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Northern Zone Rock Lobster (*Jasus edwardsii*) Fishery Stock Assessment 2018/19

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

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SARDI Aquatic Sciences
PO Box 120 Henley Beach SA 5022

July 2020

Fishery Assessment Report to PIRSA Fisheries and Aquaculture

SOUTH AUSTRALIA

Government of South Australia
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EXECUTIVE SUMMARY

This stock assessment determined the status of South Australia's Northern Zone Rock Lobster Fishery (NZRLF) through analysis of data from several long-term monitoring programs. The performance indicators in the current harvest strategy are not linked to a definition of stock status. Consequently, this assessment used a 'weight of evidence' method to determine stock status using the National Fishery Status Reporting Framework (NFSRF).

Assessment of the NZRLF relies heavily on fishery-dependent logbook and catch sampling data. Specifically, catch per unit effort (CPUE) of legal and undersized lobsters are the main indicators of legal and pre-recruit abundance.

In 2018/19, the total allowable commercial catch (TACC) in the NZRLF was 296 t. This reflects recent reductions in TACCs in both the Inner and Outer sub-regions. The total reported catch was 291.3 t (249.8 t Inner sub-region; 41.5 t Outer sub-region). Effort in 2018/19 was 330,773 potlifts, reflecting the third consecutive season that effort has decreased and the third lowest estimate on record.

The 2018/19 CPUE (November-April) was 0.89 kg/potlift, reflecting a 16% increase from 2016/17 (0.77 kg/potlift). The 2018 estimate reflects the second consecutive season that catch rate has increased.

CPUE increased in most Marine Fishing Areas (MFAs) and sub-regions in 2018/19. The exceptions were MFAs 7 and 8 where CPUE has declined over the last four seasons. Current estimates in these areas are now the lowest on record.

Fishery models show consistent long-term declines in legal-size biomass and egg production but with some increases in recent seasons. Outputs indicate a current legal-size biomass ranging from 1,100 to 1600 t, which has increased since 2016/17. This translates to an exploitation rate ranging from 18 to 26%, which is one of the lowest in the history of the fishery. However, despite recent increases in biomass, egg production in the NZRLF remains low, with the 2018/19 estimate at approximately 9 to 14% of unfished levels.

In 2018/19, the catch sampling based pre-recruit index (PRI; November-March), was 0.36 undersized/potlift which is above the Limit Reference Point (LRP) of 0.30 undersized/potlift. Evidence of recent recruitment to the fishery is supported by independent estimates from logbook and fishery model sources. In addition, puerulus settlement levels from 2016/17 to 2018/19 indicates that fishery recruitment in 2020/21 and 2022/23 may be above the long-term average (assuming a four-year lag).

In summary, there is now evidence to indicate that the status of the NZRLF stock has improved in response to recent TACC reductions. As a result, based on a weight-of-evidence approach, the NZRLF stock is classified as "**sustainable**" at the current TACC of 296 t.

Table 1. Key statistics for the NZRLF.

Statistic	**2018/19**	**2017/18**
TACC	296 t	310 t
Total commercial catch (Nov-Oct)	291.3 t	301.1 t
Total effort (Nov-Oct)	330,773 potlifts	389,771 potlifts
Commercial CPUE (Nov-Apr)	0.89 kg/potlift	0.79 kg/potlift
Pre-recruit index (Nov-Mar)	0.36 undersized/potlift	0.44 undersized/potlift
Biomass estimate (qR)	1,689 t	1,483 t
(LenMod)	1,122 t	1,039 t
Exploitation rate (qR)	18%	21%
(LenMod)	26%	32%
Status	**Sustainable**	**Depleting**

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

1 INTRODUCTION

1.1 Overview

Stock assessments for the Southern 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 2014).

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 $24.4 million in 2017/18 (Econsearch 2019). 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 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) for this sub-region. The fishing season for the Inner sub-region remained unchanged (1 November to 31 May). Details of all management arrangements for the 2018/19 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.

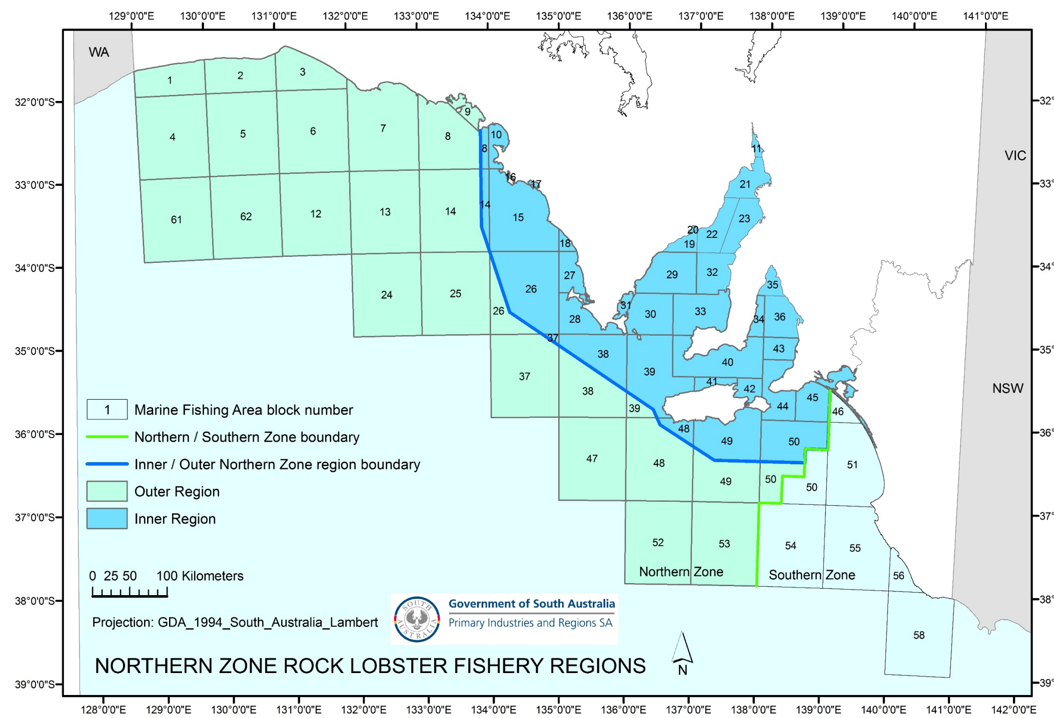

Figure 1-1 MFAs in the Northern and Southern Zones of the South Australian Rock Lobster Fishery. Blue line represents Northern Zone Inner and Outer region boundary.

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.

Table 1-2 Management arrangements for the NZRLF in 2018/19.

Management tool	Current restriction
Total Allowable Commercial Catch (TACC)	296 t (250 t Inner sub-region and 46 t Outer sub-region)
Closed season	1 June to 31 October (Inner sub-region only)
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 to 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 are non-feeding but 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. 2010a). After inshore settlement, early juveniles (<20 mm 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. 1991; 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 address to addressing 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. 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 2019.

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 where 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. 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 by André Punt 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 in number and catch per unit effort (CPUE), while conditioning on catch in 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 biomas) 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 Management Plan for the South Australian Northern Zone Rock Lobster Fishery was released in November 2014 (PIRSA 2014). The contained harvest strategy 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 rebuild the biomass of the resource and increase catch rates. This harvest strategy was amended in 2015 following a review which took into consideration information relating to spatial and temporal management of the NZRLF provided in Linnane et al. (2016).

1.6.2 Performance indicators

The primary indicator is commercial logbook CPUE (kg of legal-sized lobster/potlift) based on data from November to April, inclusive. The secondary indicator is a commercial pre-recruit index (PRI; number of undersized lobsters/potlift) based on voluntary catch sampling 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 biomass and exploitation rates.

In 2015, spatial management of the NZRLF was implemented which resulted in separate TACCs being set for both Inner and Outer sub-regions (Linnane et al. 2016; McGarvey et al. 2016). For PRI, a Limit Reference Point (LRP) of 0.30 undersized/potlift is used, below which, TACC increases cannot be considered (PIRSA 2014).

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 (Stewardson et al. 2018) (Table 1-3). 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 South Australian fish stocks.

The performance indicators in the current harvest strategy for the NZRLF are not directly linked to a definition of stock status. Consequently, this assessment used a 'weight of evidence' method to determine stock status.

Table 1-3 Stock status terminology (Stewardson et al. 2018).

	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.

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 2019. For ease of reference, figures and text refer to the starting year of each season (e.g. “2018” refers to the 2018/19 fishing season starting 1 November of 2018).

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

In addition to the above, other data sources recorded in the voluntary component of the logbook were 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) octopuses. 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 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), sex and record the reproductive condition of female lobsters (ovigerous or non-ovigerous) from all pots sampled. In addition, all bycatch are identified and counted. The latitude and longitude of each pot sampled is recorded, thereby providing information at a finer-scale 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 Peninusla (one each at Marion Bay and Stenhouse Bay) with the collectors set in groups of 5 or 10. 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 assess the NZRLF. The qR model is yearly and uses the three logbook time series of catch in weight, catch in 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 using a vector of mean lengths-at-age and LenMod using length-transition matrices. Both models estimate yearly independent recruitment.

Another difference is that LenMod estimates a separate catchability for years under quota (2003+), while the qR model does not. Both models assume a steadily rising effective effort, as 3% per year linear increases in catchability, from 1983 to 2000 when the adoption of GPS and sounder technology is known to have substantially improved fishing power, with a total increase of 51% over those years.

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 time period for computing mean unfished recruitment. This reference period is also used in other jurisdictions (e.g. Tasmania) and therefore permits State-wise consistent reporting at the stock level under the Status of Key Australian Fish Stocks (SAFS) system. Also, this reference time 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 which yields better agreement with LenMod in absolute levels of estimated stock biomass, as recommended in the 2017 review of these stock assessments (Smith, 2017).

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) used in all previous qR model estimation, preventing winter fishing from biasing downward this index of relative abundance.

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 are normal with 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 catches in number landed 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 about 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.

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) length-frequency proportions by length 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 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.

2.6 Quality assurance of data

All logbook and catch sampling data are 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 are stored in an Oracle database, backed up daily, with access restricted to SARDI Information Systems staff. All puerulus data are entered into Excel spreadsheets and stored on a SARDI network drive.

3 RESULTS

3.1 Commercial catch and effort statistics

3.1.1 Zone

In 2018, the TACC in the NZRLF was 296 t (250 t Inner sub-region, 46 t Outer sub-region). The reported logbook catch (1 November 2018 to 31 October 2019) was 291.36 t (98% of the 296 t TACC) (Figure 3-1a; Table 6-1). By sub-region, the catch was 249.87 t from the Inner sub-region (1 November to 31 May) and 41.49 t from the Outer sub-region (1 November to 31 October) (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 nine fishing seasons.

Effort in 2018 was 330,773 potlifts, reflecting a 15% decrease from 2017 (389,771 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 2018 estimate reflects the third consecutive season that effort has decreased and is the third lowest on record.

In 2018, the legal-sized CPUE was 0.89 kg/potlift, reflecting a 16% increase from 2016 (0.77 kg/potlift) (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. The 2018 estimate reflects the second consecutive season that catch rate has increased. Spatially, between 2017 and 2018, CPUE increased in both the Inner (0.78 to 0.90 kg/potlift) and Outer (0.80 to 0.83 kg/potlift) sub-regions (Table 3-1).

In 2018, the PRI of 0.36 undersized/potlift reflected an 18% decrease from 2017 (0.44 undersized/potlift) and remained above the LRP of 0.30 undersized/potlift (Figure 3-1c). Overall, estimates of PRI from the catch sampling program are highly variable. For comparison, PRI based on logbook data (where escape gaps are open) were also analysed (Figure 3-1c). Estimates from this time series have increased by 62% over the last three seasons and in 2018 the logbook based PRI was 0.21 undersized/potlift, the highest since 2010. In the NZRLF, the time taken for pre-recruits to enter into the fishable biomass is estimated to be 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 two seasons to 1.07 kg in 2018.

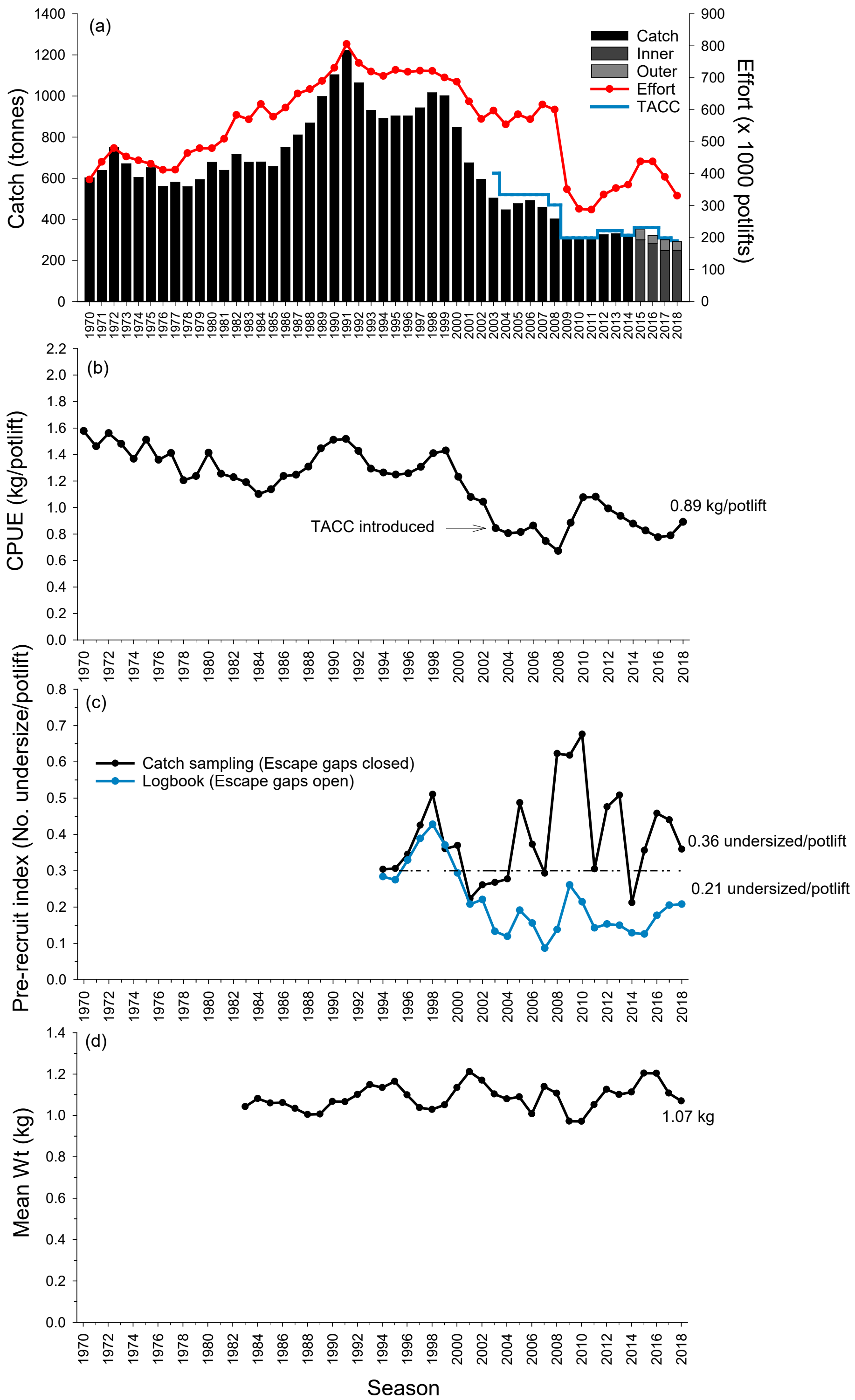

Figure 3-1 Fishery dependent outputs for the NZRLF. (a) Catch and effort including total allowable commercial catch (TACC) limit; (b) catch per unit effort (CPUE; (c) pre-recruit index (PRI) including limit reference point (dashed line); and (d) mean weight.

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 (Outer sub-region CPUE based on Nov-May data).

Inner sub-region			
Season	Catch (t)	Effort (potlifts)	CPUE (kg/potlift)
2015	301.18	378,667	0.80
2016	284.53	381,927	0.75
2017	249.18	319,290	0.78
2018	249.87	277,843	0.90
Outer sub-region			
Season	Catch (t)	Effort (potlifts)	CPUE (kg/potlift)
2015	47.99	59,367	0.94
2016	36.38	55,899	1.01
2017	52.04	70,481	0.80
2018	41.49	52,930	0.83

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

3.1.2 Within-season trends

Within-season commercial catch trends presented here are based on data from 2016 to 2018. Results from earlier seasons are assessable 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 (Figure 3-2a). In 2018, 242.25 t (84%) of the 289.77 t catch was taken during this period with the highest catch taken in January (79.2 t), and the lowest catch in May (1.29 t). Spatially, 290 t were taken from November to May from the Inner and Outer sub-regions combined, with 1.3 t taken in the Outer sub-region from June to October.

In 2018, 266,854 potlifts were recorded from November to February reflecting 82% of the total effort for the season (326,435 potlifts) (Figure 3-2a). Monthly effort was highest in January (79,801 potlifts) and lowest in May (2,502 potlifts).

Legal-sized CPUE generally tends to be highest in spring/summer at the start of the season and declines thereafter (Figure 3-2b). The increase in zonal catch rate observed in 2018 reflected higher CPUE across all months (except April) compared to 2017. In 2018, CPUE was highest in January (0.99 kg/potlift) and lowest in May (0.51 kg/potlift).

Monthly trends in catch rate of pre-recruits (i.e. PRI) based on catch sampling data have been variable in recent seasons (Figure 3-2c). Compared to 2017, monthly PRI in 2018 was lower in November, January and February. In 2018, the PRI was highest in December (0.43 undersized/potlift) and lowest in March (0.27 undersized/potlift).

Monthly legal-sized mean weight generally increases as the season progresses (Figure 3-2d). In 2018, monthly mean weight was lowest in November (0.89 kg) and highest in May (1.39 kg).

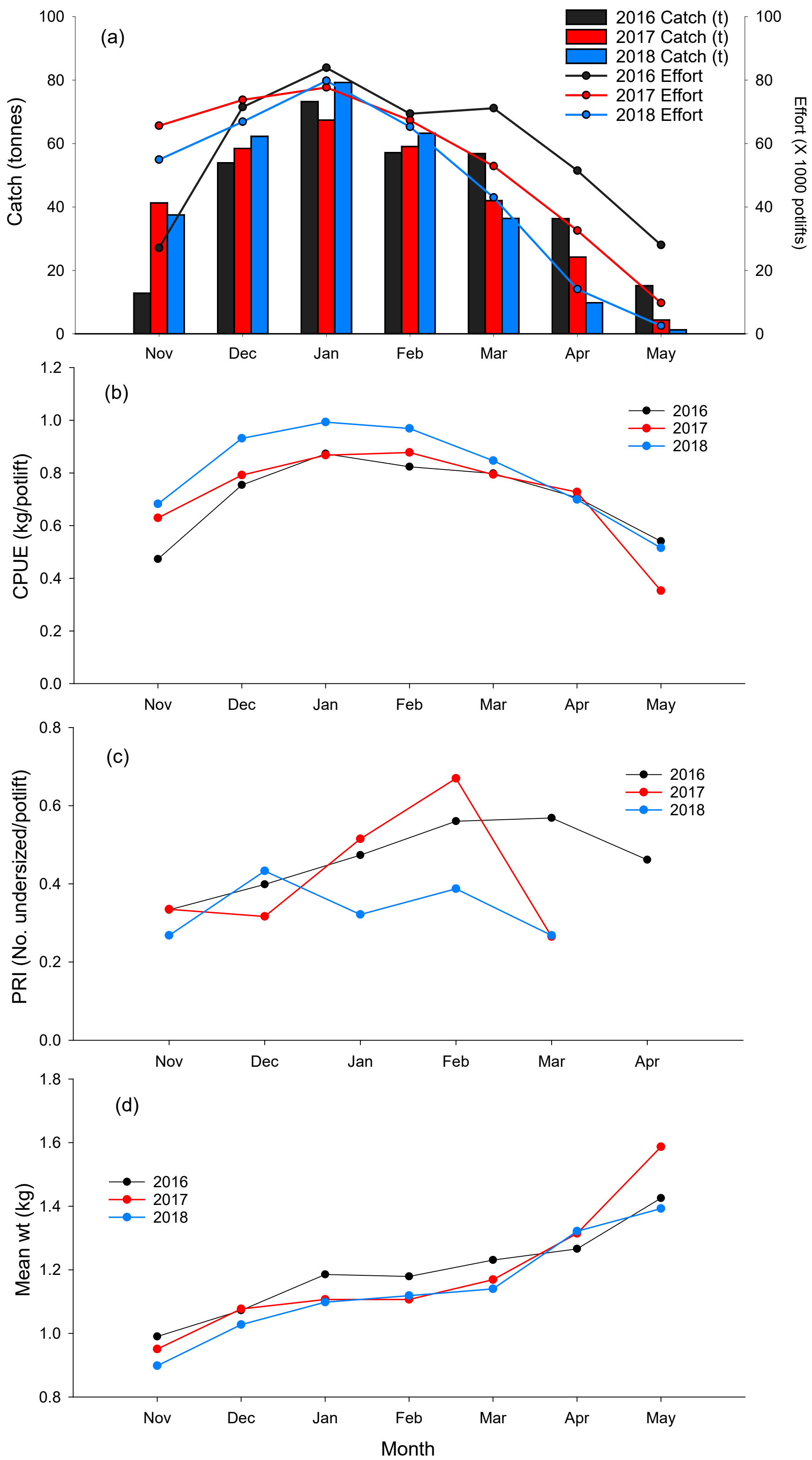

Figure 3-2 Within-season fishery dependent trends in the NZRLF. (a) Catch and effort; (b) catch per unit effort (CPUE); (c) pre-recruit index (PRI); and (d) mean weight.

3.1.3 Spatial trends

3.1.3.1 Marine Fishing Areas (MFAs)

In 2018, 87% of the catch (253 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 eight seasons. The exception was MFA 28 where catch decreased from 74 t in 2014 to 43 t in 2018 (Figure 3-3e). In 2018, within the primary MFAs, the highest catch was taken in MFA 39 (59 t) (Figure 3-4a) and the lowest in MFA 7 (3 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 66,000-91,000 potlifts annually over the last six seasons (Figure 3-4a). In 2018, effort decreased in all primary MFAs with the exception of MFA 27.

Trends in legal-sized annual 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 a generally declining trend from 2010 to 2016, catch rates have increased in almost all MFAs over the last two seasons. The exceptions are MFAs 7 and 8 (Figure 3-3f and g) where estimates remain the lowest on record.

Spatial estimates of the catch sampling 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 2018 zonal decrease in PRI was largely driven by MFAs, 39, 40, 48, 49 and 50.

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 2018, the zonal decrease in mean weight was observed in all of the primary MFAs with the exception of MFA 40 (Figure 3-4q) and MFA 50 (Figure 3-4t).

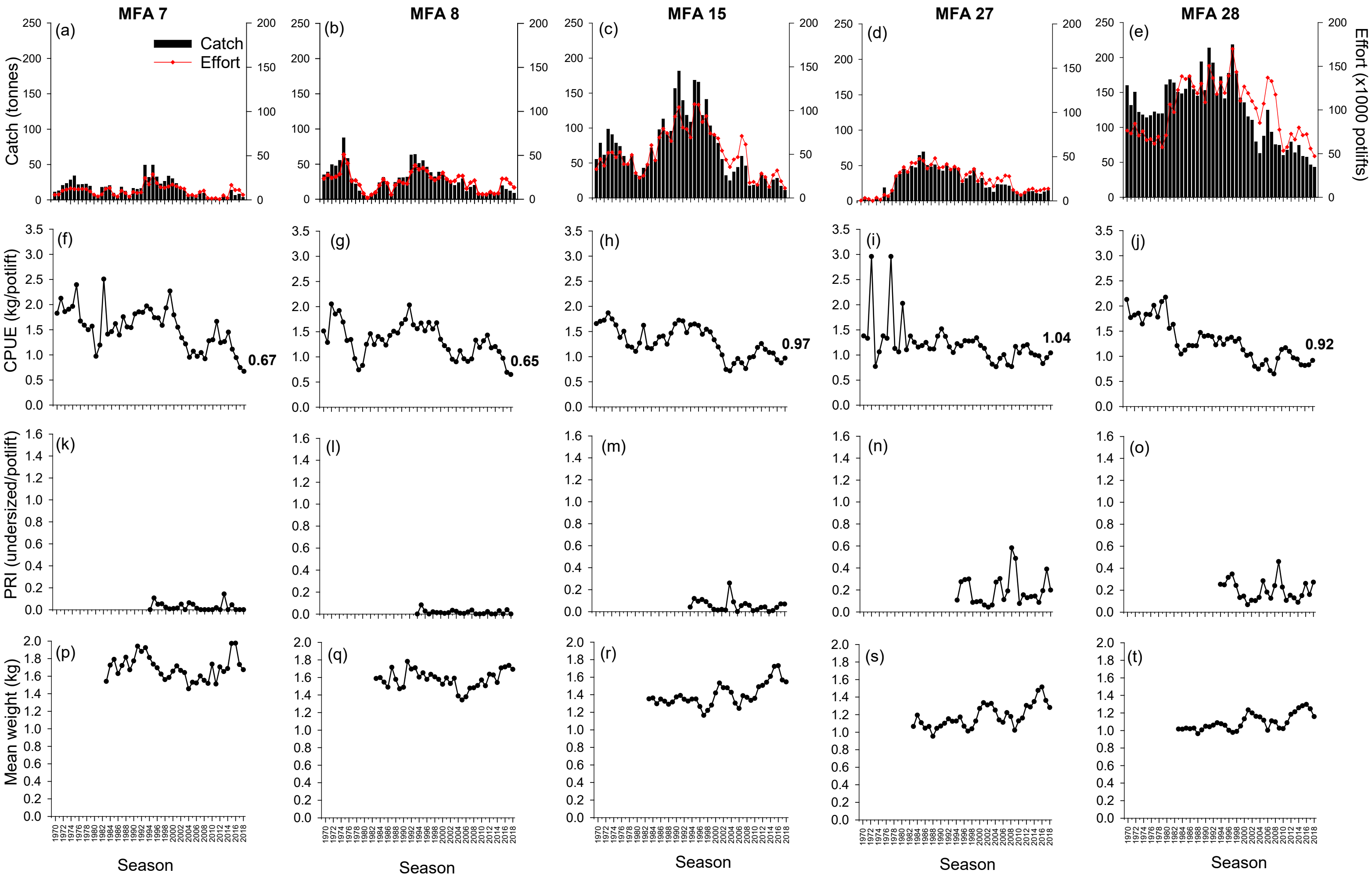

Figure 3-3 Spatial fishery dependent trends in the NZRLF for MFAs 7-28. (a-e) Catch and effort; (f-j) catch per unit effort (CPUE); (k-o) pre-recruit index (PRI); and (p-t) mean weight.

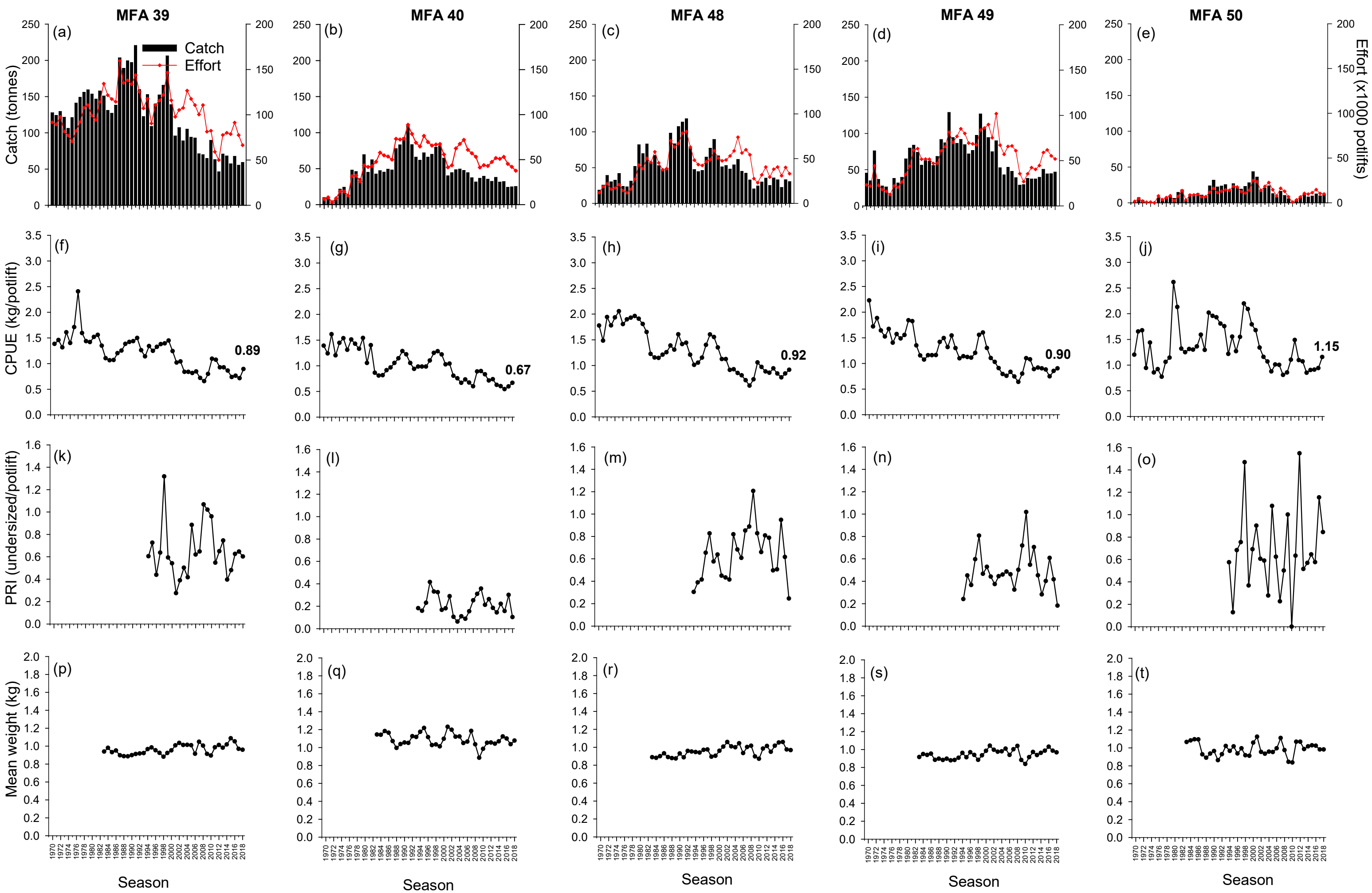

Figure 3-4 Spatial fishery dependent trends in the NZRLF for MFAs 39-50. (a-e) Catch and effort; (f-j) catch per unit effort (CPUE); (k-o) pre-recruit index (PRI); and (p-t) mean weight.

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 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 seven seasons, trends for different depth ranges largely reflect those at the zonal level, with decreases in all depth ranges from 2011 to 2016 before an increase over the next two seasons. In 2018, estimates were 0.85, 0.87, 1.04 and 0.97 kg/potlift in 0-30, 31-60, 61-90 and >90 m, respectively.

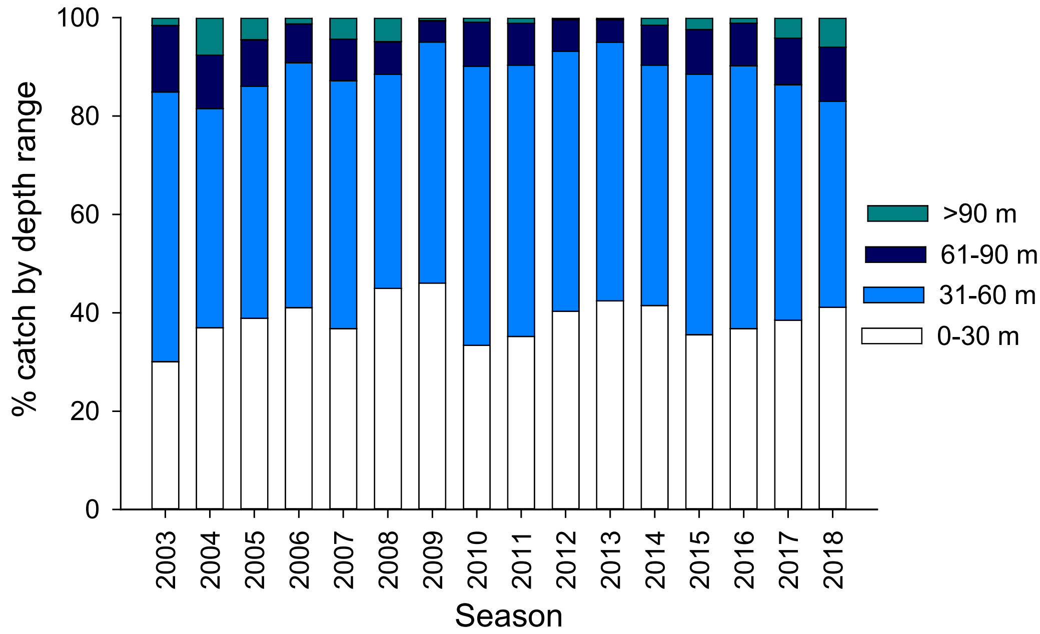

Figure 3-5 Percentage of catch taken from four depth classes in the NZRLF from 2003 to 2018.

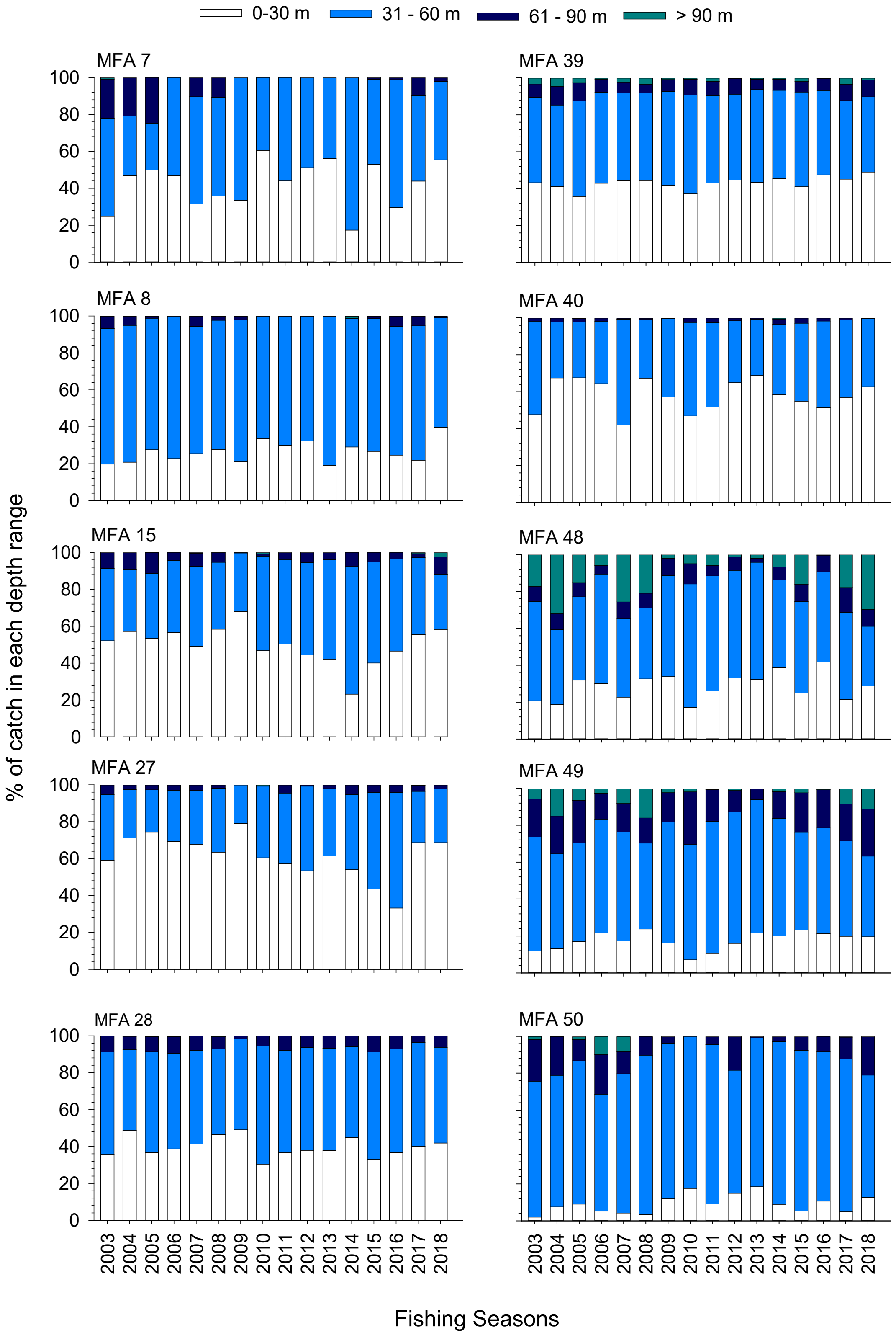

Figure 3-6 Percentage of catch in four depth ranges from 2003 to 2018 across the primary MFAs of the NZRLF.

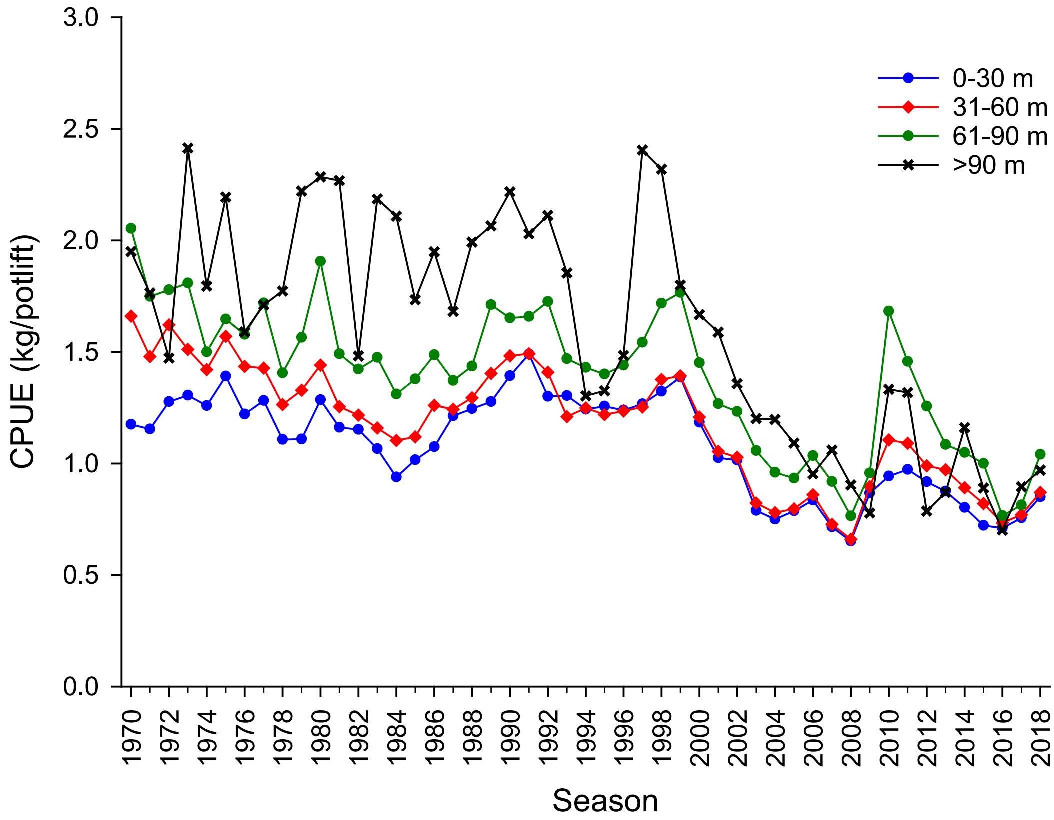

Figure 3-7 CPUE by depth in the NZRLF from 1970 to 2018.

3.1.4 Additional indices

3.1.4.1 Ovigerous (spawning) females

In 2018, the catch rate of ovigerous (spawning) female lobsters (November to October) was 0.04 spawners/potlift reflecting the fifth consecutive season that the index has increased (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). Up to 2018, the index remained below 0.04 spawners/potlift but recent increases means the current estimate is now the highest on record since 1999.

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 = 0.85).

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), has remained below 0.05 dead/potlift (Figure 3-8b). In 2018, the catch rate was of 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, the annual estimate has remained below 0.005 octopus/potlift and in 2018 was 0.003 octopus/potlift.

3.1.4.3 Average days fished

In 2018, the average number of days fished per licence holder in the NZRLF was 111 days reflecting the third consecutive season that this index has decreased (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 despite the fact that 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 fact that the 2008 estimate of 156 days fished was 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 then, the TACC has been reduced to 296 t for the 2018 season.

3.1.4.4 High-grading

Current estimates of high-grading (lobsters returned to the water due to low market value) in the NZRLF are low and in 2018 was <1 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.

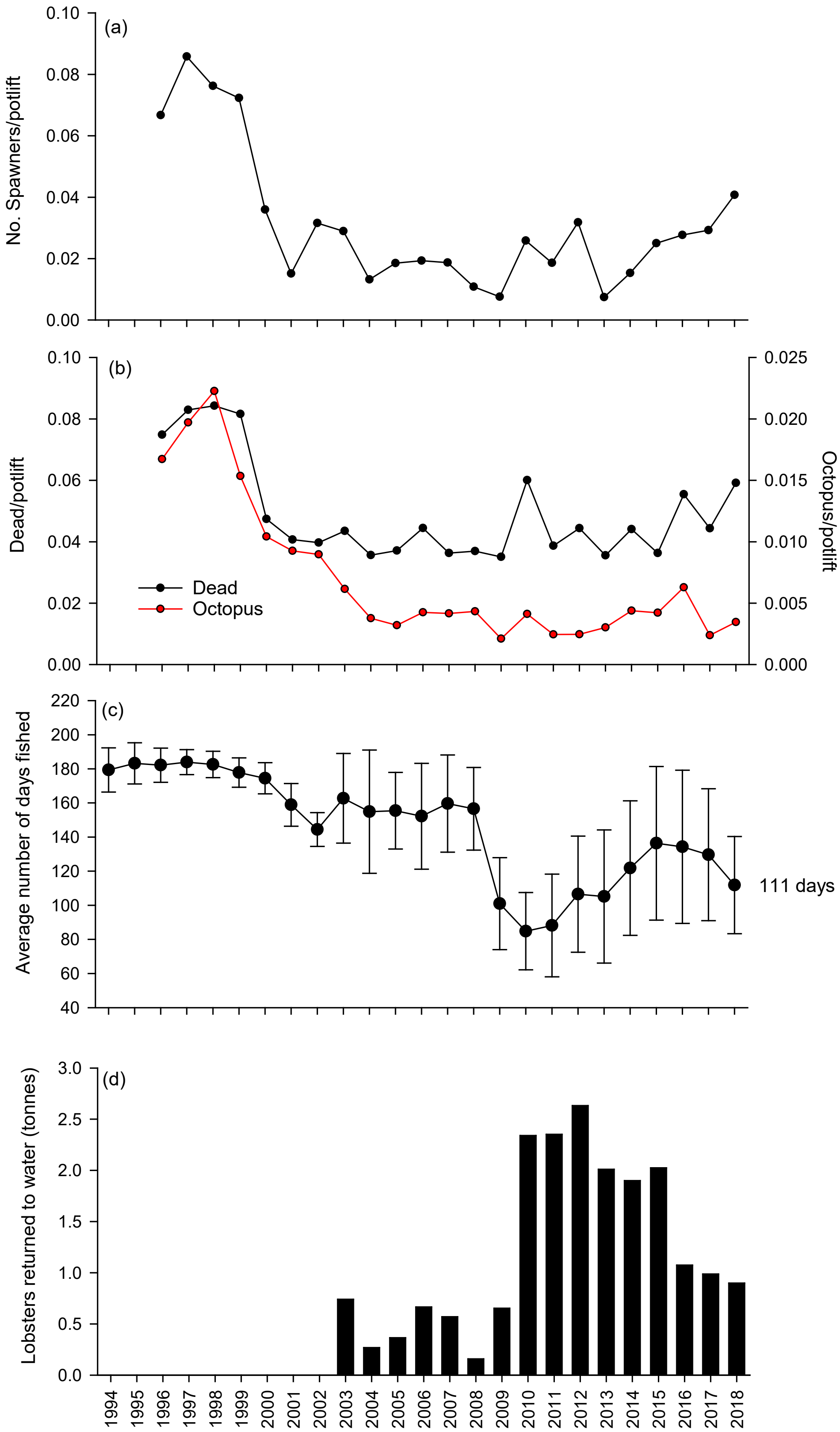

Figure 3-8 Additional fishery dependent indices in the NZRLF. (a) Catch rate of spawning lobsters; (b) predation mortality and predatory octopuses; (c) average number of days fished (with S.D.); and (d) levels of high-grading.

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/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). 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 which has ranged between 25-60% over the last five seasons, with data presented as number of lobsters/100 potlifts. In this report, length frequency data, which are generated from voluntary catch sampling, are presented from 2016-2018. Historical length frequency distributions are available in earlier reports at: http://pir.sa.gov.au/research/publications/research_reports. In 2018, 12 of the 40 active vessels (30%) participated in the catch sampling program.

Male lobsters, which generally grow faster and reach larger sizes than females, range between 70 and 200 mm CL. In contrast, few females are larger than 150 mm CL. In 2018, a total of 15,475 lobsters were sampled with a 52:48 male:female sex ratio. (Figure 3-9). Of these, 65% were within the 105 to 140 mm CL size range with 23% of lobsters in 2018 below the minimum legal size (MLS; 105 mm CL).

Length-frequency data obtained through the voluntary catch sampling program over the last three seasons support recent trends in commercial catch rate and pre-recruit indices. In 2018, 77% of lobsters measured were above the MLS compared to 66% in 2017, reflecting the increase in legal-sized CPUE over the same period (Figure 3-1b). Similarly, in relation to undersized lobster abundances, the frequency of lobster below the MLS has decreased from 33% to 23% between reflecting the decrease in catch sampling PRI estimates over the same period (Figure 3-1c).

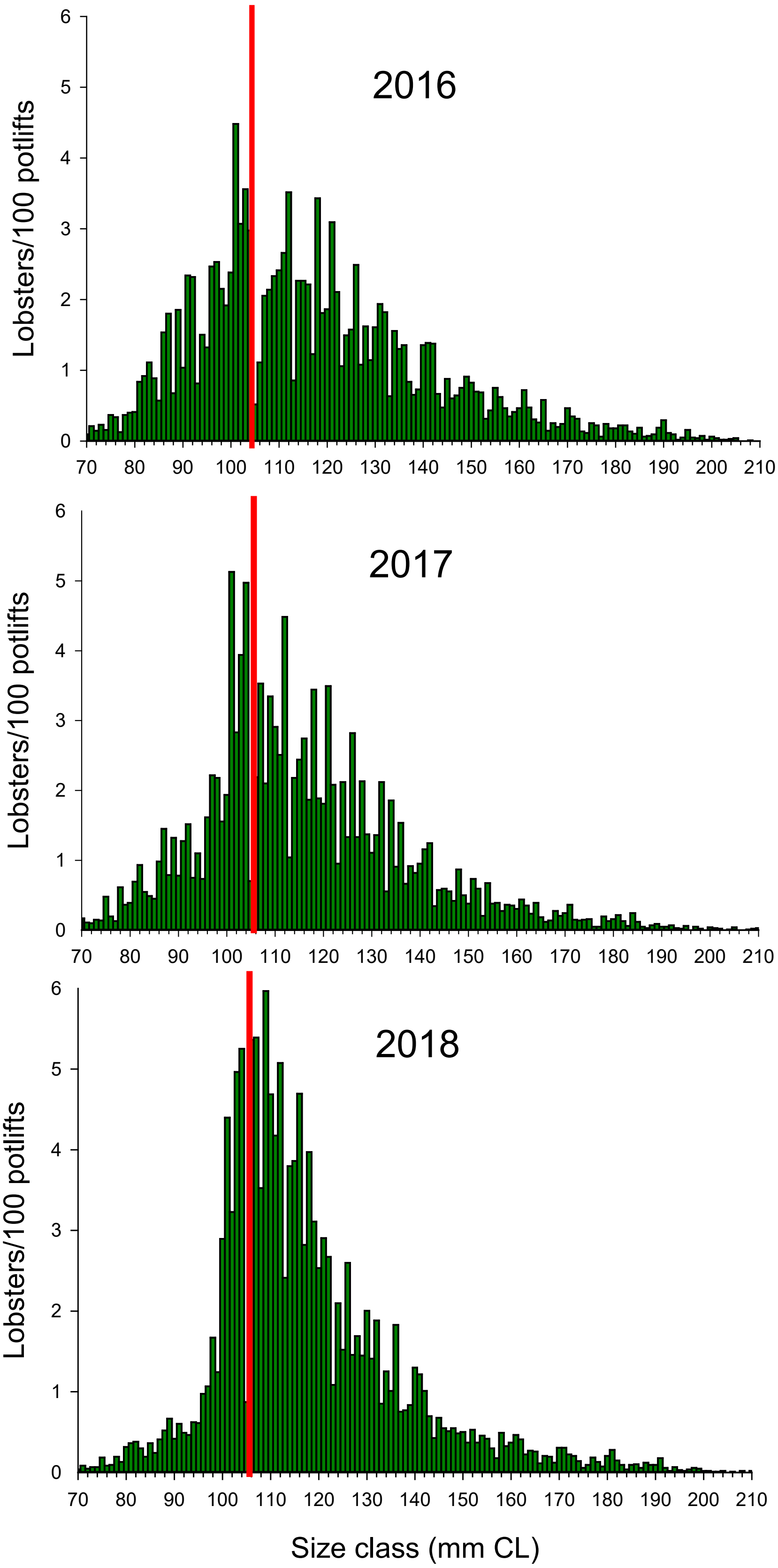

Figure 3-9 Length-frequency distributions of male and female lobsters combined in the NZRLF from 2016 to 2018 (red line indicates MLS at 105 mm CL).

3.4 Puerulus monitoring program

Puerulus settlement indices (PSIs) in the NZRLF have been highly variable over time (Figure 3-10). In 2018, the PSI was 0.60 puerulus/collector which was above both the long-term (1996-2017) mean and median estimates and the highest settlement on record. Previous research has indicated that the period between settlement and recruitment to legal size in the NZRLF is approximately three-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 = 0.82) over the period from 2003-2018 indicating that settlement indices in the NZRLF provide an indicator of future recruitment to the fishery. More recently, the above average settlements from 2016-2018 indicate that higher than average recruitment may be expected from 2020-2022.

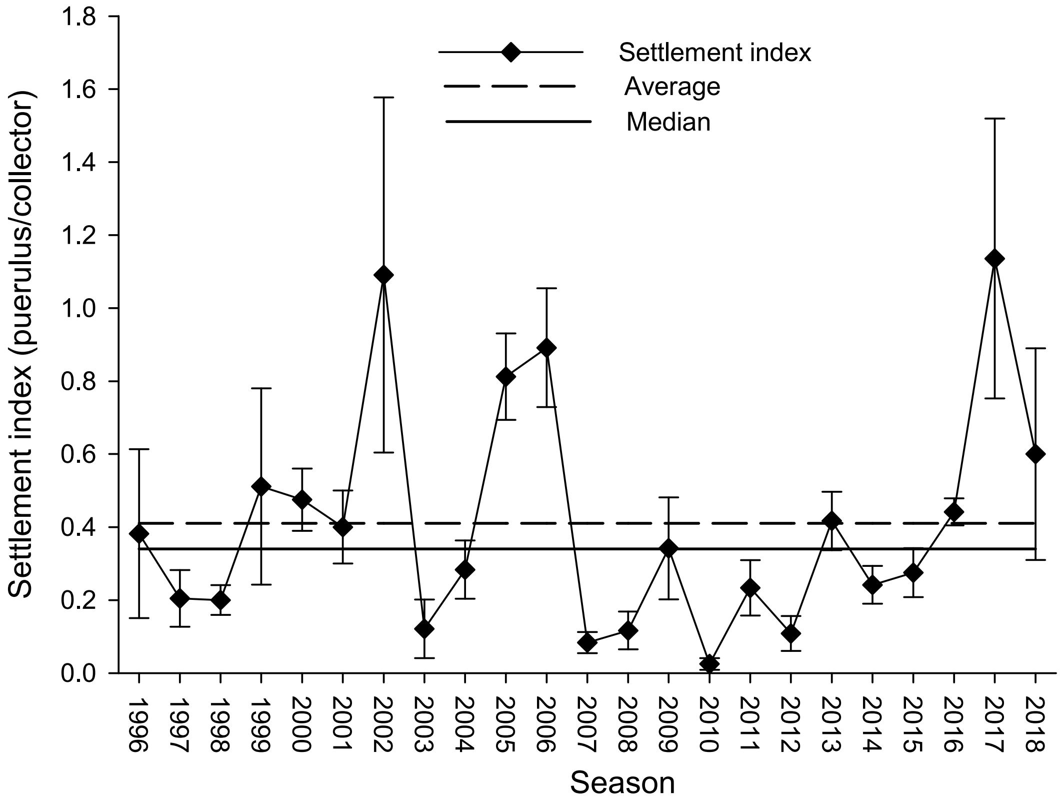

Figure 3-10 Puerulus settlement indices (mean ±SE) in the NZRLF from 1996 to 2018. Dashed and solid lines represent long-term mean (1996-2018) and median estimates respectively.

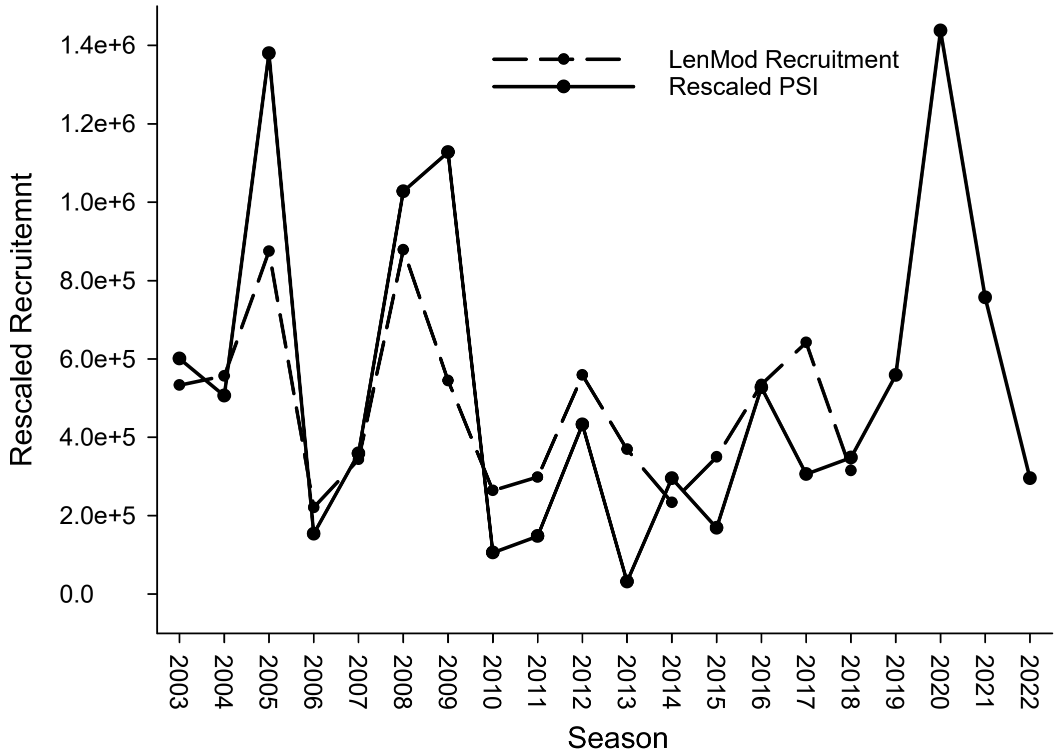

Figure 3-11 Correlations between NZRLF model estimated recruitment and rescaled puerulus settlement lagged by three years.

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). 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 2018 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 model 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 marginally increased before either gradually decreasing (qR) or remaining relatively stable (LenMod). Over the last two seasons both models show increasing biomass trends with the 2018 estimates ranging from 1,122 t (LenMod) to 1,689 t (qR). Both estimates are close to historical lows for the time series.

Corresponding to the declining trend in biomass, egg production has also decreased since the 1980s (Figure 3-12b). In 2018, total egg production was estimated to be between 134 billion (LenMod) to 175 billion (qR) which are some of lowest estimates on record. The 2018 estimates equate to between 9% (LenMod) and 14% (qR) 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 (Figure 3-12d). Over the next 5 seasons exploitation rate increased before declining since 2015. The 2018 estimate ranges from 18% (qR) to 26% (LenMod), reflecting increasing biomass and stable catch over the last two seasons.

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 2018 estimates ranged from 0.50 million (LenMod) to 0.70 (qR) million lobsters. Temporal trends in recruitment estimated by both models are strongly correlated with PRI estimates from logbook data (1994-2018) (R^2 = 0.90).

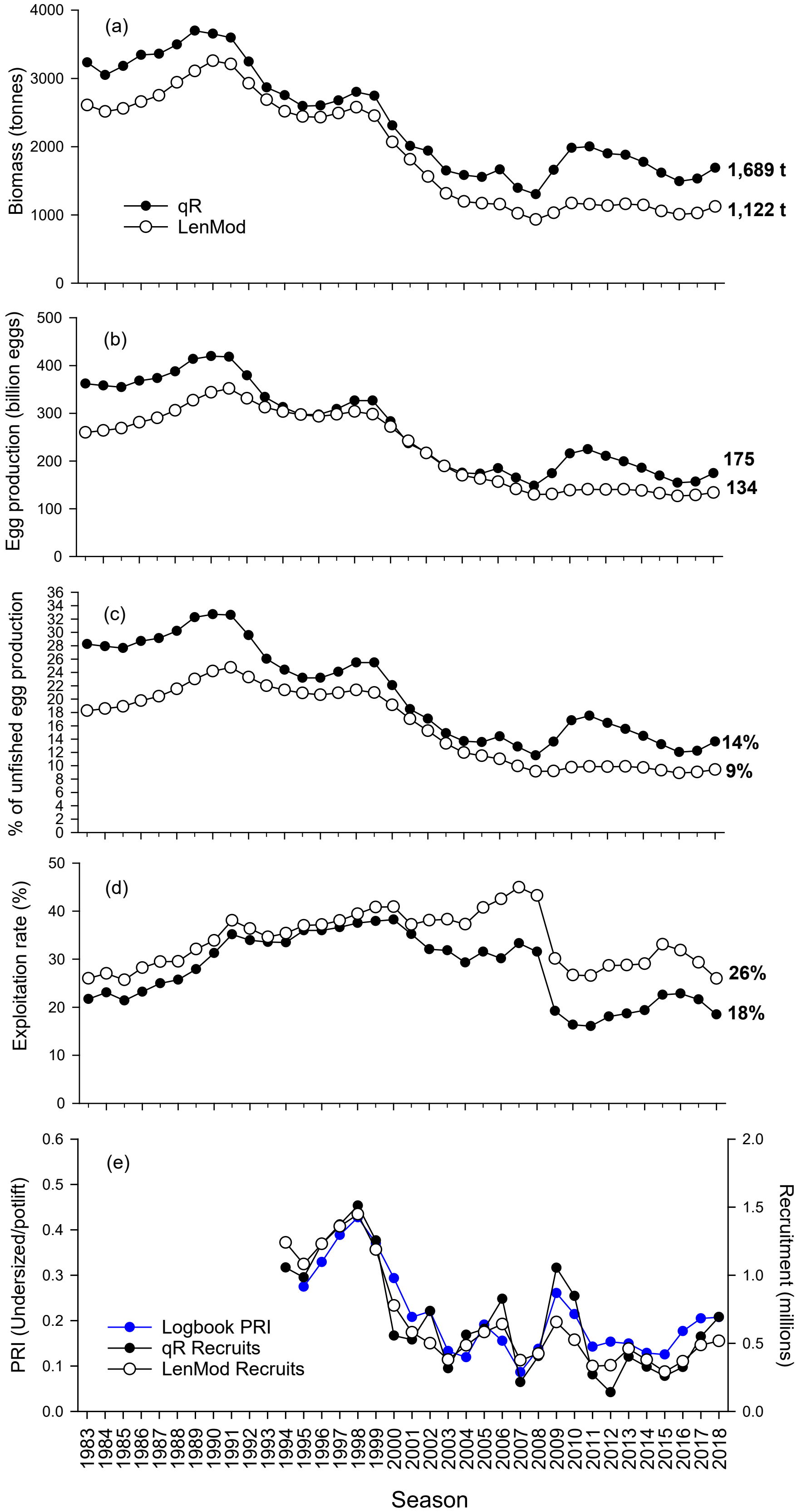

Figure 3-12 Fishery model outputs for the NZRLF. (a) Legal-size biomass; (b) Egg production; (c) % of unfished egg production; (d) Exploitation rate and; (e) Recruitment.

4 DISCUSSION

4.1 Information sources used for assessment

This overall assessment of the NZRLF resource relies heavily on commercial fishery-dependent data collected by several long-term monitoring programs. In particular, the assessment 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. A review of these information sources was undertaken in 2017 (Smith 2017) and while concluding that "*The monitoring strategies for the South Australian Rock Lobster fishery are generally in line with best practice*" it provided a number of recommendations that related specifically to fishery-dependent data and model outputs. These recommendations focused on catch rate standardisation and improvements in model performance.

While not included in the current report, standardised catch rate outputs were presented in Linnane et al. (2018). These outputs were reviewed by the NZRLF 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.

In terms of model outputs, the review recommended consistency in terms of the recruitment time-series reference period used to estimate %unfished egg production as well as changes to catchability scenarios. The qR and LenMod models have since been modified in response to these recommendations, with details of each model provided in Appendices 2 and 3 of this report. The %unfished egg production recruitment reference time period of 1990-2011 is that used in Tasmania, and now also in Victoria, permitting consistency with the indicator used to designate national stock status for this species. Both models are now more consistent in terms of the current status of the NZRLF.

4.2 Stock Status

The previous NZRLF assessment, which considered data to 31 October 2018, classified the fishery as "depleting" (Linnane et al. 2019). This reflected long-term fishery declines since the late 1990's in a range on key indicators across broad spatial and temporal scales (Linnane et al. 2010b). More recently, from 2011 to 2016, CPUE decreased by 28% reflecting a corresponding 25% decline in biomass over the same period. Poor fishery performance has necessitated significant management response over the last two decades. The current catch of 296 t reflects a considerable reduction in the TACC initially set at 625 t in 2003. In 2016, the Inner sub-region TACC was reduced from 300 t to 250 t, while the Outer sub-region was reduced from 60 t to 46 t in 2018.

There is now evidence to suggest some improvement in fishery performance following the TACC reductions. Specifically, the reduced catch is reflecting positively in terms of zonal catch rate trends. The 2018 estimate of 0.89 kg/potlift represents a 16% increase from 2016. Recent catch rate increases have been consistent across broad temporal and spatial scales. Temporally, the increases in 2018 were consistent across almost all months compared to 2017 but were most notable in the high catch period from December through to February. Catch rate 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 four seasons (since 2015) but with diverging trends in terms of performance. While the Inner sub-region catch rates have increased by 13% (from 0.80 to 0.90 kg/potlift) during this time, the Outer sub-region has decreased by 12% (from 0.94 to 083 kg/potlift) over the same period. The decline is partially driven by exceptionally poor fishery performance over the last four seasons in MFAs 7 and 8, where catch rates are now the lowest on record. In response, the TACC in the Outer sub-region was reduced from 60 t to 46 t for the 2018 season. Early signals suggest that this management decision may have arrested observed declines, with the Outer sub-region catch rate increasing from 0.80 to 0.83 kg/potlift between 2017 and 2018.

In addition to reduced catch levels, recent increases are likely driven by increased levels of recruitment to the fishery, particularly from 2015 to 2018. The current harvest strategy uses recruitment data based on the voluntary catch sampling program and in 2018, at 0.36 undersized/potlift, this indicator was above the LRP (0.30 undersized/potlift). However, Smith (2017) suggested that the best source of recruitment data in the NZRLF comes from commercial logbook sources. Logbook PRI has increased by 62% since 2015, which is supported by independent estimates of recruitment from both qR and LenMod fishery models. The lag period between PRI and legal-size CPUE is considered to be one year.

Variations in mean weight also 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 two seasons within the fishery, further supporting evidence of recent recruitment.

In relation to more 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 may be above the long-term average (assuming a four-year lag).

While differing in terms of absolute levels, 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 small increases over the last two seasons. Recent increases in biomass have reduced exploitation rates to estimates ranging from 18-26%, which are some of the lowest on record. However, despite, recent increases in legal-size biomass, overall egg production levels in the fishery remained low in 2018 at just 9-14% of unfished levels.

In 2017, the Management Advisory Committee (MAC) commenced a review of the management plan for the NZRLF. 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 are being developed. The management plan is currently in the final stages of completion and in 2021, the revised harvest strategy will be used to set a TACC for the 2021/22 season. Importantly, performance indicators in this harvest strategy are linked to a definition of stock status.

In summary, after a long-term period of fishery decline, there is now evidence to indicate that the status of the NZRLF stock has improved in 2018 in response to the recent TACC reductions. Specifically: (i) catch rates have increased by 16% over the last two seasons with improvements in fishery performance observed across broad spatial scales; (ii) the legal-size biomass estimate has increased and, consequently, exploitation rates are close to historical lows; and (iii) there is evidence of increased recruitment in the short-medium term based on PRI and PSI estimates.

As a result, based on a weight-of-evidence approach, the NZRLF stock is classified as “**sustainable**” at the current TACC of 296 t.

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 close to 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

There is a need to investigate potential 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. Quantifying a change in growth rates will require re-launching a substantial tag-recovery data program. This has been identified as a high research priority by the South Australian Research Sub-Committee 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. Should this programme be implemented across broad spatial fishery scales, this will also allow the generation of biomass trends by sub-region, which are currently hindered by the absence of accurate growth estimates from the Outer sub-region.

Given observations within other rock lobster fisheries, it is recommended that “vessel” or “skipper” factors are captured and used in future CPUE standardisation analyses.

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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 2018 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

Table 6-2 Catch, Effort (November-October) and CPUE (November-April) for the NZRLF from 1970 to 2018 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

Table 6-3 Catch, Effort and CPUE for the NZRLF from 1970 to 2018 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

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 the start of each fishing season (1 November), and n_t = the number of fishing 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 = 106.5 mm CL of (a =1) recruits. This choice of L0 specifies the 3W qR model version applied for the 2017 season status report (October 2018) and this season 2018 assessment. 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:

$$F_t = \begin{cases} q \cdot E_t, & t = 1983 \\ q \cdot \left[1 + 0.03*(t - 1983)\right] \cdot E_t, & \text{for years of 3\% yearly increasing effective effort} \\ q \cdot \left[1 + 0.03*(2000 - 1983)\right] \cdot E_t, & \text{for } t = 2000 \text{ onward} \end{cases} \cdot \tag{3}$$

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, 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 GlobalSearch routine (Loehle Global Optimizer) in Mathematica v. 8. In numerical minimisation, starting values of parameters were obtained by solving a steady-state version of the qR model for each year independently. For the starting values of parameters that do not vary over time (all those except recruitment), time averages of all yearly steady-state qR model estimates were used.

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;

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

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 $\% UEP_t = Eggs_t / UEP$.

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. Change in catchability over 1984-2000 increases this.
$\hat{C}_t^N$	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 = 8 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 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_l^s is the proportion of the settlement of animals of sex s that occurs to size-class l;

$\tilde{H}_{y,i,l'}^s$ 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 year-average legal-sized biomass during year y, averaging across T months, using mid-month population numbers (after half-month natural survival), where W_l^s is the weight of a lobster of size l and sex s:

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

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:

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

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:

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

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 l for sex s (4 mm), 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)**	$q^{\mathrm{Comm}}_{Q=1,i}$ **(2003-2018)**
November	5.7 x 10^{-7}	6.4 x 10^{-7}
December	6.8 x 10^{-7}	8.2 x 10^{-7}
January	8.7 x 10^{-7}	1.1 x 10^{-6}
February	9.3 x 10^{-7}	1.2 x 10^{-6}
March	9.3 x 10^{-7}	1.2 x 10^{-6}
April	1.2 x 10^{-6}	1.5 x 10^{-6}
May	1.9 x 10^{-6}	2.1 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:

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

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.

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

$$B_{y,i}^{e,Comm} = \sum_{s}\sum_{l} V_i^s\,(1-\tilde{p}_{i,l}^s)\,\tilde{S}_{y,i,l}^s\; W_l^s\; e^{-Mt_i/2} N_{y,i,l}^s (1-\tilde{H}_{y,i,l}^s/2) \qquad (10)$$

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 $\rho_{y,i,l}^{s,\mathrm{Comm}}$. The model-estimate of this quantity, $\hat{\rho}_{y,i,l}^{s,\mathrm{Comm}}$, takes account of the vulnerability of the gear and the numbers in each size-class and sex:

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

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

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

where $n_{y,i,l}^{s,\mathrm{Comm}}$ 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:

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

where $\hat{C}^N_{y,i} = \sum_s \sum_l V^s_i \, \tilde{S}^s_{y,i,l}(1-\tilde{p}^s_{i,l})N^s_{y,i,l}\, e^{-Mt_i/2} F^{\text{Comm}}_{y,i}$ 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:

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

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

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	

$q_{Q,i}^{\mathrm{Comm}}$	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

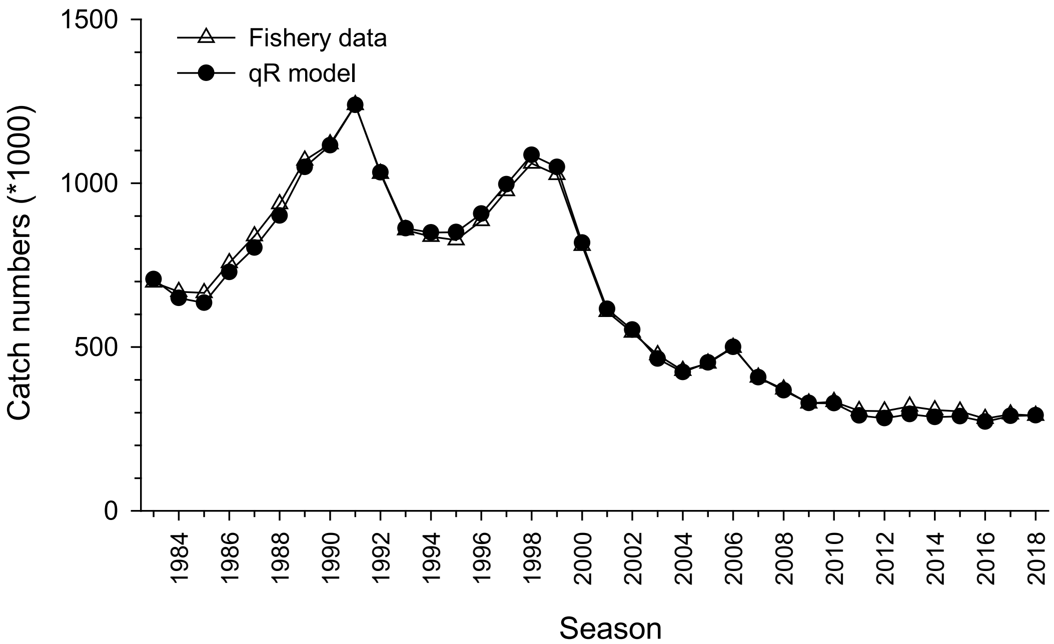

Figure 6-1 Fit of the qR model to catch in number of lobsters landed for the NZRLF, based on annual logbook catch totals from the fishery.

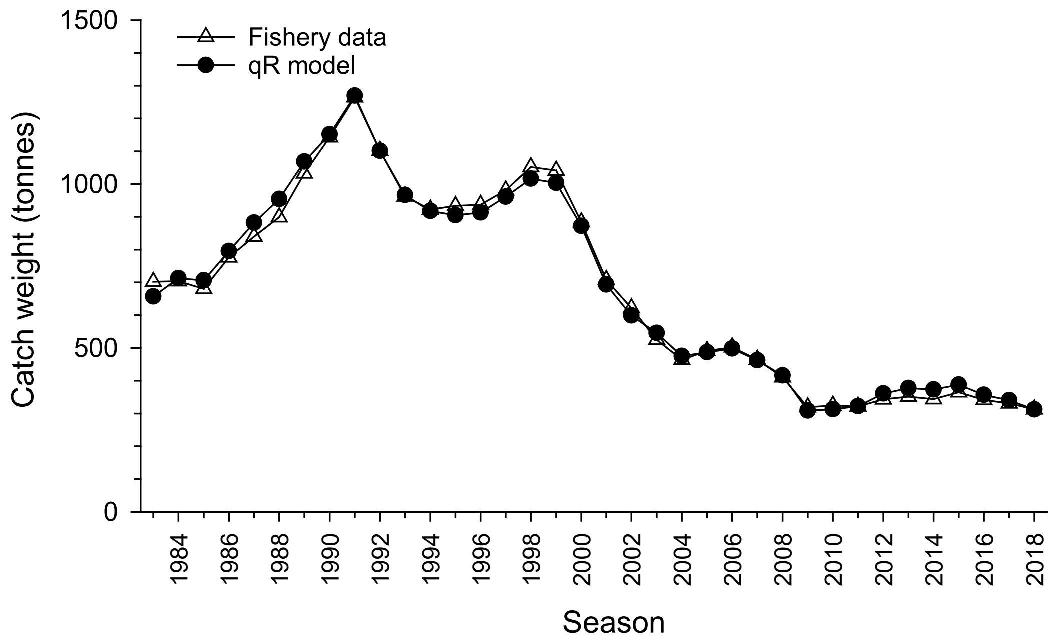

Figure 6-2 Fit of the qR model to catch in weight for the NZRLF, based on annual logbooks catch totals from the fishery.

LenMod

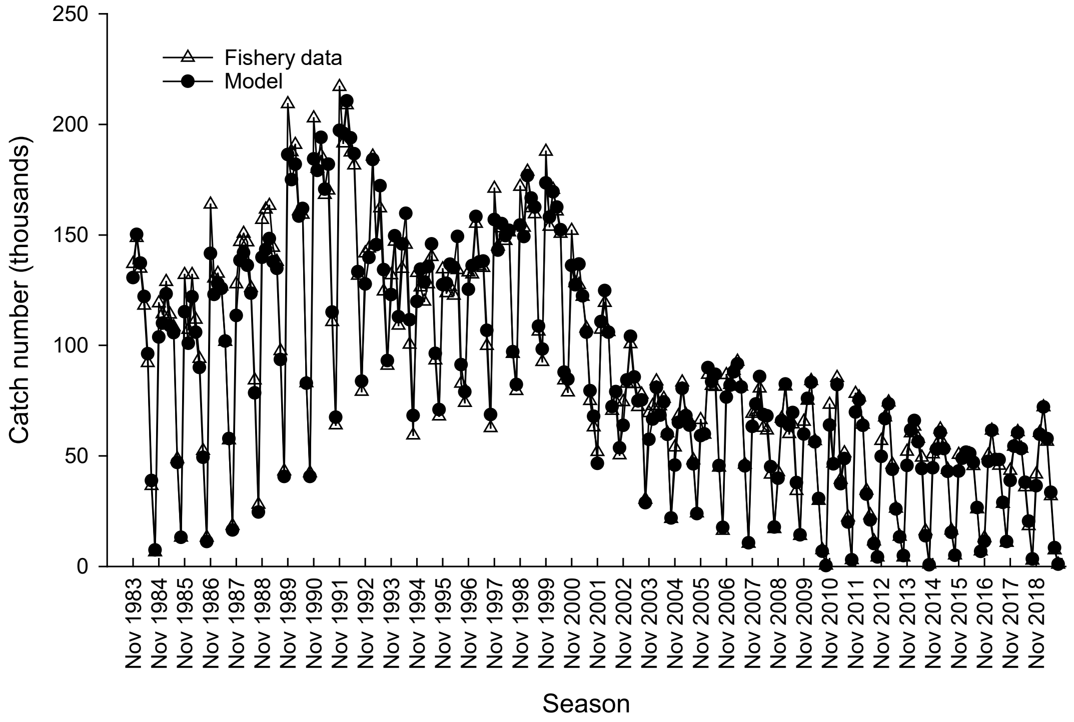

Figure 6-3 Fit of the LenMod model to monthly catch in number (Cn) for the NZRLF, based on logbook catch totals from the fishery.

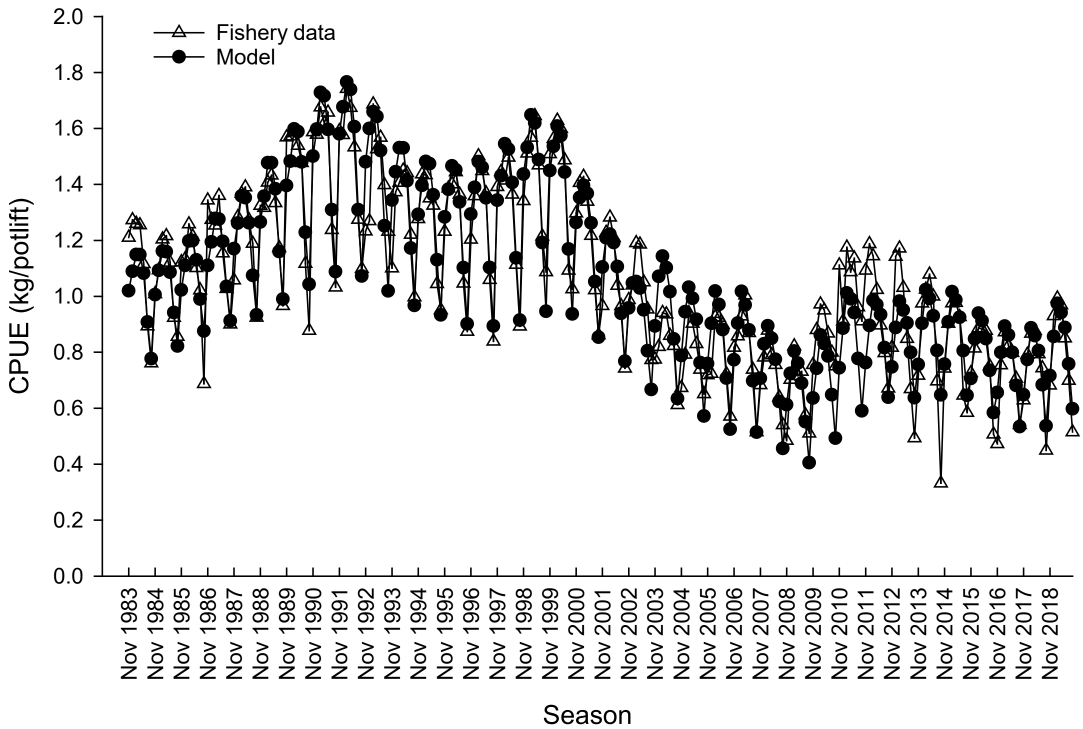

Figure 6-4 Fit of the LenMod model to monthly catch per unit effort (CPUE) for the NZRLF, based on logbook catch totals from the fishery.

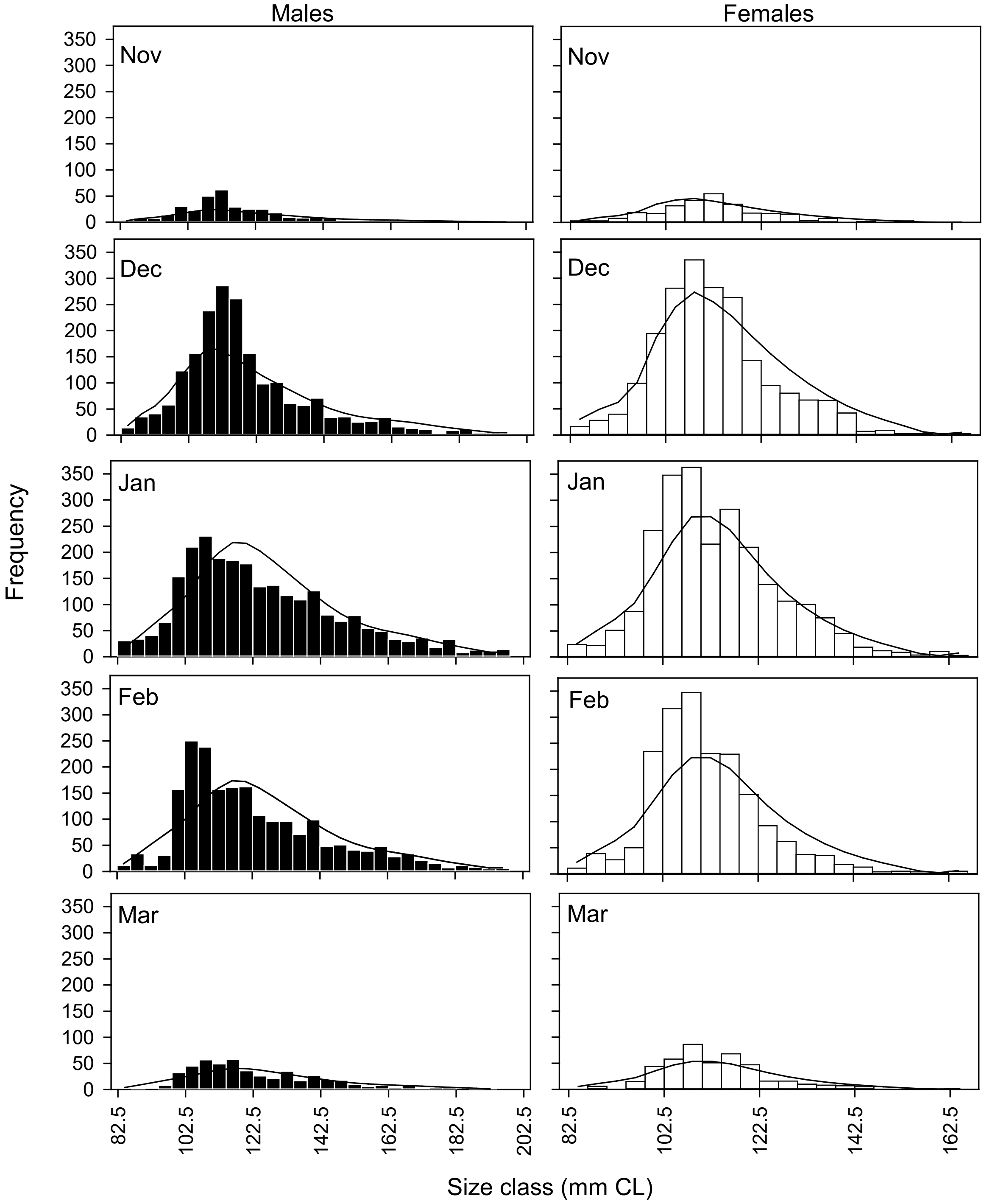

Figure 6-5 Fits of LenMod model (black line) proportions by length bin to commercial length frequency data for both males and females taken during the 2018 season in the NZRLF.