Fisheries Biology and Spatial Modelling of the Blue Swimmer Crab (*Portunus pelagicus*)

Ib Svane and Anthony Cheshire (Editors)

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Project No. 1998/116

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NON TECHNICAL SUMMARY

1998/116 Fisheries Biology and Spatial Modelling of the Blue Swimmer Crab (*Portunus pelagicus*)

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Objectives:

1. To determine key determinants of blue crab biology and fishery production.
2. To determine the main sources of variation in recruitment and other biological parameters important to the fishery.
3. To develop and formulate a quantitative production model that can be used in management of the blue crab fishery.
4. To integrate information that has been collected from this study, the "Blue Crab Fishery Biological Research Review" by J. Scandol and S.J. Kennelly and SARDI's existing research program, in an assessment of current and alternative management strategies on the SA blue crab stocks.

Outcomes achieved:

The research documented in this report has contributed significantly to the sustainable development of the South Australian blue crab (*Portunus pelagicus*) fishery by providing detailed information on the key determinants of blue crab biology including an understanding of demographic patterns of post-settlement juvenile crabs. The research has also contributed to the development, critical evaluation and implementation of a Schaefer model for the SA Blue Crab fishery. The model has been applied to the existing fishery data and used to estimate key parameters for the fishery. These findings have been considered in relation to the existing management arrangements in the fishery.

This report provides the background to the study and describes the history and development of the FRDC research project aimed to benefit the South Australian blue crab fisheries. The project was developed to address the research needs identified in a national blue crab workshop held in 1997. The need for an independent research program to support the fishery-funded collection of data was highlighted at the workshop and initiatives were also taken to complement research in other states. This program of research recognised that the value of the blue crab fishery was insufficient to support an intensive research program in any state.
The project encountered a number of difficulties that delayed implementation and resulted in a fragmented data series. This was particularly significant in relation to the tag and recapture components of the project. The preliminary results of the tagging program are presented in the appendices. A total of 6849 crabs were tagged (Spencer Gulf: 3507, Gulf St Vincent: 3342) of which 60 crabs were recaptured.

This report provides a comprehensive review of blue crab biology and the key biological determinants important to the fishery. The blue swimmer crab is known to have a wide distribution in Australia and occurs in both subtropical and temperate waters with its southernmost occurrence in South Australia where it is primarily confined to the northern parts of Spencer Gulf and Gulf St Vincent. Because reproduction and growth are temperature dependent, the species biology and ecology varies between regions; this has implications for utilization of blue swimmer crab populations as a resource. The review highlights the differences in blue swimmer crab biology between Southern Australia and other regions.
In South Australia there are well developed commercial and recreational blue swimmer crab fisheries. This report describes both the historical development of these fisheries and the current methods of production. For the management of the South Australian blue swimmer crab fisheries a sound understanding of the species biology is required. As an aid for management of the commercial fishery, a suite of key biological determinants important to the fishery has been developed. The biological determinants are described and reviewed in the context of the current use of biological reference points and methods of assessment.
The persistence of *Portunus pelagicus* populations in SA is dependent on the capacity of larvae to disperse, which is influenced by temperature and regional oceanography. An investigation is presented describing the multi-scale demographic patterns of post-settlement juvenile (<50mm carapace width) *P. pelagicus* in South Australia in order to determine key

settlement seasons, sites and habitats. The distribution and abundance of juveniles varies seasonally, with patterns probably driven by physical factors such as water temperature and the development of alternate hydrodynamic regimes such as gyres. Settlement peaks occur during summer and/or early autumn.

Length frequency data were used to explore subsequent growth of juveniles on a monthly basis and showed that newly settled juveniles have the capacity to reach fishery pre-recruit size (50-100mm) within a single summer. Regionally, the distribution of juveniles in both gulfs was spatially inconsistent. In Spencer Gulf juvenile abundances were greatest at sites between Port Pirie and Port Broughton. In Gulf St Vincent, the Barker Inlet area was found to have the greatest numbers of juvenile *P. pelagicus*, with other important nursery sites being found in the northern region of the gulf. Locally, demographic patterns were habitat specific. Post-settlement juveniles actively selected for intertidal seagrasses (*Zostera sp.* and *Heterozostera tasmanica*) over other seagrasses (*Posidonia sp.* and *Amphibolis sp.*) or unvegetated soft substrata. Where intertidal seagrasses were absent, juvenile *P. pelagicus* preferred unvegetated soft substrata to subtidal seagrass meadows. These findings reveal potentially important environmental factors and behavioural traits that may influence the demography of juvenile *P. pelagicus* in nursery habitats in South Australia.

A research need identified by the national workshop was to develop a spatial model that would apply to a typical estuary and adjacent bay, and more open marine waters. A useful start to this is in the development of a biomass dynamic (otherwise known as a Schaefer or Surplus Production) model to inform the management of this fishery. This need was highlighted in a review of the research in the South Australian blue swimmer crab conducted by James P. Scandol and Steven J. Kennelly from Centre for Research on Ecological Impacts of Coastal Cities, February 2001 (presented as an appendix to this report). The seven Terms-of-Reference included: a research review; short term monitoring advice; process issues; recommendations for a 5-year research program; consultation with stakeholders; and comments on sampling issues for ESD outcomes.

The review found that a “Schaefer” or “Surplus Production model” would be useful in providing support to fishery managers and the FMC in setting the TACC for the fishery. This report provides details of a Schaefer or Surplus Production Model that has been developed for this fishery. A problem with applying this model in support of management in the SA blue crab fishery is the fact that CPUE rose dramatically over the first 10-12 years of its operation, this makes the implementation of such a model problematical in that the model relies on measurements of CPUE to provide robust estimates of relative stock size. Acknowledging the potential limitations of this approach to modelling the fishery the report critically evaluates an implementation of the Schaefer model for the SA blue crab fishery. The specific objectives were to: 1) Outline the nature of the Schaefer model, 2) To consider the issue of CPUE as an index of stock size and to formulate an approach for transforming CPUE data to account for "learning" in the fishery, 3) To apply the model to the existing data in the fishery and thereby estimate key parameters for the fishery, and finally 4) To consider the model outputs in relation to the existing management arrangements in the fishery.

Acknowledgements

A wide range of people have made contributions to the production of this report including many that worked on the project since it's inception. Sue Murray-Jones, Martin Kumar, Paul McShane and Howel Williams are all thanked for their contributions to the original development of the project and/or to its subsequent delivery. SARDI Aquatic Sciences provided substantial additional resources to support this project. We would also like to express our appreciation to the SA blue crab fishers for their help and support.

Benefits and adoption

The blue crab fishing industry has benefited from this project through an enhanced understanding of the biology of the blue swimmer crab and the demography of post-settlement juveniles. A model for the blue crab fishery has been developed and this should provide the basis for improving our understanding of the fishery as more data, particularly fishery independent data on stock size, are obtained.

Further development

While this project has contributed significantly to an understanding of the fishery biology of the blue swimmer crab in South Australian waters and the management options for the fishery, there are still a number of unknown elements. The first is a lack of understanding of the mechanisms that govern large-scale spatial and temporal patterns of population dynamics (at the scale of the fishery). The second, third and fourth elements are the lack of understanding about the mechanisms that govern larval survival, settlement and recruitment into meta-populations. An understanding of the first element may be obtained through fishery independent surveys but this will need to be substantiated through experiments. An understanding of the second, third and fourth elements will require further studies independent of the fishery.

Modelling of the SA blue swimmer crab fishery is possible provided that the necessary tools are developed. However, the size of the fishery and the existence of a large un-recorded recreational fishery restrict such a development. Accordingly, the most economical approach appears to be in the development of direct estimates of population abundance and structure through independent sampling.

Planned outcomes

None

KEYWORDS: Blue crab biology, spatial, modelling, fishery management

CHAPTER 1: BACKGROUND OF FRDC PROJECT 98/116: THE FISHERIES BIOLOGY AND SPATIAL MODELLING OF THE BLUE SWIMMER CRAB (*PORTUNUS PELAGICUS*)

Sue Murray-Jones

History of the FRDC proposal

There was a large expansion in fishing effort on the blue crab, *Portunus pelagicus,* in South Australia when 12 experimental pot licences were issued in 1983. Subsequently, this led to concerns being raised about issues such as resource allocation and sustainability. In 1994 SARDI published a summary of current information about blue crabs (Baker and Kumar, 1994), which included recommendations for research and the management of the fishery. Research recommendations included:

- annual assessments of the relative abundance of mature and sub-recruits;
- improved quantification of catch and effort;
- collection of by-catch data from prawn trawler surveys;
- assessments of the distribution and migration of crabs in both gulfs;
- collection of gulf-specific population dynamics data eg growth, movement, and longevity;
- assessment of the effects of changes in effort and size at capture in the fishery;
- Egg-Per-Recruit modelling;
- determining spawning stock size/recruitment relationship;
- determination of oceanographic variables affecting recruitment;
- post-harvesting studies.

In 1996 a core research program was initiated. The objectives of this program (Kumar 1997b) were to:

- assess the relative abundance in both gulfs;
- validate catch and effort data;
- establish a baseline of environmental conditions for assessing potential impact on the crab fishery;
- determine size distribution and sex ratios;
- assess the relative spawning stock ratio.

In 1997, a National Workshop on Blue Swimmer Crabs was held at SARDI to bring together researchers and industry, in order to: summarise knowledge of research and management efforts in all states; evaluate the status of blue crabs at the national level; and to plan future research and management priorities (Kumar 1997a). This workshop highlighted the absence of long term catch and effort data, indices of abundance, and information on almost any fisheries parameter. Research needs for the SA fishery were outlined by Kumar (1997b) over and above the recently implemented core research program. These included:

- quantification of recreational catch;
- assessment of the stock structure and distribution in fishing areas;
- assessment of the distribution and movement of crabs in inshore and offshore waters;
- development of an index of spawning stock size and recruitment;
- identification of oceanographic variables that affect recruitment;
- post-harvesting studies.

A summary of the research being conducted in WA at the time, along with a discussion of research needs, was presented by Melville-Smith and Potter (1997). WA researchers had already submitted a proposal to the FRDC for this work for the years 1997-2000. The key research areas flagged as important and included in that proposal were to:

- determine habitat types associated with blue crabs in WA;
- determine the reproductive biology of crabs in Shark Bay;
- determine whether blue crab assemblages in WA constituted separate stocks, based on spatial patterns of genetic variation;
- determine an appropriate level of effort by understanding selectivity and efficiency of different gears used in harvesting;
- establish discard mortality for the commercial and recreational catch;
- develop a spatial model that would apply to a typical estuary and adjacent bay, and more open marine waters (Melville-Smith and Potter 1997).

In the FRDC proposal, the need for an independent research program to support the fishery-funded collection of data was highlighted. It was proposed that FRDC would fund work, to complement the basic research program initiated in 1996, and also to complement research in other states, that was consistent with the research needs highlighted at the National Workshop (Kumar 1997a). One of the key components was that this proposal would augment current research in a number of states. This recognised the fact that the value of the blue crab fishery was insufficient to support an intensive research program in any state.

A session at the 1997 National Workshop was held to discuss overarching blue crab research priorities (Kumar 1997a; *pp* 123-127). As this discussion influenced the final allocation of funding by the FRDC, it has been summarised here. Participants unanimously agreed that research should not be duplicated in each state, and that it should be undertaken in a nationally coordinated fashion. Research needs were hence divided into generic and specific studies.

Generic programs (those providing benefit to all states) included:

- survey techniques;
- sample size experiments;
- gear selectivity;
- environmental influences on factors such as growth, reproduction, movement, survivorship and habitat interactions;
- identification of biological reference indicators (e.g. juvenile abundance, recruitment relationships).

Specific studies (those of value to individual states) included a consideration of factors that were likely to be influenced by climate, such as:

- reproduction (size at first maturity);
- pre-recruitment strength;
- growth;
- movement;
- survival;
- gear vulnerability;
- habitat interactions.

The discussion also highlighted the need for management plans; an understanding of density-dependent processes; economic analyses; and information on growth/age and its relationship to size limits.

Priority for research was given to two main areas:

1. Resource quantification. As recreational fishers probably took over 50% of the catch, it was felt that any management plans needed to include 100% of the resource. Hence it was regarded as critical to quantify the recreational catch.
2. Stock assessment. This would include research on the following areas:
    - biological indicators;
    - recruitment processes and environmental influences;
    - stock structure;

- validation of fishery data;
- development of models.

Objectives of the original research proposal

Following from these workshops and the preliminary research, a proposal was developed by SARDI and submitted to FRDC who agreed to provide funding. The objectives for this project were:

1. *To determine the key determinants of blue crab production including recruitment, growth, movement and survival.*
2. *To determine the main sources of variation in biological parameters important to the fishery.*
3. *From existing genetic information and from studies of movement, determine the stock structure of blue crabs.*
4. *To integrate the information that had been collected from this study, SARDI's existing research programs, and previous work to formulate a spatially explicit production model which describes, in a quantitative way, the effects of alternative management strategies on blue crab stocks.*

Agreement on content of the final report

In consultation with the FRDC, it was agreed that the final report would provide:

1. *An introduction that presents an "overview" of the project including its history and a summary of the work undertaken.*
2. *A chapter that reviews the biology of blue crabs and incorporates all data (published or unpublished) collected during the project (addressing objectives 1 and 2).*
3. *A chapter on the application of the Schaefer model to the SA Blue Crab Fishery. This would be written to include a full description of the model explained in terms that could be understood by non-biologists and non-mathematicians (addressing objective 4).*
4. *A copy of the report produced by Scandol and Kennelly (addressing objective 4).*
5. *A chapter on recruitment processes (addressing objective 2 - recruitment).*

It was also agreed that objective 3 would not be covered because an FRDC report had already been published on the subject of blue crab genetics. Some of the material in that report was supplied by SARDI.

Summary of work formally undertaken as part of the FRDC project

Objective 1. To determine the key determinants of blue crab production including recruitment, growth, movement and survival.

Recruitment Study

Some methodological details were explicitly spelt out in the FRDC proposal, including the Carrick (unpublished) method of sampling juvenile prawns to be used for the blue crab recruitment work. There were delays in starting the recruitment survey due to the need to develop a beam trawl for sampling juvenile crabs. After some sea trials it was modified because there were some suggestions that blue crabs recruited into seagrass at least some of the time, and the available jet net (Carrick's method) was not suitable for sampling seagrass habitats.

A pilot study was conducted to look at: variance among and within sites, distance from shore and habitats; the efficiency of the two different nets, including establishment of the most appropriate tow speed, tow length, and number of replicates. These pilot studies, conducted in the initial phases of the project, indicated that beam trawl rather than jet net gave a higher efficiency for sampling juvenile crabs, and that a series of random tows rather than a fixed plot method was needed to provide data for the spatial model. Hence Carrick's method was not used, and the beam trawl was used with tickler chains in sand/shell habitats, and without ticklers in vegetated habitats. Methodological details and results are given in Chapter 3.

Growth and movement

Tagging techniques and trials

A number of different tagging techniques were trialled. These included: several types of Hallprint anchor tags; visible implant tags, including alphanumeric tags (Hallprint) and coloured elastomer (Northeast Technology); and coded wire tags. The tagging trials were conducted in aquaria to determine tag loss and mortality from the different types of tags. Coded wire tags were judged not to be viable for this project, as the portable detectors available for use on boats were very sensitive to the distance and speed of movement of the tag past the detector, and in blind trials we were not able to detect crabs tagged in this way with any certainty. We found no tag loss for elastomer and visual implant tags. Elastomer tags in the paddle of the swimmeret were clearly visible but did not allow individual identification, or the insertion of the word "reward" and a phone number, essential for getting returns from the recreational community. Some experiments were conducted with an applicator and waterproof paper, but these were not successful. Visual implants were difficult to apply, and too small to be readily visible. Hence we decided not to proceed further with these types of tags. In further tag trials, we used fine anchor tags only. Unfortunately mortality in caged crabs was high, and one month after tagging over 50% were dead. Less than 8% survived for more than 2 months.

We found no effect of tagging on survivorship using a Kaplan-Meier survival analysis (with number of days survived as the dependent variable; Wilcoxon test, χ^2=2.45, df=1, p=0.118). Tag loss was initially 12.5% for fine anchor tags, however in a subsequent trial we were able to obtain zero tag loss, by giving the tag a good tug to set the anchor and to check that the tag was effectively inserted before releasing the crab. Unfortunately only one tagged crab moulted in captivity (tagged with a short-shanked, fine anchor tag). This crab retained the tag successfully after moulting, but we were unable to assess moulting mortality due to tags because so few crabs moulted.
The final trial compared retention of tags and mortality from fine anchor tags with a long shank (as used in the WA study), and a shorter shanked tag (used with considerable success in a NSW study - R. McPherson, pers. comm.). We found no significant difference in mortality between treatments (Wilcoxon test, χ^2=4.81, df=2, p=0.09). Early mortality was the same for all treatments, however control mortality dropped to zero after 15 days, while the numbers of tagged animals continued to decline. No tags were lost. Due to the urgent need to release tagged crabs into the wild before summer, when recreational catches are high, we initiated field tagging programs as soon as possible, despite the lack of data on mortality from moulting. We used the same tags as were used in WA to facilitate direct comparisons, as these tags appeared to be the most practical for the study proposed, and there was some information available on tag mortality (S. de Lestrang, pers. comm.).

Release of crabs

We commenced tagging in September 1999, using sequentially numbered, fine anchor tags (Hallprint). In spring and early summer we tagged over 3000 crabs in each of Gulf St

Vincent and Spencer Gulf. We tagged crabs both close inshore (from a small boat) and further out, using RV Ngerin, effectively providing paired sites. Sites were selected after consultation with commercial fishers and the modeller (Dr Yongshun Xiao) and were spread around the gulfs. Crabs were caught both at night and during the day by using commercial pots with a finer mesh (5 cm) than is currently commercially allowed. A short soak time was used to reduce damage to crabs. Smaller crabs were collected by trawling at night. Selection was randomised to some degree however factors such as weather, bottom type and the numbers of crabs caught strongly influenced the deployment of tagged animals.

Tagging was also carried out in a serendipitous fashion; all crabs caught during the recruitment study were tagged and returned to the water. In addition, a number of keen recreational fishers responded to publicity and agreed to measure, tag and release crabs after receiving some training. Crabs were released at the point of capture, so as not to confound the movement study with any homing behaviour.
For all crabs, data were kept on release point, depth, sex, size and general condition. Where practical, only intact crabs were tagged, however some crabs with missing limbs were tagged, particularly if these appeared to be old injuries.

Publicity

We had very good publicity, with coverage on three television channels (several programs on one channel), five radio stations, the main Adelaide paper, local papers and magazines including Southern Fisheries (two articles including cover), SA Water (twice), and SA Angler.

Data from tagging program

Response from recreational fishers was good, with 58 tags (97% of total returns) being returned by this sector. Unfortunately, despite the widespread publicity, most recreational anglers did not keep the crab shells. They would make a note of the crab number, and provide details of where it was caught, but would usually discard the shell. Hence we were only able to use data from recreational fishers to obtain information on movement, no growth data were obtained.

Commercial fishers recovered few tags. One single tag was returned from a marine scale fisher. No returns came from the pot sector. Another tag was reported from a fish processing plant, but the processors were not sure which batch and hence which area that crab came from. Other studies have shown that retrieval rates and visibility of anchor tags is poor (e.g. Williams 1986), and this may be the reason for such poor returns. Also, in Spencer Gulf, we deployed the tags immediately prior to the start of the closed season, in order to give crabs a chance to moult and grow over summer before being recaptured. High mortality may have been a problem. However; it is worth noting that in a similar program in WA, run at approximately the same time, approximately 10% of tags deployed were returned, all but one from commercial fishers (S. de Lestang, pers. comm.).
A further tagging effort was planned from commercial boats to optimise the likelihood of returns, with the intention of tagging a further 6000 crabs, and comparing seasonal movement patterns. This, however, was not carried out.

Ultimately a total of 60 tags were recovered. Most of the recaptured crabs did not move very far, with the exception of one male that moved 38 km in a month (see preliminary data in appendix I).

Density dependent study

The original methods section in the FRDC proposal included a density dependent study. Populations of contrasting density were to be identified in order to examine the effects on growth and survival of blue crabs. The decline in frequency of tagged crabs was to be used as a primary indicator of survival, and the incremental growth of tagged crabs used as a dependent variable in comparing density in field trials. This was to be augmented with aquarium studies. A lot of effort and energy went into determining how this could be done. The following discussion summarizes the reasoning behind the decision not to continue with this component.

Blue crabs are highly mobile. Movement seems to vary temporally and spatially, and a large part of the tagging effort was directed at identifying patterns of movement. Fisheries logbook data suggest that some movement occurs on a seasonal basis, while some is due to gender differences, with males and females occupying different locations at different times. Hence even identifying areas of contrasting density was judged to be problematical, as densities fluctuate with time. Also, if some areas do support lower densities of crabs, the lower densities could be a result of many factors, such as low food supply, unsuitable sediment type, differences in vegetation structure, high predation, pollution, or unfavourable water circulation etc. Hence comparing growth rates or survival from areas with existing differences of density would not answer the primary question.

Another way to estimate density dependent growth would be to manipulate densities. With such a mobile animal, and one with the aforementioned tendency to change location, manipulating densities in an open situation would be pointless. Commercial crab fishers find that the degree to which stocks become locally depleted in a given area varies greatly between times and locations. In some areas at some times, even with heavy fishing pressure, catches do not decline over considerable periods of time, suggesting movement into the area by other crabs.

An alternative was caging; however, there is a general absence of rocky inlets in both Spencer Gulf and Gulf St Vincent, which could be fenced off. The topography is that of open coastline, with extensive mud or sand flats. Due to the size and agility of blue crabs, any enclosure would need to be very large, and roofed over completely. This would be prohibitively expensive, subject to vandalism, be a navigation and trawling hazard, and be vulnerable to storm activity. Complete enclosures would also interrupt energy flows into the system, in particular restricting the movement of both prey and predators. This would mean that both growth and survivorship data would be biased. In addition, constraining crabs that usually migrate may affect growth and survival.

Tank trials would suffer from similar artefacts. Growth and survivorship data from aquaria cannot be extrapolated into the real world. In addition crabs are very aggressive and difficult to keep in captivity (we are finding very high mortality in current aquarium-based tagging trials, even when crabs are kept in individual cages). To look at density-dependent growth and survival, crabs would need to be uncaged. If they are free to interact but do not have sand in which to bury, we found that they fight constantly and tend to have a high injury rate and hence high mortality, while providing sand in which to bury is likely to cause water quality problems.

It was felt that to try to complete the density dependent study would take more resources than were available. As the density dependent study was a relatively minor component of the overall project, and was not an objective of the study, we submitted a milestone variation (subsequently approved by FRDC) to delete this component.

Objective 2. To determine the main sources of variation in biological parameters important to the fishery.

Analysis of the recruitment survey data provided data on spatial variation in recruitment. The stock assessment program was intended to provide a time series of data from different locations, including length frequency data, proportion of immature animals, sex ratios, number of berried females, etc. However there were significant gaps in these data, the reasons for which are discussed below in the section on "General Problems". Not enough tagged crabs were returned for growth estimates, so growth was inferred from length frequency data.

Objective 3. From existing genetic information and from studies of movement, determine the stock structure of blue crabs

The South Australian program collected tissue samples and freighted them to Jenni Chaplin in Perth, who was conducting the genetic analyses for the national program. A previous genetic study was conducted within SA (Bryars and Adam 1999), and is discussed in Chapter 2.

Objective 4. To integrate available information to formulate a spatially explicit production model.

The main aim of the blue crab project at SARDI was to build a spatial model of blue crab population dynamics for the fishery in Gulf St Vincent and Spencer Gulf. All field work components e.g. the recruitment survey and tagging program, were designed to provide relevant data for the model, which would also incorporate logbook data and catch sampling data. There were some issues with the data collection discussed below in the section "General Problems.

General Problems

There was a prolonged dispute between the crab pot fishers and SARDI/PIRSA. The fishers were not able to cooperate with the tagging program, nor was any stock assessment carried out. There was a period during which fishers would not allow SARDI staff onto their boats to monitor and measure catches, and the majority did not return catch/effort log sheets. This greatly affected the program in the following ways:

- Tagging program. In a similar program in WA, 10% of tags deployed were returned over a similar time frame, all but one from commercial fishers (S. de Lestrang, pers. comm.). In Gulf St Vincent, we had a tag return rate of around 1%, all but two tags being recovered from recreational fishers. The pot fishers did not return any tags. This suggests that either the commercial pot fishers were withholding data, and/or were not actively searching for tags. Without returns from the commercial fishery, we could gain no estimates of fishing mortality, natural mortality or spatial movement rates. While we did get information about movement from the recreational fishery, this data was not of use in terms of constructing the spatial model because no information was available on recreational fishing catch and effort. Without substantial data on crab movement within the commercial fishery, no spatial model could be constructed.
- Lack of stock assessment data. The lack of data usually collected as part of routine commercial monitoring (e.g. length-frequency data, sex ratios, the proportion of berried females) also meant that it was not possible for the modeller to construct a meaningful model. For example, there would be no data on the number of crabs or sizes available, and no estimates of growth or mortality.

Other minor problems that caused general delays to the program were detailed in the project milestone reports and are summarised here for completeness:

- No component of time was allocated in the grant for pilot studies and gear validation trials.
- Late appointment of Professional Services Officer – commenced October 1998 instead of July 1998 as planned.
- Limited access to boats, equipment and personnel that were being used for other programs.
- Initial results indicated the need to revise some of the methods due to logistical problems. These samples were subsequently treated as an extension of the piloting work and used to further refine the methods.
- Inclusion of the density dependent study; this required much literature work, discussions and thought. Eventually the decision was made to drop this component, which was not a key objective of the project.

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CHAPTER 2: BLUE CRAB BIOLOGY AND KEY BIOLOGICAL DETERMINANTS IMPORTANT TO THE FISHERY

Svane, I. and S. Bryars

Abstract

The blue swimmer crab is known to have a wide distribution in Australia and occurs in both subtropical and temperate waters with its southernmost occurrence in South Australia where it is primarily confined to the northern parts of Spencer Gulf and Gulf St Vincent. Because reproduction and growth are temperature dependent, the species biology and ecology varies between regions; this has implications for utilization of blue swimmer crab populations as a resource. The review highlights the differences in blue swimmer crab biology between Southern Australia and other regions.

In South Australia there are well developed commercial and recreational blue swimmer crab fisheries. This report describes both the historical development of these fisheries and the current methods of production. For the management of the South Australian blue swimmer crab fisheries a sound understanding of the species biology is required. As an aid for management of the commercial fishery, a suite of key biological determinants important to the fishery has been developed. The biological determinants are described and reviewed in the context of the current use of biological reference points and methods of assessment.

Introduction

This chapter consist of three elements important for an understanding and utilisation of the blue swimmer crab resource in South Australia, namely a review of the current knowledge on the general biology of the blue swimmer crab, a description of the South Australian blue swimmer crab fishery, and a summary of the key biological determinants important to assess the South Australian blue swimmer crab fishery. The review is not exhaustive but is limited to what the authors found important for the SA blue swimmer crab fishery and what has been published in refereed journals.

General biology of the blue swimmer crab, *Portunus pelagicus* (L.)

The blue swimmer crab *Portunus pelagicus* (Linnaeus) (Crustacea: Decapoda: Brachyura: Portunidae: Portuninae) is a true crab species belonging to the family Portunidae. The blue swimmer crab has five pairs of legs. The first pair is chelae or claws, the following three pairs are walking legs and the last pair of legs are modified as swimming paddles. The carapace is rough in texture, broad and has a prominent projection/spine on each side. Blue swimmer crabs are active swimmers, but during inactivity they bury in the sediment, with only eyes, antennae and gill chamber openings uncovered. Males are blue and have larger claws than females, which are green-brown in colour (Figure 1).

Figure 1. Male (left) and female (right) blue swimmer crab *Portunus pelagicus* (L.) (from Svane and Hooper, 2004).

Distribution

P. pelagicus is a cosmopolitan species occurring throughout the Indo-West Pacific region from east Africa to Japan, Tahiti and northern New Zealand (Kailola *et al*., 1993). It has also invaded the Mediterranean Sea since the construction of the Suez Canal (Smith, 1982). Within Australia, *P. pelagicus* is found in a continuous northern distribution from south-west Western Australia to the New South Wales/Victorian border (Kailola *et al*., 1993). *P. pelagicus* is also found on Lord Howe Island (Kailola *et al*., 1993) and has been recorded from Port Phillip Bay in Victoria (Shinkarenko, 1979), but is not considered to be a permanent resident there. Despite its essentially tropical/sub-tropical distribution, three geographically isolated sub-populations of *P. pelagicus* occur in temperate South Australia (Bryars and Adams, 1999). A genetic study of *P. pelagicus* in Australia revealed that crabs throughout Australia consist of the same species, i.e. no evidence for sub-species (Bryars and Adams, 1999). The South Australian population is, however, genetically isolated and distinct from other Australian populations of *P. pelagicus* (Nei's Genetic Distance = 0.03-0.06, Bryars and Adams, 1999).

Within South Australia, *P. pelagicus* adult crabs are restricted to three geographically distinct regions: in some inshore bays on the West Coast (WC) of Eyre Peninsula, in Spencer Gulf (SG), and in Gulf St. Vincent (GSV) (Bryars and Adams, 1999). Within each of these three regions exact distributions are difficult to identify due to a lack of information on the occurrence of crabs in deep offshore waters and because the local distributions appear to be dynamic. In the WC region, adult crabs are most abundant in Denial Bay and Streaky Bay, with relatively few adult crabs found between those two bays. In SG and GSV, adult crabs are most abundant in the upper parts of the gulfs with relatively few adult crabs found in the lower parts of the gulfs. The coastal areas around Kangaroo Island and the southern ends of Eyre Peninsula and Yorke Peninsula are completely devoid of adult crabs, as are the sheltered coastal areas of Baird Bay, Venus Bay, Coffin Bay, and American River. Consequently, from a management point of view these three regions could be considered as separate stocks. Juvenile crabs of *P. pelagicus* appear to have a similar distribution to adult crabs in South Australia, i.e. they are mainly restricted to the WC, upper SG, and upper GSV regions (Smith, 1982). The broad-scale distribution of *P. pelagicus* larvae in South Australia is largely unknown although Bryars (1997) did find larvae throughout GSV, including the southern parts.

Habitat

The coastline of the three peninsulas Eyre, Yorke and Fleurieu and Kangaroo Island encompass the South Australian population of *P. pelagicus* adult crabs. The present day coastline of South Australia is the result of a sea-level rise that flooded the WC, SG, and GSV regions ~6 000 years ago (Williams *et al.*, 1993). It was probably after this time that the present day South Australian population of *P. pelagicus* was geographically isolated from other Australian populations of this species. In this context it is interesting to also note the presence of geographically isolated populations of some other 'tropical/sub-tropical' species in South Australia such as the western king prawn, *Melicertus latisulcatus* (see Potter *et al.*, 1991), and the mangrove, *Avicennia marina* (see Figure 3 in Duke, 1991).

Throughout its' world-wide range, adult *P. pelagicus* are found in a variety of inshore and continental shelf areas from the intertidal zone to at least 50m depth, in sandy, muddy, estuarine, and seagrass habitats (Kailola, *et al.*, 1993). *P. pelagicus* juveniles appear to be restricted to shallow inshore and intertidal areas (Smith, 1982; Williams, 1982; Robertson and Duke, 1987), moving to deeper water as they grow (Kailola, *et al.*, 1993). *P. pelagicus* larvae occur mainly in offshore oceanic waters (Meagher, 1971; Ingles and Braum, 1989; Bryars, 1997; Bryars and Havenhand, 2004), but have been found in estuarine waters in south-west Western Australia (Gaughan and Potter, 1994).

Within South Australia, adult *P. pelagicus* are mainly restricted to less than 30m depth in the WC, upper SG, and upper GSV regions, where they occupy the sandy, muddy, seagrass (*Amphibolis*, *Halophila*, *Heterozostera*, *Posidonia*, *Zostera*), and mangrove (*Avicennia marina*) habitats characteristic of these regions (Womersley and Edmonds, 1958; Shepherd and Sprigg, 1976; Butler *et al.*, 1977a, b; Womersley, 1984). Juvenile *P. pelagicus* appear to be restricted to the inshore seagrass, intertidal mudflat, and mangrove creeks of the WC, upper SG and upper GSV regions (Smith, 1982; see Chapter 3). Larval *P. pelagicus* were found to be more abundant in deeper offshore waters than the shallow inshore waters of the Port Gawler region in GSV (Bryars and Havenhand, 2004).

Apart from *P. pelagicus*, the only other common portunid species in South Australian waters are the rough rock crab, *Nectocarcinus tuberculosus*, the smooth rock crab, *Nectocarcinus integrifrons*, and the sand crab, *Ovalipes australiensis*. Crabs of the two *Nectocarcinus* species are highly abundant in upper SG and upper GSV where *P. pelagicus* crabs are mainly found, while crabs of *O. australiensis* are most abundant in the coastal regions of southern Eyre Peninsula, southern Yorke Peninsula, Fleurieu Peninsula and Kangaroo Island (Hale,

1927) where crabs of *P. pelagicus* are rare. In contrast with tropical regions of Australia, *P. pelagicus* is the only member of the sub-family Portuninae found within South Australia.

Life-cycle

As with all crustaceans, growth in *P. pelagicus* is achieved through ecdysis or 'moulting' of the exoskeleton. The courtship and mating behaviour of *P. pelagicus* is typical of portunid crabs. First an adult male crab must find an adult female crab that is ready to moult. The male and female will form a pre-corpula for eight to ten days before ecdysis of the female. During this time the female crab must moult in order for copulation and insemination to occur. After female ecdysis, when the female is in the soft-shell condition, copulation takes place over a six to eight hour period according to Meagher (1971). Sperm are transferred to the female crab in a spermatheca which she retains until the eggs are produced. Sperm can remain viable for at least 12 months (Meagher, 1971; Campbell, 1984). When an inseminated female crab has developed mature ovaries, the eggs are fertilised with the stored sperm and extruded onto the abdominal flap as a large mass or 'berry' containing up to 2,000,000 eggs (Yatsuzuka, 1962). The extrusion of eggs by female crabs is referred to as 'spawning' in this chapter. Eggs are 0.3-0.4mm in diameter (Meagher, 1971; Campbell, 1984).

Ovigerous female crabs carry the developing eggs externally until they hatch as larvae. Incubation of eggs lasts from 1-4 weeks depending on water temperature (Yatsuzuka, 1962; Meagher, 1971; Campbell, 1984). The release of larvae by ovigerous female crabs is referred to as 'hatching' in this chapter. Larvae of *P. pelagicus* are known to always hatch during night-time or early morning (Yatsuzuka, 1962; Campbell, 1984). Larvae moult through four zoeal stages and one megalopal stage, before metamorphosing into the first juvenile crab stage (Yatsuzuka, 1962). Larval stages are ~1-4mm in size, while the first juvenile crab stage is ~2.5mm carapace width (Yatsuzuka and Sakai, 1980). Carapace width measurements throughout this chapter refer to the distance across the carapace from the anterior base of the largest lateral carapace spines. The larval phase lasts for at least two weeks (Meagher, 1971; Bryars, 1997). Newly settled juvenile crabs continue to moult and grow through subsequent crab stages until reaching sexual maturity at approximately one year of age and completing the life-cycle as an adult crab (Smith, 1982). *P. pelagicus* can live for up to three years and grows to a maximum size of ~200mm carapace width (Kailola *et al*., 1993).

Reproductive biology

The reproductive biology of portunid crabs is well known. In *P. pelagicus* a variety of studies have been undertaken, primarily in tropical waters (reviewed by Kumar *et al.,* 2003). In the temperate regions of Australia, the reproductive biology of *P. pelagicus* varies markedly between regions (Meagher, 1971; Penn, 1977; Smith, 1982; Potter *et al.,* 1983). Importantly, because blue swimmer crabs are essentially tropical, marked differences are expected in their reproductive biology in southern Australia, particularly at the southern limit of their distribution.

Reproductive Cycle

Male and female *P. pelagicus* generally reach sexual maturity at a size of 70 to 90 mm carapace width, when they are approximately one year old. The spawning season lasts 3 to 4 months over the summer/autumn period. The duration of the growing season varies among individuals because those settling in early summer have a longer growing season compared with those settling in mid to late summer. In South Australian waters, crabs close to the minimum legal size (110 mm carapace width) are approximately 14 to 18 months old, sexually mature, and if they are females, have produced at least two batches of eggs within one season (Kumar *et al*., 2000; 2003).

Ovarian Development

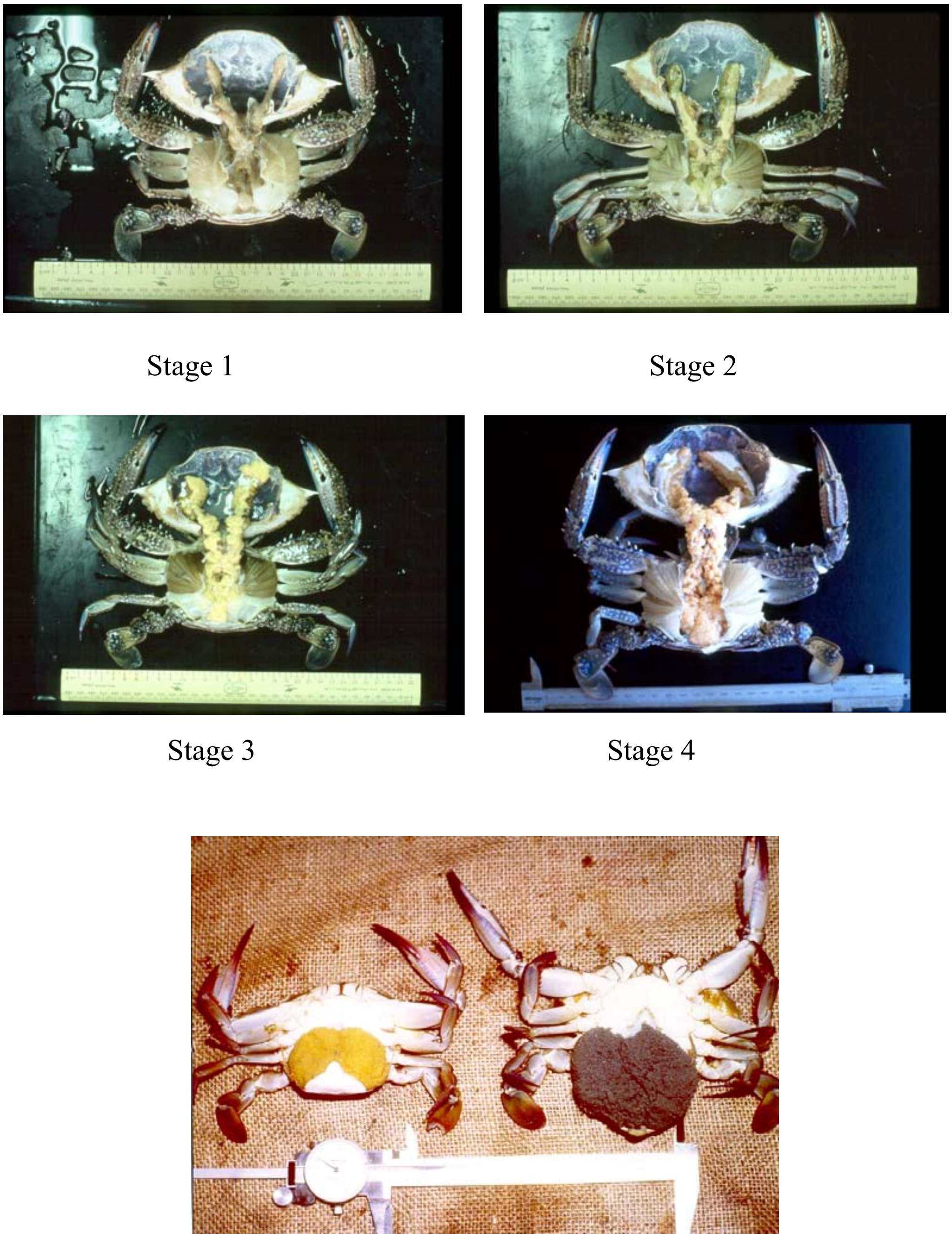
In South Australia, development of the ovaries in *P. pelagicus* is seasonal and triggered by rising water temperatures in spring. After completion of the development, the eggs are fertilised on extrusion (Smith 1982). Van Engel (1958) found that sperm in the spematheca of female *Callinectes sapidus* could remain viable for at least 12 months. This is also likely to also be the case for *P. pelagicus*. Egg extrusion is independent of the timing of copulation. The ovarian development can be classified by five visually distinguishable stages (see Sumpton *et al*., 1994; Kumar *et al*., 2000; Figure 1 and Table I) as follows:

- Stage 1(S1): Gonad immature, white or translucent
- Stage 2(S2): Gonad maturing, light yellow/orange, not extending into hepatic region
- Stage 3(S3): Gonad maturing, yellow/orange not extending into hepatic region
- Stage 4(S4): Gonad mature, dark yellow/orange extending into hepatic region
- Stage 5(S5): Ovigerus, female bearing fully matured eggs (pale to dark yellow eggs) externally.

The fourth stage of ovarian development was observed in late October to November in conjunction with rising seawater temperatures in South Australia. Kumar *et al*. (2000) demonstrated that during November, more than 40% of crabs were in advanced Stage 4, and 80% of all crabs caught were in Stages 3 or 4. Figure 2 shows the seasonal ovarian developmental stages in the blue swimmer crab.

Ovigerus Females

In tropical waters, female blue swimmer crabs are found to carry eggs right through the year. However, during a particular period in any year, a seasonal variation in the number of egg bearing females can be observed (see Kumar *et al.,* 2000). During embryonic development (Stage 5), the colour of the eggs changes from yellow to a dark grey (see Figure 2). In South Australian waters, egg bearing females have been observed throughout the year, however during late spring there is a substantial increase in the proportion of berried females (Figure 3). Data from the commercial fishery logbooks shows the proportion of berried females caught in GSV from July 2001 to June 2003 (Figure 4). In SG, a higher proportion of berried females appeared in the catch slightly later than in GSV. This pattern was consistent between years.



Stage 1 Stage 2

Stage 3 Stage 4

Stage 5

Figure 2. Ovarian stages of the blue swimmer crab (from Kumar *et al*., 2000).

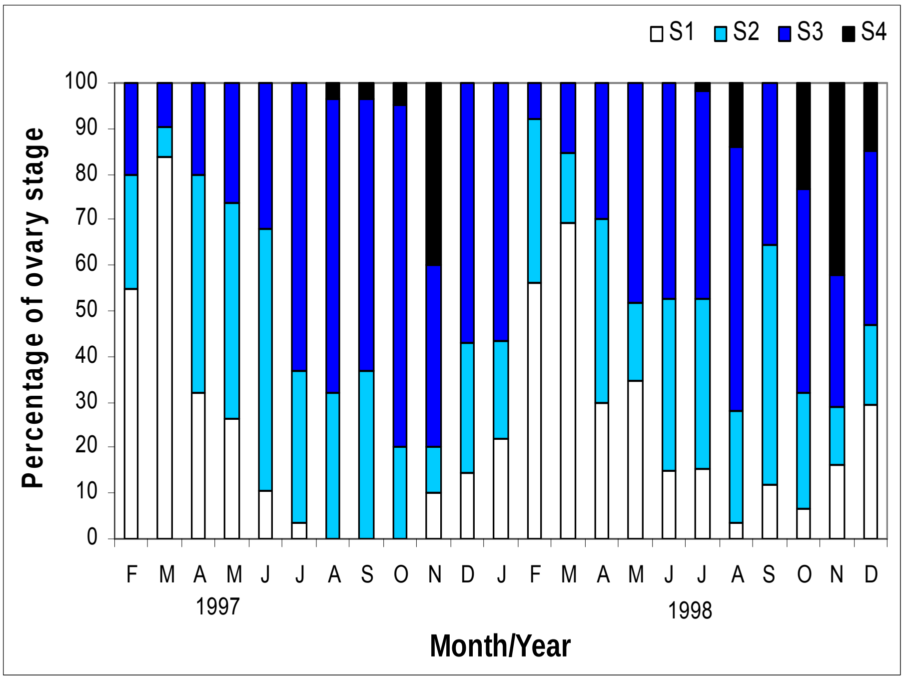


Figure 3. Ovarian development of the blue swimmer crab samples collected in South Australia during 1997 and 1998. Colour codes indicate reproductive stages (from Kumar *et al.* 2000).

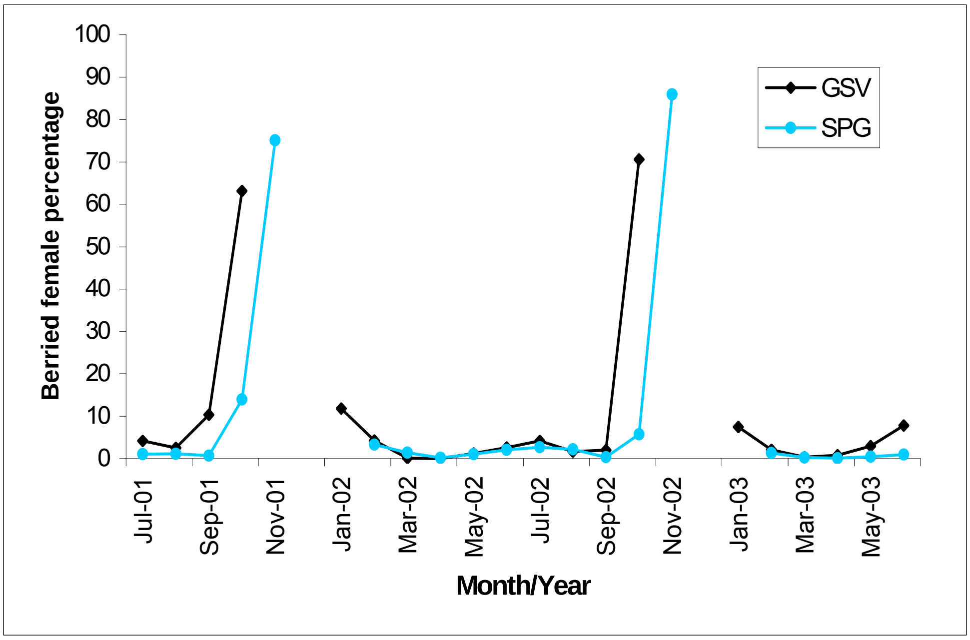


Figure 4. Abundance of berried females in the commercial catches for 2001/2002 and 2002/2003. Information collected from the commercial logbooks. GSV=Gulf St Vincent; SPG=Spencer Gulf (from Kumar *et al.,* 2000).

Table I. Summary of measurements (mean ± SD) characterizing five stages of ovarian development of the blue swimmer crab off South Australia (from Kumar *et al.*, 2003).

	Ovarian development stage				
	1	2	3	4	5 (Berried)
Reproductive state					
Number of individuals examined	14	39	64	15	40
Minimum carapace width (mm)	108.0	109.3	103.0	104.9	89.3
Carapace width (mm)	123.0±0.7	123.4±1.0	123.8±0.9	129.4±1.3	114.2±1.1
Body weight (g)	252.6±46.2	260.9±57.2	295.2±24.8	294.4±87.0	274.1±85.4
Percentage of ovarian cell stage					
1-100 µm	64.3±19.1	7.7±7.1	0	0	0
101-200 µm	35.7±29.0	69.2±27.3	14.1±25.8	0	0
201-300 µm	0	23.1±21.2	60.9±26.5	40.0±20.3	2.5±12.5
301-400 µm	0	0	23.4±24.8	60.0±18.3	92.5±23.7
>401 µm	0	0	1.6±16.7	0	5.0±15.5
Reproductive effort					
Number of individuals examined	0	5	4	4	40
Ovary weight (g)	0	3.4±0.9	7.0±3.1	17.6±2.6	54.8±22.2
Egg diameter (µm)	0	131.4±29.7	212.6±32.2	305.4±30.7	358.4±33.5
Number of eggs/g	0	82113±17922	66143±21926	38765±15799	23482±5974

Fecundity

Fecundity is calculated as the number of eggs carried externally by the female. Kumar *et al.* (2003) found that the fecundity of female crabs is size-dependent and increases up to a carapace width of 134 mm and decreased thereafter. Fecundity increased 83.9% with an increase of carapace width from 105 mm to 125 mm, implying that a single large female could produce as many eggs as two small females. Kumar *et al.* (2000) found that a female blue crab can produce between 650,000 to 1,760,000 eggs per spawning.

Spawning

The reproductive patterns of blue swimmer crabs in southern Australia are seasonal and correlated with seasonal changes in sea surface temperatures (see Kumar *et al*., 2003). Kumar *et al.* (2000, 2003) found that male blue swimmer crabs usually spawn from October to December, but occasionally through to the following January. In southern Australia, berried females are rare from April to September while in tropical waters berried females often occur throughout the year indicating continuous spawning (Shields and Wood, 1993).
Because sperm is stored in the spermatheca of the female, mating proceeds spawning. Sumpton *et al.,* (1994) observed a 100% insemination rate in post-moult female crabs in Moreton Bay, Australia. According to Kumar *et al.* (2000, 2003), ovaries develop from stage 1 to 4 throughout the year in South Australia and it is only from October to January that ovarian development to stage 5 takes place and berried females are abundant.

Multiple spawning

Multiple spawning has been observed in blue swimmer crabs. According to Meagher (1971), the female may ovulate and fertilise a second batch of eggs eight to ten days after spawning the first batch. Kumar *et al*. (2003) found that berried females carried developing oocytes at stages 2 and 3 in the ovary when carrying an external egg mass. Kumar *et al.* (2000) found that the fecundity of female crabs increased from October to December, with considerable variation. According to Campbell (1984) the number of fertilized eggs is highest in an egg-mass produced in the first batch. However, Meagher (1971) found that although blue crabs may produce more than one batch of eggs in a season, successive ovulations do not always occur.

Larval Behaviour

In contrast to the crab stages, *P. pelagicus* zoeae are totally planktonic (Yatsuzuka, 1962; Campbell, 1984; Ingles and Braum, 1989; Gaughan and Potter, 1994; Bryars, 1997), with recorded swimming speeds of ~1-3cm.s^{-1} in the laboratory (Yatsuzuka, 1962; Campbell, 1984). *P. pelagicus* megalopae may be planktonic or benthic (Yatsuzuka, 1962; Meagher, 1971; Campbell, 1984; Davis, 1988; Ingles and Braum, 1989; Bryars, 1997; Sumpton et al. 1989). The zoeal and megalopal stages swim mainly in the vertical plane and can actively regulate their vertical position in the water column (Meagher, 1971; Campbell, 1984; Ingles and Braum, 1989; Bryars, 1997). There is some evidence that the early juvenile crab stages of *P. pelagicus* are also planktonic (Meagher, 1971; Bryars, 1997). Laboratory rearing of *P. pelagicus* larvae has shown that larval survival is influenced strongly by temperature (Campbell, 1984; Bryars, 1997).

Larval Dispersal

There have been few studies conducted on the larval dispersal of *P. pelagicus*. Meagher (1971) suggested a dispersal-recruitment mechanism for *P. pelagicus* in south-west Western Australia in which early-stage zoeae move offshore during development, and later-stage larvae and juveniles return inshore to settle. Meagher's (1971) hypothesised mechanism was however based upon limited plankton sampling and laboratory work. Ingles and Braum (1989) inferred possible dispersal patterns from the horizontal distribution of *P. pelagicus* larvae in the Ragay Gulf (Phillipines), and suggested that monsoonal wind patterns have a significant effect on larval dispersal and settlement patterns in this region. Based upon laboratory work on larval tolerances and behaviour, Campbell (1984) suggested a dispersal-recruitment mechanism for *P. pelagicus* in Moreton Bay, Queensland, in which early-stage larvae move offshore and later-stage larvae return inshore to settle.

Within South Australia, Grove-Jones (1987) suggested that offshore upwellings on the West Coast cause larval dispersal away from inshore settlement habitats and that this is responsible for the repeated fishery recruitment failures in Streaky Bay on the West Coast. Grove-Jones (1987) also suggested that *P. pelagicus* larvae would be entrained within Spencer Gulf due to the formation of gyres in this region, and that colder temperatures between the West Coast, Spencer Gulf, and Gulf St Vincent would prevent significant migrations and inter-breeding between these three regions. Bryars and Adams (1999) have since confirmed this hypothesis using population genetic techniques.

Bryars (1997) proposed a conceptual dispersal-settlement model for Gulf St Vincent in which the zoael stages hatch and develop offshore, before the megalopal stage is transported back inshore by wind-generated surface currents. Bryars and Havenhand (2004) conducted a comprehensive larval sampling program off Port Gawler in Gulf St Vincent; finding that hatching and development occurs mainly in deeper (>5m) offshore waters (>5km) during the warmer months of November to March, and that zoeal development occurs in a range of depths from the neuston to at least 14 m. While major peaks in abundance usually occurred in the upper 3 m of the water column, upon consideration of the entire water column, it was evident that the majority of zoeae were located in sub-surface waters below 2 m depth. This result is in contrast to other studies that have shown a predominantly surface distribution for the zoeal stages (Meagher, 1971; Ingles and Braum, 1989).

Daylight vertical distributions of stage 1-3 zoeae were spatially and temporally variable, however (in contrast to Meagher's (1971) hypothesis) there was no evidence of vertical migration during the stage 1 zoea or for a daylight ontogenetic vertical migration throughout the four zoeal stages. Laboratory rearing of *P. pelagicus* larvae has revealed that the larval phase lasts for at least two weeks (Meagher, 1971; Campbell, 1984; Bryars, 1997), thus providing considerable potential for larval dispersal.

Meagher (1971) recorded *P. pelagicus* megalopae from surface waters at midnight and dawn in south-west Western Australia, while Ingles and Braum (1989) found *P. pelagicus* megalopae to be evenly distributed throughout the water column in the Ragay Gulf, Phillipines. In contrast, Davis (1988) stated that *P. pelagicus* megalopae were benthic in western Australian waters. In the portunid species, *P. trituberculatus*, megalopae only rise to the surface after sunset (Takaba, 1984; Shiota, 1993). Johnson (1985) reported the megalopae of *Portunus* spp. to be most abundant in surface waters offshore from Chesapeake Bay, U.S.A. In the blue crab, *Callinectes sapidus*, megalopae have a surface distribution in offshore waters but show complex vertical (tidal and diurnal) migration patterns upon entering estuaries on the east coast of the U.S.A (Tankersley and Forward, 1994).

Recruitment

Recruitment to the fishery is defined as those crabs entering the fishery, which are susceptible to being caught by the fishing gear. Blue crabs have a recognized size limit, so it is considered that recruits are crabs with a carapace width (measured from the posterior base of the spine) of less than 110 mm. Recruitment to the fishery has been found to take place during the winter months of the year, June and July (Kumar *et al*., 2000). However, recruitment into populations of the blue swimmer crab takes place after settlement and metamorphosis into the juvenile stage. In Chapter 3, a study of recruitment patterns in SA blue swimmer crab populations highlights spatial and temporal variation.

Feeding

P. pelagicus crabs have a predatory/scavenging life-style, feeding mainly on molluscs, crustaceans, and polychaetes (Edgar, 1990). In South Australia, *P. pelagicus* adults are believed to prey heavily on members of the bivalve genus *Pinna*. Adult *P. pelagicus* are themselves preyed upon by sharks, rays, and large fish (Kailola *et al.*, 1993) and in South Australia, the snapper, *Pagrus auratus*, is believed to be a major predator. In WC, upper SG, and upper GSV, *P. pelagicus* is one of the dominant brachyuran species, and, as in south-west Western Australia (Edgar, 1990), probably has an important effect on the benthic ecology of these regions. *P. pelagicus* zoeae are carnivorous, feeding only on zooplanktonic organisms in the laboratory (Yatsuzuka, 1962). *P. pelagicus* megalopae are also carnivorous but can feed on planktonic and benthic material (Yatsuzuka, 1962). The diet of *P. pelagicus* larvae in the field is unknown, but probably includes copepods (e.g. Epifanio *et al.*, 1991; McConaugha, 1992), which are abundant in South Australian waters.

Growth

The tropical/sub-tropical affinities of *P. pelagicus* are evident from the observation that the species only survives in temperate South Australia due to the increased summer water temperatures that enable reproduction and growth to occur (Smith, 1982). The growth rate of *P. pelagicus* crabs is dependent on both the size of the crab and on water temperature (Meagher, 1971). During the early juvenile stages, crabs are able to moult frequently, but adult crabs may only moult once or twice a year. In South Australia, growth of juvenile crabs is greatest during the warmer months and markedly slower during the colder autumn and winter months (Grove-Jones, 1987). Male and female crabs reach sexual maturity at 70-90 mm carapace width in South Australia (Smith, 1982), which is comparable to tropical/sub-tropical populations of *P. pelagicus* found in other regions of Australia (Potter *et al.*, 1987).

Movements

P. pelagicus crabs are highly mobile (Edgar, 1990), and while usually benthic, they can swim in the water column using their ‘swimming paddles’ located on the fifth pair of legs. Indeed, Potter *et al.* (1991) reported a specimen that travelled 20 km in one day. There is also anecdotal evidence that *P. pelagicus* adults can undergo mass migrations (e.g. Smith, 1978).

Within South Australia there is a distinct seasonal pattern of adult crab movements with animals moving into shallow inshore waters during the warmer months of September through to April and then retreating to deeper offshore waters during the colder months of May to August (Smith, 1982; Bryars and Havenhand, 2004). Ovigerous female crabs move into the deeper offshore waters of GSV and SG prior to the release of larvae (Smith, 1982).

Population Genetics

Using allozyme markers, Bryars and Adams (1999) determined that the populations of *P. pelagicus* within SG, GSV and the West Coast regions of South Australia, represent separate sub-populations with limited inter-population gene flow. Bryars and Adams (1999) inferred that inter-regional larval dispersal is restricted and that each sub-population must be dependent on its own larval supply.

Chaplin *et al.* (2001), using microsatellite markers, found assemblages of *P. pelagicus* in different embayments in South Australia often constituting genetically different meta-populations. The level of migration between these populations is probably limited and the dynamics of a population in a given embayment is likely to be determined by local factors.

The South Australian Blue Swimmer Crab Fishery

Introduction

There are commercial and recreational fisheries for *P. pelagicus* in many parts of the world (e.g. Prasad and Tampi, 1951; Ingles and Braum, 1989; Kailola *et al.,* 1993). Within Australia, there are commercial crab fisheries in Western Australia, New South Wales, Queensland, and South Australia (Kailola *et al*., 1993). In South Australia, commercial pot fisheries currently operate almost year-round in both SG and GSV, with short closures between November and January when the relative abundance of spawning females is greatest (MacDonald, 1994). Recreational fishers throughout South Australia actively pursue blue swimmer crabs during the warmer months from September through to May.

Commercial Fishery

Blue crabs were first taken as by-catch in prawn and marine scalefish fisheries in the 1970's. In 1986, the provision to sell blue crabs as by-catch by prawn fishermen was withdrawn. The South Australian government issued twelve experimental fishing permits in the early 1980's, four in the West Coast, six in Spencer Gulf (SG) and two in Gulf St Vincent (GSV). The West Coast fishery declined in 1986 and the four licence holders surrendered their entitlements. In

June 1996, interim management arrangements for the Blue Swimmer Crab Fishery (BSCF) were established. An initial management strategy was implemented along with the core research program to support the development and maintenance of a sustainable and viable fishery.

In 1997, PIRSA Fisheries proposed a strategy for a developmental period for the BSCF of 3 years (1997-99). During this period the capacity for expansion of the fishery was to be determined through research and further fishing. A limited entry fishery was created with access based on historical involvement.

The commercial fishery is based on the capture of a single species, *P. pelagicus,* although some other crab species may also be landed, such as spider, velvet and rock crabs. The commercial pot and marine scale fishery with blue crab quota are currently divided into two areas (SG and GSV, Figure 5) with two types of commercial fisheries operating in each (pot and marine scalefish). In addition, all marine scalefish licence holders have access to blue crabs in South Australian waters outside the waters defining the management of the blue crab fishery. Registered fishing devices listed on marine scale fish licences may only take blue crabs in these areas.

Commercial fishing for blue crabs outside the blue crab fishery has been seasonally based on the West Coast of South Australia in waters adjacent to the settlements of Streaky Bay and Ceduna (Figure 5). The seasonal influence of the abundance of blue crabs present in this area has been traditionally dependent on water temperature and salinity. Catches in recent years have averaged around 50 t.

The BSCF is comprised of three major stakeholder groups; the commercial pot fishery, the commercial marine scale fish fishery (MSF) and the recreational fishery. In 2002-2003, there were eight crab pot fisher licences, five in SG and three in GSV. The MSF with access to blue crab quotas was made up of fourteen licences, one in SG and thirteen in GSV.

Commercial pot fishermen generally haul their fishing gear every 24 hours using specifically designed crab pots covered with netting (Figure 6). Commercial marine scalefish fishermen operate either hoop or drop nets hauled every 20-30 minutes (Figure 7). Crabs can be stored live in tanks, iced down uncooked or cooked before being landed. Most of the commercial catch is marketed in Australia, primarily in the Sydney and Melbourne fish markets. In 2001/02, the commercial landed catch of blue crabs in South Australia was 535 t at a value of $3.46 million (Knight *et al*., 2003).

Commercial quantities of blue crabs are also taken from bays on the west coast of South Australia, however they are included as part of the MSF. In 2002/03, the west coast fishery landed catch was approximately 25.2 t from 418 boat days.

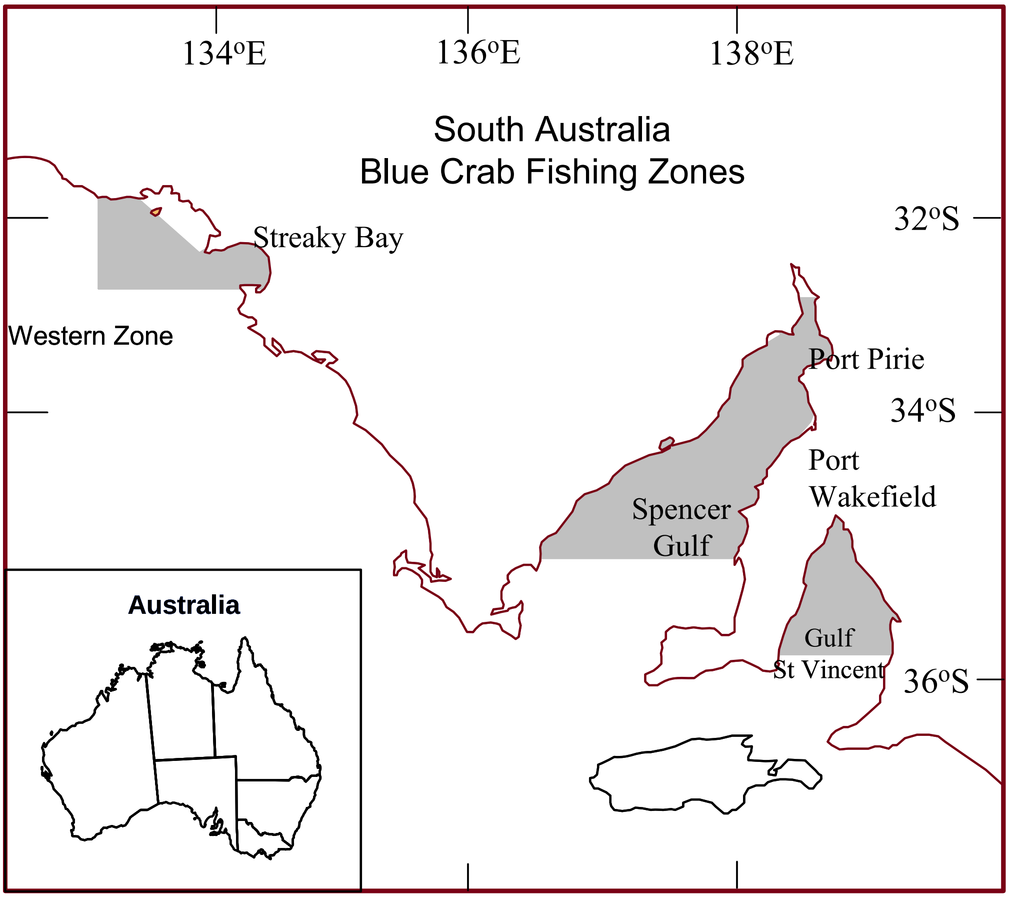


Figure 5. Locations of fishing grounds of the South Australian's blue swimmer crab fishery.

Figure 6. Commercial crab pot as used by the fishery with a mesh size of 90 mm (from Svane and Hooper, 2004).

Figure 7. Drop net as used by commercial marine scale fisher (from Svane and Hooper, 2004).

Commercial Production

The combined South Australian commercial catch for the blue swimmer crab fishery during the period 1983 to 2003 is shown in Figure 8. A quota of Total Allowable Commercial Catch (TACC) was implemented in 1996 and is indicated by dots (Figure 8). In 2002/03, the allocated TACC for the BSCF was 626.8 t, a similar TACC as for the previous two fishing seasons. The landed catch in 2002/03 for commercial fisheries in GSV and SG was 88.95% of the TACC, represented by 92.35% taken by the pot fishery and 7.65% by the MSF. Since the implementation of the TACC in 1996/97, the commercial fisheries have not reached a 100% catch of TACC.

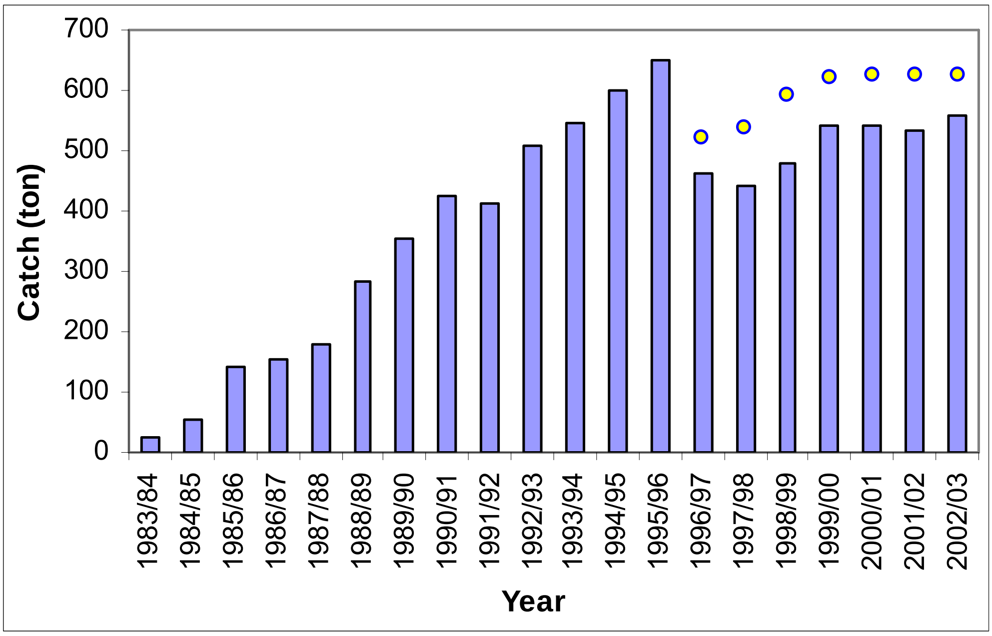


Figure 8. Total commercial catch (vertical bars) and TACC (dots) for the BSCF from 1983/84 to 2002/03.

Recreational Fishery

There are no continuous assessments of the recreational harvest of the blue swimmer crab in South Australia. McGlennon and Kinloch (1997) estimated a total catch of 161.2 t per year of which 115.8 t was taken in GSV and 45.4 t in SG. This estimate does not include the recreational shore-based fishery, which is considered to be significant.

More recently, a National Recreational and Indigenous Fishing Survey (Henry and Lyle, 2003) was conducted between May 2000 and April 2001. The estimated annual catch taken by recreational fishers during this period for South Australia was 389.8 t. A further 31.7% of the total catch was released after capture (Anon., 2003). The release rate is based upon those crabs that were discarded due to being under the legal size limit or once the bag limit had been reached. This indicates that the recreational harvest was 37.5% during 2000/2001. Estimates of regional catches, release rates, fishing locations and fishing methods are yet to be analysed.

Key Biological Determinants Important to the Fishery

A suite of key biological determinants important to the blue crab fishery can be identified in order to provide a rigorous population analysis and subsequent stock assessment. The determinants can have both temporal and spatial components adding to complexity of any population analysis. The determinants, or parameters, can be broadly categorised as those that affect 1) recruitment, 2) growth, 3) reproduction, and 4) mortality. The determinants can be expressed as a variety of biological parameters or variables as shown in Table II.

Table II. Key biological determinants important to the blue swimmer crab fishery

Parameters	Recruitment	Growth	Reproduction	Mortality
Variables	Larval supply Settlement	Temperature Food	Size Maturity Fecundity	Fishing Natural
Measure	Field surveys	Tagging Age Markers Size-frequency	Gonado-somatic Index Sex Ratio	Catch Tagging

It is well known that the environment plays an important role in the population dynamics and subsequent catchability of fish stocks. However, in most cases the data available for stock assessment are restricted to a few surveys, in addition to catch and effort data obtained from fishery logbooks. Correlations between population processes and environmental factors have been identified and hypotheses have been proposed to explain the underlying causes (e.g. Hinton and Nakono, 1996; Lehodey *et al*., 1997; Shepherd *et al.* 1984, Hunter 1983, Bertignac *et al.,* 1998; Lehodey *et al.,* 1998). However, in fisheries ecology, experimental testing of hypotheses is rare, probably due to the scale of the fisheries in relation to the scale at which experiments can be conducted. Incorporation of environmental time series into stock assessment models may provide additional power to estimate model parameters and can be applied to different processes in a given population.

Recruitment

The traditional approach in the management and exploitation of blue swimmer crab populations has been to find ways to be able to predict future catch rates and population sizes. Because there is often a delay due to the propagation of the recruitment signal in the population structure, the relationship can be used to predict future catch rates or population sizes.

Many studies show that environmental variables affect recruitment (e.g. Francis 1993). Particularly in single-year-class fisheries, variable recruitment has been attributed to environmental effects impacting on survival. The lack of clear stock-recruitment relationships in such fisheries has led managers to believe that recruitment depends only on environmental factors (see Penn *et al.,* 1995). In fisheries ecology, the traditional method that relates recruitment to environmental factors is correlation analysis of environmental time series with estimates of recruitment from a stock assessment model (Maunder and Starr, 2001; Maunder and Watters, 2002). In the SA blue swimmer crab fisheries, measurements of recruitment are related to the number of discarded crabs near sub-adult size (i.e. less than 110 mm CW) that have entered into the fishery. However, recruitment into populations occurs at a smaller size when crabs have settled and metamorphosed into juveniles. Caputi *et al*. (1998) clearly demonstrated that the stock-recruitment relationship is an integral part of stock assessment in invertebrate fisheries, recommending research surveys as the major tool, and highlighting the importance of understanding effects of the environment and fishing effort. However, to undertake recruitment studies with a high level of spatial resolution requires a substantial sampling effort that, although highly desirable, may be beyond what is financially possible in smaller crustacean fisheries such as the SA blue swimmer crab fisheries.

Recruitment to the blue swimmer crab fishery is affected by variable climatic and oceanographic factors and cannot be predicted from year to year through the use of standard stock assessment methods that rely on simple stock-recruitment relationships (Wahle, 2003). In such a situation, a possible approach is to use yield-per-recruit relationships. However, deterministic yield-per-recruit models require estimates of population parameters such as natural mortality, fishing selectivity and growth, all of which require tagging and have a large degree of uncertainty (Miller and Houde, 1998; Lipton and Bockstael, 2001). A spatially explicit yield-per-recruit analysis will be difficult to carry out due to the large number of parameters, which need to be estimated (Lipton and Bockstael, 2001).

Growth

Age-structured models are the most common method for determining the effect of fishing on population dynamics (Gulland, 1983). For marine teleosts, age can be determined by using otoliths, scales or bones (Secor *et al.,* 1995). However, this is not possible for crustaceans, including the blue swimmer crab, which periodically moult the exoskeleton thereby removing evidence of age or previous size. An alternative to direct ageing methods is modal analysis of length-frequency data (e.g. Rothschild *et al.,* 1992). Unfortunately, this method is difficult to validate because 1) growth is characterised by strong inter-annual and seasonal variability and 2) the spawning season is protracted, which leads to a wide, and sometimes multi-modal distribution of sizes per year class (Prager *et al.,* 1990; Ju *et al.,* 2001). Ju *et al.* (2002) tested successfully the extractable age-related metabolic by-product "lipofucin" sequestered in the neural tissue of eyestalks as an estimator of demographic structure of the blue crab *Callinectes sapidus*. As there is a critical need for understanding the demographic structure of blue swimmer crab populations this method may be applied.

In stock assessments, age-structured models, which include variants of sequential population analysis methods, are commonly used and may give insight into the dynamics of stocks and provide means to explore a large variety of management measures (Mesnil, 2003). However, continuous provision of reliable age data over long periods is required. Estimating the age composition of catches usually involves age-length keys, which need to be rebuilt every year. An alternative is to use surplus production models. However, fitting these simple models may raise statistical problems, and they often fail to produce reliable estimates for management purposes due to uncertainty in biological parameters like fluctuations in recruitment (Hilborn and Walters, 1992). Length-based methods may be another option if growth pattern can be modelled properly, however these require reliable age determination. There is currently a lack of methods to assess stocks for which age structures are uncertain, such as crustaceans.

Reproduction

In a blue swimmer crab population the abundance and mean size of the breeders determines the egg production of the season. Egg production is likely to influence juvenile abundance, which in turn determines abundance of pre-recruits (see Figure 9). Breeder abundance and their mean size are the variables that are likely to be important performance indicators for the fishery.

P. pelagicus is a discontinuous breeder and therefore only a fraction of the adult female population reproduces in a season. That fraction of the population and its mean size determine the quantity and quality of the egg production because egg production and egg size is a function of female size. Because larger eggs are more viable than smaller ones, egg size influences survival rates of juveniles. However, a number of environmental variables, particularly temperature, influence the egg production, growth and subsequent survival of juveniles.

Using a pre-recruitment index proportional to pre-recruit biomass, variations between years and the status of the fishery the following year could be predicted because the South Australian commercial blue swimmer crab fishery is driven by the year 1+ class animals.

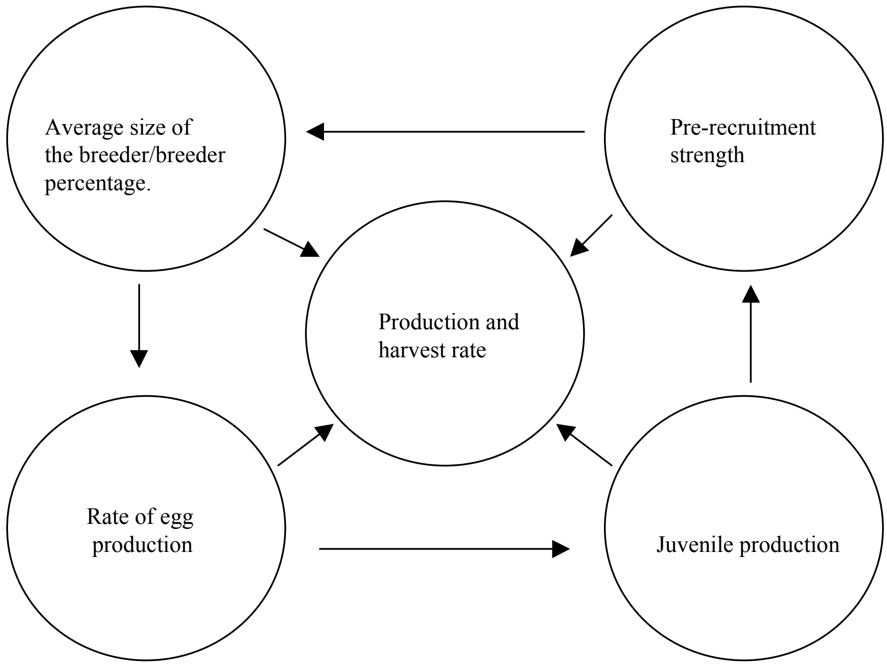


Figure 9. Blue swimmer crab reproductive variables and their relationship with fishery (from Kumar et al., 2000).

Mortality

The proportion of overall mortality that is considered “natural mortality” in exploited blue swimmer crab populations is usually not measured and managers rely entirely on “fishing mortality” measured as reported catch (see Siddeek, 2003). However, in age-structured production models the accuracy in the estimation of these parameters is important (see Smith and Addison, 2003). In a multi-user fishery such as the SA blue swimmer crab fishery, accurate estimates of fishing mortality are difficult to obtain particularly on a continuous basis, which would be required to model the fishery. The principle method to calculate mortality is by tagging but to date such an approach has not been successful.

Biological Reference Points

During the early days of the SA blue swimmer crab fishery, Biological Reference Points (BRP) were “borrowed” from finfish management with the aim of applying a simple biomass-production model (see Chapter 4). The BRP’s in the SA blue swimmer crab fishery were and still are conventional fishing mortality (F), relative exploitation rate (F_t/B_t), recruitment (R) and sex ratio (N_F/N_{F+M}). The stock biomass (B) is unknown and consequently the Total

Allowable Commercial Catch (TACC) is assigned as an arbitrary value. F is obtained through the logbook system and R is estimated from fishery independent surveys, which also provide an estimate of B (those crabs that enter pots with a mesh size of 55 mm) with a high spatial resolution. The relative exploitation rate (F_t/B_t) as the proportion of the exploitable biomass fished during a given period (t) has been suggested to be 40-50% of the 1994 level (Kumar *et al.*, 1999). As the exploitable biomass is unknown, (F_t/B_t) cannot been calculated. However, crab populations with specific life history characteristics warrant different types of BRP's particularly when applied at a broader population level. The BRP's for the SA blue swimmer crab fishery have been reviewed by Scandol and Kennelly (2001) and are presented in Chapter 5.

Target Reference Points (TRP's) and Limited Reference Points (LRP's) (see Caddy, 2002) have yet to be established. However, a set of likely responses for key indices to biological indicators has been adopted (Table III).

Table III. Likely response for key indices to biological indicators for the BSCF. Adopted from Scandol and Kennelly (2001).

⬆ increase, ⬆⬆ clear increase, ⬇decrease, ⬇⬇clear decrease, ⭘ no signal

	Size Structure		CPUE		Sex Ratio		Catch
	Pre-recruit index	Mean Size	Fishery	Survey	Males	Females	
Decrease in recruitment	⬇⬇	⬆⬆	⬇	⬇⬇	⬇	⬆	⭘
Constant recruitment	⭘	⭘	⭘	⭘	⭘	⭘	⭘
Increase in recruitment	⬆⬆	⬇	⬆	⬆⬆	⭘	⭘	⭘

Fishery Independent Surveys

In the South Australian blue swimmer crab fishery, biomass-production modelling has not been attempted due to the difficulties of estimating biomass (see Chapter 4; Kennelly and Scandol, 2002). However, rather than relying on the uncertainty of modelling, a direct estimate of biomass, or an index thereof, can be used as a guideline in recommending a Total Allowable Commercial Catch (TACC). In the SA blue swimmer crab fishery, fishery independent surveys have been conducted twice, namely in July 2002 and July 2003 (winter). The primary aim of the July fishery independent surveys was to collect information on the spatial abundance and size composition of blue crabs in SG and GSV fisheries, during the winter period, when juvenile crabs recruit to the fishery. The annual survey provides data for BRP's and information on by-catch.

The survey approach was selected to overcome the uncertainties associated with biomass-production modelling by getting a direct estimate of abundance and biological characteristics of those blue swimmer crabs that enter pots and use this information as BRP's and indicators. The survey data are statistically compared using a general linear model and other non-parametric statistical methods (see Kennelly and Scandol, 2002).

Figure 10. Research crab pot with a mesh size of 55 mm (from Svane and Hooper, 2004).

The statistical analyses was designed to compare abundance, size and sex distributions between years and fishing blocks to provide biological population data in order to determine the TACC using two types of pots with different mesh sizes, namely research pots with a mesh size of 55 mm (Fig. 10) and commercial pots with a mesh size of 90 mm (Fig. 6). The purpose of using research pots with the smaller mesh size was to obtain estimates of recruitment.

The continuous variables selected for the fishery independent survey were crab number and size (mm CW). The analyses of these two variables were performed individually. The nominal variables for number of crabs were sex (F, M), size (L=legal size, CW>=110mm; U=undersize, CW<110mm), pot type (C, R), block and year (C = commercial pot, Figure 6; R= research pot, Figure 10). An Analysis of Variance (ANOVA) design will accordingly be size(pot)*sex(pot)*pot*block*year with "size" and "sex" nested within "pot". The nominal variables for size (mm CW) were sex (F, M), pot type (C, R), block and year. An ANOVA design will accordingly be sex(pot)*pot*block*year with "sex" nested within "pot".

The use of ANOVA's requires that the data are normally distributed and that variances are homogeneous. When sampling crabs by using pots non-homogeneous variances and non-normal distribution may be a problem because of a large number of zero's (pots where no crabs had entered) and successively fewer pots with increasing numbers of crabs caught. Transformations may not solve this problem but because an ANOVA is fairly robust in relation to these requirements, factorial analyses can be performed on sub-sets of nominal variables and further substantiated by a series of non-parametric tests. The use of pots in fishery independent surveys allows only for estimates of fishable biomass, viz. crabs that enter a pot at the given time of the survey (see Kennelly and Scandol, 2002). This survey approach has been taken primarily for short-term practical reasons and needs to be revised depending on what future management options are chosen.

Discussion

The blue swimmer crab is geographically widely distributed with its main distribution area in tropical waters. This study highlights the adaptive difference in the biology of meta-populations such as those occurring in southern Australian temperate waters. As the above review has shown, the general biology of the blue swimmer crab is fairly well known. However, most studies are done at a spatial scale much smaller that that of the fishery and to effectively manage the fishery, an understanding of the mechanisms that affect spatial variability and long-term variation in population dynamics at that scale is required. The major problem in providing such data is the imbalance with the size of the fishery, and subsequent low funding, and the research effort required. Traditionally, fisheries have been modelled by using so-called biomass-production models with the assumption that catch and effort data, provided by the respective fisheries logbook systems, are proportional to biomass. In the SA blue crab fishery this has been shown not to be the case and if a fishery of that size needs to be modelled with adequate power of providing predictions of the size of future biomasses, a new approach is necessary.

The current method of management is to estimate key indices for biological indicators such as size structure, CPUE, sex ratios, and total catch. Target Reference Points (TRP's) and Limited Reference Points (LRP's) have yet to be established. The data for these estimates are sourced from an annual fishery independent survey and from the logbook system. The statistical design of the fishery independent survey is restricted (biased) by the use of pots and the estimates are consequently based on the number and quality of the crabs entering the respective pots at that time (winter) and not an independent and random population sample. In addition, the statistical design used for this analysis is for direct comparison between block (area) and year with the possibility of further analysis of any differences between gulfs. However, the design is not appropriate for long time series and there is potential for substantial statistical interactions between the main factors. In the longer term it may be worthwhile to consider alternative or additional sampling programs that provide quantitative data from deeper waters, during winter, where the largest abundance of crabs is likely to be found (see Lipton and Bockstael 2001).

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CHAPTER 3: MULTI-SCALE DEMOGRAPHIC PATTERNS OF POST-SETTLEMENT JUVENILE BLUE SWIMMER CRABS (*PORTUNUS PELAGICUS*) IN SOUTH AUSTRALIA

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Abstract

The persistence of *Portunus pelagicus* is dependent on the capacity of larvae to disperse, which is influenced by temperature and regional oceanography. We investigated the multi-scale demographic patterns of post-settlement juvenile (<50mm carapace width) *P. pelagicus* in South Australia in order to determine key settlement seasons, sites and habitats. The presence and abundance of juveniles varied inter-annually, with patterns probably driven by physical factors such as water temperature and the development of alternate hydrodynamic regimes such as gyres. The demography of juvenile *P. pelagicus* also varied seasonally, with settlement peaks occurring during summer and/or early autumn. Length frequency data were used to explore subsequent growth of juveniles on a monthly basis and showed that newly settled juveniles have the capacity to reach fishery pre-recruit size (50-100mm) within a single summer. Regionally, the distribution of juveniles in both gulfs was spatially inconsistent. In Spencer Gulf juvenile abundances were greatest at sites between Port Pirie and Port Broughton. In Gulf St Vincent, the Barker Inlet area was found to have the greatest numbers of juvenile *P. pelagicus*, with other important nursery sites being found in the northern tip of the gulf. Locally, demographic patterns were habitat specific. Post-settlement juveniles actively selected for intertidal seagrasses (*Zostera sp.* and *Heterozostera tasmanica*) over other seagrasses (*Posidonia sp.* and *Amphibolis sp*.) or unvegetated soft substrata. Where intertidal seagrasses were absent, juvenile *P. pelagicus* preferred unvegetated soft substrata to subtidal seagrass meadows. These findings reveal potentially important environmental factors and behavioural traits that may influence the demography of juvenile *P. pelagicus* in nursery. habitats in South Australia.

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Introduction

Many marine invertebrates, including decapod crustaceans, have a planktonic larval life stage after which they settle and adapt to a benthic existence (Dall *et al.* 1990, Liu and Loneragan 1997). The area and success of settlement of planktonic larvae is a factor that, together with hydrodynamic processes, helps to determine the distribution and abundance of both the juvenile and adult life stages of many crustaceans including *Portunus pelagicus* (eg. Connell 1985, Minchinton and Scheibling 1991, Morgan *et al.* 1996, Bryars 1997, Liu and Loneragan 1997). Variations in settlement over time and space are generally poorly understood and little is known about the biotic and abiotic factors that affect the density and distribution of settlers or the relationships between settlement density and post-settlement survival (Connell 1985). Based on case studies where this transition has been closely observed, variation in abundance and mortality appear to be high in the larval and settling stages (eg Orth and van Montfrans 1987, Bryars 1997). For most species, however, a more complete understanding of how juvenile recruitment patterns vary is required before we can begin to ascribe causal relationships to pre-or post-settlement processes.

Portunus pelagicus is a cosmopolitan crab species occurring throughout the Indo-Pacific region from east Africa to Japan, Tahiti and northern New Zealand (Kailola *et al.* 1993). Despite an essentially tropical/subtropical affinity, isolated populations of *P. pelagicus* are found in the temperate waters of South Australia where it is restricted to three geographically isolated regions: several inshore bays of the west coast, Spencer Gulf and Gulf St Vincent. In bays of the west coast of South Australia, adult *P. pelagicus* are most abundant in Denial Bay and Streaky Bay while in the gulfs abundances are greatest in northern latitudes (Bryars 1997). Small genetic differences have been found between each of the regional populations and as a result each could be treated as a separate meta-population for the purposes of fisheries management (Bryars 1997).

Throughout its worldwide range, *Portunus pelagicus* is found in a variety of inshore and continental shelf habitats from the intertidal zone to at least 50m depth. Juveniles are (apparently) restricted to shallow inshore areas while adults are more broadly distributed across a variety of soft sediment habitats (Smith 1982, Williams 1982, Robertson and Duke 1987, Bryars 1997). Within South Australia, adult *P. pelagicus* are mainly restricted to less than 30m depth where they occupy unvegetated sediment, seagrass (*Posidonia*, *Amphibolis*, *Halophila*, *Heterozostera*, *Zostera*, *Ruppia*, *Lepaelina*) and mangrove (*Avicennia marina*) habitats (Bryars 1997).

The persistence of *Portunus pelagicus* in South Australia is dependent on the capacity of larvae to disperse. Bryars (1997) showed that the two factors that exerted the greatest influence over the dispersal of *P. pelagicus* larvae were wind (both strength and direction) and temperature. Once hatched, larval crabs are released into the water column where they moult through four zoeal stages and one megalopal stage before settling as juvenile crabs. The time taken to progress from planktonic larvae to benthic juveniles depends largely on water temperature and is known to range from two to seven weeks (Meagher 1971, Campbell 1984, Bryars 1997). Newly settled juvenile blue crabs continue to moult and grow through subsequent stages until they reach maturity at approximately one year of age (Smith 1982). Once juvenile *Portunus pelagicus* become associated with the benthos little is known about their utilisation of different habitats (Weinstein and Brooks 1983, Hines *et al.* 1987). Studies in Chesapeake Bay (North America) have shown, however, that higher abundances of *Callinectes sapidus* (a Portunid crab with similar features and behavioural traits) occurred in areas with submerged aquatic vegetation than in unvegetated areas (Heck and Orth 1980, Heck and Thoman 1984). The portability of their findings to *Portunus pelagicus* in Australia is unknown. Nor is there a good understanding about the temporal and spatial patterns of recruitment into different habitats within South Australia.

The objective of this study was to develop a conceptual hypothesis to describe the multi-scale demographic patterns of post-settlement juvenile *Portunus pelagicus* in South Australia. We report on the abundance patterns between and within key study sites in Spencer Gulf across a period of three consecutive years. During the final year of survey, a number of additional sites were added to investigate variability in the spatial distribution of juvenile *P. pelagicus* during the summer recruitment peak.

Methods

Study area

Spencer Gulf and Gulf St Vincent support all current commercial and most recreational *Portunus pelagicus* fishing in South Australia. Although *P. pelagicus* are fished recreationally on the west coast of South Australia, populations do not support a commercial fishery and hence juvenile sampling was restricted to the two gulfs. Spencer Gulf extends for approximately 300km in a north-south direction, from Port Augusta in the north to West Cape in the south. Gulf St Vincent is a smaller embayment to the east of Spencer Gulf, extending from Port Wakefield in the north for 120km to Cape Jervis in the south (Figure 1). *Portunus pelagicus* are restricted to the northern waters of each gulf where water temperatures consistently exceed 20^{o}C in summer. In Spencer Gulf, surveys were undertaken north of Port Hughes and in Gulf St Vincent all sampling occurred north of Outer Harbour (Figure 1). The inshore areas of the northern gulfs are characterised by extensive tidal flats, often colonised by a varied seagrass flora and the grey mangrove (*Avicennia marina*). Figure 1: Map showing Spencer Gulf and Gulf St Vincent, South Australia. The study locations are marked in each gulf with circles. The additional sites marked with squares in Spencer Gulf were surveyed during the expansion of spatial sampling in 2002.

Large-scale Spatial and Temporal Recruitment Patterns in Spencer Gulf

Five sites were selected in upper Spencer Gulf (Figure 1). At each site, seagrasses dominated extensive shallow sublittoral platforms, bound inshore by unvegetated tidal flats. Juvenile *Portunus pelagicus* were sampled monthly at four sites from May 1999 through June 2000. Port Broughton was included as the fifth survey site in August 1999. Inclement weather prevented sampling at all sites in both January and February 2000. Spring and summer were identified as key recruitment periods during the monthly sampling from May 1999 to June 2000. Thus all subsequent sampling was restricted to October-December 2000 and March-April 2001 and 2002.

An aluminium beam trawl, measuring 1.2m wide and 0.75m high was used to sample juvenile *Portunus pelagicus*. The trawl net was made from 2 mm square mesh nylon screen, tapered over a 5 m length to a codend 1 m in circumference. Trawls were run parallel to shore starting at random points within either seagrass habitat or over unvegetated soft bottom (hereafter referred to as sand). All replicate trawls were separated by a scale of 10s to 100s of metres. At each site, the two habitats were adjacent, so the spatial separation of samples between habitats was the same as the spatial separation of samples within habitats.

Figure 1: Map showing Spencer Gulf and Gulf St Vincent, South Australia. The study locations are marked in each gulf with circles. The additional sites marked with squares in Spencer Gulf were surveyed during the expansion of spatial sampling in 2002.

Each month, 16 trawl shots were taken at every site, with eight replicates in each of the two habitat categories. Within seagrass, specific habitat character was recorded by securing a video camera to the beam of the net. Subsequent video analysis revealed five habitat categories: *Zostera mucronata*, *Heterozostera tasmanica*, *Posidonia sp.*, *Amphibolis sp.* and fragmented *Posidonia sp*. Thus seagrass habitat was treated firstly as a generic habitat with abundances of *Portunus pelagicus* pooled and secondly as a character specific habitat with juvenile abundances examined for intertidal seagrasses, subtidal seagrasses and on a species specific basis.

Anecdotal evidence suggested that juvenile *Portunus pelagicus* were found mostly in intertidal and shallow subtidal habitats in South Australia. Hence sampling was restricted to waters less than 10 m deep. Trawl shots lasted for 70 seconds at a speed of 1.1 ms^{-1}, a combination found to be optimal during pilot studies of trawl performance (McDonald, unpublished data). Thus each trawl shot covered an area of approximately 90 m^2. A trawl warp: depth ratio of no less than 4:1 was used at all times to maintain a suitable distance behind the vessel and to minimise lifting forces that might otherwise have caused the net to rise above the benthos during trawling. Samples were collected within two hours of high tide, so that in most instances it was necessary to sample each location on a different day. Sampling was conducted on consecutive days within each month. As a result the sampling design did not discount the possibility that variation amongst days (due to weather and other factors) could confound site differences. Site differences were, therefore, interpreted in this light although we believe that it did not detract from the validity of the study. Pilot studies at two of the five sites were conducted over consecutive days during March and April 1999 and little inter-diel variance in faunal composition (including *Portunus pelagicus*) was found in either month (McDonald, unpublished data).

Portunus pelagicus from each trawl were sorted and preserved in 10% formalin. Post-processing of trawl samples involved determining the sex of individuals where possible (typically to a minimum size of approximately 10mm), and measuring the carapace width of each crab from the anterior base of the largest lateral spines of the carapace. A dissecting microscope equipped with an ocular micrometer was used to measure individuals smaller than 20mm to the nearest 0.1mm. Those larger than 20mm were measured with vernier callipers to the nearest millimetre.

Expanded Spatial Recruitment Patterns

During the final year of research, the spatial scope of sampling was expanded to provide an indication of recruitment variability between Spencer Gulf and Gulf St Vincent, and between areas within each gulf. Habitat-specific investigations from previous years data had revealed a clear preference for intertidal seagrass (*Zostera mucronata* and *Heterozostera tasmanica*) and sand habitats. Hence trawl surveys in 2002 were restricted to those two habitat types, omitting subtidal seagrass meadows of *Posidonia sp.* and *Amphibolis sp.* from further investigation. In 2002 the spatial extent of sampling was expanded to a total of 8 sites in Spencer Gulf, with five sites being new to the study. Two original sites were removed form the study, being determined as unlikely to receive significant recruitment. Doing so enabled us to include more new sites than would otherwise have been possible within the physical limitations of our research. Fifth Creek and Port Broughton were kept as sites, exhibiting strong juvenile recruitment in the first two seasons while Cowleds Landing was kept as a reference site on the western side of Spencer Gulf.

In upper Gulf St Vincent, 5 sites with suitable habitat were also included to compare patterns between the two gulfs. Surveys over the intertidal areas of both gulfs are dependent on access during the peak period of spring tides each month. Given increased site numbers, it was necessary to reduce trawl replication to four in each habitat at each site to allow multiple sites to be surveyed each day.

Data analysis

For the purpose of analysis, we defined individuals <50mm as being juvenile, with those between 50mm and 100mm being sub-adults and recognised as pre-recruits to the fishery for *Portunus pelagicus*. In data analyses (other than graphical displays) individuals larger than 100mm were discarded as they represented adults that had entered the fishery and were therefore of no interest to a juvenile recruitment study.

Generalised linear models (GLMs) were used to accommodate non-normal response distributions. A log-link function was used, based on the assumption that the data were Poisson distributed, as is standard for count data (McCullogh and Nelder 1989). The factors site, habitat and month were fitted to the data in a full factorial model. “F” statistics from an analysis of deviance were used to detect significant effects (Chambers and Hastie 1991). Comparisons were made initially for the first 14 month period of sampling to assess spatial and temporal variability within Spencer Gulf on a monthly basis over a full calendar year. A second set of data (referred to as the “expanded spatial data set”) were analysed for the 2002 survey period and included gulfs as another factor in the model to determine whether detectable differences in settlement patterns existed between Spencer Gulf and Gulf St Vincent. Analyses were conducted with the software package “S-PLUS” (Insightful Corporation, Washington, USA).

Length data were used to produce frequency histograms that displayed patterns in juvenile recruitment between seasons and sites, and between habitats within sites. Annual patterns of post-settlement density were best reflected in data from intertidal seagrasses and that habitat category was used to explore data sets subsequent to the first years survey period.

Results

Large-scale Spatial and Temporal Recruitment Patterns in Spencer Gulf

Differences in *Portunus pelagicus* abundance between sites were apparent during this study. Fifth Creek (see Figure 1) was numerically dominant. Of 1062 individuals caught during the first year of sampling, approximately 65% (n=682) were taken from Fifth Creek (Figure 2). Despite a two month lag prior to the commencement of sampling, Port Broughton was the next most dominant numerically with 253 crabs caught in trawls over all habitats (Figure 2). Warburton Point, situated at the southern limit of distribution for *P. pelagicus* in Spencer Gulf, was the least populated site during the initial 14 months of sampling with four individual captures, three of which were adults recruited to the fishery (>100 mm).

Portunus pelagicus exhibited seasonal as well as yearly variations in abundance in both seagrass and sand habitats. In the first year of sampling few juveniles of *P. pelagicus* were caught during winter (June-August 1999). Peak abundances of juvenile crabs occurred during spring (September-November 1999) and summer (December 1999-February 2000) and tapered off again in autumn (March-May 2000) (Figure 3). Length frequency data from Fifth Creek were used to explore settlement trends and subsequent growth of juveniles on a monthly basis during the first year of surveys. A settlement pulse of juveniles occurred in October 1999. By March 2000, the cohort had grown to pre-fishery recruit size (50-100mm).

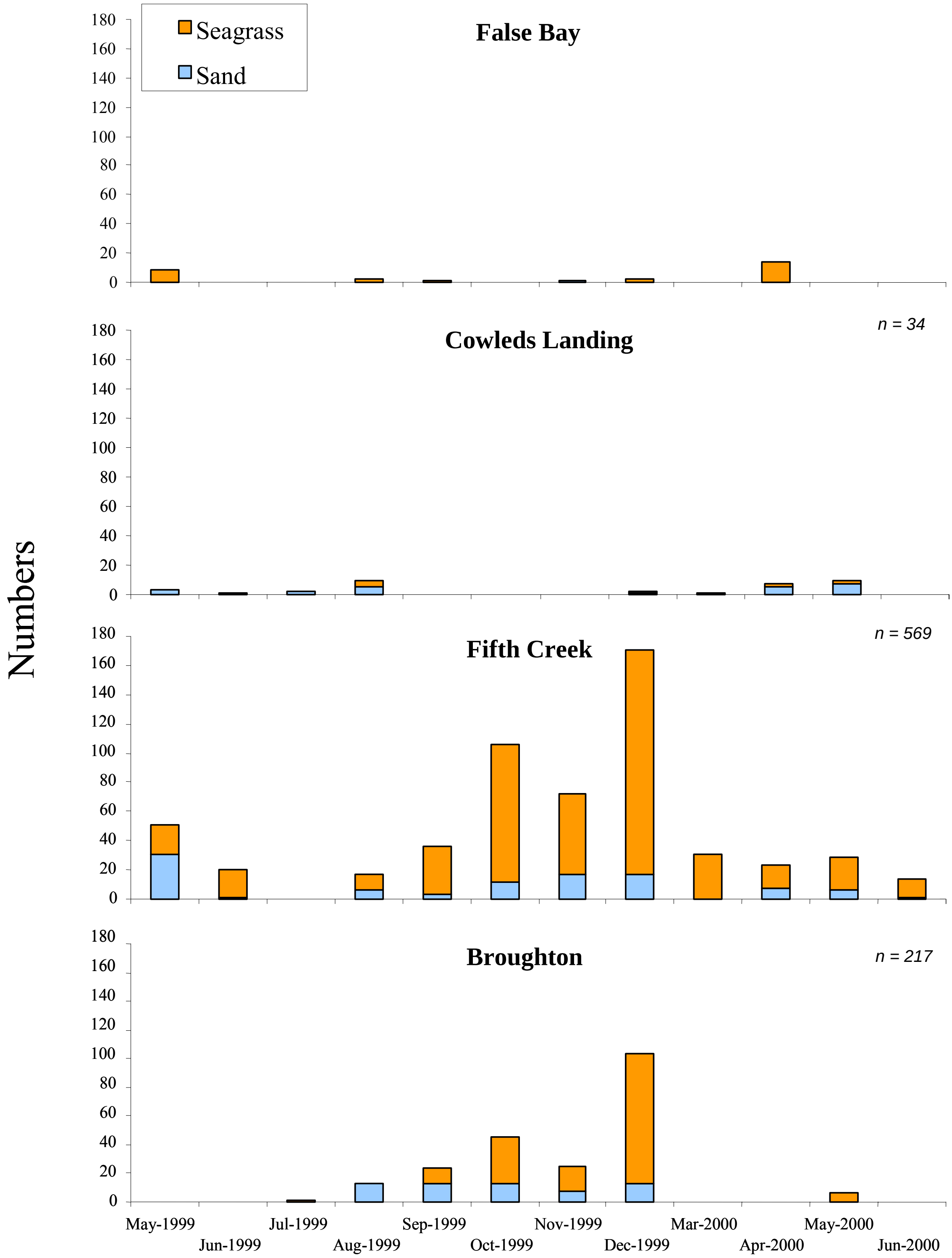

Figure 2: Monthly comparisons of abundance of blue swimmer crabs for sand and seagrass habitats at each of the five survey sites sampled in the 1999/2000 season.

Habitat Use

Of the habitats sampled, juvenile *Portunus pelagicus* (<50mm) were most abundant in meadows of *Heterozostera tasmanica* and *Zostera mucronata*, and least abundant in meadows of *Posidonia sp.* (Figure 4). *P. pelagicus* total abundances differed significantly between sites, sand and seagrass, and months of the year (Table 1). A significant interaction was evident between site and habitat, suggesting inconsistency within abundance patterns spatially. A general lack of settlement at some sites (eg. Warburton Point) led to no distinction between sand and seagrass while at sites where settlement was greater (eg. Fifth Creek) differences in abundance between sand and seagrass were clear. Site and habitat, but not month (Table 2), influenced juvenile abundances (<50mm). A marginal interaction term for month x habitat, however, may indicate that temporal patterns of juvenile *P. pelagicus* abundance are not consistent for all habitats. The inconsistency is explained by a seasonal presence in preferred habitats (either intertidal seagrasses where present or sand) and an absence all year round in others (subtidal seagrasses). Results from the GLM run for the fishery pre-recruit (50-100mm) data set were reflective of the model of total crab abundance described above (Table 3).

Expanded Spatial Recruitment Patterns

Investigations of the spatially expanded data set showed that *Portunus pelagicus* juveniles were generally more abundant in intertidal seagrass meadows than in sand in April 2002 (Table 4). Fifth Creek again had the greatest abundance of juveniles in Spencer Gulf whilst Outer Harbour was the site of greatest abundance in Gulf St Vincent. Other sites in Spencer Gulf that had high numbers of juvenile *P. pelagicus* include Port Pirie, Second Creek and Woods Point, all within a similar geographic area as Fifth Creek. In Gulf St Vincent, Bald

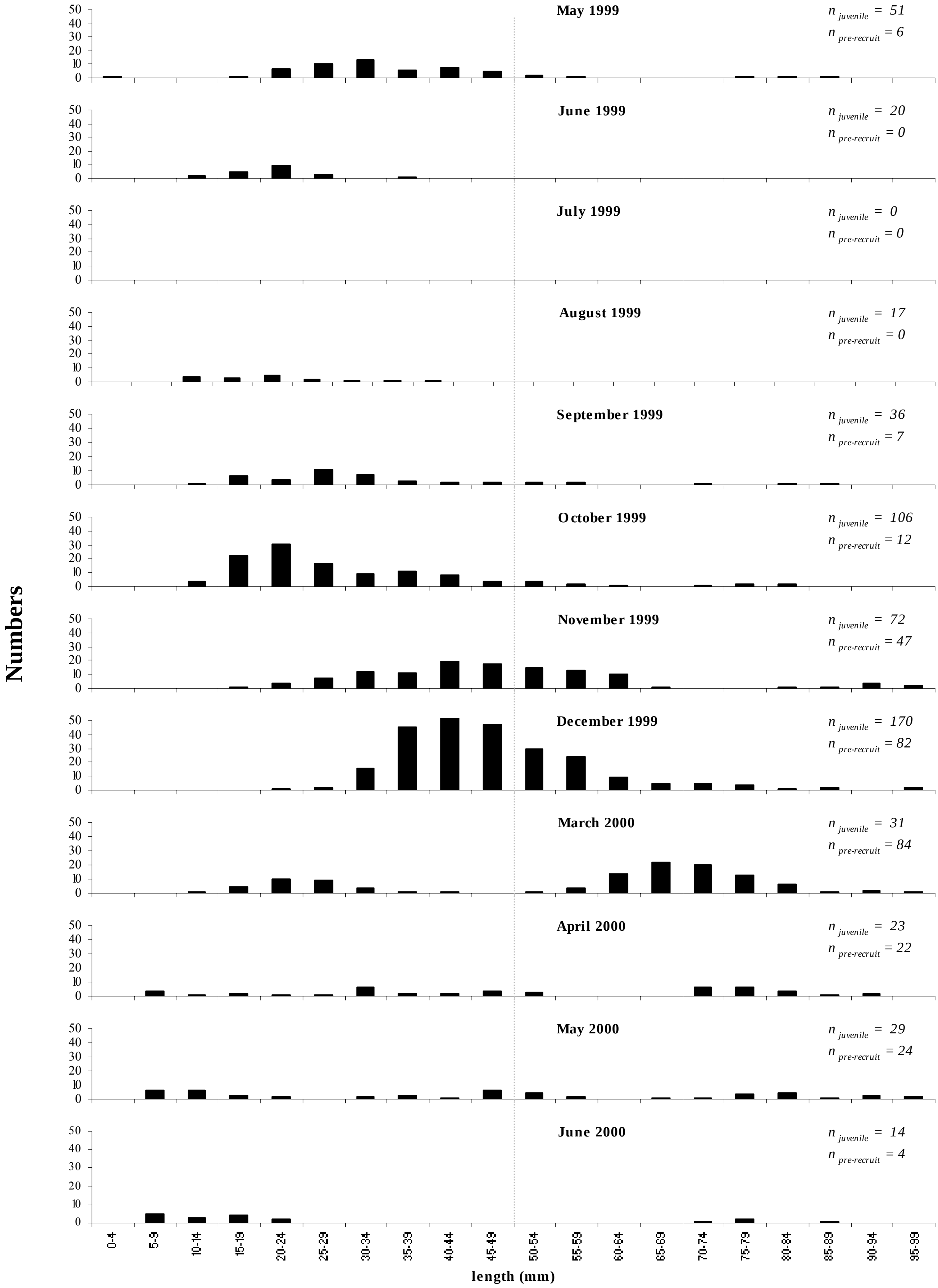

Figure 3: Monthly length frequency histograms from Fifth Creek pooled across habitats to depict seasonal settlement and subsequent growth of *Portunus pelagicus* during the first sampling season.

Table 1: GLM results comparing the total abundance of *Portunus pelagicus* between sites, months and habitats in Spencer Gulf between May 1999 and June 2000.

	Df	Deviance	F value	Pr(F)
Site	4	1626.49	69.94	**<0.001**
Mth	1	39.77	6.84	**0.009**
Habitat	1	312.78	53.80	**<0.001**
Site:Mth	4	11.32	0.48	0.745
Site:Habitat	4	99.13	4.26	**0.002**
Mth:Habitat	1	21.34	3.67	0.056
Site:Mth:Habitat	4	0.66	0.03	0.998

Table 2: GLM results comparing the abundance of juvenile *Portunus pelagicus* (<50mm) between sites, months and habitats in Spencer Gulf between May 1999 and June 2000.

	Df	Deviance	F value	Pr(F)
Site	4	1295.93	51.85	**<0.001**
Mth	1	0.05	0.01	0.930
Habitat	1	282.60	45.22	**<0.001**
Site:Mth	4	16.22	0.65	0.627
Site:Habitat	4	49.51	1.98	0.095
Mth:Habitat	1	34.08	5.45	**0.020**
Site:Mth:Habitat	4	12.27	0.49	0.742

Table 3: GLM results comparing the abundance of fishery pre-recruit *Portunus pelagicus* (50-100mm) between sites, months and habitats in Spencer Gulf between May 1999 and June 2000.

	Df	Deviance	F value	Pr(F)
Site	4	435.78	34.20	**<0.001**
Mth	1	108.75	34.14	**<0.001**
Habitat	1	55.77	17.51	**<0.001**
Site:Mth	4	3.40	0.27	0.899
Site:Habitat	4	37.92	2.98	**0.019**
Mth:Habitat	1	3.11	0.98	0.323
Site:Mth:Habitat	4	11.87	0.93	0.444

Hill had the second greatest abundances of juvenile *P. pelagicus*. No significant difference was found between the gulfs whilst month, habitat and site (nested within each gulf) all influenced the abundance of juvenile *Portunus pelagicus* (Table 5). Like before, significant interaction terms for month x site and habitat x site indicate inconsistency of juvenile distribution and/or abundance patterns spatially. For example, generally poor recruitment at Port Gawler in Gulf St Vincent and Blanche Harbour in Spencer Gulf led to no distinction between habitats and months for these sites. However, more abundant recruitment to Outer Harbour and Fifth Creek culminated in clear habitat preference and monthly patterns.

Table 4: Summary of catch data, pooled across replicates, for the expanded spatial data set incorporating sites in Gulf St Vincent (top portion of table) and Spencer Gulf (below double line) for March and April 2002.

	Sand			Seagrass			
Site	March	April	Total	March	April	Total	Grand Total
Port Arthur	19	9	28	138	25	163	191
Bald Hill	36	97	133	49	152	201	334
Port Gawler	0	0	0	45	0	45	45
Outer Harbour	16	9	25	127	343	470	495
Port Clinton	4	5	9	89	86	175	184
Port Broughton	3	1	4	62	77	139	143
Blanche Harbour	5	2	7	24	25	49	56
Chinamens Creek	5	0	5	12	32	44	49
Cowleds Landing	5	13	18	44	35	79	97
Fifth Creek	48	110	158	105	331	436	594
Port Pirie	19	20	39	62	286	348	387
Second Creek	37	60	97	60	179	239	336
Woods Point	17	51	68	21	161	182	250
Grand Total	214	377	591	838	1732	2570	3161

Table 5: Results from the 2002 (March and April) sampling season comparing the total abundance of *Portunus pelagicus* between sites nested within Spencer Gulf or Gulf St Vincent, and across months and habitat types (intertidal seagrass or unvegetated soft sediment).

	Df	Deviance	F value	Pr(F)
Gulf	1	5.64	0.68	0.412
Mth	1	370.10	44.32	**<0.001**
Habitat	1	1336.18	159.99	**<0.001**
Gulf/Site	12	1579.03	15.76	**<0.001**
Gulf:Mth	1	49.88	5.97	**0.016**
Gulf:Habitat	1	6.39	0.77	0.383
Mth:Habitat	1	4.82	0.58	0.449
Gulf/Site:Mth	10	374.93	4.49	**<0.001**
Gulf/Site:Habitat	12	337.19	3.37	**<0.001**
Gulf:Mth:Habitat	1	1.70	0.20	0.653
Gulf/Site:Mth:Habitat	10	44.94	0.54	0.861

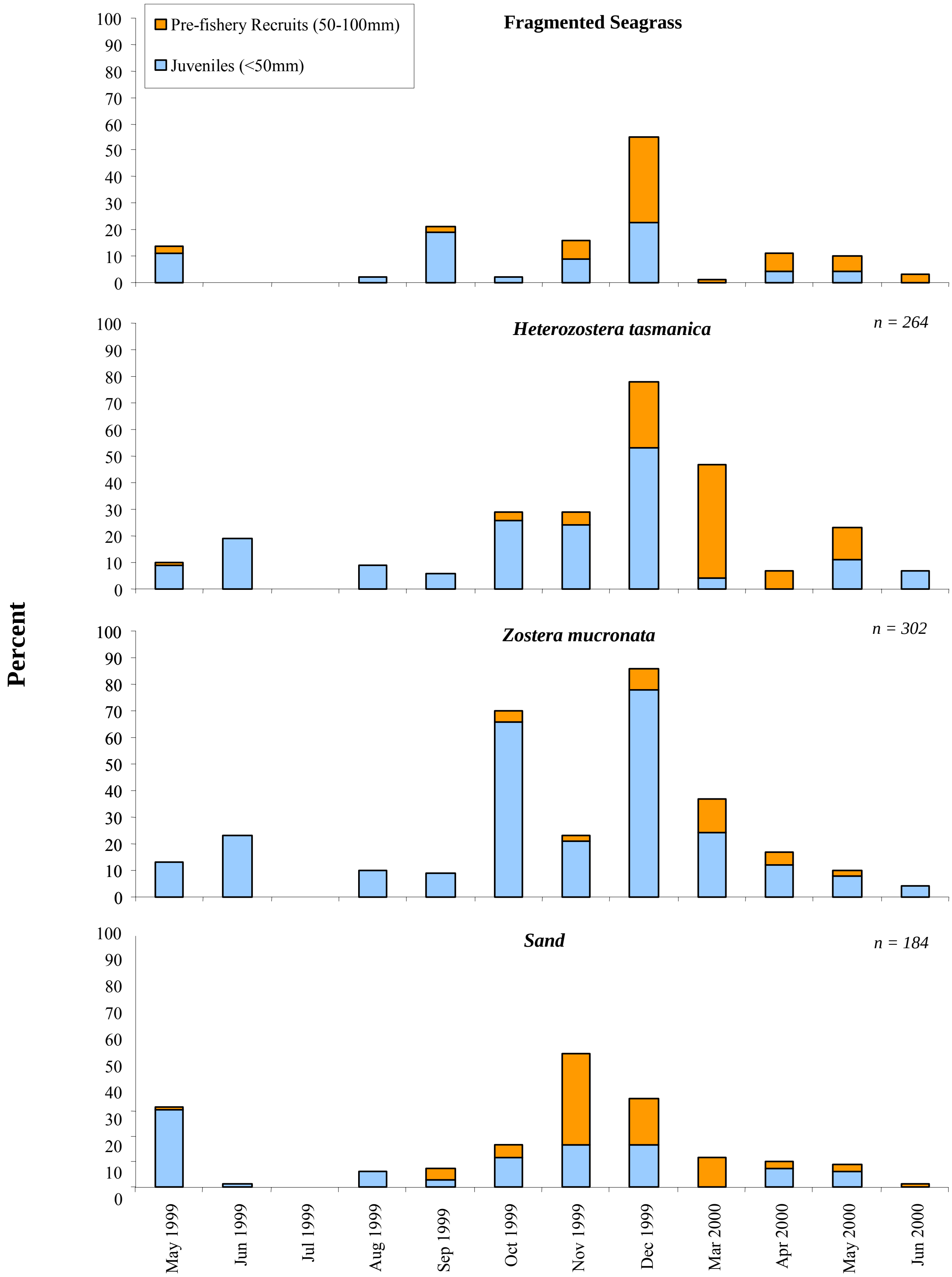

Figure 4: Monthly comparison of juvenile abundances (<50mm carapace width) for each of the different habitat categories trawled at Fifth Creek for survey period from May 1999 to June 2000.

Discussion

Large-scale Spatial and Temporal Recruitment Patterns in Spencer Gulf

It is generally accepted that several abiotic factors influence the capacity of larvae to survive and disperse in the marine environment. Research on brachyuran larval development and survival has shown that temperature is an important factor, with *Portunus pelagicus* larval development is retarded in water cooler than 20°C (Cambell 1984, Laughlin and French 1989a, Brown *et al.*1992, Nagaraj 1992, 1993, Bryars 1997). As expected from these temperature limitations the seasonal cycles of juvenile *P. pelagicus* abundance in Spencer Gulf during the first year of sampling indicated that a new year-class entered recruitment areas during the warmer months. In general, juvenile *P. pelagicus* were present from as early in spring as October through to May the following year.

During the 1999-sampling season, juveniles that recruited in spring obtained pre-fishery recruit size by early autumn. Although a significant settlement event was not apparent in late summer or autumn of the first year, substantial settlement pulses occurred in March and April of subsequent sampling seasons. Thus it appears that juvenile *Portunus pelagicus* may exhibit generally similar temporal recruitment patterns to *Melicertus latisulcatus* in Spencer Gulf. Carrick (1996) found that juveniles of *M. latisulcatus* exhibit two settlement pulses, one in spring and a more significant one in late summer or early autumn.

In South Australia, *Portunus pelagicus* begin to spawn during September/October, with peak numbers of ovigerous female crabs occurring from November to March (Smith 1982, Grove-Jones 1987, Bryars 1997). Laboratory studies have found that the duration of larval life stages for *P. pelagicus* is temperature dependent and can vary from as short as two weeks to as long as 7 weeks (Meagher 1971, Campbell 1984, Bryars 1997). Given that the 20°C threshold for larval development is close to the maximum temperature reached by all but shallow inshore waters in the gulfs of South Australia, monthly and inter-annual variations in temperatures by themselves would result in substantial annual changes in recruitment rates and timing.

Given that larvae persist as plankton for a considerable period of time (i.e. weeks rather than days), the other likely physical influence on *Portunus pelagicus* dispersal is advection, which in South Australia is strongly influenced by wind in the warmer summer months. In Spencer Gulf, general circulation is described by a northerly flow along the west coast and a southerly (or outward) flow along the eastern shore. During warmer months strong, clockwise rotating gyres form with a separation between upper and lower Spencer Gulf (Bullock 1975, Nunes and Lennon 1986, Nunes Vas *et al.*1990). Temperature disparities between land and water generate strong coastal sea breezes in the gulfs between November and March, creating an inshore drift of surface waters, correlating to the peak larval hatching times of *P. pelagicus* (Bryars 1997).

The abundances of juvenile *Portunus pelagicus* (<50mm) were significantly different between sites in Spencer Gulf during the 1999/2000 sampling season. Of the five survey sites, Fifth Creek and Port Broughton had almost all juveniles caught. Both sites are located on the eastern shore of the gulf. During the expanded spatial sampling season of 2002, *P. pelagicus* were abundant at additional sites along the east coast of Spencer Gulf, particularly in the vicinity of Fifth Creek. High abundances of juvenile *P. pelagicus* are also known to occur at other sites in the area, including Second and Fourth Creek, as well as further south at Tickera near Wallaroo (B. McDonald Pers. Obs., N. Carrick Pers. Comm.). The results suggest that the eastern shoreline of northern Spencer Gulf is an important area of nursery habitat for *P. pelagicus*.

Interestingly, few juveniles were found north of Port Pirie on either side of the gulf although previous experience has suggested that some areas near Chinamen's Creek and Blanche Harbour are important nursery grounds for *P. pelagicus* (N. Carrick Pers. Comm.). The formation of a seasonal cyclonic gyre that extends from approximately Wallaroo in the south to Port Germein in the north of Spencer Gulf is a water temperature and wind driven event dependent on the development of onshore sea breezes on opposing coasts (Nunes and Lennon 1986, Nunes Vaz *et al.*1990). Hence juvenile dispersal in the northern tip of the gulf (north of Port Germein) may be limited during years when the cyclonic gyre is strongest, restricting recruitment potential to an effective spawning stock within the northern tip of the gulf. Settlement in the northern reaches may be more prolific in years when the gyre is weaker and tidal currents are able to distribute larvae from a broader source area farther north. Further research is needed to test the strength of this hypothesis, however, and would rely on an expansion of temporal sampling to cover a number of years in conjunction with more detailed environmental and hydrodynamic assessments of northern Spencer Gulf.

Habitat Use

Juvenile *Portunus pelagicus* were more abundant in intertidal seagrass meadows (typically *Zostera sp.* or *Heterzostera tasmanica*) than they were in meadows of *Posidonia sp.* or over sand habitat. The larval and juvenile stages of many benthic species are known to actively select certain substrates (Scheltema 1974, Heck and Thoman 1984, Guidetti 2000, Tanner and Deakin 2001). Seagrass beds tend to support a more diverse and dense assemblage of fauna than sand habitats (Orth and Heck 1980, Pollard 1984, Rozas and Odun 1988, Bell and Pollard 1989, Guidetti 2000). Laughlin (1982) showed that many of the species found over seagrass meadows featured in the diet of *Callinectes sapidus*, and Orth and van Montfrans (1987) suggest that a greater abundance of food could potentially support higher densities of the same species. The growth rate of *C. sapidus* was found to be significantly higher in seagrass meadows than in sand supporting the hypothesis that juveniles in seagrass receive a significant trophic advantage (Perkins-Visser *et al.*1996). Further advantage is likely provided by the refuge function of seagrass (Heck and Thoman 1981, Perkins-Visser *et al.*1996). Further research may be able to determine the exact mechanism(s) for seagrass habitat selection that causes preferential selection of intertidal seagrasses over subtidal communities of *Posidonia* and *Amphibolis*

Alternatively, seagrass meadows are known to influence local hydrodynamics, which may enhance the passive settlement of megalopae into a meadow. It has been demonstrated that seagrasses modify current regimes resulting in the deposition of passive sediment particles (Fonseca *et al.*1982) but little is known about the response of actively swimming larvae to such current flow modifications. Given low post-settlement abundances in nearby subtidal seagrass communities, however, the passive influence of hydrodynamics does not satisfactorily explain disparities in *Portunus pelagicus* abundances between structured habitats.

Small-scale variations in the supply of megalopae to areas of habitat could, in part, account for what at many sites was a ten-fold or more increase in the number of juvenile *P. pelagicus* in the intertidal seagrass meadows compared to other habitats. In our sampling design, however, the spatial separation of trawls between habitats was the same as the spatial separation of samples within habitats and if the above was true a patchy distribution within habitats that matched the differences between habitats would be expected, this was not the case. Based on the abundance of competent larvae distributed generally throughout the offshore water column in Gulf St Vincent (see Bryars 1997), it is unlikely that supply rates are substantially different at a scale of 10s to 100s of metres.

Expanded Spatial Recruitment Patterns

Recruitment of juvenile *Portunus pelagicus* to nursery habitats in the gulfs appears to be synchronous, with no disparity in the timing of settlement events apparent between Spencer

Gulf and Gulf St Vincent. Of the five survey sites in Gulf St Vincent, Outer Harbour had the highest abundances of juveniles. All three sites at the top of the gulf showed strong recruitment patterns, and at all of the sites surveyed, intertidal seagrasses had a greater abundance of juvenile *P. pelagicus* than sand. An interesting disparity in the settlement pattern is Port Gawler. Situated between Bald Hill and Outer Harbour on the eastern shore of Gulf St Vincent, and with expansive intertidal flats, strong recruitment pulses were expected but not found. Without a continuation of research that traces juvenile settlement over a number of years, however, it is impossible to conclude that the patterns described in 2002 are consistently true for Gulf St Vincent.

Conclusion

The demographic patterns of post settlement *Portunus pelagicus* in South Australia are multi-scaled. Broadly, the presence and abundance of juveniles varies inter-annually, with patterns probably driven largely by physical factors such as water temperature and the development of alternate hydrodynamic regimes such as gyres. The demography of *P. pelagicus* also varies seasonally, with juvenile settlement peaks occurring during summer or early autumn depending on seasonal sea temperature patterns. Importantly, the sensitivity of larval and post-settlement juvenile *P. pelagicus* to environmental variability suggests the need for further research to investigate relationships between yearly recruitment abundances to nursery habitats, subsequent fishery pre-recruits and ultimately recruitment to the fisheries.

Regionally, the distribution of juveniles in Spencer Gulf appears skewed towards sites on the eastern coastline and in particular to sites between Port Pirie and Port Broughton. Expanded surveys would need to examine the influence of a seasonal gyre in northern Spencer Gulf with varying strength depending on environmental variables. In years when the gyre is weak it may be that juvenile settlement is more widely distributed through the upper regions of Spencer Gulf. In Gulf St Vincent, the Barker Inlet region was found to have the greatest numbers of juvenile *Portunus pelagicus*, with other important nursery sites being found in the northern tip of the gulf.

Locally, demographic patterns were habitat specific. Post-settlement juveniles actively selected for intertidal seagrasses (*Zostera sp.* and *Heterozostera tasmanica*) over other seagrasses (*Posidonia sp.* and *Amphibolis sp*.) or unvegetated soft substrata. It is possible that the trophic advantage and refuge presented by intertidal seagrasses attracts greater abundances of juvenile *Portunus pelagicus* than adjacent habitats. Further research is required to determine the exact nature of habitat specific demographics, however.

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CHAPTER 4: CRITICAL EVALUATION OF THE USE OF A SURPLUS PRODUCTION (SCHAEFER) MODEL FOR THE SOUTH AUSTRALIAN BLUE CRAB FISHERY.

Anthony C. Cheshire and Richard McGarvey

Introduction

A recent review of research on the SA Blue Crab fishery (Scandol and Kennelly 2000; reprinted in Appendices) recommended the development of data-generating models to test and refine the currently selected fishery performance indicators. In discussions with the author (AC) reviewer 2 (SK) indicated that a useful starting point would be the development of a biomass dynamic (otherwise known as a Schaefer or Surplus Production) model to inform the management of this fishery (Steve Kennelly pers. comm.). The review went on to argue that such a model would be useful in providing support to fishery managers and the FMC in setting the TACC for the fishery.

Not withstanding this assertion, Chen and Kennelly (1999) had previously noted that a Schaefer model could not be used to discriminate between a spanner crab stock comprising "a small biomass of rapidly growing animals or a large, slow growing biomass." In so doing they referred to published work by Hilborn and Walters (1992) who had previously noted that confounding of growth rates and initial biomass is a common problem in biomass dynamic models particularly when there is little contrast in abundances and fishing effort. In essence, whilst recommending that such a model be developed the limitations of this modelling strategy need to be recognised.

A further problem with the SA Blue Crab fishery is the fact that CPUE in this fishery rose dramatically over the first 10-12 years of its operation. This fact alone makes the implementation of such a model problematical in that it relies on CPUE to provide robust estimates of relative stock size. Indeed, Scandol and Kennelly (2000) qualified their recommendation about the development of this sort of model by acknowledging this problem in relation to the SA fishery.

Acknowledging the potential limitations of this approach to modelling this paper aims to develop and critically evaluate an implementation of the Schaefer model for the SA Blue Crab fishery. The specific objectives are to:

1. Outline the nature of the Schaefer model.
2. To consider the issue of CPUE as an index of stock size and to formulate an approach for transforming CPUE data to account for "learning" in the fishery.
3. To apply the model to the existing data in the fishery and thereby estimate key parameters for the fishery.
4. To consider the model outputs in relation to the existing management arrangements in the fishery.

The biomass dynamic or Schaefer model

The Schaefer model is widely used to support fisheries stock assessments because it provides a relatively simple approach to estimation of stock size using fishery dependant catch and effort data (Smith and Addison 2003). The model aims to estimate a number of parameters including the virgin biomass, the biomass growth rate and the exploitation rate. Estimation of these parameters then allows the calculation of a number of other related parameters including exploitation rate and the stock size at any time t.

The Schaefer model employs a simple mathematical construct that assumes that stock biomass is a function of growth rate and fishing mortality according to the general formula:

$$B_{t+1} = B_t + R_t . B_t - C_t \qquad (1)$$

In this B_t represents the stock biomass (at time t; B_{t+1} is biomass 1 year later[1]), R_t represents the biomass growth rate and C_t the fishing related mortality.

The terms for biomass growth rate (R_t) and fishing mortality (C_t) may have a variety of different formulations. In most cases R_t is considered to be a non-linear function linked to stock biomass (B_t) that accounts for feedback between stock biomass and the carrying capacity of the system. A logistic function is commonly used to represent this and has the general form:

[1] Although the time series does not have to be annual if data exists for catch and CPUE over shorter time periods.

$$R_t = r.\left[1 - \frac{B_t}{K}\right] \quad (2)$$

This formulation embodies a constant biomass growth rate (r), which is modulated by feedback, such that the biomass growth rate (R_t) tends to zero[2] as the stock size (B_t) approaches the environmental carrying capacity (K). K is also assumed to be a constant but almost certainly varies from year to year particularly in relation to changing environmental circumstances such as food supply.

Fishing related mortality is generally derived directly from the fishery statistics but can be expanded to include terms related to recreational or illegal fishing and (in the context of the blue-crab fishery) to include fishing in both the MSF and pot sectors. In the current implementation of the model C_t has been defined as:

$$C_t = CPot_t + CMSF_t \quad (3)$$

where $CPot_t$ is the annual catch from the pot fishery sector and $CMSF_t$ is the annual catch from the marine scale sector.

By implication the other forms of fishing mortality are incorporated into the estimate of r which represents an averaged growth rate after accounting for other forms of mortality (natural mortality, recreational catch and illegal catch) and recruitment in the population. In the absence of any independent estimates these parameters are assumed to be constant. This assumption is made because life history data on natural mortality are lacking, recreational catches have only been estimated on a couple of occasions and illegal fishing has not been quantified. Our lack of data on these parameters does however introduce a source of error into the model. In particular the fundamental assumptions that natural mortality and recruitment are constant is clearly not true for this system (see preceding chapter).

Given these assumptions the overall model is therefore:

$$B_{t+1} = B_t + r.\left[1 - \frac{B_t}{K}\right].B_t - \left[CPot_t + CMSF_t\right] \quad (4)$$

---

[2] As $B_t \rightarrow K$ then $B_t/K \rightarrow 1$ and $r.(1-B_t/K) \rightarrow 0$.

Having established a generalised model for the biomass dynamic (change in B through time) it remains to parameterise the model. In essence quantification of three terms is required:

B_0 is the standing biomass before the fishery commenced and needs to be evaluated in order to provide an initialisation value for the model (Biomass at time 0),

r the biomass growth rate and

K the carrying capacity of the system.

This has been further simplified by assuming that, prior to commencement of the fishery, the standing biomass was at the same level as the carrying capacity (i.e. $B_0 = K$).

In most fisheries it is assumed that B_t can also be estimated from the fishery dependant data. The general assumption is that:

$$B_t = q.E_t \tag{5}$$

where q is an index of catchability and E_t is the catch per unit effort for that fishing period. A simplifying assumption is that q is constant for the full range of biomasses (for all values of B_t) although this is not necessarily the case and a number of alternative formulations have been considered in the literature (Smith and Addison 2003). Furthermore, for a fishery such as the blue crab fishery where we have separate sectors (MSF and pot sector) each of which has a different fishing methodology it is possible to derive separate formulations for B_t including:

$$B_t = q_{MSF}.EMSF_t \tag{6}$$

$$B_t = q_{Pot}.EPot_t \tag{7}$$

where $EMSF_t$ and $EPot_t$ represent the CPUE for the MSF and Pot sectors respectively.

With these separate sets of equations for B_t it is possible to fit the commercial catch and effort data to the model using a strategy of minimising residuals and thereby obtain estimates for all of the parameters including q_{MSF}, q_{Pot}, r and K.

The following provides an analysis of the South Australian blue crab fishery data in the context of this formulation of the Schaefer model.

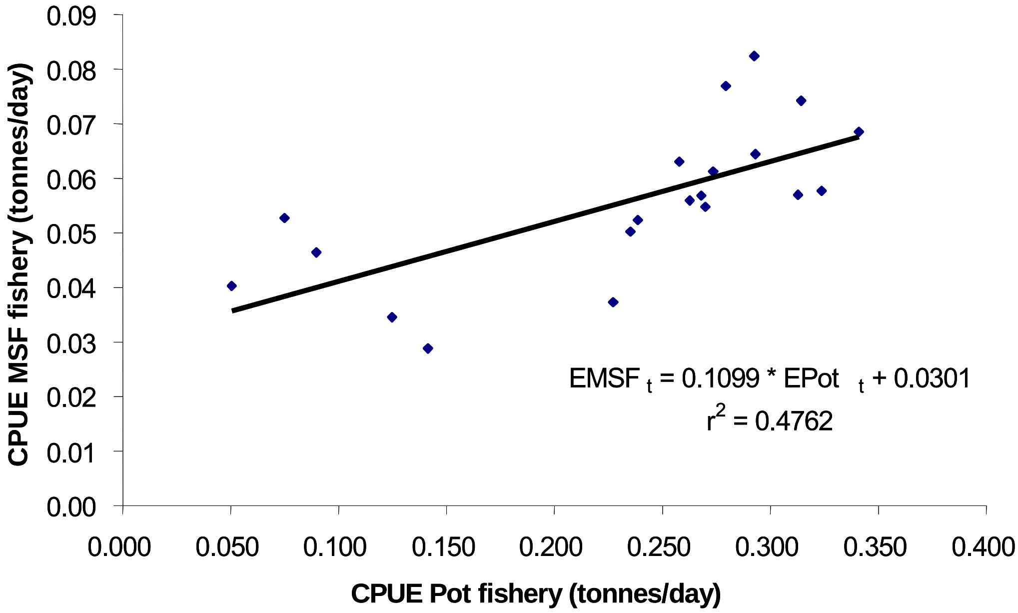

Figure 1: Comparative CPUE between pot and MSF sectors of the blue crab fishery. The positive correlation indicates that CPUE is following similar general patterns in the two sectors. The low value for r^2 indicates that the correlation is not strong and factors other than stock biomass impact on catch rates.

CPUE as an index of stock size

Data on CPUE for both the MSF and pot fishery sectors has been collected for over 20 years and published in a series of stock assessment reports including the most recent report (Svane and Hooper 2004). Generally it would be expected that, if CPUE were a useful index of stock size then, the pattern of CPUE (highs and lows) would be approximately the same between the two fishery sectors. This can be formally tested by a correlation analysis (Figure 1), which aims to assess the extent to which a knowledge of the CPUE in one fishery sector (e.g. Pot sector) provides a capacity to predict CPUE in the other sector (i.e. MSF sector).

Overall although there is a positive correlation between the values, the goodness of fit is relatively low ($r^2 = 0.4762$) which indicates that trends in CPUE in the pot fishery are poorly reflected in terms of CPUE in the MS fishery (Figure 1).

An alternative perspective on the utility of CPUE as an index of stock biomass can be obtained by looking at the plot of CPUE in the fishery through time. In general one would expect that CPUE would fall as the stock is depleted through harvesting of the biomass. Under ideal circumstances (in a sustainably managed fishery) this depletion would level off at a biomass representing the point at which the catch equals the stock growth during any given year. From equation 1 this would occur when $B_{t+1} = B_t$, which requires $C_t = R_t.B_t$.

In the SA blue crab fishery this expectation is not realized (Figure 2). In reality the CPUE for both the pot and MSF sectors rose significantly over the first 10-12 years of the fishery, which implies that either biomass or effective effort increased substantially over that period.

Superficially the assumption that stock size (biomass) increased over this period appears highly improbable. There is however the possibility that, coincidental with the establishment of the fishery, there have been other changes in the ecosystem that have resulted in either an increase in the quality and/or the spatial extent of blue crab habitats. It is known, for example, that extensive modification of benthic habitats and ecosystems associated with prawn trawling have occurred in both Gulfs (Tanner 2002, Svane 2003). The alternative argument, that the increase in CPUE reflects an increase in effective effort, would be consistent with some degree of "learning" in the fishery resulting in an increasing CPUE as fishers became more adept at catching fish either through better knowledge of locations where catches are more abundant and / or through improvements in gear (optimal net configurations, soak times etc) and the application of technologies (including GPS systems etc).

Not withstanding this assumption there are two alternative arguments that need to be considered. If the argument that effective effort has increased over the lifetime of the fishery is not accepted then one can only conclude that CPUE is either a poor indicator of stock size or that the stock size has increased over time as a consequence of some other factor such as changes in the quality or areal extent of suitable habitat.

In such a circumstance a surplus production (Schaefer) model will require an alternative set of data, presumably obtained through fishery independent surveys, to estimate stock size.

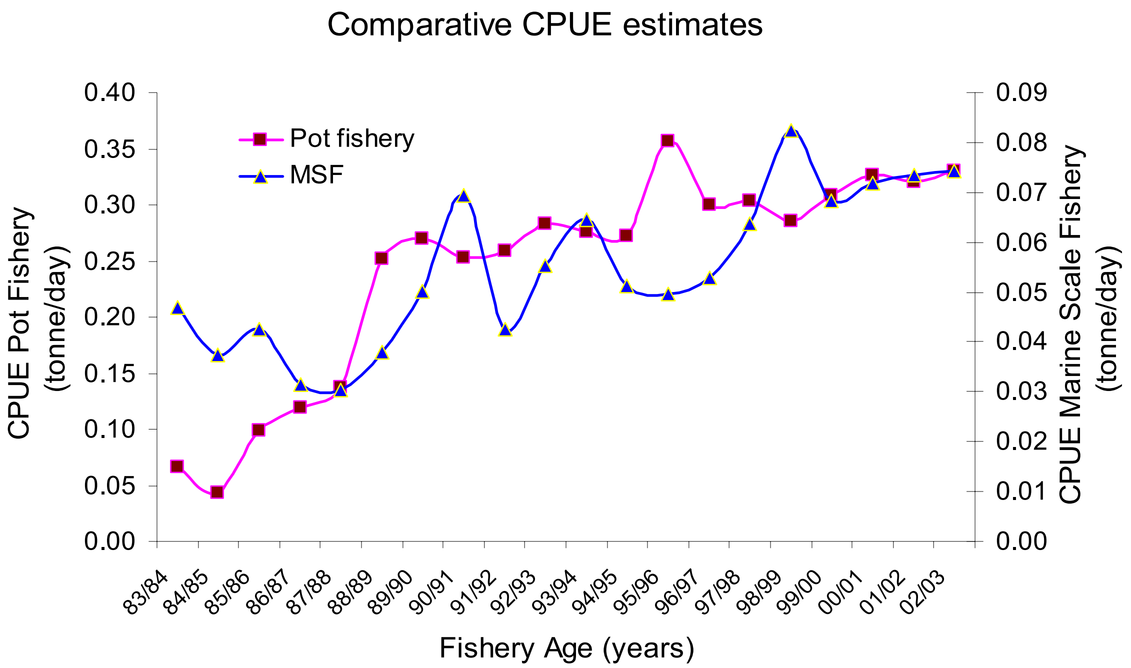

Figure 2: Plot showing change in CPUE over time in both the Pot and MSF sectors of the SA blue crab fishery.

Alternatively, if the argument (that effective effort has changed over the lifetime of the fishery) is accepted, then it follows that this change would affect the utility of CPUE as an indicator of stock biomass. To address this issue the CPUE data need to be transformed to account for these changes in effective effort through time.

Standardisation of effective effort

If it were assumed that the changes in CPUE in the pot fishery are related to "learning" then effective effort would be expected to follow a pattern very similar to that illustrated by the data. The CPUE would be low during the early years of the fishery, increasing through time until it reached a maximal level by which time fishers are operating with maximal effect given existing knowledge and technologies. Such learning can be modelled empirically by fitting a non-linear equation to the CPUE data over time and then using this to transform effort across the lifetime of the fishery.

An exponential model with the following formulation lends itself to this purpose where:

$$E_t = E_{Add} \cdot \left[1 - e^{-\left(\frac{t}{E_k}\right)} \right] + E_{base} \tag{8}$$

$$E_{Max} = E_{Add} + E_{base} \tag{9}$$

In this formulation, effective effort changes through time (defined as E_t). Initially the effective effort starts at a base level (E_{base}) and increases towards a maximal level E_{max}. The rate of increase in effective effort is determined by the parameter E_k which is essentially a parameter describing the rate of learning in the fishery; low values implying very fast learning and high values indicating that learning is a slower process. E_{Add} is a parameter that quantifies the extent to which learning increases the overall value for effective effort.

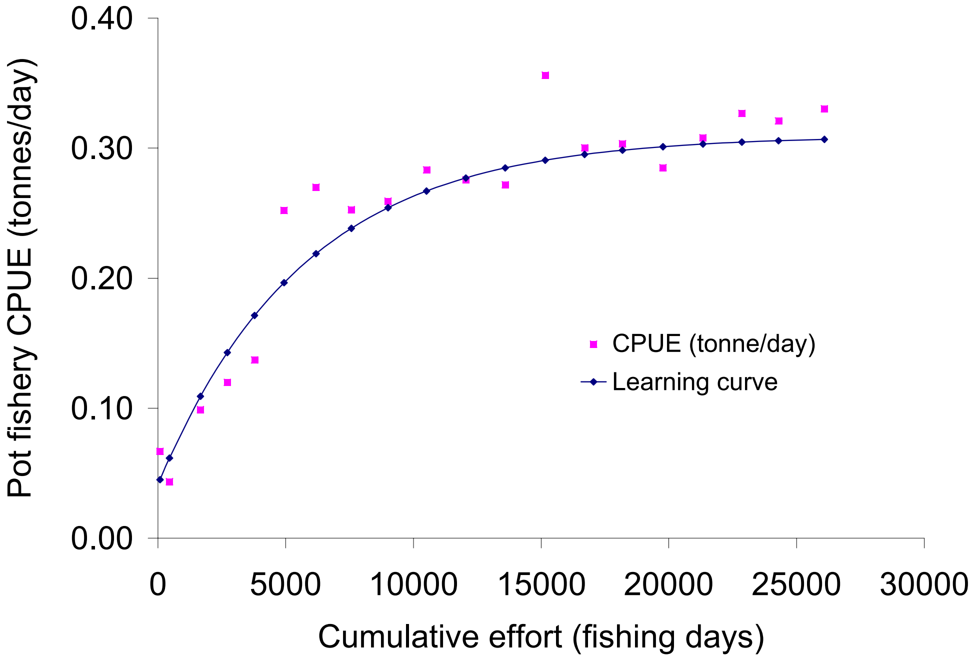

Figure 3: Plot showing the change in effective effort scaled against CPUE in the Pot Fishery over the lifetime of the fishery from 1983/84 to 2002/03.

This model provides a curvilinear approximation of the changes in effective effort through time and is illustrated graphically in Figure 3 where the solid line provides an indication of the changes in CPUE that would be expected based on improvements in effective effort alone. The differences that remain between the observed CPUE and the modelled value (indicated by this line) are then assumed to represent noise (error) in the data and / or changes in the stock size in relation to fishing mortality.

Application of this model to the data largely removes the trend of increased CPUE over time and thereby the implication that stock size has also increased over time (Figure 4).

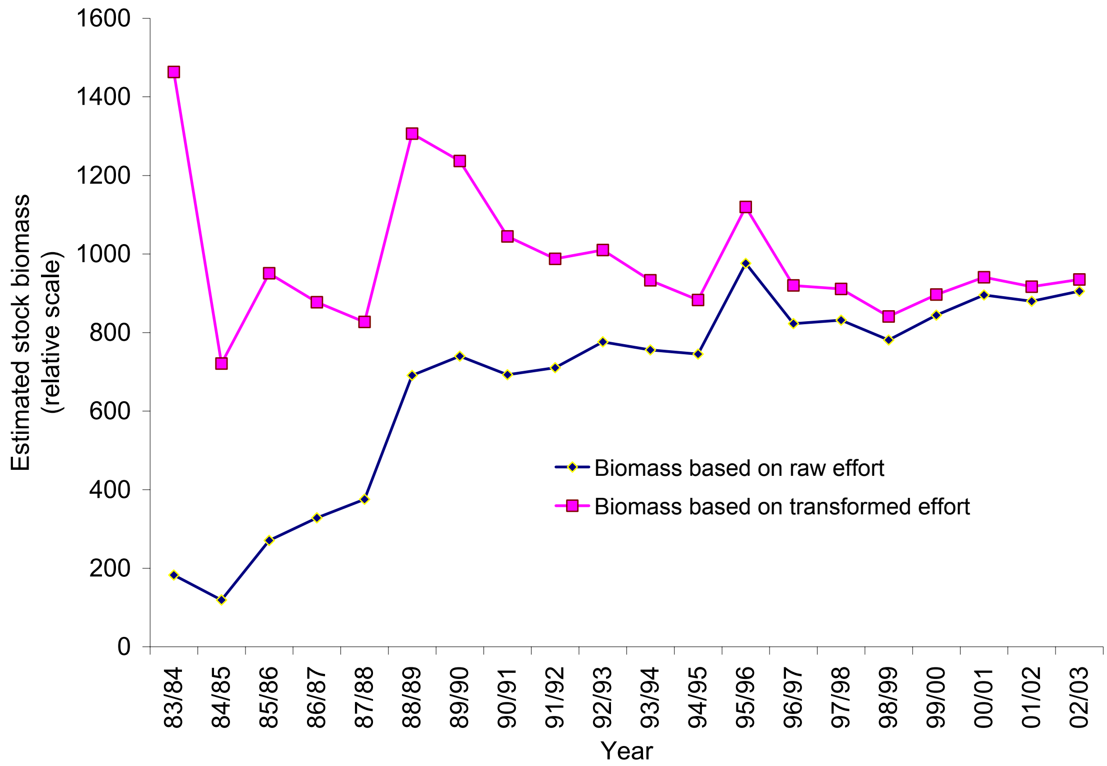

Figure 4: Plot showing the estimates of biomass (relative scale based on CPUE) using the transformation detailed in equation 8 compared with the untransformed estimate obtained from the raw data. The two lines converge

Application of the Schaefer model to estimate stock size

Having accounted for the inconsistencies between the raw measures of CPUE and the expected trend in stock size the Schaefer model was then parameterised. Estimates for the model parameters were obtained by fitting the data on catch in the MSF and Pot sectors ($CMSF_t$ and $CPOT_t$) with the transformed estimates of CPUE from the Pot sector[3] ($Epot_t$). Fits were obtained using the SOLVER utility in EXCEL to minimise the least squares residual of the estimates obtained for Bt from equations 4 and 7 respectively. Although simpler in form this approach is identical to the use of a maximum likelihood estimator where the variance estimates of the data are unknown (and thereby assumed to be constant).

The model fit provided an estimate for the values of q_{Pot}, r and K. The virgin biomass (B_0) was assumed to be equal to K implying that the initial biomass (stock size prior to 1983) was maximal and equal to the carrying capacity of the system.

In order to test the stability of the parameter estimates from the model a Monte-Carlo simulation was performed by introducing a random error of up to ±15% into the catch data. This error was then propagated into estimates of CPUE and the model re-fitted to the data. Final estimates (which were used as the basis for obtaining predictions from the model) were based on the average estimates obtained from 1000 separate runs of the model. Parameter values obtained from this exercise, including estimates of error, are detailed in Table 1.

Model estimates of stock size and exploitation rates

The time series representing estimates of stock biomass (Figure 5) can be evaluated by parameterising equation 4 with the values obtained from the Monte-Carlo simulation

[3] In theory this could also be done with CPUE from the MSF sector ($EMSF_t$). However, an attempt to implement this failed because the model could not provide a robust solution. When trying to fit the data to the MSF sector data many estimates for K and r were negative which is a biologically meaningless solution. It was decided therefore to use only the Pot sector CPUE data (which currently has around ten times the catch of the MSF sector). The catch data from the MSF sector were incorporated into the term for fishing related mortality. The only real justification for excluding the MSF CPUE data from the model would be an argument that the signal to noise ratio in the MSF sector is too low to provide useful information to parameterise the model.

(Table 1). When applied to these data the time series indicates a change in stock biomass over time reducing from around 1100 tonnes in 1983 to around 830 tonnes at the present time. This change is consistent with expectations for a stock that is being fished and demonstrates that fishing pressure has reduced stock size to around 75% of the virgin biomass (based on biomass at the start of each season). Considered in isolation a reduction in biomass to 75% of B_0 would not be concerning. Not withstanding this however, the harvest rate of around 520 tonnes per annum is much more significant suggesting that around 60% of the stock is removed each season. The inference to be drawn from this result would be that the fishery is reliant on very high levels of recruitment from one year to the next in order to maintain stocks.

Table 1: Parameter estimates obtained from a Monte-Carlo simulation comprising 1000 runs of the model incorporating a 15% random error into the catch data.

Parameter being estimated	Estimated parameter value	Standard deviation of parameter estimate	Upper 95% confidence interval	Lower 95% confidence interval	Percentage error
K (tonne)	1100	52	1137	1064	4.7%
r	2.58	0.19	2.72	2.45	7.3%
q_{Pot}	3088	227	3248	2928	7.3%

Whereas this time series (Figure 5) provides a representation of the changes in stock size and exploitation over the lifetime of the fishery the quantification should be viewed with a great deal of caution. The parameter estimates are, at best, unreliable and potentially quite erroneous. The model has not been validated in any way either through fishery independent surveys or through any form of jack-knife analysis with the existing data from the fishery.

The analysis in Figure 6 provides a case in point. The plot illustrates the extent to which the two estimates of biomass (derived from CPUE compared with application of Schaefer model) provide a coherent view of the status of the fishery. The diagonal line running from the bottom-left to the top-right corner of the plot represents the expectation for these data. In essence, for a perfect correlation all points would fall on this line. In fact there is no correlation at all. The line describing the points has an r^2 value that is not significantly different to 0 implying there is no relationship between the two estimates.

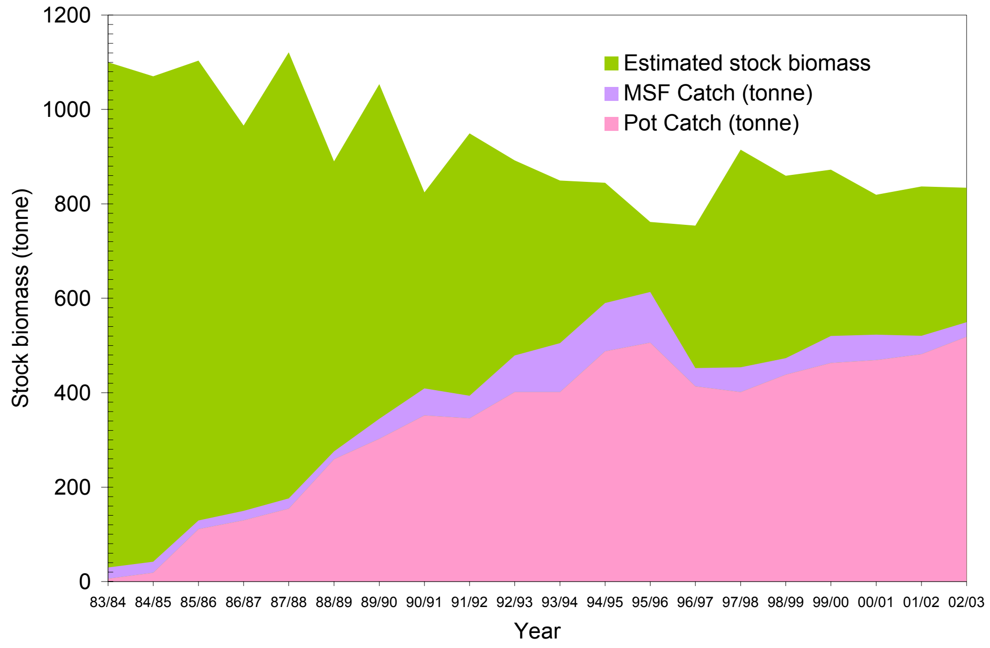

Figure 5: Time series of estimated stock biomass and the catch from the Pot and MSF sectors. Current exploitation rate is estimated at around 67% of total biomass.

Whereas this test is arguably very rigorous, especially given the limited domain over which data have been collected, it does illustrate the potential scope for error in parameter estimation. The two estimates of stock biomass may differ by as much as 80% depending upon whether they have been estimated using the model or the CPUE estimator. Overall, this suggests that the confidence limits that should be applied to the estimation are probably quite broad.

In essence, until the model has been independently validated it will have no utility as a management tool. Indeed, to place any reliance on a model such as this is likely to lead to entirely erroneous conclusions about the status of the fishery. The major threat is that the model will provide fishers and managers with a false sense of confidence about the quality of their knowledge and the concomitant risk profile of the fishery and thereby lead to insufficient caution in relation to key decisions about exploitation strategies.

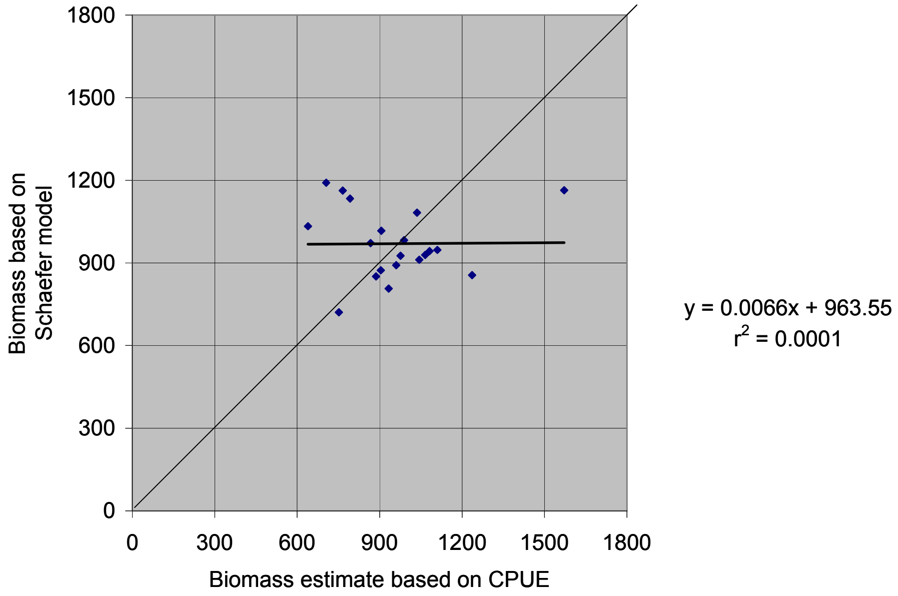

Figure 6: Regression analysis showing goodness of fit between the estimates of biomass based on CPUE compared with the estimate derived from the Schaefer model.

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APPENDIX 1: RESULTS FROM THE BLUE SWIMMER CRAB TAGGING PROGRAM

Introduction

A tagging program was undertaken to assess growth and migratory patterns in both Spencer Gulf and Gulf St Vincent.

Methods

- initial trials: elastomer, coded wire tags, visual implants
- tried a few different filament types
- no diff. in mortality
- very few moults ie couldn't assess

Fig. 1. Tag type and position of a tag on a male blue swimmer crab.

- hence using same tags as WA for comparison of data
- primarily for movement data
- tagging 12000 crabs, 6K/gulf
- inshore and offshore
- collected by pots and trawling on *RV Ngerin*

Results

- Tagged 6849
- NO returns at present by commercial fishers
- Movement of tagged crabs in Spencer Gulf.

Table I. Preliminary results of the tagging program for blue swimmer crabs

	Gulf St Vincent	Spencer Gulf	Total
Tagged	3342	3507	6849
Returned	52	8	60
Distance moved			
-minimum	0.015 km	2.61 km	
-maximum	38.25 km	8.575	
% males tagged	70.8%	85.7%	78.3%
% legal tagged (CW>110mm)	79.3%	51.5%	65.4%

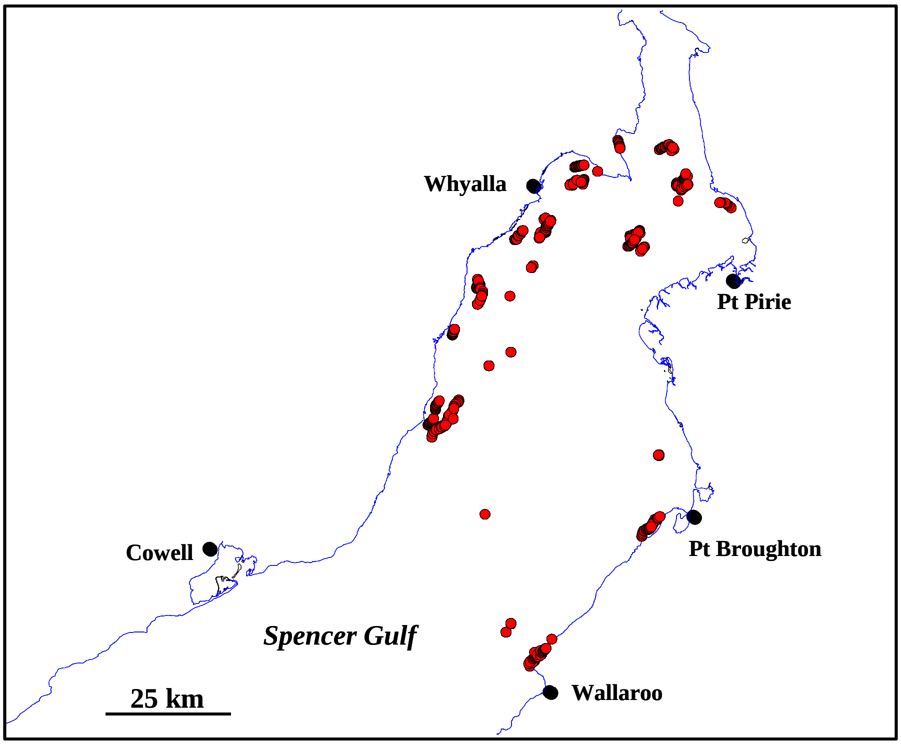

Fig. 2. Tagging locations in Spencer Gulf, each point represents a tagging location.

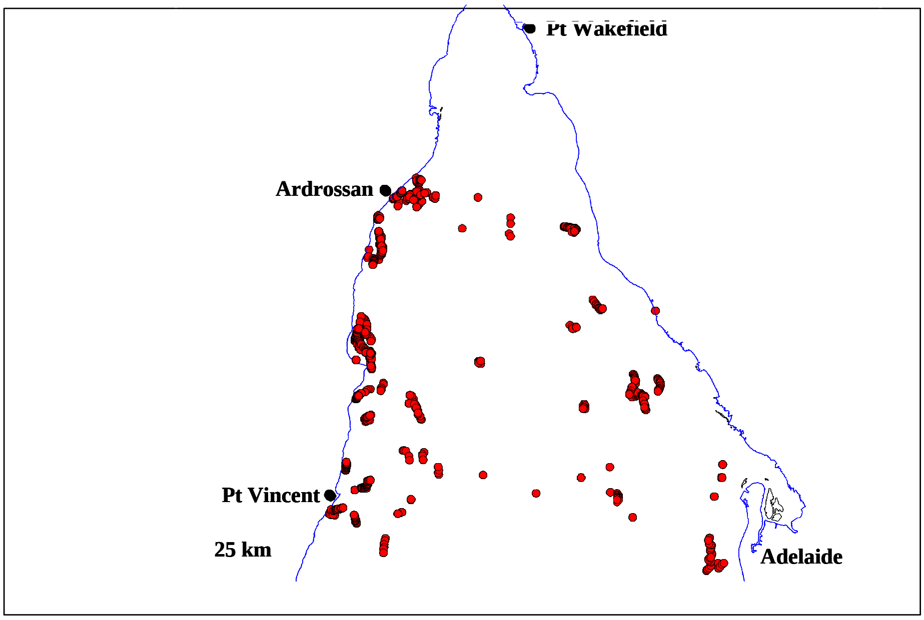

Fig. 3. Tagging locations in Gulf St Vincent, each point represents a tagging location.

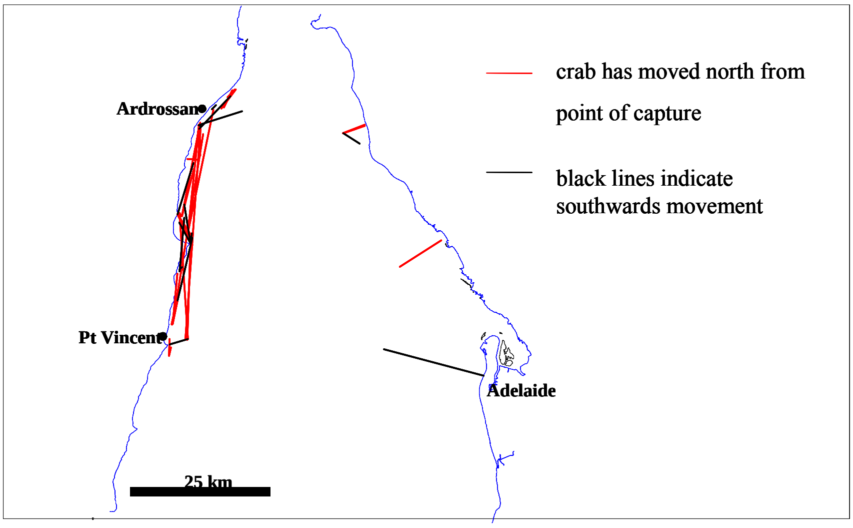

Fig. 4. Preliminary tagging results for Gulf St Vincent showing direction of movements.

APPENDIX 2: INTELLECTUAL PROPERTY

None

APPENDIX 3: STAFF

South Australian Research and Development Institute (SARDI)

Principal Investigator: Professor Anthony Cheshire

Co-Investigator: Dr Ib Svane

The following researchers contributed to the report:

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Dr Steven J. Kennelly

Bryan McDonald

Dr Jason Tanner

Dr Simon Bryars

Dr Martin Kumar

The following people were involved in the research during its conception / development.

Dr Paul McShane

Dr Howel Williams

APPENDIX 4: REPRINT OF THE REVIEW BY SCANDOL AND KENNELLY

BLUE CRAB FISHERY BIOLOGICAL RESEARCH REVIEW

James P. Scandol

Steven J. Kennelly

Centre for Research on Ecological Impacts of Coastal Cities
Marine Ecology Laboratories (A11)
University of Sydney
NSW 2006

February, 2001

FINAL REPORT

EXECUTIVE SUMMARY:

A review of the research in the South Australian Blue Swimmer Crab (*Portunus pelagicus*) fishery was completed. The seven Terms-of-Reference included: a research review; short term monitoring advice; process issues; recommendations for a 5-year research program; consultation with stakeholders; and comments on sampling issues for ESD outcomes. Documents provided by PIRSA, SARDI and the BCFMC were examined but the existing reviews of the crab's biology and the fishery have not been rewritten. Rather, a strategic assessment of the monitoring-sampling strategies (being undertaken for stock sustainability) was completed. Designs of an "appropriate annual monitoring program" are compromised until the objectives of the program are clarified. Once clearly articulated objectives are available a power analysis or risk analysis calculation should be completed and used to guide the sampling program. The current stock indicators: catch, relative exploitation rate, pre-recruit index and sex-ratio, were also critiqued. The process being used to interpret the quantitative estimates of the four indicators for a TACC is not transparent. An independent TAC Committee could be considered, but at the very least, an increased awareness of the difficulties of setting a TACC from the available information should be cultivated. Qualitative costs and benefits of the fishery dependent and/or independent monitoring (sampling) program are provided. There are many process benefits of co-operative monitoring (sampling) programs that would be strengthened by more effective and timely reporting procedures. Future research should be prioritised by management needs and could include: continual review of research and management for similar fisheries; computer simulation to evaluate the monitoring (sampling) and TAC setting process; robust sampling of catch rates; and, research on the recreational fishery. Extensive consultation with stakeholders of the fishery was completed by one of us (SK). The research and monitoring required for ESD (Schedule 4 Amendments) has not been considered for reasons given in the review.

TERMS OF REFERENCE:

1. Undertake an independent review of the research programs in support of the Blue Crab Fishery, which are required to fulfil management obligations to Government under Project 1.

2. Advise on an appropriate annual monitoring program to deliver against the current agreed performance indicators.

3. Advise on the mechanisms for communication of the results of research to the commercial fishing sector and how that can be improved, including general communication and interpretation of research.

4. Advise on a 5-year research program to ensure that the current performance indicators remain relevant to management of the fishery.

5. Consult with stakeholders within the blue crab fishery including industry (Pot and Marine Scalefish), recreational, South Australian Research and Development Institute (SARDI) and Primary Industries and Resources South Australia (PIRSA) representatives on the research program.

6. Assess the minimum requirements needed to address the proposed guidelines for ecological sustainability of commercial fisheries (Environment Australia) and advise on any additional research monitoring required.

7. Complete this review within a period of 8 weeks from contract date.

BACKGROUND

A review of research for any fishery must begin with a determination of what are the most important questions to be answered. That is, it is necessary to determine which management tools are to be used in the fishery and how current and future research can contribute to them. The South Australian Blue Crab fishery is currently characterized by being relatively small (501t and $2.2m in 1998/99) and involving a very small number of operators (6 pot fishers who crab full-time and 24 scale fishers who crab part-time). It is also recognized that this fishery is quite healthy and shows no obvious signs of over-fishing. The main management tools used are:

1. various input controls like spatial and temporal closures, size limits, a ban on the taking of berried females, bag limits for recreational fishers; and

2. an output control which involves the setting of an annual Total Allowable Commercial Catch (TACC) which itself is divided into Individual Transferable Quotas (ITQs) for the small number of fishers involved.

All evidence obtained during this review indicates that most stakeholders – i.e. most commercial and recreational fishers, the managers of the resource and the scientists responsible for monitoring/sampling it - are generally satisfied with the input controls currently in place. These controls have been developed over a long period of time, with the net result that there is little controversy associated with them, nor calls to change them. In contrast, the annual TACC is the main tool used to manage catches in this fishery and therefore generates substantial discussion and controversy.

The mono-specific nature of this fishery, its reasonably high per-unit value, small number of operators and the life-history of the target species all combine to indicate that it is appropriate to use of a TACC-based quota management regime. The current administrative system to do this appears to be working well but the research used to support this process has come under significant criticism and ultimately resulted in this review.

TR 1

UNDERTAKE AN INDEPENDENT REVIEW OF THE RESEARCH PROGRAMS IN SUPPORT OF THE BLUE CRAB FISHERY, WHICH ARE REQUIRED TO FULFIL MANAGEMENT OBLIGATIONS TO GOVERNMENT UNDER PROJECT 1

This review does not summarize or provide a detailed critique of all the documentation used for this review, nor will it give detailed summaries of the meetings held and the field trip. The many documents provided by PIRSA on this fishery include stock assessments, draft management plans, reports, preprints of publications and review articles/reports on the fishery and the research about this fishery. There is little value in repeating that information here. The main difference between this current review and previous reviews/summaries on this fishery is that the current review is independent of the influence of PIRSA, SARDI and the commercial and recreational sectors in the fishery. This provides the opportunity to give an overall strategic view of research in this fishery and, more importantly, how it may be improved so as to achieve the management obligations. These management objectives are taken to be (from the draft Management Plan for the Blue Crab Fishery, dated 19-Apr-2000):

1. To ensure sustainable harvests from the blue crab resource;
2. To ensure equitable allocation of the blue crab resource to the commercial and recreational sectors;
3. To provide efficient and cost effective management of the fishery;
4. To provide for secure access to the resource for each sector;
5. To minimise the impact of blue crab fishing on the environment;

6. To provide society with benefits (social, environmental and financial) from the blue crab resource.

We are focussing this review upon objective 1. Recommendations supporting the other objectives will be made but a detailed analysis of all these objectives cannot be dealt with in this review.

In general, the documents examined on research into blue crabs in South Australia can be summarized as: large in number; quite well-produced; mostly in the "grey" scientific literature (without anonymous peer-review); extending over a long period of time; and involving a large number of scientists. Many of the documents contained information that was repeated in other documents - particularly introductory and descriptive detail.

The overall impression one gets from reviewing the research done in this fishery is that it has been sporadic (i.e. intensive at times, minimal at others) and slightly unfocused. This is unsurprising given the opportunistic nature of research funding for Australian fisheries. There appears to be sufficient biological information known about the target species to manage the fishery (for example fecundity relationships with size) but there is a paucity of information about how the stock has been impacted by the development of the fishery.

Nevertheless, this small fishery is comprised of a number of technically skilled and committed operators who obviously have substantial confidence in their fishery. The latter is evident by their strong desire to buy and/or lease quota and their unwillingness to part with it. This group of fishers should place research into this fishery in an excellent position, allowing the collection of quality information on the fishery from its fishers who are adept at gathering the necessary data for their own and, until recently, SARDI's use. This has not occurred and it is appropriate to summarize why.

First, there has been a significant deterioration in communication and increasing distrust between the commercial fishers in this fishery and SARDI scientists. Some of this has come from industry's concerns over the confidentiality and use of data, and some has come from the non-transparency of the calculations and interpretations used to recommend TACCs (people tend to distrust what they do not understand). There has also been a lengthy history of quite negative personal interactions between individual scientists and fishers and there has been controversy over the fate of cost-savings in research not being re-distributed to industry. The latter has led to fishers withholding some data from scientists following legal advice. There has also been concern over the seemingly high cost of research that is fully recoverable from quota holders in this fishery, who view the research providers as holding something of a monopoly. Industry is also concerned over a lack of reporting on the data they gather in forms that are accessible and understandable to them.

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Kumar, M. National strategy for research and development programs on the blue swimmer crab *Portunus pelagicus*. SARDI Internal document.

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TR2

ADVISE ON AN APPROPRIATE ANNUAL MONITORING PROGRAM TO DELIVER AGAINST THE CURRENT AGREED PERFORMANCE INDICATORS

1. An Appropriate Annual Monitoring Program

The Draft Management Plan outlines indictors for stock sustainability and the economic efficiency of the fishery. Only the former will be addressed in this review. The agreed stock sustainability indicators are:

- catch;
- relative exploitation rate;
- pre-recruit [index], and;
- sex-ratio.

Each of these indicators is discussed in more detail below. Before such comments it is important to clarify the meaning of “an appropriate annual monitoring program”. This statement begs the question of what it is to be appropriate for. To answer this question the fishery must articulate how large a change they want to be able to detect in any of these indicators. For example, a monitoring (we prefer the word sampling as it is more precise and we will use it hereafter) program to detect a 5% change in sex-ratio will require far more sampling than a program to detect a 30% change. Consideration must also be given to what the base year or years of the comparison is to be. Quantitative design of an “appropriate” annual monitoring/sampling program will require:

- assumptions about the underlying variability of the indicators (probably available from existing data);

- an articulation of the hypotheses that are being tested (for example: that the sex ratio in 2001/02 is significantly different than it was 2000/01);
- statements of the probabilities of Type I and Type II errors that will be considered acceptable, and;
- statements of the effect size that is to be considered important.

Such an analysis - essentially a power analysis - is difficult but certainly not impossible and SARDI would have the technical expertise to complete such a task. Readers should revise Peterman (1990) if they are unfamiliar with these issues. The BCFMC and PIRSA should be consulted on such a project as it will involve assumptions and value judgements, particularly regarding Type I and Type II errors . Mapstone et al. (1996) provide a good example of this procedure in their analysis of the effects of line fishing experiment on the Great Barrier Reef. A similar analysis could be completed using Bayesian logics (for an introduction see Hilborn and Mangel 1997, also see Punt and Hilborn 1997) and would take the form of a quantitative risk and decision analysis. The determining factor with these sorts of statistical strategies ought to be the ability to communicate the methods and results to stakeholders.

In section TR4.2 we discuss extensions to this analysis that should be considered within a 5-year research program.

2. Catch

Total commercial catch is unlikely to be a robust indicator of the exploitable stock. Changes to commercial catch can be caused by changes in effort, fishing efficiency (catchability) or catch recording procedures. Eventually a reduction in exploitable biomass will result in lower commercial landings but this signal will be confounded with many other processes and will probably be too late. Nevertheless, assessment and allocation procedures require estimates or assumptions about total (commercial and recreational) catches so this information must be obtained or estimated as accurately as possible. A logbook program should be sufficient to record commercial catches.

The difficulty and costs associated with measuring recreational catches are such that the total catches will only ever be known with limited precision. Mechanisms need to be developed to detect a large change in recreational catches that would compromise the conclusions of models that assume recreational catches were constant (see section TR4.2).

3. Relative Exploitation Rate

Meaningful estimation of absolute exploitation rate probably requires a more extensive and contrasting time-series of data than are available for this fishery. The model provided by Dr Xiao is somewhat difficult to interpret. The strengths and weaknesses of his approach need to be made more transparent in the assessment documentation. We are somewhat concerned that the unconstrained production model uses commercial fishing effort as input data. Fig 39 of the 1999 Assessment Report (particularly for pot-fishers) shows that commercial CPUE is increasing (or constant). Commercial CPUE therefore cannot be a robust indicator of the exploitable unless recruitment to the fishery has been increasing since harvesting began. The production model developed by SARDI does not make such a simplifying assumption but the impacts of these effort data on the outcomes of the modelling are not obvious. As discussed in section TR4.2, this model should be tested on synthetic data to examine the contribution to the management of the fishery that conclusions from this modelling process would have (particularly if something went wrong).

4. Pre-recruit [index]

The capability to predict recruitment into a fishery is a noble objective for the fishery and should be pursued as it has the potential to enhance stock sustainability. Whether this can be achieved via the analysis of length structures (such as the proportion of undersized crabs in catches) requires additional investigation (see section TR4.2). Many errors could compromise this predictive capability, for example: inaccurate reporting of small crabs, and a high discard mortality rate of small crabs. Clearly the skills of those responsible for the sampling of size-structures need to reflect the best available practices. Once again, the BCFMC and SARDI need to negotiate a compromise to this sampling strategy. Fishery-independent sampling could be prohibitively expensive and fishery-dependent sampling could compromise the outcomes: a middle ground should exist.

Figure 45 from the 1999 Assessment Report gives a good example of the importance of getting the sampling right. The increase in undersized crabs between 1997 and 1998 could be interpreted in two ways. If sampling was representative of the exploitable biomass, the increase most probably results from an increase in recruitment. If sampling was not representative, the change could simply be a different harvest strategy (gear, times, areas etc.). Unfortunately, given that standard errors were not drawn on the graph, it is difficult to determine if there has been any change at all!

5. Sex-ratio

The use of the sex-ratio as an indicator of the spawning stock is sound as long as the indicator for the total stock is robust (which, if you are using catch, it is not). An important value of sex-ratio data is to determine if there has been unequal targeting or vulnerability of either sex. Excessive removal of males could cause sperm limitation and erode the reproductive potential of the stock. Other comments on using the sex-ratio to monitor the state of the population are a re-iteration of those regarding the pre-recruit index. At one point the researchers must determine if the changes they hope to detect with this indicator could actually be detected given the defined sampling program.

6. Setting the Total Allowable Commercial Catch

This is probably the most frustrating aspect of the Fishery Assessment Reports (1999 and 2000) and the management process. There is a mechanism being used to determine a TAC from the state of the indicators but it is not articulated. This makes the TAC determination appear ad hoc. Table 1 (of the 2000 Assessment) is very cryptic. Why is the limit reference of TAC 80% of the target TAC? How are the four indicators compared (numerically weighted) ? The relative exploitation rate comes from a production model, which is not straightforward to interpret (what are the costs associated with this?). How much variability is there in any of the estimates? All these important issues are just glossed over! We see two options to resolve the issue:

Option 1 *Exact Specification of TAC Setting Process (which would involve):*

- articulation of the outcome that is being sought by setting the TACC;
- specification of the quantitative uncertainty associated with the estimated indicator values (for example standard errors or posterior probability distributions);
- a description of how information from the four indicators is to be combined, and;
- an indication of the level of risk that is being taken by setting the TACC (probability that a particular outcome won't be achieved with the TACC).

In summary, the assessor should provide the exact algorithm used to set the TACC from the indicators. This would be a difficult task, but not an impossible one. An application of simple decision analysis (Chechile 1991) would enable a calculation of this sort.

Option 2　　　An Independent TAC Committee

An independent TAC Committee could replace Option 1. This Committee would simply perform the above reasoning by discussion and negotiation. Thus, the technical process (Option One) would be replaced by a narrative process (Option Two). The TAC Committee should be independent of SARDI, PIRSA and the BCFMC.

Determination a TACC from estimates of the four indicators is not a straightforward process. We leave it to SARDI, PIRSA and the BCFMC to determine the most appropriate option. NSW Fisheries uses an independent TAC Committee to resolve this issue. PIRSA should compare and contrast the strategies used by other agencies (see Lyle 1998).

South Australia has developed strategies for setting the TACC in quota-managed fisheries. Changing these strategies without due process is likely to be counter productive. Regardless of this, setting a TACC is a difficult and error-prone task. The Newfoundland cod fishery was particularly data-rich but human failure in the interpretation of stock indicators has caused huge socio-economic impacts (Walters and Maguire 1996). Individuals responsible for this task should read widely and not take their decision lightly.

Authors of the assessment reports should present alternative models of the blue crab resource (even if the models are only qualitative), along with the likely consequences on the stock from different levels of TACC. Such a table could focus discussions during the TACC setting process.

7. Costs

Costing of research and management services for fisheries is, and will continue to be, controversial. Nevertheless, the destructive impacts of subsidisation to fisheries are well appreciated in Australia and globally (Mace 1996). In Australia, various mechanisms of cost-recovery are in place in all state and federal agencies to avoid this. Rather than attempt to estimate the cost of an "appropriate" monitoring program we've included a simple qualitative cost-benefit table (Table 1) summarising issues associated with executing the sampling program using fishery-dependent and independent resources.

Table 1. Qualitative cost-benefit analysis for the options of executing the sampling program.

Option	**Cost**	**Benefit**
Fishery-dependent.	As dollar costed by the fishery including compensation for reduced fishing opportunity and decreased flexibility of fishing activity. Potential issues associated with reduced credibility of data from third parties. Dollar and opportunity costs associated with training and auditing.	Involvement of the fishery with the collection of data about the resource. Improved ownership by the fishery of the research and sampling process. Increased spatial and temporal coverage per dollar.
Fishery-independent.	As dollar costed by SARDI. Reduced involvement of the industry with collection of data about the resource. Reduced spatial and temporal coverage per dollar.	Reduced concern from third parties about the credibility of the data.
Mixture (e.g. fishery dependent sampling with SARDI observers - but other options will exist).	Dollar costs intermediate to either of the above options.	Involvement of the fishery with the collection of data about the resource. Reduced concern from third parties about the credibility of the data. Improved ownership by the fishery of the research and sampling process.

It should be possible to explore ways to reduce dollar costs further because the technology onboard these vessels suggests that a relatively cheap telephone-based recording system may be appropriate. There could also be savings on data-entry costs by scanning log-sheets instead of using data-entry clerks.

TR3

ADVISE ON THE MECHANISMS FOR COMMUNICATION OF THE RESULTS OF RESEARCH TO THE COMMERCIAL FISHING SECTOR AND HOW THAT CAN BE IMPROVED, INCLUDING GENERAL COMMUNICATION AND INTERPRETATION OF RESEARCH

Most of these problems could be overcome by opening up dialogue between SARDI scientists and the fishermen. Given the responsibilities of public sector employment, the initial impetus for this should sit with SARDI and/or PIRSA. Independent facilitators should be employed to help negotiate solutions to defined problems if either party requests this. Both parties should note that any attempt to determine a negotiated settlement will fail if neither party is willing to compromise. Given the amount of goodwill and positive attitude of the fishers within this fishery (and their small number), together with the goodwill, experience and expertise of the relevant SARDI scientists, solutions to defined problems should be able to be found.

Regardless of whether data is collected by fishery-independent or fishery-dependent means, there is a requirement that the sampling results are regularly reported in a form that is easily comprehendible by all primary stakeholders - particularly the commercial fishers whose livelihoods could be seriously impacted by information contained within these datasets.

Assuming that streamlined processes are in place for the input and quality control of data, it should be feasible for SARDI personnel to write "reporting scripts" that generate up-to-date reports (include colour graphs and tables) at least every 12 months but possibly every 6 months. These reports should plot the new data collected, tabulate simple descriptive statistics and compare these with previous years. Members of the fishery must be made aware that a TACC cannot be calculated by running a computer program (see section TR2.6 Option 1 for the type of algorithm necessary). Expert judgement, interpretation and synthesis will always be required. Regular reports should also contain a non-technical summary and an indication of the consequences of the new data on the stock. These could be distributed via the world-wide-web to reduce costs and increase transparency.

TR4

ADVISE ON A 5-YEAR RESEARCH PROGRAM TO ENSURE THAT THE CURRENT PERFORMANCE INDICATORS REMAIN RELEVANT TO MANAGEMENT OF THE FISHERY

1. A Strategic Research Plan

Martin Kumar's "National Strategy for Research and Development Programs on the Blue Swimmer Crab, *Portunus pelagicus*" is an important document. A summary should be included in the Final Management Plan with explicit links drawn between management needs and research outcomes. Understanding the research and management of other blue crab fisheries in Australia and similar species overseas is crucial. It will be difficult to defend current research and management as "world's best practice" if the responsible authorities have little idea of what is occurring elsewhere. There is little doubt that publishable studies could be completed on migration, growth, discard mortalities, bycatch reduction, etc. but a process is required for prioritisation. Given that many objectives for management are socio-economic, consideration should be given to the completion of research that will support the achievement of these objectives.

2. Evaluation of the Sampling and Management Plan

A specific research project that could be considered is a test or evaluation of the monitoring/sampling and management system. In simpler language: will the research and management strategy achieve the stock sustainability issues it claims? Such an analysis would be completed by:

- preparing a simulation model of the fishery (the operating model to use the terminology in Hilborn and Walters 1992);
- for each time step:
  - o sample the indicators from the simulation model using the same protocol defined above (including the likely biases arising from the method);
  - o interpret the indicators using the methods described above (section TR1) and set the TACC accordingly;
  - o harvest that TACC in the next time step and then continue;
- evaluating how the fishery performed (with respect to stock status) with this sampling and management arrangement;

- testing the robustness of the indicators, the sampling protocol and the management arrangement to (at least):
    - large increases/decreases in natural or fishing mortality (recreational and commercial);
    - recruitment failure or strong recruitment into the fishery;
    - changes to the assumptions of the dynamics of the fishery.

Researchers should ensure that the industry is involved with this project. For example, give members of the BCFMC an opportunity to examine the results of a simulated failing fishery. What would they do when presented with such information? Understand their response and identify flaws in the communication processes with simulations rather than discover them under a situation of crisis.

From such studies it may be evident that the current sampling strategies are inadequate to sustainably manage the fishery. Additional sampling of size-structures and sex-ratios (particularly of small crabs) may be required. The questions of whether these should be fishery-dependent or independent surveys (or a mixture of both) should be resolved by examining the proposed outcomes, available resources and process concerns (such as industry ownership). This issue has already been addressed in this review.

3. Sampling of Catch Rates

Every stakeholder of fisheries understands the limitations of using commercial catch-per- unit-effort (CPUE) as an indicator of stock abundance. Collection of commercial effort data is a particularly error-prone business. For example, simply by a visual examination of the time series of CPUE data published in the blue crab stock assessment reports, we can tell that commercial CPUE does not give an informative signal from the fishery (see section TR2.3). Nevertheless, the superiority of catch rates (as opposed to catches alone) as an indicator of stock abundance still stands.

A robust indicator of exploitable stock biomass will require a fishery-independent sampling scheme. However, it does not follow that fishermen cannot complete the actual sampling. Extensive involvement of industry will constrain costs but could impact the credibility of these data unless strict quality control procedures are in place. The BCFMC and SARDI need to negotiate a solution to this issue.

4. Research in Recreational Catch

The second area for further research involves the recreational sector. Recreational fishing on blue crabs in South Australia is a large unquantified component of the fishery and future research should aim to quantify it and then bring it into the total-allowable catch (TAC) process by somehow determining a Total Allowable Recreational Catch (TARC). Such a system is a long way off at present and relies on working through many socio-political issues. At present, however, some information is currently being gathered on recreational fishing for blue crabs in South Australia by the National Recreational Survey which is likely to produce a reasonable estimate of this component of the catch. Because of this current project, we believe that there is no immediate need to do any further work on quantifying the recreational catch until the results from that study are available. Eventually a TARC may be estimated and enforced through a suite of input controls on recreational fishers - who, under a cost-recovery scheme would be required to contribute a proportional amount to management, enforcement and research.

5. A Stock Assessment and Population Dynamics Model

Modelling would be a helpful method for structuring thinking and analyses of this fishery. The power analysis suggested (section TR1.1) and the evaluation of management (section TR4.2) will both require a particular representation of the population dynamics. Existing models developed by Dr Xiao should be straightforward to adapt to these tasks.

The analyses that have been recommended above (section TR1.1 and TR4.2) will require a length-structured population model that would generate simulated data. Consideration should be given to trying to fit this model to available data (for forecasts) but we would not be optimistic that this would work given the paucity of data available. The initial emphasis for additional modelling work should be to use data-generating models to test and refine the currently selected indicators.

TR5

CONSULT WITH STAKEHOLDERS WITHIN THE BLUE CRAB FISHERY INCLUDING INDUSTRY (POT AND MARINE SCALEFISH), RECREATIONAL, SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE (SARDI) AND PRIMARY INDUSTRIES AND RESOURCES SOUTH AUSTRALIA (PIRSA) REPRESENTATIVES ON THE RESEARCH PROGRAM

1. Overview

Consultation with stakeholders for the preparation of this review included travel to Adelaide to meet with as many stakeholders in this fishery as possible. This involved meetings with representatives from the various commercial sectors in the fishery, representatives of the recreational sector, SARDI scientists and PIRSA Fisheries Managers. During this trip, one of us (SK) gathered a great deal of information about the fishery, its past and proposed research initiatives, and its research needs. We also collected as much written material about these things as possible. One of us (SK) met with one of the key stakeholders in this fishery and experienced the fishery first-hand via a pot-based fishing trip for blue crabs on Gulf St Vincent.

2. Meetings and discussions held

1. B. Loiterton (Blue crab Fisheries Manager, PIRSA)
2. W. Zacharin (A/Director of Fisheries, PIRSA)
3. H. Williams (SARDI), S. Boxshall (SARDI) and Y. Xiao (SARDI)
4. A. McCLeary (Chair, Blue Crab FMC)
5. N. McDonald (SAFIC and Blue crab FMC)
6. G. Barker, D. Barnes, T., Barnes and B. Evans (Blue Crab FMC member and other Pot Sector Fishers)
7. B. Butson, (Blue Crab FMC, Scalefish Sector Fisher)
8. M. Smallridge (Extension Officer, Blue Crab FMC)
9. T. Watts, (Blue crab FMC, SARFAC)
10. D. Holder (Blue crab FMC, Pot Sector Fisher)
11. A. Cheshire (SARDI)

3. Field trip

On 18th July SK visited Adelaide on a second trip in order to experience a typical fishing trip done by one of the key pot fishers in Gulf St. Vincent. This was an extremely valuable exercise, allowing discussion about a range of management and research issues for this fishery with one of its main stakeholders. Particularly useful was the first-hand examination of the fishing method used, the level of catches taken, the capabilities of the crew for data-recording and the potential for fishery-dependent sampling (the Appendix contains two photographs from the trip).

TR6

ASSESS THE MINIMUM REQUIREMENTS NEEDED TO ADDRESS THE PROPOSED GUIDELINES FOR ECOLOGICAL SUSTAINABILITY OF COMMERCIAL FISHERIES (ENVIRONMENT AUSTRALIA) AND ADVISE ON ANY ADDITIONAL RESEARCH MONITORING REQUIRED

As one of us (JS) discussed with PIRSA, this Term of Reference is a “big ask” and probably should not have been included in the initial contract. There is a simple reason for this: nationwide processes for managing the requirements from Environment Australia (Schedule 4 Amendments of the Commonwealth Wildlife Protection (Regulation of Exports and Imports) Act) are being finalised as this document is being written. The South Australian government will inevitably be preparing responses for all fisheries under its jurisdiction. It would be inefficient to deal with each fishery on a separate basis. Once the “template” has been prepared then comments and actions arising from this review could be used to justify and improve the sustainability of the blue crab fishery.

TR7

COMPLETE THIS REVIEW WITHIN A PERIOD OF 8 WEEKS FROM CONTRACT DATE

The review was submitted in draft form to PIRSA in August 2000. Dr Kennelly left the employment of The University of Sydney soon after that date to take up a senior position at NSW Fisheries. It was not appropriate for him to revise the review in his new position. PIRSA voiced concerns about some aspects of the review in December 2000. Dr Scandol took responsibility for the review and forwarded an amended version to PIRSA in February 2001.

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Appendix: Photographs from the Field Trip

Figure 1 Checking a crab pot.

Figure 2 Sorting the catch.