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Spencer Gulf Prawn *Penaeus* (*Melicertus*) *latisulcatus* Fishery

C. J. Noell and G. E. Hooper

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PO Box 120 Henley Beach SA 5022

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Fishery Assessment Report to PIRSA Fisheries and Aquaculture

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EXECUTIVE SUMMARY

This report provides a biennial assessment of the Spencer Gulf Prawn Fishery (SGPF) for the 2016/17 and 2017/18 fishing years.

The aims of this report were to: (i) provide brief synopses of the management of the fishery and biology of the Western King Prawn (*Penaeus* (*Melicertus*) *latisulcatus*); (ii) review the performance of the fishery; (iii) determine the current status of the resource; and (iv) identify future research and monitoring needs.

The total harvest by the SGPF reached 2,038 t in 2016/17 and 2,197 t in 2017/18. With fishing taking place as a fleet over 53 nights in both years, these harvests translated into a catch per unit effort (CPUE) of 102.5 and 112.8 kg h^{-1}, respectively.

Key fishery performance and fleet metrics are summarised as follows:

	Spencer Gulf Prawn Fishery	
	2016/17	**2017/18**
Status	**Sustainable**	**Sustainable**
Indicator	**Survey $CPUE_{adults}$**	**Survey $CPUE_{recruits}$**
Total harvest	**2,038 t**	**2,197 t**
Total effort	**19,885 h**	**19,472 h**
Commercial CPUE	**102.5 kg h^{-1}**	**112.8 kg h^{-1}**
Number of licences/vessels	**39**	**39**
Nights fished	**53 (fleet) 2,055 (vessel-nights)**	**53 (fleet) 2,060 (vessel-nights)**

Size grade composition of the annual harvest and the mean 7-kg ‘bucket count’ indicate a slight downward trend in average prawn size over the past several years. This may be attributed to the revised size criteria in the harvest strategy, where a trade-off between higher minimum catches and smaller prawn size criteria provided greater flexibility in terms of area opened to fishing. Alternatively, it could be a result of consecutive high-recruitment years reducing the average prawn size.

The mean survey CPUE of ‘adult’ prawns (size grades comprising fewer than 20 prawns per pound) and ‘newly recruited’ prawns (more than 20 prawns per pound, i.e. ‘20+’ grade) were variable throughout 2016/17 and 2017/18, but mostly remained above their respective lower reference points (RPs). This resulted in the development of standard fishing strategies, except for an increasing fishing strategy after the February 2017 survey, owing to the mean survey $CPUE_{adults}$ exceeding the upper RP.

Mean egg production estimates of 673 and 551 M eggs trawl-h^{-1} from November surveys in 2016 and 2017, respectively, remained above the RP (500 M eggs trawl-h^{-1}) for more than a decade. A newly developed recruitment index based on ‘20+’ grade prawns (considered more reliable than the previous length-based measure of recruitment) was estimated at 4.79 lb min^{-1} during February 2017 and 7.88 lb min^{-1} in February 2018. Both recruitment estimates were above the RP (2.38 lb min^{-1}) with the latter being the highest recorded.

The weighted mean $CPUE_{adults}$ (± 95% CI) from the November, February and April surveys during 2016/17 and 2017/18 were 3.93 ± 0.16 and 3.83 ± 0.17 lb min^{-1}, respectively, both of which are above the trigger reference point (TRP; 2.50 lb min^{-1}). Under the definition in the harvest strategy, the stock is classified as ‘**sustainable**’.

Future research needs will primarily be focused on establishing an ecosystem monitoring and assessment program that meets Marine Stewardship Council (MSC) 2.0 principles. Specifically, this is expected to include updating the estimated trawl footprint, documenting the ecological assets conserved by the SGPF to mitigate their ecological footprint, and establishing details of bycatch monitoring work.

Keywords: Western King Prawn, *Penaeus* (*Melicertus*) *latisulcatus*, fishery stock assessment, stock status, catch per unit effort (CPUE).

1. INTRODUCTION

1.1. Overview

This report is the twelfth in a series that has been updated annually and/or biennially since 2003 as part of the South Australian Research and Development Institute (SARDI) Aquatic Sciences' ongoing assessment program for the Spencer Gulf Prawn Fishery (SGPF) (Carrick 2003; Dixon et al. 2005, 2007; Dixon and Hooper 2008; Dixon et al. 2009, 2010, 2012, 2013; Noell et al. 2014; Noell and Hooper 2015, 2017). The report updates the last assessment (Noell and Hooper 2017) with information obtained for the 2016/17 and 2017/18 fishing years. The aims of this report were to: (i) provide brief synopses of the management of the fishery and biology of the Western King Prawn; (ii) review the performance of the fishery; (iii) determine the current status of the resource; and (iv) identify future research needs.

1.2. Description of the fishery

1.2.1. Fishery location

There are three commercial prawn fisheries in South Australia: (i) SGPF; (ii) Gulf St Vincent Prawn Fishery (GSVPF); and (iii) West Coast Prawn Fishery (WCPF). All exclusively target the Western King Prawn (*Penaeus* (*Melicertus*) *latisulcatus*). The SGPF is the largest in terms of total area (22,367 km^2), production (latest 10-year mean: 1,929 t), and number of licence holders/vessels (39).

The SGPF encompasses the waters of Spencer Gulf north from Cape Catastrophe, Eyre Peninsula (34°9.119′S, 136°00.184′E) to Cape Spencer, Yorke Peninsula (35°17.993′S, 136°52.835′E). It comprises ten regions that represent the main trawl grounds of the fishery. These regions are subdivided into a total of 125 commercial fishing blocks (Figure 1.1).

1.2.2. The Spencer Gulf environment

Spencer Gulf is a large shallow body of water with a mean depth of 23 m, and a maximum depth of 87 m at its entrance in the south. The predominant sediment is sand and mud, and seagrass habitats are common at depths less than 10 m.

Spencer Gulf is situated in a semi-arid climate where annual evaporation far exceeds precipitation. Due to excessive evaporation, the gulf is classified as an inverse estuary, attaining salinities that are greater than the surrounding ocean and increase towards the head of the gulf (Nunes and Lennon 1986). Inverse estuaries are further characterised by an outflow of dense, saline water in bottom layers and an inflow of oceanic water in surface layers. In Spencer Gulf, this density-driven circulation is influenced by the earth's rotation, such that the dense saline outflows occur along the eastern side, whereas surface inflows occur along the western side (Kämpf et al. 2009). This gives rise to an overall clockwise circulation pattern.

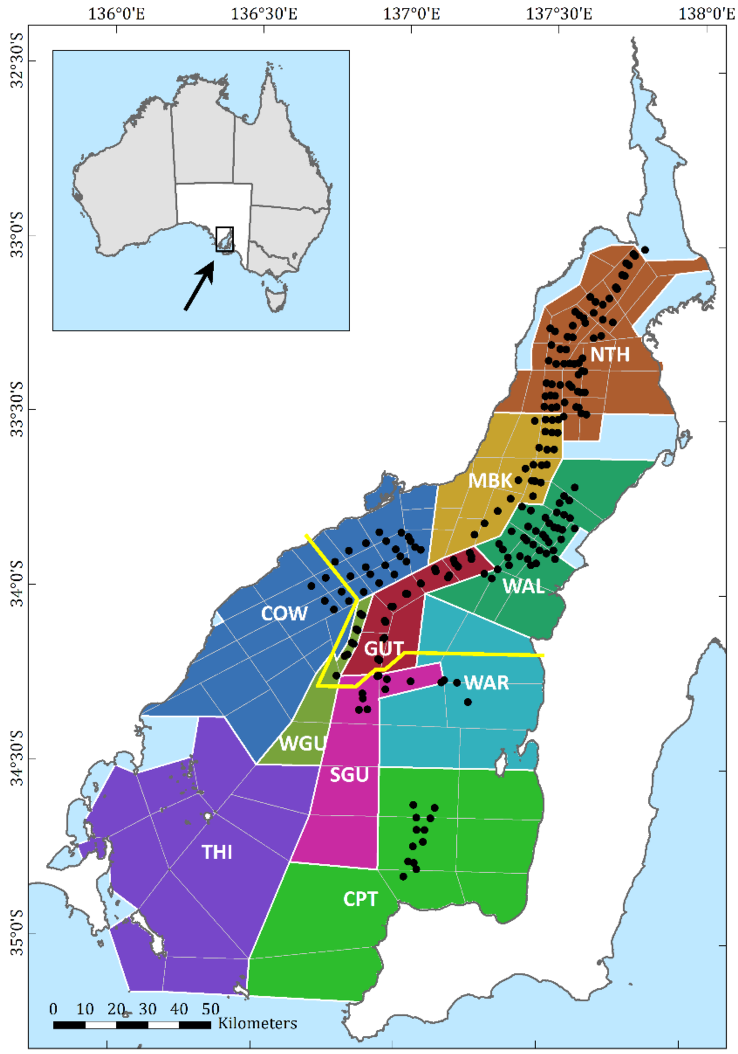

Figure 1.1. Stock assessment survey locations (black symbols), fishing blocks and regions of the Spencer Gulf Prawn Fishery. Inset map shows location of the fishery in South Australia. Also shown is the Mid/North–Southern Gulf boundary (yellow line) used in fishing strategy development (see Section 1.7.3). Region abbreviations: COW, Cowell; CPT, Corny Point; GUT, Gutter; MBK, Middlebank/Shoalwater; NTH, North; SGU, South Gutter; THI, Thistle; WAL, Wallaroo; WAR, Wardang; WGU, West Gutter.

Sea surface temperatures (SSTs) in the South Australian gulfs are lower and more variable than in northern fisheries that target the Western King Prawn (e.g. Broome and Shark Bay in Western Australia, Figure 1.2). In Spencer Gulf, SST fluctuates seasonally between ~12°C and ~24°C (Nunes and Lennon 1986) and, in summer months, is characterised by warmer surface waters in the north, cooler surface waters in the south, and considerably lower temperatures in the surrounding open ocean (Figure 1.3).

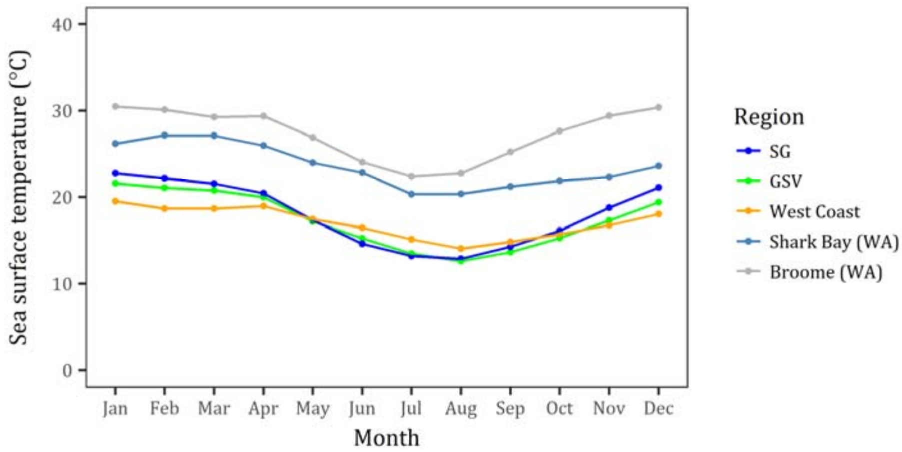

Figure 1.2. Mean monthly sea surface temperatures in 2012 for the South Australian and Western Australian (WA) prawn fisheries that target Western King Prawn.

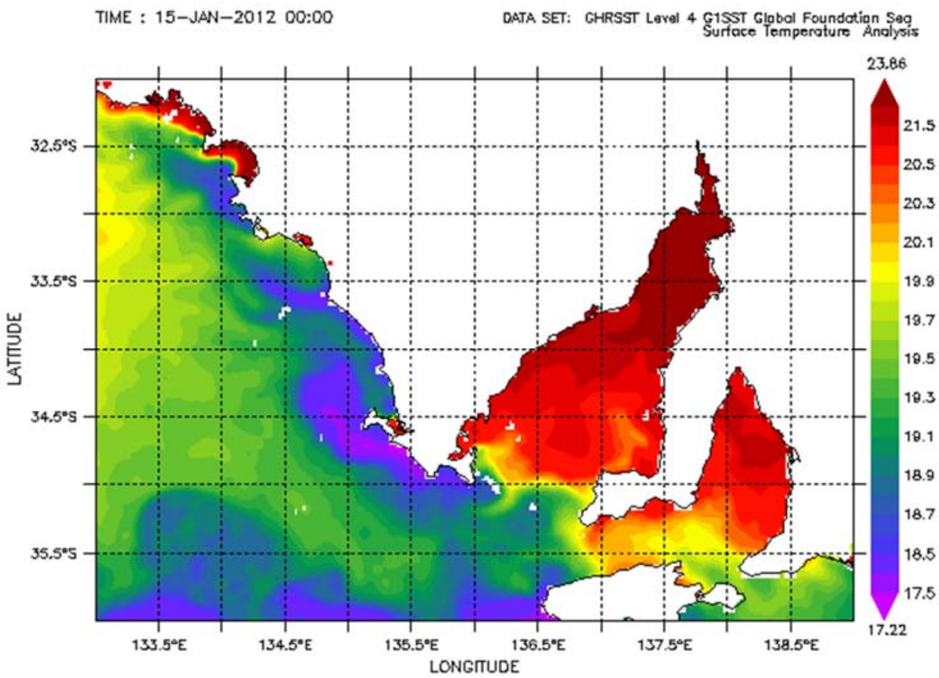

Figure 1.3. Sea surface temperatures (°C) of the continental shelf and gulf waters of South Australia during January 2012. Source: NASA (2013).

1.2.3. Nursery areas

In South Australian waters, juvenile prawns occur predominately on intertidal sand and mudflats, generally located between shallow subtidal/intertidal seagrass beds and mangroves higher on the shoreline (PIRSA 2003). In Spencer Gulf, the density of juveniles is greater in the mid-intertidal zone compared to lower and upper zones (Roberts et al. 2005), while in Gulf St Vincent, densities of juveniles are similar across the intertidal zones (Kangas and Jackson 1998).

Based on Bryars' (2003) inventory of important coastal fishery habitats in South Australia, Dixon et al. (2013) estimated that 76% of the Spencer Gulf coastline comprises appropriate habitat for prawn nursery areas (i.e. tidal flat only, 51%, and mangrove forests[1], 25%) (Table 1.1). Most of these habitat types are in upper Spencer Gulf. Surveys of juvenile prawns have shown that greatest abundances generally occurred at sites within this region (Roberts et al. 2005).

Table 1.1. Fishery habitat areas and the estimated distance and proportion of coastline of tidal flat and mangrove forest for each of South Australia's prawn fisheries.

Fishery	Fishery habitat areas	Coastline (km)	Tidal flat only		Mangrove	
			km	%	km	%
Spencer Gulf	15	992	508	51	245	25
Gulf St Vincent	11	551	225	41	79	14
West Coast	16	1310	310	24	45	3

In a study of penaeid prawn fisheries around the world, Pauly and Ingles (1999) demonstrated a significant relationship between mangrove area and fisheries production, thus supporting the widely held view that intertidal vegetation (particularly mangroves) plays a major role in penaeid prawn recruitment.

1.2.4. Commercial fishery

Prawns are harvested at night using demersal otter trawls configured with two nets (Figure 1.4). It has become standard practice in the fishery to use 'crab bags' to exclude bycatches of Blue Swimmer Crabs (*Portunus* armatus) and mega-fauna (Figure 1.5), 'hoppers' for efficient sorting of the catch and rapid return of bycatch (Figure 1.4), and 'graders' to sort the prawns into marketable size categories (Figure 1.4). All vessels operating in the SGPF process and freeze the catch on-board prior to landing.

The SGPF is the third most valuable prawn fishery in Australia ($41.9M[2] in 2016/17; EconSearch 2018) behind Queensland's East Coast Otter Trawl Fishery ($96M in 2017; Department of Agriculture and Fisheries 2018) and the Commonwealth's Northern Prawn Fishery (NPF; $118.1 in 2016/17; Larcombe et al. 2018). In terms of value per licence holder, the SGPF is ranked second (39 licences, ~$1.0M per licence) behind the NPF (52 licences, $2.27M per licence).

South Australia's prawn fisheries are the only substantial single-species prawn fisheries in Australia. However, it is not the only fishery to target the Western King Prawn. In 2016, the Western King Prawn was also targeted and harvested by Western Australia's Shark Bay (1,010 t) and Exmouth Gulf (201 t) prawn fisheries, respectively (Kangas et al. 2018a; 2018b).

[1] Mangrove forest always overlapped with tidal flat but is considered separate to habitat comprising only tidal flat.
[2] Gross value of production (GVP) for the SGPF includes the West Coast Prawn Fishery, which is estimated to be <10%.

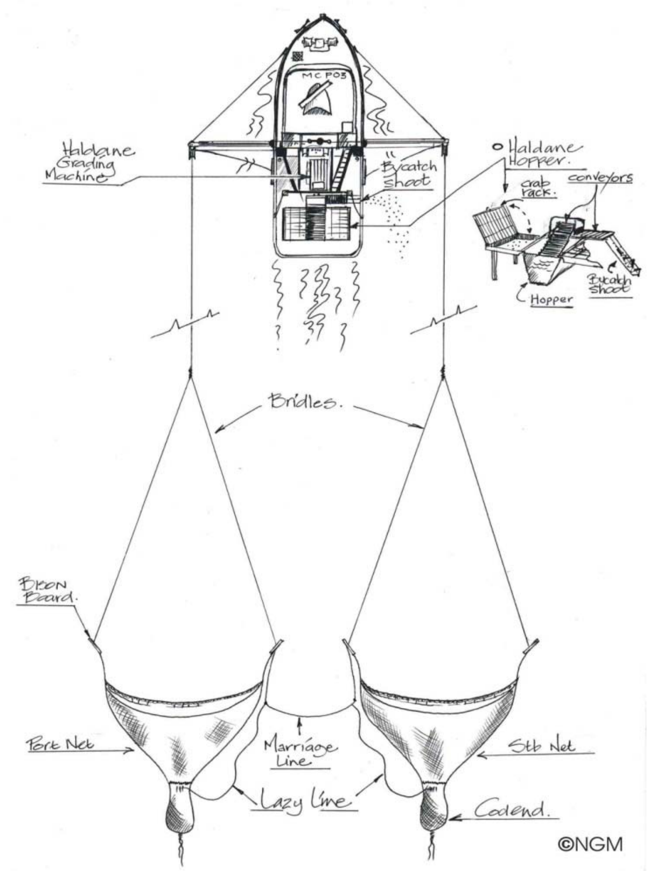

Figure 1.4. Double rig trawl net configuration, hopper and size grader used in the Spencer Gulf Prawn Fishery. Source: Carrick (2003).

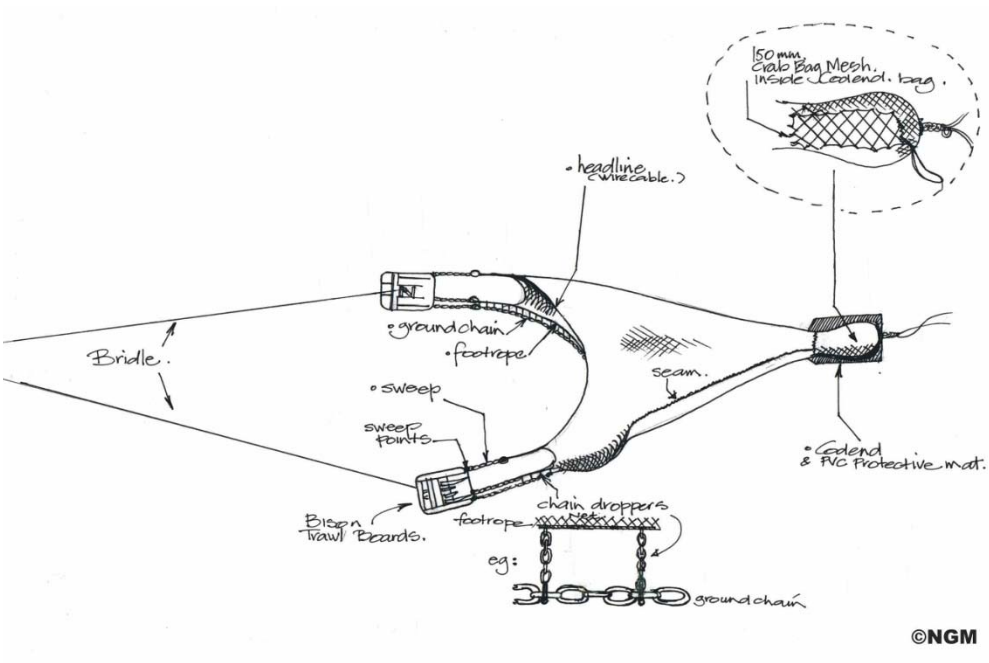

Figure 1.5. Trawl net configuration showing trawl boards, head rope, ground chain and cod end with crab bag. Source: Carrick (2003).

1.2.5. Recreational, traditional and illegal catch

Under current fisheries legislation, it is prohibited for any person to take Western King Prawns from waters less than 10 m in depth. As prawn trawl nets can only be used by the commercial fishing sector, the catch by the recreational sector and Aboriginal traditional fishing is negligible (Anon. 2003). The illegal take of prawns is assumed to also be negligible.

1.3. Management of the fishery

1.3.1. Legislation

The SGPF is managed by Primary Industries and Regions South Australia (PIRSA) Fisheries and Aquaculture in accordance with a Management Plan (PIRSA 2014) and legislative framework provided within the *Fisheries Management Act 2007*, *Fisheries Management (General) Regulations 2007* and *Fisheries Management (Prawn Fisheries) Regulations 2006*.

1.3.2. Current management arrangements for the commercial sector

Management arrangements for the SGPF have evolved since the fishery began in the late 1960s (Table 1.2). Now, the SGPF is a limited entry fishery with 39 licensed operators. Trawling activity is prohibited during daylight hours and in waters less than 10 m in depth. Effort is restricted by spatial and temporal closures, vessel size and power, and configuration of trawl gear (including type and number of nets towed, maximum headline length and minimum mesh size) (Table 1.3).

Table 1.2. Key management milestones over the history of the Spencer Gulf Prawn Fishery.

Year	Management milestone
1968	Licences restricted; trawling prohibited in waters <10 m; commercial catch and effort recording began
1969	*Prawn Resources Regulations 1969* established. Spencer Gulf divided into two zones.
1971	Spencer Gulf zones removed
1974	Spatial closure north of Point Lowly introduced
1976	Licences restricted to 39
1981	Spatial closure adjacent to Port Broughton introduced
1982	*Fisheries Act 1982* introduced
1984	*Scheme of Management (Spencer Gulf Prawn Fishery) Regulations 1984* introduced
1991	*Fisheries (Scheme of Management – Prawn Fisheries) Regulations 1991* introduced
1995	*Fisheries (Management Committees) Regulations 1995* introduced
1998	First management plan implemented
2006	*Fisheries Management (Prawn Fisheries) Regulations 2006* introduced
2007	Second management plan implemented; *Fisheries Management Act 2007* introduced
2014	Third management plan implemented (PIRSA 2014)
2017	Fisheries Management (Prawn Fisheries) Regulations 2017 introduced
2019	Fourth management plan (currently in draft version) scheduled to come into effect

Table 1.3. Current management arrangements for the Spencer Gulf Prawn Fishery.

Management control	Specification
Target species	Western King Prawn (*Penaeus* (*Melicertus*) *latisulcatus*)
Permitted by-product species	Slipper Lobster (*Ibacus* spp.), Southern Calamari (*Sepioteuthis australis*)
Limited entry	Yes
Number of licences	39
Corporate ownership of licences	Yes
Licence transferability	Yes
Minimum depth for trawling	10 m
Method of capture	Demersal otter trawl
Trawl net configuration	Single or double rig (double rig exclusively used)
Maximum total headline length	29.26 m
Minimum mesh size	4.5 cm
Maximum length of vessel	22 m
Maximum engine capacity	336 kW
Catch and effort data	Daily logbook, submitted monthly
Recreational fishery	Restricted to depths ≥10 m; hand nets only

For the purpose of this report, the ‘fishing year’ is defined as the 12-month period from 1 October to 30 September the following year. However, fishing generally only occurs during the months of November and December and from March to June between the last and first quarter of the moon (i.e. during waning crescent and waxing crescent phases either side of the dark moon). These fishing areas are co-administered/managed by PIRSA Fisheries and Aquaculture and the ‘Coordinator-at-Sea’ appointed by the Spencer Gulf and West Coast Prawn Fishermen’s Association (SGWCPFA) under Regulation 10 of the *Fisheries Management (Prawn Fisheries) Regulations 2017*.

1.4. Biology of the Western King Prawn

A detailed synopsis on the biology of the Western King Prawn can be found in a previous stock assessment report (Noell and Hooper 2015). The following sections include brief summaries of biological information relevant to this assessment.

1.4.1. Distribution

The Western King Prawn is distributed throughout the Indo-west Pacific (Grey et al. 1983). Its distribution in South Australia is unique, as it is at its lowest temperature range, restricted to waters of Spencer Gulf, Gulf St Vincent and along the West Coast. Several authors have provided detailed accounts of this species’ distribution in Spencer Gulf (King 1977; Sluczanowski 1980; Carrick 1982, 1996). The Western King Prawn is a benthic species that prefers sandy areas to seagrass or vegetated habitats (Tanner and Deakin 2001). Juvenile and adult prawns show a strong diel behavioral pattern of daytime burial and nocturnal activity (Rasheed and Bull 1992; Primavera and Lebata 2000). Strong lunar and seasonal differences in activity are also exhibited, where prawn activity (and catchability) is greater during the new (dark) moon phase of the lunar cycle and warmer months.

1.4.2. Length-weight relationship

The relationship between carapace length (*L*, mm) and weight (*W*, g) for the Western King Prawn from Spencer Gulf is described by a power function (males: $W = 0.00124\ L^{2.76}$; females: $W = 0.00175\ L^{2.66}$; Carrick 2003).

1.4.3. Reproductive biology

In Spencer Gulf, adult Western King Prawns aggregate, mature, mate and spawn in deep water (>10 m) between October and April, with the main spawning period being earlier in the fishing year (October to January), peaking in November (SARDI, unpublished data). While the water temperature range of 17–25°C for spawning of Western King Prawn (Penn 1980; Courtney and Dredge 1988) generally occurs from November to May in Spencer Gulf, the majority of spawning in the gulf is restricted to earlier in the fishing year. This is likely to be associated with optimising reproductive success from shorter larval durations and higher larval survival at that time of year (Roberts et al. 2012).

The increasing proportion of maturity (*P*) with carapace length for female Western King Prawns in Spencer Gulf is described by a logistic model ($P = 8.3\times10^{-6} + [1/(1+e^{-0.277(L-36.45)})]$), with the size-at-maturity (L_{50}) estimated at 36.5 mm (Carrick 2003). Spawning frequency for the Western King Prawn appears to be related to moulting frequency, indicating that multiple spawning events occur within a season, and females are likely to spawn over multiple seasons (Penn 1980).

There are no data on the fecundity of the Western King Prawn in Spencer Gulf; however, for Gulf St Vincent populations, fecundity (*F*) increases exponentially with carapace length ($F = 0.794\ L^{3.46}$; M. Kangas unpublished, cited in Carrick 2003).

1.4.4. Larval and juvenile stages

The life cycle of the Western King Prawn consists of an offshore phase, where spawning of adults and drift and growth of larvae occurs, and an inshore phase, where settlement of post-larvae and growth through to the juvenile stage occurs. Post-larvae produced from early in the spawning period (i.e. October/November), settle in inshore nursery areas at 2–3 mm *L* during December or January before emigrating to deeper water in May or June (Carrick 1996). Alternatively, post-larvae produced from spawning after January settle in nurseries from March, grow slowly, then 'over-winter' in the nursery areas before recruiting to the trawl grounds in February of the following year (Carrick 2003).

Temperature, salinity and food availability are generally considered to have the most influence on larval growth and survival in penaeid prawns (Preston 1985; Carrick 2003; Jackson and Burford 2003). Larval rearing experiments have demonstrated that an increase in temperature over a range of 17–25°C resulted in an increase in growth rate, shorter larval period and an increase in larval survival for Western King Prawn (Roberts et al. 2012; Rodgers et al. 2013), thus demonstrating the strong tropical affinity of this species.

1.4.5. Stock structure

While the South Australian Museum found significant genetic differences between South Australian and Western Australian Western King Prawn samples (cited in Carrick 2003), Richardson (1982) found no evidence of genetic isolation among South Australian populations. Notwithstanding the possibility that South Australia's prawn fisheries may comprise a single stock, they continue to be managed as three separate units based on historic arrangements.

1.4.6. Growth

Prawns undergo a series of moults to increase their size incrementally. The shedding of hard body parts during moulting means that the age of individuals cannot be reliably determined. Instead, tag-recapture studies for the Western King Prawn in Spencer Gulf indicate strong seasonal growth, with maximum growth rates for both sexes occurring in early March, and little or no growth from late July to mid-October for males and from late August to late September for females (Carrick and Ostendorf 2005).

1.4.7. Movement

Using the same tag-recapture data as those for describing growth, Carrick (2003) described three general movement patterns of the Western King Prawn in Spencer Gulf: (i) north to south movement in northern Spencer Gulf; (ii) east to northeast movement from northern Cowell and the top of the Gutter; and (iii) southeast movement from southern Cowell and the Gutter towards Corny Point (Figure 1.1).

1.5. Research program

In 2015/16, the frequency of stock assessment reports for the SGPF changed from annual to biennial. This provided opportunities for other research to be undertaken in alternate years. Given that stock status is determined before the start of each fishing year, a biennial stock assessment program was considered to be a cost-effective approach to pursuing other research needs and interests for the fishery without compromising the main objective of determining the annual status and harvest strategy for the following year.

The biennial stock assessment program comprises seven components: (i) a review and update of the biology of the Western King Prawn; (ii) analysis of survey data; (iii) analysis of commercial catch and effort data; (iv) evaluation of fishery performance with respect to fishing strategies and biological performance indicators in the Management Plan; (v) recent end-of-year stock status determinations; (vi) recommendations for future research; and (vii) preparation and provision of a stock assessment report.

The SARDI stock assessment program has been supplemented with research on the early-life history (Carrick 1996; Tanner and Deakin 2001; Roberts et al. 2005, 2012; Rodgers et al. 2013), population dynamics and fisheries modelling (King 1977; Sluczanowski 1984; Carrick and Ostendorf 2005; McLeay et al. 2015; Noell et al. 2015), gear selectivity (Dixon et al. 2014; Kennelly and Broadhurst 2014; Noell et al. 2018) and ecosystem-based assessments (Svane et al. 2009; Currie et al. 2011; Mayfield et al. 2014; Burnell et al. 2015; Noell 2017).

Juvenile prawn surveys are conducted in upper Spencer Gulf in March/April each year by SARDI. Historically, these surveys were conducted periodically until 2003 at up to 32 sites to determine spatial and temporal patterns in juvenile prawn abundance (Roberts et al. 2005). Since 2009, surveys have been completed annually; however, the number of sites has been gradually rationalised to two, and the aims have been redirected to simple monitoring of the presence/absence of juveniles and signs of any disease.

1.6. Information sources

1.6.1. Stock assessment surveys

Stock assessment surveys are conducted three times each fishing year, i.e. November, February and April, using industry vessels, skippers and crews, with independent observers placed on each vessel, to collect data on prawn size and catch per unit effort (CPUE). These data serve two important purposes: (i) determine the mean survey CPUE of ‘adult’ and ‘newly recruited’ prawns (consisting of industry grades with fewer and more than 20 prawns per pound, respectively) in surveys as measures of targeted and recruitment biomass; and (ii) inform the development of fishing strategies according to the harvest strategy (Section 1.7) in the current management plan (PIRSA 2014; hereafter referred to as the the Management Plan). Additionally, data from the November survey provides information on egg production, and data from the February survey provides information on recruitment.

The current survey design was adopted in November 2004 to ensure consistent spatial and temporal replication of survey shots, and thereby improve the robustness of surveys as a measure of relative biomass. There are a total of 205 fixed locations completed for stock assessment surveys (Figure 1.1). While all survey locations provide a comprehensive coverage of the gulf for determining areas to be subsequently opened for fishing, a subset of these locations (180 for November survey, 182 for February survey, and 159 for April survey) have consistently been used since 2004/05 to determine the nature of the fishing strategy following each survey and the stock status at the end of the year.

1.6.2. Commercial logbook data

Licence holders are required to complete and submit a daily catch and effort logbook to SARDI Aquatic Sciences at the end of each month. A monthly unloading logbook is also completed to enable validation and adjustment of daily catch estimates.

Since the reporting of commercial catch and effort began in 1968, there have been a number of modifications to improve the information available for assessment. From July 1987, the previously used regular grid for reporting catch and effort was replaced with 125 irregularly shaped fishing blocks (Figure 1.1) — ranging in size from 29–1,029 km^2 (mean: 166 km^2) — to better reflect the fishing grounds and differences in prawn size and abundance (Carrick 2003). Other logbook reporting requirements include the exact location (GPS coordinates) for at least three trawl shots per night, a breakdown of the prawn catch by industry size-grade, and retained by-product (Southern Calamari, *Sepioteuthis australis*, and Slipper Lobster, *Ibacus* spp.).

1.7. Harvest strategy

1.7.1. Management Plan

The Management Plan for the South Australian commercial Spencer Gulf Prawn Fishery was released in October 2014, and is currently undergoing a 5-year revision. An important feature of the Management Plan is the harvest strategy, which was developed by a working group of the SGWCPFA that consisted of representatives from industry, PIRSA Fisheries and Aquaculture and SARDI Aquatic Sciences. The harvest strategy comprises a harvest decision framework that operates at three levels: (i) annual stock status; (ii) monthly fishing strategies; and (iii) associated prawn size and catch criteria that are monitored daily.

1.7.2. Stock status determination

The harvest strategy incorporates a method for determining annual stock status. While multiple lines of evidence were used previously to determine stock status, the revised harvest strategy adds a decision rule whereby stock status classification is explicitly linked to an indicator of relative biomass. For the SGPF, this indicator of relative biomass is the weighted mean $CPUE_{adults}$ obtained from three fishery-independent surveys, which are conducted around November, February and April each fishing year. Weightings used for this calculation are based on the perceived representativeness of each survey as an indicator of the relative biomass and, therefore, its contribution towards an end-of-year stock status (0.20 for November, 0.35 for February and 0.45 for April). Consistent with most South Australian-managed fisheries, the stock status classification for the SGPF has been developed to align with the terminology of the national status reporting framework (i.e. 'sustainable', 'transitional' or 'overfished'; Stewardson et al. 2018).

For as long as the stock status has been determined for the SGPF, the fishery has been classified as sustainable, irrespective of the method used to determine status (i.e. historically, using multiple lines of evidence or, since 2014/15, the weighted mean of survey $CPUE_{adults}$). Associated with a sustainable stock, the harvest strategy describes a hierarchical set of fishing strategies and prawn size and catch criteria that apply in the following year, which collectively aim to maximise economic yield by limiting effort spatially and temporally. In the event that the fishery would become classified as transitional or overfished, the harvest strategy provides measures that aim to promote stock recovery either by restricting the number of fishing nights (transitional) or closing the fishery for the whole year (overfished).

1.7.3. Fishing strategy development

When the fishery is classified as a sustainable stock, the fishing strategy is developed immediately after each stock assessment survey so that the fleet is able to commence fishing the next night. Based on the mean survey $CPUE_{adults}$ and $CPUE_{recruits}$ and associated reference points (RPs) (Table 1.4), the survey result/fishing strategy is categorised as conservative, standard or increasing (Table 1.5). Each of these categories, in turn, has associated criteria for prawn size and catch (Table 1.6), which influence the area(s) that are opened to fishing and the number of fishing nights, respectively, except during

November and December. While the November/December fishing period is still subject to a prawn size criterion, it is largely influenced by a catch cap for the fleet (Table 1.7), which aims to provide a compromise between restricting harvests during the peak spawning period and taking advantage of high market prices for smaller (less fecund) prawns prior to Christmas. Once the nature of the fishing strategy has been determined following a stock assessment survey, the decision rules and criteria of that strategy remain in place until the next stock assessment survey is completed.

Table 1.4. Reference points for survey $CPUE_{adults}$ and $CPUE_{recruits}$. Abbreviations: RP_{lower}, lower reference point; RP_{upper}, upper reference point.

Survey	$CPUE_{adults}$ (lb min^{-1})		$CPUE_{recruits}$ (lb min^{-1})
	RP_{lower}	RP_{upper}	RP_{lower}
November	2.46	3.81	0.76
February	2.54	3.68	1.44
April	3.75	6.48	1.63

Table 1.5. Decision table for determining nature of the fishing strategy when the fishery is classified as sustainable. -, not applicable.

Survey $CPUE_{adults}$	Survey $CPUE_{recruits}$	Strategy
<LRP	-	Conservative*
≥LRP and <URP	-	Standard
≥URP	<LRP	Standard
≥URP	≥LRP	Increasing

* Conservative strategy implemented only if this result occurs over two consecutive surveys.

Table 1.6. Fishing strategy size and catch criteria by area and month.

Area	Criteria	Post-February survey			Post-April survey		
		Conservative	Standard	Increasing	Conservative	Standard	Increasing
Mid/North	7-kg bucket count	≤220	≤240	≤260	≤240	≤260	≤260
	Nightly catch (kg)	≥600	≥500	≥500	≥600	≥500	≥400
or	7-kg bucket count	≤200	≤220	≤240	≤220	≤240	≤260
	Nightly catch (kg)	≥400	≥400	≥400	≥400	≥400	≥400
Southern	7-kg bucket count	≤230	≤260	≤260	≤240	≤260	≤260
	Nightly catch (kg)*	≥400	≥350	≥350	≥400	≥350	≥350

* Applicable over two consecutive nights, for southern area only.

Table 1.7. Decision table for determining the pre-Christmas fleet catch cap from the November mean survey $CPUE_{adults}$.

Survey $CPUE_{adults}$ (lb min^{-1})	Fleet catch cap (t)
<1.04	0
1.04	120
1.38	200
1.72	300
1.93	350
2.13	375
2.37	400
2.68	425
2.99	450
3.30	475
3.61	500
3.92	525
4.23	550

The fishing strategy is considered to generally reflect the status of the resource, and their criteria are devised to ensure that catch and effort levels are appropriate to ensure sustainability. For example, a low mean survey $CPUE_{adults}$ indicates a low relative biomass of targeted prawns, and may lead to a conservative strategy, which aims to increase $CPUE_{adults}$ back to historic levels. During the fishing period, the industry 'Committee-at-Sea' (CAS) monitors the catch of the fleet with respect to size and catch criteria of the fishing strategy and, where necessary, or when they determine it is in the interests of longer-term yields for the fishery, will reduce the size of the area fished, postpone fishing, or cease fishing altogether.

The potential for external factors to have an unduly influence on survey CPUEs is recognised in the harvest strategy via a meta-rule which specifies that a conservative fishing strategy is mandatory only when the mean $CPUE_{adults}$ falls below its lower reference point (RP_{lower}) over two consecutive surveys. It is also important to recognise that the RP_{lower} for $CPUE_{adults}$ does not imply overfishing; rather, it represents the lower historic range, which is still above the sustainable limit, and can therefore be considered an economic limit.

1.7.4. Performance indicators

The extent to which the fishery achieves goals and objectives of the Management Plan is assessed using a combination of biological performance indicators (PIs). The primary PI, the weighted mean survey $CPUE_{adults}$, has a prescribed management outcome (i.e. stock status), whereas the secondary PIs (estimates of recruitment and egg production, and mean commercial CPUE) only have the ability to influence decisions within the parameters of the harvest strategy framework (Table 1.8). Each PI is evaluated against a RP.

Table 1.8. Performance indicators and reference points for the SGPF. Abbreviation: LRP, limit reference point.

Performance indicator	Data source	Reference point
Primary		
1. Weighted mean survey $CPUE_{adults}$ (lb min^{-1})	All three stock assessment surveys	≥1.75 (LRP)
Secondary		
2. Recruitment index (lb min^{-1})	February survey	≥2.38
3. Mean egg production (M eggs trawl-h^{-1})	November survey	≥500
4. Mean commercial CPUE (kg h^{-1})	Commercial fishing logbooks	≥80

2. METHODS

2.1. Stock assessment surveys

2.1.1. Data collection

The three annual stock assessment surveys generally require 16 or 18 vessel-nights using several commercial trawlers (with an independent observer onboard) over two consecutive nights around the new moon. Due to the timing of the lunar cycle, the 'November' surveys in 2016/17 and 2017/18 were actually undertaken in late October to ensure that the fishery could complete two fishing periods (between the last quarter and first quarter of the moon) and thereby supply markets with prawns in time for the Christmas period.

Each survey involved 30-min trawl shots along a predetermined path at 205 locations (with the aid of a marine chart plotter). The distance trawled at each location depends on trawl speed (3–5 knots), which is influenced by vessel power, tide and weather conditions. Data collected at each location included total catch, catch of '20+' grade prawns (more than 20 prawns per pound; generally referred to as 'recruits'), number of nets used, trawl duration, tide direction, and number of prawns in a 7-kg bucket (referred to in the industry as a 'bucket count' and used as a rapid measure of average prawn size). A length-frequency sample of 100 prawns was also measured at each location.

2.1.2. Egg production

Annual egg production of Western King Prawns in Spencer Gulf was estimated using an egg production model, which has been used since 2004/05. The model calculations are based on biological data collected from the November survey, and rely on several parameters (Table 2.1) and assumptions: (i) catchability of prawns is constant; (ii) the number of times a female spawns in a spawning period; (iii) spawning frequency does not vary with size; (iv) natural mortality is zero; (v) the proportion of females within each industry size grade category does not vary during the spawning period; and (vi) sex-specific length-frequency data are representative of the population.

Table 2.1. Egg production parameters for each industry grade category.

Parameter	Industry size grade category					Source
	‘U8’	‘U10’	‘10/15’	‘16/20’	‘20+’	
No. spawnings, *s*	3	3	3	3	3	Penn (1980).
Batch fecundity, *f*	634685	499103	350237	223417	131831	Length-weight, length-fecundity relationships (Carrick 2003).
Proportion females, *p*	0.978	0.927	0.397	0.287	0.181	Fish processors (unpubl. data).
Proportion mature, *m*	0.981	0.953	0.849	0.575	0.237	Length-weight, length-maturity relationships (Carrick 2003).
Fertilisation success, *z*	0.99	0.98	0.90	0.85	0.40	Courtney and Dredge (1988).
Mean weight (g) of individuals, *w*	60	50	38	27	18	Fish processors (unpubl. data).

Mean egg production E (in M eggs trawl-h^{-1}) is calculated using the equation:

$$\overline{E} = \frac{\sum_{j=1}^{X} \frac{2C_j}{N_j T_j G_j} \left(\sum_{i=1}^{5} Q_i W_i \right)}{10^6 X}$$

where, for shot location *j* of *X*, *C* is total catch weight (kg; excludes soft and broken prawns), *N* is number of nets used, *T* is tow duration (h), *G* is total graded weight (kg), *W* is weight of grade category *i* (kg), and *Q* is a model quotient:

$$Q_i = \frac{s_i f_i p_i m_i z_i 1000}{w_i}$$

where *s*, *f*, *p*, *m*, *z* and *w* are the parameters defined above for grade category *I* (Table 2.1).

The calculation of $\overline{E}$ is interpreted as the potential number of fertilised eggs per trawl hour that females could have contributed throughout the spawning period.

2.1.3. Recruitment

The recruitment index was calculated as the survey CPUE$_{recruits}$ (‘20+’ grade prawns) from 34 locations in the upper gulf during February surveys. This replaces a length-based measure of recruitment (Carrick 2003) as it was considered more representative of the sampled population and therefore more accurate (Advice Note to PIRSA Fisheries and Aquaculture, July 2018). Despite the redundancy of the length-based measure, its relationship with CPUE$_{recruits}$ was used to convert the old RP (1,225 recruits nm^{-1}) into a new but equivalent RP (2.38 lb min^{-1}) for recalculation and assessment of the recruitment index time series.

The mean CPUE$_{recruits}$ was also determined for all locations from each survey, 2004/05 to 2017/18, to identify temporal (inter and intra-annual) trends in relative abundance of recruits throughout the gulf.

2.2. Commercial fishing logbook data

2.2.1. Catch, effort and CPUE

Catch and effort data were obtained from two sources: (i) annual (1968–1973) and monthly data (January 1973–June 1988) from South Australian Fishing Industry Council (SAFIC) annual reports; and (ii) daily and monthly data (July 1988–June 2016) from catch and effort logbooks. Estimated prawn catch for each shot was adjusted using validated catches reported in monthly unloading logbooks.

Catch and effort data are presented temporally (fishing year and month) and spatially (region, as defined in Figure 1.1). Catch is also presented for the early spawning period (October to December) compared to all other fishing months. Commercial CPUE was calculated by dividing the adjusted catch by effort, and expressed in kg h^{-1} (unlike the survey CPUE, which is conventionally given in lb min^{-1} because of the marketing of size grades in number of prawns per pound).

2.2.2. Prawn size

Information on prawn size was obtained from industry size grade data for fishing years 1997/98 and 2002/03–2017/18. Industry size grades generally refer to the number of prawns per pound (e.g. 'U10' means fewer than 10 prawns per pound). Since 2002/03, up to 24 size grades have been used to describe the size of prawns in the commercial catch due to different marketing practices among the industry. To ensure consistent interpretation of prawn size, size grades were converted to broader size categories of extra-large (XL), large (L), medium (M), and small (S) (Table 2.2). For analysis of trends within years, a fifth category, soft and broken (S&B), was established for prawns that were not graded.

Table 2.2. Conversion of industry grades reported in commercial logbooks to broader categories for analysis. Also shown for each grade is the estimated median bucket count (prawns 7 kg^{-1}). -, not applicable.

Broad size category	Industry size grades reported in logbook	Median bucket count
Extra-large (XL)	'U6'	92
	'XL'	100
	'U8'	108
	'U10', 'L'	139
Large (L)	'9/12'	162
	'U12'	169
	'LM', '10/15'	193
	'13/15'	216
	'10/20' (50%), '12/18' (50%)	231
Medium (M)	'10/20' (50%), '12/18' (50%)	231
	'M', '16/20'	277
Small (S)	'SM', '19/25'	339
	'21/25'	354
	'S', '20+', '21/30'	393
	'26+'	431
	'30+', '31/40'	547
	'41/50'	630
Soft and broken (S&B)	'S&B', 'B&D', 'MIX', 'REJ', 'SMS', 'ERR', *(blank)*	-

Prawn size was also examined in terms of bucket count based on median values estimated for each size grade (e.g. '10/15' grade was estimated at 12.5 prawns per pound or 193 prawns 7 kg^{-1}) (Table

2.2). The mean nightly bucket count ($\overline{B}$) for the fleet was calculated from the grade weights provided in commercial logbooks and the median bucket count for each grade using the equation:

$$\overline{B} = \frac{\sum_{j=1}^{39}\left(\sum_{i=1}^{24}(W_i \times B_i)\right)_j}{\sum_{j=1}^{39}\left(\sum_{i=1}^{24}W_i\right)_j}$$

where W and B are grade weight and 7-kg bucket count, respectively, for grade i and vessel j.

Mean annual bucket count ($\overline{B_Y}$) was calculated using the equation:

$$\overline{B_Y} = \frac{\sum_{i=1}^{k}\left(C_i \times \overline{B_i}\right)}{\sum_{i=1}^{k}C_i}$$

where C is the total catch by the fleet on night i of a fishing year that comprises k nights.

2.3. Catch standardisation

CPUEs obtained from stock assessment surveys or fishing are assumed to be proportional to prawn abundance. Ideally, however, before CPUEs are used as the most reliable indicator of relative biomass, the catch is standardised to remove the influence of variables that are not related to abundance. While fishing strategy development, and monitoring and adjustment in real time largely precludes the use of standardised catches for incorporation in the harvest strategy of the SGPF, it nevertheless provides valuable information for fishery modelling (Noell et al. 2015), along with some assurance that harvest decisions are consistent with the use of observed CPUE as an index of relative abundance.

Generalised linear modelling (GLM; Nelder and Wedderburn 1972), the most common method for standardising catch data from fisheries (Maunder and Punt 2004), was employed for the standardisation of survey and fishery catches. Analyses were performed using the R programming language (R Core Team 2018) on survey catches (kg trawl-shot^{-1}) at survey locations used for subsequent fishing strategy development from 2004/05–2017/18 and daily logbook catches (kg vessel-night^{-1}) from 1990/91–2015/16. Survey catches (per 30-min trawl-shot) were adjusted to two nets where necessary.

Box-Cox transformation (Box and Cox 1964) and diagnostic plots indicated that, among different distributional assumptions tested, a Gaussian error distribution and identity link fitted to cube root transformed catches were appropriate for survey and fishery catch data. The analyses included fixed terms (Xβ), and followed the terminology and notation of Noell et al. (2015). Where data (X_1, X_2, …X_{10}) were relevant and available, the models were fitted to estimate the following parameter effects:

- Scalar model intercept β_0;
- Abundance β_1 for data X_1 (fishing year-survey/month combined factor);
- Region β_2 for data X_2 (amalgamation of fishing blocks; 10 regions) (Figure 1.1);

- Vessel β_3 for data X_3 (identified by licence number; 39 licences);
- Tide direction β_4 for data X_4 (‘against’, ‘slack’ or ‘with’; relative to the towing direction);
- Tide strength β_5 for data X_5 (m h^{-1}; sum of the absolute differences between consecutive high and low water marks at Whyalla over a ~24 h period (from noon) divided by the actual hours elapsed; survey only) (BOM 2018a);
- Sea surface temperature β_6 for data X_6 (daily mean near the middle of the gulf at 33.88°S, 137.38°E, derived from satellite data, smoothed with moving average of 7 days to keep daily variation generally within ± 0.2°C) (NASA 2018);
- Luminosity β_7 for data X_7 (fraction of moon illuminated at midnight AEST) (USNO 2018);
- Luminosity (lagged) β_8 for data X_8 (moon phase shifted 7 days; only considered when the primary variable β_7 was significant);
- Cloud cover β_9 for data X_9 (mean fraction from three-hourly readings, measured in eighths, between 1800 and 0600 hours) (BOM 2018b); and
- Fishing effort β_{10} for data X_{10} (hours).

The most parsimonious model for survey and fishery catches (Table 2.3) was obtained by removing non-significant terms in analysis of deviance (type II method; Noell et al. 2015) according to the *F*-statistic.

Table 2.3. Final GLMs used to standardise survey (2004/05–2017/18) and fishery (1990/91–2017/18) CPUE. -, not applicable.

Survey	
Response:	(kg trawl-shot^{-1})$^{0.33}$
Fixed terms:	$\beta_0 + X_1\beta_1 + X_2\beta_2 + X_3\beta_3 + X_4\beta_4 + X_7\beta_7$
Offset	β_{10}
Predictions:	β_1
Fishery	
Response:	(kg vessel-night^{-1})$^{0.33}$
Fixed terms:	$\beta_0 + X_1\beta_1 + X_2\beta_2 + X_3\beta_3 + X_7\beta_7 + X_8\beta_8 + X_{10}\beta_{10}$
Offset	-
Predictions:	β_1

The ‘effects’ package in R was used to determine predicted means for the main effects of the model (e.g. year-survey/month) by setting other numeric variables to their mean values (except fishing effort, which was specified), and by setting factors to their proportional distribution in the data by averaging over contrasts (Fox 2003; Fox and Hong 2009). Survey effort was virtually constant (mean 0.48 h) and therefore treated as an offset term, whereas fishing effort had a multimodal distribution, so the mean of the largest two modes (9.33 h) (as determined by the R package ‘mixdist’, Macdonald and Du 2012) was used to represent typical effort per vessel-night in the fleet. As the predicted means were on the transformed scale, the cubic-root bias correction $\mu^3 + 3\mu\sigma^2$ was required to back-transform to their original scale (Kendall et al. 1983), where μ is the predicted mean on the transformed scale, and σ^2 is the model variance. Model-predicted means were converted to kg h^{-1} for fishery catches and, to comply with industry convention, lb min^{-1} for survey catches.

2.4. Trawl footprint

To estimate the trawl footprint of the SGPF, we obtained available high resolution vessel position data accounting for ~40% of the total trawl effort over 17 years (2001/02–2017/18). Footprint is defined as the area of seabed trawled at a mean annual trawl intensity above a predetermined level over a specified time period. The trawl footprint estimate was based on the densities of simulated trawl lines (Noell et al. 2017). Using the pixellate function in the 'spatstat' package in R, the aggregated trawl lines with each successive year were gridded at a resolution of 30 × 30 m. This output resolution was chosen as it is comparable to the combined trawl width[3] (29.92 m) used across the fleet, and coarser resolutions result in markedly overestimated trawled area and, consequently, underestimated untrawled area (Figure 2.1; Amoroso et al. 2018).

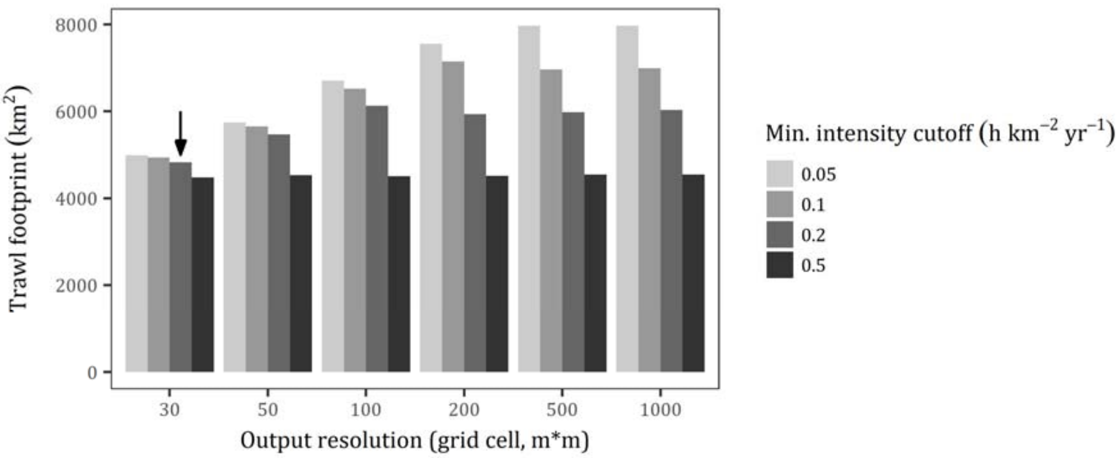

Figure 2.1. Effect of output resolution and minimum intensity cutoff (i.e. for low intensity trawling) on the total trawl footprint estimate of the SGPF over 17 years (2001/02–2017/18). The arrow indicates the settings used in the current assessment.

Each grid cell was assigned a density value d, which equaled the sum of trawl line lengths within the cell (m cell^{-1}), and related to trawl intensity i (in h km^{-2}) according to the formula:

$$d = iyps\left(\frac{x}{1000}\right)^2$$

where y is number of years, p is mean coverage (proportion of total effort), s is mean vessel speed (m h^{-1}) and x is grid cell dimension (m). The tessellate function was then used to group cells by intensity category, where cutoffs were similar to those used by Currie et al. (2011), except we used a minimum cutoff of 0.2 h km^{-2} yr^{-1} rather than 0.1 h km^{-2} yr^{-1} (i.e. 0–0.2 h km^{-2} yr^{-1} = 'no/neglible fishing', 0.2–1 h km^{-2} yr^{-1} = 'low', 1–10 h km^{-2} yr^{-1} = 'moderate, >10 h km^{-2} yr^{-1} = 'high'). The higher minimum cutoff was considered a feasible strategy to counteract the overestimation of the trawl footprint as a result of

[3] In this study, trawl width is the total distance between both pairs of otter boards (of a double-rig configuration) at the leading edges. It is variable, and depends on sweep length, board dimensions, vessel speed and angle of attack (G. Palmer, pers. comm.).

isolated trawl paths, which are likely to be errors (Noell 2017). The area of the trawl footprint was calculated as the sum of cells falling within the low, moderate and high intensity categories.

Trawl footprint estimates in this assessment are based on the cumulative effect of additional trawl effort with each successive year from 2001/02–2017/18, rather than shorter timeframes, which would be considered to underrepresent the true estimate. As such, we did not consider it appropriate to compare the trawl footprint estimates of 2016/17 and 2017/18 with the composite trawl footprint for the entire 17-year period. Instead, we examined the change in the trawl footprint estimate for 2001/02–2015/16 with the addition of 2016/17 and, likewise, the change in the estimate for 2001/02–2016/17 with the addition of 2017/18.

2.5. Verification of survey data

As survey results are calculated within only a few hours after the survey, there is limited time to verify the accuracy of the electronic logbook data provided by the skippers. An extensive quality assurance process (Section 2.6) was followed to validate the survey data some months after their completion. Unvalidated and validated survey results are presented in this report and compared to determine whether there would have been any implications to the actual fishing strategy applied. Detailed maps for each survey and subsequent harvest periods throughout 2016/17 and 2017/18 are provided in Appendix A.

2.6. Quality assurance of data

2.6.1. Research planning

The research requirements for 2016/17 and 2017/18 were discussed at various times with fisheries managers and industry representatives, and subsequently presented as research scopes to confirm their understanding of proposed research and deliverables. This ensured that the proposed research was consistent with the needs of PIRSA Fisheries and Aquaculture and to meet the obligations in the *Fisheries Management Act 2007.*

2.6.2. Data collection

Commercial fishers were advised on the procedures and requirements for conducting surveys and completion of the required fishing logbook on a regular basis, usually at the commencement of each fishing season. The data provided by commercial fishers were checked by SARDI Aquatic Sciences prior to acceptance and potential errors corrected through direct correspondence with individual commercial fishers. Independent observers were trained to record survey data using methods described in stock assessment reports for the SGPF and by following standard operating procedures in an observer handbook that is updated annually by SARDI.

2.6.3. Data entry, validation, storage and security

All logbook data were entered and validated according to the quality assurance protocols identified for the SGPF in the SARDI Information Systems Quality Assurance and Data Integrity Report (Vainickis

2010). Data were stored in an Oracle database, backed up daily, with access restricted to SARDI Information Systems staff. Extracts from the database were provided to SARDI prawn researchers on request. All fishery-independent data were entered into another Oracle database. Accuracy of survey data entry was verified by: 1) performing a series of checks for any inconsistencies or errors in the data file; and 2) checking a subset of the data (20%) against the original data sheets, including any errors that could not be resolved from examining the file alone. Once validated, data were uploaded and stored on a network drive with restricted access to SARDI staff involved in research projects in the Crustaceans Subprogram.

2.6.4. Data and statistical analyses

Data were extracted from the databases using established protocols. Accuracy of the data extracted was checked by comparing pivot table summaries with previous data extractions. Accuracy of data analysis was achieved by carrying out analysis for multiple years at a time (where possible) to reproduce the results of previous assessments.

2.6.5. Data interpretation and report writing

The results, interpretation and conclusions provided in the report were discussed with peers, PIRSA Fisheries and Aquaculture and industry representatives (including some licence holders). All co-authors reviewed the report prior to the report being formally reviewed by two independent scientists at SARDI Aquatic Sciences in accordance with the SARDI report review process. External review of the report was done by the Prawn Fisheries Manager at PIRSA Fisheries and Aquaculture.

3. RESULTS

3.1. Stock assessment surveys

3.1.1. Survey CPUEs

In 2016/17 and 2017/18, the mean survey $CPUE_{adults}$ remained above the RP_{lower} for all three annual stock assessment surveys, except for November 2017, when the $CPUE_{adults}$ fell below the RP_{lower} for November surveys for the first time (Figure 3.1a). Survey $CPUE_{adults}$ exceeded its upper reference point (RP_{upper}) in February 2017, and was the second highest recorded for all February surveys (following the highest in February 2016) (Figure 3.1b). Similarly, the mean survey $CPUE_{recruits}$ remained above the respective RP_{lower} for all surveys in 2016/17 and 2017/18. (Figure 3.1).

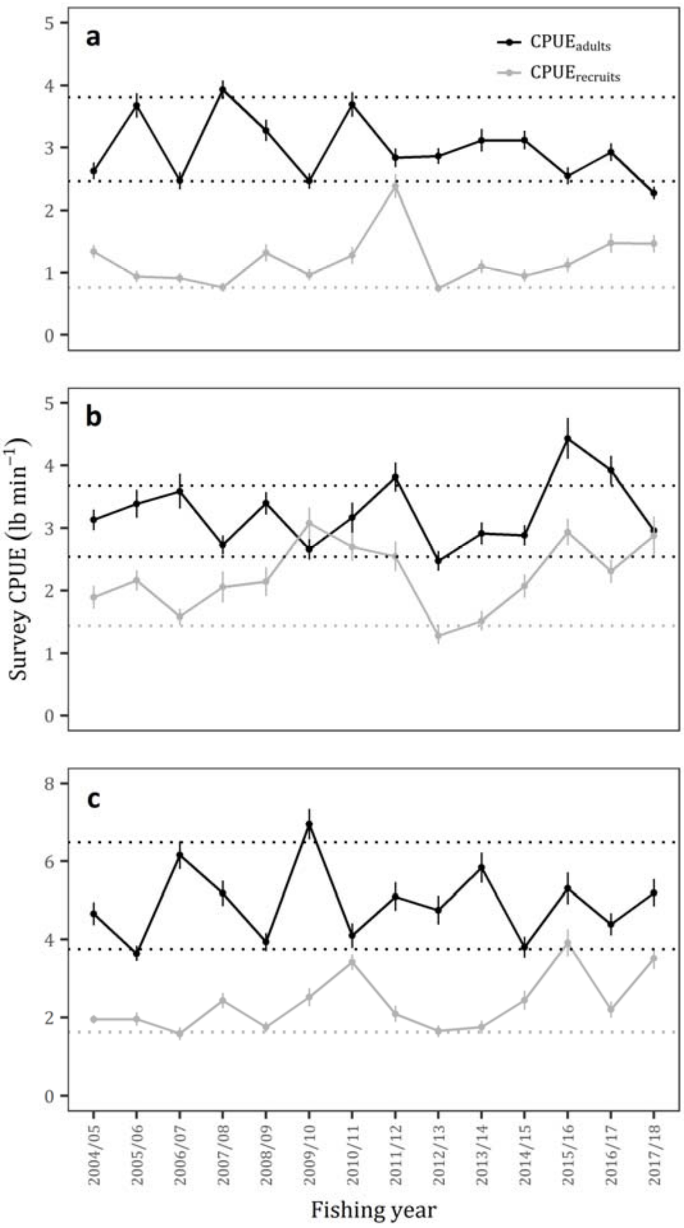

Figure 3.1. Survey mean $CPUE_{adults}$ and $CPUE_{recruits}$ (± 1 SE) during (a) November, (b) February, and (c) April surveys, 2004/05–2017/18. Black dotted lines indicate lower and upper reference points for $CPUE_{adults}$, and grey dotted line indicates the lower reference point for $CPUE_{recruits}$.

3.1.2. Standardisation of survey catches

The final GLM for survey catches (converted to CPUE) from 2004/05 to 2017/18 included the significant terms: year-survey, region, vessel, tide direction and luminosity (Table 3.1; see Table B-1, Appendix B for model coefficients). Model-predicted means were similar in overall trend as observed data (Figure 3.2); however, a low overall goodness of fit (adjusted R^2 value 0.34) suggests other unaccounted sources of variability.

Table 3.1. Analysis of deviance (type II test) for the GLM used to standardise survey catches. Abbreviations: SS, sum of squares; df, degrees of freedom; *F*, *F*-statistic. R^2_{adj} = 0.34.

Effect	SS	df	*F*
Fishing year-survey (β_1)	705	41	21.4***
Region (β_2)	2586	8	402.8***
Vessel (β_3)	104	27	4.8***
Tide direction (β_4)	110	4	34.2***
Luminosity (β_7)	19	1	24.2***
Residuals	6506	8108	

Significance: *** p < 0.001.

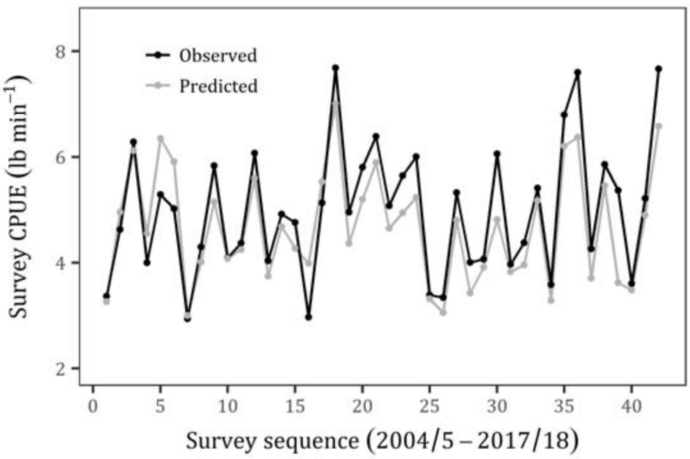

Figure 3.2. Observed and model-predicted mean CPUE for all surveys, 2004/05–2017/18.

3.1.3. Egg production

Annual estimates of egg production in November 2016 (673 ± 28 M eggs trawl-h^{-1}) and 2017 (551 ± 28 M eggs trawl-h^{-1}) continued a decline since November 2013 (Figure 3.3). Despite this decline, egg production has remained above its RP (500 M eggs trawl-h^{-1}) since November 2007 (Figure 3.3).

3.1.4. Recruitment

The mean survey CPUE$_{recruits}$ from 34 locations during February surveys (the recruitment index) has remained above its RP (2.38 lb min^{-1}) since the current survey design began in 2004/05 (Figure 3.4). The recruitment index in February 2017 (4.79 ± 0.42 lb min^{-1}) was double the RP, before it climbed to the highest recorded value in February 2018 (7.88 ± 0.98 lb min^{-1}), more than triple the RP (Figure 3.4).

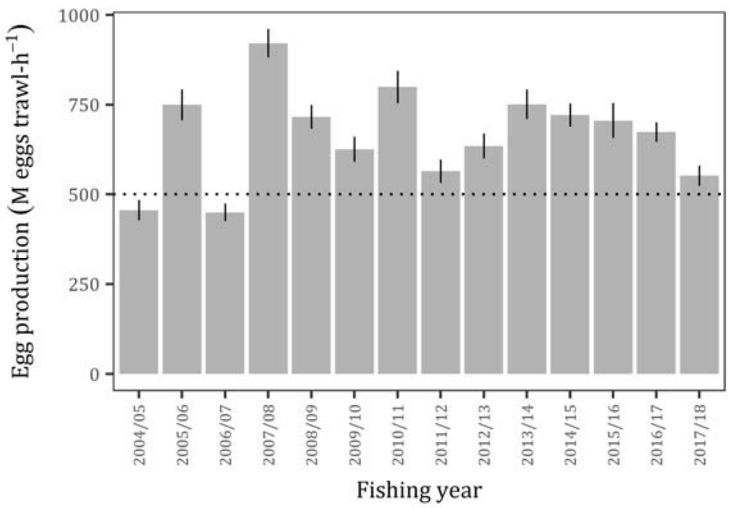

Figure 3.3. Mean egg production (± 1 SE) during November surveys, 2004/05–2017/18. The dotted line indicates the reference point (500 M eggs trawl-h^{-1}).

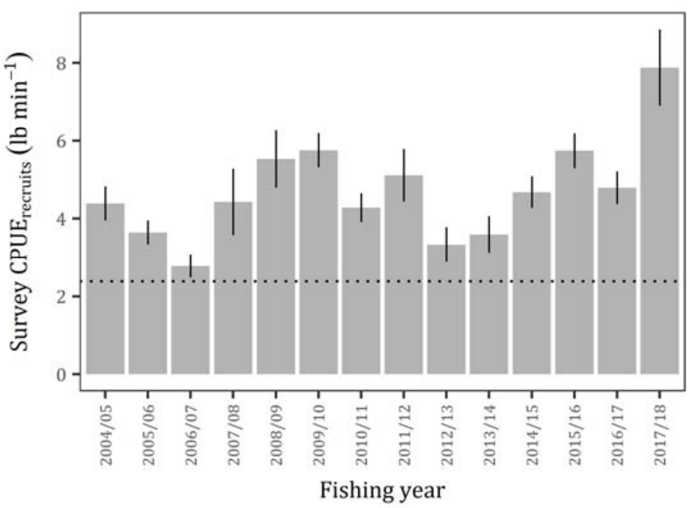

Figure 3.4. Recruitment index (± 1 SE) from 34 shot locations in upper Spencer Gulf during February surveys, 2004/05–2017/18. The dotted line represents the reference point (2.38 lb min^{-1}).

Of the three annual surveys since 2004/05, February and April surveys have yielded the highest mean $CPUE_{recruits}$ (Figure 3.5). Consistent with the historic high recruitment index in February 2018, the mean $CPUE_{recruits}$ throughout broader Spencer Gulf in February and April 2018 are among the highest recorded for their respective surveys (Figures 3.4 and 3.5).

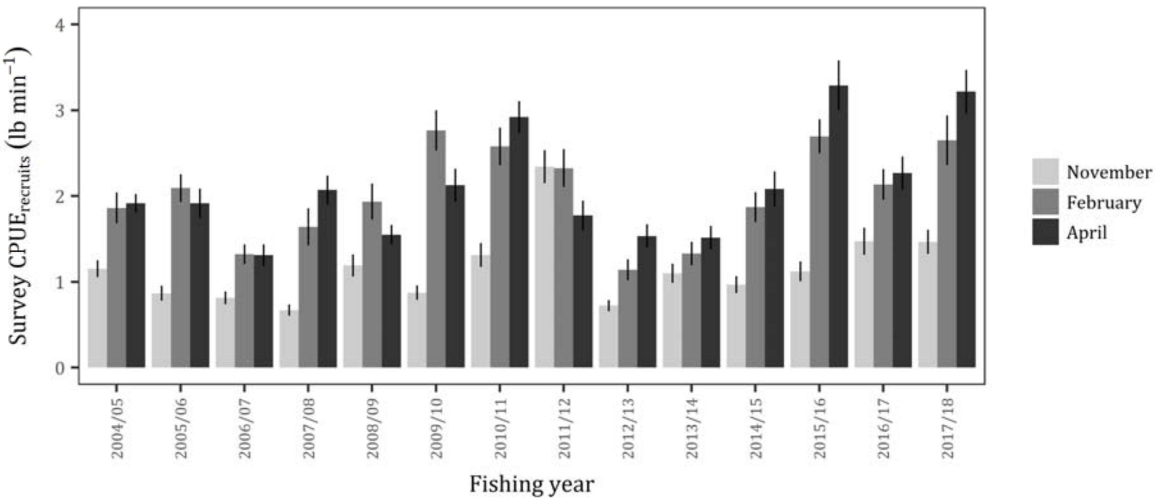

Figure 3.5. Survey mean CPUE$_{recruits}$ (± 1 SE) throughout Spencer Gulf during November, February and April surveys, 2004/05–2017/18.

3.2. Catch and effort statistics

3.2.1. Annual trends

The total harvest of 2,038 t in 2016/17 and 2,197 t in 2017/18 are within the historical range and at the 69th and 82nd percentiles, respectively, since 1973/74 (mean ± SD: 1,917 t ± 298 t; CV 15%) (Figure 3.6a).

Annual total effort over the history of the fishery can be characterised by three distinct periods (piecewise regression, R^2 = 0.95). Effort increased rapidly from 6,795 h in 1968 to 45,786 h in 1978/79 (Figure 3.6b). Since the peak of 1978/79, effort declined by 972 h per year until 2001/02, and thereafter plateaued with a mean (and SD) of 18,756 ± 1,208 h (CV 6.4%), which is 41% of the historic peak in 1978/79 (Figure 3.6b). Total effort of 19,885 h in 2016/17 and 19,472 h in 2017/18 (Figure 3.6b) are within 6% of the stable-effort mean, and were distributed over 53 nights and 2,055 and 2,060 vessel-nights, respectively.

Annual CPUE has varied greatly over the fishery's history, but there appears to be two general trends (piecewise regression, R^2 = 0.73). From 1968 to 1984/85, CPUE fluctuated around a mean (and SD) of 53.0 ± 9.7 kg h^{-1} (CV 18%), and thereafter increased at a mean rate of 2.0 kg h^{-1} per year (Figure 3.6c). The CPUE averaged 102.5 kg h^{-1} in 2016/17 and 112.8 kg h^{-1} in 2017/18 (Figure 3.6c).

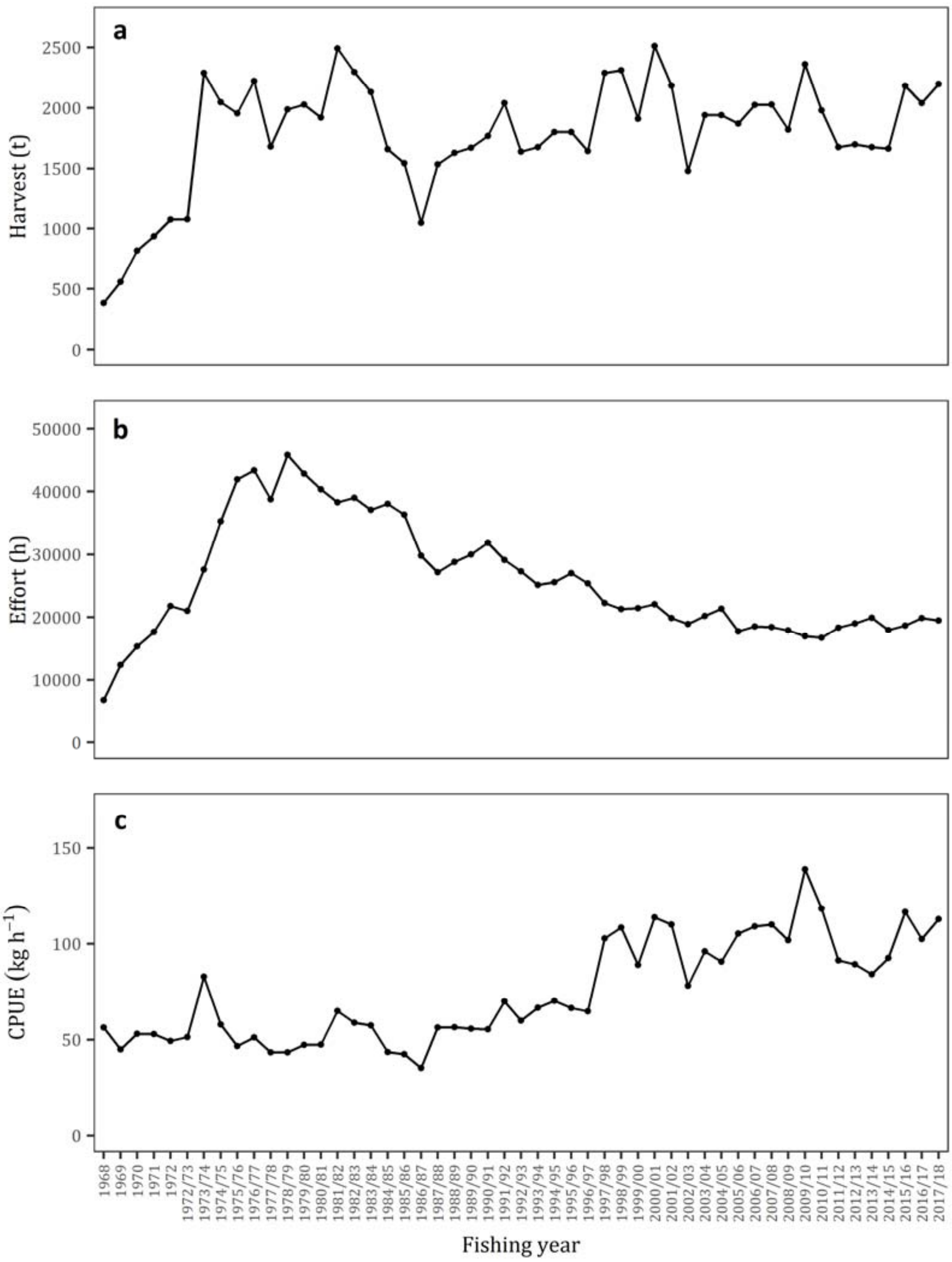

Figure 3.6. Annual (a) harvest, (b) effort and (c) CPUE, 1968–2015/16.

3.2.2. Seasonal trends

Between 1981/82 and 1986/87, annual harvest declined from the record high of 2,491 t to the record low of 1,048 t (Figure 3.7). This period of decline followed consecutive increases in the pre-Christmas harvest (i.e. October to December, during the early spawning period) from 297 t in 1979/80 to 833 t in 1983/84 (Figure 3.7). This is the only period in the history of the fishery that pre-Christmas harvests have exceeded 500 t in consecutive years (1981/82–1983/84). Since the introduction of logbooks in 1973/74, the pre-Christmas harvest has exceeded 500 t on five separate occasions (1991/92, 1995/96, 1998/99, 2001/02 and 2010/11) (Figure 3.7). Each time, a decline in annual harvest was observed in the following year. The pre-Christmas harvest was 444 t in 2016/17 and 417 t in 2017/18 (Figure 3.7), which represent 22% and 19% of their respective total harvests (cf. historic mean of 23% since 1973/74).

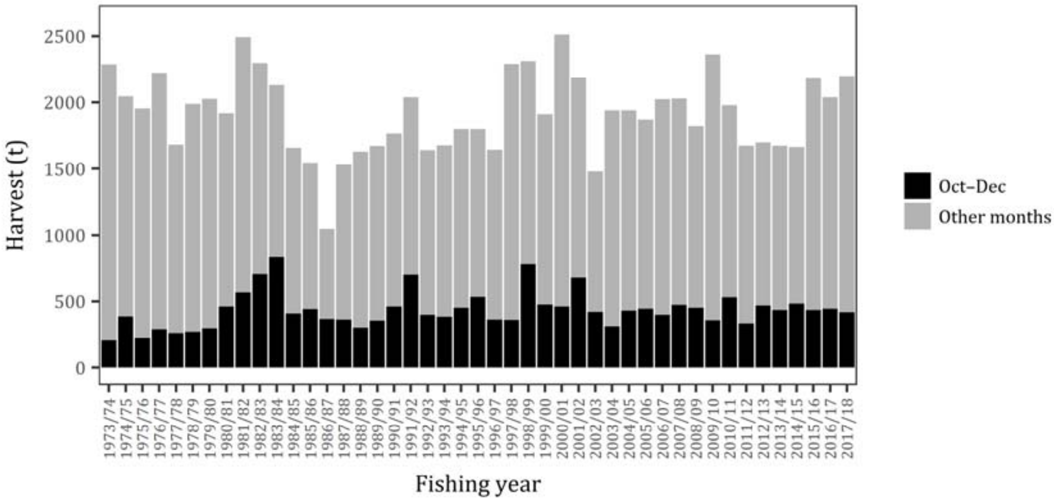

Figure 3.7. Annual harvest separated into the pre-Christmas period (October–December) and other months of the fishing year, 1973/74–2017/18.

Based on the catch and effort database since 1990/91, most of the annual harvest is taken over six months, in November and December, and March to June, with greatest harvests in April and May, while fishing occasionally takes place in October, February and July (Figure 3.8a). The monthly distribution of total harvests in 2016/17 and 2017/18 followed this general pattern (Figure 3.8a).

For the six main fishing months, the historic distribution of monthly mean CPUEs suggests that CPUE tends to rise and fall in unison with monthly harvests (Figure 3.8b). Similar to the distribution of harvests, the monthly CPUEs in 2016/17 and 2017/18 followed the long-term trend, although the mean CPUE in March 2017 appeared relatively high (Figure 3.8b).

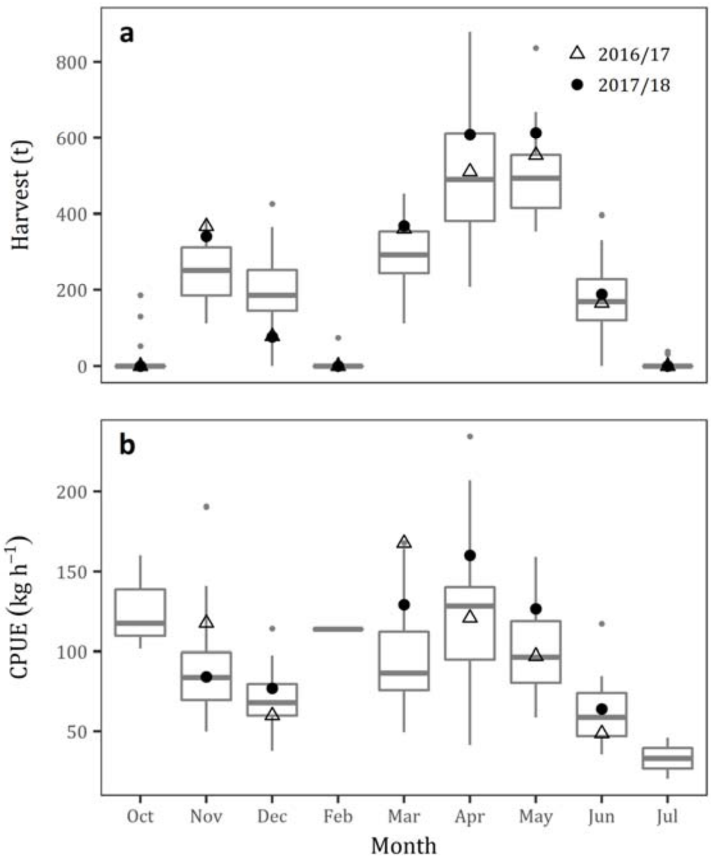

Figure 3.8. Monthly distribution of (a) annual harvest and (b) CPUE, 1990/91–2017/18. Fishing years 2016/17 and 2017/18 are highlighted. The boxplot displays the median (thick horizontal line), first and third quartiles (the interquartile range, IQR; box), the spread of values no further than 1.5 IQR beyond the IQR (whiskers), and all outliers (points).

3.2.3. Regional trends

Since 1990/91, harvests from the three regions in the upper gulf, including North, Middlebank/Shoalwater and Wallaroo, have collectively made up 63–84% of the annual total harvest (Figure 3.9a). The contributions of these regions to the total harvest in 2016/17 (76%) and 2017/18 (77%) were within the historic range and slightly higher than the annual mean (74%) (Figure 3.9a).

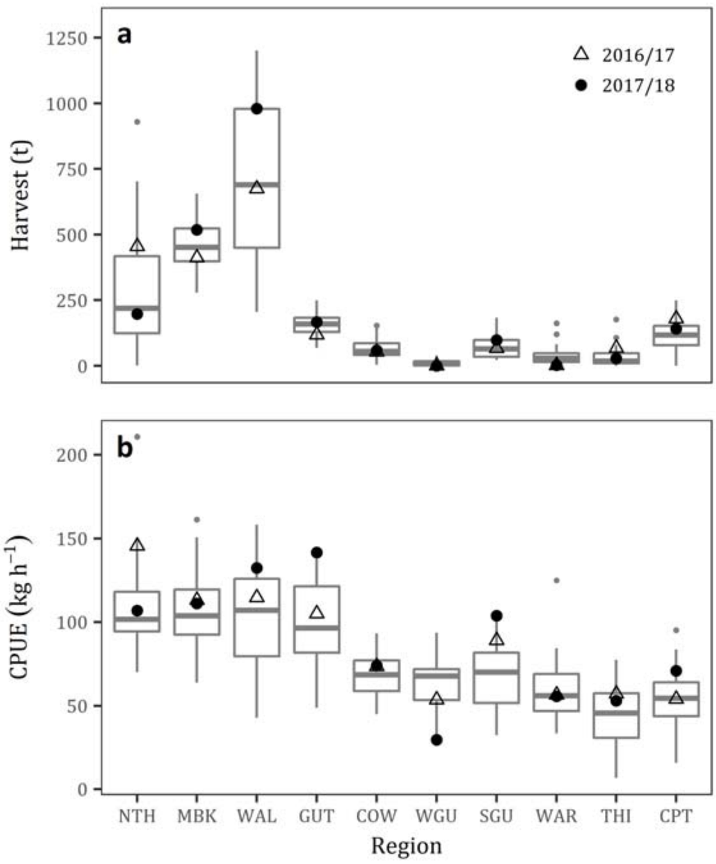

Figure 3.9. Regional distribution of (a) harvest and (b) CPUE, 1990/91–2017/18. Fishing years 2016/17 and 2017/18 are highlighted. See Figure 3.8 for boxplot features. See Figure 1.1 for abbreviations of regions.

Fishery CPUEs are generally higher in the same three regions in the upper gulf than regions further south (Figure 3.9b). While this pattern was generally observed in 2016/17 and 2017/18, the mean CPUEs during 2017/18 were relatively high in Gutter and South Gutter regions and low in West Gutter (Figure 3.9b).

3.2.4. Standardisation of fishery catches

The final GLM for standardising fishery catches (converted to CPUE) from 1990/91–2017/18 included the significant terms: year-month, region, vessel, luminosity (including the lag term) and effort (Table 3.2; see Table B-2, Appendix B for model coefficients). Among these variables, effort had the greatest influence. The model-predicted means adequately captured a similar overall trend as observed data (Figure 3.10). Overall goodness of fit was high, with an adjusted R^2 value of 0.71.

Table 3.2. Analysis of deviance (type II test) for the GLM used to standardise fishery catches. Abbreviations: SS, sum of squares; df, degrees of freedom; *F*, *F*-statistic. R^2_{adj} = 0.71.

Effect	SS	df	*F*
Fishing year-month (β_1)	91401	171	336***
Region (β_2)	17701	10	1111***
Vessel (β_3)	3408	38	56***
Luminosity (β_7)	8311	1	5218***
Luminosity (7-day lag) (β_8)	5166	1	3244***
Effort (β_{10})	188590	1	118410***
Residuals	130584	81990	

Significance: *** $p < 0.001$.

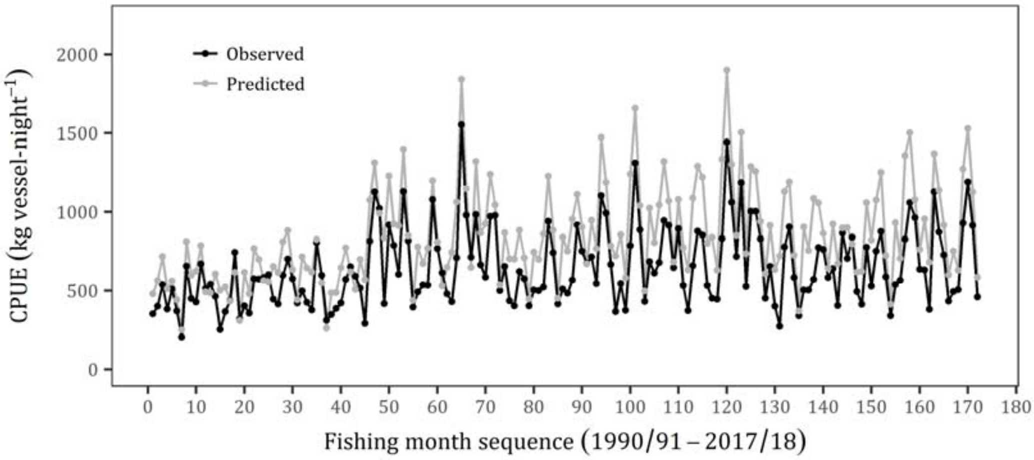

Figure 3.10. Observed and model-predicted mean CPUE for all months fished, 1990/91–2017/18.

The model-predicted effect of luminosity suggests that, between the last quarter and first quarter of the lunar cycle (the general fishing period), mean CPUE starts at 724 kg vessel-night^{-1}, reaches a maximum of 946 kg vessel-night^{-1} around the night before the new (dark) moon, and then falls to 549 kg vessel-night^{-1} (Figure 3.11).

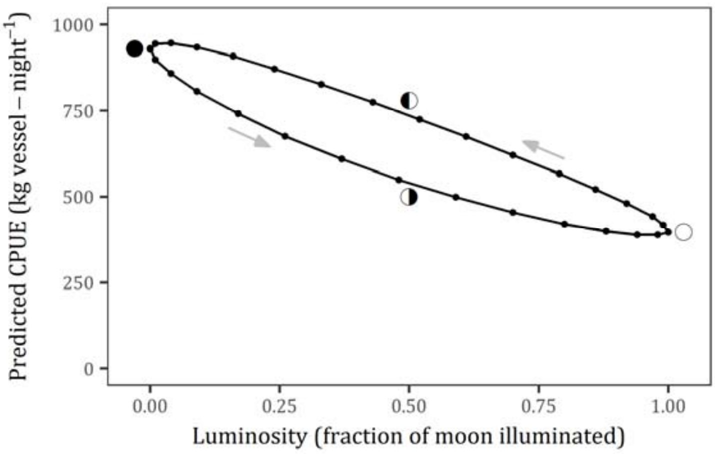

Figure 3.11. Observed and model-predicted mean CPUE by luminosity (fraction of the moon illuminated).

For those months in which surveys and fishing have taken place since 2004/05, a high correlation is evident between normalised survey and fishery CPUE (Figure 3.12), indicating that the survey CPUE is indicative of the abundance and subsequent harvest of prawns.

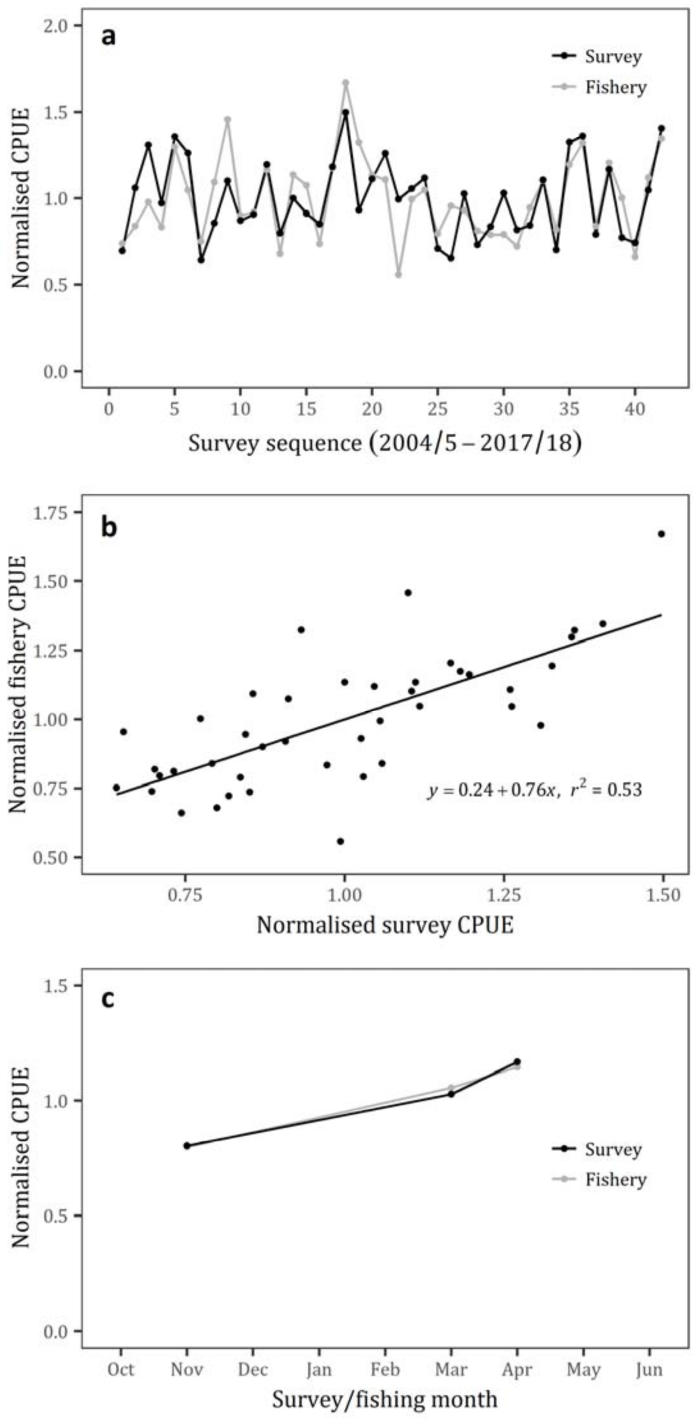

Figure 3.12. Comparison of model-predicted survey and fishery CPUEs (normalised) (a) for all surveys, 2004/05–2017/18, (b) by regression, and (c) by survey/fishing month.

3.2.5. Prawn size

In 1978/79, small prawns made up ~40% of the annual harvest. Since 2002/03, however, this size category has generally contributed less than 7% (Figure 3.13). This reduction in the proportion of small prawns has been offset by at least two-fold increases in the proportions of large (from 21% to 39–51%) and extra-large prawns (from 6% to 13–24%) (Figure 3.13). In 2016/17 and 2017/18/16, the proportion of small prawns of 8% and 7%, respectively, were at the upper end of its range since 2002/03, while the proportion of large prawns of 39% and 40% were at the lower end of its range (Figure 3.13). The proportion of soft and broken prawns ranges between 5% and 8%.

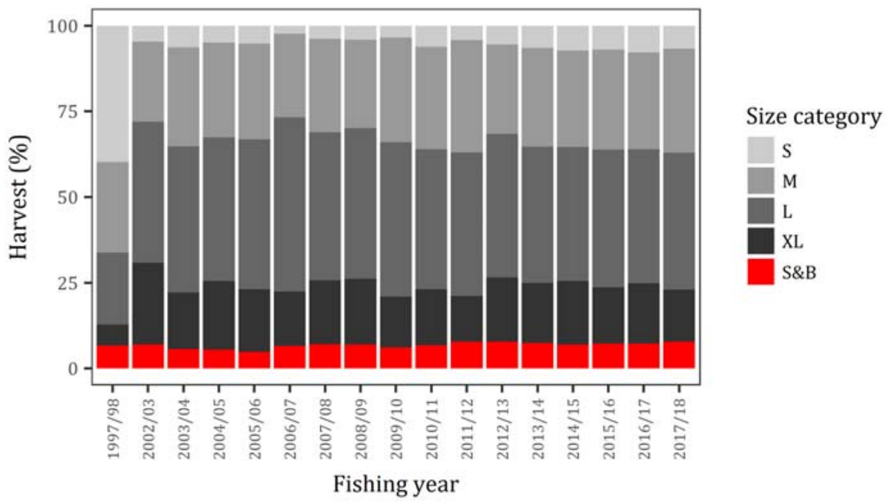

Figure 3.13. Size composition of annual harvest, 1997/98 and 2002/03–2017/18. Abbreviations: S, small; M, medium; L, large; XL, extra-large; S&B, soft and broken.

Annual mean bucket counts of 222 prawns 7 kg^{-1} in 2016/17 and 223 prawns 7 kg^{-1} for 2016/17 and 2017/18, respectively, are among the most since 2002/03, and indicate relatively small prawns on average (Figure 3.14).

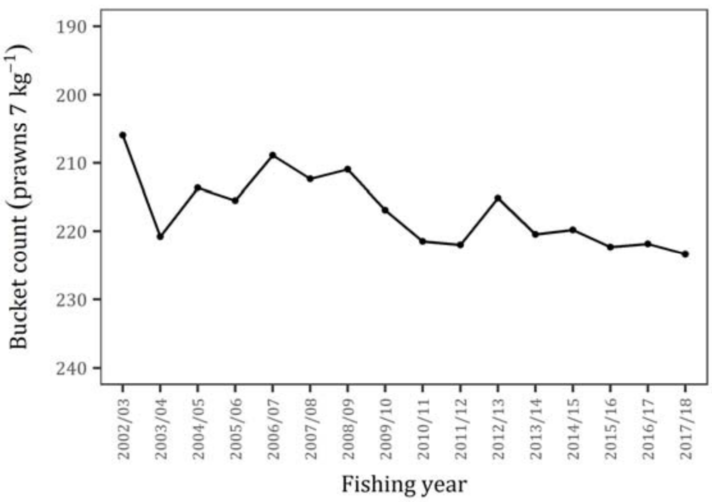

Figure 3.14. Estimated annual mean bucket count, 2002/03–2017/18. Note: the y-axis scale is reversed to denote decreasing (increasing) prawn size with higher (lower) bucket counts.

3.3. Trawl footprint

Based on available GPS coordinates of trawl midpoints over the 17-year period since 2001/02 (representing approximately 40% of total effort), the trawl footprint of the SGPF is estimated to be 4,828 km^2 (Figures 3.15 and 3.16). Within the footprint, 488 km^2 (10%) was trawled at high intensity (>10 h km^{-2} yr^{-1}), 2,791 km^2 (58%) at moderate intensity (1–10 h km^{-2} yr^{-1}), and 1,550 km^2 (32%) at low intensity (0.2–1 h km^{-2} yr^{-1}) (Figure 3.16). It appears that the total footprint estimate may be beginning to plateau, with an expansion from 2016/17 (4,757 km^2) of 1.5%, compared to an expansion of 3.9% in the previous year (from 4,579 km^2 in 2015/16) (Figure 3.16). The composition of the footprint over these three years (since 2015/16) demonstrates that the greatest change occurred for the low intensity category, with a net increase of 245 km^2 (compared to a net reduction of 10 km^2 for the moderate intensity category and a net increase of 14.5 km^2 for the high intensity category) (Figure 3.16).

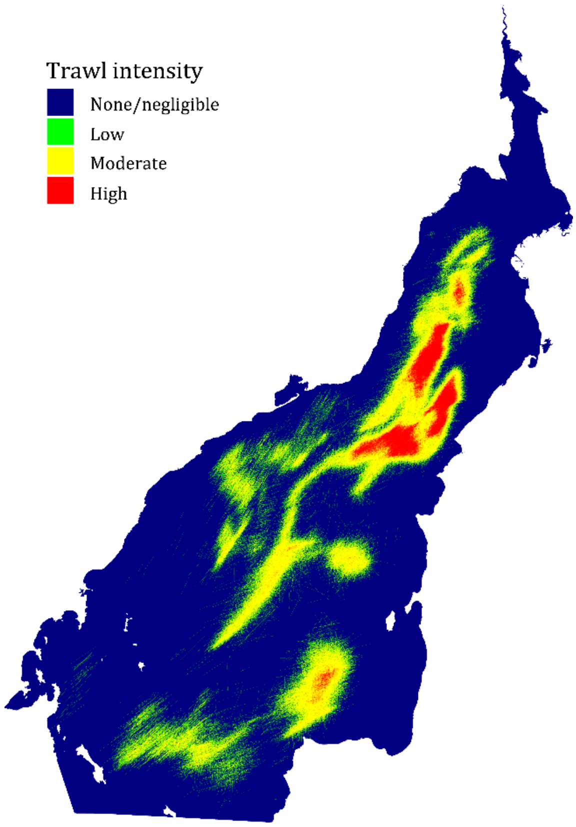

Figure 3.15. Trawl footprint of the SGPF (based on ~40% of the total effort, 2001/02–2017/18), and the high (>10 h km^{-2} yr^{-1}), moderate (1–10 h km^{-2} yr^{-1}), and low (0.2–1 h km^{-2} yr^{-1}) trawl intensity areas within the footprint.

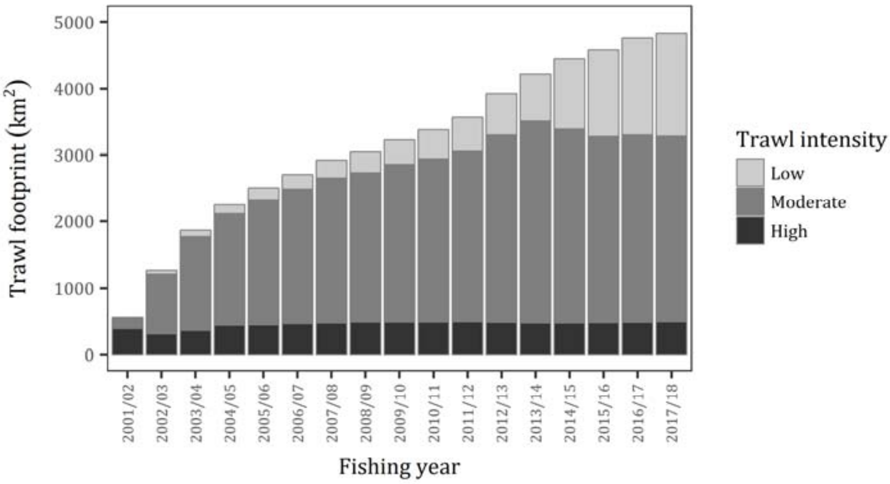

Figure 3.16. Cumulative effect on the trawl footprint of the SGPF with each successive year, 2001/02–2017/18, and proportion of trawl intensity category within the footprint. See Figure 3.15 for definition of trawl intensity categories.

3.4. Fishing strategy assessment

The mean $CPUE_{adults}$ for the November 2016 and 2017 surveys were 2.90 and 2.41 lb min^{-1}, respectively, which led to catch caps for the fleet of 425 and 400 t (Table 3.3). In accordance with the rules for developing fishing strategies (Section 1.7.3), survey $CPUE_{adults}$ and $CPUE_{recruits}$ led to an increasing strategy following the February 2017 survey, a conservative catch cap in November/December 2017, and standard strategy following all other surveys (Table 3.3).

Table 3.3. Summary of reference points and mean survey $CPUE_{adults}$ and $CPUE_{recruits}$ (unvalidated and validated) for the 2016/17 and 2017/18 stock assessment surveys, and subsequent fishing strategy and decision rules. Where two criteria are given for bucket count or mean nightly catch, the first refers to the northern part of the gulf and the second refers to the southern part of the gulf.

Survey	$CPUE_{adults}$ (lb min^{-1})				$CPUE_{recruits}$ (lb min^{-1})			Survey result / fishing strategy	Fleet catch cap (t)	7-kg bucket count	Nightly catch (kg)
	RP_{lower}	RP_{upper}	Unvalid.	Valid.	RP_{lower}	Unvalid.	Valid.				
2016/17											
November	2.46	3.81	2.90	2.92	0.76	1.40	1.47	Standard	425 t	≤260	≥300*
February	2.54	3.68	4.03	3.92	1.44	2.15	2.31	Increasing	-	≤260	≥500/350
April	3.75	6.48	4.43	4.39	1.63	2.13	2.20	Standard	-	≤260	≥500/350
2017/18											
November	2.46	3.81	2.41	2.27	0.76	1.33	1.46	Conservative	400 t	≤260	≥450/350*
February	2.54	3.68	3.06	2.96	1.44	2.80	2.88	Standard	-	≤240/260	≥500/350
April	3.75	6.48	5.24	5.19	1.63	3.51	3.51	Standard	-	≤260	≥500/350

* Nightly catch criteria not prescribed for November/December fishing in Management Plan (decision made by the Committee-at-Sea).

At the end of fishing years 2016/17 and 2017/18, a series of checks were performed on the survey data to verify their accuracy and resolve any errors. This process indicated that, before validation, there was a tendency for $CPUE_{adults}$ to be underestimated by up to 10% and $CPUE_{recruits}$ to be overestimated by up to 5% (Table 3.3).

3.5. Fishery performance

All four PIs were above their respective RPs for 2016/17 and 2017/18 (Table 3.4). The weighted mean survey $CPUE_{adults}$ (± 95% CI) was 3.93 ± 0.16 lb min^{-1} and 3.83 ± 0.17 lb min^{-1}, respectively, both of which are above the limit reference point (LRP, 1.75 lb min^{-1}) and the trigger reference point (TRP, 2.50 lb min^{-1}) (Figure 3.17).

Table 3.4. Performance of the Spencer Gulf Prawn Fishery in 2016/17 and 2017/18 with respect to primary and secondary performance indicators (PIs) and their reference points (RPs). Abbreviation: LRP, limit reference point. Green shading indicates that all PIs were above their respective RP.

Performance indicator	Reference point	2016/17	2017/18
Primary			
1. Weighted mean survey $CPUE_{adults}$ (lb min^{-1})	≥1.75 (LRP)	3.93	3.83
Secondary			
2. Recruitment index (lb min^{-1})	≥2.38	4.79	7.88
3. Mean egg production (M eggs trawl-h^{-1})	≥500	673	551
4. Mean commercial CPUE (kg h^{-1})	≥80	102.5	112.8

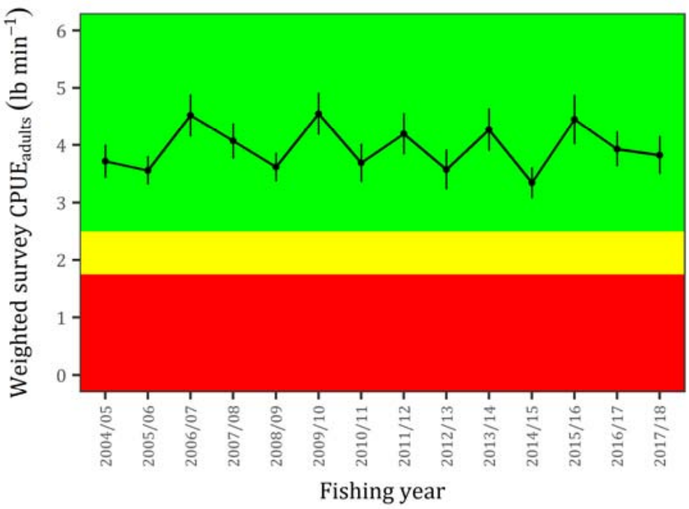

Figure 3.17. Weighted mean survey $CPUE_{adults}$ (± 95% CI), 2004/05–2017/18, and corresponding stock status classification (green shading indicates a sustainable stock, yellow indicates a transitional stock, and red indicates an overfished stock).

4. DISCUSSION

4.1. Main information sources for the fishery

Extensive information was available to assess the Western King Prawn stock and general performance of the SGPF for 2016/17 and 2017/18. This included: (i) current management arrangements of the fishery (PIRSA 2014); (ii) more than a decade's worth of annual stock assessment reports (Carrick 2003; Dixon et al. 2005, 2007; Dixon and Hooper 2008; Dixon et al. 2009, 2010, 2012, 2013; Noell et al. 2014; Noell and Hooper 2015, 2017); (iii) comprehensive biological synopsis of the Western King Prawn (Noell et al. 2015); (iii) catch rate and prawn size data obtained from three annual stock assessment surveys; and (iv) commercial catch, effort and prawn size data.

4.1.1. Stock assessment surveys

All three annual stock assessment surveys were completed during 2016/17 and 2017/18, with fishing strategies developed immediately afterwards in accordance with a sustainable stock (as described in Advice Notes to PIRSA Fisheries and Aquaculture in September 2016 and August 2017). Mean survey $CPUE_{adults}$ and $CPUE_{recruits}$ were variable throughout 2016/17 and 2017/18, but mostly remained above their respective RP_{lower}, resulting in the development of standard fishing strategies, except after the February 2017 survey, when an increasing strategy was adopted owing to the mean $CPUE_{adults}$ from the February survey exceeding its RP_{upper}. While the $CPUE_{adults}$ from the November 2017 survey fell below its RP_{lower}, indicating a 'conservative result', the Management Plan acknowledges that external factors can unduly and adversely influence catch rates, and therefore includes the provision that a conservative strategy is required only after two consecutive surveys with a conservative result. It should be noted here that for any given survey, the lower and upper RPs are not used in the conventional sense for determining stock status, but rather they were designed to maintain the relative biomass within historic levels and are assumed to be well above a level at which overfishing is likely to have occurred. As the previous survey (April 2017) yielded a standard result, a standard strategy was maintained after the November 2017 survey. The $CPUE_{adults}$ in the February 2018 survey returned above the $RP_{lower,}$ which meant that, along with the $CPUE_{recruits}$ being above its $RP_{lower,}$ the fleet fished to a standard strategy for the remainder of the 2017/18 fishing year.

The development of fishing strategies immediately after stock assessment surveys is one of the features that have placed the SGPF as a leader in co-management. However, a limitation to this real-time management system was identified in a previous stock assessment when validation of survey data revealed a difference between results obtained immediately after surveys and validated results some months after, which ultimately led to a different fishing strategy (Noell et al. 2014). Again, for 2016/17 and 2017/18, there were differences between unvalidated and validated data, although this did not affect most of the fishing strategy outcomes — in terms of size and catch criteria — except the lower validated $CPUE_{adults}$ for the November 2017 survey did indicate a corresponding catch cap for the fleet of 375 t rather than 400 t. Closer examination of unvalidated and validated survey data for both years indicated that most errors were systematic, owing to an underestimation of $CPUE_{recruits}$ in the electronic logbooks compared to the unloaded grade weights (assumed correct), resulting in the unvalidated mean $CPUE_{recruits}$ being up to 9% less than the validated $CPUE_{recruits}$. This also had the counteracting effect on the unvalidated $CPUE_{adults}$ overestimating the 'true' value by up to 6%. Another main reason for the latter discrepancy is likely be attributed to the inclusion of S&B prawns as adult prawns when $CPUE_{adults}$ should strictly comprise only size grades (excluding '20+' grades, or recruits). This practice may be related to the practicalities of conducting surveys and the expeditious nature of implementing a real-time management system immediately after surveys. While the inclusion of S&B prawns as adults would inevitably cause validated $CPUE_{adults}$ to be upwardly biased, the fact that the harvest strategy was designed around survey data collation and analysis procedures that have remained the same since 2004/05 suggests that it would not be beneficial to change this practice.

The assumption in many fishery assessments that abundance is proportional to CPUE necessitates the removal of factors (not related to abundance) that may otherwise unduly influence CPUE and interpretation of biomass. This assessment provided an update of the standardisation of survey and fishery catches using GLMs to remove the influence of these factors (Noell et al. 2015). In addition to a year-survey effect, region, vessel, tide direction and luminosity each had a significant influence on survey catches. Back-transformed predicted means for region and tide direction demonstrated similar effects as observed catches, where catches generally declined from north to south of the gulf. Nevertheless, while standardised catches tracked the nominal trend reasonably well for the year-survey means, only 34% of the total deviance in survey catches was explained by the model (region being the most important).

Estimates of egg production and recruitment derived from November and February surveys, respectively, remained above their respective RPs for 2016/17 and 2017/18, although appear to be trending in opposite directions. Egg production in 2017/18 is at its lowest point in more than a decade and may therefore warrant close monitoring over the next year or so. This could involve calculation of provisional estimates for November 2018 before the commencement of the 2019/20 fishing year (in November 2019) and November 2019 before fishing resumes in March 2020. Early estimates of egg production should provide the opportunity for industry (through the SGWCPFA Management Committee) to be more responsive about the specific application of the fishing strategy (i.e. more or less conservative) within the parameters of the harvest strategy. One such example is to more explicitly align the fishing strategy with outcomes of the biophysical model for Western King Prawns in Spencer Gulf, which identified areas that consistently contribute to larval settlement success (and, presumably, likelihood of future recruitment) (McLeay et al. 2016). In contrast to the downward trend for egg production, the recruitment index indicates the fishery is in a healthy state, as it has remained above the RP since the current survey design began (2004/05), and the latest estimate, obtained in February 2018, was the highest recorded and more than three times the RP.

4.1.2. Commercial logbook data

Unlike stock assessment survey results for this fishery, which are independent and provide an index of biomass for the Western King Prawn, annual harvests are considered to be more of an economic indicator. For this reason, total harvest is no longer a performance indicator in the Management Plan. Nevertheless, 2016/17 and 2017/18 saw the return and consolidation of annual harvests above 2,000 t (long-term mean since 1973/74 is 1,917 t) following four consecutive years in which harvests did not reach 1,700 t. Along with annual effort only slightly above typical levels, the annual harvests of 2016/17 and 2017/18 translated into relatively productive years in terms of CPUE. While commercial CPUE is also important from an economic perspective, it also provides some indication of the stock (albeit a fishery-dependent measure) and was therefore retained as a secondary PI (along with the primary PI, weighted mean survey $CPUE_{adults}$, and other secondary PIs, egg production and recruitment index).

The breakdown of the annual harvest by size category and the mean bucket count indicate a slight downward trend in average prawn size over the last several years. In the 2013/14 assessment (Noell and Hooper 2015), it was presumed that the relatively high proportion of small prawns in the total harvest was probably attributed to greater catches taken from the North region, where prawns are generally in high density but of small size, away from the traditional fishing grounds of Wallaroo and Middlebank/Shoalwater. However, given that the regional breakdown of harvests in subsequent years reverted to a more traditional pattern, the latest assessment (Noell and Hooper 2017) alternatively suggested that the revised size criteria in the harvest strategy may result in an increase in the proportion of small prawns. When the current harvest strategy was being developed, one of the aims was to offset less conservative size criteria (i.e. higher bucket counts to provide greater flexibility in terms of area opened to fishing) by restricting the number of nights (higher minimum nightly catch) by region. While it appears that the size composition of the annual harvests has been impacted by the revised harvest rules and criteria, it may also be interpreted as a result of consecutive high-recruitment years, where, despite apparent typical catches of larger prawns, the continued influx of new recruits is having a disproportionate effect on the size composition and bucket count.

Standardisation of fishery catches fared better than for surveys, with 71% of the total deviance explained by the model. Significant variables were effort, region, vessel and luminosity (the latter identified by the combination of luminosity and luminosity with a lag). Of these, effort had, by far, the greatest influence on catch. It is widely known that the lunar phase influences the CPUE of prawns. A much stronger lunar effect was found for fishery catches compared to survey catches, but that is due to a lack of contrast in the luminosity during surveys since surveys are consistently done on the night before and on the new moon, whereas fishing occurs over a larger part of the lunar cycle.

The high-resolution spatial data for ~40% of the total effort, obtained from commercial logbooks, were used to estimate the trawl footprint of the SGPF and the intensity of trawling within that footprint. We demonstrated that, in general, there was a consistent spatial fishing pattern each year (Noell 2017), but the cumulative area fished to 2017/18 was the largest recorded. Ongoing annual and cumulative estimates of the trawl footprint will provide information on whether the fishery continues to largely fish the same areas or is expanding into ‘new’ areas. A key measure to distinguish between these will be the rate of increase in the cumulative area fished. A substantial reduction in this rate, indicated by a plateauing of the cumulative trawled area, would suggest that the trawl footprint was approaching saturation.

4.2. Stock status

A key feature of the current harvest strategy in the Management Plan is that it explicitly links a weighted mean survey $CPUE_{adults}$ from all three stock assessment surveys to an end-of-year stock status classification, which is delineated by the LRP and TRP. The weighting factors of 0.20 for November, 0.35 for February and 0.45 for April are measures of the perceived importance of each survey in reflecting the stock biomass to determine stock status at the end of the fishing year. Importance was based on their measure of relative exploitable biomass, recruitment, and timing, using the methodology described in the Management Plan (PIRSA 2014). It also adopts a consistent stock status terminology to that of the national status reporting framework (Stewardson et al. 2018). The determination of an end-of-year stock status for the SGPF is important as each status classification (sustainable, transitional and overfished) drives a specific set of fishing strategies, decision rules and criteria that are applicable in the following year. Advanced notice of this information (i.e. before the start of the fishing year) provides PIRSA Fisheries and Aquaculture with a clear understanding of the stock status for the fishery and how it was derived, and provides industry with greater certainty for planning its fishing operations for the year ahead.

Following validation of mean survey $CPUE_{adults}$ for November, February and April surveys during 2016/17 and 2017/18, the weighted mean $CPUE_{adults}$ (± 95% CI) was 3.93 ± 0.16 and 3.83 ± 0.17 lb min^{-1}, respectively; both of which are above the LRP of 1.75 lb min^{-1} and TRP of 2.50 lb min^{-1}. Under the definition in the harvest strategy, the stock is classified as '**sustainable**'.

4.3. Future research needs

The most pressing research need for the SGPF is the development and implementation of an ecological monitoring program that meets Marine Stewardship Council (MSC) 2.0 principles and monitors ecological impacts of fishing activities on the marine environment. It has been identified that the ecological monitoring program should comprise three main components:

1. Ongoing annual estimates of trawl footprint;
2. Determining the nature and extent of the ecological assets conserved by the SGPF to mitigate their ecological footprint (includes current research proposal to the Fisheries Research and Development Corporation, FRDC); and
3. Establishing ongoing bycatch monitoring and assessment work to enhance the FRDC project, with a focus on threatened, endangered and protected species (particularly syngnathids), commercial species from other fisheries (e.g. King George Whiting, Snapper) and sessile epibenthos (to characterise habitat type on trawl grounds).

These components have recently been captured in the second four-year research scope for the SGPF, 2019/20–2022/23, and will be primarily be undertaken in the alternate years of the biennial assessment with support from and/or collaboration with PIRSA Fisheries and Aquaculture and industry.

REFERENCES

Amoroso RO, Pitcher CR, Rijnsdorp AD, McConnaughey RA, Parma AM, Suuronen P, et al. (2018). Bottom trawl fishing footprints on the world's continental shelves. Proceedings of the National Academy of Sciences. 115(43):E10275–E10282.

Anon. (2003). Interim results of the National Recreational and Indigenous Fishing Survey. Southern Fisheries Magazine:Autumn.

BOM (2018a). Tide predictions for Australia, South Pacific and Antarctica. Bureau of Meteorology. Available at http://www.bom.gov.au/australia/tides/#!/sa-gulf (last accessed 14 September 2018).

BOM (2018b). Climate data online. Available at http://www.bom.gov.au (last accessed 14 December 2018).

Box GEP, Cox DR (1964). An analysis of transformations. Journal of the Royal Statistical Society Series B (Methodological):211–252.

Bryars S (2003). An Inventory of Important Coastal Fisheries Habitats in South Australia. Adelaide: Primary Industries and Resources South Australia, Fish Habitat Program.

Burnell OW, Barrett SL, Hooper GE, Beckmann CL, Sorokin SJ, Noell CJ (2015). Spatial and temporal reassessment of by-catch in the Spencer Gulf Prawn Fishery. Report to PIRSA Fisheries and Aquaculture. SARDI Publication No. F2015/000414-1, SARDI Research Report Series No. 854. Adelaide: South Australian Research and Development Institute (Aquatic Sciences), 128 pp.

Carrick NA (1982). Spencer Gulf Prawn Fishery: surveys increase our knowledge. SAFIC. 6:3–32.

Carrick NA (1996). Key factors which affect prawn recruitment and implications to harvesting prawn stocks. Fisheries Research and Develoment Corporation, Project No. 1991/003. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

Carrick NA (2003). Spencer Gulf Prawn (*Melicertus latisulcatus*) Fishery. Fishery assessment report to PIRSA Fisheries. RD03/0079-2. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

Carrick NA, Ostendorf B (2005). Modelling prawn movement and spatial dynamics in the Spencer Gulf and West Coast Prawn Fisheries. Canberra, Australia.

Courtney AJ, Dredge MCL (1988). Female reproductive biology and spawning periodicity of two species of king prawns, *Penaeus longistylus* Kubo and *Penaeus latisulcatus* Kishinouye, from Queensland's East Coast Fishery. Australian Journal of Marine and Freshwater Research. 39:729–741.

Currie DR, Dixon CD, Roberts SD, Hooper GE, Sorokin SJ, Ward TM (2011). Relative importance of environmental gradients and historical trawling effort in determining the composition and distribution of benthic macro-biota in a large inverse estuary. Fisheries Research. 107:184–195.

Department of Agriculture and Fisheries (2018). Queensland fisheries summary report. Department of Agriculture and Fisheries, Queensland Government, 62 pp.

Dixon C, Clark S, Hill W (2014). South Australian prawn fisheries improving environmental practices. CFOC Investment Project OC13-00090. Final report for the Caring for our Country initiave of the Australian Government. Spencer Gulf and West Coast Prawn Fishermen's Association. Port Lincoln, South Australia: Spencer Gulf and West Coast Prawn Fishermen's Association.

Dixon CD, Hooper GE (2008). Spencer Gulf Prawn (*Melicertus latisulcatus*) Fishery 2006/07. Fishery assessment report to PIRSA Fisheries. SARDI Publication No.F2007/000770-2, SARDI Research Report Series No.322. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

Dixon CD, Hooper GE, Burch P (2012). Spencer Gulf Prawn *Penaeus (Melicertus) latisulcatus* Fishery 2010/11. Fishery assessment report to PIRSA Fisheries and Aquaculture. SARDI Publication No. F2007/000770-5, SARDI Research Report Series No. 603. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

Dixon CD, Hooper GE, Roberts SD (2009). Spencer Gulf Prawn *Penaeus* (*Melicertus*) *latisulcatus* Fishery 2007/08. Fishery assessment report to PIRSA Fisheries. SARDI Publication No. F2007/000770-3, SARDI Research Report Series No. 387. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

Dixon CD, Hooper GE, Roberts SD (2010). Spencer Gulf Prawn *Penaeus* (*Melicertus*) *latisulcatus* Fishery 2008/09. Fishery assessment report to PIRSA Fisheries. SARDI Publication No. F2007/000770-4, SARDI Research Report Series No. 511. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

Dixon CD, Noell CJ, Hooper GE (2013). Spencer Gulf Prawn *Penaeus (Melicertus) latisulcatus* Fishery 2011/12. Fishery assessment report to PIRSA Fisheries and Aquaculture. SARDI Publication No. F2007/000770-6, SARDI Research Report Series No. 685. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

Dixon CD, Roberts SD, Hooper GE (2007). Spencer Gulf Prawn *(Melicertus latisulcatus)* Fishery 2005/06. Fishery assessment report to PIRSA Fisheries. SARDI Publication No. F2007/000770-1, SARDI Research Report Series No. 237. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

Dixon CD, Roberts SD, Ward TM (2005). Spencer Gulf Prawn (*Melicertus latisulcatus*) Fishery. Fishery assessment report to PIRSA Fisheries. SARDI Report No. RD03/0079-3. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

Dixon CD, Sloan S (2007). Management Plan for the South Australian Spencer Gulf Prawn Fishery. South Australian Fisheries Management Series Paper No. 54. Adelaide: Primary Industries and Resources South Australia (Fisheries).

EconSearch (2018). Economic indicators for the Spencer Gulf & West Coast Prawn Fisheries 2016/17. A report to PIRSA Fisheries and Aquaculture. Adelaide, South Australia, 74 pp.

Fox J (2003). Effect displays in R for generalised linear models. Journal of Statistical Software. 8:1–27.

Fox J, Hong J (2009). Effect displays in R for multinomial and proportional-odds logit models: Extensions to the effects package. Journal of Statistical Software. 32:1–24.

Gillett R (2008). Global Study of Shrimp Fisheries. Rome: Food and Agriculture Organization of the United Nations.

Grey DL, Dall W, Baker A (1983). A Guide to the Australian Penaeid Prawns. Darwin: Department of Primary Production of the Northern Territory.

Jackson CJ, Burford MA (2003). The effects of temperature and salinity on growth and survival of larval shrimp *Penaeus semisulcatus* (Decapoda: Penaeoidea). Journal of Crustacean Biology. 23:819–826.

Kämpf J, Brokensha C, Bolton T (2009). Hindcasts of the fate of desalination brine in large inverse estuaries: Spencer Gulf and Gulf St. Vincent, South Australia. Desalination and Water Treatment. 2:325–333.

Kangas MI, Jackson WB (1998). Sampling juvenile *Penaeus latisulcatus* Kishinouye with a water-jet net compared with a beam-trawl: spatial and temporal variation and nursery areas in Gulf St Vincent, South Australia. Marine and Freshwater Research. 49:517–523.

Kangas M, Sporer E, Wilkin S, Cavalli P, Oliver R (2018a). Gascoyne Shark Bay Prawn Resource status report 2017. In: Gaughan DJ, Santoro K (eds). Status Reports of the Fisheries and Aquatic Resources of Western Australia 2016/17: The State of the Fisheries, pp. 76–80. Western Australia: Department of Primary Industries and Regional Development.

Kangas M, Sporer E, Wilkin S, Koefoed I, Cavalli P, Pickles L (2018b). Gascoyne Exmouth Gulf Prawn Resource status report 2017. In: Gaughan DJ, Santoro K (eds). Status Reports of the Fisheries and Aquatic Resources of Western Australia 2016/17: The State of the Fisheries, pp. 88–93. Western Australia: Department of Primary Industries and Regional Development.

Kendall MG, Stuart A, Ord JK (1983). The Advanced Theory of Statistics, vol. 3. London: Griffin.

Kennelly SJ, Broadhurst MK (2014). Mitigating the bycatch of giant cuttlefish *Sepia apama* and blue swimmer crabs *Portunus armatus* in an Australian penaeid-trawl fishery. Endangered Species Research. 26:161–166.

King MG (1977). The biology of the western king prawn, *Penaeus latisulcatus* Kishinouye, and aspects of the fishery in South Australia (Master's Thesis). Adelaide: University of Adelaide, South Australia, 167 pp.

Larcombe J, Marton N, Curtotti R (2018). Northern Prawn Fishery. In: Patterson H, Larcombe J, Nicol S, Curtotti R (eds). Fishery status report 2018, pp 64–86. Canberra: Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES).

Macdonald P, Du J (2012). Mixdist: finite mixture distribution models. R package version 0.5-4.

Maunder MN, Punt AE (2004). Standardizing catch and effort data: a review of recent approaches. Fisheries Research. 70:141–159.

Mayfield S, Ferguson GJ, Chick R, Dixon C, Noell C (2014). A reporting framework for ecosystem-based assessment of Australian prawn trawl fisheries: a Spencer Gulf prawn trawl fishery case study. Final report to the Fisheries Research and Development Corporation, FRDC Project No. 2011/062. South Australian Research and Development Institute (Aquatic Sciences), 74 pp.

McLeay L, Doubell M, Roberts S, Dixon C, Andreacchio L, James C, et al. (2015). Prawn and crab harvest optimisation: a bio-physical management tool. Final report to the Fisheries Research and Development Corporation, FRDC Project No. 2008/011. South Australian Research and Development Institute (Aquatic Sciences), 79 pp.

NASA (2013). Physical Oceanography Distributed Active Archive Center. Available at https://podaac.jpl.nasa.gov/SeaSurfaceTemperature (last accessed 8 November 2013).

Nelder JA, Wedderburn RWM (1972). Generalized linear models. Journal of the Royal Statistical Society Series A (General). 135:370–384.

Noell CJ (2017). Determining the trawl footprint of the Spencer Gulf Prawn Fishery. Report to PIRSA Fisheries and Aquaculture. SARDI Publication No. F2016/000565-1, SARDI Research Report Series No. 939. Adelaide: South Australian Research and Development Institute (Aquatic Sciences), 21 pp.

Noell CJ, Broadhurst MK, Kennelly SJ (2018). Refining a Nordmøre-grid bycatch reduction device for the Spencer Gulf penaeid-trawl fishery. PLoS ONE 13(11): e0207117. https://doi.org/10.1371/journal.pone.0207117.

Noell CJ, Hooper GE (2015). Spencer Gulf Prawn *Penaeus (Melicertus) latisulcatus* Fishery 2013/14. Fishery assessment report to PIRSA Fisheries and Aquaculture. SARDI Publication No. F2007/000770-8, SARDI Research Report Series No. 843. Adelaide: South Australian Research and Development Institute (Aquatic Sciences), 68 pp.

Noell CJ, Hooper GE (2017). Spencer Gulf Prawn *Penaeus (Melicertus) latisulcatus* Fishery. Fishery assessment report to PIRSA Fisheries and Aquaculture. SARDI Publication No. F2007/000770-9, SARDI Research Report Series No. 950. Adelaide: South Australian Research and Development Institute (Aquatic Sciences), 76 pp.

Noell CJ, Hooper GE, Beckmann CL (2014). Spencer Gulf Prawn *Penaeus (Melicertus) latisulcatus* Fishery 2012/13. Fishery assessment report to PIRSA Fisheries and Aquaculture. SARDI Publication No. F2007/000770-7, SARDI Research Report Series No. 788. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

Noell CJ, O'Neill MF, Carroll JD, Dixon CD (2015). A bio-economic model for South Australia's prawn trawl fisheries. Final Report to the Australian Seafood Cooperative Research Centre, Project No. 2011/750. Adelaide: South Australian Research and Development Institute (Aquatic Sciences), 115 pp.

Nunes RA, Lennon GW (1986). Physical property distributions and seasonal trends in Spencer Gulf, South Australia: an inverse estuary Australian Journal of Marine and Freshwater Research. 37:39–53.

Pauly D, Ingles J (1999). The relationship between shrimp yields and intertidal vegetation (mangrove) areas: a reassessment. In: Yáñez-Aracibia A, Lara-Domínguez AL (eds). Ecosistemas de Manglar en América Tropical. Instituto de Ecología A.C. México, UICN/ORMA, Costa Rica, NOAA/NMFS Silver Spring MD USA.

Penn JW (1980). Spawning and fecundity of the western king prawn, *Penaeus latisulcatus* Kishinouye, in Western Australian waters. Australian Journal of Marine and Freshwater Research. 31:21–35.

PIRSA (2003). Ecological assessment of the South Australian Spencer Gulf Prawn Fishery, Gulf St Vincent Prawn Fishery and West Coast Prawn Fishery. Adelaide, South Australia: Primary Industries and Resources South Australia (Fisheries).

PIRSA (2014). Management plan for the South Australian commercial Spencer Gulf Prawn Fishery. South Australian Fisheries Management Series, No. 67. Adelaide: Primary Industries and Regions South Australia, 81 pp.

Preston N (1985). The combined effects of temperature and salinity on hatching success and the survival, growth, and development of the larval stages of *Metapenaeus bennettae* (Racek & Dall). Journal of Experimental Marine Biology and Ecology. 85:57–74.

Primavera JH, Lebata MJHL (2000). Size and diel differences in activity patterns of *Metapenaeus ensis*, *Penaeus latisulcatus* and *P. merguiensis*. Marine and Freshwater Behaviour and Physiology. 33:173–185.

R Core Team (2018). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Available at http://www.R-project.org/ (last accessed 30 May 2019).

Rasheed MA, Bull CM (1992). Behaviour of the western king prawn, *Penaeus latisulcatus* Kishinouye: effect of food dispersion and crowding. Australian Journal of Marine and Freshwater Research. 43:745–751.

Richardson BJ (1982). Geographical distribution of electrophoretically detected protein variation in Australian commercial fishes. III. Western king prawn, *Penaeus latisulcatus* Kishinouye. Australian Journal of Marine and Freshwater Research. 33:933–937.

Roberts SD, Dixon CD, Andreacchio L (2012). Temperature dependent larval duration and survival of the western king prawn, *Penaeus (Melicertus) latisulcatus* Kishinouye, from Spencer Gulf, South Australia. Journal of Experimental Marine Biology and Ecology. 411:14–22.

Roberts SD, Dixon CD, Ward TM (2005). Assessment of juvenile prawn (*Melicertis latisulcatus*) surveys in Spencer Gulf, South Australia. Report to PIRSA Fisheries. SARDI Aquatic Sciences Publication No. RD04/0211-2, SARDI Research Report Series No. 95. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

Rodgers GG, Roberts SD, Dixon CD (2013). The effects of temperature on larval size in the western king prawn, *Penaeus (Melicertus) latisulcatus* Kishinouye, from Spencer Gulf, South Australia: implications for fishery management. Marine and Freshwater Research. 64:976–985.

Sluczanowski PR (1980). The modelling and optimal control of the Spencer Gulf Prawn Fishery (PhD Thesis). London: Imperial College (University of London).

Sluczanowski PR (1984). Modelling and optimal control: a case study based on the Spencer Gulf prawn fishery for *Penaeus latisulcatus* Kishinouye. Journal du Conseil. 41:211–225.

Stewardson C, Andrews J, Ashby C, Haddon M, Hartmann K, Hone P et al. (eds) (2018), Status of Australian fish stocks reports 2018. Fisheries Research and Development Corporation, Canberra.

Svane I, Hammett Z, Lauer P (2009). Impacts of trawling on benthic macro-fauna and -flora of the Spencer Gulf prawn fishing grounds. Estuarine, Coastal and Shelf Science. 82:621–631.

Tanner JE, Deakin S (2001). Active habitat selection for sand by juvenile western king prawns, *Melicertus latisulcatus* (Kishinouye). Journal of Experimental Marine Biology and Ecology. 261:199–209.

USNO (2018). Fraction of the moon illuminated. Physical Oceanography Distributed Active Archive Center. Available at http://aa.usno.navy.mil/data/docs/MoonFraction.php (last accessed 14 September 2018).

Vainickis AA (2010). SARDI Aquatic Sciences information systems quality assurance and data integrity report. SARDI Publication No. F2009/000267-2, SARDI Research Report Series No. 497. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).

APPENDIX A. MAPPING OF SURVEY AND FISHING RESULTS

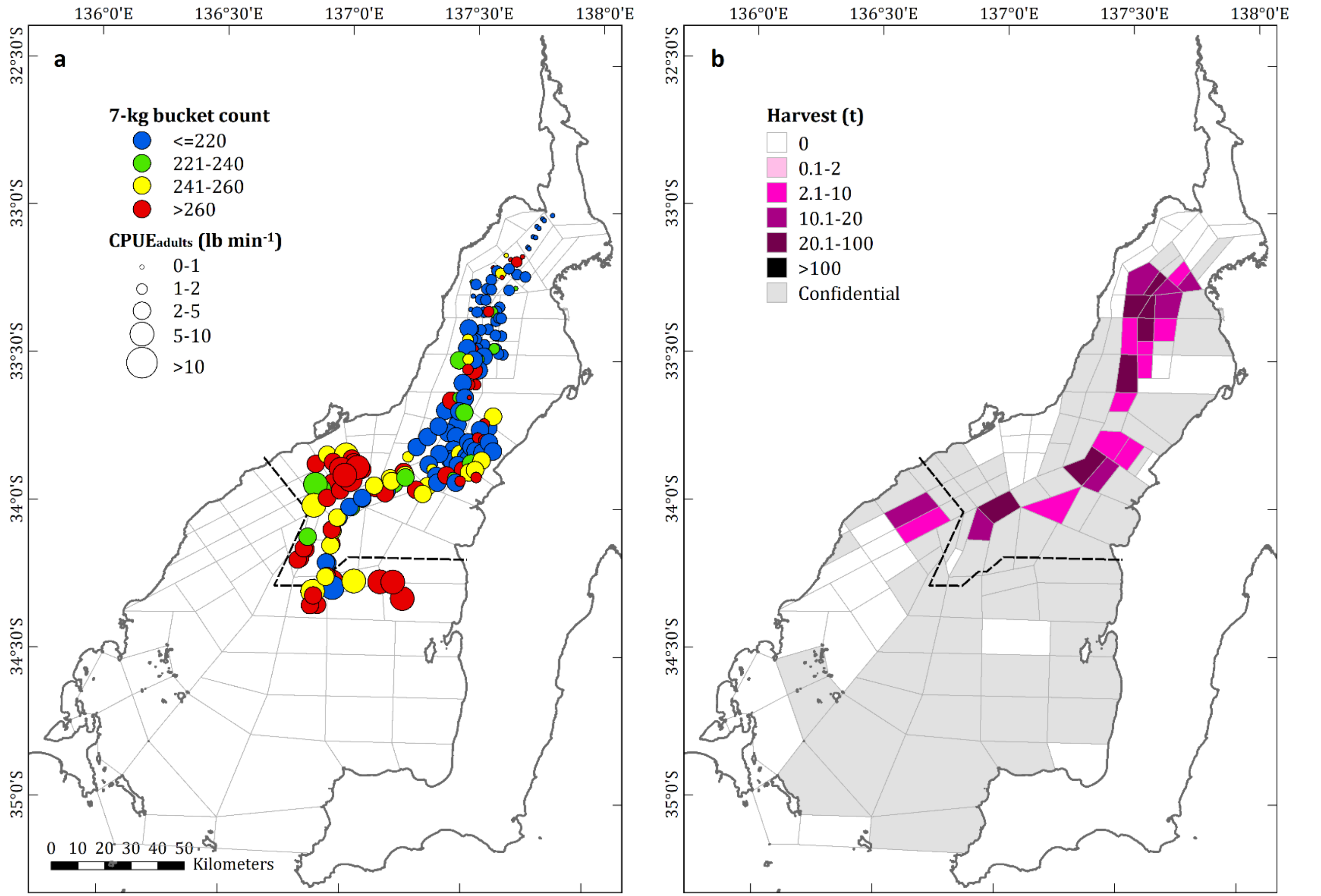

Figure A-1. (a) Results of November 2016 survey (30, 31 October 2016) and (b) subsequent harvest by block during fishing periods 1 (2–8 November 2016) and 2 (27 November–4 December 2016).

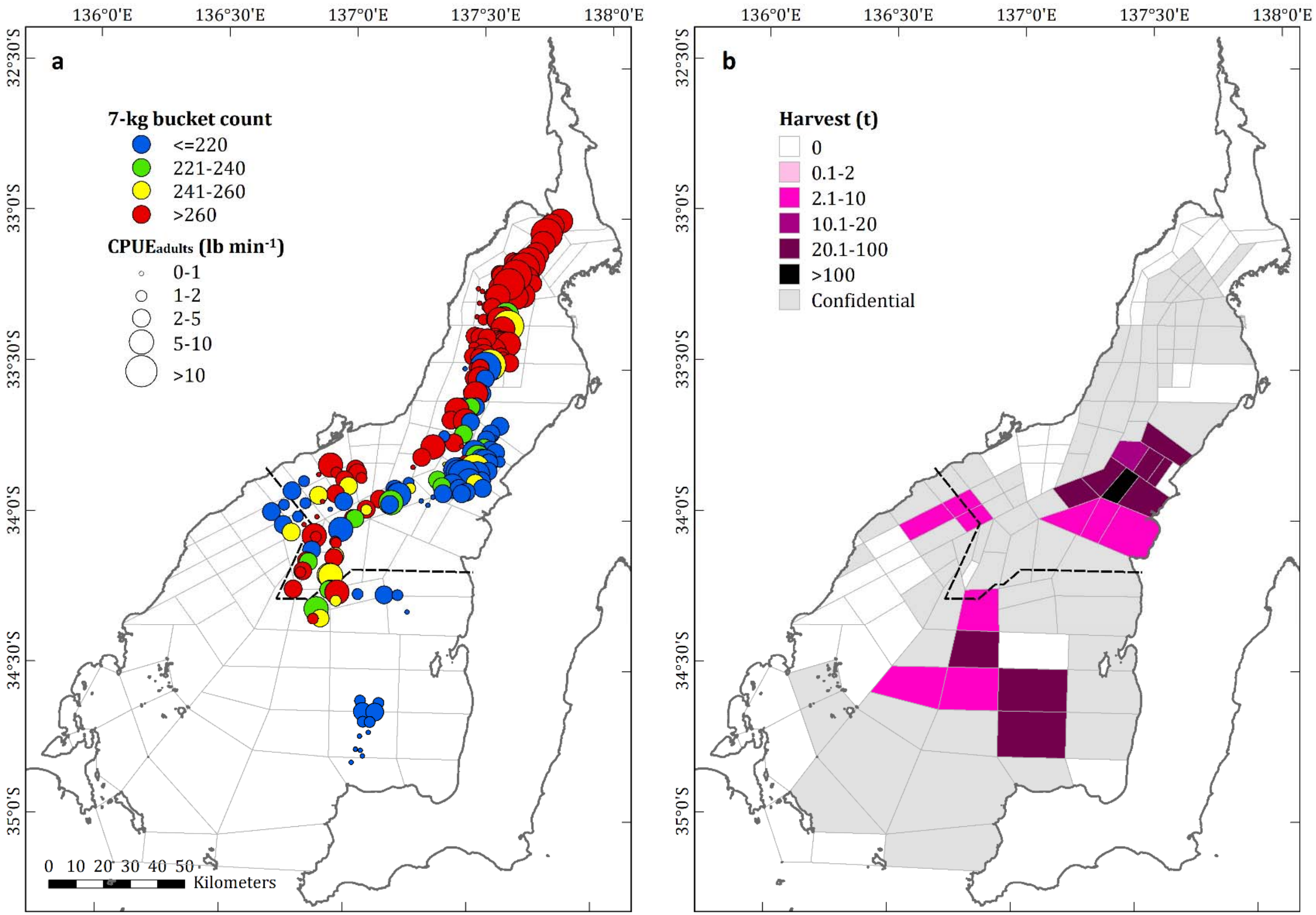

Figure A-2. (a) Results of February 2017 survey (26–28 February 2017) and (b) subsequent harvest by block during fishing periods 3 (25 March–4 April 2017) and 4 (21 and 22 March 2017).

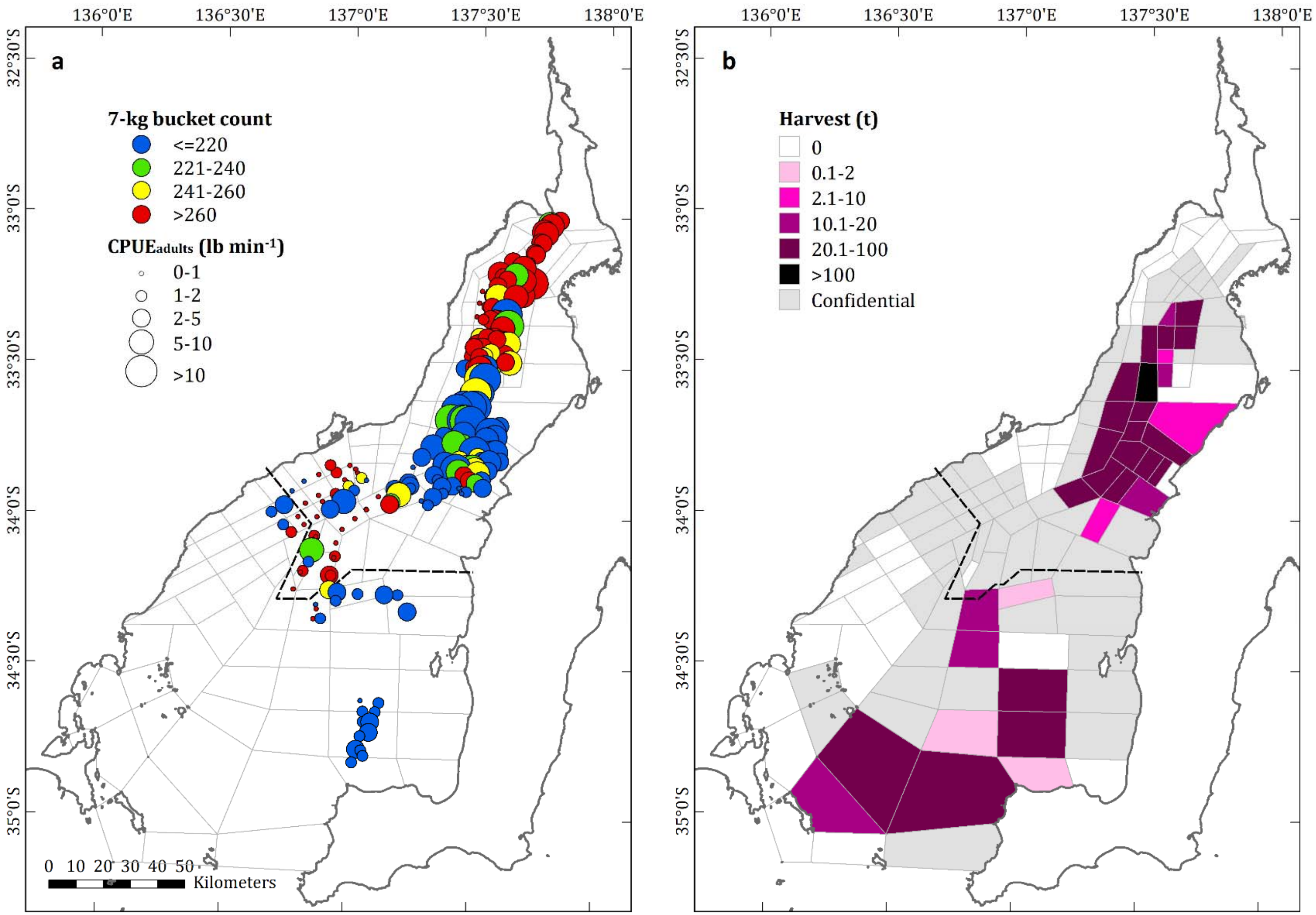

Figure A-3. (a) Results of April 2017 survey (23, 24 April 2017) and (b) subsequent harvest by block during fishing periods 5 (26 April–5 May 2017), 6 (23 May–2 June 2017) and 7 (22–27 June 2017).

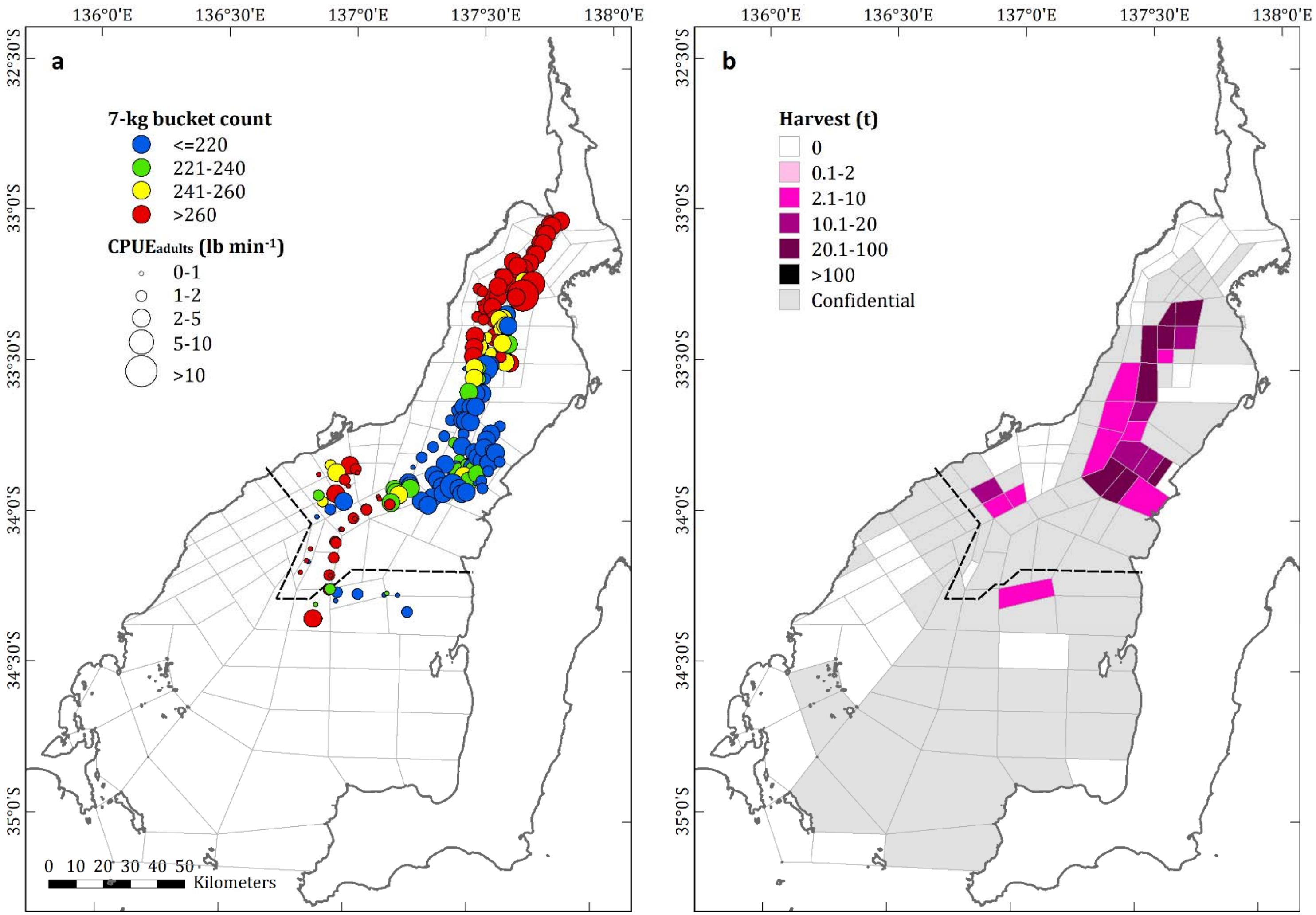

Figure A-4. (a) Results of November 2017 survey (19–22 October 2017) and (b) subsequent harvest by block during fishing periods 1 (14–26 November 2017) and 2 (14–16 December 2017).

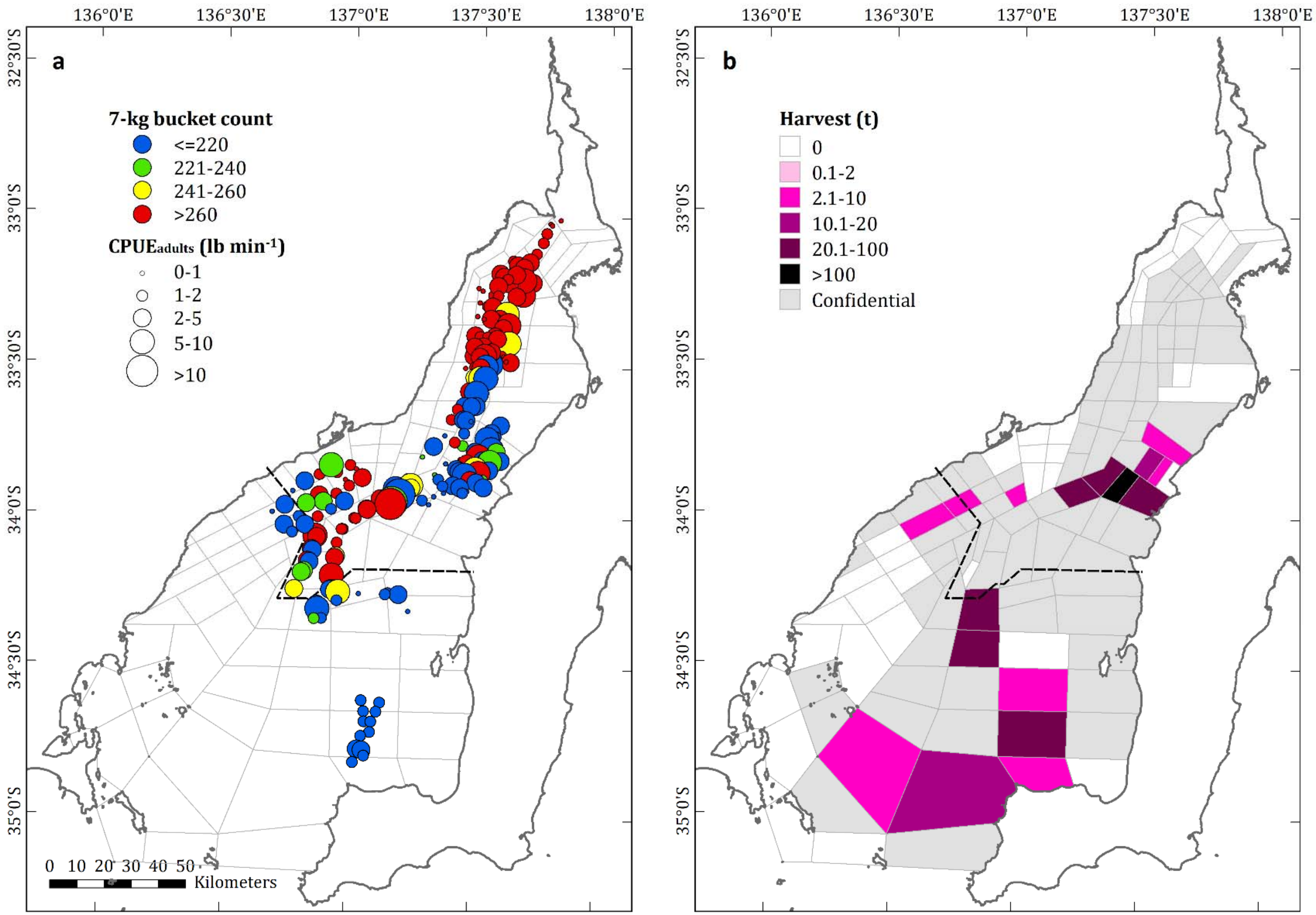

Figure A-5. (a) Results of February 2018 survey (15–17 February 2018) and (b) subsequent harvest by block during fishing periods 3 (15–23 March 2018) and 4 (11 and 12 April 2018).

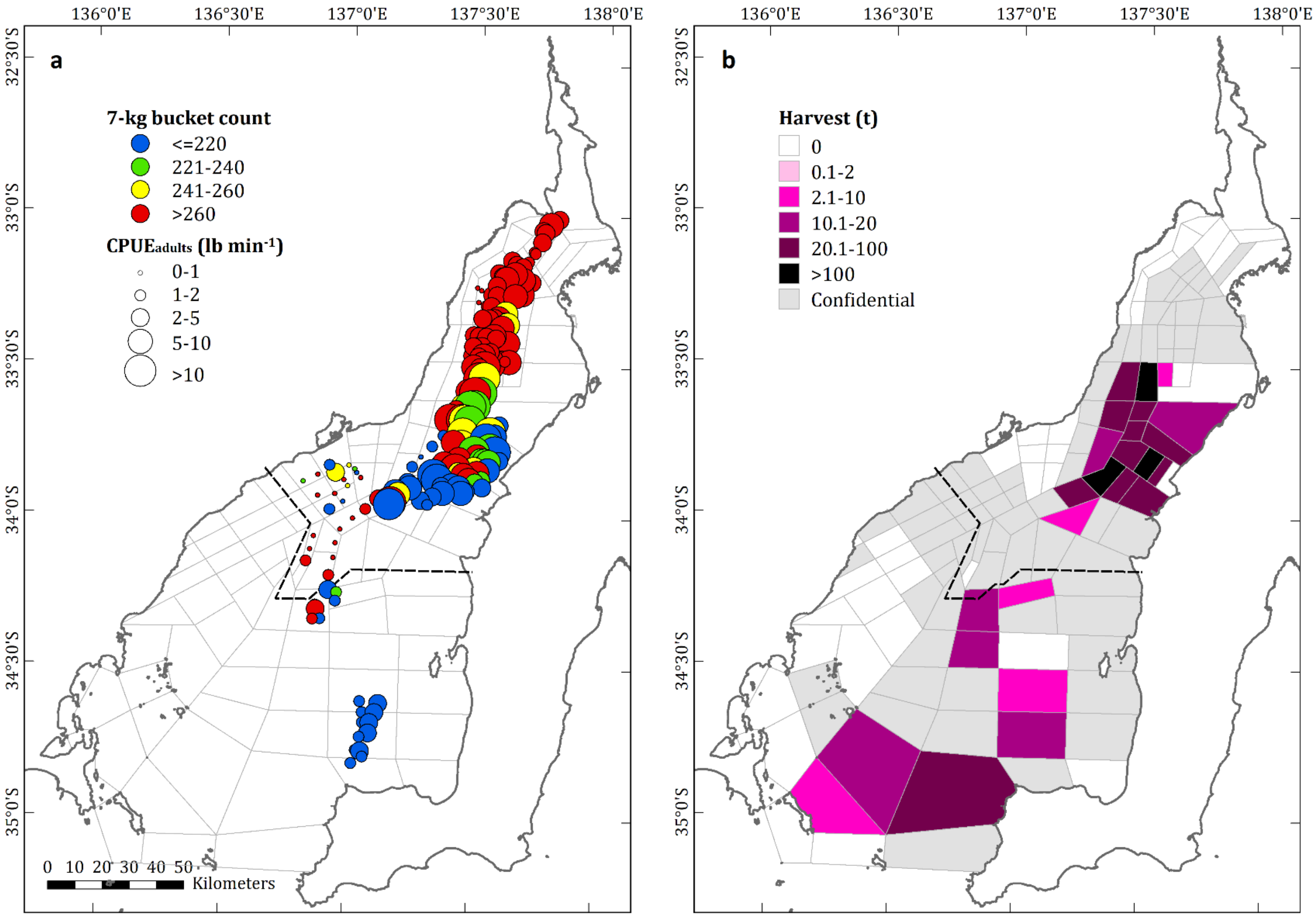

Figure A-6. (a) Results of April 2018 survey (14, 15 April 2018) and (b) subsequent harvest by block during fishing periods 5 (17–24 April 2018), 6 (11–23 May 2018) and 7 (12–19 June 2018).

APPENDIX B. GLM SUMMARY OUTPUTS

Table B-1. Summary output from R of the GLM used to standardise survey catches.

```
Call:
glm2(formula = catch_cbrt ~ YEARSURV + REGION + VESSEL + TIDEDIR +
    LUM, family = gaussian(link = "identity"), data = d.sg, offset = EFFORT)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-4.1384  -0.5290   0.0027   0.5527   3.6292

Coefficients:
                          Estimate Std. Error t value Pr(>|t|)
(Intercept)               2.024585   0.215265   9.405  < 2e-16 ***
YEARSURV2004/05_SURV2     0.558391   0.102791   5.432 5.72e-08 ***
YEARSURV2004/05_SURV3     0.868636   0.104944   8.277  < 2e-16 ***
YEARSURV2005/06_SURV1     0.438360   0.151957   2.885 0.003927 **
YEARSURV2005/06_SURV2     0.924204   0.149034   6.201 5.87e-10 ***
YEARSURV2005/06_SURV3     0.815462   0.151463   5.384 7.49e-08 ***
YEARSURV2006/07_SURV1    -0.102906   0.098677  -1.043 0.297045
YEARSURV2006/07_SURV2     0.265576   0.098472   2.697 0.007012 **
YEARSURV2006/07_SURV3     0.612377   0.098167   6.238 4.65e-10 ***
YEARSURV2007/08_SURV1     0.288840   0.098178   2.942 0.003270 **
YEARSURV2007/08_SURV2     0.343321   0.099551   3.449 0.000566 ***
YEARSURV2007/08_SURV3     0.734398   0.100129   7.334 2.44e-13 ***
YEARSURV2008/09_SURV1     0.174998   0.100120   1.748 0.080521 .
YEARSURV2008/09_SURV2     0.477951   0.097198   4.917 8.95e-07 ***
YEARSURV2008/09_SURV3     0.350098   0.099788   3.508 0.000453 ***
YEARSURV2009/10_SURV1     0.257206   0.147137   1.748 0.080489 .
YEARSURV2009/10_SURV2     0.717252   0.146270   4.904 9.59e-07 ***
YEARSURV2009/10_SURV3     1.078568   0.097985  11.007  < 2e-16 ***
YEARSURV2010/11_SURV1     0.380178   0.099992   3.802 0.000145 ***
YEARSURV2010/11_SURV2     0.627376   0.098300   6.382 1.84e-10 ***
YEARSURV2010/11_SURV3     0.812165   0.099893   8.130 4.91e-16 ***
YEARSURV2011/12_SURV1     0.468518   0.100876   4.645 3.46e-06 ***
YEARSURV2011/12_SURV2     0.553976   0.098025   5.651 1.65e-08 ***
YEARSURV2011/12_SURV3     0.636013   0.097445   6.527 7.12e-11 ***
YEARSURV2012/13_SURV1     0.021206   0.099711   0.213 0.831585
YEARSURV2012/13_SURV2    -0.081730   0.101371  -0.806 0.420124
YEARSURV2012/13_SURV3     0.513435   0.098302   5.223 1.80e-07 ***
YEARSURV2013/14_SURV1     0.060464   0.101144   0.598 0.549992
YEARSURV2013/14_SURV2     0.234132   0.097604   2.399 0.016471 *
YEARSURV2013/14_SURV3     0.518402   0.102548   5.055 4.39e-07 ***
YEARSURV2014/15_SURV1     0.204930   0.102659   1.996 0.045944 *
YEARSURV2014/15_SURV2     0.247058   0.100525   2.458 0.014005 *
YEARSURV2014/15_SURV3     0.619550   0.098280   6.304 3.05e-10 ***
YEARSURV2015/16_SURV1     0.008330   0.100572   0.083 0.933991
YEARSURV2015/16_SURV2     0.889496   0.097544   9.119  < 2e-16 ***
YEARSURV2015/16_SURV3     0.929815   0.098168   9.472  < 2e-16 ***
YEARSURV2016/17_SURV1     0.162565   0.102609   1.584 0.113160
YEARSURV2016/17_SURV2     0.698138   0.100066   6.977 3.26e-12 ***
YEARSURV2016/17_SURV3     0.132064   0.140305   0.941 0.346599
YEARSURV2017/18_SURV1     0.081520   0.101599   0.802 0.422359
YEARSURV2017/18_SURV2     0.541614   0.104746   5.171 2.39e-07 ***
YEARSURV2017/18_SURV3     0.978954   0.103158   9.490  < 2e-16 ***
REGIONCPT                -0.410966   0.057193  -7.186 7.29e-13 ***
REGIONGUT                 0.676079   0.042187  16.026  < 2e-16 ***
REGIONMBK                 1.027986   0.042559  24.154  < 2e-16 ***
REGIONNTH                 1.465042   0.035381  41.408  < 2e-16 ***
REGIONSGU                -0.057732   0.059792  -0.966 0.334299
REGIONWAL                 0.493180   0.037611  13.113  < 2e-16 ***
REGIONWAR                -0.548770   0.074440  -7.372 1.85e-13 ***
REGIONWGU                 0.394450   0.057959   6.806 1.08e-11 ***
VESSEL02                  0.147960   0.058500   2.529 0.011450 *
VESSEL03                  0.162966   0.113941   1.430 0.152678
VESSEL04                  0.003783   0.060842   0.062 0.950429
VESSEL05                 -0.070152   0.057532  -1.219 0.222749
VESSEL06                 -0.128992   0.077462  -1.665 0.095905 .
VESSEL07                 -0.212429   0.349191  -0.608 0.542975
VESSEL08                 -0.071296   0.059176  -1.205 0.228313
VESSEL09                 -0.145286   0.115966  -1.253 0.210302
VESSEL10                  0.155760   0.060604   2.570 0.010183 *
VESSEL11                  0.286526   0.060219   4.758 1.99e-06 ***
VESSEL12                  0.108499   0.077614   1.398 0.162172
VESSEL13                  0.095684   0.066326   1.443 0.149166
VESSEL14                 -0.021143   0.061462  -0.344 0.730859
VESSEL15                  0.468425   0.102614   4.565 5.07e-06 ***
VESSEL16                  0.398233   0.155439   2.562 0.010425 *
VESSEL17                  0.027382   0.100357   0.273 0.784975
VESSEL18                 -0.171585   0.107867  -1.591 0.111714
VESSEL19                 -0.124712   0.176720  -0.706 0.480393
VESSEL20                  0.012071   0.055203   0.219 0.826916
VESSEL21                  0.257459   0.151495   1.699 0.089271 .
```

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VESSEL22                   0.097911   0.103816   0.943 0.345647    
VESSEL23                   0.304817   0.160614   1.898 0.057756 .  
VESSEL24                   0.070721   0.090412   0.782 0.434120    
VESSEL25                   0.200394   0.056655   3.537 0.000407 ***
VESSEL26                   0.137448   0.065798   2.089 0.036744 *  
VESSEL27                   0.195587   0.058549   3.341 0.000840 ***
VESSEL28                   0.096524   0.054539   1.770 0.076795 .  
TIDEDIRAT                 -0.152690   0.197394  -0.774 0.439232    
TIDEDIRna                 -0.366722   0.226552  -1.619 0.105549    
TIDEDIRST                 -0.108629   0.198765  -0.547 0.584724    
TIDEDIRWT                  0.106174   0.197503   0.538 0.590881    
LUM                        3.229654   0.656753   4.918 8.93e-07 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for gaussian family taken to be 0.8023973)

    Null deviance: 10444.2  on 8189  degrees of freedom
Residual deviance:  6505.8  on 8108  degrees of freedom
AIC: 21523

Number of Fisher Scoring iterations: 2
```

Table B-2. Summary output from R of the GLM used to standardise fishery catches.

```
Call:
glm2(formula = catch_cbrt ~ FYEAR_MONTH + REG_ID + EFFORT + LIC_NO +
    LUM + LUMLAG7, family = gaussian(link = "identity"), data = d.sg)

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-10.5600   -0.7888   -0.0464    0.7499   11.2283

Coefficients:
                       Estimate Std. Error t value Pr(>|t|)
(Intercept)            1.494761   1.265001   1.182 0.237357
FYEAR_MONTH1990/91_12  0.437468   0.072658   6.021 1.74e-09 ***
FYEAR_MONTH1990/91_3   1.145186   0.068974  16.603  < 2e-16 ***
FYEAR_MONTH1990/91_4   0.170998   0.075559   2.263 0.023632 *
FYEAR_MONTH1990/91_5   0.422957   0.069343   6.099 1.07e-09 ***
FYEAR_MONTH1990/91_6  -0.226794   0.073830  -3.072 0.002128 **
FYEAR_MONTH1990/91_7  -1.585668   0.117888 -13.451  < 2e-16 ***
FYEAR_MONTH1991/92_11  1.531466   0.074553  20.542  < 2e-16 ***
FYEAR_MONTH1991/92_12  0.602655   0.071959   8.375  < 2e-16 ***
FYEAR_MONTH1991/92_3   0.732549   0.069296  10.571  < 2e-16 ***
FYEAR_MONTH1991/92_4   1.427905   0.074192  19.246  < 2e-16 ***
FYEAR_MONTH1991/92_5   0.069255   0.069806   0.992 0.321144
FYEAR_MONTH1991/92_6   0.026526   0.082781   0.320 0.748636
FYEAR_MONTH1992/93_11  0.644507   0.073536   8.764  < 2e-16 ***
FYEAR_MONTH1992/93_12  0.123439   0.080105   1.541 0.123330
FYEAR_MONTH1992/93_3   0.233161   0.069330   3.363 0.000771 ***
FYEAR_MONTH1992/93_4  -0.274921   0.073360  -3.748 0.000179 ***
FYEAR_MONTH1992/93_5   0.695154   0.070900   9.805  < 2e-16 ***
FYEAR_MONTH1992/93_6  -1.101215   0.082562 -13.338  < 2e-16 ***
FYEAR_MONTH1993/94_11  0.692487   0.078967   8.769  < 2e-16 ***
FYEAR_MONTH1993/94_12  0.001777   0.075278   0.024 0.981167
FYEAR_MONTH1993/94_3   1.360433   0.077817  17.483  < 2e-16 ***
FYEAR_MONTH1993/94_4   1.066014   0.084838  12.565  < 2e-16 ***
FYEAR_MONTH1993/94_5   0.435470   0.071014   6.132 8.71e-10 ***
FYEAR_MONTH1993/94_6   0.394711   0.072526   5.442 5.27e-08 ***
FYEAR_MONTH1994/95_11  0.874593   0.076347  11.455  < 2e-16 ***
FYEAR_MONTH1994/95_12  0.690668   0.076961   8.974  < 2e-16 ***
FYEAR_MONTH1994/95_3   1.523423   0.071450  21.322  < 2e-16 ***
FYEAR_MONTH1994/95_4   1.799708   0.073288  24.557  < 2e-16 ***
FYEAR_MONTH1994/95_5   0.779294   0.073132  10.656  < 2e-16 ***
FYEAR_MONTH1994/95_6  -0.222181   0.086384  -2.572 0.010112 *
FYEAR_MONTH1995/96_11  1.139811   0.072974  15.619  < 2e-16 ***
FYEAR_MONTH1995/96_12  0.826007   0.077241  10.694  < 2e-16 ***
FYEAR_MONTH1995/96_3   0.702113   0.074077   9.478  < 2e-16 ***
FYEAR_MONTH1995/96_4   1.580015   0.076577  20.633  < 2e-16 ***
FYEAR_MONTH1995/96_5   0.363797   0.069034   5.270 1.37e-07 ***
FYEAR_MONTH1995/96_6  -1.486416   0.081465 -18.246  < 2e-16 ***
FYEAR_MONTH1996/97_11  0.032724   0.088004   0.372 0.710005
FYEAR_MONTH1996/97_12  0.045897   0.072966   0.629 0.529343
FYEAR_MONTH1996/97_3   0.832987   0.072970  11.415  < 2e-16 ***
FYEAR_MONTH1996/97_4   1.371712   0.078755  17.418  < 2e-16 ***
FYEAR_MONTH1996/97_5   0.713678   0.072547   9.837  < 2e-16 ***
FYEAR_MONTH1996/97_6   0.151893   0.075618   2.009 0.044573 *
FYEAR_MONTH1997/98_11  1.067041   0.077486  13.771  < 2e-16 ***
FYEAR_MONTH1997/98_12  0.470050   0.085900   5.472 4.46e-08 ***
FYEAR_MONTH1997/98_3   2.463679   0.078143  31.528  < 2e-16 ***
FYEAR_MONTH1997/98_4   3.177583   0.074433  42.690  < 2e-16 ***
FYEAR_MONTH1997/98_5   2.184839   0.068914  31.704  < 2e-16 ***
FYEAR_MONTH1997/98_6   1.623227   0.142376  11.401  < 2e-16 ***
FYEAR_MONTH1998/99_11  2.938315   0.083071  35.371  < 2e-16 ***
FYEAR_MONTH1998/99_12  1.947397   0.075827  25.682  < 2e-16 ***
FYEAR_MONTH1998/99_3   1.908040   0.074834  25.497  < 2e-16 ***
FYEAR_MONTH1998/99_4   3.410071   0.073550  46.364  < 2e-16 ***
FYEAR_MONTH1998/99_5   1.677567   0.076215  22.011  < 2e-16 ***
FYEAR_MONTH1998/99_6  -0.247570   0.107934  -2.294 0.021810 *
FYEAR_MONTH1999/00_11  1.399466   0.089221  15.685  < 2e-16 ***
FYEAR_MONTH1999/00_12  0.948861   0.073822  12.853  < 2e-16 ***
FYEAR_MONTH1999/00_3   1.369345   0.079965  17.124  < 2e-16 ***
FYEAR_MONTH1999/00_4   2.849557   0.077731  36.659  < 2e-16 ***
FYEAR_MONTH1999/00_5   1.520666   0.073860  20.588  < 2e-16 ***
FYEAR_MONTH1999/00_6   0.266768   0.085353   3.125 0.001776 **
FYEAR_MONTH2000/01_11  0.847342   0.074851  11.320  < 2e-16 ***
FYEAR_MONTH2000/01_12  1.258001   0.080038  15.718  < 2e-16 ***
FYEAR_MONTH2000/01_3   2.422350   0.084922  28.524  < 2e-16 ***
FYEAR_MONTH2000/01_4   4.497890   0.074792  60.138  < 2e-16 ***
FYEAR_MONTH2000/01_5   2.693646   0.071505  37.671  < 2e-16 ***
FYEAR_MONTH2000/01_6   0.841642   0.086413   9.740  < 2e-16 ***
FYEAR_MONTH2001/02_11  3.202121   0.088172  36.317  < 2e-16 ***
FYEAR_MONTH2001/02_12  1.733455   0.075122  23.075  < 2e-16 ***
FYEAR_MONTH2001/02_3   1.949542   0.078537  24.823  < 2e-16 ***
FYEAR_MONTH2001/02_4   2.964758   0.074656  39.712  < 2e-16 ***
FYEAR_MONTH2001/02_5   2.359577   0.076166  30.979  < 2e-16 ***
FYEAR_MONTH2001/02_6   0.299879   0.089935   3.334 0.000855 ***
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FYEAR_MONTH2002/03_11  1.742840   0.084002  20.748  < 2e-16 ***
FYEAR_MONTH2002/03_12  1.085406   0.081364  13.340  < 2e-16 ***
FYEAR_MONTH2002/03_3   1.078172   0.081334  13.256  < 2e-16 ***
FYEAR_MONTH2002/03_4   1.803304   0.075267  23.959  < 2e-16 ***
FYEAR_MONTH2002/03_5   1.115842   0.068524  16.284  < 2e-16 ***
FYEAR_MONTH2002/03_6  -0.183932   0.108737  -1.692 0.090740 .
FYEAR_MONTH2003/04_11  1.262824   0.092207  13.695  < 2e-16 ***
FYEAR_MONTH2003/04_12  1.072529   0.087009  12.327  < 2e-16 ***
FYEAR_MONTH2003/04_3   1.713884   0.073053  23.461  < 2e-16 ***
FYEAR_MONTH2003/04_4   2.930806   0.072158  40.616  < 2e-16 ***
FYEAR_MONTH2003/04_5   1.806645   0.071145  25.394  < 2e-16 ***
FYEAR_MONTH2003/04_6  -0.165257   0.081615  -2.025 0.042888 *
FYEAR_MONTH2004/05_11  1.640676   0.090048  18.220  < 2e-16 ***
FYEAR_MONTH2004/05_12  1.291258   0.074411  17.353  < 2e-16 ***
FYEAR_MONTH2004/05_3   2.054816   0.075326  27.279  < 2e-16 ***
FYEAR_MONTH2004/05_4   2.576438   0.075807  33.987  < 2e-16 ***
FYEAR_MONTH2004/05_5   1.876086   0.075156  24.962  < 2e-16 ***
FYEAR_MONTH2004/05_6   0.943677   0.080906  11.664  < 2e-16 ***
FYEAR_MONTH2005/06_11  2.033076   0.084095  24.176  < 2e-16 ***
FYEAR_MONTH2005/06_12  1.353756   0.087480  15.475  < 2e-16 ***
FYEAR_MONTH2005/06_3   3.614733   0.081794  44.193  < 2e-16 ***
FYEAR_MONTH2005/06_4   2.814953   0.079737  35.303  < 2e-16 ***
FYEAR_MONTH2005/06_5   1.426108   0.070404  20.256  < 2e-16 ***
FYEAR_MONTH2005/06_6   1.165340   0.117854   9.888  < 2e-16 ***
FYEAR_MONTH2006/07_11  1.695572   0.079462  21.338  < 2e-16 ***
FYEAR_MONTH2006/07_12  0.529061   0.081503   6.491 8.56e-11 ***
FYEAR_MONTH2006/07_3   2.974030   0.087580  33.958  < 2e-16 ***
FYEAR_MONTH2006/07_4   4.071682   0.076220  53.420  < 2e-16 ***
FYEAR_MONTH2006/07_5   2.348314   0.073411  31.989  < 2e-16 ***
FYEAR_MONTH2006/07_6   0.102006   0.088030   1.159 0.246556
FYEAR_MONTH2007/08_11  2.292055   0.087907  26.074  < 2e-16 ***
FYEAR_MONTH2007/08_12  1.503407   0.081561  18.433  < 2e-16 ***
FYEAR_MONTH2007/08_3   2.362555   0.091460  25.832  < 2e-16 ***
FYEAR_MONTH2007/08_4   3.201925   0.076649  41.774  < 2e-16 ***
FYEAR_MONTH2007/08_5   2.439107   0.073298  33.277  < 2e-16 ***
FYEAR_MONTH2007/08_6   0.999526   0.077535  12.891  < 2e-16 ***
FYEAR_MONTH2008/09_10  2.471683   0.175491  14.084  < 2e-16 ***
FYEAR_MONTH2008/09_11  1.379779   0.072874  18.934  < 2e-16 ***
FYEAR_MONTH2008/09_12  0.765516   0.106752   7.171 7.51e-13 ***
FYEAR_MONTH2008/09_2   2.497743   0.131553  18.987  < 2e-16 ***
FYEAR_MONTH2008/09_3   3.112318   0.076732  40.561  < 2e-16 ***
FYEAR_MONTH2008/09_4   2.912309   0.081432  35.764  < 2e-16 ***
FYEAR_MONTH2008/09_5   1.489878   0.067021  22.230  < 2e-16 ***
FYEAR_MONTH2009/10_11  1.633183   0.082844  19.714  < 2e-16 ***
FYEAR_MONTH2009/10_12  0.761289   0.081564   9.334  < 2e-16 ***
FYEAR_MONTH2009/10_3   3.237245   0.083743  38.657  < 2e-16 ***
FYEAR_MONTH2009/10_4   4.628541   0.074291  62.303  < 2e-16 ***
FYEAR_MONTH2009/10_5   3.148500   0.074385  42.327  < 2e-16 ***
FYEAR_MONTH2009/10_6   1.687000   0.086425  19.520  < 2e-16 ***
FYEAR_MONTH2010/11_11  3.688514   0.088977  41.454  < 2e-16 ***
FYEAR_MONTH2010/11_12  1.223123   0.088830  13.769  < 2e-16 ***
FYEAR_MONTH2010/11_3   3.110298   0.090515  34.362  < 2e-16 ***
FYEAR_MONTH2010/11_4   3.021814   0.079077  38.214  < 2e-16 ***
FYEAR_MONTH2010/11_5   1.999666   0.072714  27.500  < 2e-16 ***
FYEAR_MONTH2010/11_6   0.657382   0.083987   7.827 5.05e-15 ***
FYEAR_MONTH2011/12_10  1.916623   0.103944  18.439  < 2e-16 ***
FYEAR_MONTH2011/12_11  0.778381   0.079307   9.815  < 2e-16 ***
FYEAR_MONTH2011/12_12  1.157405   0.149304   7.752 9.15e-15 ***
FYEAR_MONTH2011/12_3   2.636660   0.082570  31.932  < 2e-16 ***
FYEAR_MONTH2011/12_4   2.819996   0.072480  38.907  < 2e-16 ***
FYEAR_MONTH2011/12_5   1.178025   0.072874  16.165  < 2e-16 ***
FYEAR_MONTH2011/12_6  -0.668286   0.092938  -7.191 6.50e-13 ***
FYEAR_MONTH2012/13_11  1.876680   0.085273  22.008  < 2e-16 ***
FYEAR_MONTH2012/13_12  1.305147   0.074487  17.522  < 2e-16 ***
FYEAR_MONTH2012/13_3   2.494048   0.099375  25.097  < 2e-16 ***
FYEAR_MONTH2012/13_4   2.404078   0.072629  33.101  < 2e-16 ***
FYEAR_MONTH2012/13_5   1.732114   0.075523  22.935  < 2e-16 ***
FYEAR_MONTH2012/13_6   0.812936   0.086877   9.357  < 2e-16 ***
FYEAR_MONTH2013/14_11  1.945380   0.081897  23.754  < 2e-16 ***
FYEAR_MONTH2013/14_12  0.955675   0.080840  11.822  < 2e-16 ***
FYEAR_MONTH2013/14_3   1.854384   0.123603  15.003  < 2e-16 ***
FYEAR_MONTH2013/14_4   1.862344   0.078211  23.812  < 2e-16 ***
FYEAR_MONTH2013/14_5   1.471014   0.072520  20.284  < 2e-16 ***
FYEAR_MONTH2013/14_6   0.703067   0.080507   8.733  < 2e-16 ***
FYEAR_MONTH2013/14_7   0.720631   0.143567   5.019 5.19e-07 ***
FYEAR_MONTH2014/15_10  2.410312   0.097810  24.643  < 2e-16 ***
FYEAR_MONTH2014/15_11  1.567595   0.075200  20.846  < 2e-16 ***
FYEAR_MONTH2014/15_3   2.459557   0.092884  26.480  < 2e-16 ***
FYEAR_MONTH2014/15_4   3.004821   0.073168  41.067  < 2e-16 ***
FYEAR_MONTH2014/15_5   1.175629   0.073163  16.069  < 2e-16 ***
FYEAR_MONTH2014/15_6  -0.399717   0.101135  -3.952 7.75e-05 ***
FYEAR_MONTH2015/16_11  1.973527   0.079778  24.738  < 2e-16 ***
FYEAR_MONTH2015/16_12  1.091147   0.086084  12.675  < 2e-16 ***
FYEAR_MONTH2015/16_3   3.300414   0.090529  36.457  < 2e-16 ***
FYEAR_MONTH2015/16_4   3.684811   0.073159  50.367  < 2e-16 ***
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FYEAR_MONTH2015/16_5   2.469662   0.073518  33.593  < 2e-16 ***
FYEAR_MONTH2015/16_6   1.336151   0.081653  16.364  < 2e-16 ***
FYEAR_MONTH2016/17_11  2.057171   0.074700  27.539  < 2e-16 ***
FYEAR_MONTH2016/17_12  0.992784   0.103489   9.593  < 2e-16 ***
FYEAR_MONTH2016/17_3   3.332859   0.088010  37.869  < 2e-16 ***
FYEAR_MONTH2016/17_4   2.664016   0.074017  35.992  < 2e-16 ***
FYEAR_MONTH2016/17_5   1.923571   0.069782  27.566  < 2e-16 ***
FYEAR_MONTH2016/17_6   0.618967   0.083764   7.389 1.49e-13 ***
FYEAR_MONTH2017/18_11  1.289758   0.071288  18.092  < 2e-16 ***
FYEAR_MONTH2017/18_12  0.762481   0.116245   6.559 5.44e-11 ***
FYEAR_MONTH2017/18_3   3.061235   0.082618  37.053  < 2e-16 ***
FYEAR_MONTH2017/18_4   3.754750   0.076854  48.855  < 2e-16 ***
FYEAR_MONTH2017/18_5   2.624321   0.071642  36.631  < 2e-16 ***
FYEAR_MONTH2017/18_6   0.547447   0.081540   6.714 1.91e-11 ***
REG_IDCOW              0.093993   1.263568   0.074 0.940703
REG_IDCPT             -0.638292   1.263495  -0.505 0.613434
REG_IDGUT              0.686443   1.263497   0.543 0.586933
REG_IDMBK              1.083745   1.263421   0.858 0.391013
REG_IDNTH              1.557054   1.263468   1.232 0.217816
REG_IDSGU             -0.033275   1.263534  -0.026 0.978990
REG_IDTHI             -0.387743   1.263664  -0.307 0.758966
REG_IDWAL              0.788081   1.263412   0.624 0.532779
REG_IDWAR             -0.244368   1.263661  -0.193 0.846661
REG_IDWGU              0.317246   1.264161   0.251 0.801850
EFFORT                 0.535244   0.001555 344.108  < 2e-16 ***
VESSEL02               0.474989   0.044026  10.789  < 2e-16 ***
VESSEL03               0.759027   0.039287  19.320  < 2e-16 ***
VESSEL04               0.377346   0.040891   9.228  < 2e-16 ***
VESSEL05               0.246934   0.041460   5.956 2.60e-09 ***
VESSEL06               0.669738   0.040387  16.583  < 2e-16 ***
VESSEL07               0.441017   0.042690  10.331  < 2e-16 ***
VESSEL08               0.624470   0.039936  15.637  < 2e-16 ***
VESSEL09               0.713590   0.042745  16.694  < 2e-16 ***
VESSEL10               0.095675   0.040340   2.372 0.017709 *
VESSEL11               0.403883   0.041683   9.689  < 2e-16 ***
VESSEL12               0.317248   0.040598   7.814 5.59e-15 ***
VESSEL13               0.384742   0.042476   9.058  < 2e-16 ***
VESSEL14               0.570321   0.043019  13.257  < 2e-16 ***
VESSEL15               0.464684   0.040149  11.574  < 2e-16 ***
VESSEL16               0.816818   0.043483  18.785  < 2e-16 ***
VESSEL17               0.035939   0.043408   0.828 0.407710
VESSEL18               0.322880   0.039584   8.157 3.49e-16 ***
VESSEL19               0.651824   0.041821  15.586  < 2e-16 ***
VESSEL20               0.413493   0.041692   9.918  < 2e-16 ***
VESSEL21               0.490467   0.041619  11.785  < 2e-16 ***
VESSEL22               0.535619   0.043215  12.394  < 2e-16 ***
VESSEL23               0.291366   0.043293   6.730 1.71e-11 ***
VESSEL24               0.764294   0.041740  18.311  < 2e-16 ***
VESSEL25               0.402209   0.040891   9.836  < 2e-16 ***
VESSEL26               0.772639   0.040864  18.908  < 2e-16 ***
VESSEL27               0.657733   0.040492  16.243  < 2e-16 ***
VESSEL28               0.810321   0.041663  19.449  < 2e-16 ***
VESSEL29               0.461924   0.041877  11.031  < 2e-16 ***
VESSEL30               0.746515   0.041382  18.040  < 2e-16 ***
VESSEL31               0.656230   0.041584  15.781  < 2e-16 ***
VESSEL32               0.525478   0.039561  13.283  < 2e-16 ***
VESSEL33               0.718067   0.042436  16.921  < 2e-16 ***
VESSEL34               0.554041   0.043661  12.690  < 2e-16 ***
VESSEL35               0.396603   0.042753   9.277  < 2e-16 ***
VESSEL36               0.163734   0.041956   3.903 9.53e-05 ***
VESSEL37               0.603626   0.042486  14.208  < 2e-16 ***
VESSEL38               0.379839   0.042527   8.932  < 2e-16 ***
VESSEL39               0.404669   0.041879   9.663  < 2e-16 ***
LUM                   -2.503793   0.034662 -72.235  < 2e-16 ***
LUMLAG7                0.916885   0.016099  56.955  < 2e-16 ***
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Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for gaussian family taken to be 1.592684)

    Null deviance: 460937  on 82212  degrees of freedom
Residual deviance: 130584  on 81990  degrees of freedom
AIC: 271799

Number of Fisher Scoring iterations: 2
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