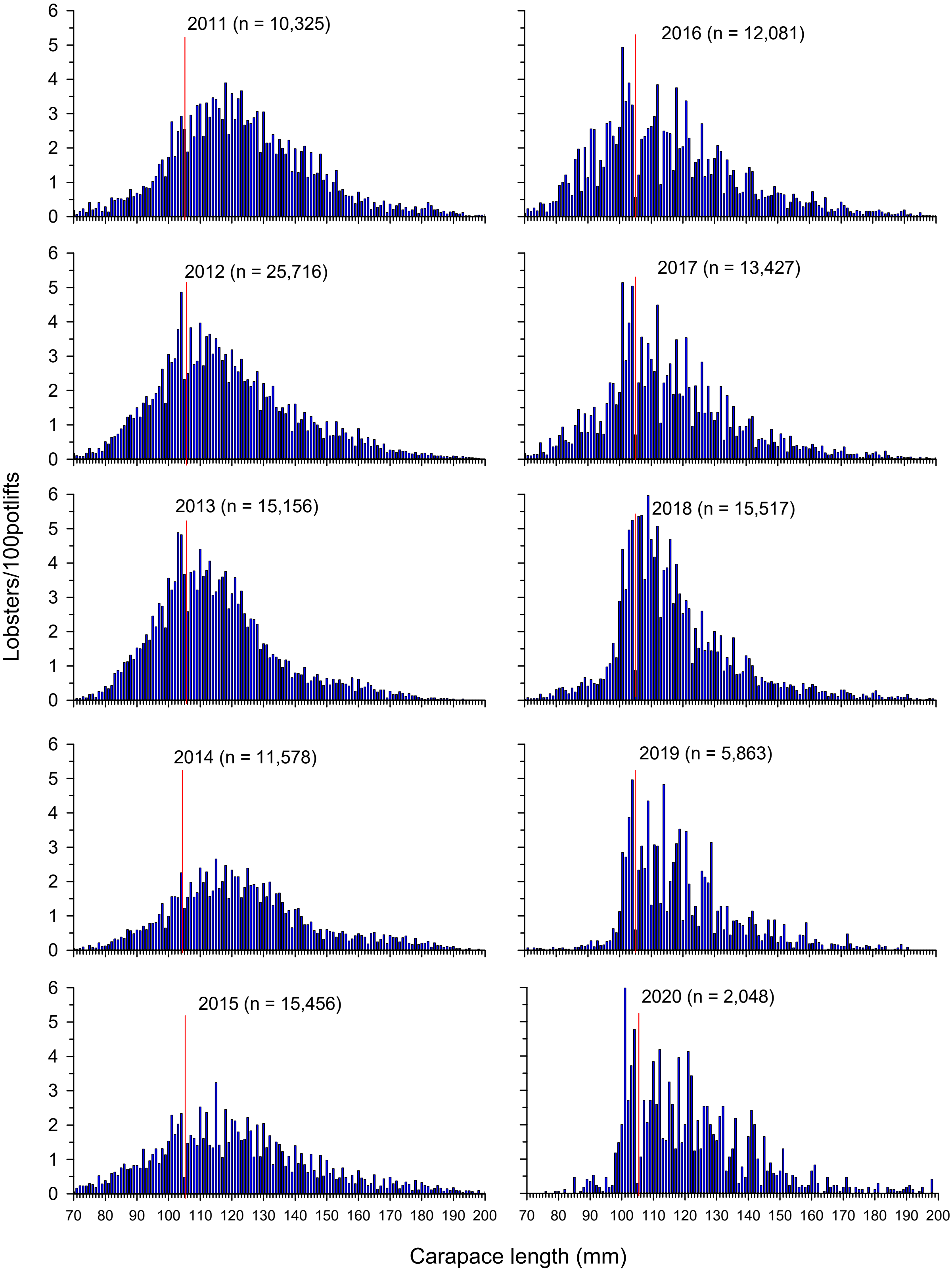

Figure 3-9 Length-frequency distributions of male and female lobsters combined in the NZRLF from 2011 to 2020 (red line indicates MLS at 105 mm CL).

3.4 Puerulus monitoring program

Puerulus settlement indices (PSIs) in the NZRLF have been highly variable over time (Figure 3-10). In 2020, the PSI was 0.50 puerulus/collector which was above both the long-term (1996-2020) mean and median estimates. Previous research has indicated that the period between settlement and recruitment to legal size in the NZRLF is approximately three to four years with undersized numbers correlated after three years (Linnane et al. 2014). Based on this relationship, rescaled PSIs were correlated with estimates of model recruitment from the LenMod fishery model using a three-year lag (see Section 3.5) (Figure 3-11). Puerulus settlement and recruitment were correlated (R^2 = 0.69) over the period from 2003–2020 indicating that settlement indices in the NZRLF provide an indicator of future recruitment to the fishery. More recently, the above average settlements observed from 2016–2018 indicate that higher than average recruitment may be expected during the 2020–2022 seasons.

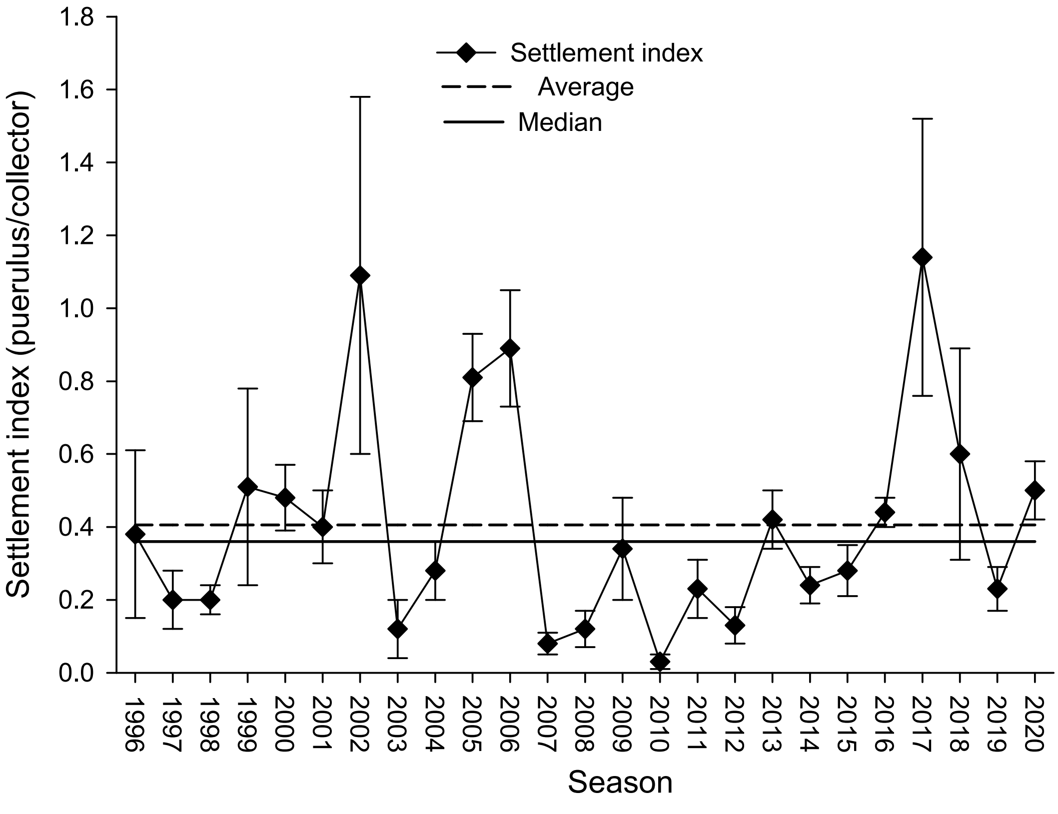

Figure 3-10 Puerulus settlement indices (mean ±SE) in the NZRLF from 1996 to 2020. Dashed and solid lines represent long-term mean (1996-2020) and median estimates respectively.

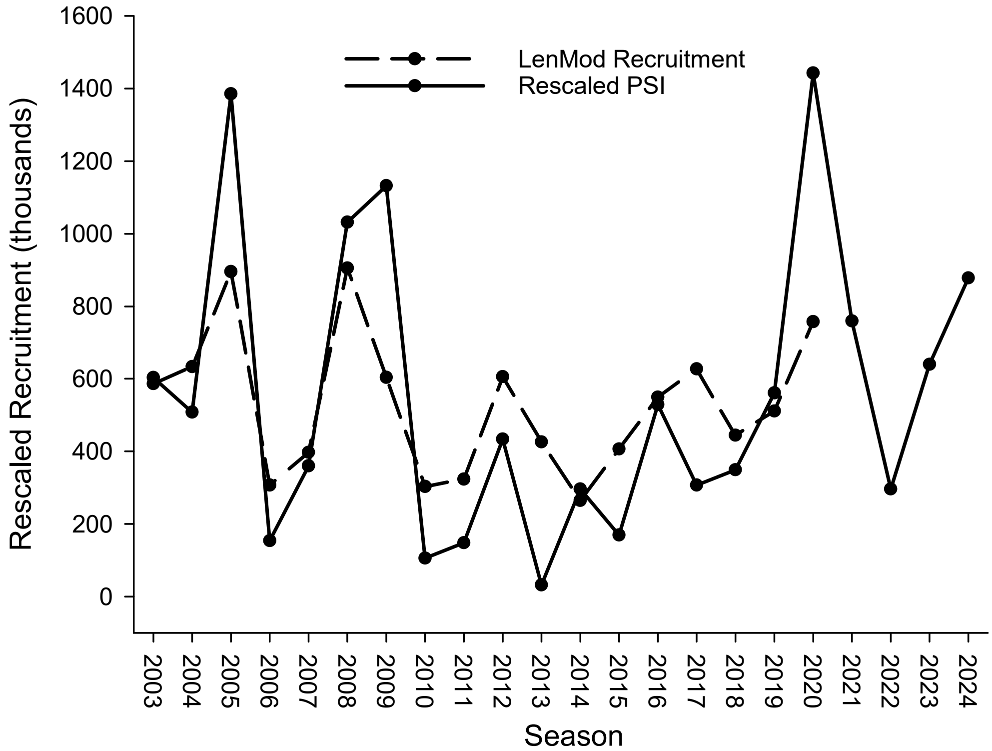

Figure 3-11 Correlations between NZRLF model estimated recruitment and rescaled puerulus settlement lagged by three years.

3.5 qR" and "LenMod" stock assessment models

3.5.1 Model fits

Both the qR and LenMod fishery models show good fits to the available data (Appendix 4). The qR model fitted closely to logbook totals of yearly catch in number (Figure 6-1) and catch in weight (Figure 6-2). For LenMod, monthly model estimates of catch in number and catch rate fitted closely to the reported monthly logbook catch in number (Cn) (Figure 6-3) and catch rate (Figure 6-4, for months fitted by LenMod). In addition, both male and female model estimates fitted well to length-frequency data from voluntary catch sampling as shown in monthly fits from the 2020 season (Figure 6-5). Catchability estimates from LenMod are provided in Table 6-5.

3.5.2 Model outputs

The NZRLF qR and LenMod models show close agreement in estimated trends for indicators of performance and status. Both models indicate a general decline in legal-sized lobster biomass in the NZRLF from the late 1980s to 2008 (Figure 3-12a). Over the next two seasons biomass increased before either gradually decreasing (qR) or remaining relatively stable (LenMod). Over the last four seasons both models show increasing biomass trends with the 2020 estimate at approximately 1,388 t.

Corresponding to the declining trend in biomass, egg production has also decreased since the 1980s (Figure 3-12b). In 2020, total egg production was estimated to be approximately 149 billion which is one of the lowest estimates on record. The 2020 estimate equates to approximately 11% of unfished egg production (Figure 3-12c).

In response to declines in biomass and egg production, exploitation rate was considerably reduced in 2009 when the TACC was lowered to 310 t from 470 t (Figure 3-12d). Over the next 5 seasons exploitation rate increased before declining after 2015. The 2020 estimate is approximately 19%, which is the lowest estimate on record.

Outputs from the qR model suggest that recruitment has been highly variable but in recent seasons has been low in a historical context (Figure 3-12e). In 2020 estimates were approximately 0.50 million lobsters. Temporal trends in recruitment estimated by both models are strongly correlated with PRI estimates from logbook data (1994–2020) (R^2 = 0.91).

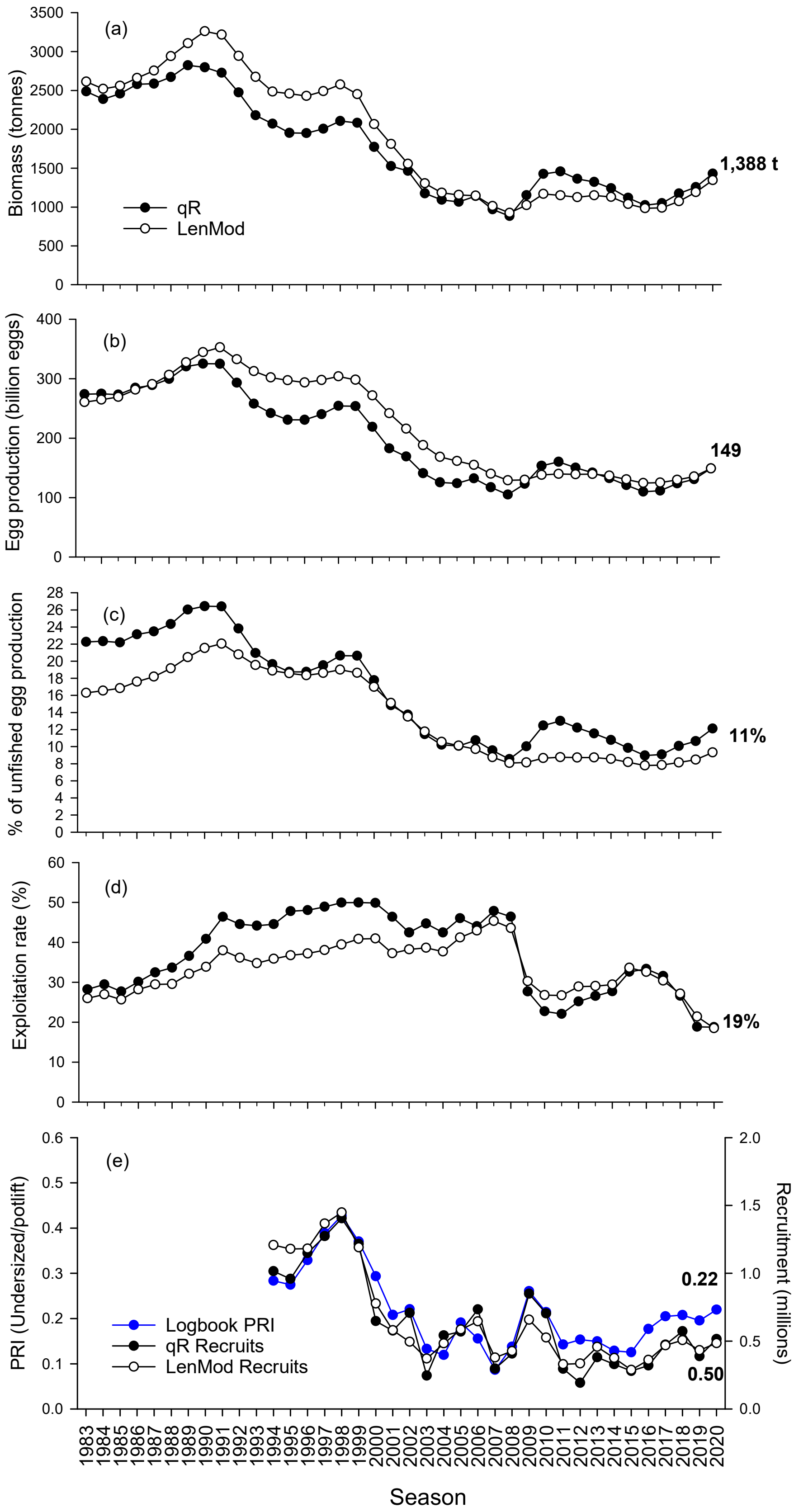

Figure 3-12 Fishery model outputs for the NZRLF. (a) Legal-size biomass; (b) Egg production; (c) % of unfished egg production; (d) Exploitation rate; and (e) Recruitment.

4 DISCUSSION

4.1 Information sources used for assessment

Assessment of the NZRLF resource relies heavily on commercial fishery-dependent data collected from several long-term monitoring programs. In particular, it places considerable emphasis on assessing catch rate trends of both legal and undersized lobsters. These are supported by outputs from both the qR and LenMod fishery models as well as onboard observer catch sampling.

Current catch rates are not standardised. Linnane et al. (2018) presented standardised estimates which were reviewed by the South Australian Rock Lobster Harvest Strategy Working Group (HSWG) which noted the close agreement between nominal and standardised time-series. The HSWG recommended that periodic catch rate standardisation should be continued, but that nominal catch rate could remain as the primary indicator of lobster abundance.

4.2 Stock Status

The 2020 season reflected the second consecutive year the NZRLF was impacted by overseas market issues due to a combination of international trade disputes and COVID. The impact can be observed in within-season trends, e.g. catch in February of 2020 was reduced to 6 t when normally up to 60 t of lobster are landed. These impacts can affect important indicators such as catch rate, at least on a monthly level. For example, the low CPUE estimate observed in February 2020 is clearly a reflection of market influences, rather than a reduction in lobster abundance. Despite these impacts, there are clear signals to indicate that the status of the NZRLF has improved in recent seasons.

The current TACC in the NZRLF of 296 t is low in a historical context having been reduced from 360 t in 2016. Following an extended period of decline, some positive signals within key fishery indicators are now being observed. Legal-sized catch rates have increased by 36% since 2016 and are now the highest since 2011. Temporally, the increases were consistent across all months and particularly through the high catch period from December through to February. Spatially, CPUE has increased in almost all of the primary MFAs and depth ranges where lobsters are targeted.

At the broader spatial scale, Inner and Outer sub-regions have been in place for six seasons (since 2015) but with some differences in terms of performance. While the Inner sub-region catch rates have increased by 30%, those in the Outer sub-region has remained relatively stable. In response, the TACC in the Outer sub-region was reduced from 60 t to 46 t in 2018. Over the last two seasons, catch in the Outer sub-region has been low with 17 t and 27 t taken in 2019 and 2020, respectively, making assessment of the region difficult. That withstanding, the recent catch levels would indicate that the overall exploitation rate is low. In addition, the catch rates in two key MFAs (7 and 8) have increased since 2016.

As well as reduced catch levels, recent increases in catch rate are likely driven by improved recruitment to the fishable biomass, particularly over the last five seasons. After a long-term decline from 1998 to 2015, undersized abundances have increased by 69% and are above the TrRP. Given that the period between PRI and recruitment to the fishery is approximately one year, this has translated to increases in legal-size CPUE.

Recent recruitment increases are supported by independent model estimates of recruitment as well as current trends in mean weight. Variations in mean weight inform fishery recruitment with lower mean weights resulting from influxes of small lobsters into the fishable biomass and higher mean weights resulting from several consecutive years of low recruitment. Decreases in mean weight were observed over the last four seasons, further supporting evidence of fishery recruitment.

In relation to increased medium-term recruitment, correlations between PSI and model estimated recruitment in the NZRLF are strong when assuming a three to four-year period from settlement to recruitment. Given the above average settlement from 2016 to 2018 (noting that 2017 was the highest on record), this indicates that recruitment in 2020 and 2022 is predicted be above the long-term average (assuming a four-year lag).

Outputs from the qR and LenMod fishery models are in close agreement in relation to the current stock status. Both models show a consistent long-term decline in legal-size biomass and corresponding levels of egg production (<20% of unfished) but with some increases over the last four seasons. Recent increases in biomass have reduced exploitation rates to approximately 19% which is the lowest on record. However, despite recent increases in legal-size biomass, overall egg production levels in the fishery remained low in 2020 at just 11% of unfished levels.

In 2021, a new Management Plan for the NZRLF was formally adopted (PIRSA 2021). To address low levels of egg production, testing has focused on increasing %UEP in the NZRLF towards a stock improvement target of 20% UEP by 2035. In addition, given observed divergent performances between Inner and Outer sub-regions, separate harvest strategies for each region have been developed with the primary performance indicator (legal-size CPUE) at the zonal level now linked to a definition of stock status (Table 1-6). In 2020, the CPUE was 1.05 kg/potlift, which is above the TrRP of 0.60 kg/potlift. As a result, the SZRLF stock is classified as "**sustainable**". This means that the current fishing mortality is being adequately controlled to avoid the stock becoming recruitment impaired.

4.3 Assessment Uncertainties

One of the notable uncertainties in this assessment is the reliance on fishery-dependent data as an indicator of stock abundance. Specifically, catch rate estimates, based on fishery-dependent data, can be influenced by factors such as gear selectivity, changes in fishing patterns, fleet efficiency or fleet dynamics over time (Maunder et al. 2006). However, two lines of evidence suggest that the catch rate trends detailed in this report are robust indicators of overall lobster abundance. Firstly, trends are highly consistent across large spatial scales. For example, across the ten major MFAs of the fishery, catch rate simultaneously decreased from the late-1990s to 2009, marginally increased over the next two seasons to 2011, before again declining to near historical lows over the next six seasons. Similar trends were also observed across a range of depth categories within MFAs. These fishery-wide trends suggest recruitment and subsequent survival in the NZRLF occur consistently across large spatial scales, and that these trends are well reflected in the broad seasonal and spatial coverage (>300,000 potlifts annually) used to compute catch rate.

Secondly, a previous stock assessment report (Linnane et al. 2018) highlighted that when nominal catch rate was standardised for factors such as year, month, depth, MFA, mean weight, licence and consumer price index (CPI), the nominal and standardised CPUE time series were closely aligned. While no meaningful difference and therefore no improvement was observed, the standardisation did not include two factors thought to be important in other lobster fisheries. Specifically, standard catch logs in South Australian lobster do not record the "vessel" or "skipper". In the Victorian rock lobster fishery, "vessel" and "skipper" were identified as the two most important factors in legal-size lobster catch rate standardisation (Feenstra et al. 2019).

4.4 Future Work

The uncertainties with overseas markets have made research planning difficult over the past two seasons. This is because many research projects require industry collaboration in terms of vessel time/support which cannot be guaranteed in the current market environment.

The FRDC project "*Assessing efficiency of alternative rock lobster pot designs*" is due for completion in 2022. Future work will determine if differences in catchability are significant in alternative pots, and if so, how this is addressed in current harvest strategies.

There is a need to investigate changes in growth rates within the fishery over time. Most growth information in the models is based on the large-scale tag/recapture program undertaken from 1993 to 1996 (Linnane et al. 2005). Quantifying a change in growth rate will require re-launching a substantial tag-recovery program. This has been identified as a high research priority given the importance of accurate growth transition matrices and mean weight-at-age in the estimation of absolute biomass within the two fishery assessment models.

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6 APPENDICES

6.1 Appendix 1. NZRLF Catch, Effort and CPUE data

Table 6-1 Catch, Effort (November-October) and CPUE (November-April) for the NZRLF from 1970 to 2020 by zone.

Season	Catch (t)	Effort (000's potlifts)	CPUE (kg/potlift)
1970	602	382	1.58
1971	638	437	1.46
1972	749	480	1.56
1973	671	453	1.48
1974	603	441	1.37
1975	651	431	1.51
1976	560	412	1.36
1977	581	412	1.41
1978	559	464	1.21
1979	593	480	1.24
1980	677	479	1.41
1981	638	509	1.25
1982	716	583	1.23
1983	678	570	1.19
1984	680	617	1.10
1985	657	578	1.14
1986	750	606	1.24
1987	811	650	1.25
1988	868	664	1.31
1989	997	690	1.45
1990	1104	731	1.51
1991	1222	805	1.52
1992	1064	746	1.43
1993	930	719	1.29
1994	891	705	1.26
1995	903	724	1.25
1996	904	718	1.26
1997	943	722	1.31
1998	1016	721	1.41
1999	1001	700	1.43
2000	846	687	1.23
2001	675	626	1.08
2002	595	571	1.04
2003	503	597	0.84
2004	446	554	0.81
2005	476	585	0.81
2006	492	570	0.86
2007	459	616	0.75
2008	403	600	0.67
2009	310	351	0.88
2010	312	290	1.08
2011	307	287	1.08
2012	325	334	0.99
2013	330	355	0.94
2014	321	366	0.88
2015	349	438	0.83
2016	321	438	0.77
2017	301	389	0.79
2018	291	330	0.89
2019	253	304	0.89
2020	249	249	1.05

Table 6-2 Catch, Effort (November-October) and CPUE (November-April) for the NZRLF from 1970 to 2020 by MFA (7, 8, 15, 27, 28).

	MFA 7			MFA 8			MFA 15			MFA 27			MFA 28		
Season	Catch (t)	Effort (000's potlifts)	CPUE (kg/potlift)	Catch (t)	Effort (000's potlifts)	CPUE (kg/potlift)	Catch (t)	Effort (000's potlifts)	CPUE (kg/potlift)	Catch (t)	Effort (000's potlifts)	CPUE (kg/potlift)	Catch (t)	Effort (000's potlifts)	CPUE (kg/potlift)
1970	11	6	1.82	35	23	1.51	55	33	1.66	0	0	1.38	160	77	2.13
1971	13	6	2.12	39	28	1.29	79	45	1.70	5	3	1.33	131	73	1.77
1972	20	10	1.86	49	24	2.05	61	37	1.72	3	2	2.96	150	84	1.82
1973	23	12	1.90	47	26	1.85	98	52	1.87	1	0	0.77	122	71	1.85
1974	28	13	1.96	55	29	1.92	90	52	1.75	4	4	1.06	118	76	1.64
1975	34	12	2.39	87	51	1.69	78	46	1.63	2	2	1.38	114	66	1.83
1976	21	12	1.67	58	41	1.32	74	53	1.38	19	7	1.33	117	67	1.83
1977	22	12	1.59	29	21	1.34	60	39	1.50	6	6	2.96	122	61	2.01
1978	22	12	1.50	22	22	0.96	49	39	1.21	16	12	1.13	119	70	1.78
1979	19	10	1.57	12	16	0.74	60	49	1.19	35	28	1.06	119	57	2.09
1980	6	6	0.97	5	7	0.83	33	29	1.10	38	32	2.02	161	71	2.17
1981	5	4	1.19	2	2	1.25	31	23	1.27	45	38	1.10	168	106	1.55
1982	18	6	2.51	8	5	1.46	43	26	1.62	42	33	1.37	164	97	1.63
1983	18	13	1.41	10	8	1.24	49	38	1.18	49	43	1.25	150	123	1.21
1984	20	14	1.46	23	16	1.40	72	61	1.16	47	43	1.15	148	139	1.04
1985	9	6	1.62	31	23	1.34	55	43	1.26	64	48	1.18	155	135	1.12
1986	5	4	1.39	23	18	1.23	98	69	1.39	69	46	1.25	172	139	1.22
1987	18	10	1.76	8	5	1.42	113	79	1.41	50	37	1.12	154	127	1.21
1988	12	8	1.55	24	16	1.51	93	74	1.25	48	41	1.12	145	119	1.21
1989	6	4	1.54	30	21	1.47	95	65	1.47	51	48	1.37	194	130	1.47
1990	16	9	1.81	31	18	1.66	156	93	1.65	44	37	1.52	153	109	1.40
1991	15	8	1.85	31	18	1.74	181	104	1.72	42	38	1.37	214	151	1.41
1992	16	9	1.84	63	31	2.03	139	81	1.71	50	42	1.16	192	137	1.39
1993	49	25	1.97	64	39	1.64	118	79	1.48	43	36	1.05	146	118	1.23
1994	32	18	1.91	51	34	1.56	108	69	1.63	48	39	1.22	172	132	1.37
1995	49	29	1.74	55	36	1.67	168	107	1.65	46	36	1.18	141	120	1.23
1996	32	19	1.73	46	32	1.52	165	107	1.62	25	22	1.28	177	139	1.34
1997	23	14	1.59	38	25	1.68	118	87	1.44	31	30	1.27	218	170	1.38
1998	26	14	1.93	32	22	1.55	141	94	1.54	36	32	1.27	177	143	1.30
1999	34	15	2.27	39	24	1.68	103	74	1.49	46	36	1.34	142	111	1.35
2000	30	17	1.79	38	30	1.35	91	72	1.33	25	22	1.19	135	127	1.13
2001	23	16	1.55	27	23	1.22	78	68	1.19	32	31	1.13	115	119	1.02
2002	18	14	1.34	23	20	1.14	55	54	1.03	18	20	0.95	110	110	1.04
2003	13	13	1.22	20	21	0.95	32	44	0.74	19	24	0.81	79	102	0.80
2004	5	5	0.95	23	27	0.90	24	35	0.72	12	17	0.76	63	85	0.75
2005	6	6	1.07	29	27	1.12	37	44	0.86	23	26	0.93	87	107	0.83
2006	4	4	0.97	11	12	0.96	44	47	0.96	23	23	1.00	125	137	0.93
2007	9	9	1.04	17	19	0.91	60	71	0.88	23	29	0.80	93	133	0.71
2008	9	11	0.92	20	21	0.96	46	61	0.76	21	28	0.77	75	118	0.65
2009	3	2	1.28	8	6	1.33	17	17	0.98	15	13	1.17	74	78	0.96
2010	2	2	1.30	7	6	1.19	18	18	1.00	10	9	1.04	60	53	1.13
2011	3	2	1.66	7	5	1.32	18	15	1.18	8	7	1.18	67	58	1.17
2012	1	1	1.24	10	8	1.43	34	28	1.26	11	10	1.20	79	73	1.10
2013	6	5	1.26	7	6	1.18	27	24	1.14	13	13	1.04	64	66	0.97
2014	3	2	1.45	8	7	1.20	13	13	1.08	13	14	1.00	74	80	0.94
2015	14	17	1.11	19	23	1.11	26	26	1.07	11	11	0.98	58	71	0.83
2016	6	11	0.94	14	23	0.97	28	32	0.94	10	12	0.83	57	72	0.82
2017	8	11	0.74	12	18	0.69	17	19	0.87	13	14	0.94	46	56	0.83
2018	3	6	0.67	8	13	0.65	10	11	0.97	15	14	1.04	43	47	0.92
2019	<1	<1	0.84	4	6	0.79	13	12	1.19	9	11	0.86	38	46	0.89
2020	2	2	0.85	5	7	0.83	6	6	1.07	11	11	1.00	41	38	1.11

Table 6-3 Catch, Effort and CPUE for the NZRLF from 1970 to 2020 by MFA (39, 40, 48, 49, 50).

	MFA 39			MFA 40			MFA 48			MFA 49			MFA 50		
Season	Catch (t)	Effort (000's potlifts)	CPUE (kg/potlift)	Catch (t)	Effort (000's potlifts)	CPUE (kg/potlift)	Catch (t)	Effort (000's potlifts)	CPUE (kg/potlift)	Catch (t)	Effort (000's potlifts)	CPUE (kg/potlift)	Catch (t)	Effort (000's potlifts)	CPUE (kg/potlift)
1970	128	92	1.38	10	6	1.39	18	12	1.78	45	23	2.23	2	2	1.20
1971	124	89	1.46	11	8	1.24	26	19	1.48	35	22	1.72	7	4	1.65
1972	129	98	1.31	5	3	1.61	39	22	1.94	76	44	1.88	3	2	1.68
1973	121	81	1.61	9	7	1.20	30	16	1.78	37	23	1.64	1	1	0.94
1974	106	77	1.40	22	15	1.44	32	17	1.93	28	18	1.52	1	1	1.44
1975	121	70	1.71	24	15	1.53	42	21	2.05	26	16	1.67	0	0	0.85
1976	141	82	2.41	13	10	1.31	24	14	1.80	17	12	1.40	7	8	0.92
1977	149	92	1.59	48	32	1.51	23	12	1.90	38	22	1.57	3	4	0.77
1978	156	108	1.44	46	32	1.43	31	16	1.93	32	21	1.49	6	6	1.06
1979	159	111	1.42	36	26	1.33	52	27	1.96	39	26	1.55	9	8	1.14
1980	154	99	1.52	69	44	1.54	82	43	1.91	65	35	1.84	6	2	2.61
1981	147	94	1.56	45	42	1.05	69	39	1.80	80	44	1.82	15	7	2.13
1982	158	114	1.35	62	43	1.40	83	50	1.65	84	62	1.35	18	14	1.32
1983	151	134	1.10	43	48	0.86	56	46	1.22	74	63	1.15	4	3	1.25
1984	131	122	1.06	47	58	0.81	67	58	1.15	56	52	1.07	12	9	1.31
1985	127	117	1.07	45	55	0.81	53	45	1.14	62	52	1.16	12	9	1.30
1986	138	114	1.20	49	54	0.91	46	38	1.21	62	52	1.16	13	9	1.36
1987	203	160	1.25	48	50	0.96	49	39	1.26	56	47	1.16	11	7	1.59
1988	189	135	1.38	78	73	1.05	98	70	1.39	68	47	1.42	9	7	1.29
1989	199	138	1.42	83	72	1.14	83	63	1.31	92	61	1.49	24	12	2.02
1990	197	134	1.43	93	73	1.28	107	67	1.60	87	65	1.32	32	16	1.96
1991	221	144	1.50	109	89	1.22	113	78	1.41	129	81	1.54	22	11	1.93
1992	160	125	1.26	83	78	1.05	118	80	1.44	94	70	1.30	23	13	1.81
1993	122	107	1.14	66	69	0.94	77	63	1.21	86	77	1.10	25	14	1.76
1994	153	118	1.34	62	65	0.98	47	48	1.01	92	85	1.14	17	14	1.22
1995	109	90	1.25	72	76	0.98	44	43	1.05	84	80	1.12	27	18	1.55
1996	140	111	1.32	66	70	0.98	46	42	1.15	72	69	1.11	21	18	1.27
1997	152	116	1.38	70	66	1.10	65	47	1.40	77	69	1.20	19	12	1.55
1998	166	122	1.39	80	67	1.25	77	49	1.60	97	67	1.56	23	11	2.20
1999	206	147	1.45	82	67	1.28	89	59	1.55	127	84	1.60	28	14	2.09
2000	139	116	1.24	64	56	1.22	66	51	1.35	106	86	1.30	44	25	1.79
2001	96	98	1.02	40	42	1.03	51	48	1.12	94	90	1.10	36	24	1.68
2002	107	105	1.04	44	44	1.04	53	49	1.12	75	75	1.03	18	14	1.34
2003	89	108	0.84	48	62	0.80	48	53	0.91	90	102	0.91	20	18	1.16
2004	105	127	0.84	49	67	0.75	54	59	0.92	53	67	0.79	24	23	1.07
2005	94	117	0.81	47	72	0.67	61	74	0.85	43	57	0.75	13	15	0.87
2006	93	111	0.84	44	61	0.73	45	56	0.81	53	66	0.83	7	8	1.01
2007	71	100	0.72	37	57	0.67	42	60	0.71	48	66	0.74	16	16	1.00
2008	70	111	0.65	32	53	0.60	33	54	0.61	39	61	0.64	10	13	0.81
2009	65	81	0.79	37	41	0.89	20	28	0.73	29	36	0.80	6	7	0.85
2010	90	82	1.09	39	44	0.89	24	23	1.06	29	27	1.10	1	1	1.10
2011	63	59	1.07	35	43	0.83	30	32	0.97	38	35	1.08	4	3	1.49
2012	46	50	0.92	32	47	0.71	35	41	0.88	37	42	0.89	7	7	1.10
2013	71	78	0.92	38	52	0.74	25	30	0.86	37	40	0.92	11	11	1.07
2014	68	80	0.86	31	51	0.62	36	38	0.94	39	45	0.90	8	10	0.85
2015	57	79	0.74	32	53	0.60	33	41	0.84	50	59	0.88	9	11	0.90
2016	68	91	0.76	24	45	0.54	22	31	0.77	44	62	0.75	12	15	0.91
2017	55	77	0.71	25	42	0.60	33	40	0.84	44	55	0.85	10	10	0.94
2018	59	66	0.89	25	38	0.67	30	33	0.91	47	52	0.90	11	10	1.16
2019	52	65	0.83	37	55	0.70	25	29	0.95	38	44	0.95	13	10	1.18
2020	49	51	1.04	33	42	0.73	35	31	1.19	46	42	1.14	13	8	1.46

6.2 Appendix 2. Specifications of the qR model including equations, assumptions and model parameters

Overview

The qR fishery stock assessment model operates on a yearly time-step. It is an age-based model, with a maximum age of 20+. As data input, it fits to yearly totals for commercial lobster catch in both weight and numbers landed, and conditions on yearly fishing effort. A prior value for instantaneous natural mortality rate is assumed. A vector for mean weight-at-age was estimated from yearly growth increments inferred from tag-recovery data and an assumed length for age-1 lobsters (length of legal recruits).

Data and fixed parameter inputs

Annual lobster catch in the South Australian lobster fisheries is reported in logbooks by weight (C_t^W) and by numbers (C_t^N). Effort (E_t) is reported as yearly pot lifts. The model year (t = 1983, …, 1983+ n_t -1) runs from 1 June ending 31 May, with winter defined as June-October inclusive, and n_t = the number of seasons modelled from 1983 to the most recent year. The effort data inputted into the qR model are corrected, to ignore the lower catch rates of winter fishing as an index of stock abundance. Age is subscripted by a, where a=1 refers to lobsters reaching legal minimum length during or in the winter before a given fishing season, and the plus-group age a=20+ refers to the highest age group including all lobsters of age 20 years and older. The mean weights-at-age $\{w_a;\ a=1,20+\}$ of harvested lobsters (McGarvey et al. 1999) are computed from GROTAG (Francis 1988) estimates of von Bertalanffy length-dependent yearly growth using tag-recoveries from the zone, and an assumed length L0 = 105 mm CL + one-half-year's growth of (a=1) recruits. This choice of L0 specifies the qR model version (6W) applied for the 2020 season assessment, and is the best approximation to mean body length of newly recruited lobsters in the absence of ageing. An instantaneous natural mortality rate of M=0.1 yr^{-1} is widely assumed for this species (e.g. Annala and Breen 1989) and genus (Johnston and Bergh 1993).

The population dynamics model

The qR model is effort-conditioned. A Baranov mortality submodel is assumed, where population number declines exponentially due to mortality within each yearly time step. Recruitment of lobsters to the legal stock in each year is a freely estimated parameter. In the Northern Zone qR model, as in Northern Zone LenMod, a 3% yearly increase in effective effort from 1984 to 2000 is assumed based on discussions with industry and managers, modelled as a rising catchability in these pre-quota years.

Model variables are listed in Table 6-4. The array of lobster numbers by age and year, $N_{a,t}$, varies over yearly time due to incoming recruitment, $N_{1,t} = R_t$, occurring at the start of each year t and due to outgoing mortality through each year. Natural and fishing mortality were assumed to be independent of age. Growth is expressed in the vector of mean weights at age. Yearly cohort losses due to natural mortality and harvesting for ages 1-19 years old are written;

$$N_{a+1,t+1} = N_{a,t} \cdot \exp\left(-Z_t\right), \tag{1a}$$

where total instantaneous mortality rate $Z_t = F_t + M$. For the age 20+ 'plus group', the survival equation is written

$$N_{20+,t+1} = \left[N_{19,t} + N_{20+,t}\right] \cdot \exp\left(-Z_t\right). \tag{1b}$$

Deaths due to harvesting were summed over age to yield predicted catches by number ($\hat{C}_t^N$) and weight ($\hat{C}_t^W$) for fitting to data in each year of the logbook time series:

:

$$\hat{C}_t^N = \frac{F_t}{Z_t} \cdot \left\{1 - \exp\left(-Z_t\right)\right\} \cdot \sum_{a=1}^{20+} N_{a,t} \tag{2a}$$

$$\hat{C}_t^W = \frac{F_t}{Z_t} \cdot \left\{1 - \exp\left(-Z_t\right)\right\} \cdot \sum_{a=1}^{20+} w_a N_{a,t} \tag{2b}$$

Fishing mortality is assumed to vary in proportion to reported yearly effort, E_t , related by a catchability coefficient, q:

$$F_t = \begin{cases} q \cdot E_t, & t = 1983 \\ q \cdot \left[1 + 0.03*(t - 1983)\right] \cdot E_t, & \text{for years of 3\% yearly increasing effective effort} \\ q \cdot \left[1 + 0.03*(2000 - 1983)\right] \cdot E_t, & \text{for } t = \text{2000-2002} \\ q^{\text{Quota}} \cdot E_t, & \text{for years 2003 onwards under quota management} \end{cases} . \tag{3}$$

The initial population age vector ($N_{a,1983}$) is estimated assuming a stationary age structure using the first-year estimated recruitment R_{1983} and a freely estimated F_0:

$$\begin{cases} N_{1,1983} = R_{1983} \\ N_{2,1983} = R_{1983} \exp\left[-\left(M + F_0\right)\right] \\ N_{a+1,1983} = N_{a,1983} \exp\left[-\left(M + F_0\right)\right], \quad a = 2,19 \\ N_{20+,1983} = N_{19,1983} \exp\left[-\left(M + F_0\right)\right] \Big/ \left\{1 - \exp\left[-\left(M + F_0\right)\right]\right\} \end{cases}$$

Likelihood function

The negative log likelihood is written:

$$-\log L = n_t \log \sigma_N + \frac{1}{2 \cdot \sigma_N^{\ 2}} \sum_{t=1983}^{1983+n_t-1} \left(C_t^N - \hat{C}_t^N\right)^2 + n_t \log \sigma_W + \frac{1}{2 \cdot \sigma_W^{\ 2}} \sum_{t=1983}^{1983+n_t-1} \left(C_t^W - \hat{C}_t^W\right)^2 . \quad (4)$$

Variances of the two normal likelihood components of Eq. 4 (for catches in numbers and in weight) were written in terms of a single estimated coefficient-of-variation parameter (σ_C) and the respective data time series means:

$$\sigma_N = \sigma_C \cdot \overline{C}^N \quad (5a)$$

$$\sigma_W = \sigma_C \cdot \overline{C}^W . \quad (5b)$$

Estimates of free parameters, q, q^{Quota}, σ_C, F_0, and yearly recruit numbers $\left\{R_t ; t = 1983, 1983 + n_t - 1\right\}$, were obtained by minimising the negative log-likelihood using the R software environment version 3.6.2 with function "optimr (option nlminb) of package "optimx".

The output indicator of yearly biomass was computed as the sum over all ages of population number by age times mean weight at age. For both LenMod and qR models, biomass is reported as a year-average (rather than start-year) quantity. For qR, where population declines Baranov exponentially through each yearly model time step, year-average biomass is computed by analytically integrating over the negative-exponential survival through each 12-month year, giving;

$$B_t = \sum_{a=1}^{20+} w_a N_{a,t} \left[1/Z_t\right]\left[1 - \exp\left(-Z_t\right)\right]. \quad (6)$$

Yearly egg production by female lobsters at the start of each fishing season (in spring) was computed as;

$$Eggs_t = \sum_{a=1}^{20+} m_a f_a N_{a,t} / 2 , \qquad (7)$$

where m_a and f_a are sampled vectors of maturity and fecundity versus age (Prescott et al. 1996), and a sex ratio of one-half was assumed. The unfished level of egg production UEP is computed by setting fishing mortality rate equal to zero and re-running the qR model dynamics for 2* n_t (two times the number of estimated years), taking the final-year value of this unfished equilibrium egg production to be UEP. The reference time period for the constant level of recruitment assumed for all years in this zero-F equilibrium UEP run is the mean of historical estimated recruitment over 1990-2011. The reported yearly percentage of unfished egg production is $\%UEP_t = Eggs_t / UEP$.

Catchability

The qR catchability parameter estimates are q = 4.5×10^{-7} potlifts^{-1} and q^{Quota} = 4.9×10^{-7} potlifts^{-1} for pre- and post-TACC management (before 2003 and from 2003 onward), respectively.

Model adjustments for 2019/20 due to COVID market disruption

A large reduction in access to the Chinese market for South Australian lobster exports occurred when the COVID pandemic response was implemented, starting after 22 January 2020. This induced changes in fishing practices, and lower levels of fishing activity. To prevent this from biasing qR model estimates, only catch rates reported up to 22 January were used as the 2019/20 index of abundance.

To remove the impact of disrupted fishing on the inputs to the qR model, a 'COVID correction was applied to effectively remove the reported post-22-January 2020 catch rate data from the 2019/20 qR input data set. The qR model consists of three data components for season 2019: (1) catch in weight taken as given over the full 12-month fishing season, (2) effort calculated via COVID-corrected catch rates as described below and, (3) catch in number which was not corrected after analysis showed that removing the post-22-January data had negligible impact on mean weight.

The four steps taken to correct catch rates andcalculate the yearly effort qR input for the 2019/20 season (using only catch rate information up to 22 January) are detailed as follows. First, two sets of catch and effort data were created, one including the regular non-winter period of data (November-May), and a second that includes only catch and effort up to 22 January 2020. Second, a linear statistical model was fitted relating catch rate that includes data only up to 22 January to the data for the regular ('Reg') season catch rate:

*CwPUEReg[iy] ~ aCwPUEReg22Jan + bCwPUEReg22Jan * CwPUE22Jan[iy]. (A3.1)*

This linear model was fitted to data from seasons 2003-2018. The 2019/20 season was naturally excluded since the estimated parameters will be used to rescale catch rate and effort for that latest season. The two estimated parameters, the intercept (aCwPUEReg22Jan) and coefficient (bCwPUEReg22Jan) in this linear relationship, quantify the expected regular season catch rate given catch rate only up to 22 January in a typical season. We chose 2003 onward as the past seasons to be fitted given that average recruitment levels decreased around 2003. Third, we computed what the regular season catch rate, was expected to be for 2019/20 given the catch rate observed up to 22 January:

*CwPUECorReg[2019] = aCwPUEReg22Jan + bCwPUEReg22Jan*CwPUE22Jan[2019]. (A3.2)*

Finally, we computed the COVID corrected measure of yearly effort for 2019/20 to be taken as input to the qR model:

ECOVIDReg[2019] = CwAllMonths[2019] / CwPUECorReg[2019]. (A3.3)

where *CwAllMonths* is the yearly catch weight data for the full 12 months of the 2019 season.

The resulting COVID-corrected catch rate is CwPUECorReg[2019] = 0.915. The raw yearly catch rate in 2019 was 0.862. The COVID-corrected catch rate was thus 6.1% higher. Thus we estimate a correction of about 6% higher for expected full season catch rate inferred when only data up to 22 January 2020 are used compared to the nominal (raw) 2019/20 NZ catch rate. The higher COVID-corrected catch rate value was used to compute yearly effort in qR model estimates for 2019/20.

This correction procedure was also run for mean weight in 2019. The resulting corrected mean weight differed negligibly (by only 0.01%) from NZ nominal, and so no correction to mean weight or qR catch in number was needed or applied.

Incorporating recreational catch

The proportion of catch taken by recreational sector in the NZ was estimated to vary from around 2% in 2008, rising to 6% in the 2013 recreational survey. Previously, the qR model used only the more reliable commercial catch and effort data. For this assessment and in future reports, all qR data inputs, yearly totals for catch in weight, catch in number and effort, are scaled upward by the same yearly varying proportion of recreational catch-in-weight used in LenMod.

Table 6-4 Variables of the qR model dynamics and likelihood assessment estimator.

Model Variable	Description
a	subscript for age, 1 to 20+ (the last age group representing ages 20 years and older)
n_t	number of fishing seasons modelled
t	subscript for yearly fishing season, 1983 to 1983+ n_t -1
$N_{a,t}$	number of lobsters of age a , at the start of year t
R_t	estimated number of recruits at start of year t
F_t	instantaneous fishing mortality rate in year t
q	estimated 1983 catchability coefficient for pre-quota (pre-2003) years. Change in catchability over 1984-2000 increases this.
q^{Quota}	estimated catchability coefficient for years under quota (2003+)
$\hat{C}_t^N$	model numbers of lobsters caught in year t
$\hat{C}_t^W$	model weight of catch in year t
N_t	total population number at start of year t
B_t	biomass of lobsters averaged across year t
σ_N	sigma of yearly normal likelihood residuals about model-predicted $\hat{C}_t^N$
σ_W	sigma of yearly normal likelihood residuals for data about model-predicted $\hat{C}_t^W$
σ_C	estimated coefficient of variation relating σ_N and σ_W to data means $\overline{C}^N$ and $\overline{C}^W$
F_0	estimated fishing mortality used to generate the first-year vector of numbers at age
$\hat{C}_t^N$	model number of lobsters caught in year t
$\hat{C}_t^W$	model weight of catch in year t
N_t	total population number at start of year t
B_t	biomass of lobsters averaged across year t
$Eggs_t$	eggs produced by female lobsters at start of year t
UEP	unfished egg production, based on average recruitment 1990-2011

$\%UEP_t$	percentage of unfished egg production in year t

6.3 Appendix 3. Specifications of the length-structured model (LenMod) including equations, assumptions and model parameters

Overview

LenMod is a population dynamics model that operates on a fishing season defined over, for the Northern Zone Rock Lobster Fishery, T= 7 time-steps (months), starting with the opening of the fishing season in November (i =1) to May (i =7), with a multi-month June-October (i =8) time step covering each closed winter season. However, from season 2015 the winter season is open for fishing in parts of the Northern Zone Rock Lobster Fishery. The duration of the i th time-step (i =1,..,T) in units of years is denoted t_i. Lobster size-classes are in 4 mm bins, the lowest length bin defined as 82.5-86.5 mm CL, with 29 bins for males and 21 for females. The model population array, $N^s_{y,i,l}$, is the number of lobsters by length bin (l), sex (s), fishing season (y; hereafter referred to as year), and month (i).

The population dynamics model

Basic dynamics

The equation that specifies $N^s_{y,i,l}$ takes account of natural mortality M (instantaneous yearly rate), fishing mortality, growth, and settlement under the assumption that harvest occurs before growth and settlement:

$$N^s_{y,i+1,l} = \sum_{l'} X^s_{l',l,i} \, N^s_{y,i,l'} \, e^{-Mt_i} \, \{1-\tilde{H}^s_{y,i,l'}\} + \Omega^s_i \Phi^s_l \, R_y \qquad (1)$$

where:

$X^s_{l',l,i}$ is the fraction of the animals of sex s in size-class l' that grow into size-class l during time-step i ;

Ω^s_i is the fraction of the settlement that occurs to sex s during time-step i ($\sum_s \sum_i \Omega^s_i = 1$);

Φ^s_l is the proportion of the settlement of animals of sex s that occurs to size-class l ;

$\tilde{H}^s_{y,i,l'}$ is the exploitation rate on animals of sex s in size-class l' at the start of time-step i of year y over all fleets; and

R_y is the settlement of animals during year y:

$$R_y = \overline{R}\ e^{\varepsilon_y - (\sigma_{R,y})^2/2} \tag{2}$$

where: $\overline{R}$ is mean settlement, ε_y is the "settlement residual" for year y, $\sigma_{R,y}$ is the standard deviation of the random fluctuations in settlement for year y:

$$\sigma_{R,y}^2 = \begin{cases} \tilde{\sigma}_R^2\, \tilde{\tau}^{(y_{\text{start}} - y)} & \text{if } y \le y_{start} \\ \tilde{\sigma}_R^2 & \text{otherwise} \end{cases} \tag{3}$$

$\tilde{\sigma}_R$ is the extent of variation in settlement for years after y_{start}, and $\tilde{\tau}$ determines the extent to which $\sigma_{R,y}$ changes with time ($\tilde{\tau} < 1$ means that the settlement will be closer to the mean settlement for the years before y_{start}).

$B_y^{AvgTotLeg}$ is the reported year-average legal-sized biomass during year y, averaging across T months, using start-month population numbers (after half-month natural survival), where W_l^s is the weight of a lobster of size l and sex s:

$$B_y^{AvgTotLeg} = \frac{1}{T}\sum_{i=1}^{T}\sum_{s}\sum_{l>=LML} W_l^s\ e^{-M_i/2} N_{y,i,l}^s\ . \tag{4}$$

Reported yearly exploitation rate is defined as the sum of commercial landed catch in weight data across the months divided by the year-average legal-sized biomass. Egg production is given by the following equation for the case in which spawning is assumed to occur at the start of time-step i_m of year y:

$$Eggs_y = \sum_l m_l\, f_l\, N_{y,i_s,l}^{\text{f}} \tag{5}$$

where m_l and f_l are previously estimated vectors of maturity and fecundity versus length for females in size-class l, i_s is the time-step in which spawning occurs (i_s = month 1), and $N_{y,i_m,l}^{\text{f}}$ is the total number of females. The unfished level of egg production is computed by setting all estimated parameters to their values (except recruitment) from the stock assessment run, setting catches to zero, and re-running LenMod for 40 years, sufficient to achieve equilibrium. Recruitment for this zero-catch run is set to the average over the years 1990-2011. The % of unfished egg production in each year is computed as the ratio of $Eggs_y$ divided by the final zero-catch equilibrium level of egg production.

Catches

$C^f_{y,i}$, which is the landed catch in weight data by fleet f during time-step i of year y. In addition to landed catch, commercial data includes information on spawning lobsters and those brought up dead in the pots, while five surveys (1998, 2001, 2004, 2007, and 2013) are used as the basis to estimate catches for the recreational fleets. $C^f_{y,i}$ is used in defining the fully-selected exploitation rate for fleet f during time-step i of year y, $F^f_{y,i}$, is calculated as follows:

$$F^f_{y,i} = \frac{(1+d^f_{y,i})C^f_{y,i}}{\sum_l \sum_s \tilde{S}^{s,f}_{y,i,l}(1-\tilde{p}^s_{i,l})V^s_i W^s_l N^s_{y,i,l} e^{-Mt_i/2}} \qquad (6)$$

where

$d^f_{y,i}$ is the ratio of the discarded dead catch to the legal-size catch for fleet f (only for commercials fleets, and is 0 for recreationals);

V^s_i is the relative sex vulnerability, determined separately for each month i, which, if estimated, is either being fixed at a value of 1 for males ($V^{males}_i = 1$) and estimated for females, or fixed at a value of 1 for females ($V^{females}_i = 1$) and estimated for males, or fixed to 1 for both sexes;

$\tilde{p}^s_{i,l}$ is the proportion of mature animals of sex s in length-class l which are returned live during time-step i because they are spawning (0 for males); and

$\tilde{S}^s_{y,i,l}$ is the vulnerability by length for the gear used on animals of sex s in size-class l during time-step i of year y and incorporates the legal minimum size as:

$$\tilde{S}^s_{y,i,l} = \begin{cases} 0 & \text{if } L^s_l + \Delta L^s_l \le \text{LML}_y \\ S^s_{y,i,l} & \text{if } L^s_l \ge \text{LML}_y \\ S^s_{y,i,l}(L^s_l + \Delta L^s_l - \text{LML}_y)/\Delta L^s_l & \text{otherwise} \end{cases} \qquad (7)$$

where $\tilde{S}^{s,f}_{y,i,l} = \tilde{S}^{s}_{y,i,l}$ as it is assumed that at any time when recreational fishing takes place the same gear is used as for the commercial fishery. L^s_l is the lower limit of size-class l for sex s, ΔL^s_l is the width of a size-class (4 mm) l for sex s, LML_y is the legal minimum size during year y, $S^s_{y,i,l}$ is the vulnerability of the gear used on animals of sex s in size-class l. There were two changes in LML_y changing from 98.5 mm to 102 mm in 1994 and then to 105 mm in 2000.

$F^f_{y,i}$, is used to define $\tilde{H}^s_{y,i,l'}$ as follows:

$$\tilde{H}^s_{y,i,l} = \sum_f \tilde{S}^s_{y,i,l}(1-\tilde{p}^s_{i,l})V^s_i\, F^f_{y,i} \tag{8}$$

Catchability

The catchability parameter is estimated separately by month (i) and for two time periods, before (1983-2002) and under (2003+) TACC management. In addition, in the Northern Zone, catchability is assumed to increase by 3% per year from 1984 to 2000, when it reaches the value shown under $q^{\mathrm{Comm}}_{Q=0,i}$, where subscript $Q=0$ indicates not under quota. Further details on the definition of catchability ($q^{\mathrm{Comm}}_{Q,i}$) are given in this Appendix.

Table 6-5 Catchability estimates from LenMod for the NZRLF.

Month of fishing season (i)	$q^{\mathrm{Comm}}_{Q=0,i}$ **(2000-2002)**	$q^{\mathrm{Comm}}_{Q=1,i}$ **(2003-2020)**
November	5.7 x 10^{-7}	6.5 x 10^{-7}
December	6.7 x 10^{-7}	8.3 x 10^{-7}
January	8.6 x 10^{-7}	1.1 x 10^{-6}
February	9.2 x 10^{-7}	1.2 x 10^{-6}
March	9.2 x 10^{-7}	1.2 x 10^{-6}
April	1.1 x 10^{-6}	1.5 x 10^{-6}
May	1.7 x 10^{-6}	2.0 x 10^{-6}

Initial conditions

It is impossible to project this model from unexploited equilibrium owing to a lack of historical catch records for the entire period of exploitation. Instead, it is assumed that the population was in equilibrium with respect to the average catch over the first five years for which catches are available in year $y_{start}-20$. This approach to specifying the initial state of the stock differs from that traditionally adopted for assessments of rock lobster off Tasmania and Victoria (Punt and Kennedy 1997; Hobday and Punt 2001) in that no attempt is made to estimate an initial exploitation rate. The settlements for years $y_{start}-20$ to $y_{start}-1$ are treated as estimable so that the model is not in equilibrium at the start of year y_{start}.

The objective function

The objective function summarises the information collected from the fishery and contains contributions from three data sources:

a) Commercial catch rates,
b) length-sex frequency data from sampling of commercial pot lifts, and
c) commercial catches in number.

Catch-rate data

The contribution of the catch-rate data for the commercial fishery to the likelihood function is given by:

$$L_{1.a}=\prod_{y}\prod_{i}\frac{1}{I_{y,i}^{\mathrm{Comm}}\sqrt{2\pi}\,\sigma_{q,Q,i}^{Comm}}\exp\left(-\frac{(\ell\mathrm{n}I_{y,i}^{\mathrm{Comm}}-\ell\mathrm{n}(q_y q_{Q,i}^{\mathrm{Comm}}\,B_{y,i}^{e,\mathrm{Comm}}))^2}{2(\sigma_{q,Q,i}^{Comm})^2}\right) \quad (9)$$

where:

$q_{Q,i}^{\mathrm{Comm}}$ is the commercial catchability coefficient which varies by time-step (month) i and for each of two periods of years namely before (1983-2002) and after (2003+), inception of TACC (differentiated by index {Q = 0,1}, 0 for years prior to quota, and 1 for years under quota);

q_y is a constant multiplier factor specific for each year;

$I_{y,i}^{\mathrm{Comm}}$ is the catch-rate index for the commercial fleet for year y and time-step i;

$\sigma_{q,Q,i}^{Comm}$ is the standard deviation of the observation error for the commercial fleet for time-step i and for each of two periods of years indexed by Q for before and after inception of TACC.

The maximum likelihood estimates for $q_{Q,i}^{\mathrm{Comm}}$ and $\sigma_{q,Q,i}^{Comm}$ were obtained analytically. Catchability is modelled as rising over the years from 1983 to 1999 relative to 2000, via a multiplier factor (q_y) which rises linearly by 0.03 per year from 1983 (0.66) to 1999 (0.98) and 1.0 for years 2000 and later.

$B_{y,i}^{e,\text{Comm}}$ is the exploitable biomass available to the commercial fishery (and recreational fishery) midway into time-step i of year y:

$$B_{y,i}^{e,Comm} = \sum_{s}\sum_{l} V_i^s (1-\tilde{p}_{i,l}^s)\tilde{S}_{y,i,l}^s \; W_l^s \; e^{-Mt_i/2} N_{y,i,l}^s (1-\tilde{H}_{y,i,l}^s/2)$$

(10)

Length-frequency data

Length and sex frequency data are available from a sampling program which has been conducted since 1991. This program involves voluntary reporting on the contents of pot lifts by some commercial fishers. The observed fraction, during time-step i of year y by the commercial fishery, of the catch (in number) of animals of sex s in size-class l (including undersize) is denoted $\rho_{y,i,l}^{s,\text{Comm}}$. The model-estimate of this quantity, $\hat{\rho}_{y,i,l}^{s,\text{Comm}}$, takes account of the vulnerability of the gear and the numbers in each size-class and sex:

$$\hat{\rho}_{y,i,l}^{s,\text{Comm}} = \tilde{S}_{y,i,l}^s V_i^s (1-\tilde{p}_{i,l}^s) N_{y,i,l}^s \Big/ \sum_{s'}\sum_{l'} \tilde{S}_{y,i,l'}^{s'} V_i^{s'} (1-\tilde{p}_{i,l'}^{s'}) N_{y,i,l'}^{s'} \qquad (11.a)$$

The observed value of $\rho_{y,i,l}^{s,\text{Comm}}$ is assumed to be multinomially distributed, giving the length-sex frequency likelihood function (ignoring multiplicative constants):

$$L_2 = \prod_{y}\prod_{i}\prod_{l}\prod_{s}\left(\hat{\rho}_{y,i,l}^{s,\text{Comm}}\right)^{n_{y,i,l}^{s,\text{Comm}}\omega} \qquad (11.b)$$

where $n_{y,i,l}^{s,\text{Comm}}$ is the observed number of lobsters in the sampling program in time-step i of year y of sex s and size-class l, and ω is a down-weighting constant factor to reduce influence of this data relative to the catch-effort data sets (since catch sampling is not random and selectivity is not stationary). Undersize length-sex frequencies are fit as part of the full length-sex frequency data from the sampling program, with the model catch number predictions being proportional to:

$$S_{y,i,l}^s V_i^s (1-\tilde{p}_{i,l}^s) N_{y,i,l}^s e^{-Mt_i/2} \qquad (12.a)$$

The length-sex frequencies for spawners are also assumed to be multinomial samples, except the model catch number predictions are proportional to:

$$S_{y,i,l}^s V_i^s \tilde{p}_{i,l}^s N_{y,i,l}^s e^{-Mt_i/2} \qquad (12.b)$$

Catch-in-number

The commercial catches in number, $C^N_{y,i}$, are assumed to be lognormally distributed. The contribution of these data to the likelihood function is therefore given by:

$$L_3 = \prod_f \prod_y \prod_i \frac{1}{C^N_{y,i}\sqrt{2\pi}\sigma_N} \exp\left(-\frac{(\ell n C^N_{y,i} - \ell n \hat{C}^{N,\mathrm{Comm}}_{y,i})^2}{2\sigma^2_N}\right) \qquad (13)$$

where $\hat{C}^N_{y,i} = \sum_s \sum_l V^s_i \, \tilde{S}^s_{y,i,l} (1-\tilde{p}^s_{i,l}) N^s_{y,i,l} \, e^{-Mt_i/2} F^{\mathrm{Comm}}_{y,i}$ and σ^{Comm}_N is the standard deviation of the observation error in catch numbers, assumed to apply over all time. The spawner discards are also fitted under the assumption that they are lognormally distributed.

Parameter estimation

Table 6-6 lists the parameters of the population dynamics model and the objective function, and highlights those parameters assumed to be known exactly and those parameters whose values are estimated by fitting the model to the data. Vulnerability-at-length for specified combinations of months is estimated, separately for each sex, by a logistic function of length. Female spawner fractions are based on auxiliary information.

A constraint is placed on the settlement residuals to stabilise the estimation and prevent confounding with mean recruitment. The following term was included in the objective function:

$$P = 0.5 \sum_y (\varepsilon_y)^2 / (\sigma^2_{R,y}). \qquad (14)$$

Estimates of all parameters were obtained by minimising the negative log-likelihood using ADMB v 12.0 (Fournier et al. 2012) MinGW 64Bit.

Table 6-6 Parameters of the length-structured model (LenMod) and their sources for the Northern Zone Rock Lobster Fishery.

Parameter	Description	Value	Sources
ε_y	The settlement residuals for year y	Estimated	
$\ell n(\bar{R})$	Mean settlement	Estimated	
$\tilde{\sigma}_R$	The extent of variation in settlement for years after y_{start}	0.75	Assumed
$\tilde{\tau}$	The extent to which $\sigma_{R,y}$ changes with time	1.0	Assumed
$X^s_{l',l,i}$	Growth transition matrix	Matrices by sex for months 2 and 7.	Estimated using method of McGarvey and Feenstra (2001).
M	Natural mortality	0.1 yr^{-1}	Conventional assumption
V^s_i	Relative vulnerability by sex by time-step	Fixed at 1 for all months and both sexes.	
$S^s_{y,i,l}$	Vulnerability of the gear by sex, size-class, time-step, and year.	Estimated as logistic functions of length per sex, shared across years, but separately for Nov, Dec, Jan-March, April, and May-winter.	
$\tilde{p}^s_{i,l}$	Proportion of mature spawning animals by sex, size-class and time-step		Estimated externally
Ω^s_i	Fraction of the settlement by time-step and sex	Estimated	
Φ^s_l	Proportion of the settlement of animals by sex and size-class	First six length bins: males =0.2, 0.25, 0.2, 0.15, 0.1, 0.05; females = 0.2, 0.25, 0.2, 0.15, 0.1, 0.05	Assumed
Q_l	Egg production as a function of size		Estimated externally
W^s_l	Mass as a function of size and sex	Power function of length	Estimated externally
i_{m}	The time-step in which spawning occurs	1	

$q_{Q,i}^{\text{Comm}}$	Catchability for the commercial fleet by time-step i and for each of two periods of years namely before and after inception of TACC	Estimated	
q_y	Constant multiplier factor on catchability specific for each year	Rising values ranging from 0.66 to 1.0 over 1983-2000.	Assumed
$\sigma_{q,Q,i}^{Comm}$	Standard deviation of the observation errors for time-step i and for each of two periods of years namely before and after inception of TACC for the commercial fleet.	Estimated	
σ_N^{Comm}	Standard deviation of the observation error in commercial catch in numbers	Estimated	
ω	Down-weighting factor for length-sex data	0.0125	Assumed

6.4 Appendix 4. Model fits

qR model

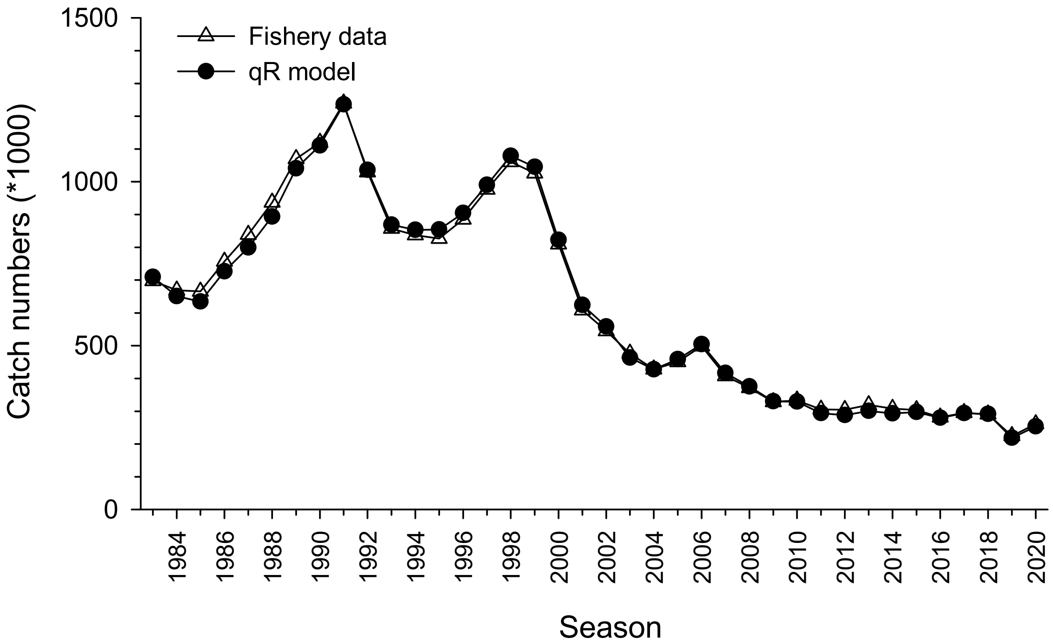

Figure 6-1 Fit of the qR model to catch in number of lobsters landed for the NZRLF, based on annual logbook catch totals from the fishery.

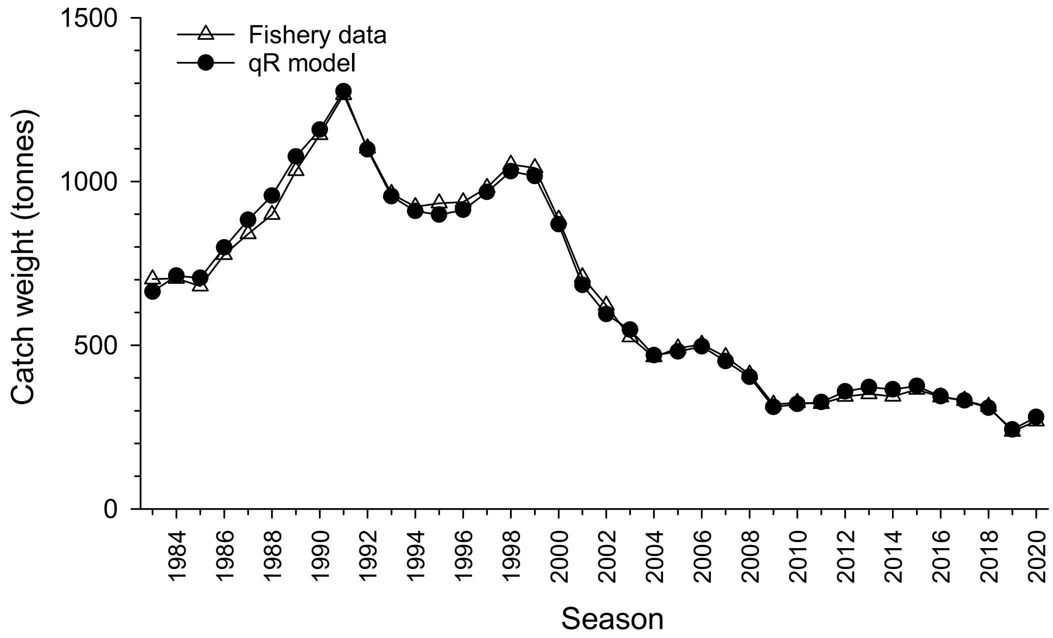

Figure 6-2 Fit of the qR model to catch in weight for the NZRLF, based on annual logbooks catch totals from the fishery.

LenMod

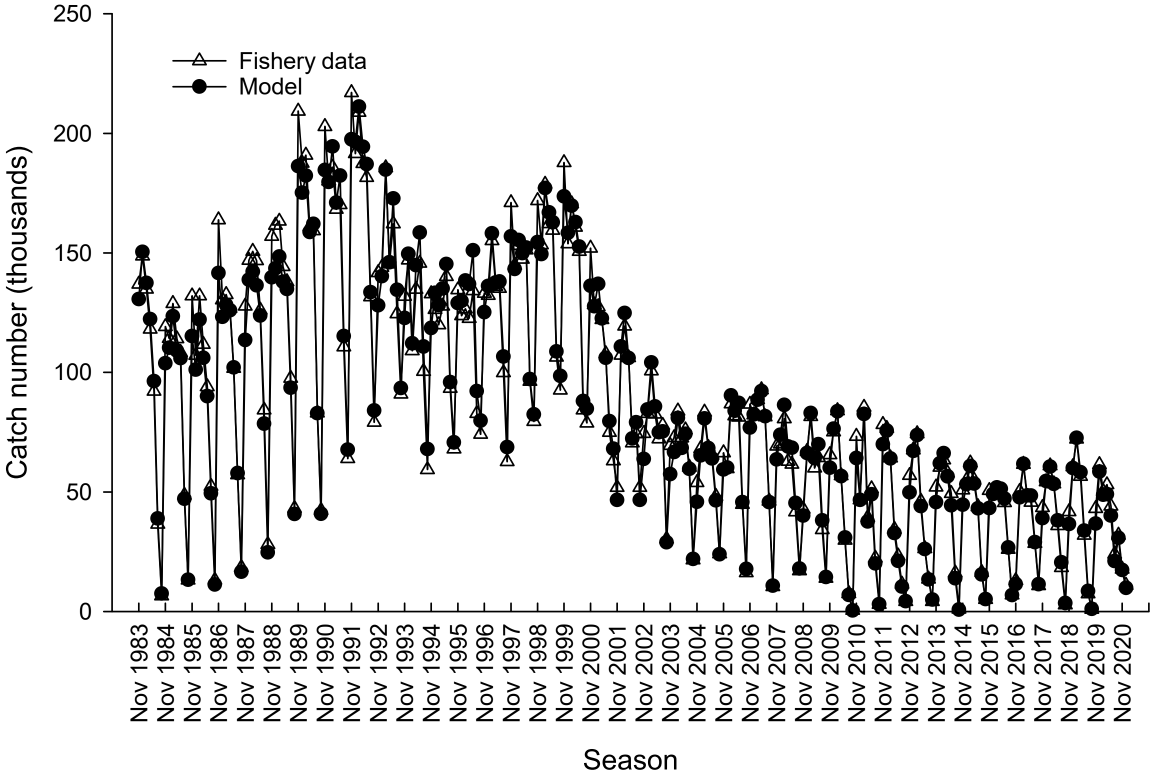

Figure 6-3 Fit of the LenMod model to monthly catch in number (Cn) for the NZRLF, based on logbook catch totals from the fishery.

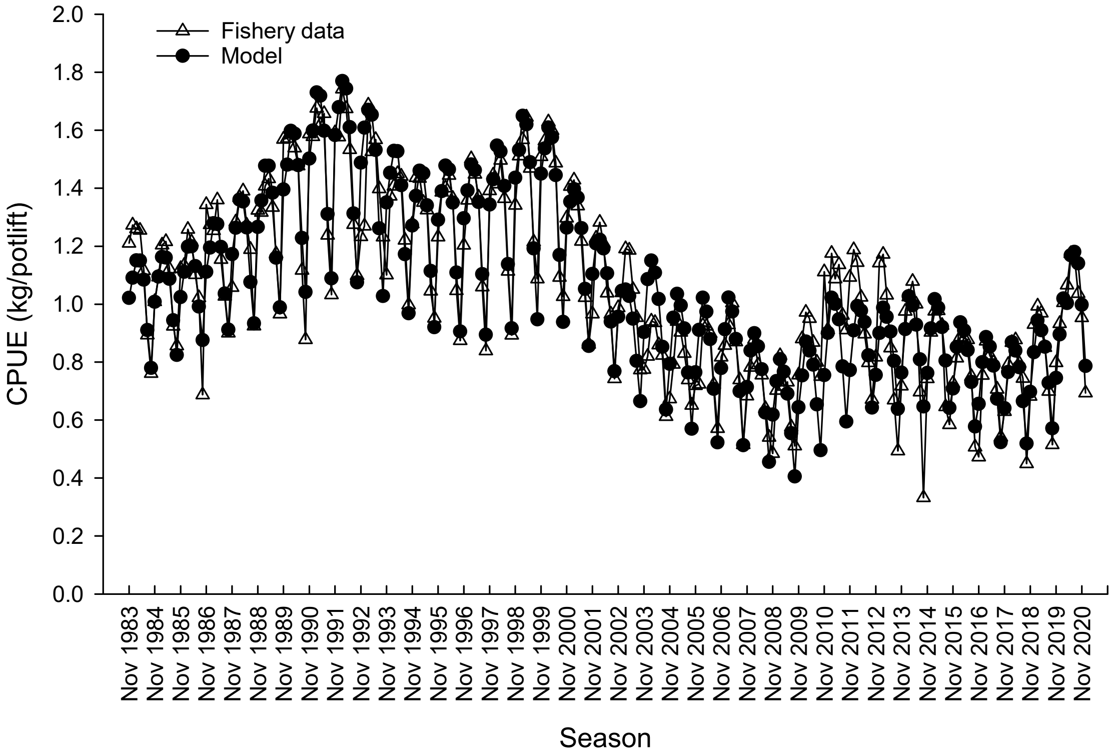

Figure 6-4 Fit of the LenMod model to monthly catch per unit effort (CPUE) for the NZRLF, based on logbook catch totals from the fishery.

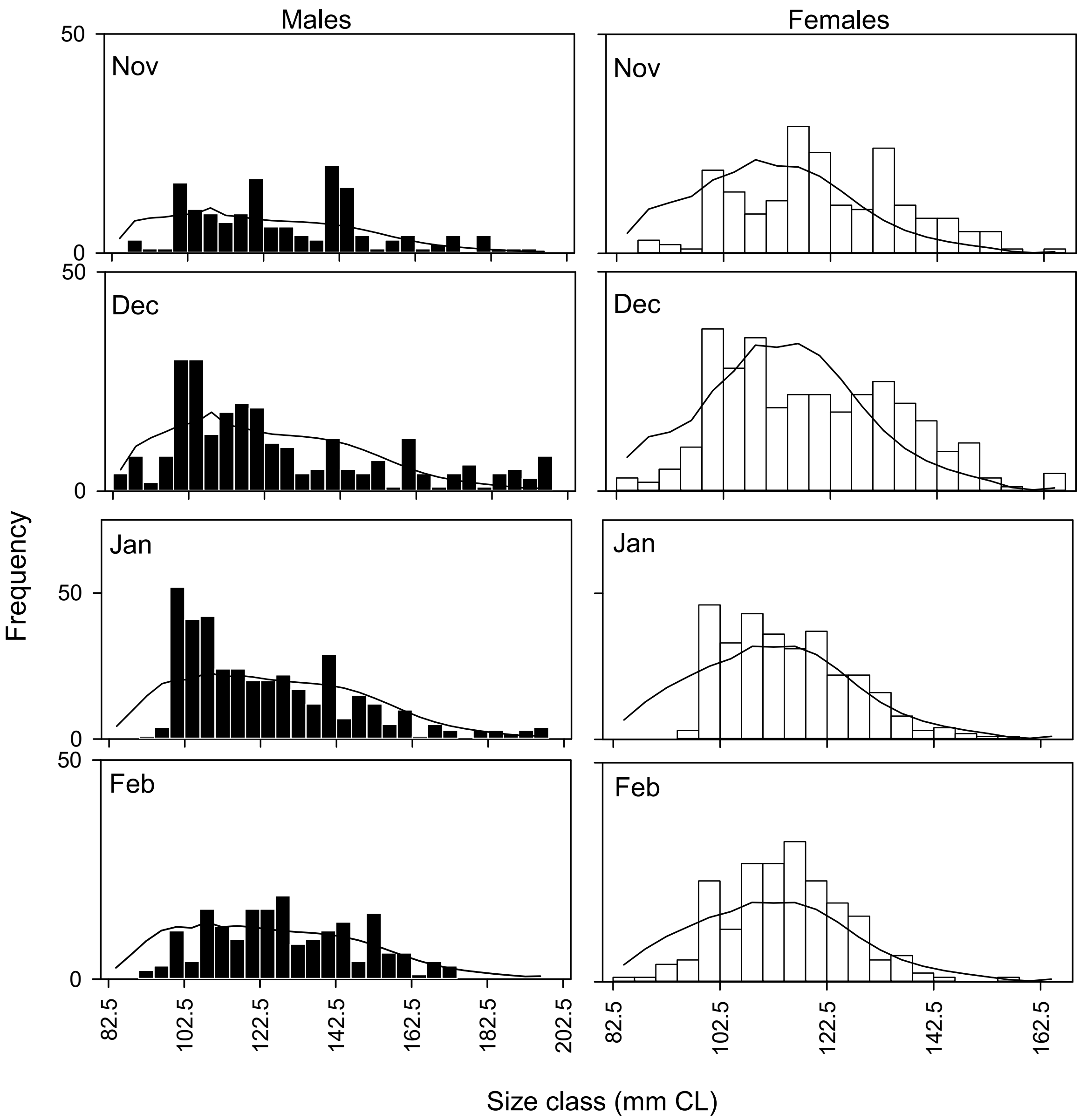

Figure 6-5 Fits of LenMod model (black line) proportions by length bin to commercial length frequency data for both males and females taken during the 2020 season in the NZRLF.