Fisheries Research 109 (2011) 119–130

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Decline of a blue swimmer crab (*Portunus pelagicus*) fishery in Western Australia—History, contributing factors and future management strategy

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ARTICLE INFO

Article history:
Received 25 May 2010
Received in revised form 25 January 2011
Accepted 25 January 2011

Keywords:
Blue swimmer crabs
Portunidae
Fishery decline
Juvenile recruitment
Breeding stock
Catch prediction
Management
Decision rule framework

ABSTRACT

Commercial blue swimmer crab (*Portunus pelagicus*) catches in Cockburn Sound, Western Australia, have declined significantly since 2000, due to low stock abundance resulting in closure of the fishery in December 2006. The fishery has remained closed for 3 years with predicted catches, based on juvenile recruitment indices, indicating that recovery has been slow. Like many other blue swimmer crab fisheries, management relied on a minimum legal size set well above the size at sexual maturity to allow crabs to spawn at least once before entering the fishery to presumably provide adequate protection to the breeding stock. However, a combination of biological, environmental and fishery-dependent factors contributed to a collapse and include: (1) vulnerability to environmental fluctuations as this species is at the southern extreme of its temperature tolerance, (2) a life cycle contained within an embayment and is self-recruiting, (3) a change in fishing method from gill nets to traps which increased fishing pressure on pre-spawning females in winter and reduced egg production to one age class, (4) four consecutive years of cooler water temperatures resulting in poor recruitment and (5) continued high fishing pressure during years of low recruitment resulting in low breeding stock. The strength of recruitment (juvenile 0+) from the previous season's spawn (September to January), and the residual stock (1+) near the completion of the current fishing season, have been incorporated in an abundance index that indicates the size of the next season's breeding stock and predicts the commercial catch. This catch prediction has been used in the development of a draft decision-rule framework for the future management of this fishery to determine the appropriate amount of fishing effort. The application of this approach to research and management may assist the sustainability of other blue swimmer crab fisheries at the extreme of their natural distributions.

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1. Introduction

The blue swimmer crab, *Portunus pelagicus*, occurs in nearshore, marine embayment and estuarine systems throughout the Indo-West Pacific region (Stephenson, 1962). They live in a wide range of inshore and continental shelf habitats, including sandy, muddy or algal and seagrass habitats, from the intertidal zone to at least 50 m depth (Williams, 1982; Edgar, 1990). In Western Australia (WA) their distribution extends along the entire coast (Fig. 1) with the majority of commercial and recreational fishing concentrated in coastal embayments and estuaries between 34° and 24°S. The Western Australian commercial blue swimmer crab fishery is the largest in Australia, with a total commercial catch of 888 t valued at $4.4 million in 2007/08 (Johnston and Harris, 2009). They are also a highly valued species to recreational fishers, and represent the most important inshore recreationally fished species in the south-west of Western Australia in terms of numbers caught (Sumner and Williamson, 1999; Sumner et al., 2000). Commercial fishing pressure and popularity with recreational fishers is placing considerable pressure on *P. pelagicus* stocks in some areas of the state (Sumner et al., 2000). One such area is Cockburn Sound; a shallow marine embayment approximately 100 km^2 in area, located 20 km southwest of Perth (Fig. 1).

The reproductive cycle of blue swimmer crabs within Cockburn Sound is influenced strongly by water temperature, as these waters are at the southern extreme of this species temperature range (de Lestang et al., 2010). Consequently the spawning period is restricted to spring/summer, whereas in more tropical waters spawning occurs year round (de Lestang et al., 2003b). In Cockburn Sound, mating occurs in late austral summer–autumn (January to April), when both mature females that have finished spawning and recently matured females are soft-shelled (Kangas, 2000). Unlike blue crabs (*Callinectes sapidus*) in North America, the pubertal moult for female *P. pelagicus* is not terminal. These females store the sperm for a number of months over winter, after which

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doi:10.1016/j.fishres.2011.01.027

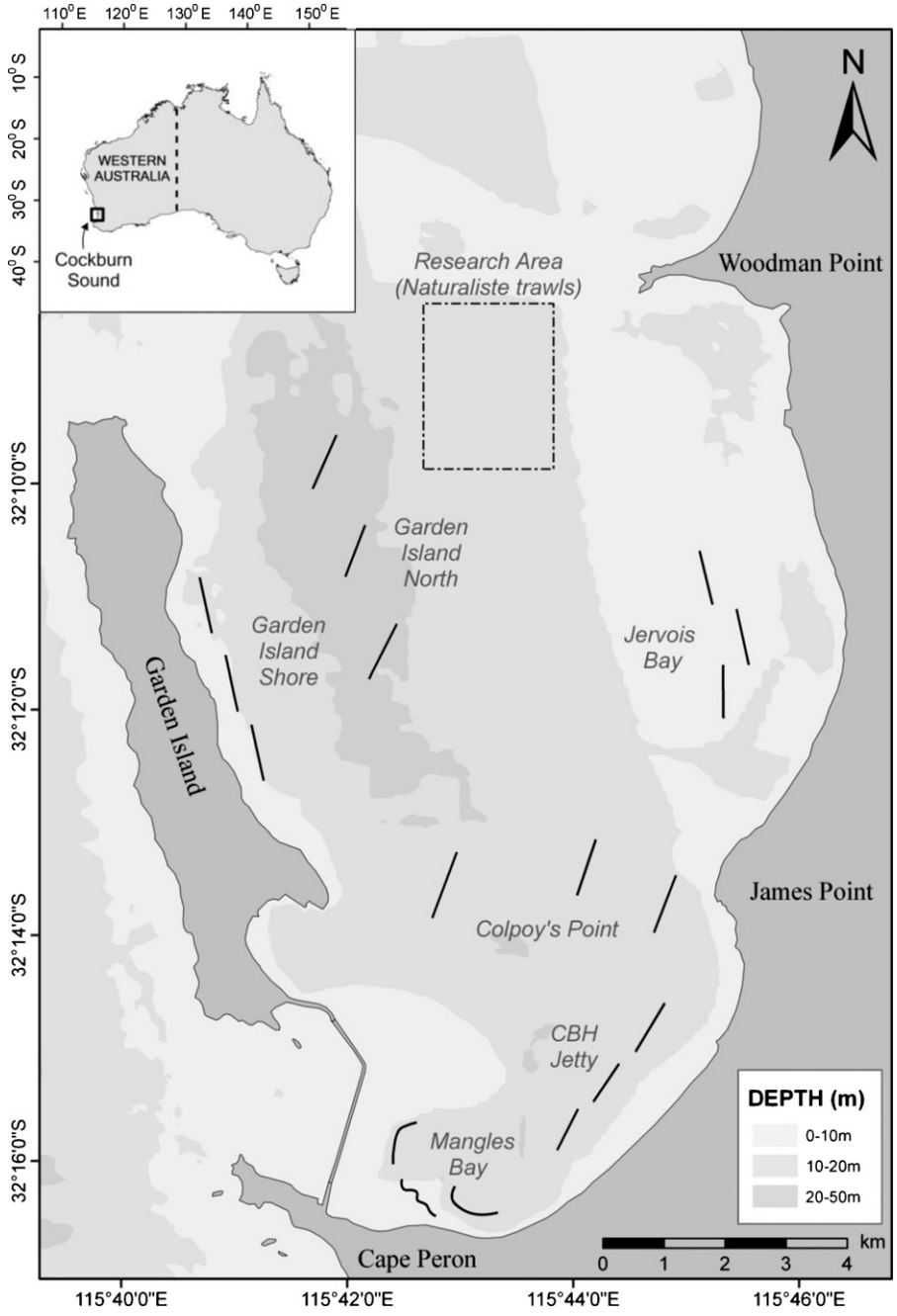

Fig. 1. Map highlighting the location of Cockburn Sound within Western Australia and the sites sampled during juvenile trawl surveys (- - -) and *Naturaliste* trawl surveys within the Research Area conducted by the Department of Fisheries.

eggs are extruded and fertilised, with females becoming ovigerous and spawning between October and January (Penn, 1977; Smith, 1982). Incubation takes 10–18 days, depending upon water temperature and the larval phase extends for up to six weeks, with larvae drifting as far as 60 km out to sea, before settling inshore (Kangas, 2000). Rapid growth occurs over summer during the juvenile phase, with juveniles able to be caught by trap/trawl between March and June after which they move into the deeper waters of the basin in Cockburn Sound. In Cockburn Sound, maturation generally occurs in less than 12 months between 86 and 96 mm carapace width (CW) (de Lestang et al., 2003a). They attain minimum legal size (130 mm CW commercial and 127 mm CW recreational) in late summer the following year (March–May) when they are approximately 14–18 months of age. Most animals in exploited crab stocks have died either through natural or fishing mortality by the time they are 20 months old (Potter et al., 2001), but without fishing pressure, blue swimmer crabs can live for three to four years.

Genetic studies have indicated that the population of blue swimmer crabs in Cockburn Sound is generally independent from other stocks in the State (Chaplin et al., 2001). Recent research has shown that crab populations in Cockburn Sound, and adjacent locations, are genetically similar, although it is believed that limited mixing of stocks occurs between these adjacent water bodies (Chaplin and Sezmis, 2008). This implies that it is unlikely there would be pronounced recruitment of blue swimmer crabs from outside of Cockburn Sound into this embayment. Hence, adverse changes in environmental conditions or high levels of fishing pressure in the

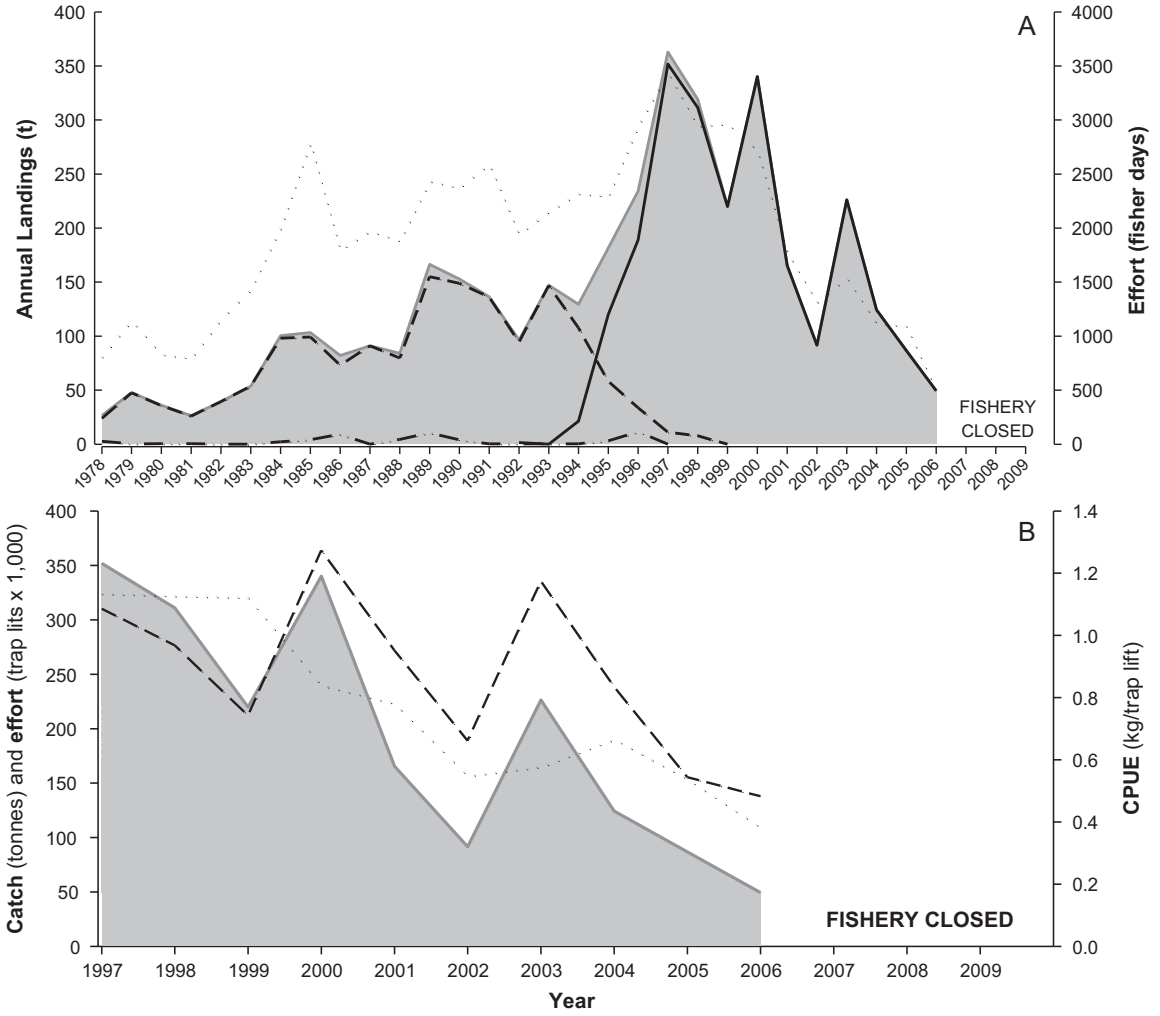

Fig. 2. (A) Annual commercial blue swimmer crab catch (t) from the Cockburn Sound Crab Managed Fishery by fishing method and overall effort (fisher days) irrespective of method. Total catch (■); gill nets (- - -); crab traps (-); other (–···–) and effort (···). (B) Annual commercial blue swimmer crab catch (t) (■) from the Cockburn Sound Crab Managed Fishery using traps indicating effort (trap lifts) (···) and catch per unit effort (kg/traplift) (- - -). Annual catch for both A and B is presented as commercial fishing season i.e. 2006 covers the period from December 2005 to November 2006.

embayment could have highly detrimental and long-term effects on crab stocks in Cockburn Sound (Chaplin et al., 2001).

Commercial crab fishing in Cockburn Sound started in the 1970s and traditionally used gill nets. Few restrictions were placed on commercial fishing activities other than a prohibition on taking berried females and a minimum size limit (130 mm CW commercial and 127 mm CW recreational). In 1994/95 the fishery was converted from gill nets to purpose-designed traps to reduce the impact on non-target species (Fig. 2). The fishery was then managed through input controls which regulated fishing methods and gear specifications, seasonal and daily time restrictions, retainable species, minimum size limits and the number of licences. A spawning closure in October and November was introduced in 1999. However, the principal management tool to ensure adequate breeding stock involved minimum size limits set well above size at sexual maturity (de Lestang et al., 2003a). This allowed crabs to spawn at least once prior to entering the fishery and under average recruitment was thought to provide adequate protection to breeding females. Commercial fishers operated from 1 December to 30 September, with a closed spawning season between 1 October and 30 November to protect the berried females that are present in the Sound in large numbers at that time of year. Currently, there are 12 license holders sharing a total allocation of 800 crab traps.

Commercial catches in Cockburn Sound have fluctuated dramatically, and were attributed to changes in commercial fishing practices and normal variations in recruitment strength (Bellchambers et al., 2006). A juvenile index was developed to measure this variability and to predict the following season's catch (Bellchambers et al., 2006). However, despite these efforts, commercial catches declined significantly since 2000 and the fishery was closed to commercial and recreational fishers in December 2006. Prior to its decline, Cockburn Sound represented the second largest commercial blue swimmer crab fishery in Western Australia, with catches peaking at 362 t in 1997/98. The recreational sector of the fishery has been managed through bag limits, with catches between 18 and 23 t, representing between 5% and 15% of total catch (Sumner and Williamson, 1999; Sumner and Malseed, 2004; Bellchambers et al., 2005). Like commercial catch, recreational catch estimates in 2005/06 indicated they had also declined significantly to approximately 3 t (Sumner, unpubl. data, Department of Fisheries, Western Australia).

The objectives of this paper were to: (1) document the catch history of the blue swimmer crab fishery in Cockburn Sound, (2) outline the key factors that contributed to its collapse, (3) refine the juvenile (0+) index developed by Bellchambers et al. (2006) to include a greater number of recruitment areas and a residual stock (1+) component for predicting future catches during closure and

recovery, and (4) propose a decision rule framework to guide the future management of this fishery to ensure sustainability.

2. Methods

2.1. Study site

Cockburn Sound (32.10°S, 115.43°E) is the largest protected marine embayment on the lower west coast of Western Australia, measuring 15 km long and up to 10 km wide with an area *ca* 100 km^{-2} (Fig. 1).

2.2. Commercial catch and effort

Commercial fishers submit statutory monthly returns that report catch of all retained species and an estimate of fishing effort (days fished per month and mean number of traps used per day in that month). Annual commercial catch (t) and effort (fisher days – total number of days fished per year) in Cockburn Sound is presented by fishing season; 1st December to the following 30th September inclusive, and is referred to as the next calendar year (e.g. the 2001 fishing season covers December 1st 2000 to September 30th 2001 inclusive). The catch is reported by weight (tonnes) and effort is presented in numbers of fisher days to allow comparison between the two historical fishing methods of netting and trapping.

2.3. Commercial monitoring

Monitoring of commercial blue swimmer crab catch and effort has been conducted by research staff since 1999. Commercial fishers were accompanied during daily crabbing operations throughout the fishing season and the day's catch and effort recorded. Each fisher serviced 100–200 hourglass traps (set in lines of 10–20 traps) daily, with all crabbers operating in the fishery surveyed during the season. Monitoring was undertaken on three randomised days during each month of the fishing season from 1999 to 2004, after which two days per month were monitored. Carapace width (the distance between the tips of the two lateral spines of the carapace measured to the nearest millimetre), sex, female berried status (the presence/absence of externally visible eggs protruding from beneath the abdominal flap), the number of traps in the line, soak time (number of hours the traps have been in the water since they were last serviced) and a latitude, longitude and depth were recorded.

Following the closure of the fishery in December 2006, a commercial crab fisher was contracted to replicate commercial fishing in Cockburn Sound. Accompanied by research staff, the fisher set 100 traps in lines of 10, twice a month within the traditional fishing grounds. Standard commercial hourglass traps were used and soak time for all traps was 24 h.

2.4. Fishery-independent sampling – breeding stock

Trawling for blue swimmer crabs in Cockburn Sound was conducted aboard the research trawler *RV Naturaliste* (22.7 m in length) between 2001 and 2008. The research trawler employed a twin-rig otter trawl, towing nets with a combined headrope length of 12 fathoms (22 m). Each net had 50 mm mesh in the wings and 45 mm mesh in the cod-ends. The nets were demersal with a 10 mm ground chain that was positioned two links in front of the ground rope. A net efficiency factor (0.6 × net headrope length in metres) was incorporated to adjust for the effective spread of the net on the seabed (de Lestang et al., 2003c), giving the effective opening of each net to be 7.3 m wide by 1 m high. Fishing was conducted at night, with trawling restricted to the Research Area (Fig. 1). All trawls were 20 min in duration with trawling commencing approximately 30 min after sunset. Carapace width, sex, and female berried status was recorded.

2.5. Fishery-independent sampling – juveniles

Monthly research trawling to collect data on juvenile crab abundance has been conducted since 2002. Three replicate 750 m trawls were undertaken at up to six different sites during the recruitment period (March to August) each year (Fig. 1). Garden Island North, Colpoys Point and CBH Jetty sites were selected on the basis of a historical juvenile trawl program initiated by Bellchambers et al. (2006). The additional sites were selected according to their suitability as juvenile nursery areas within Cockburn Sound in order to refine the original juvenile index developed by Bellchambers et al. (2006). Of the variation in juvenile catch rates explained by the new model, 40% of that was accounted for by location. Sampling was conducted aboard a 7.5 m research vessel, trawling at a speed of 2.8 kts. The trawl net had a headrope of 5 m, with 51 mm mesh in the panels and 25 mm mesh in the codend. A net efficiency factor (0.6 × net headrope length in metres) was incorporated to adjust for the effective spread of the net on the seabed (de Lestang et al., 2003c), giving the net an effective opening of 3 m wide by 0.5 m high. Trawling commenced each sample night 30 min after sunset, with a warp length to depth ratio of 5:1 observed. The carapace width, sex, and female berried status were recorded. Crabs were allocated to juveniles (0+) and residuals (1+) according to size (using a monthly carapace width that separated the two year-classes obtained from a seasonal von Bertalanffy growth curve) (Bellchambers et al., 2006).

Juvenile blue swimmer crab trawl data collected between 1998 and 2000 (de Lestang et al., 2003a,b) are also presented. Methodology for this monthly trawling replicated that described above, other than that sampling was conducted during daylight hours. A period where day-time and night-time sampling overlapped was used to calculate a conversion factor of 6 from daytime trawl catch rates to night time trawl catch rates to standardise between the two datasets. This conversion factor was applied to the data prior to calculating the juvenile index.

2.6. Catch prediction model

Catch rates (animals caught per 100 m^2 trawled) of juveniles (0+) and residuals (1+) were log transformed i.e. log (catch rate + 0.1) before undertaking an ANOVA to take into account the skewed distribution of abundance data. The standardised annual index of abundance of these catch rates was then taken to be the least-squares mean (LSM) (SAS Institute Inc., 1989) of the factor, year, in an ANOVA model that included the main effects of year (1998–2009), month (April–June) and location (Mangles Bay, Colpoy's Point, CBH Jetty, Garden Island North and Jervois Bay) as well as the two-way interactions of month with year and location. The ANOVA model for residuals used the main effects of year (1998–2009) and month (August–September or the last two collected months if August–September are not available). The resulting LSMs where back-transformed to an annual standardised index of abundance of juveniles and residuals that takes into account the month and location of fishing.

LSMs have been used due to the unbalanced nature of the data (an unequal number of trawls for each site in month and year). Having derived standardised indices for juveniles (0+) ($x_{0,t}$) and residual (1+) ($x_{1,t}$) in year t, the commercial catch (y_t) for season t was modelled as $\log(y_t) = a + b\log(x_{0,t-1} + dx_{1,t-1}) + \varepsilon_t$ where a, b and d (d is a parameter that adjusts for each of the age classes having a different contribution to overall catch and for $x_{1,s}$ having been estimated using data collected by a different method – potting – than that used for estimating $x_{0,s}$ – trawling) are parameters to be estimated, and

$\varepsilon_t \sim N(0, \sigma^2)$ is the error for season t. This relationship can be used to provide a catch forecast for the upcoming fishing season and an estimate of the catch for seasons that were not fished (2007–2009) assuming that fishing effort remained at similar levels throughout the period being assessed.

2.7. Decision rule framework

A decision-rule framework using juvenile and residual index data to determine the appropriate level of fishing for the coming season has been developed to assist with the future management of the Cockburn Sound crab fishery. A linear relationship comparing the historical percentage of commercial crab catches taken per month prior to the closure (recalculated on a 15 December to 30 June season length) and the juvenile and residual index derived for the Cockburn Sound crab fishery catch prediction model to set an appropriate length for the commercial season.

The juvenile (0+) and residual (1+) index generated for the catch prediction model forms the *x*-axis of the decision-rule framework. The *y*-axis provides a measure of the mean proportion of annual commercial trap catch that is taken at any given month during the season and is based on historical commercial catch and effort data prior to the closure. This approach determines the minimum level of recruitment before fishing is allowed and the maximum level where the fishery is opened for the whole season (15 December–30 June).

3. Results

3.1. Commercial catch history

Commercial fishing for blue swimmer crabs in Cockburn Sound began in the 1970s, with fishers setting gill nets primarily through the summer months. Over the next 20 years, annual catch and effort increased steadily from 30 t (687 fishing days) in 1978 to 147 t (2109 fishing days) in 1993 (Fig. 2A). In the mid 1990s commercial fishers trialled purpose-designed hourglass traps and annual catch rose dramatically from 129 t in 1994 to 362 t in 1997. From 1996 to 2000, the fishery recorded the five highest annual commercial catches between 220 and 362 t (Fig. 2A).

The move from gill nets to hourglass traps resulted in an increase in catch and effort across the commercial season (December to September), with the most significant escalation in the autumn/winter months from April through to the close of the season (Fig. 3). Between 1979 and 1994, gill net fishers landed an average 26 t over April–September from a combined 625 fishing days (42 kg/day). Following the conversion from nets to hourglass traps, the mean catch from April to September (1996–2006) increased almost four-fold with trap fishers landing an average 93 t from 969 fishing days (96 kg/day) (Fig. 3). Hence, the dramatic increase in catch was not solely due to an increase in effort, but also due to the greater efficiency of the purpose-designed hourglass traps.

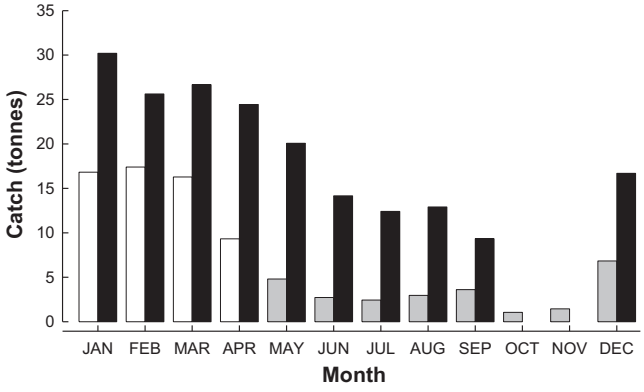

Fig. 3. Mean monthly commercial blue swimmer crab catch (t) using gill nets (■) between 1977–1994 and hourglass traps (▩) in Cockburn Sound between 1996–2006.

Following the second highest annual catch on record of 340 t in 2000, the catch and catch per unit effort (kg/trap lift) has been in decline (with the exception of the good catch recorded in 2003) with 50 t and 0.5 kg/traplift recorded in 2006, which represented the lowest annual catch and CPUE since 1982 and resulted in the closure of the fishery to both commercial and recreational fishing (Fig. 2A, B).

Most of the annual commercial catch in the Cockburn Sound fishery is taken during the summer months. After beginning in December, 30% of the catch is landed by the end of January, and over half by the end of March. The winter months from June to September contributed less than 25% of the catch.

3.2. Trawl surveys

The decline of the commercial blue swimmer crab catch was also reflected in the numbers of crabs collected during research trawl surveys. *Naturaliste* trawl surveys in 2002 showed a mean catch rate of 17.9 ± 1.7 crabs·1000 m^{-2}, which declined to 13.4 ± 1.7 crabs·1000 m^{-2} in 2003. The mean trawl catch rate fell to 2.3 ± 0.3 crabs·1000 m^{-2} in 2004 with the lowest catch rate of 1.2 ± 0.2 crabs·1000 m^{-2} recorded in 2006, with the fishery closed in December of that year. Since the closure numbers of crabs captured during research trawl surveys has increased gradually to 5.5 ± 1.5 crabs·1000 m^{-2} in 2008.

Trends in length frequency analyses were consistent between years, within months and between vessels and was not greatly influenced by the location of commercial fishing vessels being monitored within Cockburn Sound. Monthly catch monitoring aboard commercial crab vessels showed that at the beginning of the season in December, the catch was composed predominantly of female blue swimmer crabs (Fig. 4). Within two weeks the catch was divided evenly between male and female crabs, and by January was almost exclusively male (Fig. 4). Up to 90% of the female crabs captured during December were ovigerous. Male crabs then dominated the commercial catch through the summer months, with mean proportions declining from 79% in January to 69% in March. Over a four-week period in March or April, the catch switched from predominantly male to mainly non-ovigerous female crabs. This high proportion of females in the commercial catch continued through the rest of the season, with mean proportions from April to September increasing from 63% to 81% (Fig. 4). Ovigerous females first appear in September or October, with spawning triggered by the rise in spring water temperatures.

Regardless of fluctuations in crab abundance, this pattern of variation in sex ratio of the commercial catch was consistent between years. However, during the closure period of the fishery since December 2006, the ratio of male and female crabs caught in traps at different times of the year has changed. Catches during the summer months are still dominated by male crabs, with 69–81% of the catch being male between January and March (Fig. 5). However, while female crabs enter traps in March/April, males continue to make up the majority of the catch until June and are caught in significant quantities through to December when they become dominant in catches again. Prior to the closure, 33% of crabs caught by the commercial fishery in the month of April were male. Following the closure, the mean proportion of males from April to June rose to between 62% and 66% (Fig. 5).

Since the closure of the fishery, the size of blue swimmer crabs captured in traps has increased significantly. When the fishery was

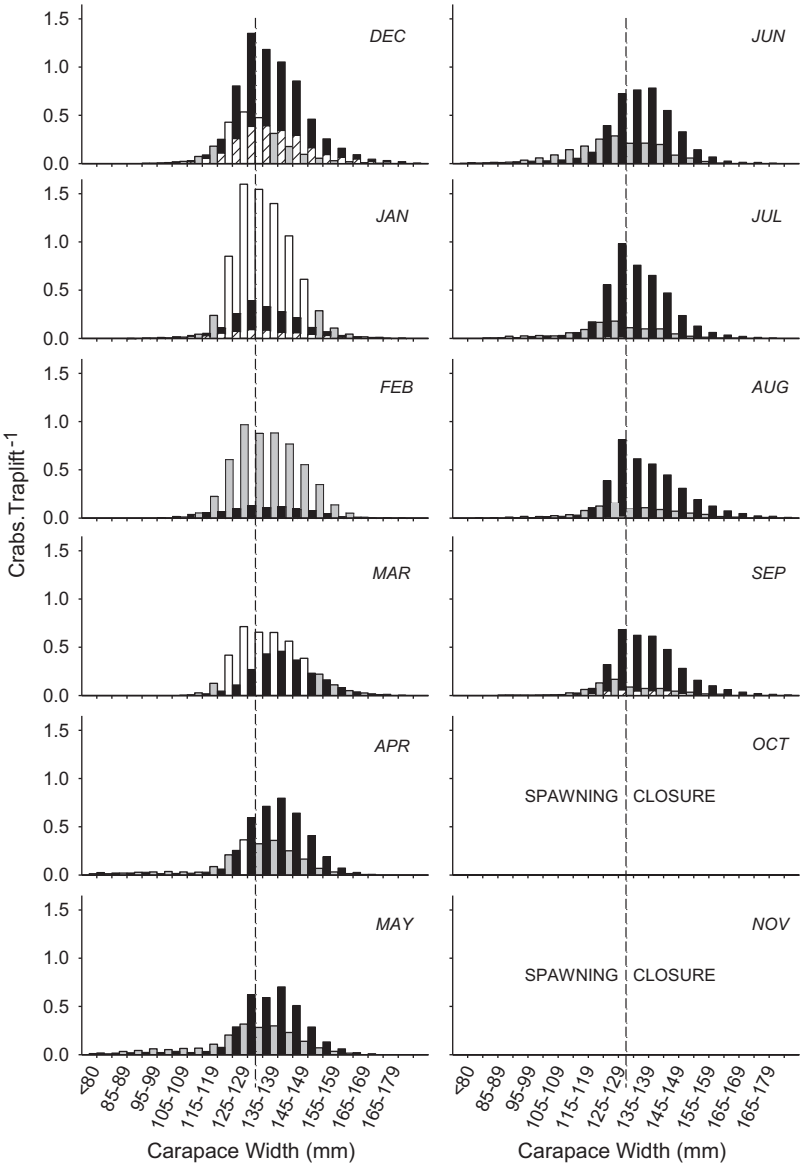

Fig. 4. Pooled length frequency distributions of male (▒), female (■), and ovigerous female (▨) blue swimmer crabs by month from catch monitoring surveys aboard commercial vessels in Cockburn Sound between January 1999 to September 2006. Minimum commercial size limit (- - -).

open, the mean size of males and females in the commercial catch during December was 131 mmCW and 134 mmCW, respectively (Fig. 4). As the season progressed, mean size increased slightly through to March (136 mmCW for males; 138 mmCW for females) before decreasing by July to 129 mmCW for males and 133 mmCW for females (Fig. 5). Since the closure, crabs captured in December had a mean carapace width of 137 mmCW and 138 mmCW for males and females, respectively, increasing to 148 mmCW for males and 152 mmCW for females by March. But rather than decrease, the mean size of crabs remained relatively constant through to November (Fig. 5).

3.3. Catch prediction model

Between 1999 and 2002, the juvenile index fell from 4.4 to 1.5 (Fig. 6A). The index continued to fall to its lowest level in 2006 at just 0.1 (Fig. 6A). Since the closure of the fishery in December 2006, a modest improvement in the strength of recruitment has been evident increasing to 0.59 in 2008 (Fig. 6A).

The main pulse of crab recruitment to the Cockburn Sound fishery during the period 2002–2005 occurred in autumn from March to May (Fig. 7). Between 2002 and 2005, the mean total number of crabs caught was 6 and 15 at the CBH Jetty and Colpoy's Point sites, respectively, during January and February, with numbers peaking at 130 juvenile crabs in April. Mean total numbers of juveniles captured in trawls at these sites declined by August (Fig. 7). The year the fishery closed (2006), recruitment was low in all months (Fig. 7). Post closure, the numbers of juveniles have increased but the traditional higher abundance pulse between March and May has not been evident, with numbers spread more evenly between March and August (Fig. 7).

A catch prediction model incorporating both the strength of recruitment and the residual stock remaining towards the end of the commercial season has been calculated (Fig. 8). The model was used to predict potential commercial catch during the closure as a tool to assess the recovery of the fishery ($R^2 = 0.83$). After a commercial catch of 50 t in the Cockburn Sound crab fishery for 2006, the 2006 juvenile and residual index of 0.74 provided for a predicted commercial catch of just 77 t for the 2007 fishing season. Indicative

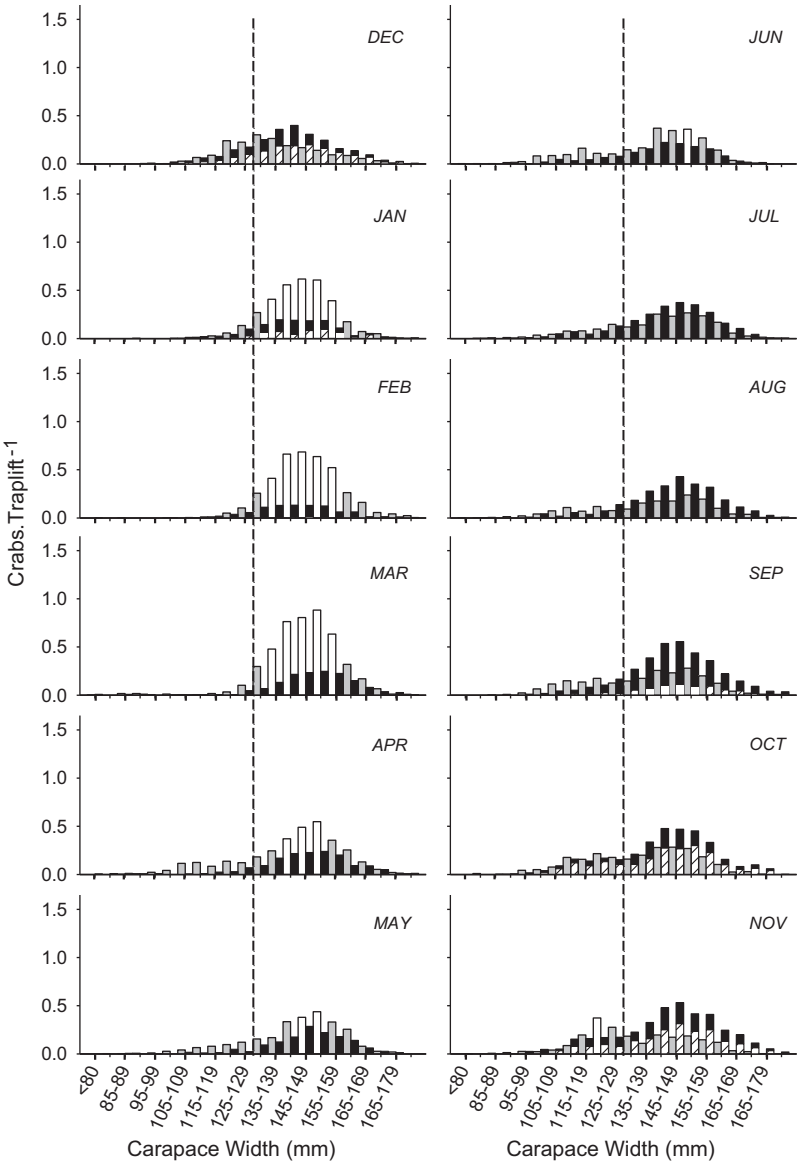

Fig. 5. Pooled length frequency distributions of male (▒), female (■), and ovigerous female (▨) blue swimmer crabs by month from catch monitoring surveys aboard a commercial vessel in Cockburn Sound between December 2006 and November 2008. Minimum commercial size limit (- - -).

of the gradual recovery of the Cockburn Sound crab stock, the 2007 index of 1.12 predicted a potential commercial catch of 113 t for the 2008 season, and the 2008 index of 1.59 predicted a commercial catch of 156 t for the 2009 season (Fig. 8).

3.4. Spawning stock

The decline and continuing recovery of the blue swimmer crab breeding stock in Cockburn Sound has mirrored the temporal fluctuation described in annual commercial catch and juvenile recruitment. The strength of the breeding stock has been quantified using data from commercial catch monitoring surveys conducted in the Cockburn Sound fishery during December (Fig. 6B). The mean abundance of mature female crabs captured in commercial crab traps during December remained between 6 and 10 crabs traplift^{-1} from 1999 to 2003. The level of breeding stock fell in 2004 and remained between 2 and 3 crabs traplift^{-1} through 2007. Only after two years of closure have female numbers improved to 5 crabs traplift^{-1} in 2008, although these levels are still low compared to earlier years (Fig. 6B).

Despite the limited data set (2004–2008), a recovering trend was also apparent in the mean abundance of mature female blue swimmer crabs captured during December trawl surveys aboard *RV Naturaliste* in the Research Area of Cockburn Sound. A mean abundance of 8 crabs·1000 m^{-2} trawled was recorded in 2004, dropping to just 1.5 crabs·1000 m^{-2} in 2005 (Fig. 6C). Numbers of captured female crabs has recovered slightly between 2006 and 2008 to 2.0 crabs·1000 m^{-2} trawled (Fig. 6C).

3.5. Management – decision rule framework

A draft decision-rule framework to assist with the future management of the Cockburn Sound crab fishery has been developed using juvenile and residual index data calculated from fishery independent juvenile trawl surveys and fishery dependant commercial monitoring programs (August and September) to determine the appropriate level of fishing for the coming season (Fig. 9). A linear relationship uses pre-closure commercial crab catch history against the annual juvenile and residual index derived for the Cockburn Sound crab fishery catch prediction model to set an appropriate

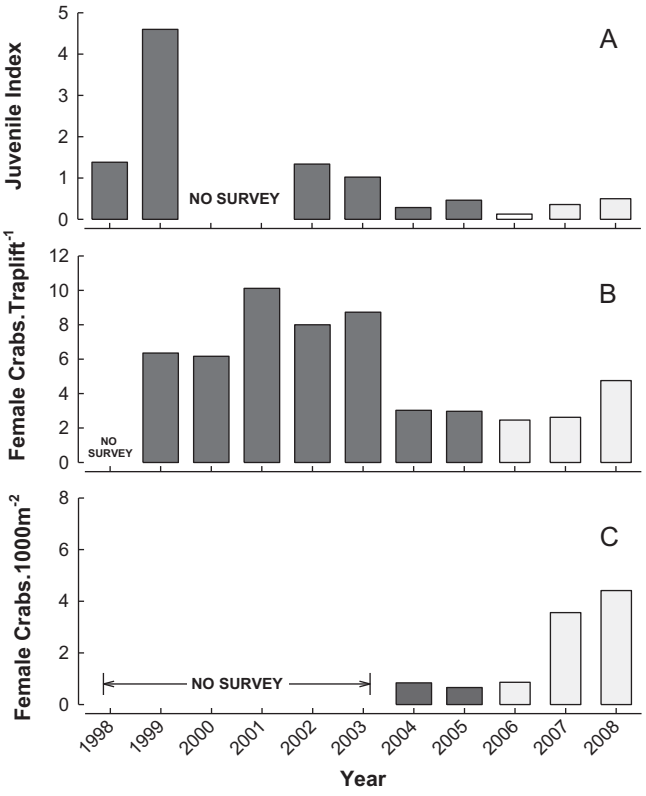

Fig. 6. (A) Annual standardised index of juvenile recruitment for blue swimmer crabs in Cockburn Sound based on research trawl data collected between April–August at all known juvenile recruitment sites. No juvenile sampling was conducted in 2000 and 2001. (B) Annual mean abundance of residual (1+) female blue swimmer crabs captured during December from catch monitoring surveys aboard commercial crab vessels operating in Cockburn Sound between 1999 and 2008. Dark grey bars indicate years when the fishery was open; light grey bars indicate years when the fishery was closed. (C) Annual mean abundance of residual (1+) female blue swimmer crabs captured during December from trawl surveys aboard the Department of Fisheries *RV Naturaliste* in Cockburn Sound between 2004 and 2008.

length for the commercial season (Fig. 9). For years when the juvenile and residual index is relatively low ($\leq$1.5), the length of season can be manipulated to ensure an adequate proportion of the crab biomass will remain unfished to provide a further buffer for spawning stocks (additional egg production). If the annual juvenile and residual index is below a prescribed level (0.8), the fishery will be closed as the predicted catch will be $\leq$100 t (Fig. 8). As the index

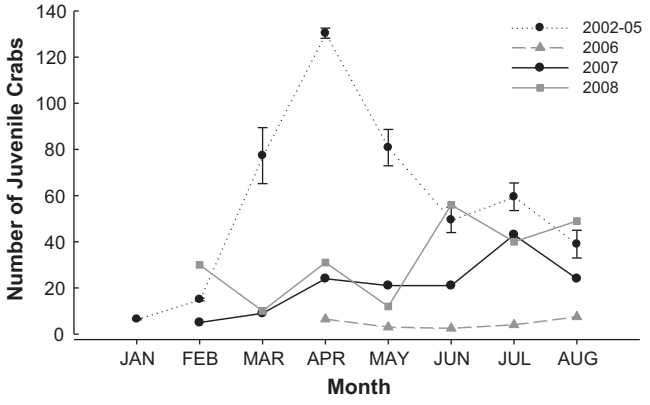

Fig. 7. Total number of juvenile (0+) blue swimmer crabs captured during monthly trawls at 3 replicate sites at the CBH Jetty and 3 replicate sites Colpoy's Point in Cockburn Sound. Data between 2002 and 2005 was averaged per month.

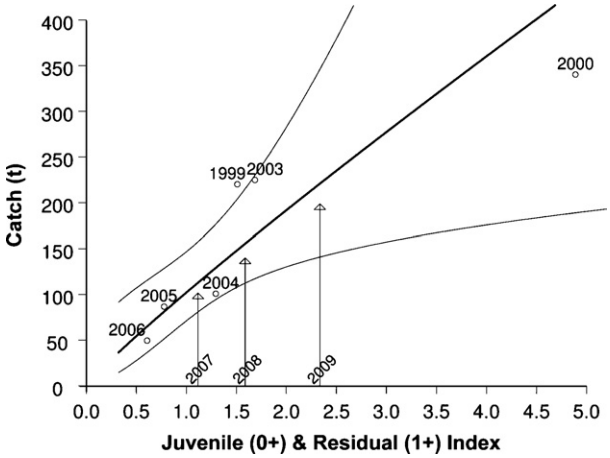

Fig. 8. The relationship between commercial crab landings and the 0+ (juvenile) and 1+ (residual) index based on data collected from juvenile trawls at all sites sampled in Cockburn Sound between April and August for 0+ (juvenile) and May to August for 1+ (residuals). The commercial catch for each year (◯ and labelled with the year of catch) is plotted against the juvenile and residual index from the previous sampling year (e.g. point labelled 2006 represents the commercial catch for the 2006 fishing season (December 05–September 06) plotted against the juvenile and residual index of the previous year of 0.6). The arrows indicate predicted commercial catch for that year if the fishery had opened, based on the previous years juvenile and residual index (2007 predicted catch of 77t based on index of 0.71 from 2006). No data are presented for 1998, 2001 and 2002 as juvenile recruitment surveys were not undertaken in 1997, 2000 or 2001, hence the juvenile index could not be calculated for these years.

rises above 0.8, the fishery will open for increased lengths of time. A juvenile/residual index of 1.4, for example, would allow the fishery to open from December 15 to the end of January, while indexes of 2.1 and 2.4 would allow the season to remain open until mid March and the end of April, respectively. Once the juvenile and residual index for a particular year is above 2.8, the fishery will open for a full season to the end of June (Fig. 9). Finishing the season in June will provide protection to pre-spawning female crabs as fishing through the winter months will no longer occur.

Under this framework, the fishery remained closed during the 2007 season as the juvenile and residual index for 2006 was just 0.13. The 2007 index of 0.37 and 2008 index of 0.59 were again both below the index threshold of 0.8, so the fishery remained closed during the 2008 and 2009 fishing seasons (Fig. 9).

4. Discussion

The historically large fluctuations in commercial blue swimmer catches in Cockburn Sound have previously been attributed to changes in commercial fishing practices, normal variations in recruitment and natural mortality (Bellchambers et al., 2006). However, since 2002/03 commercial and recreational catches have declined significantly, resulting in closure of the fishery in December 2006. The fishery has remained closed with predicted catches, based on juvenile recruitment indices, below historic levels. This paper demonstrates that using a minimum legal size for both the commercial and recreational crab fishery set well above size at sexual maturity and limited entry was not adequate for managing this fishery sustainably. The resultant collapse of the blue swimmer crab fishery in Cockburn Sound can be attributed to a combination of factors related to the biology and distribution of this species, fishery dependent influences and environmental conditions.

P. pelagicus is a tropical species, with a wide distribution in Western Australia ranging between latitudes 34–20° South. The temperate waters of Cockburn Sound (~32°S) are towards the southern extreme of its distribution and consequently *P. pelagicus* is highly vulnerable to environmental fluctuations in this, and

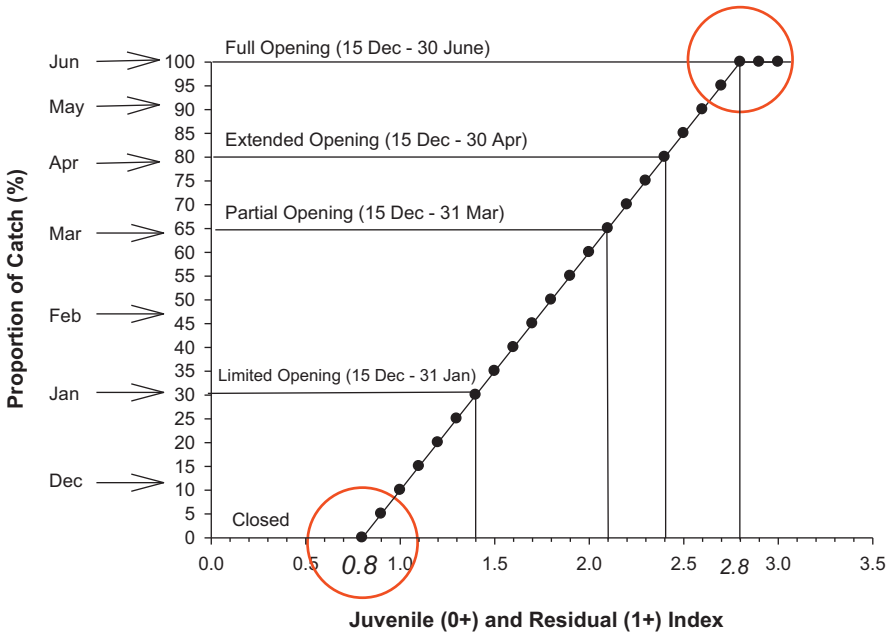

Fig. 9. A draft decision-rule framework for the Cockburn Sound Crab Managed Fishery, which will assist in the management of the annual commercial catch. The framework adjusts the length of the commercial season according to a juvenile and residual index derived from monthly trawl surveys.

other southern fisheries, of Western Australia. More specifically the spawning period of blue swimmer crabs in these southern waters is limited to spring/summer whereas in more tropical waters of Western Australia such as Shark Bay spawning occurs year round, hence increasing spawning and recruitment potential (de Lestang et al., 2003b). A strong correlation has been found between water temperature and recruitment success, with poor recruitment resulting from years where lower than average water temperature were reported in the months of August and September prior to spawning (de Lestang et al., 2010). This scenario occurred in 4 consecutive years between 2002 and 2005 where temperatures ranged between 15.72 °C and 16.25 °C and below the average of 16.5 °C for Cockburn Sound. This extended cooler pre-spawning period was an unusual occurrence and an important contributing factor in the decline of the Cockburn Sound crab fishery. Conversely, when August and September water temperatures were above average such as in1998 (17.3 °C) and 2001 (17.0 °C), good recruitment occurred the following year. Furthermore, while water temperatures encountered by developing larvae in Cockburn Sound influence larval survival and subsequent recruitment success, the timing of spawning has also been found to significantly influence recruitment success, with early spawning (August/September) years having increased recruitment success (de Lestang et al., 2010).

Such variations in temperature and recruitment success have often been linked with subsequent large variations in catches in many commercial decapod fisheries (Perry et al., 1995; Zheng and Kruse, 1999). A similar trend is evident in other blue swimmer crab populations on the edge of their species distribution such as the South Australian blue swimmer crab fishery where it has been predicted that post-larval settlement would be greatest during years with abnormally warm summers (Bryars and Havenhand, 2006). It also partially explained the large historical variations in blue swimmer crab catches in the Cockburn Sound fishery. High levels of fishing pressure, coupled with four years of reduced recruitment due to lower than average water temperatures in pre-spawning months, resulted in a significant reduction in the levels of egg production in this fishery (de Lestang et al., 2010). This reduction occurred after 2003/04 and catch levels remained low until closure of the fishery in 2006. So the combination of vulnerability to temperature fluctuations on account of its temperate environment, coupled with high fishing pressure over 4 consecutive cooler years resulted in recruitment overfishing of this species.

The Chesapeake Bay blue crab fishery, once the most productive estuarine system in America, has experienced a similar decline where sustained fishing mortality and habitat degradation has led to ~70% decline in blue crab (*C. sapidus*) abundance, 84% decline in its spawning stock and historically low levels of juvenile recruitment (Zohar et al., 2008; Hines et al., 2008). Most alarmingly there has been a con-current decline in the blue crab spawning stock and in turn, decreased larval abundance and recruitment (Lipcius and Stockhausen, 2002). This reduction and close relationship between spawning stock and recruitment is evident in Cockburn Sound (de Lestang et al., 2010), although the reported reduction in the size of males (Abbe, 2002) and size of females and mean size at maturity (Lipcius and Stockhausen, 2002) needs to be explored in this fishery. The key consequence of this diminished spawning stock and recruitment has been a heightened probability of recruitment failure and reduced resilience to demographic and environmental stochasticity (Lipcius and Stockhausen, 2002). This situation occurred in Cockburn Sound where the spawning stock levels were fished down to a level where adverse environmental conditions (consecutive years of cooler than average water temperatures) resulted in recruitment failure. It is believed this factor has been a key reason why spawning stock in Chesapeake Bay has not recovered despite increasingly restrictive management and reductions in fishing pressure (Aguilar et al., 2008). Concerns remain about the resilience of the blue crab stock, as well as blue swimmer crab stock in Cockburn Sound, to natural perturbations and further high levels of harvest as both are tropical species and at the latitudinal limit of the geographic range. In particular, blue crabs, suffer over-wintering mortality, the risk of which is highest for mature post-copulatory females which therefore require increased protection from fishing at this time (Aguilar et al., 2008).

Chesapeake Bay blue crabs undertake long distance migrations over multiple habitats with larval migration from the Atlantic Ocean into upper reaches of the bay and rivers and migration of juveniles and subadults out of the tributaries to spawn in the lower deeper areas of the bay (Hines et al., 2008; Aguilar et al., 2008).

By contrast, blue swimmer crabs in Cockburn Sound are a self-recruiting population with little immigration into, or emigration out of, the fishery from neighbouring water bodies. Genetic studies have confirmed that the population of blue swimmer crabs is generally independent from other stocks in the state (Chaplin et al., 2001) and although neighbouring crab populations in Swan River and Warnbro Sound are genetically similar to those in Cockburn Sound, little mixing occurs (Chaplin and Sezmis, 2008). Chaplin et al. (2001) warned that adverse changes in environmental conditions or high levels of fishing pressure could have highly detrimental long-term effects on the population.

Conversion from gill nets to traps in 1994/95 clearly increased the commercial catch of blue swimmer crabs in Cockburn Sound, which peaked at 362 t in 1996/97. This dramatic increase was due to an over-estimate of the net to trap conversion factor (100 traps:1200 m set net) and resultant over-allocation of traps within the fishery. Recalculation of the conversion factor to 67 traps:1200 m set net and a significant reduction in traps (Melville-Smith et al., 1999), resulted in what was believed to be a return to historical levels and stabilised CPUE. However, it is now apparent that although a recalculation of the net to trap conversion factor reduced the number of traps in the fishery from 1600 to 800 (Melville-Smith et al., 1999), the reduction in effort was not enough with levels of catch unsustainable in the long term.

More importantly, conversion to traps resulted in a dramatic increase in catch and effort during the winter months (April–September) where catches were predominantly mated pre-spawning females, compared with gill net catches which were lower in winter due to lower fishing effort (Figs. 3 and 4). This reduced the potential future egg production within the fishery to one age class by effectively targeting the breeding females over winter, prior to spawning. This had not been the case previously as the majority of gill net fishing occurred over summer with very little effort occurring in winter. This increased heavy fishing pressure on pre-spawning females continued during the 3 consecutive years of lower than average water temperatures and subsequent poor recruitment (2003/04, 2004/05, 2005/06), resulting in low breeding stock levels. Unfortunately, the introduction of a spawning closure in October and November in 1999 and prohibition on berried females did little to protect the breeding stock, which were being targeted during the preceding months prior to extrusion of eggs.

Western Australian tiger prawn (*Penaeus esculentus*) stocks in Exmouth Gulf (Penn and Caputi, 1986) and Shark Bay (Caputi et al., 1998) have experienced similar stock collapses on account of recruitment overfishing. Both stocks are at the edge of their species distributions with restricted spawning periods and fluctuations in abundance due to environmental conditions. Like Cockburn Sound, life cycles were all contained within embayments and vulnerable to fishing once recruited onto available fishing grounds. Although no change in fishing method occurred in the prawn fisheries, the fishing power of the vessels increased significantly and the introduction of peeling machines enabled prawns to be targeted earlier in the season at a much smaller size. The tiger prawn stocks had two additional factors that contributed to their overfishing that did not occur in the crab fishery. The tiger prawns were driven to a low level on account of higher abundances of king prawns on the same grounds, and the targeting of prawns prior to spawning, whereas crab stocks are targeted after the first year class has completed spawning.

During the development of a juvenile index Bellchambers et al. (2006) used 0+ juveniles from both sexes in the middle and northern regions of Cockburn Sound to derive the most accurate index for predicting the following seasons commercial catch. This was supported by reports that juvenile crabs were first found in the southern nearshore areas and at ~50 mm CW these juveniles moved into deeper southern offshore waters, then flowed into middle and northern regions of the embayment (Potter et al., 2001). Following the collapse of the fishery, a longer time series of data and additional recruitment sites allowed a refinement of the juvenile index which showed that the use of a greater number of recruitment sites more accurately re-created subsequent recruitment trends in the fishery. The decline in recruitment is clearly shown with highest recruitment indices immediately following conversion to traps in the late 1990s, followed by a steady decline in recruitment with lowest indices in 2006, the year the fishery closed (Fig. 6A). These trends are supported by declines in the mean catch rates of male and female crabs and numbers of juvenile crabs over the same time period (Fig. 7).

The abundance of juvenile crabs has also been used successfully to measure recruitment for blue crab (*C. sapidus*) fisheries in Delaware Bay (Khan et al., 1998) and Chesapeake Bay (Lipcius and van Engel, 1990; Lipcius and Stockhausen, 2002), and for the tanner crab (*Chionoectes bairdii*) fishery in the Eastern Bering Sea (Zheng et al., 1998). Although these studies did not use these models to predict subsequent catch, larval, post larval or juvenile settlement indices have proved useful in forecasting abundance of decapod crustaceans. For example, in the Western Australian rock lobster (*Panulirus cygnus*) fishery, catches are accurately predicted 3–4 years in advance, based on the densities of post-larval lobsters (puerulus) (Caputi et al., 1995).

Given that the Cockburn Sound crab fishery is now closed, the current juvenile index catch prediction model is an important management tool for assessing the recovery of stocks and ultimately predicting potential commercial catch if, and when, the fishery re-opens. The assessment undertaken in this study has shown that the most accurate catch prediction estimate has been derived from both the 0+ and 1+ components of the population (Fig. 8). This is due to the very large 1+ cohort that will contribute significantly to commercial catch once the fishery re-opens. Using only 0+ in the model would presumably underestimate the potential catch. Had the fishery operated in the 2007, 2008 or 2009 seasons, predicted catch would have been 77 t, 113 t and 156 t, respectively. These catch levels were below acceptable levels and the fishery has remained closed.

The recovery of the Cockburn Sound crab fishery has been relatively slow with only minor increases over the past 3 years in recruitment (Figs. 6 and 7). Spatial differences in the rate of recovery of juvenile abundance are evident, with higher numbers of juveniles in Mangles Bay and Jervois Bay, whereas areas of CBH jetty and Colpoys Point have had minimal recovery. These spatial variations in recruitment are most likely attributed to the higher coverage of seagrass beds in nursery areas, such as Mangles Bay and Jervois Bay (Kendrick et al., 2002) and validate the inclusion of multiple sites in the development of a juvenile index. A similarly slow rate of recovery has occurred for female abundance, with numbers of female crabs/traplift only increasing after 2 years of closure in 2008 and numbers/m^2 increasing only incrementally between 2006 and 2008 (Fig. 6B, C). This slow recovery of juvenile and adult crab abundance is supported by historical trawl data where the total number of crabs m^{-2} in 2008 remains considerably lower than years where trap fishing occurred and catches were reasonable. A change in the sex ratio pattern following closure has occurred where males now dominate the commercial catch for longer, until June, with females only becoming dominant from July through to November. This three month lag in the dominance of females is explained by higher numbers of males in traps, which would have previously been depleted by fishing.

This slow rate of recovery is surprising as blue swimmer crabs are a highly fecund short-lived species, and were thought to be capable of recovering quickly in the absence of commercial and recreational fishing. This was based on the strong stock–recruit relationship ($R^2 = 0.94$, $p < 0.001$, df = 9) determined by de Lestang

et al. (2010). It is possible that breeding stock levels had been fished to such low levels that despite warmer years in 2006 and 2007, recruitment has remained poor. Consequently the fishery has remained closed for three years.

Future management arrangements for this fishery will limit the level of fishing effort in winter months to protect the mated pre-spawning females and provide a buffer to breeding stock. Furthermore, as the ratio of males to females changes from predominantly males between January and March to females between April and September, fishing effort in the months where females dominate the catch will be minimised to increase overall egg production, particularly during years when water temperatures and resultant recruitment have been low. The decision-rule framework will be a valuable management tool for determining the appropriate amount of fishing in the Cockburn Sound crab fishery each season. Using the juvenile and residual index, the level of predicted catch to be fished by the commercial and recreational sectors will be controlled by the length of fishing season, minimum size and effort (trap number) restrictions. This management strategy was chosen to alleviate fishing pressure on mated pre-spawning females, provide a buffer to spawning stock by allowing a proportion of residual stock to remain in the water and reduce the number of traps in what is considered to be a small fishery with an excess of gear and latent effort.

Alternative management arrangements have been implemented for recovering crab stocks in Chesapeake Bay in accordance with the greater complexity of its life cycle, long distance larval, juvenile and sub-adult migrations, nursery habitat and recruitment depletion, variations in temperature and salinity throughout the geographic range of the fishery and multi-state management. These strategies include sanctuary zones to protect the spawning females and establishment of migration corridors to protect females when they undergo the long distance migration after mating to lower Bay spawning areas (Aguilar et al., 2008). The drastic depletion of blue crab seed stock resulted in a continuous decline of juvenile abundance in nursery habitats along tributaries of Chesapeake Bay (Lipcius et al., 2005) and has also made the blue crab an excellent candidate for restocking. The aim of this program is to recover spawning biomass and in turn larval abundance and recruitment to restore the blue crab population (Zohar et al., 2008). Over-wintering mortality and variations in temperature and salinity and macro- and micro-habitat throughout the Bay make the timing and location of release crucial to successful restocking in the fishery (Aguilar et al., 2008; Hines et al., 2008; Zohar et al., 2008). The small spatial area of Cockburn Sound and absence of long distance migrations into and out of estuaries suggests the migration corridors and sanctuary zones within Cockburn Sound would not be appropriate. A ban on winter fishing on post-copulatory pre-spawning females as well as the existing spawning closure in September and October effectively acts in a similar way to the migration corridors and sanctuary zones in Chesapeake Bay. However, stock enhancement into known nursery areas of Cockburn Sound could be a potentially useful tool if crab stocks do not recover fully under new management regimes as nursery areas are recognised and survival of released animals could be monitored effectively with the co-operation of the fishing industry.

At this stage the Cockburn Sound crab fishery will remain closed until breeding stock and recruitment have recovered. It is anticipated that the high productivity of these stocks should result in a full recovery, provided environmental conditions are favourable.

Acknowledgements

The authors would like to thank Scott Evans, Josh Dornan, Brooke Hay, Chris Marsh, Ben Hebiton and the crew of *RV Flinders* and *RV Naturaliste* for assistance with fieldwork, and gratefully acknowledge the support of Cockburn Sound commercial crab fishers, particularly Brad, Aaron and Mark Martin for their assistance during the closure. In addition, the authors wish to thank colleagues Simon de Lestang and Lynda Bellchambers for use of early historical data on this fishery and two anonymous reviewers for their critical commentary on earlier versions of this manuscript. This work was partially funded by the Development and Better Interest Fund (DBIF) from the Western Australian Government and Australian Fisheries Research and Development Corporation (FRDC).

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