Prawn and crab harvest optimisation: a bio-physical management tool

Final Report to the Fisheries Research and Development Corporation

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Abbreviations

AUD – Australian Dollars
BCF – Blue Swimmer Crab Fishery
ESD – Ecologically Sustainable Development
GIS – Geographic Information System
GVP – Gross Value of Production
PIRSA – Primary Industries and Regions South Australia
ROMS – Regional Ocean Modelling System
SABCPFA – South Australian Blue Crab Pot Fishers Association
SARDI – South Australian Research and Development Institute
SAROM – South Australian Regional Ocean Model
SGM – Spencer Gulf Model
SGPF – Spencer Gulf Prawn Fishery
SGWCPFA – Spencer Gulf and West Coast Prawn Fisherman's Association
t – tonnes
TST – Tidal stream transport

Executive Summary

This report is the first comprehensive study to model the interaction between physical-oceanographic processes and patterns of larval settlement for Western King Prawn (*Penaeus* (*Melicertus*) *latisulcatus*) and Blue Swimmer Crab (*Portunus armatus*) in South Australia. Research conducted by SARDI Aquatic Sciences combined data from stock assessment surveys, tank trials, published research, and climate and ocean sensors to identify the key areas in Spencer Gulf that contribute to larval settlement success of these two commercially important species. Information relevant to Western King Prawn was used to assess how different harvest strategies may maximise catch while minimising the potential threat of recruitment overfishing during pre-Christmas fishing periods that coincide with spawning. The study provides stakeholders with additional information to enhance harvest strategies and maximise production opportunities for these species. The bio-physical models developed in the project have also provided some insights into the potential effects of climate change on stock-recruitment relationships.

Knowledge of the interactions between physical and biological processes in marine environments is fundamental to understanding how fish stocks respond to pressures of resource use and environmental impacts such as global climate change. One of the goals of fisheries management is to maximise production while preventing recruitment overfishing. However, for most fisheries, stock-recruitment relationships are poorly understood due to the lack of knowledge on how marine bio-physical processes act on different life history stages with varied behavioural traits, before they recruit to the fishery.

In marine crustacean fisheries, patterns of larval dispersal, distribution and abundance are major factors regulating recruitment and population size, and are controlled by a combination of factors including the reproductive behaviour of adults, physiological tolerances and behaviour of larvae, and local hydro-meteorological processes. Recent advances in the techniques used to model oceanic processes have led to accurate predictions of the scale and direction of larval dispersal and settlement within areas that fisheries operate. Bio-physical models are now able to predict patterns of larval dispersal and settlement by coupling knowledge about the biology and behaviour of a species to information about local hydrodynamics. This information is useful for fisheries management in highlighting the habitats that are most important to early life history stages and the spawning locations that contribute most to fisheries production.

Western King Prawn and Blue Swimmer Crab are targeted in Spencer Gulf, South Australia, by the Spencer Gulf Prawn Fishery (SGPF) and the Blue Crab Fishery (BCF), respectively. Fishing prior to Christmas is aimed at the lucrative Christmas market and is coincidental with the onset of the spawning periods for these two species. Catches of Western King Prawn are capped during the early spawning season to protect egg production, and increase recruitment stability and annual catch. However, potential underutilisation of the resource may result if the key areas for egg production and recruitment are not linked. The fishing season for Blue Swimmer Crab was recently extended to December, raising concerns regarding the potential impacts of fishing on egg production and subsequent larval dispersal into nursery areas of northern Spencer Gulf.

This project was developed to 1) improve the understanding of the biological and oceanographic processes that affect the distribution of Western King Prawn and Blue Swimmer Crab larvae between spawning and larval settlement; 2) identify the areas most critical for their spawning and larval settlement success; 3) enhance the harvest strategy for these species during the spawning season to maximise catch and minimise impacts on future recruitment; and 4) develop a tool to help identify the potential effects of global climate change on stock-recruitment relationships for these species.

The specific objectives of this project were to:

1. Develop biological models relating to the reproductive and larval biology of Western King Prawn and Blue Swimmer Crab in Spencer Gulf.
2. Develop a passive particle hydrodynamic model for Spencer Gulf.
3. Develop the base-case bio-physical model to simulate Western King Prawn and Blue Swimmer Crab larval dispersal, and assess the effects of different environmental conditions (e.g. water temperature) on larval recruitment.
4. Test scenarios to optimise the harvest of Western King Prawn during the early spawning season.

We used data from tank trials, published research, and climate and ocean sensors to develop a bio-physical model to simulate patterns of larval dispersal and settlement for Western King Prawn and Blue Swimmer Crab in Spencer Gulf. This model was coupled with information relating to the spawning characteristics of these species to identify the key areas in Spencer Gulf contributing to larval settlement success.

Tank trials were successful in calculating the lengths of larval duration for Western King Prawn in response to a range of different temperatures typical to Spencer Gulf. This was critical to estimating the time scales over which the bio-physical model should be run. Outputs of the bio-physical model indicated that total rates of larval settlement were maximised for Western King Prawn when tidal currents and atmospheric physical-forcing components were coupled with active larval swimming behaviour and relatively cooler average gulf temperatures typical of November when the peak in spawning occurs. The importance of larval swimming behaviour to the settlement success of Western King Prawn larvae was highlighted by large increases (up to

45%) in larval settlement rates when swimming behaviour was added into the bio-physical model. Cooler average gulf temperature inputs into the bio-physical model also sustained longer larval durations and increased larval settlement rates by over 12% compared to warmer gulf conditions. The lower settlement rates modelled under warmer gulf conditions lead to the hypothesis that any increases in the water temperature of Spencer Gulf due to climate change may reduce the probability of larvae originating in the southern gulf from reaching the northern recruitment grounds, potentially reducing overall recruitment success and future prawn biomass.

Fishery-dependent data for Blue Swimmer Crab indicated that the areas with the largest percentage of spawning females were generally located in the eastern gulf north of Wallaroo. This region also contributed to the highest rates of settlement of blue-swimmer crab larvae. These areas may make the largest contributions to larval settlement but a more stratified sampling approach to help estimate egg production and crab biomass is required. These data would help to develop and optimise future harvest strategies for the BCF.

For Western King Prawn, reproductive information was coupled with data from the bio-physical model to determine the sensitivity of larval settlement rates to spatial changes in fishing. Consistent patterns were observed in the areas contributing most to larval settlement success for all years surveyed between 2009 and 2012. Sensitivity analyses indicated that changes in the spatial patterns of pre-Christmas fishing could lead to further improvements in overall rates of larval settlement while maintaining or improving the levels of catch. Real time application of the bio-physical model in the future using data collected from pre-Christmas surveys could allow target exploitation rates to be capped within the areas that most contribute to larval settlement, thereby helping to maximise rates of larval settlement and catch across the fishery. This would augment current management strategies for pre-Christmas fishing in the SGPF and help to manage the potential threats of recruitment overfishing.

Keywords

Western King Prawn, Blue Swimmer Crab, *Penaeus (Melicertus) latisulcatus*, *Portunus armatus*, larvae, larval settlement, recruitment, bio-physical model, crustacean fishery, Spencer Gulf Prawn Fishery, Blue Crab Fishery.

1 Introduction

Knowledge of the interactions between physical and biological processes in marine environments is fundamental to understanding how fish stocks respond to pressures of resource use and environmental impacts such as global climate change. For commercial fisheries, one of the major goals of management is to prevent recruitment overfishing (i.e. to prevent depletion of the spawning stock to a level where it does not have the capacity to replenish itself). However, for most fisheries, stock-recruitment relationships are poorly understood due to the length of time occurring between spawning and recruitment to the fishery (months/years), and the combination of physical and biological processes that act on different life history stages during this time.

In marine crustacean fisheries, patterns of larval dispersal, distribution and abundance are major factors regulating recruitment and population size, and are controlled by a combination of factors including the reproductive behaviour of adults, physiological tolerances and behaviour of larvae (e.g. vertical migration swimming behaviour), and local hydro-meteorological processes such as wind-driven and tidal currents (Roberts et al. 2012). Historically, predictions of how marine larvae are affected by physical circulation processes were complicated by the difficulty of modelling their dispersal. Relatively recent advances in the techniques used to model oceanic processes have led to accurate predictions in the scale and direction of larval dispersal and settlement within areas that fisheries operate (Condie et al. 1999; Pederson et al. 2003; Rochette et al. 2012). Bio-physical models are now able to predict patterns of larval dispersal and settlement by coupling knowledge about the biology and behaviour of a species to information about local hydrodynamics. This information is useful for fisheries management in highlighting the habitats that are most important to early life history stages and spawning locations that contribute most to fisheries recruitment and production (Pedersen et al. 2003; Queiroga et al. 2007).

Western King Prawn (*Penaeus (Melicertus) latisulcatus*) and Blue Swimmer Crab *(Portunus armatus*) are targeted in Spencer Gulf, South Australia, by the Spencer Gulf Prawn Fishery (SGPF) and the Blue Crab Fishery (BCF), respectively. These fisheries are classified as biologically sustainable under Australia's national agreed framework for fisheries (Flood et al. 2014) and were valued at approximately $AUD 27M and $4.9M GVP in 2012/13, respectively (Econsearch 2014a, b). The life history patterns of these species are similar. Both species have an offshore adult life history phase and an inshore juvenile phase (Figure 1 and Figure 2), and share nursery grounds located in intertidal mangrove areas. Adult Western King Prawn spawn in the warmer austral months between October/November and March/April (Dixon et al. 2013; Roberts et al. 2012). After spawning, eggs undergo metamorphosis through four main stages: nauplii, zoea, mysis and post-larvae. Post-larvae settle in inshore nursery areas when they reach 2–3 mm carapace length (CL) and remain there for 6–12 months (Carrick *et al*. 1996; Carrick 2003).

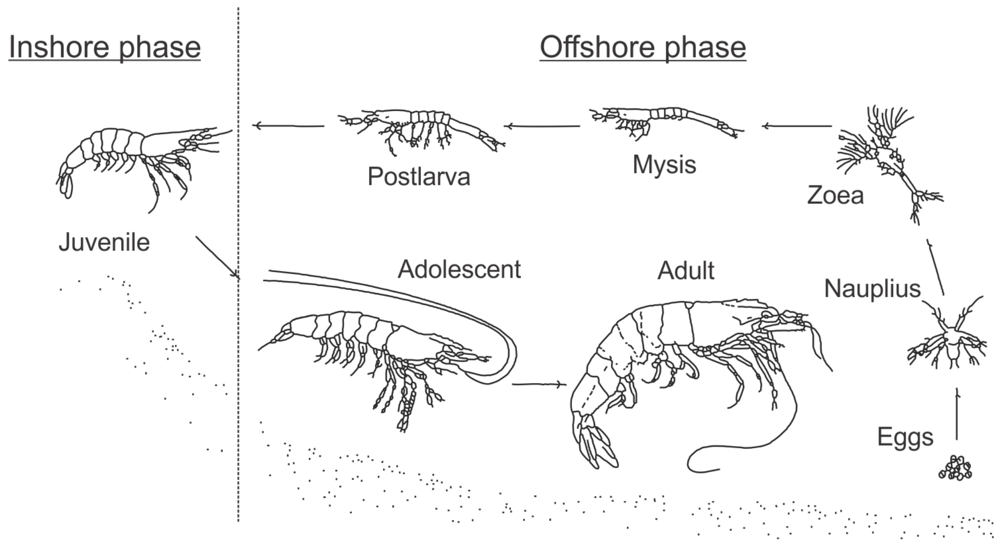

Figure 1. Life cycle of the Western King Prawn (Source: Kailola et al. 1993).

Blue Swimmer Crab also spawn in the warmer summer months between November and February (Kumar et al. 2000). After spawning, the eggs undergo metamorphosis through four zoeal stages and one megalopal stage before developing into the first juvenile crab stage after a period of one to two months (Yatsuzuka 1962; Meagher 1971; Bryars and Adams 1997) (Figure 2). Juveniles produced from spawning events in November to May grow rapidly in nursery areas before migrating to deeper water after approximately 8–12 months.

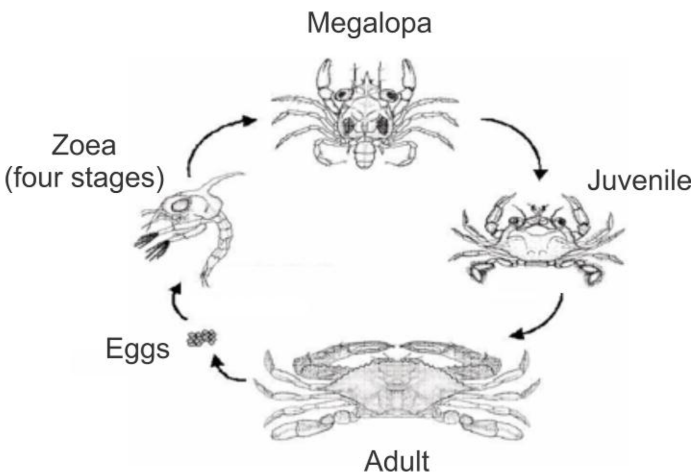

Figure 2. Life cycle of the Blue Swimmer Crab (Source: adapted from Bilbay 2014).

While the general life history strategies of these species within Spencer Gulf are well known, the factors affecting the dispersal and settlement of their larvae are less understood. The rate at which larvae develop affects the resulting time-scale over which physical oceanic processes act on their dispersal. Temperature is widely accepted to be a major influence on the development rates of marine invertebrate larvae (Preston 1985; Jackson and Burford, 2003; Bryars and Havenhand, 2006), and is a key factor influencing larval duration of decapod larvae in temperate systems where seasonal variations in temperature can be large (Rothlisberg 1979; Preston 1985; Nunes and Lennon 1986; Bermudes and Ritar 2008).

For Blue Swimmer Crab, larval duration has been estimated to range between 26 and 45 days in response to changes in seasonal water temperatures measured in Gulf St Vincent, adjacent to Spencer Gulf, in South Australia (Bryars and Havenhand 2006). The larval duration of Western King Prawn has been estimated from laboratory experiments at higher water temperatures than those typical of Spencer Gulf (8 days to reach postlarvae at 29.3 °C; Shokita (1984)). However, larval durations at lower temperatures have not previously been documented. This information was identified as a priority of this project to estimate the time scales over which the bio-physical model should be run and to best predict patterns of larval dispersal and settlement for Western King Prawn in Spencer Gulf.

The oceanographic factors affecting the dispersal and settlement of Western King Prawn and Blue Swimmer Crab larvae within Spencer Gulf are also not well understood. Spencer Gulf is a semi-enclosed marine system that is uniquely classified as a hypersaline inverse estuary (Nunes and Lennon 1986). Water temperatures fluctuate seasonally between 12 °C and 24 °C, with higher summer temperatures and colder winter temperatures in the north compared to the south (Nunes and Lennon 1986). Evaporation exceeds precipitation year round, leading to the formation of dense salty water in shallower waters of the upper gulf and clockwise water circulation around the gulf that is modulated by strong tidal currents and vertical mixing (Nunes and Lennon 1986; Lennon et al. 1987; Middleton et al. 2013).

Previous research (FRDC project 2009/046) validated a hydrodynamic model for Spencer Gulf and simulated oceanic connectivity processes within the gulf using particle tracking procedures. This project builds on those findings by analysing oceanographic information collected at finer spatial and temporal scales, and integrating it with data on larval behaviour and duration to model patterns of dispersal and settlement for Western King Prawn and Blue Swimmer Crab larvae in Spencer Gulf. This bio-physical modelling approach aims to provide information to enhance the understanding of larval dispersal and stock recruitment relationships for each fishery.

The SGPF is a demersal trawl fishery that targets Western King Prawn at night over a fishing season comprising two pre-Christmas fishing periods of 10 to 20 days, and several periods throughout March–June of 35 to 40 days (total of ~50 days). Fishing prior to Christmas is aimed at the lucrative Christmas market and is coincidental with the onset of the spawning period when most females carry ripe or developing gonads (Dixon et al. 2013). Previous stock assessment research undertaken for the SGPF identified a negative relationship between the volume of prawns harvested during the early spawning season (prior to Christmas) and subsequent recruitment to the fishery (Dixon et al. 2007). In response to this finding, Primary Industries and Regions South Australia (PIRSA) (Fisheries and Aquaculture), and the Spencer Gulf and West Coast Prawn Fisherman's Association (SGWCPFA) agreed to cap catches during the early spawning season with the aim of increasing recruitment stability and annual catch. This policy has the potential to result in under-utilisation of the resource, particularly if the key areas for egg production and recruitment are not linked.

The BCF in Spencer Gulf is a quota-based fishery that uses pots and drop-nets to catch Blue Swimmer Crab (*Portunus armatus*) throughout the year except for a closed season between 21 December and 19 February. Fishing for Blue Swimmer Crab over summer is coincidental with the spawning season but is regulated by returning reproductively active 'ripe' females back to the water to optimise spawning success (Noell et al. 2014). Recruitment of Blue Swimmer Crab to the BCF in Spencer Gulf has remained relatively stable since fishing commenced, and the fishing season was extended to December in 2004/05 to take advantage of the lucrative Christmas market. The South Australian Blue Crab Pot Fishers Association (SABCPFA) raised concerns regarding the potential impacts of this protracted temporal change in fishing on larval productivity and dispersal into nursery areas of northern Spencer Gulf.

In 2008, SARDI Aquatic Sciences developed this FRDC Project (2008/011) in conjunction with the SGWCPFA and the SABCPFA to:

1) Improve the understanding of the biological and physical oceanographic processes that affect the distribution of Western King Prawn and Blue Swimmer Crab larvae between spawning and larval settlement;

2) Identify the areas most critical for spawning and settlement success; and

3) Enhance the harvest strategy for Western King Prawn and Blue Swimmer Crab during the spawning season.

2 Need

1) There is a need to incorporate environmental data in models of larval dispersal to improve the understanding of stock-recruitment relationships for two major crustacean fisheries, the SGPF and BCF in Spencer Gulf.

2) There is a need to identify regions critical for spawning and settlement success for Western King Prawn and Blue Swimmer Crab in Spencer Gulf.

3) There is a need to improve harvest strategies for Western King Prawn during the pre-Christmas fishing period, to maximise catch and minimise the impact on future recruitment to the fishery.

4) There is a need to understand the effect of natural variations in physical environmental parameters (including winds, tides and salinity) on larval ecology and recruitment success for Western King Prawn and Blue Swimmer Crab in Spencer Gulf.

5) There is a need to develop tools to address the potential impacts of climate change to these major fishery resources by understanding the effects of temperature change on stock-recruitment relationships.

3 Objectives

Based on the above needs the objectives of this project were to:

1) Develop models relating to the reproductive and larval biology of Western King Prawn and Blue Swimmer Crab in Spencer Gulf.

2) Develop a passive particle hydrodynamic model for Spencer Gulf.

3) Develop the base-case bio-physical model to simulate Western King Prawn and Blue Swimmer Crab larval dispersal, and assess the effects of different environmental conditions (e.g. water temperature) on larval recruitment.

4) Test scenarios to better optimise the harvest of Western King Prawn during the early spawning season.

4 Methods

4.1 Biological models

4.1.1 Overview of data sources

Several types of biological data are required to model patterns in the dispersal, distribution and abundance of crustacean larvae. Firstly, information relating to larval duration is needed so that the time-scale over which oceanic processes act to disperse larvae while in the planktonic phase can be quantified. Research relating to the larval development and duration of Western King Prawn was undertaken as a priority of this FRDC project and is reported below. Data relating to larval duration of Blue Swimmer Crab was sourced from Bryars and Havenhand (2006). An understanding is also required of how larval dispersal is affected by their swimming behaviour. This information was sourced from pre-existing studies that are detailed below, and provided key inputs into the final bio-physical model. Patterns of larval dispersal, distribution and abundance are also affected by the spatial distribution and reproductive phenology of adult stages. Information relating to the reproductive biology and spawning distribution of Western King Prawn and Blue Swimmer Crab in this study was sourced from pre-existing data-sets collected as part of annual stock assessment surveys undertaken by SARDI for the BCF and SGPF.

4.1.2 Larval duration

4.1.2.1 Western King Prawn

Samples of female prawns with visibly mature gonads (ripe) were collected from northern Spencer Gulf using standard otter trawl gear on board the fishing vessel 'Miss Anita'. Prawns with minimal trawl damage were immediately placed in recovery tanks consisting of 60 L plastic bins filled with seawater. Tanks had continuous water exchange and were aerated using battery powered air pumps. On return to port, prawns were transported live within the recovery tanks to laboratory facilities of SARDI at West Beach, Adelaide, within ~2 hours, where they were transferred to 230 L tanks (3–4 animals per tank) filled with static aerated seawater maintained at an ambient temperature of between 21 and 23 °C, and salinity of 38 ‰.

Female prawns spawned within 24 hours post capture. After spawning, eggs (~300 µm diameter) were siphoned from the tank and rinsed for 10 minutes in a 100 L container fitted with 150 µm mesh. Eggs were then placed back into clean 230 L tanks for hatching. Eggs generally hatched between 15–36 h after spawning, and nauplii were immediately removed from the spawning tanks for experimental use.

Prior to stocking, all tank water was sterilised using 15 mL sodium hypochlorite (12.5% w/v chlorine) solution overnight, neutralised with 1 g of sodium thiosulphate per 5 mL sodium hypochlorite, and prophylactically treated with 2 ppm probiotics (Sanolife). Probiotics (2 ppm) were administered to tanks on a daily basis to reduce the potential of disease (Hai et al. 2009).

Sixteen 100 L static experimental bags were used to stock prawn larvae within 170 L tanks maintained with controlled seawater exchange and connected to a heat exchange system. Four experimental bags (replicates) were housed in each of four experimental tanks, with each tank comprising one temperature treatment of either: 17, 20, 22.5 or 25 °C. Experimental bags were supported using 12 mm plastic pipe and connectors to make a cylindrical frame. Daily water changes commenced at day 5 at 10–15% of the volume of each bag. All seawater was filtered to 5 µm and UV treated before delivery to both bag and tank. During the experiment, photoperiod, light intensity, salinity, pH, and total ammonia were maintained at: 12 D, 193 lux (fluorescent tubes), and 38.0 ± 0.04 ‰ (SE), 8.15 ± 0.01 (SE) and 0.06 ± 0.01 mg.L^{-1} (SE), respectively.

Each experimental bag was initially stocked at 118.5 ± 7.6 nauplii.L^{-1}. Initial, day 1 water temperature and salinity was the same as the spawning tanks (ambient: 21 °C and 38 ‰, respectively) but subsequently adjusted over a 24 h period. This achieved different temperatures for each treatment by day 2. Larval stages and densities were recorded on a daily basis.

Feeding of larvae began with the introduction of micro-algae (*Chaetoceros muelleri, Isochrysis sp*.) at a concentration of ~1x10^4 cells.mL^{-1} when larvae reached the third naupliar sub-stage. Algal concentrations were monitored and maintained between ~1 x 10^4–1 x 10^5 cells.mL^{-1} during development of the zoea and at >1 x 10^5 cells.mL^{-1} during development of mysis stages. Enriched rotifers (*Brachionus plicatilis*) (RotiSelco ALG, INVE Aquaculture, Belgium) were introduced during early stages of zoea development and maintained between 2–10 rotifers.larva^{-1} during the later stages of zoea development. Rotifers were replaced with newly hatched *Artemia nauplii* at a concentration of ~15–30 nauplii.larva^{-1} when prawn larvae reached the mysis stage. Feeding was conducted on a daily basis, taking into consideration residual feed, and all feed concentrations were at, or greater than satiation to enhance survival and prevent any potential impacts of starvation on measures of larval duration (Preston 1985).

Larvae sampled from each tank were sieved through 150 µm mesh and viewed under a light microscope. Larval stages were assigned based on morphological progression as outlined in Shokita (1984). For the purposes of this report four main larval stages are considered: nauplius (approximate body length (BL) (335–445 µm), zoea (approximate BL 850–

2160 µm), mysis (sub-stages 1–3; approximate BL 2.4–3.7 mm) and postlarva (approximate BL >3.7 mm) (Figure 1). Tank experiments ended when 100% of larvae had reached the postlarval stage. To estimate larval duration, the time (in days) taken to reach each stage (nauplius, zoea, mysis, post-larvae) for each tank was defined as the time when larval densities for each stage peaked. This provided mean stage-specific larval duration (for tanks pooled).

To determine the relationship between temperature and the mean time (in days) to reach each main stage, power curves were fitted to the data using Model I regression techniques. Two separate analyses were conducted: (1) using data from our study only, and (2) using data from our study and additional data points from Shokita (1984). Data provided from Shokita (1984) encompassed larval durations at higher temperatures (zoea: 2 d at 29.7 °C; mysis: 5 d at 28.8 °C; postlarvae: 8 d at 29.3 °C). Power curves were of the form: $D = aT^b$, where D is mean time in days to reach each stage, a is a constant, T is temperature (°C) and b is a constant. Significance testing for the regression analyses was determined using ANOVA. Homoscedasticity and normality of the data were determined by Levene's test and visually assessed using residual plots. In all cases, significance was accepted at $P<0.05$. Data analyses were performed using SPSS software (SPSS, version 17.0) and values are presented as mean ± standard error.

For a more detailed description of the methods relating to this research and extension of its results refer to Roberts et al. (2012).

4.1.2.2 Blue Swimmer Crab

Bryars and Havenhand (2006) studied the effects of temperature on larval development period. Larval development times of 39.5 days from constant-temperature trial 1 (20 °C) were used as inputs in the bio-physical model for blue swimmer larval dispersal in Spencer Gulf.

4.1.3 Larval behaviour

4.1.3.1 Western King Prawn

The swimming characteristics of Western King Prawn larvae for each developmental stage applied in the bio-physical model were based on studies of penaeid prawns in the Gulf of Carpentaria (Rothlisberg 1982; Rothlisberg et al. 1995; 1996; Condie et al. 1999). The model for larval swimming behaviour included an initial period of 2 days when larvae are passive. After this time, nauplii to early/mid mysis stages were modelled as having a diurnal vertical migration (DVM) pattern where larvae swim near the bottom from dawn to dusk, and migrate into the water column between dusk and dawn. Late mysis and post larvae stages were modelled at day 26 to settle and switch from DVM behaviour to tidal stream transport (TST) behaviour synchronised with the tidal cycle. Larvae located in shallow areas (<15 m) were assumed to remain on the seabed during ebb tides and swim vertically into the water column between dusk and dawn during flood tides in response to increasing hydrostatic pressure. Vertical swimming speeds of larvae were modelled incrementally from 0.4 to 8 $cm.s^{-1}$ for each larval stage (nauplii to post-larvae).

4.1.3.2 Blue Swimmer Crab

The swimming characteristics of Blue Swimmer Crab larvae for each developmental stage applied in the bio-physical model were based on studies of Meagher (1971) and Campbell (1984), where for the first 26 days of development, zoea are assumed to remain passive. After this time, megalopae are assumed to exhibit a DVM pattern of swimming behaviour, where they migrate towards the surface between dusk and dawn at swimming speeds of 3 $cm.s^{-1}$.

4.1.4 Adult reproduction

To identify the areas critical for spawning of Blue Swimmer Crab and Western King Prawn and enable harvest sensitivity analyses for Western King Prawn, information relating to the reproductive biology of adult Blue Swimmer Crab and Western King Prawn was analysed from pre-existing data-sets collected as part of annual stock assessment surveys for the BCF and SGPF.

4.1.4.1 Western King Prawn

Surveys

Spatially stratified, fishery-independent, stock-assessment surveys have been undertaken by SARDI Aquatic Sciences in October/November, February and April of the fishing season since 2004. Between 179 and 206 sites were surveyed in Spencer Gulf in October/November between 2009 and 2012. Survey locations are shown in Figure 3 and are located within areas (‘fishing blocks’) of the fishery where the majority of the historic catch has been taken. Surveys use SGPF industry vessels with independent observers to collect data on the total catch of prawns, trawl time, trawl distance, trawl direction and water temperature. Samples of prawns are taken from the catch to obtain information relating to sex, length, weight and sex ratio. Data from prawns sampled in October and November, the key months of spawning activity, provided information relating to the spatial characteristics of reproduction during the spawning season and were used to estimate egg production. To enable development of the biological and bio-physical models for prawns and undertake harvest sensitivity analyses, the main trawl ground targeted by the SGPF was split into Areas 1–19 (Figure 3).

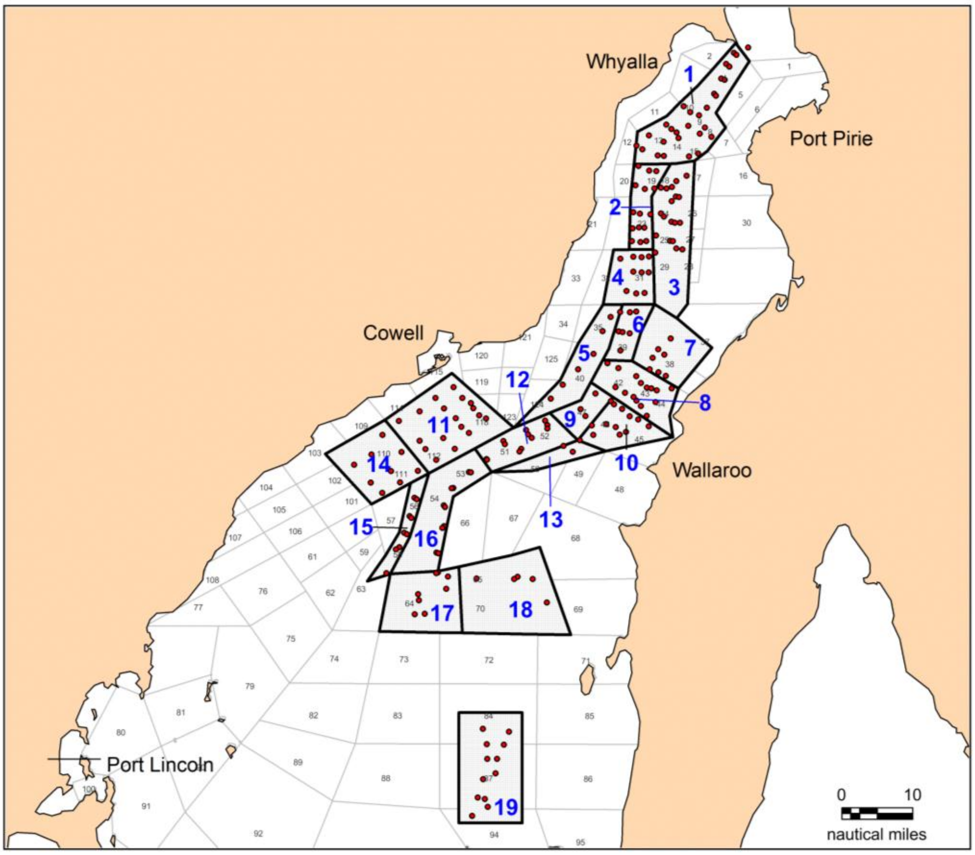

Figure 3. Map showing the distribution of 1) stock assessment survey sites throughout Spencer Gulf between 2009 and 2012 (red dots); 2) traditional fishing 'blocks' used in the fishery to report catch (blocks 1–125)(delineated by light grey grid lines); and 3) Areas 1–19 that were used to develop the biological and bio-physical models (delineated by bold black grid lines).

Adult reproductive parameters

To estimate egg production of prawns within each Area (1–19) in the pre-Christmas (October/November) fishing period, data were collected for a number of adult reproductive parameters. These parameters and their data constituents were:

1) Prawn size: The carapace length (CL, mm) and weight (g) of male and female prawns were measured from a sample of ~100 prawns from each survey shot undertaken in the pre-Christmas (October/November) fishing period between 2009 and 2012.

2) The total sample weight of female prawns: The total sample weight (g) of female prawns (FWt_{sample}) was measured from the sample of prawns captured in each survey shot undertaken in the pre-Christmas (October/November) fishing period between 2009 and 2012.

3) The total survey catch-weight of female prawns: The total weight of female prawns (FWt_{ttl})(kg) caught in each survey shot during pre-Christmas (October/November)

surveys between 2009 and 2012 was estimated by multiplying the total survey catch weight (kg) by the sex-weight ratio of females sampled in each survey shot.

4) Maturity: The proportion of female prawns (egg bearing) that were likely to be mature at a given size (M_p) was estimated from the logistic equation taken from Carrick (1996):

$$Mp = 8.3 * 10^{-6} + \left[\frac{1}{1 + e^{-(0.277\,(CL - 36.45))}} \right]$$

where the carapace length (CL) at which 50% of the female population are mature is estimated at 36.5 mm (Figure 4).

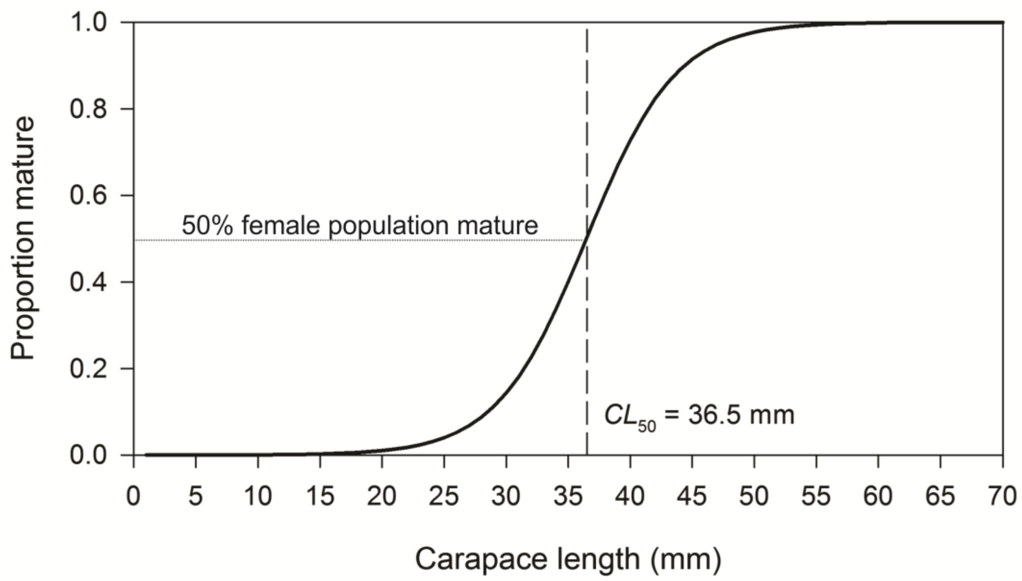

Figure 4. The relationship between carapace length and sexual maturity of female Western King Prawn in Spencer Gulf.

5) Fertilisation success: The fertilisation success (FS) of a prawn of a given size was determined by fitting a logistic curve to the data published for Western King Prawn in Courtney and Dredge (1988).

6) Fecundity: The length specific fecundity (F) of Western King Prawn was estimated from laboratory analyses of the ovaries of 28 female prawns sampled in Spencer Gulf during the November 2007 survey. The relationship between female carapace length (CL, mm) and fecundity was determined by linear regression analysis and used to estimate F for female prawns in all size classes sampled.

Egg Production

The total pre-Christmas (October/November) egg production of adult Western King Prawn in each Area (1–19) was calculated from the adult reproductive parameters above using a number of steps:

1) The total number of fertilised eggs produced by each size class (CL, mm) of female prawns sampled from each survey shot was calculated as:

$$EP_{CL} = F_{CL} * Mp_{CL} * FS_{CL} * N\ Females_{CL}$$

where:

F_{CL} is the estimated fecundity of female prawns within a given size class (CL) defined by linear regression analysis (Section 4.1.4.1);

Mp_{CL} is the estimated proportion of female prawns likely to be mature within a given size class (CL) (Section 4.1.4.1);

FS_{CL} is the estimated fertilisation success (FS) within a given size class (CL) (Section 4.1.4.1); and

N $Females_{CL}$ is the number of females within a given size class (CL).

2) Egg production of all female Western King Prawn sampled in each survey shot (EP_{shot}) was then calculated as:

$$EP_{shot} = \left(\frac{\sum EP_{CL}}{FWt_{sample}} \right) * FWt_{ttl} * 1000$$

3) The total egg production for prawns in each area (EP_{area}) (Areas 1–19) was then scaled to the total distance trawled by surveys in each area, and the area available to fishing. This was calculated as:

$$EP_{area} = \frac{\sum EP_{shot}}{\%\ \text{area trawled in surveys}} * 100$$

Analyses of egg production presented in this report are underpinned by a range of assumptions including:

1) catchability of prawns is constant during the pre-Christmas surveys;
2) mean survey catch rate in each area (Areas 1–19) is representative of the population density in the whole area;
3) spawning fraction of female prawns is constant during the pre-Christmas surveys and between locations and years;
4) spawning frequency is constant and does not vary with prawn size;
5) fecundity is constant between locations and years;
6) prawn size at maturity doesn't vary with time;
7) natural mortality of eggs is zero during each pre-Christmas fishing period;
8) percentage of females does not vary within an area (Areas 1–19) during the spawning season;
9) sex-specific length frequency data from surveys were representative of the population in each area.

4.1.4.2 Blue Swimmer Crab

Surveys

A voluntary fishery-dependent pot-sampling program has been undertaken in Spencer Gulf by members of the BCF since 2006. Data collected in the program include GPS coordinates of pot locations, and the sex, size and reproductive condition of individual crabs. Because the sampling program is fishery-dependent, sampling locations are not spatially stratified. Consequently, reliable estimates of total pre-Christmas egg production within the fishery could not be calculated. However, the data provided by the sampling program allows broad analysis of the key regions in Spencer Gulf used for spawning.

In 2009, 2010, 2012 and 2013, a total of 2,725 females were sampled across a total of 461 locations during the pre-Christmas period (November and December). These data were used to identify the key regions in Spencer Gulf used for spawning (note that 2011 was excluded from this study due to limited pre-Christmas fishing and data). To enable spatial analyses of reproductive information and develop bio-physical models for Blue Swimmer Crab, the main grounds targeted by the BCF were split into 14 areas. The areas sampled and used in all analyses are consistent with locations of historical commercial fishing and are depicted in

Figure 5 (Noell et al. 2014).

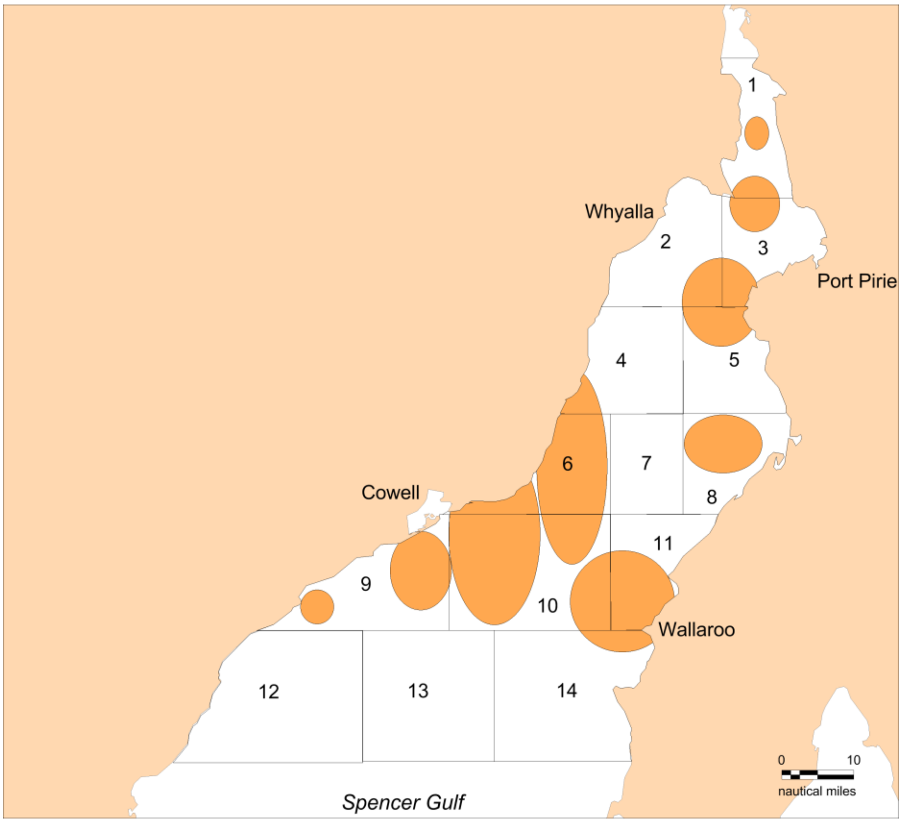

Figure 5. Map showing the areas of Blue Swimmer Crab fishery-dependent pot-sampling in Spencer Gulf between 2009 and 2012 and the Areas (1–14) used to develop the biological and bio-physical models.

Adult reproductive parameters

To assess the spatial reproductive characteristics of Blue Swimmer Crab spawning within Spencer Gulf in the pre-Christmas (November/December) fishing period, data were analysed for a number of reproductive parameters. These parameters and their data constituents were:

1) Female crab size: The carapace width (CW, cm) of 2,725 individual females caught by fishers during the pre-Christmas (November/December) fishing period.

2) Spawning fraction: Pre-Christmas spawning fraction was estimated as the proportion of the females that were recorded as bearing fully matured eggs ("berried") in the catch.

3) Fecundity: The size-specific fecundity (F) of Blue Swimmer Crab (CW, cm) was estimated from linear regression analysis taken from Kumar et al (2000):

$$F = 26.139*CW^{4.3685}$$

4.2 Bio-physical model

A bio-physical model was developed to simulate patterns of larval dispersal and settlement for Western King Prawn and Blue Swimmer Crab in Spencer Gulf. The bio-physical model coupled a three-dimensional hydrodynamic model to an offline Lagrangian particle-tracking model. Parameters of the bio-physical model were derived from the physical ocean characteristics of Spencer Gulf, and biological characteristics of larval duration and behaviour for Western King Prawn and Blue Swimmer Crab (Sections 5.1.1 and 5.1.2).

4.2.1 Hydrodynamic modelling

Ocean circulation within Spencer Gulf was simulated using the Regional Ocean Modelling System (ROMS). ROMS is a high resolution, three-dimensional, free-surface, hydrostatic, primitive-equation ocean model that uses stretched, terrain-following coordinates in the vertical dimension (Shchepetkin and McWilliams 2005). The ROMS developed for Spencer Gulf (hereby referred to as the Spencer Gulf Model, SGM) had a horizontal grid spacing of 600m (312 x 616 grid points) and 15 vertical layers. The SGM incorporated a time step of 150 seconds to allow the model to solve the dominant tidal currents occurring in Spencer Gulf. Conditions for velocity, temperature and salinity in two-dimensions at the open boundaries were obtained from the output of a previously developed large-scale model, the South Australian Regional Ocean Model (SAROM). The SAROM was developed as part of the FRDC Project 2009/046, 'PIRSA Initiative II: carrying capacity of Spencer Gulf: hydrodynamic and biogeochemical measurement, modelling and performance monitoring', (Middleton et al. 2013). Tidal forcing was imposed at the open boundaries of both the SGM and SAROM. Values for the tidal constants were obtained from the *TPXO7.2 global data base* (Egbert and Erofeeva 2002). The atmospheric forcing components of both models consisted of monthly mean values of wind stress, net freshwater flux, net heat flux and downwards shortwave radiation averaged over a ten-year period from July 1999 to December 2008. Wind stress and net freshwater flux was estimated using a combination of local meteorological data and data from the *NCEP global database* (Kanamitsu et al. 2002). The net heat-flux and downwards shortwave radiation were based on *OAFlux* (Objectively Analysed Flux data, Yu et al. 2008). Initial states of temperature and salinity in the SAROM were interpolated from the *CARS 2006 atlas* of monthly means (Dunn and Ridgway 2002). The vertical eddy viscosity and diffusivity for both models were computed using the Mellor-Yamada 2.5 level turbulence closure scheme and the horizontal eddy viscosity and diffusivity were set to 20 $m^2.s^{-1}$ and 1 $m^2.s^{-1}$, respectively.

4.2.2 Larval tracking model

4.2.2.1 Overview

The offline Lagrangian particle-tracking model used to develop the bio-physical model was the Larval Dispersal model (LTRANS) described in North et al. (2006, 2008). In summary, LTRANS uses outputs from the ROMS hydrodynamic model to track the trajectories of particles in three dimensions. It takes into account particle advection, vertical turbulent particle motion, reflective boundary conditions, larval behaviour and settlement (North et al. 2008).

For three-dimensional particle movements, current predictions from the SGM were interpolated in both space and time to give a fine-resolution current field for the advection of particles using a 4th order Runge-Kutta advection scheme. To simulate the influence of bottom friction on currents, a logarithmic reduction in current velocities is implemented in LTRANS within the bottom vertical layer. Two-dimensional water properties (e.g. surface height, water depth) are interpolated in space relative to the particle location.

The influence of sub-grid scale turbulence on particle motions is simulated using a random displacement model with a horizontal diffusivity equivalent to 1 m^2s^{-1} and a vertical diffusivity equivalent to the shear in the water column (Visser 1997). Particles passing through horizontal boundaries due to turbulence or advection are reflected back into the model domain. Particles moving through vertical boundaries are placed just above/below the bottom/surface, respectively.

4.2.2.2 Initial conditions and source/sink regions

Larvae were seeded onto a regular grid covering the entire region of Spencer Gulf at an interval of 1.2 km (every second grid cell) for all water depths greater than 15 m and as far south as Port Lincoln (-34° 48’ 00’’) (Figure 6). At each grid point, 12 larvae were released, giving a total of 7500 larvae for each simulation. Larvae were released 0.3 m above the bottom for Western King Prawn and 1 m below the surface for Blue Swimmer Crab.

The connectivity of larvae from their source in individual fishing areas (Areas 1–19: Western King Prawn; Areas 1 to 14: Blue Swimmer Crab) to their sinks on settlement grounds was modelled for different combinations of tidal-physical and atmospheric-physical forcing and larval behaviour (Section 4.2.2.3). Areas used in the model were based on an aggregation of traditional fishing blocks used to report catch in the SGPF and BCF (Figure 6). The areas used are also representative of the locations where the majority of the fishing is undertaken in both fisheries and of the locations regularly surveyed by SARDI Aquatic Sciences for stock assessment purposes. A total of 18 settlement grounds (sinks) (Figure 6) were defined for the areas of tidal flat and mangrove forest in Spencer Gulf that are considered to be the main nursery grounds (Bryars 2003).

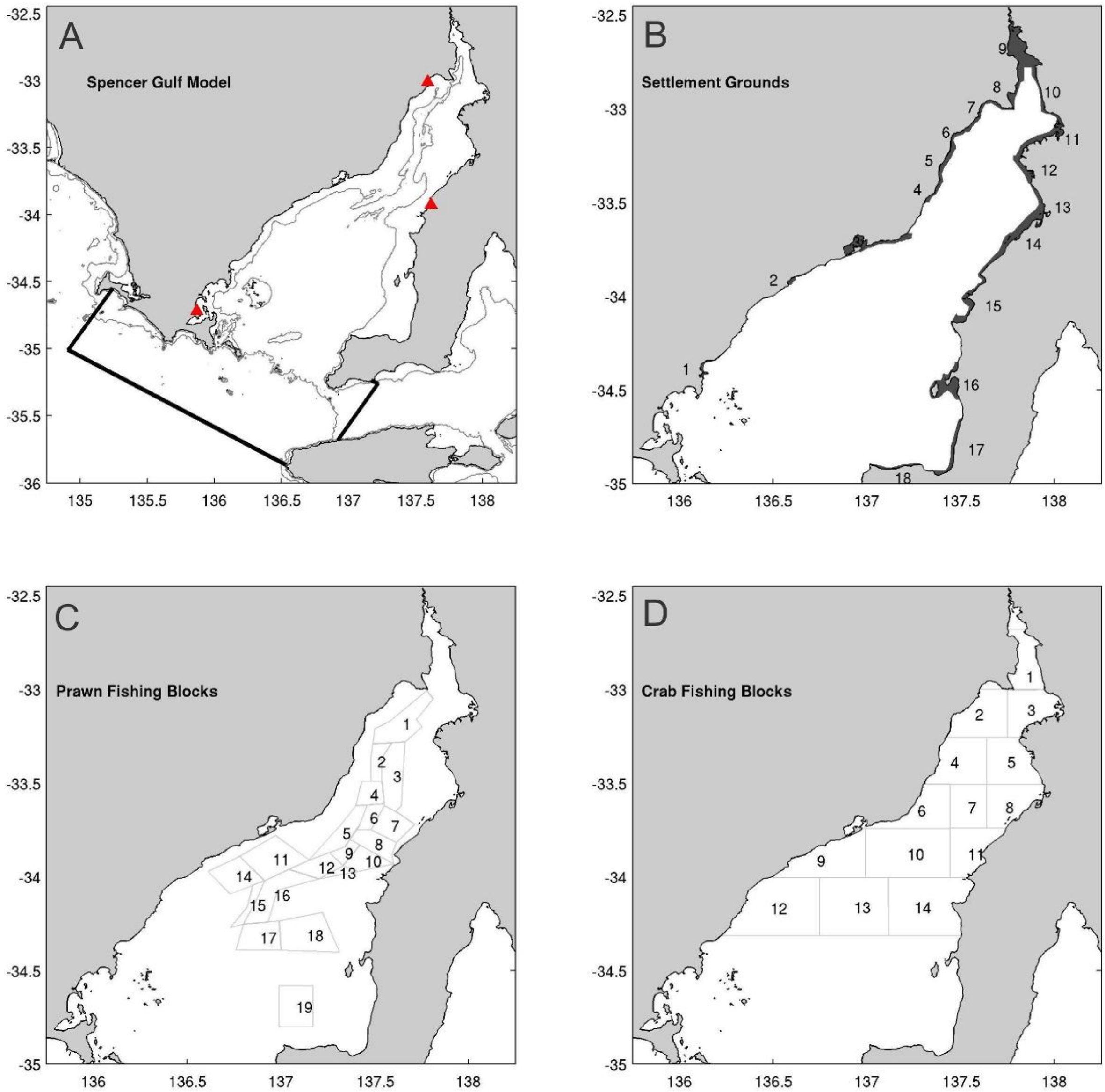

Figure 6. Maps showing the locations of areas within Spencer Gulf used in the bio-physical model. A) the southern model boundary (black line), sea-level measurement locations ▲, water depths of 10 m and 50 m (light grey contour lines); B) Settlement Grounds (1–18) (Bryars 2003); C) Source Areas (1–19) for Western King Prawn larvae; D) Source Areas (1–14) for Blue Swimmer Crab larvae.

4.2.2.3 Modelled scenarios of larval dispersal and settlement

Five different scenarios of larval dispersal and settlement were simulated by different runs of the bio-physical model. Model runs are summarised below and in Table 1. For Western King Prawn, 1 to 4 scenarios of larval dispersal and development were tested. All four scenarios were based on peak spawning occurring on November 1. Scenarios varied as follows:

Scenario 1: This model run incorporated tidal physical forcing components and atmospheric physical forcing components (evaporation, precipitation and wind) but excluded information about larval swimming behaviour. The model used a mean temperature of 16.9 °C estimated from satellite imagery (1986–2004) for the Gulf for November 1, and a corresponding larval development period of 46 days (including a 20 day post-larval phase) (Physical Oceanography Distributed Active Archive Centre (PODACC); Roberts et al. 2012).

Scenario 2: This model run incorporated tidal physical forcing components but excluded atmospheric physical forcing components. Larval swimming behaviour was also incorporated. The model used a mean temperature of 16.9 °C estimated from satellite imagery for the Gulf for November 1, and a corresponding larval development period of 46 days (including a 20 day post-larval phase) (Roberts et al. 2012).

Scenario 3: This model run incorporated tidal physical-forcing components, atmospheric physical-forcing components and larval-swimming behaviour. The model used a mean temperature of 16.9 °C estimated from satellite imagery for the Gulf for November 1, and a corresponding larval development period of 46 days (including a 20 day post-larval phase) (Roberts et al. 2012).

Scenario 4: This model run incorporated tidal physical forcing components, atmospheric physical forcing components and larval swimming behaviour. The model simulated an above average Gulf temperature at spawning of 19.9 °C and a corresponding larval-development period of 39 days (including a 20 day post-larval phase) (Roberts et al. 2012).

Scenario 5: This scenario was run specifically for Blue Swimmer Crab with a peak in spawning assumed as occurring on December 10. The model run incorporated tidal physical-forcing components, atmospheric physical-forcing components and larval swimming behaviour (DVM only). The model assumed an average Gulf temperature at spawning of 20 °C and a larval development period of 40 days (Bryars and Havenhand 2006).

Table 1. Summary of the scenarios tested by the bio-physical model for Western King Prawn (WKP) and Blue Swimmer Crab (BSC) larvae detailing the length over which the model was run, and whether physical forcing (tides and temperature) parameters and vertical migration behaviour were included.

Scenario	Run Period	Species	Tides	Climatology	Behaviour
1	1 Nov – 17 Dec	WKP	Yes	Yes	None
2	1 Nov – 17 Dec	WKP	Yes	None	Yes
3	1 Nov – 17 Dec	WKP	Yes	Yes	Yes
4	1 Nov – 05 Dec	WKP	Yes	Yes	Yes
5	10 Dec – 18 Jan	BSC	Yes	Yes	Yes

4.3 Harvest sensitivity analyses

Harvest sensitivity analyses were undertaken to assess how settlement rates of Western King Prawn larvae would respond to hypothetical changes in the spatial distribution of catch and amount of catch taken in the SGPF. Several steps were performed to undertake the sensitivity analyses:

1) Pre-fished estimates of total potential egg production (EP_{area}) for each area between 2009 and 2012 were calculated (see Section 4.1.4.1). These estimates were then converted to the amount of female catch potentially available within an area by the equation:

$$\text{Total female catch potentially available (kg)} = \frac{EP_{area}}{EP_{females.kg^{-1}}}$$

where:

$$EP_{females.kg^{-1}} = \frac{\sum EP_{shot}}{\sum FWt_{ttl}}$$ (see Section 4.1.4.1)

2) Pre-Christmas catch estimates were then calculated by extracting, through Geographic Information System (GIS) procedures, geo-referenced catch data obtained from ~33% trawls between 2009 and 2012. This enabled the relative proportion of catch in each area to be estimated. The total catch (i.e. 100% of trawls) in each area was then estimated by apportioning the total pre-Christmas catch, which was recorded from daily commercial catch and effort logbook data, among Areas 1–19.

3) Pre-Christmas exploitation rates on female biomass (and egg production) for each area and year were then estimated by the equation:

$$\text{Exploitation rate} = \frac{\text{Total estimated female catch recorded}}{\text{Total female catch potentially available}}$$

4) Pre-Christmas exploitation rates were then used to assess the resulting settlement success (as determined from the bio-physical model) for each area (Areas 1–19) of the fishery between 2009 and 2012. These data provided a baseline to hypothetically test how levels of larval settlement may be affected by changes in the distribution and amount of pre-Christmas catch in different Areas (1–19) of the fishery.

Larval settlement success for each hypothetical fishing scenario was calculated using settlement rates obtained under Scenario 3 of the bio-physical model (see Section 5.2.1.2). Scenario 3 was considered to most closely represent the biological and physical ocean parameters acting on larval dispersal and settlement of Western King Prawn in Spencer Gulf during the pre-Christmas spawning period.

Harvest sensitivity analyses were run for the following scenarios for pre-Christmas fishing periods in 2010 and 2011. These years represent the lowest (333 t) and highest (532 t) levels of pre-Christmas catch recorded, respectively, between 2009 and 2012.

1) Baseline (i.e. the actual estimated exploitation rate determined by the amount of pre-Christmas catch taken in each area).
2) Excluding fishing from the top 5 Areas (1–19) contributing to settlement and redistributing the catch from these areas proportionately to all other fishing areas.
3) Setting female exploitation rate to 5% in the top 5 areas contributing to settlement and maintaining female exploitation rates in all other areas at baseline levels.
4) Setting female exploitation rate to 5% in the top 5 areas contributing to settlement and 30% in all other areas.
5) Setting female exploitation rate to 5% in the top 5 areas contributing to settlement and 25% in all other areas.
6) Setting female exploitation rate to 2.5% in the top 5 areas contributing to settlement and 30% in all other areas.

7) Setting female exploitation rate to 2.5% in the top 5 areas contributing to settlement and 35% in all other areas.

8) Setting female exploitation rate to 0% in the top 5 areas contributing to settlement and 35% in all other areas.

5 Results

5.1 Biological models

5.1.1 Larval duration models

5.1.1.1 Western King Prawn

There was an inverse relationship between water temperature and the time taken for Western King Prawn larvae to reach post larvae from hatching. Mean larval duration ranged from 12.7 ± 0.2 days at a mean temperature of 24.36 ± 0.08 °C (25 °C treatment) to 31.3 ± 1.4 days at a mean temperature of 17.12 ± 0.02 °C (17°C treatment) (Table 2). Maximum larval durations (i.e. time for 100% of larvae to reach the post larva stage) for the 25°C and 17°C treatments were 14 and 33 days, respectively. Mean stage-specific duration was greatest for the zoea stage in the 17°C (14.9 ± 0.1 days), 20°C (8.8 ± 0.5 days) and 22.5°C (6.5 ± 0.3 days) treatments, representing 48%, 44% and 43% of total larval duration periods, respectively. Larval duration was similar between the zoea and mysis stages in the 25 °C treatment (5.0 ± 0.4 and 5.2 ± 0.2 days, respectively), together representing 80% of the total larval duration period at this temperature (Table 2).

Table 2. Mean (±SE) duration of Western King Prawn larvae cultured at four constant temperatures. Data are presented for four developmental stages: N=Nauplius, Z=Zoea, M=Mysis and PL=Postlarva.

Treatment	Mean temperature (°C)	Stage	Temperature (°C)	Duration to reach stage from hatching (d)	Stage-specific duration (d)
17	17.12 (0.02)	N	20.10 (0.04)	–	5.4 (0.2)
		Z	17.91 (0.02)	5.4 (0.2)	14.9 (0.1)
		M	17.07 (0.06)	20.3 (0.3)	11.0 (1.7)
		PL	16.85 (0.02)	31.3 (1.4)	–
20	20.35 (0.02)	N	20.20 (0.16)	–	3.0 (0.0)
		Z	20.31 (0.04)	3.0 (0.0)	8.8 (0.5)
		M	20.52 (0.02)	11.8 (0.5)	8.3 (0.3)
		PL	20.19 (0.03)	20.0 (0.4)	–
22.5	22.17 (0.02)	N	22.50 (0.18)	–	3.0 (0.0)
		Z	22.16 (0.01)	3.0 (0.0)	6.5 (0.3)
		M	22.20 (0.01)	9.5 (0.3)	5.6 (0.2)
		PL	22.15 (0.05)	15.1 (0.1)	–
25	24.36 (0.08)	N	21.80 (0.12)	–	2.5 (0.3)
		Z	23.37 (0.35)	2.5 (0.3)	5.0 (0.4)
		M	24.47 (0.09)	7.5 (0.3)	5.2 (0.2)
		PL	24.59 (0.03)	12.7 (0.2)	–

Power curves fitted to data from: (1) the current study only (16.9–24.6 °C) and (2) the current study plus that of Shokita (1984) (16.9–29.7 °C) (Figure 7) provided a high degree of predictive power (r^2 ≥0.84) particularly for mysis and post-larva stages (r^2 ≥0.99) (Table 3). Data from the current study showed a statistically significant relationship between temperature and larval duration (days) for the time to reach mysis and post-larva stages (P<0.005), but not for the time to reach zoea (P=0.06). With additional data points at higher temperatures, sourced from Shokita (1984), the relationship between temperature and larval duration improved and was significant for all stages (PZ, P<0.03; M and PL, P<0.001) (Table 3).

The power relationships exhibit a curvilinear slope indicating that larval duration is more sensitive to a temperature change at the lower end of the 17–30 °C temperature range (Figure 7). For example, the mean time to reach the post-larva stage at constant temperatures of 23 °C and 25 °C (a 2 °C change) was 14.5 and 11.8 days, respectively (i.e. a difference of 2.7 days or 19%), while the mean time to reach the post larva stage at constant temperatures of 17 °C and 19 °C (also a 2 °C change) was 30.3 and 23.1 days, respectively (i.e. a difference of 7.2 days or 24%). Also, the effect of temperature on larval duration is greater in late larval stages (e.g. post-larval duration is relatively shorter in response to increases in temperature when compared to larval duration of zoea)(Figure 7).

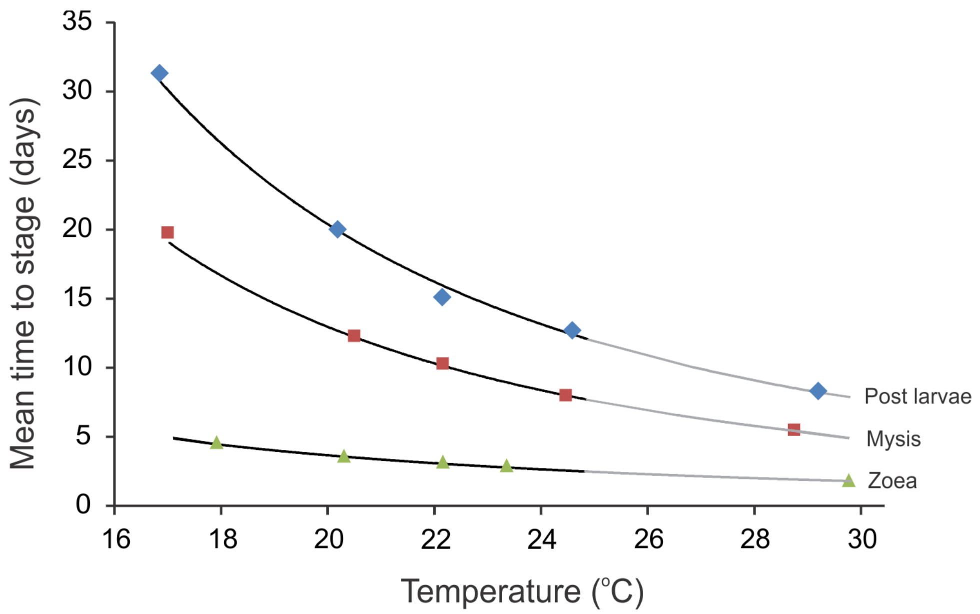

Figure 7. Mean time (d) to reach zoea, mysis, and postlarva stages from hatching at constant temperatures. Black data points and black fitted power curves indicate data from our study, while grey indicates where data from Shokita (1984) were included.

Table 3. Results of regression analyses for mean time (days) for eggs to reach zoea, mysis, and post-larva stages at constant temperatures. Two groups of analyses were conducted using: (1) data from our study only, and (2) data from our study plus an extra data point from Shokita (1984). Curves were of the form D = aTb; D, mean time (days) to each stage; a, constant; T, temperature (°C); b, constant; asterisk indicates significant P value (<0.05). SE, standard error.

Stage	a (SE)	b (SE)	r^2	F	P
1) Z	11,821.6 (24,985.9)	-2.693 (0.696)	0.882	15	0.061
1) M	52,644.1 (14,600.7)	-2.776 (0.091)	0.998	927	0.001*
1) PL	30,994.9 (13,877.1)	-2.446 (0.147)	0.993	275	0.004*
2) Z	781.0 (1,093.0)	-1.790 (0.450)	0.841	16	0.028*
2) M	37,644.6 (9,140.0)	-2.664 (0.078)	0.997	1163	0.000*
2) PL	30,900.8 (7,731.8)	-2.445 (0.081)	0.997	922	0.000*

5.1.1.2 Blue Swimmer Crab

The development periods for Blue Swimmer Crab larvae used to simulate larval dispersal and settlement in the bio-physical model are taken from previous research and described in Section 4.1.2.2.

5.1.2 Larval behaviour models

The day-night swimming characteristics of Western King Prawn and Blue Swimmer Crab larvae used to simulate larval dispersal and settlement in the bio-physical model are taken from previous research and described in Section 4.1.3.2.

5.1.3 Adult reproductive models

5.1.3.1 Western King Prawn

5.1.3.1.1 Female prawn size

The average length (mm, CL) of female prawns was estimated from samples of 100 prawns taken from a total of 747 survey shots undertaken in the pre-Christmas (October/November) fishing period between 2009 and 2012. Average prawn size (mm, CL) caught in each Area (1–19) is presented relative to the prawn grades used in the fishery (extra-large to small) which are based on the number of individual prawns comprising one pound (lb) (e.g. extra-large = under 10 (U10) prawns per pound) (Figure 8).

Between 2009 and 2012, small (grade 20+, <35 mm CL) and medium (grade 16–20, 35–39 mm CL) prawns were caught consistently in Areas 1 and 16. Extra-large (grade U10, >46 mm CL) and large (grade 10–15, 39–46 mm CL) female prawns were caught consistently in Areas 2–13, and Areas 17 and 19 (Figure 8). In 2012, the fishery caught extra-large (grade U10, >46 mm CL) female prawns from a cluster of areas located in eastern Spencer Gulf (Areas 7–10 and 13). These areas are situated near to Wallaroo, one of the main ports used by the SGPF.

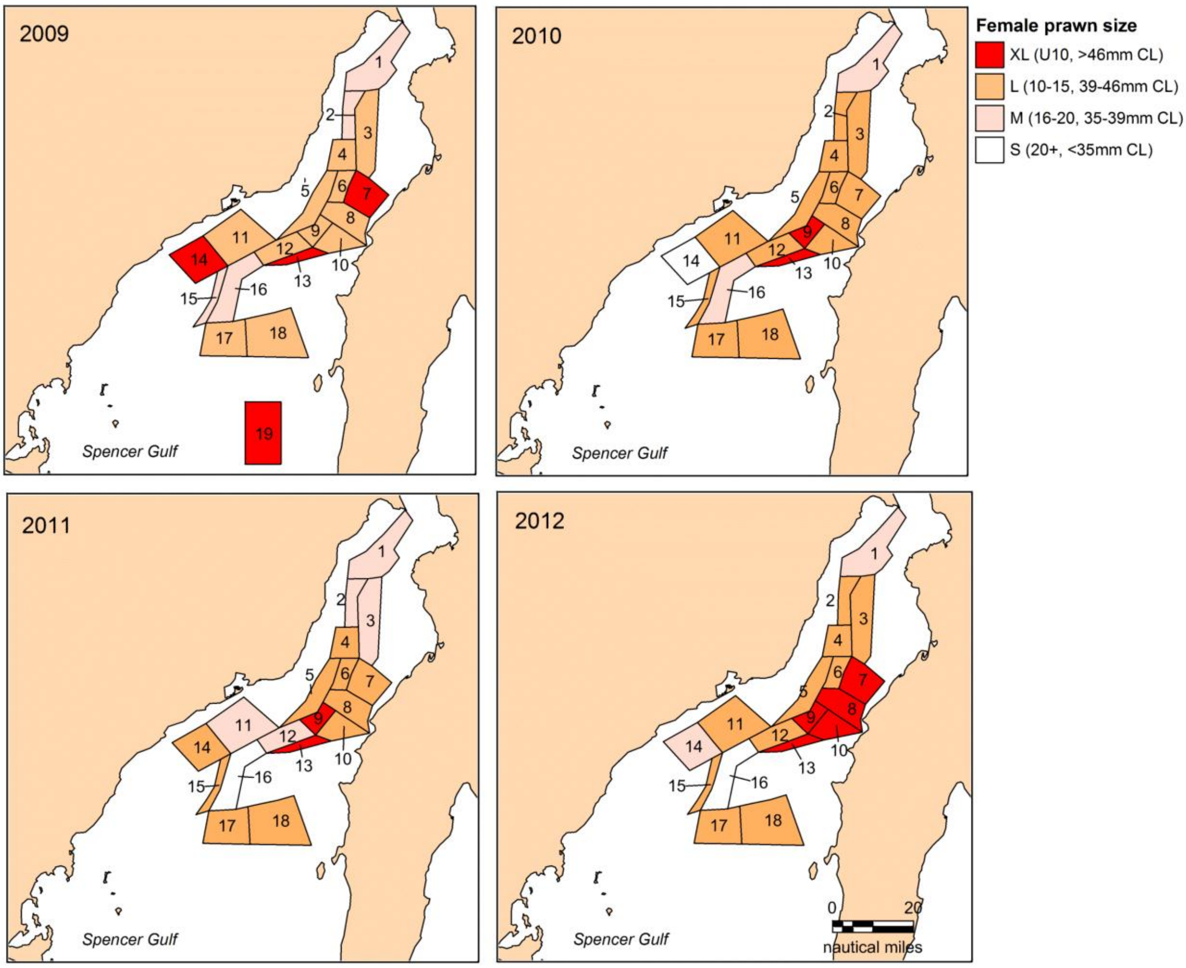

Figure 8. The average size (CL, mm) of female Western King Prawn caught in Areas 1–19 by pre-Christmas fishing surveys between 2009 and 2012.

5.1.3.1.2 Total sample weight of female prawns (FWt_{sample}) and total survey catch weight of female prawns (FWt_{ttl})

The total survey catch weight of female prawns was estimated from the weight ratio of male to female prawns sampled from 747 survey shots undertaken in the pre-Christmas (October/November) fishing period between 2009 and 2012. The total weight of female prawns (FWt_{sample}) sampled from each shot ranged from 529 g (N=22 females) in 2011 to 5692 g (N=133 females) in 2010. The total weight of female prawns (FWt_{ttl}) caught in each survey shot ranged from 1 kg in 2009 and 2012 to 140 kg in 2011.

5.1.3.1.3 The maturity of females in each size class (Mp)

The proportion of female prawns (egg bearing) likely to be mature at a given size (M_p) is taken from Carrick (1996) and described in Section 4.1.4.1.

5.1.3.1.4 Fertilisation success (FS)

The fertilisation success of a female prawn of a given size was determined by fitting a logistic curve to the data of Courtney and Dredge (1988). Fertilisation success increased with size and was described by the equation:

$$FS= A/(1 + \exp(-k*(x-xc)))$$

where A is the asymptote, xc is the size at which 50% of females are fertilised (33.6 mm CL), and *K* is a constant proportional to the size at which fertilisation increases with size (Figure 9).

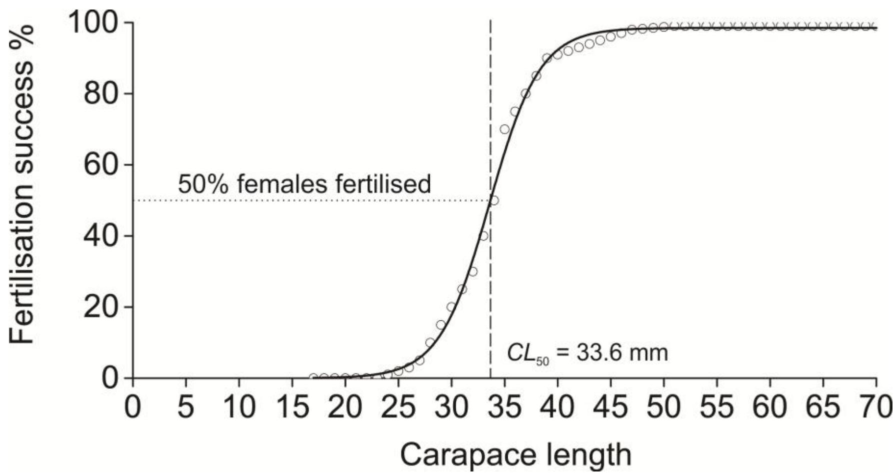

Figure 9. The relationship between carapace length and fertilisation success for female Western King Prawn (adapted from Courtney and Dredge 1988).

5.1.3.1.5 Fecundity (F)

Length-specific fecundity was estimated from laboratory analyses of the ovaries of 28 female prawns sampled in the November 2007 survey. Power curves fitted to these data provided a high degree of predictive power (r^2 =0.81). Fecundity increased exponentially with carapace length with female prawns of 50 mm (CL) producing over 200,000 eggs in each batch (Figure 10).

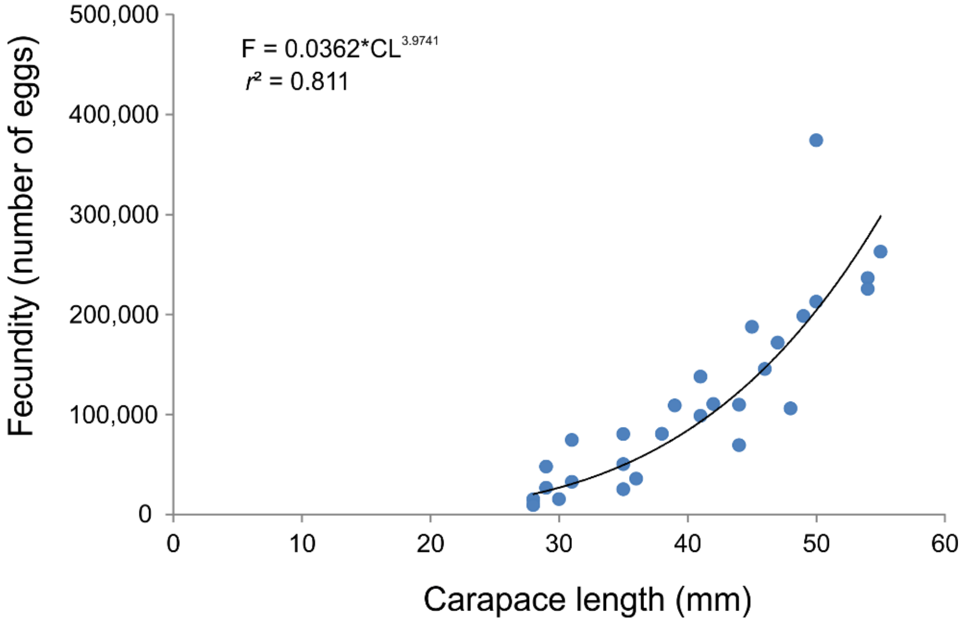

Figure 10. The relationship between fecundity (number of eggs) and carapace length (CL, mm) for female Western King Prawn in Spencer Gulf.

5.1.3.1.6 Egg production

Pre-Christmas surveys undertaken in Areas 1–19 between 2009 and 2012 covered total trawled areas ranging between 10.3 and 12.8 km^2 (Table 4). The areas surveyed comprised between 0.23% and 0.25% of the estimated total area available to fishing. Total egg production (EP_{area}) in each area estimated from pre-Christmas (October/November) surveys ranged from 37 billion eggs in Area 13 (2012) and Area 15 (2009) to 543.1 billion eggs in Area 1 in 2010 (Table 4). Total pre-Christmas egg production for all areas in each year ranged from 2,568 billion eggs in 2012 to 3,629 billion eggs in 2010 (Table 4).

Areas 1, 3 and 11 ranked in the top five areas contributing to egg production in all years between 2009 and 2012 (Table 4, Figure 11). Areas 4, 7 and 16 ranked in the top five areas contributing to egg production in two out of four years surveyed between 2009 and 2012 (Table 4, Figure 11).

High egg densities ranging from 0.760 to 2.429 billion eggs/km^2 (EP_{area}/km^2) were consistently recorded from Areas 1 and 13 in all years surveyed. Areas 4, 6 and 9 also recorded some of the highest egg densities (0.733 to 1.881 billion eggs/km^2) of all regions in at least two of the four years surveyed (Table 4).

Table 4. Egg production calculated from pre-Christmas surveys undertaken in Areas 1–19 between 2009 and 2012.

	2009				**2010**				**2011**				**2012**			
Area number	**Area trawled by survey km²**	**Total available area km²**	**EP_{area} (x billion)**	**EP_{area}/ km²**	**Area trawled by survey km²**	**Total available area km²**	**EP_{area} (x billion)**	**EP_{area}/ km²**	**Area trawled by survey km²**	**Total available area km²**	**EP_{area} (x billion)**	**EP_{area}/ km²**	**Area trawled by survey km²**	**Total available area km²**	**EP_{area} (x billion)**	**EP_{area}/ km²**
1	1.07	393.2	360.5	0.917	1.18	393.2	543.1	1.381	1.10	393.2	361.6	0.920	1.17	393.2	321.3	0.817
2	0.80	139.7	59.7	0.427	0.87	139.7	182.0	1.303	0.75	139.7	113.8	0.815	0.92	139.7	90.5	0.648
3	1.25	369.1	195.7	0.530	0.95	369.1	391.9	1.062	0.69	369.1	355.7	0.964	1.11	369.1	231.9	0.628
4	0.67	166.9	94.0	0.563	0.64	166.9	309.9	1.857	0.58	166.9	244.8	1.467	0.69	166.9	116.2	0.696
5	0.40	266.5	104.9	0.394	0.41	266.5	222.6	0.835	0.43	266.5	115.9	0.435	0.39	266.5	64.9	0.244
6	0.40	117.3	94.3	0.804	0.40	117.3	91.7	0.782	0.41	117.3	110.6	0.943	0.38	117.3	73.8	0.629
7	0.35	247.6	179.0	0.723	0.51	247.6	186.6	0.754	0.61	247.6	169.8	0.686	0.61	247.6	157.1	0.634
8	0.96	230.2	162.3	0.705	1.00	230.2	96.2	0.418	1.08	230.2	93.3	0.405	1.06	230.2	130.1	0.565
9	0.19	96.2	72.9	0.758	0.21	96.2	181.0	1.881	0.20	96.2	85.9	0.893	0.20	96.2	70.5	0.733
10	0.77	193.4	125.0	0.646	0.84	193.4	115.6	0.598	0.86	193.4	92.7	0.479	0.79	193.4	143.9	0.744
11	1.26	461.7	350.6	0.759	1.12	461.7	322.4	0.698	0.83	461.7	234.4	0.508	1.32	461.7	311.9	0.676
12	0.83	207.4	134.0	0.646	0.75	207.4	115.6	0.557	0.71	207.4	68.7	0.331	0.74	207.4	160.2	0.772
13	0.16	48.7	42.9	0.881	0.21	48.7	118.3	2.429	0.21	48.7	60.3	1.238	0.20	48.7	37.0	0.760
14	0.65	320.2	102.4	0.320	0.07	320.2	110.1	0.344	0.07	320.2	81.8	0.255	0.07	320.2	107.1	0.334
15	0.64	97.9	37.0	0.378	0.35	97.9	56.0	0.572	0.32	97.9	71.7	0.732	0.33	97.9	59.1	0.604
16	0.67	372.1	235.0	0.632	0.80	372.1	308.8	0.830	0.55	372.1	82.2	0.221	0.40	372.1	139.8	0.376
17	0.42	322.4	113.7	0.353	0.50	322.4	121.9	0.378	0.40	322.4	162.4	0.504	0.48	322.4	182.4	0.566
18	0.48	512.2	63.6	0.124	0.55	512.2	155.5	0.304	0.50	512.2	148.8	0.291	0.55	512.2	170.9	0.334
19	0.78	475.7	113.1	0.238												
TTL	**12.8**	**5038.4**	**2,641**		**11.4**	**4562.7**	**3,629**		**10.3**	**4562.7**	**2,654**		**11.4**	**4562.7**	**2,568**	

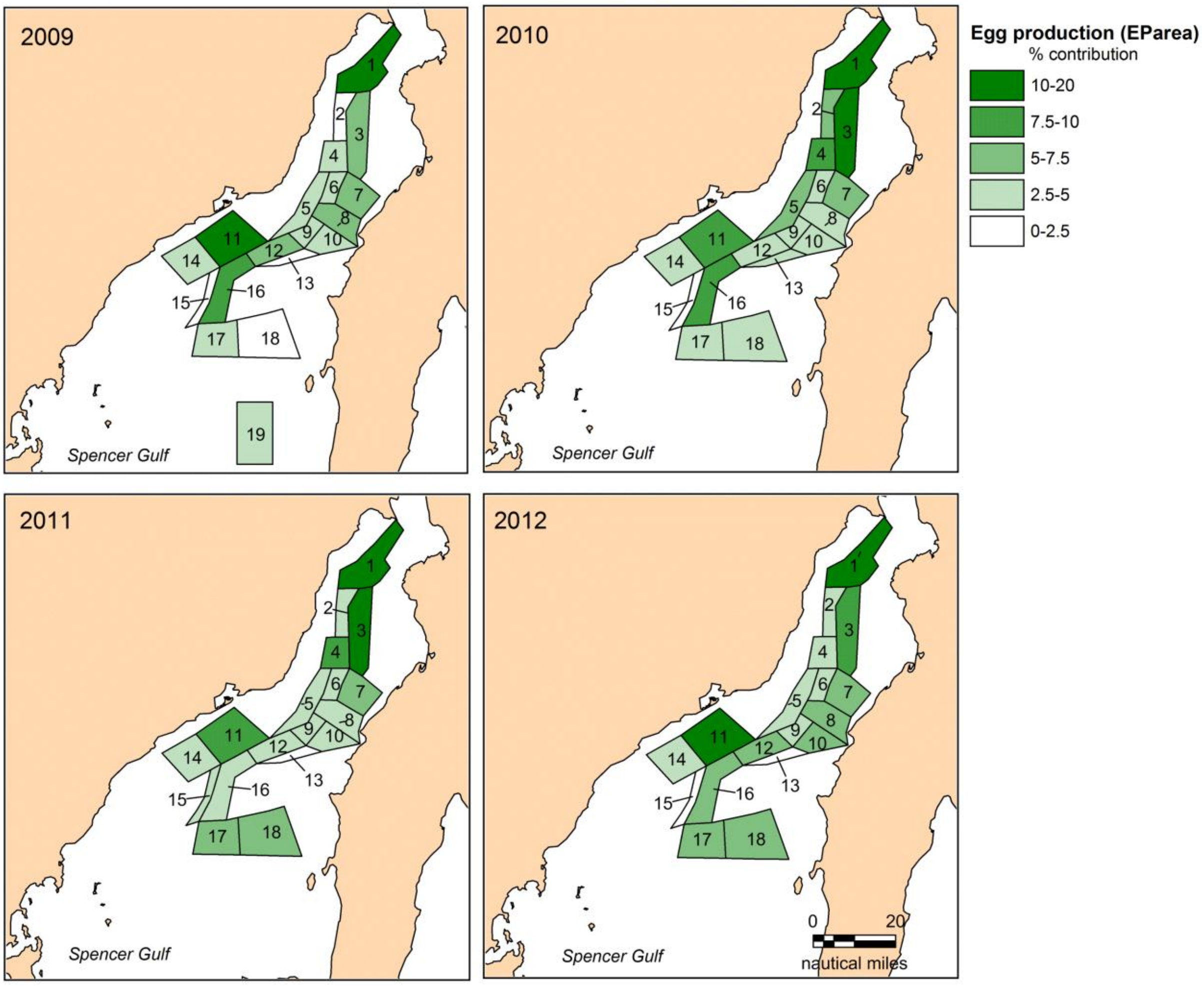

Figure 11. Pre-Christmas percentage contribution of Areas 1–19 to total prawn egg production (EP_{area}) between 2009 and 2012.

5.1.3.2 Blue Swimmer Crab

5.1.3.2.1 Female crab size

The average size (mm, CW) of female crabs in each Area (1–14) is depicted in Figure 12. Many areas were not sampled during normal fishing operations of the BCF, however larger average female sizes (CW >11 cm) were consistently recorded from Areas 9, 10, 11 and 14 in at least two of the four years surveyed between 2009 and 2013.

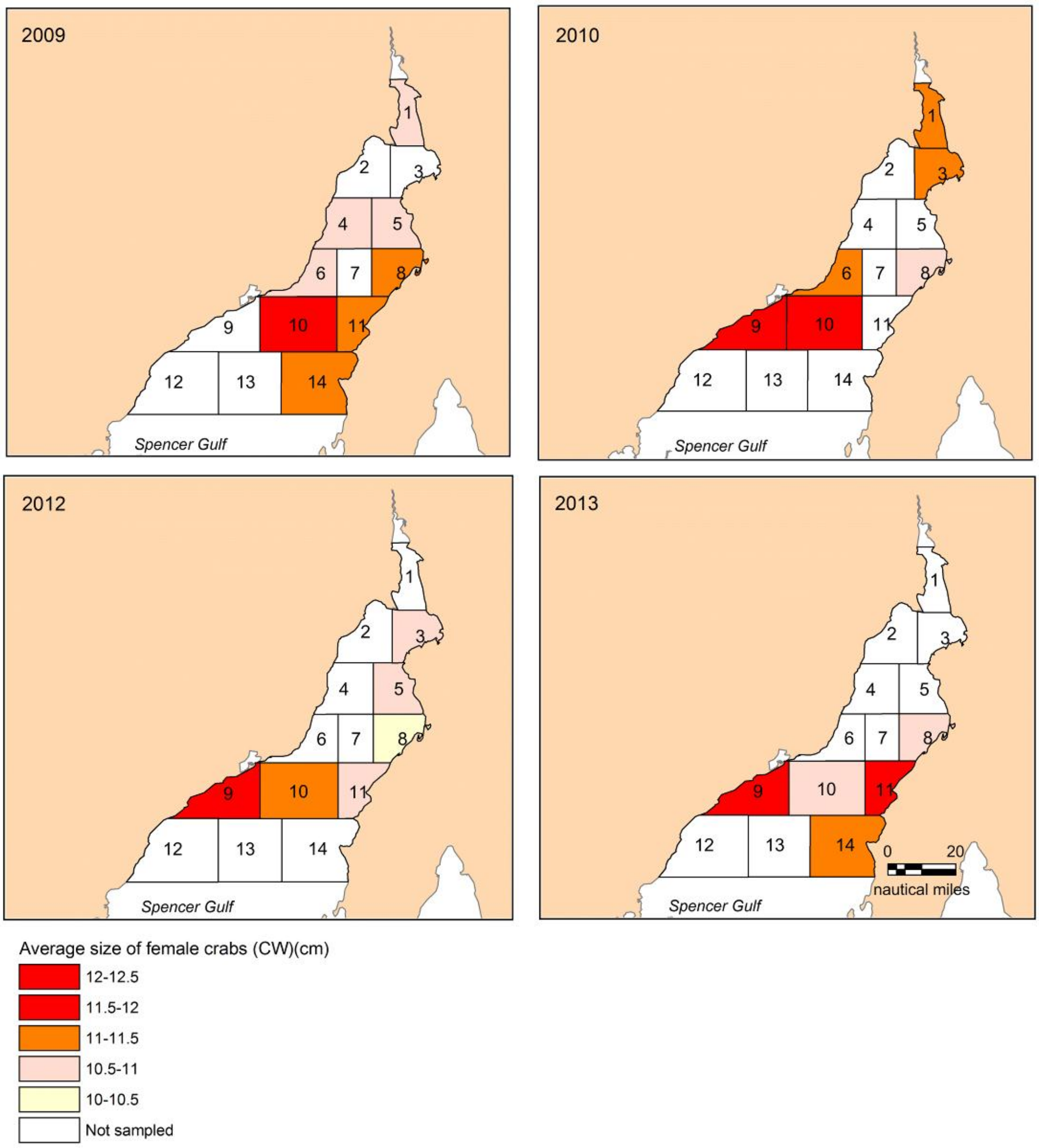

Figure 12. Average size of female crabs in each Area (1–14) in 2009, 2010, 2012 and 2013.

5.1.3.2.2 Spawning Fraction

The percentage of berried females in each Area (1–14) is depicted in Figure 13. Many areas were not sampled during normal fishing operations of the BCF, however >25% females from Areas 3, 5 and 8 were berried in at least two of the four years surveyed between 2009 and 2013.

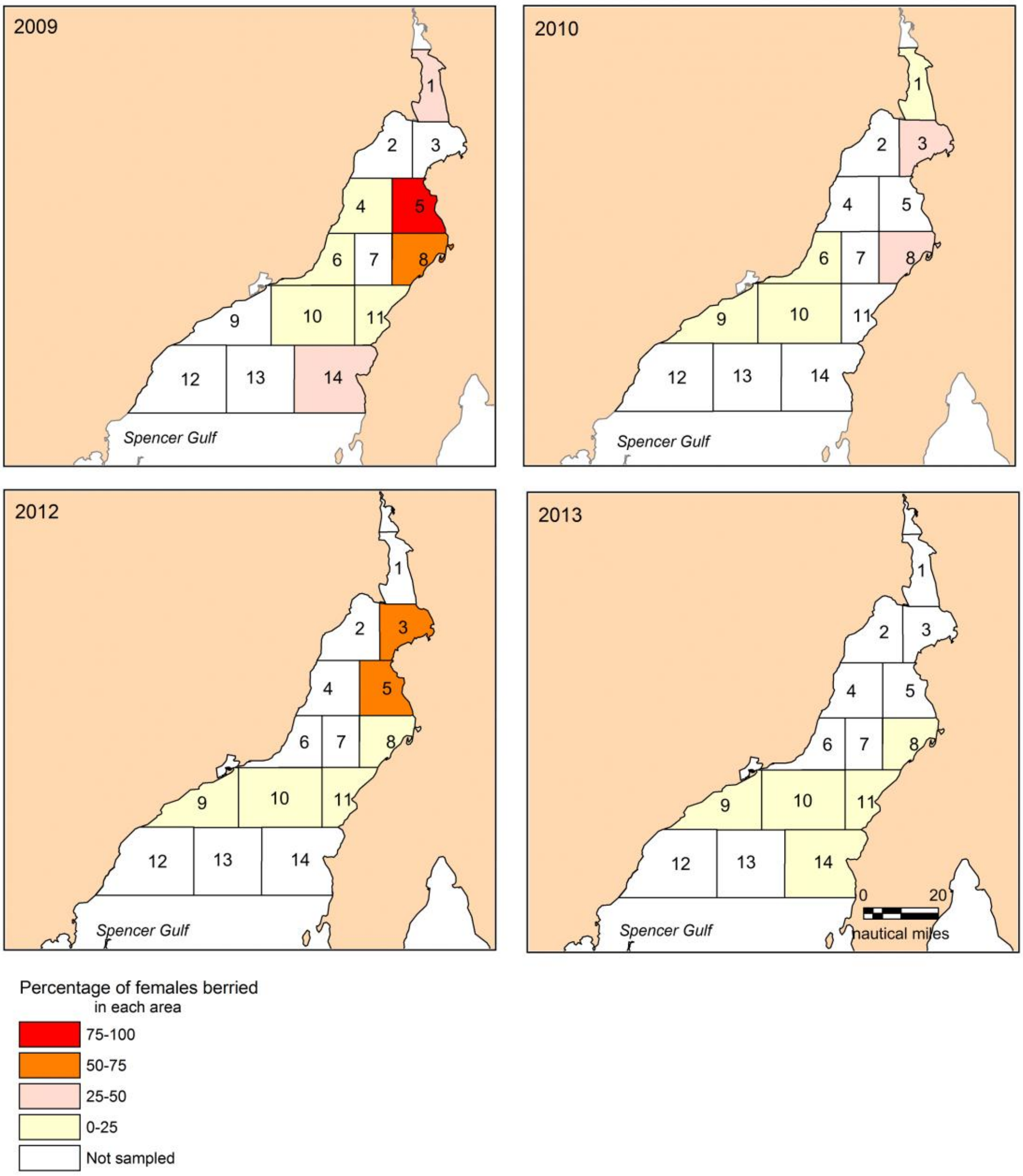

Figure 13. Percentage of berried crabs in each Area (1–14) in 2009, 2010, 2012 and 2013.

5.1.3.2.3 Fecundity

The average fecundity of berried females in each Area (1–14) is depicted in Figure 14. Spatial patterns in the average fecundity of females in each area resemble those exhibited for average size of females in each area (see above). Areas 10 and 11 had females with the highest measures of average fecundity (>1.15 million eggs per female) in at least two of the four years surveyed between 2009 and 2013.

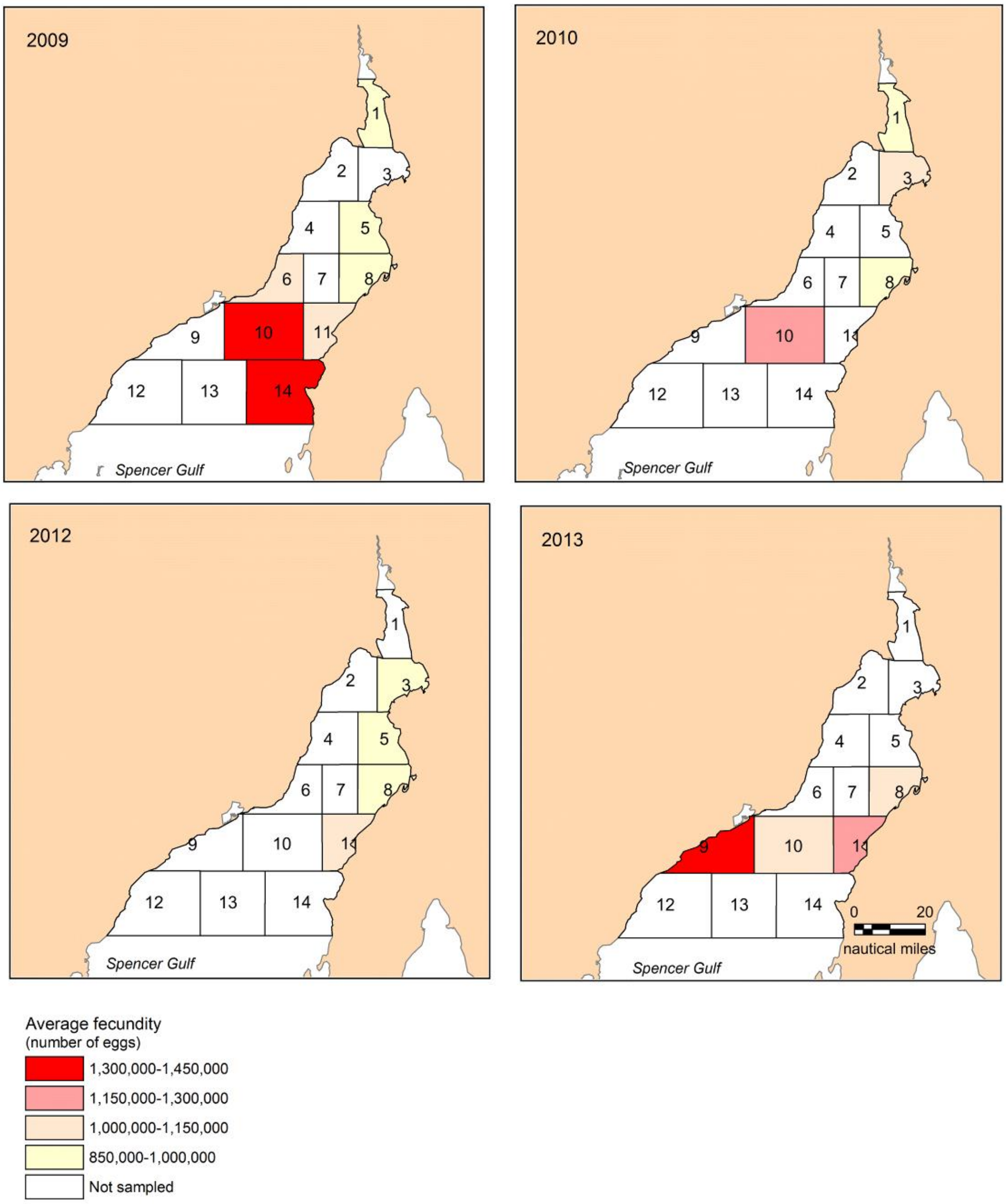

Figure 14. Average fecundity of berried crabs in each Area (1–14) in 2009, 2010, 2012 and 2013.

5.2 Bio-physical model for Spencer Gulf

5.2.1 Hydrodynamic modelling

5.2.1.1 Model validation

The hydrodynamic flow in Spencer Gulf was forced by climatological surface winds and heat fluxes, as well as the tidal surface elevations occurring at the open boundaries defined by the model (SGM). The tidal wave in Spencer Gulf takes just over 6 hours to travel the length of the gulf. Variations in tidal heights within the gulf are brought about by changes in the width and depth (narrowing and shallowing) of the gulf. As a result, the tidal wave front travels faster and is more advanced in the deep water around the centre of the gulf than it is in the comparatively shallow water at the coast.

Comparison of tides (amplitude and phase) predicted by the SGM with tidal heights determined from local tidal harmonics measured at three sites around Spencer Gulf show strong agreement (Figure 15). The model predictions capture both dodge tides and the interaction between the four main tidal constituents. Tidal amplitudes and phases were in agreement to within 5%. Average simulated tidal currents in Spencer Gulf were in the order of 0.5 to 1.0 ms^{-1} and are consistent with previous estimates (Easton 1978).

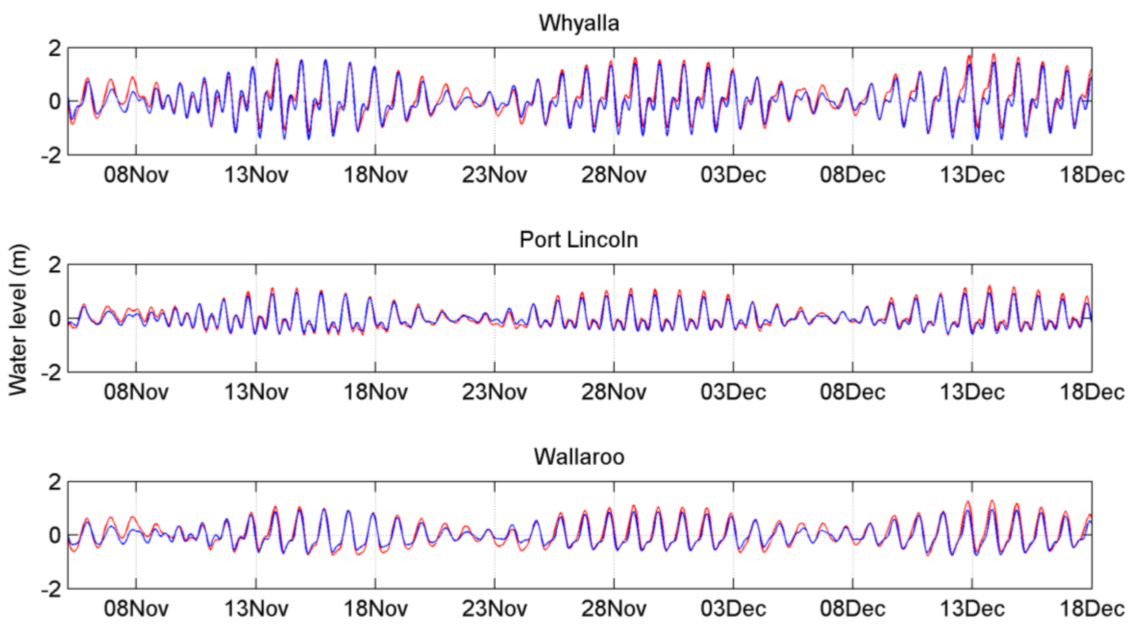

Figure 15. Comparison of sea level predicted by the SGM hydrodynamic model (red line) with local tidal harmonics at three sites in Spencer Gulf.

Residual current speeds were relatively lower than tidal current speeds, with a mean current speed of approximately 0.05 ms^{-1} estimated over the simulation period. Residual current speeds estimated for Spencer Gulf were consistent with previous estimates provided for gravity currents (Lennon et al. 1987) and wind generated currents (Bullock 1975). The residual circulation estimated over the simulation period (i.e. November–January) was characterised by a net northward flow along the coasts and a weak southward return flow along the central axis of the gulf (Figure 16). The model indicated that exchange between shelf and gulf waters was limited during this period due to the development of a thermohaline front at the entrance of Spencer Gulf in summer.

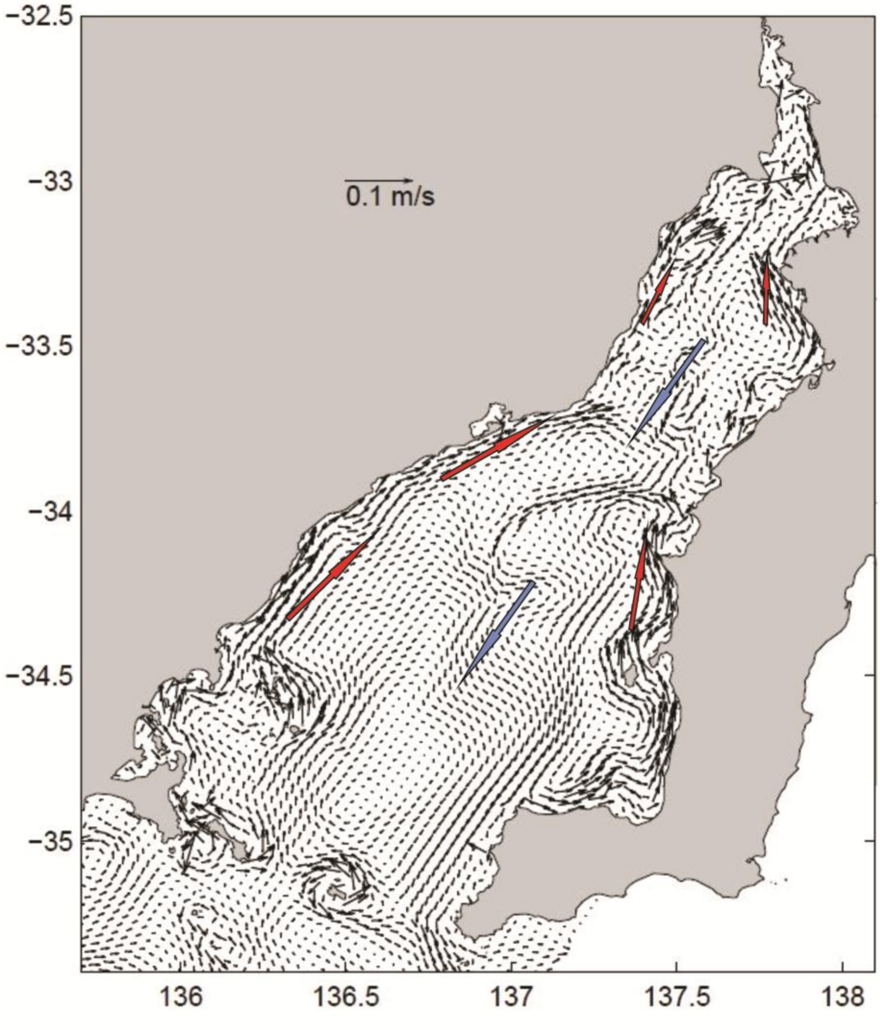

Figure 16. Depth-averaged residual currents from the hydrodynamic model time-averaged over the simulation period (1 November to 17 December). Red arrows depict net northward flow; blue arrows depict net southerly flow.

5.2.1.2 Patterns of larval dispersal and connectivity

Larval dispersal patterns simulated by Scenario 1 (i.e. passive particles/ no larval behaviour) of the bio-physical model indicated that larvae were largely entrained away from the coasts into a high-density outflow occurring along the eastern side of the central axis of Spencer Gulf. This resulted in a continuously decreasing flux of larvae into nursery grounds following the settlement cue set at day 26. At the end of the simulation, 1.2% of all larvae initiated within the Areas 1–19 had settled in the settlement grounds, with the majority of larvae pooling in the south-eastern basin of lower Spencer Gulf (Figure 17).

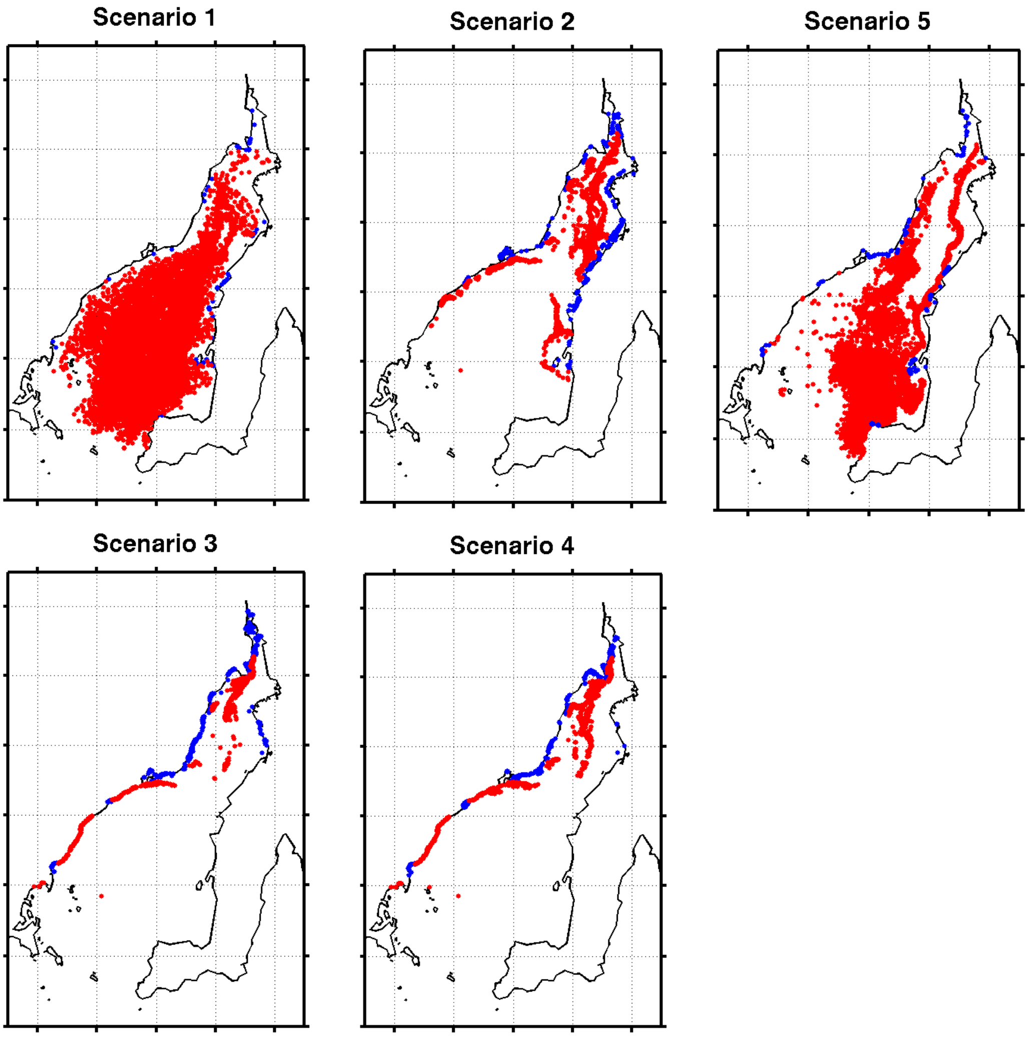

Figure 17. Final distribution of settled (blue) and non-settled (red) larvae simulated under each of the five scenarios tested by the bio-physical model (see Section 4.2.2.3, Table 1 for descriptions of each scenario).

Areas located in the northern and eastern parts of the SGPF (i.e. Areas 1, 3, 4 and 7) provided the highest sources of larval supply to nursery habitats under Scenario 1. However, <10% of larvae originating from each area achieved settlement (Figure 18).

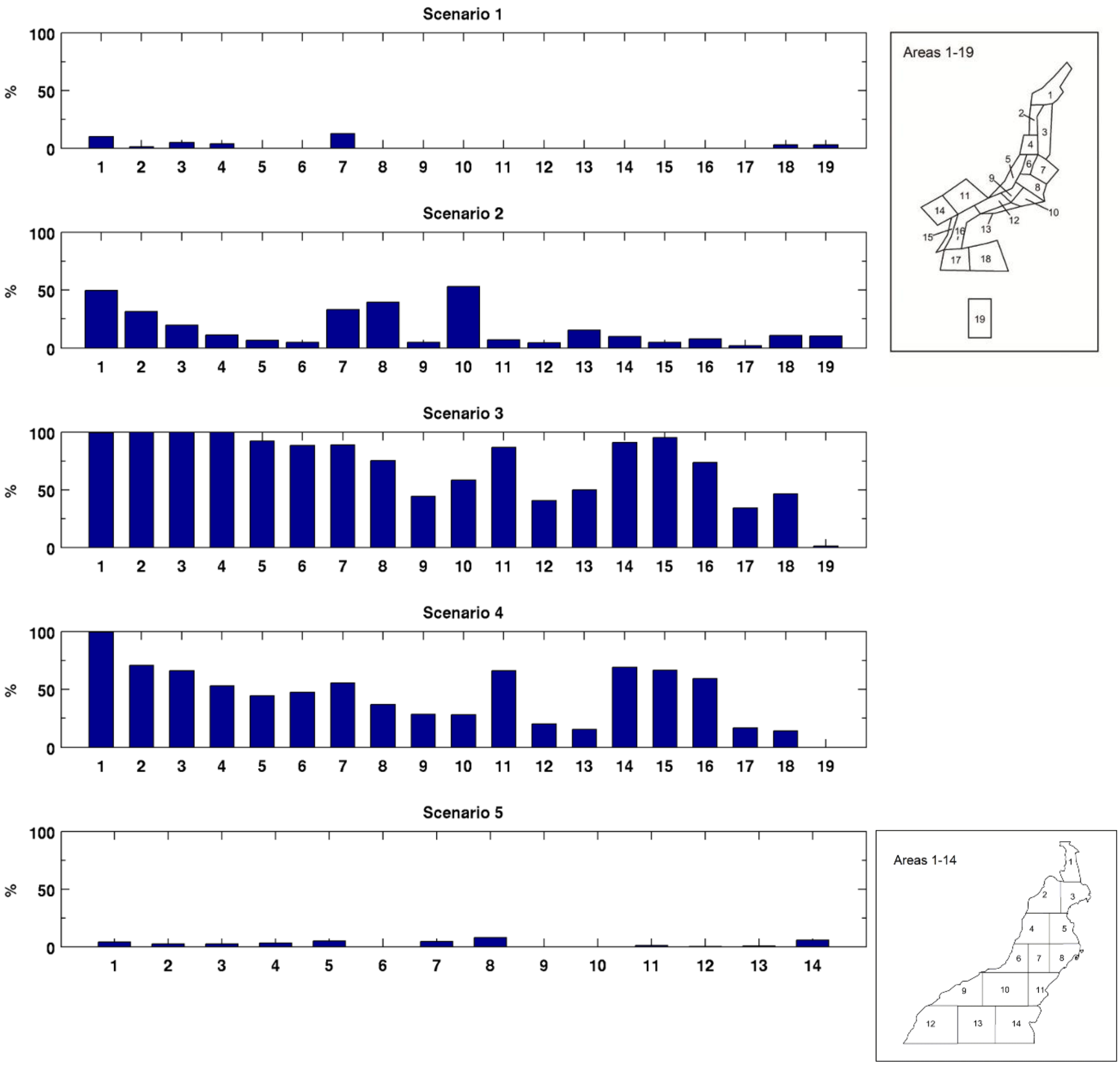

Figure 18. Percentage of larvae achieving settlement from each Area (1–19) of the SGPF. Bio-physical model Scenarios 1 to 5 are shown (see Section 4.2.2.3, Table 1 for descriptions of each scenario).

Larval dispersal simulated by Scenario 1 indicated that the major settlement grounds were predominantly located in the upper north-west (i.e. Settlement Ground 8) and lower south-east of Spencer Gulf (i.e. Settlement Grounds 15, 16 and 18) (Figure 19).

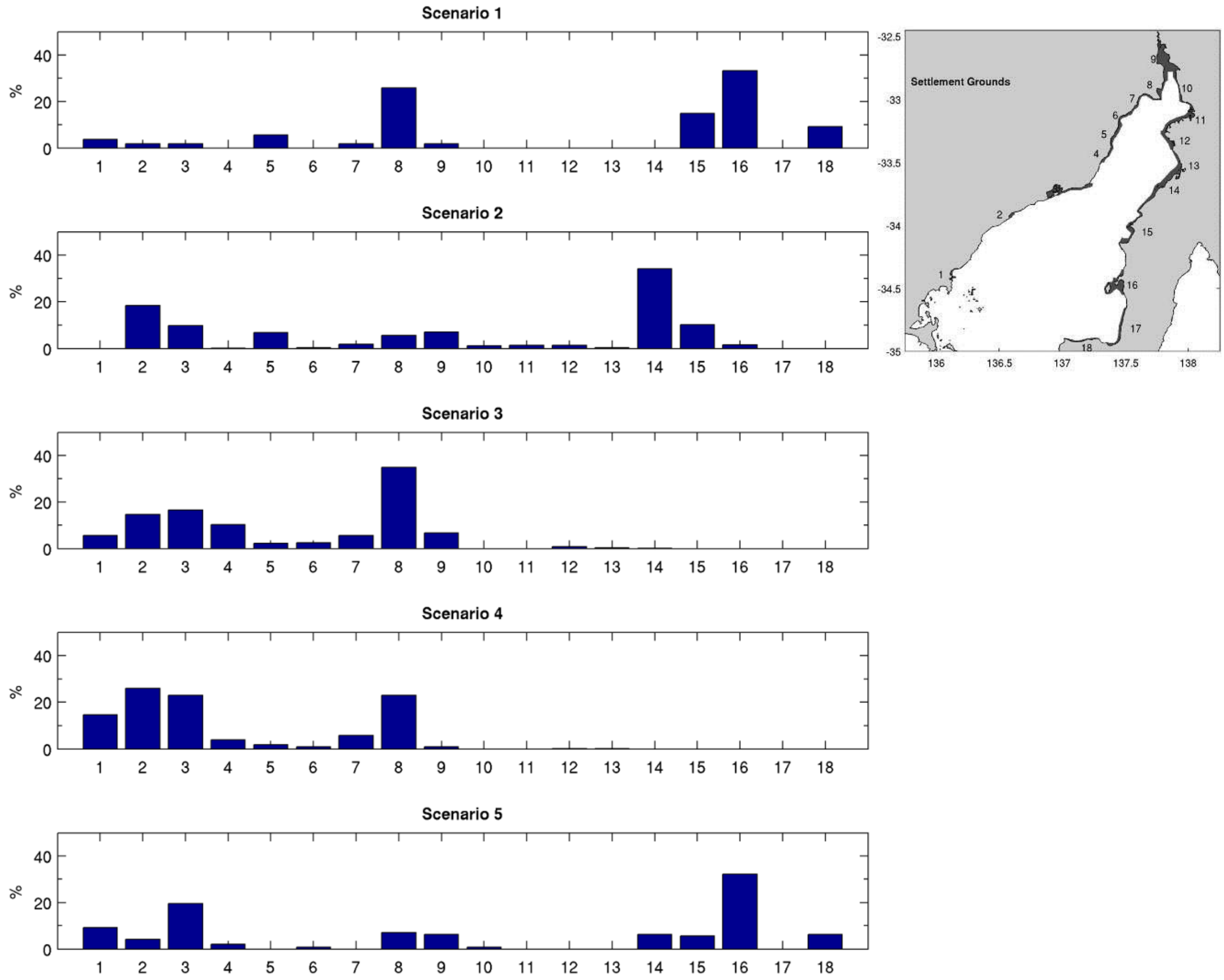

Figure 19. Percentage of larvae settled in each Settlement Ground (1–18) at the end of each Scenario (1 to 5) run by the bio-physical model. The locations of settlement grounds are also shown for reference.

Inclusion of larval behaviour traits (DVM and TST) in Scenarios 2–4 of the bio-physical model (see Section 4.2.2.3) resulted in large increases in the total percentage of Western King Prawn larvae that achieved settlement when compared to Scenario 1 (Figures 17 and 18). Vertical migration behaviour exhibited by late larval stages, and in particular late mysis and post-larval stages through TST behaviour, resulted in their entrainment within the relatively high-speed surface currents of the model, and dispersal both northward and to coastal settlement grounds (Figure 17).

In Scenario 2 of the bio-physical model, which included only tidal currents, 12% of all larvae initiated within Areas 1 to 19 reached the settlement grounds. Dominant source areas were located in the upper and eastern-central parts of Spencer Gulf where between 25% and 60% of larvae initiated within Areas 1, 2, 7, 8 and 10 achieved settlement (Figure 18). Major settlement grounds were identified on the central-western coast of Spencer Gulf in settlement grounds 2 and 3, and on the central-eastern coast of Spencer Gulf in Settlement Grounds 14 and 15. These nursery areas accounted for 72% of all settled larvae at the end of the model run (Figure 19).

In Scenarios 3 and 4 of the bio-physical model, which included tidal currents, as well as atmospheric forcing components (Section 4.2.2.3), rates of larval settlement were higher than observed in Scenario 2. The locations of larval source and sink regions also changed in comparison to the locations identified in Scenario 2 (Figures 17–19). In Scenario 3, 47% of all larvae initiated within the Areas 1 to 19 reached the settlement grounds. Major source regions were located in upper and central-eastern Spencer Gulf, with over 75% of larvae from Areas 1 to 8, 11, 14 and 15 achieving settlement (Figure 18). In comparison to Scenario 3, total settlement rates in Scenario 4 from Areas 1 to 19 were lower (35%) due to higher modelled temperatures resulting in shortened larval durations and a reduced amount of time for larvae to reach suitable settlement grounds. There was also a general reduction in the percentage of larvae reaching settlement grounds from each area, with the largest decreases in rates of settlement observed in Areas 2–8 in the upper gulf region (Figure 18).

In Scenarios 3 and 4 of the bio-physical model, the main settlement grounds were located on the western and north-western coast of Spencer Gulf, with over 90% of all larvae achieving settlement at the end of the simulations in Settlement Grounds 1–8 (Figure 17 and 19). The reduced larval development times in Scenario 4 relative to Scenario 3 also resulted in relatively higher rates of larval settlement on grounds on the western side of Spencer Gulf (Settlement Grounds 1, 2 and 3) (Figure 19).

Scenario 5 of the bio-physical model was developed to assess the dispersal of Blue Swimmer Crab larvae. Similar to Scenario 1, which was developed for passive particles, Scenario 5 indicated that larvae were largely entrained away from the coasts into a high-density outflow occurring along the eastern side of the central axis of Spencer Gulf. However in contrast to Scenario 1, the inclusion of DVM behaviour of blue-swimmer crab larvae after day 26 resulted in relatively higher rates of dispersal to settlement grounds (Figure 17 and 18).

The total rates of larval settlement under Scenario 5 were lower than those observed for Western King Prawn under Scenarios 3 and 4. At the end of the model run, 2% of all Blue Swimmer Crab larvae originating from Areas 1 to 19 had reached the settlement grounds, with the majority pooling in the southern and western-central regions of lower Spencer Gulf (Figure 17). Areas 5, 7, 8 and 14 provided the largest potential sources of larvae to the nursery grounds with over 7% of larvae initiated from Area 8 achieving settlement (Figure 18). The highest rates of settlement (6–32%) were observed in Settlement Grounds 1–3 on the south western coast of Spencer Gulf, Settlement Grounds 8 and 9 in northern Spencer Gulf, and Settlement Grounds 14, 15, 16 and 18 on the south eastern coast of Spencer Gulf (Figure 19). Settlement Grounds on the south eastern coast of Spencer Gulf (14, 15, 16 and 18) contributed to 50% of all Blue Swimmer Crab larvae achieving settlement (Figure 19).

5.3 Harvest sensitivity analyses – case study: the Spencer Gulf Prawn Fishery

5.3.1 Overview

By combining data on the larval and reproductive biology of Western King Prawn, with outputs of the bio-physical models, and pre-Christmas catches in the SGPF, the historical impacts of pre-Christmas fishing on larval settlement could be assessed. The pre-Christmas fishing exploitation rates on Western King Prawn and their effects on larval settlement provided a baseline from which to undertake harvest sensitivity analyses to assess how hypothetical changes in the spatial distribution of catch could impact overall rates of larval settlement.

5.3.2 Areas contributing to larval settlement success (pre-fishing)

The number of larvae reaching the settlement grounds from each area within the SGPF was a function of the total egg production occurring within an area (Section 5.1.3.1), as determined by the number and size of female prawns (Section 5.1.3.1), and the bio-physical processes acting in that area that contribute to settlement success (Section 5.2.1.2). The overall contribution of each area in the SGPF to total larval settlement between 2009 and 2012 is shown in Table 5 and Figure 20.

Areas 1, 3 and 11 ranked in the top 5 areas contributing to larval settlement success in all years surveyed (Table 5) due to the high egg production occurring in these areas combined with the high rates of settlement estimated by the bio-physical model. These areas contributed between 40.7% and 42.4% of all larvae reaching settlement between 2009 and 2012 (Table 5). Area 1 in the north of the SGPF provided the most larvae to the settlement grounds in Spencer Gulf in all years between 2009 and 2012, contributing between 16.1% and 18.1% of the total larvae that reached settlement (Table 5, Figure 20). Areas 4, 7 and 16 also ranked in the top 5 areas in at least two years surveyed (Table 5).

In contrast Areas 9, 13 and 15 and 17 ranked in the bottom five areas contributing to total larval settlement success in at least three of the four years surveyed between 2009 and 2012. This was due largely to either the small areas (km^2) that these areas contribute to the fishery (e.g. Areas 9, 13, 15) or the combination of low egg production and/or settlement success originating from these areas (e.g. Areas 15 and 17).

Table 5. Percentage contribution of each area to total larval settlement in Spencer Gulf between 2009 and 2012.

AREA	2009	2010	2011	2012
1	17.7	18.1	16.5	16.1
2	3.0	6.1	5.2	4.6
3	9.7	13.2	16.3	11.7
4	4.6	10.4	11.2	5.8
5	4.8	6.9	4.9	3.0
6	4.1	2.7	4.5	3.3
7	7.9	5.6	6.9	7.0
8	6.0	2.4	3.2	4.9
9	1.6	2.7	1.7	1.6
10	3.6	2.3	2.5	4.2
11	15.0	9.4	9.3	13.6
12	2.7	1.6	1.3	3.2
13	1.1	2.0	1.4	0.9
14	4.6	3.4	3.4	4.9
15	1.7	1.8	3.1	2.8
16	8.5	7.6	2.8	5.2
17	1.9	1.4	2.5	3.1
18	1.5	2.4	3.2	4.0
19	0.1			

rank 1	(red)
rank 2	(yellow)
rank 3	(green)
rank 4	(blue)
rank 5	(pink)

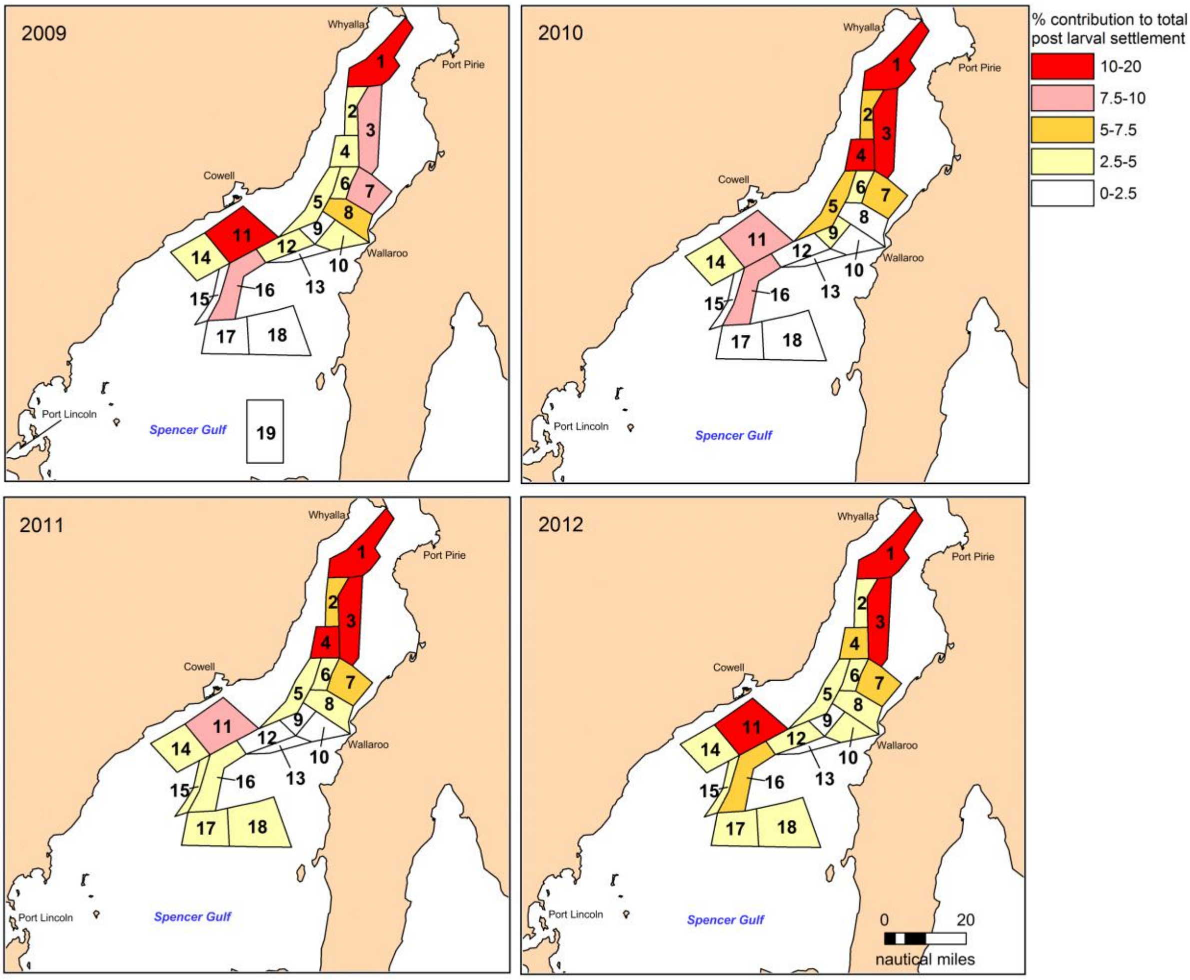

Figure 20. Percentage contribution of Areas 1–19 to Western King Prawn larval settlement (prior to fishing) between 2009 and 2012.

5.3.3 Distribution of catch

Total pre-Christmas catch of Western King Prawn varied from 333 t in 2011 to 532 t in 2010. Catches were generally higher in central and eastern parts of the fishery (Figure 21). Areas 4 and 7 ranked in the top 3 areas for catch in all years between 2009 and 2012, comprising between 22% and 56% of the total pre-Christmas catch landed in 2012 and 2011, respectively. Catches from Area 4 ranged from 51 t in 2009 to 185 t in 2010 (Figure 21). Catches in Area 7 ranged from 49 t in 2012 to 126 t in 2011 (Figure 21). Areas 3, 9 and 10 also ranked in the top 5 areas for catch, recording catches of over 30 t in at least two years surveyed between 2009 and 2012 (Figure 21). Areas 3, 4, 7, 9 and 10 accounted for between 52% and 71% of the total pre-Christmas catch landed in each year between 2009 and 2012.

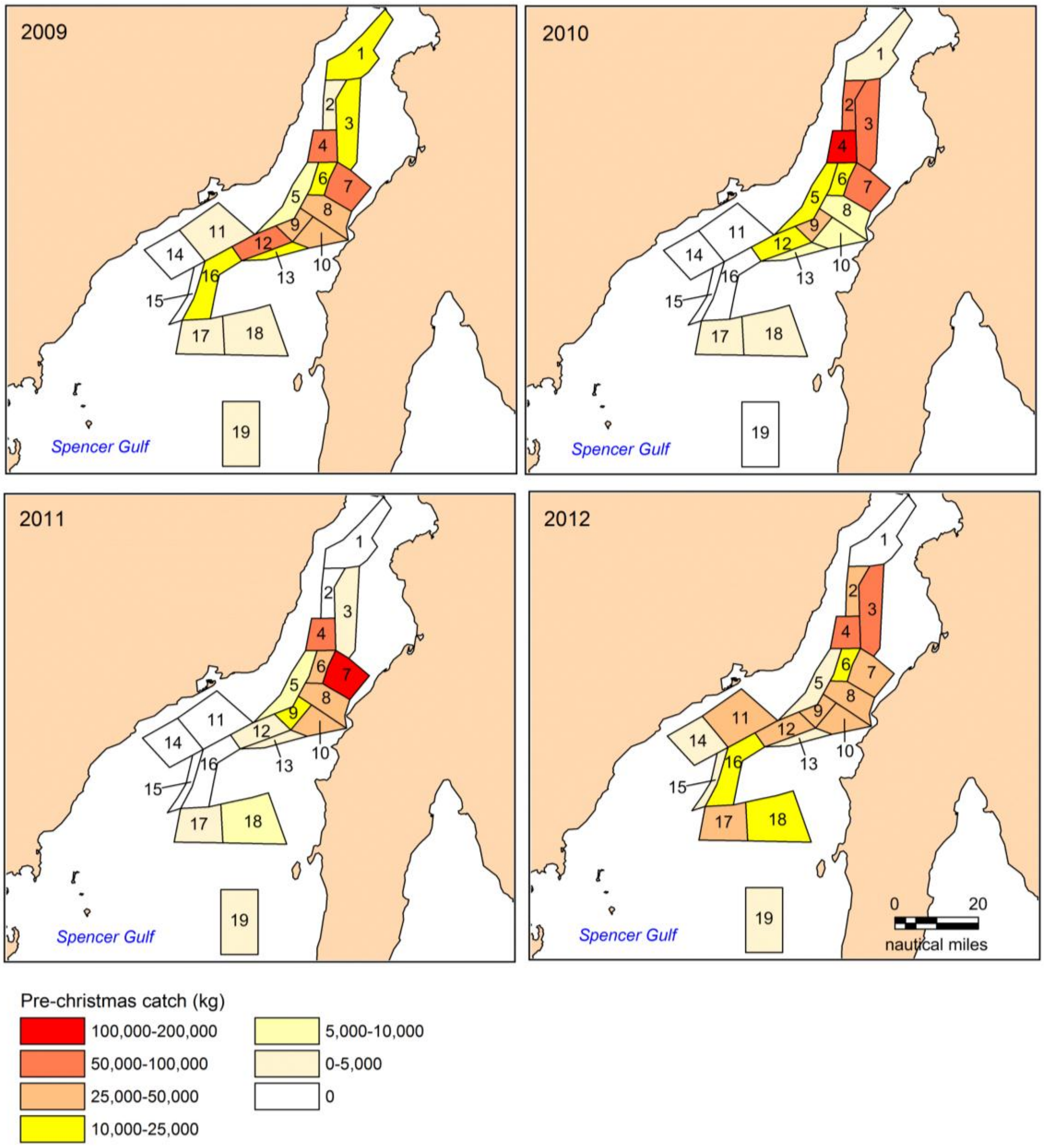

Figure 21. Pre-Christmas catch of Western King Prawn in Areas 1–19 between 2009 and 2012.

5.3.4 Effects of fishing on larval settlement

The effects of pre-Christmas fishing on rates of larval settlement from each area between 2009 and 2012 are summarised in Table 6. Total larval settlement rates (% reduction in settlers, Table 6) were most affected by fishing in years when the pre-Christmas catch was highest. Pre-Christmas catches were highest in 2010 and 2012 at approximately 532 t and 468 t, respectively, resulting in total exploitation rates on larval settlement of between 19.2 and 21.1%, respectively. This contrasts with exploitation rates of between 14.2% in 2011 and 14.6% in 2009, when pre-Christmas catches were below 360 t.

Exploitation rates on larval settlement varied in each area but were generally highest in areas where the highest levels of catch were recorded. Catches in areas where over 50 t were recorded resulted in exploitation rates of between 21.2% (Area 4, 2011) and 85.8% (Area 7, 2011) (Table 6). High exploitation rates were also calculated for some areas where catches <50 t were landed, such as Area 9 in 2009 (69.8%) and 2012 (66.3%), and Area 13 in 2009 (60.0%), reflecting the relatively high catch and low biomass of prawns in these areas.

Table 6. Pre-Christmas fishing effects on larval settlement showing the key model outputs for each area and year between 2009 and 2012: egg production (EP_{area}), total catch (kg), and exploitation rates (percentage reduction in the number of larvae produced i.e. "% reduction in settlers"). Settlement rates as determined from Scenario 3 of the bio-physical model are shown in column 2. Totals for each year are shown in bold.

		2009			**2010**			**2011**			**2012**		
AREA	**Settlement rate**	**EP_{area} ($x10^9$)**	**Total catch (kg)**	**% reduction in settlers**	**EP_{area} ($x10^9$)**	**Total catch (kg)**	**% reduction in settlers**	**EP_{area} ($x10^9$)**	**Total catch (kg)**	**% reduction in settlers**	**EP_{area} ($x10^9$)**	**Total catch (kg)**	**% reduction in settlers**
1	99.4	360.5	16,680	3.7	543.1	163	0.0	361.6	0	0.0	321.3	0	0.0
2	100.0	59.7	773	0.9	182.0	77,021	34.0	113.8	0	0.0	90.5	36,431	30.3
3	100.0	195.7	11,380	5.3	391.9	52,882	13.5	355.7	264	0.0	231.9	65,003	23.4
4	100.0	94.0	50,962	59.5	309.9	185,034	82.5	244.8	58,670	21.2	116.2	51,875	53.1
5	92.4	104.9	8,365	10.6	222.6	10,662	8.3	115.9	6,728	6.8	64.9	2,650	6.9
6	88.5	94.3	16,021	22.3	91.7	23,064	46.6	110.6	38,310	51.1	73.8	20,110	41.0
7	88.9	179.0	54,888	39.3	186.6	94,845	48.3	169.8	126,317	85.8	157.1	49,198	46.5
8	75.4	162.3	32,859	20.7	96.2	7,209	8.2	93.3	32,792	32.2	130.1	31,767	29.6
9	44.4	72.9	38,214	69.8	181.0	31,134	33.1	85.9	21,167	49.6	70.5	29,813	66.3
10	58.4	125.0	39,761	35.2	115.6	9,727	12.4	92.7	28,455	39.6	143.9	48,874	54.1
11	86.6	350.6	683	0.2	322.4	0	0.0	234.4	0	0.0	311.9	35,492	13.8
12	40.3	134.0	52,911	52.6	115.6	24,334	28.7	68.7	4,737	4.6	160.2	27,747	24.8
13	50.0	42.9	16,254	60.0	118.3	8,070	16.1	60.3	1,757	5.8	37.0	1,925	11.1
14	91.0	102.4	0	0.0	110.1	0	0.0	81.8	0	0.0	107.1	175	0.2
15	95.2	37.0	0	0.0	56.0	0	0.0	71.7	0	0.0	59.1	298	0.4
16	73.5	235.0	10,130	3.6	308.8	0	0.0	82.2	0	0.0	139.8	12,810	4.6
17	34.1	113.7	2,590	2.4	121.9	4,044	3.0	162.4	360	0.2	182.4	37,915	23.6
18	46.4	63.6	4,756	6.4	155.5	3,922	2.9	148.8	9,847	6.7	170.9	14,959	11.8
19	1.1	113.1	319	0.3	0.0	0	N/A	N/A	3,562	N/A	N/A	708	N/A
Total EP (all areas)		**2,641**			**3,629**			**2,654**			**2,569**		
Total pre-Christmas catch (kg)			**357,546**			**532,113**			**332,965**			**467,749**	
Total % reduction in number of settlers				**14.6**			**19.2**			**14.2**			**21.1**

5.3.5 Harvest sensitivity analyses

The fishing exploitation rates detailed in Table 6 provided a baseline to test how hypothetical changes in the distribution and amount of pre-Christmas catch in different Areas (1–19) of the fishery might affect total rates of larval settlement. Seven different harvest scenarios were tested using survey data collected in 2010 and 2011 when pre-Christmas catches were high (532 t) and low (332 t), respectively (see Section 4.3 for details of each scenario). The scenarios hypothetically altered the rates of exploitation on adult (female) prawns in each area of the fishery to assess changes in the 1) potential rates of larval settlement from each area and 2) amount of catch taken from each area.

In 2010, overall exploitation rates on larval settlement were 19.2%. Under Scenario 2, the proportional redistribution of all catch taken from the top five areas contributing to settlement (Areas 1, 3, 4, 11 and 16) to all other areas resulted in a 3.2% improvement in larval settlement (Table 7). The largest improvement to the total rates of larval settlement (7.4%) were identified under Scenario 3 where exploitation rates were set at 5% in the top five areas contributing to settlement and maintained at baseline levels for all other areas. However, total pre-Christmas catch under Scenario 3 decreased by 19.2 t. In contrast, the largest increases in catch (42.4 t) were observed under Scenario 7 where exploitation rates were set at 2.5% in the top five areas contributing to settlement and 35% in all other areas (Table 7). Rates of settlement under Scenario 7 were also increased by 3.3% (Table 7) indicating the potential dual benefit afforded to both larval settlement rates and catch under this harvest Scenario.

In 2011, overall exploitation rates on larval settlement due to fishing were 14.2%. Proportional redistribution of catch taken from the top five areas contributing to settlement (Areas 1, 3, 4, 7 and 11) among all other areas resulted in a 0.8% improvement in larval settlement (Table 7). Similar to 2010, the largest improvements in settlement (5.3%) were identified under Scenario 3 where exploitation rates were set at 5% in the top five areas contributing to settlement and maintained at baseline levels for all other areas. Total pre-Christmas catch under Scenario 3 also decreased in 2011 by 87 t. The best increases in catch were observed under Scenario 7, where exploitation rates of 2.5% in the top five areas contributing to settlement and 35% in all other areas resulted in catch increases of 227 t but reduced overall settlement rates by 1.2% (Table 7). Both catch and rates of settlement were improved under Scenarios 5 (1.3%, 132.4 t), Scenario 6 (0.8%, 154.2 t) and Scenario 8 (0.3% and 176 t) indicating the potential dual benefit afforded to both larval settlement rates and catch under these harvest Scenarios (Table 7).

Table 7. Modelled effects of different harvest scenarios on rates of larval settlement and catch during pre-Christmas fishing periods in 2010 and 2011. Harvest scenarios are shown for reference. Green = increase in settlement/catch; red = decrease in settlement/catch.

	2010					2011				
Harvest Scenario	Recorded fishing exploitation rate	Modelled exploitation rate under each harvest scenario	Change in settlement (%)	Modelled catch under each harvest scenario	Change in catch (t)	Recorded fishing exploitation rate	Modelled exploitation rate under each harvest scenario	Change in settlement (%)	Modelled catch under each harvest scenario	Change in catch (t)
1. Baseline	**19.2**			**532,113**		**14.2**			**332,964**	
2	19.2	16.1	3.2	532,113	0.0	14.2	13.4	0.8	332,964	0.0
3	19.2	11.8	7.4	512,883	-19.2	14.2	8.9	5.3	245,958	-87.0
4	19.2	15.3	3.9	550,796	18.7	14.2	14.9	-0.7	538,107	205.1
5	19.2	13.3	6.0	476,007	-56.1	14.2	12.9	1.3	465,390	132.4
6	19.2	13.9	5.4	499,764	-32.3	14.2	13.4	0.8	487,204	154.2
7	19.2	15.9	3.3	574,553	42.4	14.2	15.4	-1.2	559,921	227.0
8	19.2	14.4	4.8	523,522	-8.6	14.2	13.9	0.3	509,018	176.1

Harvest Scenario	Top areas 2010	Top areas 2011
1. Baseline		
2. No fishing in top 5 areas contributing to settlement and historical catch from these areas redistributed proportionately among other areas	1, 3, 4, 11, 16	1, 3, 4, 7, 11
3. Exploitation rates set at 5% in top 5 areas, and maintained at baseline levels in other areas		
4. Exploitation rates set at 5% in top 5 areas & 30% in other areas		
5. Exploitation rates set at 5% in top 5 areas & 25% in other areas		
6. Exploitation rates set at 2.5% in top 5 areas & 30% in other areas		
7. Exploitation rates set at 2.5% in top 5 areas & 35% in other areas		
8. Exploitation rates set at 0% in top 5 areas & 35% in other areas		

6 Discussion

This study has improved the understanding of how biological and physical-oceanographic processes contribute to patterns of larval settlement for Western King Prawn and Blue Swimmer Crab in Spencer Gulf. It has identified the key areas that contribute to their spawning and settlement success, and provided fisheries managers with additional information to enhance harvest strategies and further production opportunities for these species during their pre-Christmas spawning season. It has also provided some preliminary insights into the potential effects of climate change through an increased understanding of how increases in temperature affect larval duration and subsequent settlement success of Western King Prawn larvae.

6.1 Larval duration

Bio-physical models to simulate larval dispersal are sensitive to the time scale over which ocean processes act on larval stages (Pedersen et al. 2003; Criales et al. 2007; Queiroga et al. 2007; López-Duarte and Tankersley 2009). The tank trial experiments conducted in this study were critical in calculating the lengths of larval duration for Western King Prawn in response to a range of different temperatures that are typical of Spencer Gulf. This information was important in providing the time scales over which the bio-physical model should be run under different gulf temperature regimes.

Tank trials indicated that water temperature was negatively correlated with larval duration. This relationship was best described by a power relationship, with lower temperatures resulting in longer total larval durations. Our study showed that stage-specific larval durations were generally longest for the zoea stage and shortest for the nauplius stage, and that the time taken to reach the post larval stage for Western King Prawn ranged from 12.7 days (at 24.4°C) to 31.3 days (at 17.1°C).

The larval periods measured under the constant temperatures of our tank trials are not likely to be representative of the larval duration periods that would occur in the wild where temperatures vary seasonally. For Western King Prawn in Spencer Gulf, larval development is likely to be slower at the beginning of the spawning season in October and November due to the lower average water temperatures occurring in these months. As the spawning season progresses, larval development is likely to be more rapid in response to the warming of gulf waters. Gulf temperatures may also fluctuate at finer spatial scales according to local depth or current regimes and these factors influence the total time that larvae remain planktonic. Such seasonal temperature-dependent variations in larval duration have previously been documented for Blue Swimmer Crab in gulf waters of South Australia (Bryars and Havenhand 2006).

Although South Australia's gulfs are situated at a temperate latitude, they are unique in that water temperatures are 'seasonally sub-tropical' (Shepherd 1984) and harbour a suite of species with tropical affinities, including: Blue Swimmer Crab, Western King Prawn, syngnathids (pipefishes), Yellowfin Whiting (*Sillago schomburgkii*), and Blue Sprat (*Spratelloides robustus*) (Bryars and Adams 1997; Edyvane and Shepherd 1999; Rogers et al. 2003; Bryars and Havenhand 2006; Currie et al. 2011). The relatively short larval period of Western King Prawn compared to other penaeid species (Dall et al. 1990) may have allowed them to successfully inhabit the waters of South Australia's gulfs where the optimum temperatures for spawning and larval development occur over short time periods. This life history trait may have contributed to the species having one of the widest worldwide geographical distributions of all penaeid species.

6.2 Adult reproductive biology

6.2.1 Western King Prawn

Rates of larval dispersal and settlement are sensitive to the spatial distribution and reproductive phenology of the adult life stage. Spatially stratified, fishery-independent, stock-assessment surveys have been undertaken by SARDI Aquatic Sciences for Western King Prawn since 2004. Although the areas surveyed between 2009 and 2012 represent a small proportion of the total area available to fishing (0.23–0.25%), they are spatially representative of the total fishing area, and provide a robust representation of egg production characteristics across the fishery between 2009 and 2012. It should also be noted that values of egg production presented in this report are conservative relative to Spencer Gulf as a whole, due to unquantified egg production occurring outside the main areas of fishing.

There were consistent spatial patterns in egg production for Western King Prawn in all years. Areas 1, 3, 4 and 7 in the north and eastern parts of the fishery contributed up to 43% of the total pre-Christmas egg production between 2009 and 2012 and also recorded some of the highest egg densities. These areas comprise 23% of the total area of the fishery. Areas 11 and 16 located in the south-west of the fishery also contributed large numbers of eggs to total egg production, however, as indicated by the relatively low egg densities recorded in these areas, the high egg production estimates from these areas were largely driven by the relatively large total area (km^2) that they cover (~17% of total fishing area).

Estimates of egg production are influenced by the fecundity of female prawns, their level of maturity and measures of fertilisation success. These parameters are, in turn, sensitive to prawn size. However, estimates of egg production are likely to be more influenced by the number (biomass) of female prawns sampled within a given area than prawn size alone. This is highlighted through a comparison of estimates provided for egg production and prawn size in Area 1. The high egg production calculated for all years in Area 1 corresponded to high densities of female prawns sampled from this area despite only medium-sized prawns (35–39 mm CL) being present.

6.2.2 Blue Swimmer Crab

A voluntary fishery-dependent pot-sampling program has been undertaken in Spencer Gulf by members of the BCF since 2006. The primary purpose of the pot sampling program is to collect fishery-dependent data relating to the abundance of pre-recruits and legal sized catch. Many areas of the fishery have not been sampled during normal pre-Christmas fishing operations, and as a consequence, the sampling undertaken has not provided data suitable for robust calculations of egg production. Estimates of egg production also require data relating to the size-specific maturity and spawning frequency of female crabs. These data were also not available. However, the data collected in the program provide some broad insight into the spatial patterns of reproduction for Blue Swimmer Crab in Spencer Gulf during the peak time of their spawning season.

Larger, more fecund, female crabs were generally sampled from areas located in southern Spencer Gulf. However, the areas with the largest percentage of spawning females (>25%) were generally located in the eastern gulf in Areas 3, 5 and 8 to the north of Wallaroo. Areas 5 and 8 were also shown by the bio-physical model to contribute to the highest rates of settlement of blue-swimmer crab larvae. Depending on the density of crabs found in these areas, it is possible that areas in the eastern gulf to the north of Wallaroo make the largest contributions to egg production and larval settlement. A more stratified approach to sampling Blue Swimmer Crab across their distribution in the future, coupled with reproductive information relating to spawning frequency and size at maturity for crabs in different parts of Spencer Gulf would help to reliably estimate egg production across their distribution. It would also enable relative estimates of crab biomass to be calculated thereby allowing estimation of fishing exploitation. This information would be useful to assist management of the fishery.

It is worth noting that fishing mortality on berried female crabs is currently managed by returning them to the water. The effects of catch and release on egg production are unquantified and may warrant future research. If egg production is negatively impacted by catch and release, future harvest strategies for the fishery would benefit from identifying the areas that contribute most to egg production so that any impacts to egg production due to catch and release are minimised through spatial management arrangements.

6.3 The bio-physical model

The bio-physical model developed in this study builds on earlier larval modelling studies of the Spencer Gulf region by incorporating LTRANS to take into account particle advection, vertical turbulent particle motion, reflective boundary conditions, larval behaviour and settlement (Nixon and Noye 1995; North et al. 2008). The results of the five scenarios run by the bio-physical model provide some insights into the key factors affecting transport and dispersal of Western King Prawn and Blue Swimmer Crab larvae in Spencer Gulf. In particular, overall rates of larval settlement were maximised for Western King Prawn when tidal and atmospheric physical forcing components were coupled with larval swimming behaviour and longer larval durations.

The incorporation of active swimming behaviour (DVM and TST) for Western King Prawn, under Scenarios 2–4 increased rates of larval settlement by up to 45% when compared to the passive behaviour modelled under Scenario 1. The Scenario 1 model resulted in larvae with little or reduced swimming ability being entrained away from the coast within a gulf circulation pattern caused by the southward movement of high-density water formed at the head of Spencer Gulf. These results support other studies that indicate vertical swimming behaviour is an important influence on larval dispersal (Jacobsen et al. 1990; Nixon and Noye 1995; Rothlisberg et al. 1995; Levin 2006; Pineda et al. 2007; Vance and Pendrey 2008). The large positive effects on larval settlement of including DVM and TST larval swimming behaviour in the bio-physical model highlight the sensitivity of the model to these parameters, and the importance of effectively quantifying such behaviours to predict the transport of larvae from offshore spawning areas to inshore settlement habitats.

The importance of vertical migratory behaviour to decapod larvae recruiting to estuarine systems is well documented (Jones et al. 1970; Rothlisberg 1982; Rothlisberg et al. 1995; 1996; Condie et al. 1999; Criales et al. 2007). Its importance to the settlement success of Western King Prawn larvae is highlighted in this study by the large differences in larval settlement rates between Scenario 3 where vertical migratory behaviour was included, and Scenario 1 where larvae were modelled as passive. Rates of settlement up to 45% higher were recorded in Scenario 3 indicating that vertical migratory behaviour including TST is an important adaptation allowing post larval prawns to maximise transport via the strong semi-diurnal tidal currents typical of Spencer Gulf (Nunes Vaz 2014).

The relatively high rates of larval settlement for Western King Prawn observed under Scenario 3 of the bio-physical model compared to Scenario 4 indicate that temperature is also an important factor influencing total rates of larval settlement. The relatively cooler gulf temperatures of 16.9 °C modelled under Scenario 3 are typical of Spencer Gulf in November and sustained longer larval durations compared to Scenario 4. When coupled with stage specific DVM and TST larval behaviour, this allowed settlement rates over 12% higher than estimated under the warmer gulf conditions modelled under Scenario 4.

These results have important implications from a climate change perspective. Research undertaken as part of this study and published in Roberts et al. (2012) indicates that larval durations are likely to be longer in southern Spencer Gulf compared to northern Spencer Gulf due to the lower average temperatures in the southern gulf. Results from the bio-physical model developed in this project indicate that the longer larval durations occurring under typical average temperatures of southern Spencer Gulf likely enhance their probability of reaching northern settlement grounds. Any increase in water temperature in Spencer Gulf caused by global warming would decrease larval duration times, thereby reducing the probability of larvae that originate in this area from reaching the northern settlement grounds. The effect of such a climatic shift on larval settlement would also largely be influenced by the impacts of climate change on benthic habitats favourable to prawn reproduction, and how the behavioural responses and spatial distribution of adults adapt to any increases in temperature during the spawning period. Such responses remain unquantified.

There are some limitations to the physical and biological models developed in this study. Although a three-dimensional hydrodynamic model was used, it was forced using monthly averaged climatology data. The effects of physical processes such as wind and circulation on larval dispersal over shorter time scales were not included but may be important in determining overall rates of larval settlement. Moreover, the bio-physical model did not incorporate rates of natural larval mortality via predation, or in response to changes in temperature and salinity. Mortality responses of larval to temperature were measured in tank trials conducted for Western King Prawn by Roberts et al. (2012). Instantaneous (daily) rates of mortality did not vary with temperature indicating that overall mortality rates were more influenced by larval duration than temperature. In the wild, larval mortality responses to environmental factors are difficult and costly to measure, and show wide spatio-temporal variability (Preston 1985; Preston et al. 1992; Bryars and Havenhand 2006). Spatio-temporal variation in mortality rates may vary the total settlement rates presented in this report, but could be incorporated into future versions of the bio-physical model if information becomes available.

6.4 Harvest sensitivity analyses

Stock assessment surveys for Western King Prawn conducted in Spencer Gulf provided a robust representation of their reproductive characteristics across the fishery between 2009 and 2012. The data collected coupled well with outputs of the bio-physical model to assess the sensitivity of larval settlement rates to spatial changes in harvest. Consistent patterns were observed in the areas contributing most to larval settlement success for all years surveyed. Areas 1, 3 and 11 consistently ranked in the top five areas contributing to total larval settlement. These areas alone contributed to over 40% of all larvae reaching settlement in each year between 2009 and 2012. The high rates of larval settlement modelled from these areas were due to the combination of high egg production (EP_{area}) estimates and the high rates of larval settlement success determined by the bio-physical model. This result highlights that total contributions to larval settlement from each area are sensitive to the levels of prawn biomass within an area that lead to high levels of egg production, and the rates of settlement achieved from those areas.

Within-season management occurs in the SGPF whereby data obtained from stock assessment surveys is used to control fishing operations within each 'fishing run' over the fishing season (PIRSA 2014). Stock assessment survey results provide information to set the allowable pre-Christmas catch, as well as identifying fishing areas that meet the target prawn size (>250 prawns per 7 kg bucket). Pre-Christmas management decisions are based on stock assessment surveys conducted in October or November, and have largely kept exploitation rates in Areas 1, 3 and 11 low (below 10% on 9 out of 12 occasions) between 2009 and 2012. This was largely due to the smaller-than target size of prawns in these areas that resulted in spatial restrictions on fishing prior to Christmas, and has coincidentally protected areas of the fishery that most contribute to larval settlement. Industry members of the SGPF have also understood that the northern areas of the fishery are generally important to larval settlement and, ultimately, to successful recruitment, but have lacked the quantitative data to test different harvest strategies as presented in this study. Although current management measures have helped to maintain high rates of larval settlement to some degree, the sensitivity analyses conducted in this project indicate that further refinements in the spatial patterns of pre-Christmas fishing could lead to improvements in overall rates of larval settlement while maintaining the amount of pre-Christmas catch.

By proportionately redistributing the potential amount of pre-Christmas catch taken from the top areas contributing to larval settlement, rates of larval settlement could be improved by up to 3.2% in years indicating high prawn biomass (e.g. 2010; 532 t) or 0.8% in years indicating low biomass (e.g. 2011; 332 t), while maintaining pre-Christmas catch at its recorded ('baseline') level. Improvements to *both* catch and overall larval settlement rates might be realised under high catch pre-Christmas fishing levels (e.g. 2010; 532 t) by capping exploitation rates (on larval settlement) at 2.5% in the top five areas contributing to larval settlement, and maintaining exploitation rates in all other areas at 35%. Under this fishing scenario (2010, Scenario 7) rates of larval settlement could be improved by up to 3.3% while increasing the level of catch by 42.4 t. This would equate to a potential total increase in pre-Christmas catch value of over AUD $800,000 (based on an estimated beach price of $19.42 kg – SARDI unpublished data).

Similarly in 2011, both total catch and rates of settlement were improved under Scenarios 5 (1.3%, 132.4 t, respectively), Scenario 6 (0.8%, 154.2 t, respectively) and Scenario 8 (0.3% and 176 t, respectively) again highlighting the potential dual benefit provided to both larval settlement and catch by reducing fishing in the areas contributing to high rates of larval settlement. All these harvest scenarios capped exploitation rates in the top five areas contributing to larval settlement by between 0% (Scenario 8) and 5% (Scenario 5), while setting exploitation rates in all other areas to between 25% (Scenario 5) and 35% (Scenario 8). If the hypothetical changes in catch could be realised in all areas under these harvest scenarios, the maximum benefit to the fishery would occur under Scenario 6 with a potential total increase in pre-Christmas catch of 154 t valued at nearly $3M (based on an estimated beach price of $19.42 kg – SARDI unpublished data).

It is important to note that the hypothetical harvest scenarios proposed in this report do not account for the economic viability of fishing at the proposed rates of exploitation defined under each scenario nor take into account reference points for pre-Christmas fishing defined under the SGPF Management Plan (PIRSA 2014). The prawn sizes and catch rates determined by stock assessment information are assessed against targets defined for these indicators under the current harvest strategy for the fishery and determine the area open to fishing (PIRSA 2014). Nonetheless, the information provided in this project through linking survey estimates of egg production with larval settlement rates, confirms and identifies the areas that are important for future recruitment to the fishery.

Future pre-Christmas fishing strategies could be further refined through real-time application of survey data in the models developed in this study to provide information relating to the fishing areas most likely contributing to larval settlement success. This information would augment current pre-Christmas management decisions and help to protect future recruitment. Development of timely and efficient data entry procedures would be required to incorporate the information into the bio-physical model and return results at the time needed by managers to set pre-Christmas fishing boundaries. Moreover, any application of the bio-physical model in management decisions should also use data collected from the survey period relating to the temperature characteristics of Spencer Gulf and ideally be ground truthed by field-surveys that collect information relating to the density of post larvae in nursery areas within the SGPF. This would enable inter-annual comparison of post larval settlement rates under varying regimes of temperature and fishing effort, and allow the efficacy of pre-Christmas fishing management strategies to be examined.

An ‘E-log’ data management system for real time management of catch and effort data is currently being developed for use in the SGPF. Application of this system using a different system interface would enable fishers and fishery observers to upload real time data relevant to the variables required as model inputs (e.g. shot information, prawn size and sex, Gulf temperatures). Data collected through such a system would potentially allow timely application of the bio-physical model thereby allowing real-time identification of the areas that are predicted to contribute most to egg production and larval settlement. This could allow target exploitation rates to be set within the areas that most contribute to egg production and larval settlement, thereby helping to maximise harvest levels during spawning while managing the potential threats of recruitment overfishing.

7 Conclusion

The four objectives of this study were to: 1) develop models relating to the reproductive and larval biology of Western King Prawn and Blue Swimmer Crab in Spencer Gulf; 2) develop a passive particle hydrodynamic model for Spencer Gulf; 3) develop the base-case bio-physical model to simulate Western King Prawn and Blue Swimmer Crab larval dispersal, and assess the effects of different environmental conditions (e.g. water temperature) on larval recruitment; and 4) test scenarios to better optimise the harvest of Western King Prawn during the early spawning season. These four objectives were achieved.

We used data from tank trials, published research, and climate and ocean sensors to develop a bio-physical model to simulate patterns of larval dispersal and settlement for Western King Prawn and Blue Swimmer Crab in Spencer Gulf. This model was coupled with information from stock assessment surveys relating to the spawning characteristics of these species to identify the key areas in Spencer Gulf contributing to larval settlement success.

Tank trials were successful in calculating the lengths of larval duration for Western King Prawn in response to a range of different temperatures typical to Spencer Gulf. This was key information in providing the time scales over which the bio-physical model should be run. The bio-physical model indicated that overall rates of larval settlement were maximised for Western King Prawn when tidal and atmospheric physical-forcing components were coupled with larval swimming behaviour and longer larval durations. The importance of vertical migratory behaviour to larval settlement success of Western King Prawn was highlighted by large increases in larval settlement rates when vertical migration behaviour was incorporated into the bio-physical model. Cooler gulf temperature inputs into the model, which were typical of Spencer Gulf in November, also helped to sustain longer larval durations and increased larval settlement rates when compared to warmer gulf conditions. This model result indicates that global warming may reduce larval duration and total larval settlement rates for Western King Prawn.

Fishery-dependent data indicated that the areas with the largest percentage of spawning female Blue Swimmer Crab (>25%) were generally located in the eastern gulf north of Wallaroo. This region also contributed to the highest rates of settlement of Blue Swimmer Crab larvae. The density of crabs in these areas is unknown from the available data, however it is possible that these areas make the largest contributions to egg production and larval settlement. A more stratified approach to sampling Blue Swimmer Crab across their distribution in the future is required to better estimate egg production. These data would also enable relative estimates of crab biomass to be calculated and help to optimise harvest strategies for the BCF.

For Western King Prawn, reproductive information was coupled with data from the bio-physical model to determine the sensitivity of larval settlement rates to spatial changes in harvest. Consistent patterns were observed in the areas contributing most to larval settlement success for all years surveyed between 2009 and 2012. Sensitivity analyses indicated that changes in the spatial patterns of pre-Christmas fishing could lead to further improvements in overall rates of larval settlement while maintaining or improving the levels of catch. Real time application of the bio-physical model in the future using data collected from pre-Christmas surveys could allow target exploitation rates to be capped within the areas that most contribute to larval settlement, thereby helping to maximise rates of larval settlement and catch across the fishery. This would augment current management strategies for pre-Christmas fishing in the SGPF and help to manage the potential threats of recruitment overfishing.

8 Implications

Maximising fisheries production and minimising the impacts to fish stocks and their ecosystems are key objectives of fisheries management throughout the world. Under principles of ESD, fisheries are now required to demonstrate sustainable exploitation of fish stocks through their management plans and harvest strategies. Historically the links between oceanographic processes and larval settlement have been hampered by the inability to couple hydrodynamic models with knowledge relating to the larval biology and behaviour. Recent advances in the techniques used to model oceanic processes have led to accurate predictions in the scale and direction of larval dispersal and settlement within areas that fisheries operate.

Results from the bio-physical model developed in this study highlighted the areas of the SGPF and BCF that contribute most to fisheries recruitment and production. Harvest sensitivity analyses based on these results indicate that current spatial management arrangements for the SGPF could be augmented by additional information provided by the bio-physical model to further improve overall rates of larval settlement while maintaining or improving fisheries production. Future pre-Christmas fishing strategies could be further refined through application of real-time survey and oceanographic data in the models developed in this study to provide information relating to the fishing areas most likely contributing to larval settlement success. Such information would assist in enhancing sustainable development of the SGPF by helping to manage the potential threats of recruitment overfishing.

9 Recommendations

The following recommendations have been developed from this project:

1. Pre-Christmas fishing effort in Areas 1, 3 and 11 of the SGPF should be managed in real-time, based on stock assessment survey results, to maximise larval settlement success while adjusting exploitation rates in other areas to maintain levels of pre-Christmas catch established annually under harvest arrangements for the fishery.

2. Data entry systems should be developed so that stock assessment survey data collected in pre-Christmas fishing periods can be applied within bio-physical models in real time to identify areas of the fishery most likely contributing to larval settlement success.

3. A more stratified stock assessment survey design should be developed for Blue Swimmer Crab in Spencer Gulf to estimate egg production and biomass across their distribution.

10 Extension and Adoption

This project has enhanced the understanding of the physical and biological processes that affect transport, dispersal and settlement rates of crustacean larvae within Spencer Gulf. The results will provide stakeholders in the Western King Prawn and Blue Crab fisheries of Spencer Gulf with critical information to enhance future research directions and improve management strategies for their fisheries in the context of spatial management. Members of the SGPF will be well placed to use these findings in conjunction with those obtained from the prawn bio-economic project (ASCRC 2011/750) to optimise both economic and biological performance in the SGPF.

Overall, information provided in this report provides opportunities to better maximise resource use while helping to minimise the potential impacts of fishing. This, in turn, should provide flow-on economic benefits through sustained or improved harvests and licence values, supporting the principles of ESD developed for Australian wild fisheries (Fletcher et al. 2002). Ideally approaches used in this research will be extended to similar fisheries in southern Australia.

Project coverage

During the course of this project, there have been numerous discussions with stakeholders. For example, a presentation outlining the objectives and preliminary results of the project was delivered to the SGWCPFA on 12 September 2014. Subsequently, the SGWCPFA and SABCPFA were provided copies of the presentation for comment and comments were addressed in subsequent versions. This report has been widely distributed (see Appendix 3) with recipients including the Australian Council of Prawn Fisheries, South Australian Spencer Gulf, Gulf St Vincent and West Coast prawn fisheries, Northern Prawn Fishery, prawn fisheries of Western Australia and Marine Stewardship Council assessors.

The project team has maintained on-going contact with members of the SGWCPFA and SABCPFA about the project’s progress and they have been helpful and cooperative in providing information and assistance. This research has been reported in the December 2014 Newsletter of the Australian Society of Fish Biology and will continue to be reported through SARDIs public corporate communications program. Research findings have been, and will continue to be, published in peer reviewed scientific journals and reported to fisheries managers.

11 Project materials developed

The following scientific papers relating to this project have been published or have been submitted for review in peer-reviewed scientific literature:

1. Roberts, S.D., Dixon, C.D., 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.

2. Rodgers, G.G., Roberts, S.D. and Dixon, C.D. (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.

3. McLeay, L.J., Doubell, M., Dixon, C., James, C. and Luick, J. (in review). A bio-physical model to optimise larval recruitment and sustainable harvest in southern Australia's largest prawn fishery. *Fisheries Oceanography.*

This FRDC project contributed to funding of a PhD through Flinders University. The PhD, which is currently under revision, is being undertaken by Ms Nadine Hackett and is titled "Reproductive biology of the western king prawn *Penaeus* (*Melicertus*) *latisulcatus* (Kishinouye 1896) in Spencer Gulf and Gulf St Vincent, South Australia".

The research was also reported in the December 2014 Newsletter of the Australian Society of Fish Biology.

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13 Appendices

Appendix 1. Intellectual Property

No intellectual property has been identified. The report and resulting manuscripts are intended for wide dissemination and distribution.

Appendix 2. Staff

Lachlan McLeay – Principal Investigator (SARDI)

Mark Doubell – Co-investigator (SARDI)

Shane Roberts – Co-investigator (SARDI)

Cameron Dixon – Co-investigator (SARDI)

Lorenzo Andreacchio – Technical support (SARDI)

Charles James – Technical (modelling) support (SARDI)

John Luick – Technical (modelling) support (SARDI)

Bennan Chen – Technical support (SARDI)

Wayne Hutchinson – Technical support (SARDI)

Carlos Teixeira – Technical support (SARDI)

Angelo Tsolos – Data support (SARDI)

Graham Hooper – Technical support (SARDI)

Neil Chigwidden, Chris Small, Dave Kerr, Andrew Sellick (Crew - RV Ngerin) (SARDI)

Nadine Hackett (PhD Student)(Flinders University)

Members of the Spencer Gulf and West Coast Prawn Fisherman’s Association.

Appendix 3. Report Distribution List

Name	Organisation	Address	Suburb	State	Post code	Country
Legal Deposit Unit	State Library of South Australia	GPO Box 419	Adelaide	SA	5001	Australia
Legal Deposit Unit	National Library of Australia		Canberra	ACT	2600	Australia
Parliamentary Librarian	Parliamentary Library of SA	GPO Box 572	Adelaide	SA	5001	Australia
SARDI Library	SARDI- Aquatic Sciences	PO Box 120	Henley Beach	SA	5022	Australia
Graham Stewart	Australian Council of Prawn Fisheries	PO Box 393	Floreat	WA	6014	Australia
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