Ichthyoplankton assemblages associated with pink snapper (*Pagrus auratus*) spawning aggregations in coastal embayments of southwestern Australia

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Pink snapper (*Pagrus auratus*) form spawning aggregations during the austral spring/summer in three adjacent, sheltered, coastal embayments in southwestern Australia (Cockburn Sound, Warnbro Sound and Owen Anchorage). Larval fishes were sampled in these embayments, as well as in the more exposed adjacent waters of Five Fathom Bank, to ascertain which teleost species utilised these areas for spawning concurrently with *P. auratus*. Obliquely towed bongo nets (500 μm mesh) were used to collect icthyoplankton in November 2007 over three days during the new moon period when spawning of *P. auratus* is known to peak. A total of 13 270 larvae from 30 teleost families was collected with an overall mean larval fish concentration of 1.91 m^{-3} (± s.e. 0.28). Larval fish assemblages were significantly different in each of the three embayments and Five Fathom Bank, reflecting the degree of shelter, water-circulation patterns and associated benthic habitats. The highest larval fish concentrations were recorded in Cockburn Sound (3.69 m^{-3} ± s.e. 0.05) and the lowest along Five Fathom Bank (0.16 m^{-3} ± s.e. 0.02). *P. auratus* larvae were only present in samples from the three embayments. The most abundant larvae were those of the Australian anchovy (*Engraulis australis*), which occurred predominantly in Cockburn Sound and, to a lesser extent, Owen Anchorage. The most ubiquitous larvae included the longspine dragonet (*Callionymus goodladi*) and leatherjackets (Monacanthidae). This study provides circumstantial evidence that eggs and larvae of *P. auratus* and other teleosts are retained in the sheltered waters of Cockburn and Warnbro Sounds during spring/summer.

KEYWORDS: coastal embayments, Cockburn Sound, fish eggs, fish larvae, ichthyoplankton, *Pagrus auratus*, southwestern Australia.

INTRODUCTION

Dispersal of the pelagic eggs and larvae of teleost fishes by meso-scale and regional physical processes has been the pervasive paradigm in the literature, although recent studies have led to the reconsideration of the scales of larval transport (Pineda *et al*. 2007). In particular, the complex flows in shallow coastal waters, where bathymetry, topography, wind-forcing and other factors combine, can result in smaller dispersal kernels and retention of larvae (Gawarkiewicz *et al*. 2007). Likewise, the spawning behaviour of fishes can contribute to the extent of the dispersal kernels of their offspring, and a particularly interesting example is when adults swim to specific sites and aggregate for spawning. Well-known aggregation spawners include species of the families Serranidae, Sciaenidae, Lutjanidae and Sparidae and, as their spawning aggregations are temporally and spatially consistent (predictable), there are many examples of heavy fishing exploitation on such spawning aggregations (Colin *et al.* 2003; Sadovy & Cheung 2003).

Pink snapper (*Pagrus auratus* Forster 1801) is a species of Sparidae that is widely distributed throughout the temperate waters of Australia and New Zealand (Paulin 1990). It forms large spawning aggregations in the sheltered embayments of Port Phillip Bay (Coutin *et al.* 2003), Spencer Gulf and Gulf St Vincent (Fowler & Jennings 2003) and Shark Bay (Jackson & Cheng 2001). Despite *P. auratus* being widely distributed in Western Australia, very few spawning and nursery areas have been located (Wakefield 2006; Jackson 2007; Lenanton *et al.* 2009). Between Kalbarri (28°S) and Geographe Bay (34°S), the only identified locations for spawning aggregations of large adults (i.e. >70 cm total length, TL) and regular annual occurrences of 0+ juveniles are the three adjacent embayments of Cockburn Sound, Warnbro Sound and Owen Anchorage, located near Fremantle (32°S) (Lenanton 1974; Wakefield 2006; Lenanton *et al.* 2009).

Cockburn Sound, Owen Anchorage and Warnbro Sound are prominent geographic features along the linear, lower west coast of Australia and, to the west of the embayments, the more exposed waters of Five Fathom Bank are located (Figure 1). These embayments are generally shallow (~20 m maximum depth), occur within a microtidal zone (D'Adamo 1992) and are subject to moderate seas and swell from the south to southwest direction (Lemm *et al.* 1999). Swell waves generally lose energy when crossing the coastal reefs, banks and sills and it has been estimated that oceanic swell height is reduced to 10% at the shorelines of Owen Anchorage and Warnbro Sound and to about 5% in southern Cockburn Sound (Department of Environmental Protection 1996; Hegge *et al.* 1996). The geomorphology of Cockburn and Warnbro Sounds and the prevailing southwesterly winds during spring/summer result in a counterclockwise gyre in each of these two semi-enclosed embayments (Steedman & Craig 1983; Gersbach 1993).

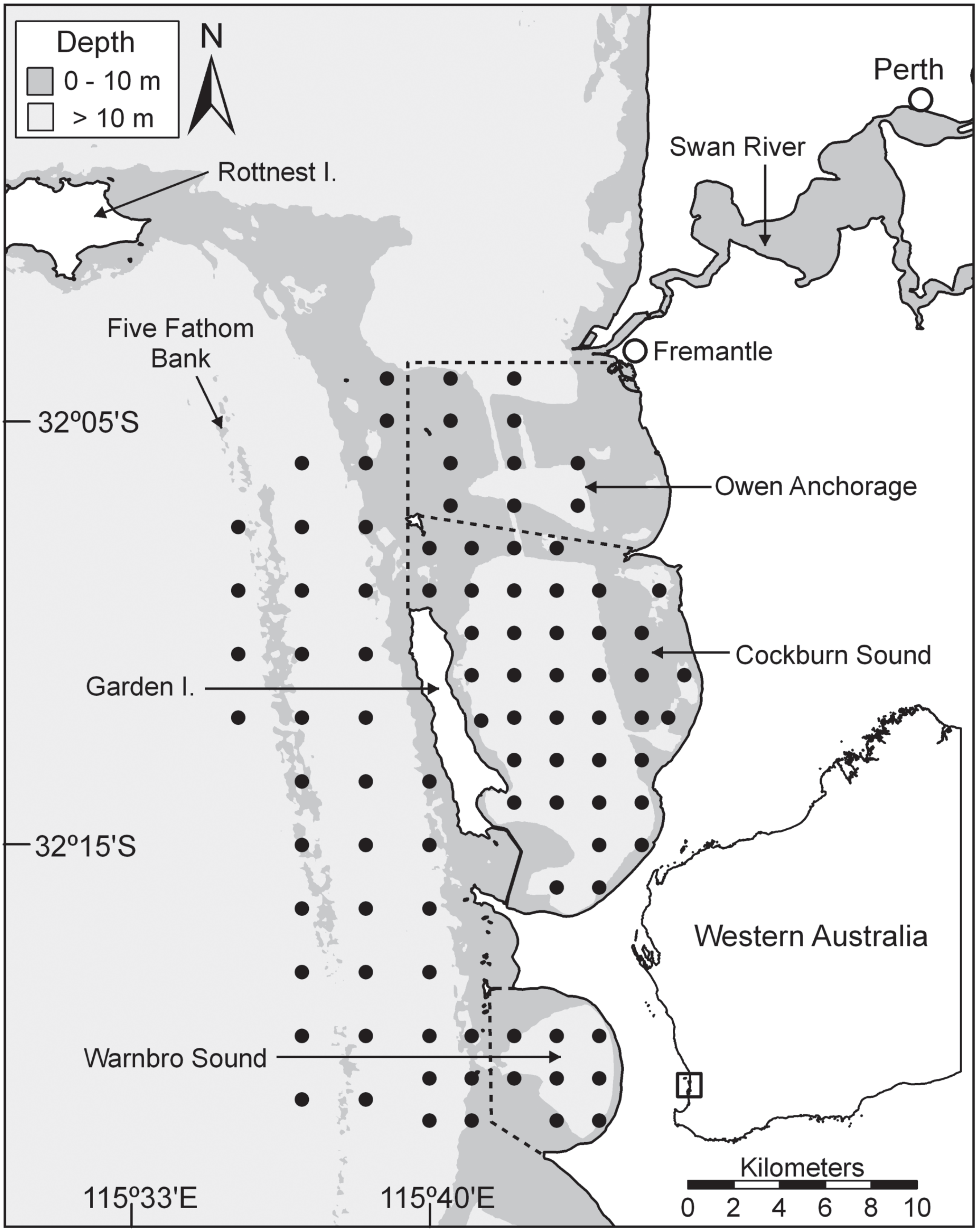

Figure 1 Stations where ichthyoplankton was sampled in four locations (Owen Anchorage, Cockburn Sound, Warnbro Sound and Five Fathom Bank) off southwestern Australia in November 2007.

The spawning periodicity of *P. auratus* aggregations in Cockburn Sound is correlated with water temperature and lunar phase (Wakefield 2010) and also coincides with the formation of the seasonal wind-driven gyres within Cockburn and Warnbro Sounds. Particle-tracking model projections based on depth-averaged water movement have suggested a high probability of retention of *P. auratus* eggs and larvae in Cockburn Sound (Doak 2004; Wakefield 2006). The occurrence of the early life stages of other fish species utilising the retentive dynamics in these embayments concurrently with *P. auratus* is unknown.

Ichthyoplankton sampling by the Western Australian Department of Fisheries is routinely conducted in Cockburn Sound and surrounding areas during the peak reproductive period of *P. auratus* (new moon in November) to facilitate spawning biomass estimates using the daily-egg-production method. The fish larvae collected in these samples were available for this study. The primary aim was to identify the distributions and abundances of fish larvae in Cockburn Sound and adjacent waters to ascertain which species use these embayments as spawning areas concurrently with *P. auratus*. It was hypothesised that the larval fish assemblages of Cockburn and Warnbro Sounds would differ from those of the surrounding exposed coastal waters due to their protected, semi-enclosed nature and the retentive dynamics of their seasonal gyres.

METHODS

Ichthyoplankton was sampled during daylight from 10–12 November 2007 (coinciding with the new moon phase). Sampling was conducted at 88 stations arranged in a 1 nautical mile grid in Cockburn and Warnbro Sounds and a 1.5 nautical mile grid in Owen Anchorage and Five Fathom Bank (Figure 1). The sampling period (relative to the peak temporal reproductive period of *P. auratus*) and station locations were determined from a previous study (Wakefield 2010). The stations were sampled over three consecutive days starting with those in Cockburn Sound, followed by Owen Anchorage and northern Five Fathom Bank, and then Warnbro Sound and southern Five Fathom Bank on the last day. Spawning periodicity of *P. auratus* in these embayments is temporally and spatially specific and highly correlated with environmental cycles, with diel spawning events occurring over consecutive nights during the three hours following the high tide (Wakefield 2006, 2010). Thus, eggs and larvae of this species were considered equally available in each embayment during each of the three days sampled.

Ichthyoplankton was collected using bongo nets with 60 cm diameter openings and 500 μm mesh. A 'General Oceanics' mechanical flowmeter was attached to the mouth of one net to establish the volume filtered. Nets were towed obliquely for two minutes with the vessel travelling at ~2 knots. The warp (length of rope) used for each tow was about 2.5 times the depth at each station, allowing the net to be towed through the water column from just above the seafloor to the surface (Wakefield 2010). The two plankton nets were washed thoroughly and their contents placed into a single sample jar and preserved with 5% buffered formalin. At each station, temperature and salinity were recorded from a bucket of surface water using a WTW 315i conductivity meter with a WTW tetracon®325 conductivity cell. Mean hourly wind speed (km/h) and direction (°) for the 14 days preceding sampling were obtained from the Garden Island meteorological station upon request from the Australian Bureau of Meteorology.

Pagrus auratus eggs were identified from the plankton samples according to Wakefield (2006), separated and stored in 5% buffered formalin. Fish larvae were also separated and stored in 70% ethanol. Fish larvae were identified to the best taxonomic resolution possible using a dissecting microscope and available literature (Moser *et al.* 1984; Neira *et al.* 1998; Leis & Carson-Ewart 2000). Larval concentrations were expressed as the number of larvae per cubic metre of water and maps of egg and larval distribution were generated with Surfer 8.0 (Golden Software Inc.) using kriging interpolation. Body lengths (standard length, SL) of all *P. auratus* larvae and a subsample of 100 *Engraulis australis* larvae were measured to the nearest 0.1 mm using an eyepiece micrometer.

Analysis of variance (ANOVA) using SPSS 17.0 followed by Tukey's *post-hoc* tests were used to test for differences in mean larval fish concentrations and numbers of families between locations (fixed factor). A logarithmic transformation was made to larval concentrations to condense the spread of the data and conform to the assumption of homogenous variances between locations, based on the gradient of the lineal relationship between the logarithms of the standard deviation and mean abundances of species according to Clarke & Warwick (2001). Analyses of larval fish assemblages were carried out using the software PRIMER (Version 6.1.4: Clarke & Gorley 2006). Larval fish concentrations were log (x+1) transformed and the Bray–Curtis distance measure was used to preserve the abundance structure of the dataset when constructing a similarity matrix. Non-metric multidimensional scaling (nMDS ordination) was used to explore the spatial variation in the larval fish assemblages. An analysis of similarities (ANOSIM) was used to test for significant differences, following which, pair-wise comparisons were conducted. ANOSIM is based on rank similarity, with the significance assessed using the R statistic, which is comparable among all pair-wise tests. R statistic values range between -1 and 1, with values of 1 indicating that larval fish assemblages at all stations within a location are more similar to each other than any stations from different locations. Significant ANOSIM results were further explored using similarity percentages (SIMPER: Clarke & Gorley 2006) to identify the larval fish taxa that typified and distinguished locations. Typifying taxa had similarity to standard deviation ratios (Sim/SD) >1 and percentage contribution >5% to that location. Distinguishing taxa were determined by dissimilarity to standard deviation ratios (Diss/SD) >1 and percentage contributions >5% to the locations being compared.

The biota and environment matching routine (BIOENV: Clarke & Gorley 2006) was used to test the degree to which environmental variables influenced larval fish assemblages. Benthic habitats were ascertained from available maps (Department of Environmental Protection 1996) and the dominant habitat type within a radius of 500 m (centred on each station) was assigned to each station. Draftsman's plots were used to examine whether any variables were correlated and whether any transformations were needed based on the spread of data. Environmental data were normalised as variables were in different units and the Euclidean distance measure was used.

RESULTS

Larval fish assemblages

A total of 13 270 fish larvae (30 families and 53 taxa) was collected with an overall mean concentration of 1.91 m^{-3} (± s.e. 0.28, range 0.01-12.34 m^{-3}). Larval fish concentrations were significantly different between locations (ANOVA, F = 47.6, p <0.001: Figure 2). Larval concentrations in Cockburn Sound (3.69 m^{-3} ± s.e. 0.50) were significantly higher than in all other locations (all p values <0.001), and concentrations in Warnbro Sound (1.71 m^{-3} ± s.e. 0.44) were significantly higher than in Owen Anchorage (0.92 m^{-3} ± s.e. 0.29) and Five Fathom Bank (0.16 m^{-3} ± s.e. 0.02) (p <0.01 for both). Much of the variation between locations was attributed to markedly higher abundances of larvae of the anchovy *E. australis* in Cockburn Sound (3.05 m^{-3} ± s.e. 0.61) and, to a lesser extent, Owen Anchorage (0.34 m^{-3} ± s.e. 0.21) than in other locations (Figure 2).

All locations displayed distinct larval fish compositions with a suite of families often characterising each (Figure 3). Owen Anchorage was dominated by larval fish of the families Engraulidae (36%) and Pomacentridae (31%) and Five Fathom Bank was dominated by Percophidae (23%) and Monacanthidae (19%). The Cockburn Sound assemblage was clearly dominated by Engraulidae (83%, including yolk sac stage larvae), whereas Warnbro Sound was dominated by Clupeidae (30%), Callionymidae (16%) and Sparidae (14%). Larvae of *Parapercis haackei* (Pinguipedidae) were recorded in considerably higher concentrations in Cockburn Sound (0.049 m^{-3}) than all other locations (Appendix 1). *Pegasus volitans* larvae (Pegasidae) were specific to Cockburn and Warnbro Sounds (0.013 and 0.015 larvae m^{-3}, respectively) and *Creedia haswelli* larvae (Creediidae) were specific to the waters of Five Fathom Bank (0.006 larvae m^{-3}: Appendix 1).

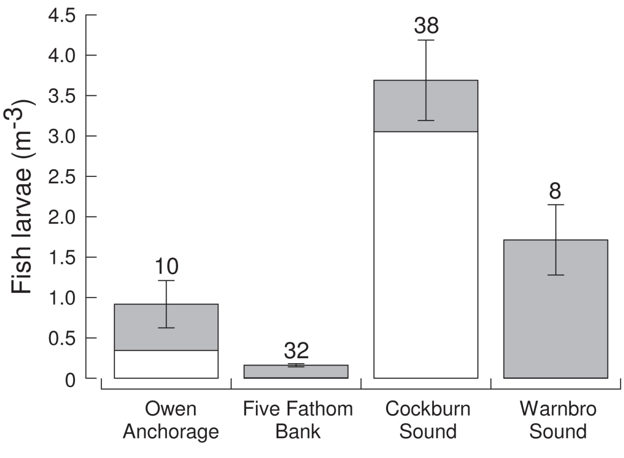

Figure 2 Mean concentration of fish larvae (m^{-3} ± s.e.) for each location off southwestern Australia. *Engraulis australis* larvae are indicated as white bars and all other taxa by grey bars. Number of stations sampled per location shown above the bars.

There was a significant difference between the numbers of families recorded among locations (ANOVA, F = 33.7, p <0.001). Five Fathom Bank was significantly less diverse at the family level than all other locations (p values <0.05). Warnbro Sound had significantly richer family level diversity than all other locations (p values <0.001), particularly in the southern waters with up to 16 families recorded. Jervoise Bay, in northeastern Cockburn Sound, also showed a high family richness.

Overall, there was significant separation between larval fish assemblages among locations (ANOSIM global R = 0.617, p <0.001: Figure 4). Tight clustering of assemblage data from stations in Cockburn and Warnbro Sounds in the nMDS plot indicated low variability between stations, whereas data from stations at the more exposed sites of Owen Anchorage and Five Fathom Bank showed greater separation and thus higher variability in larval assemblages (Figure 4). Pair-wise comparisons showed assemblages from all locations to differ significantly from one another (p values <0.01: Table 1). Cockburn Sound and Five Fathom Bank had the most dissimilar larval fish assemblages (R = 0.728) and Five Fathom Bank and Owen Anchorage the most similar (R = 0.380). Typifying taxa were identified by SIMPER with Cockburn Sound characterised by *E. australis* (yolk sac and larvae) and *C. goodladi*, and Warnbro Sound characterised by *C. goodladi*, *S. sagax*, *P. auratus* and *Pseudocaranx* sp. (Table 2). With the exception of *Pseudocaranx* sp., these typifying species essentially distinguished the larval assemblages of both sounds from those of the other locations (Table 2). Owen Anchorage was distinguished from Five Fathom Bank and Warnbro Sound by the higher prevalence of Monacanthidae (Table 2).

Abundance and distribution of taxa

Eggs of *P. auratus* occurred in three highly concentrated nodes in each of the deeper central waters of the adjacent embayments of Warnbro Sound (40–44 m^{-3}), Cockburn Sound (12–16 m^{-3}) and Owen Anchorage (4–8 m^{-3}, Figure 5). Larvae of *P. auratus* occurred in relatively high concentrations in Warnbro Sound (0.70–0.77 m^{-3}) and moderate concentrations (0.07–0.21 m^{-3}) in northern Cockburn Sound, but were markedly less abundant in

Table 1 ANOSIM pairwise comparisons between locations showing R statistics and p values

Groups	R statistic	p value
Cockburn Sound vs Five Fathom Bank	0.728	0.001**
Cockburn Sound vs Warnbro Sound	0.683	0.001**
Five Fathom Bank vs Warnbro Sound	0.548	0.001**
Cockburn Sound vs Owen Anchorage	0.510	0.003**
Owen Anchorage vs Warnbro Sound	0.404	0.001**
Five Fathom Bank vs Owen Anchorage	0.380	0.001**

** significant at 1% sig. level.

Table 2 Larval fish taxa identified by SIMPER as those that typified larval assemblages within each location or distinguished larval assemblages between locations.

	Owen Anchorage	**Five Fathom Bank**	**Cockburn Sound**	**Warnbro Sound**
Owen Anchorage (OA)	-	-	-	-
Five Fathom Bank (FF)	Monacanthidae spp. (OA)	-	-	-
Cockburn Sound (CS)	*E. australis* (CS) *E. australis* (ys) (CS) *C. goodladi* (CS)	*E. australis* (CS) *E. australis* (ys) (CS) *C. goodladi* (CS)	*E. australis* *E. australis* (ys) *C. goodladi*	-
Warnbro Sound (WS)	*S. sagax* (WS) *C. goodladi* (WS) *P. auratus* (WS) Monacanthidae spp. (OA)	*S. sagax* (WS) *C. goodladi* (WS) *P. auratus* (WS)	*E. australis* (CS) *E. australis* (ys) (CS) *S. sagax* (WS) *C. goodladi* (CS	*C. goodladi* *S. sagax* *P. auratus* *Pseudocaranx* sp.

The location where distinguishing taxa from each pairwise comparison were most abundant is indicated by superscripts.
ys, yolk sac larvae.

Owen Anchorage (Figure 5). The majority of *P. auratus* larvae were in the preflexion stages of development (including some still with yolk sac), with a mean body length of 3.2 mm (± s.e. 0.06, n = 240: Figure 6).

Larvae of *E. australis* were almost exclusively collected in the deeper central waters of Cockburn Sound (10.5–12.0 m^{-3}: Figure 5). The majority of *E. australis* larvae were in yolk sac or very early preflexion stages of development with a mean body length of 3.2 mm (± s.e. 0.09, n = 100: Figure 6). Larvae of *S. sagax* were exclusive to Warnbro Sound, with relatively high concentrations (0.8–1.6 m^{-3}) occurring in the southeast of this embayment (Figure 5).

The most ubiquitous larval fish taxa collected across all four locations were *Callionymus goodladi* and Monacanthidae spp. The highest concentrations of *C. goodladi* larvae were recorded at Mangles Bay in southern Cockburn Sound (1.20–1.35 m^{-3}), the deeper central waters of Cockburn Sound (0.45–0.90 m^{-3}) and southern Warnbro Sound (0.45–0.60 m^{-3}: Figure 5). The highest concentrations of Monacanthidae larvae were recorded in the east of Cockburn Sound at Jervoise Bay (0.10–0.45 m^{-3}), Mangles Bay (0.1–0.3 m^{-3}) and in northwestern Owen Anchorage (0.1–0.3 m^{-3}: Figure 5).

Larvae of other commercially and recreationally important taxa collected included those of *Pseudocaranx* sp. and Sillaginidae spp. (Figure 5). Larvae of *Pseudocaranx* sp. occurred in the three adjacent embayments, with higher abundances (0.04–0.07 m^{-3})

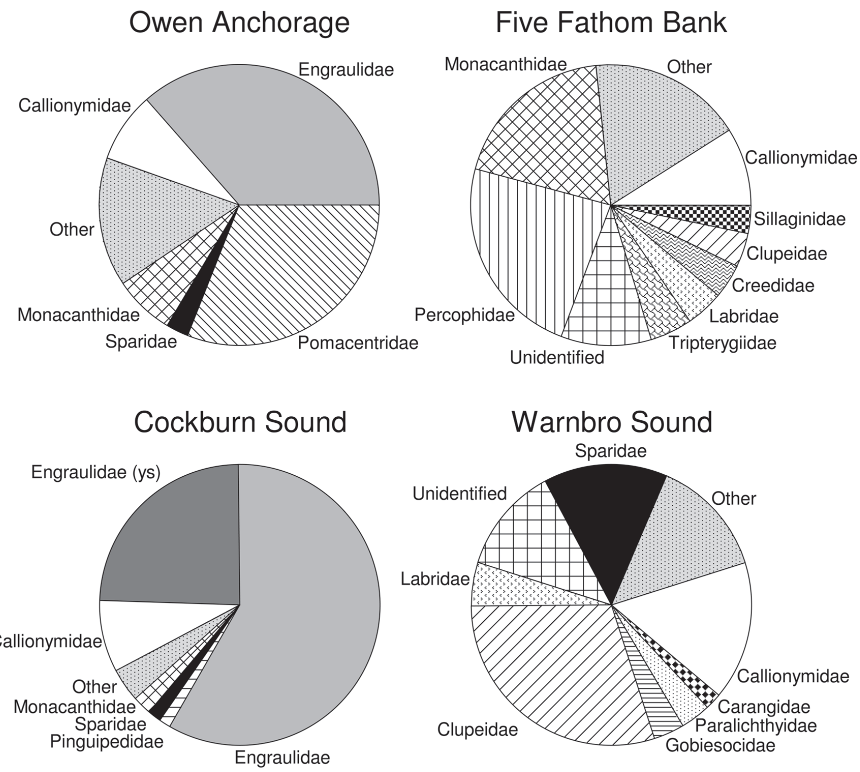

Figure 3 Percentage contributions (m^{-3}) by dominant teleost families to the ichthyoplankton at each location. (ys, yolk sac stage larvae).

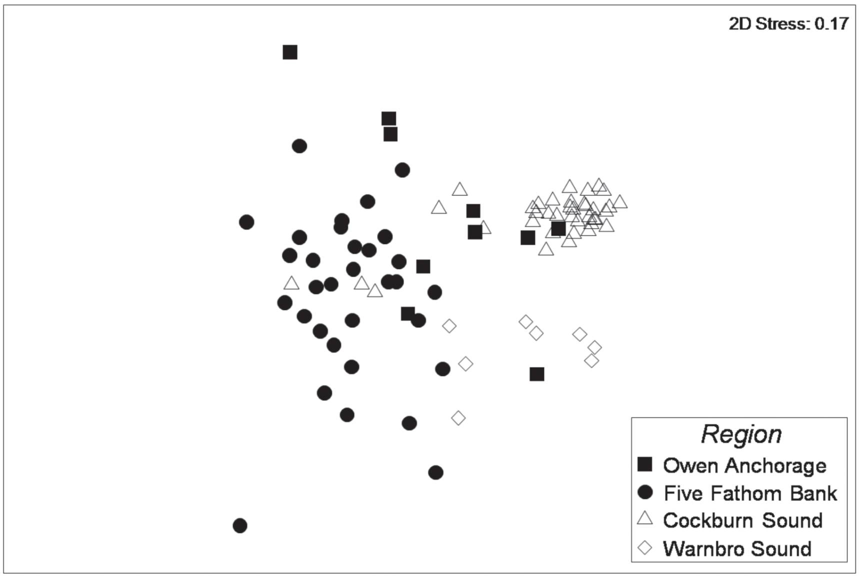

Figure 4 Non-metric multidimensional scaling (nMDS) plot showing the distinction of larval fish assemblages for each station from each of the four locations sampled.

occurring in Warnbro Sound (Figure 5). Larvae of Sillaginidae occurred in higher concentrations in southeastern Warnbro Sound (0.06–0.11 m^{-3}) and in low to moderate concentrations (0.02–0.08 m^{-3}) along Five Fathom Bank and Cockburn Sound (Figure 5).

Larval fishes hatched from demersal versus pelagic eggs showed different spatial distributions across the study area. Larvae originating from demersal eggs were most strongly clustered around stations in northwestern Owen Anchorage (<2.2 larvae m^{-3}), whilst larvae originating from pelagic eggs occurred predominantly in the deeper central waters of Cockburn Sound (<12.5 larvae m^{-3}). The spatial distribution of larvae hatched from pelagic eggs was largely dominated by the single dominant species, *E. australis*. Excluding this species, other larval fishes hatched from pelagic eggs showed highest concentrations in southeastern Warnbro Sound (2.80–3.15 larvae m^{-3}), and moderate concentrations in Mangles Bay (1.40–1.75 larvae m^{-3}) and the deeper central waters of Cockburn Sound (0.70–1.05 larvae m^{-3}).

Environmental and physical parameters

Daily wind conditions during the 14 days leading up to sampling displayed a characteristic late spring pattern, with winds predominantly from the east to southeast (μ = 18.9 km/h) in the morning before shifting south to southwest and increasing in velocity (μ = 25.8 km/h) in the afternoon. Depth of stations ranged from 3 to 28 m, sea-surface temperatures averaged 20.0°C (± s.e. 0.09) and surface salinity averaged 35.6 ‰ (± s.e. 0.02). BIOENV was used to relate environmental and physical parameters to larval assemblages and revealed significant (p <0.001) but weak positive correlations with benthic habitat, depth, salinity and sea-surface temperature. The most predictive environmental variable was benthic habitat (ρ = 0.345).

DISCUSSION

This study provides circumstantial evidence that, to varying degrees, many temperate Australian fish species spawn at the same time as *P. auratus.* The larval fish assemblages recorded in the four areas of this study were markedly different within a relatively small geographic area (~500 km²), with concentrations generally higher in the protected marine embayments of Cockburn and Warnbro Sounds. The larval fish concentrations were greater than those recorded in previous studies from southwestern Australia (Gaughan *et al.* 1990; Kendrick 1993; Young & Potter 2003; Muhling *et al.* 2008a) and in similar marine embayments in southeastern Australia, e.g. Port Phillip Bay (Jenkins 1986; Neira & Sporcic 2002).

The differences in both taxonomic diversity and abundances of fish larvae between the four locations over such a small geographic range could be attributed to differences in shelter from wave energy, benthic habitat and anthropogenic influences. However, the seasonally occurring hydrodynamic gyres in Cockburn and Warnbro Sounds, which are driven by local geomorphology and the prevailing southwesterly winds during the austral spring/summer (Steedman & Craig 1983; Gersbach 1993), could result in high levels of retention in Cockburn and Warnbro Sounds during this period. Retention of fish eggs and larvae by the gyres has been predicted from particle tracking in hydrodynamic models based on typical weather conditions (Apai 2001) and applied to seasonal patterns of *P. auratus* egg abundance (Doak 2004). The spatial distribution of *P. auratus* eggs and larvae from this study provides circumstantial evidence of the retention of their early pelagic life stages in Cockburn and Warnbro Sounds.

Ichthyoplankton sampling was purposely conducted during the peak reproductive period for *P. auratus* and the highly concentrated nodes of eggs in each of the embayments in 2007 concurs with the findings of a previous study (Wakefield 2006, 2010). However, despite all three embayments having high concentrations of *P. auratus* eggs, similar concentration nodes of larvae were only apparent in Cockburn and Warnbro Sounds. The hydrodynamic retention of *P. auratus* progeny in Cockburn and Warnbro Sounds is similar to that reported for eggs and larvae of *P. auratus* from discrete locations in Shark Bay, Western Australia (Nahas *et al.*

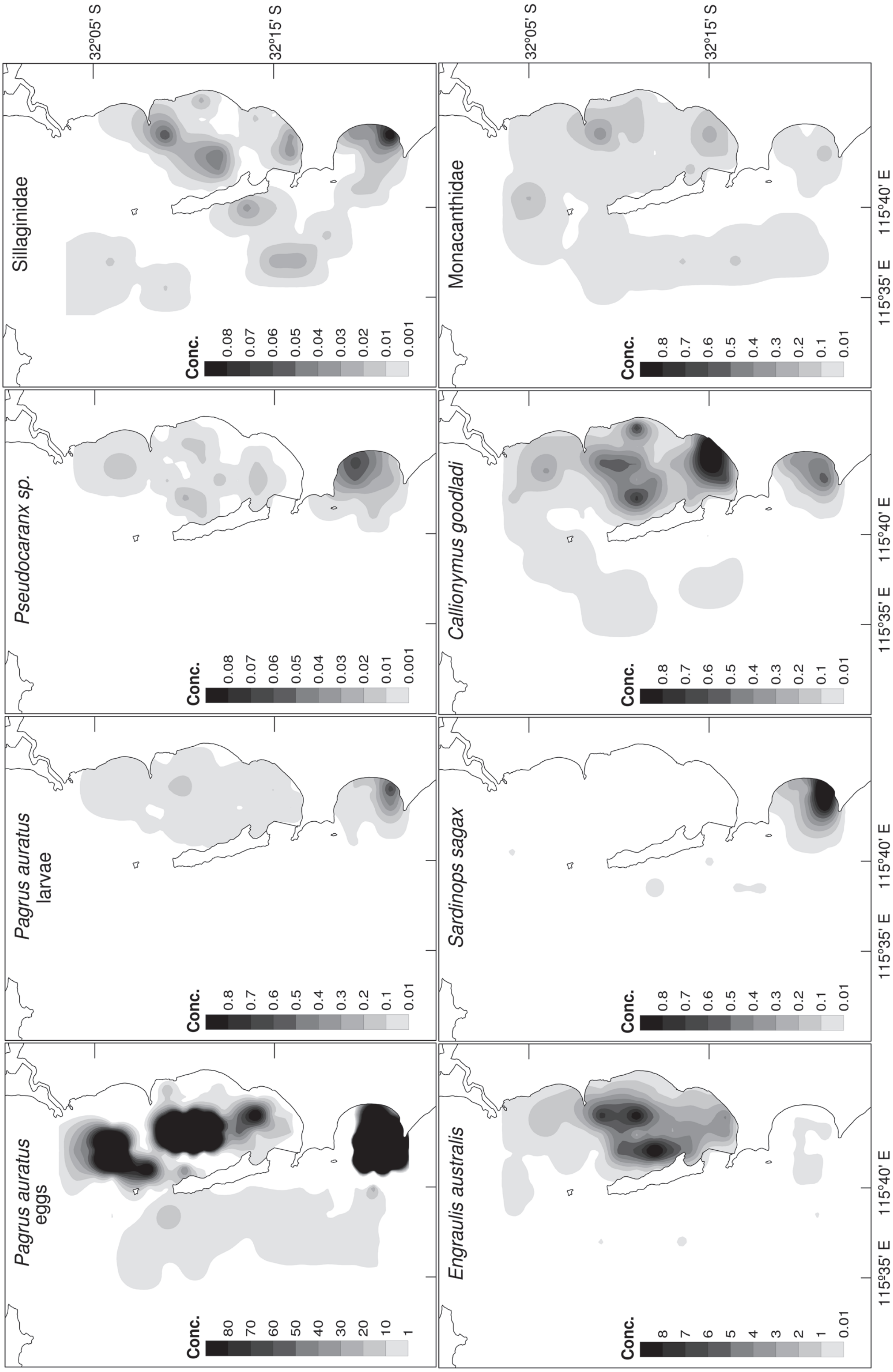

Figure 5 Spatial distributions of *Pagrus auratus* eggs, and larvae (m^{-3}) of those species that typified assemblages in each location.

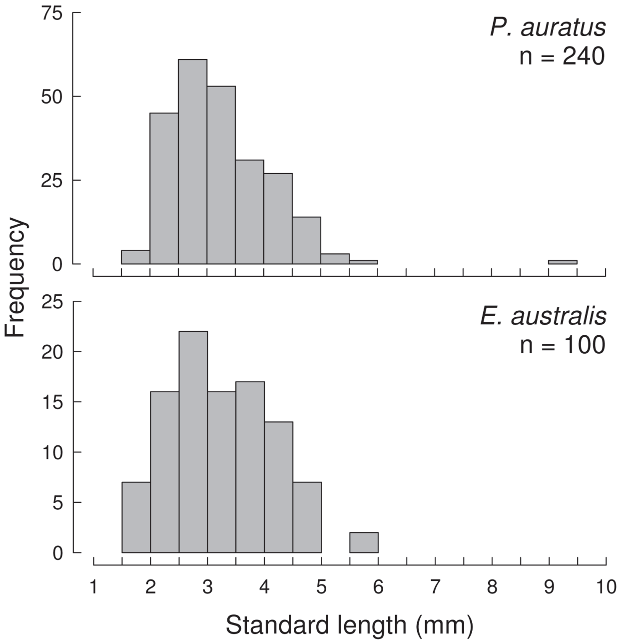

Figure 6 Length–frequency distributions of *Pagrus auratus* and *Engraulis australis* larvae from the study area.

2003). In South Australia and Victoria, such spawning aggregation locations have been identified as important recruitment sources, responsible for large or entire contributions of annual cohorts to adult stocks in coastal waters (Fowler *et al.* 2005; Hamer *et al.* 2005). It is likely that Cockburn and Warnbro Sounds also represent important recruitment locations for adjacent adult stocks of *P. auratus*, considering the egg and larvae retention indicated in this study and their significance as juvenile habitat areas (Lenanton 1974; Wakefield *et al.* 2011).

The larvae of some other fish species (e.g. *Pseudocaranx* sp. and *Parapercis haackei*) were also exclusive to the three adjacent embayments. The wavy grubfish, *P. haackei*, commonly occurs in sand and rubble habitats in relatively protected waters (Hutchins & Swainston 1999) and the trevallies of the genus *Pseudocaranx* are usually associated with sand and seagrass habitats in coastal areas including estuaries (Hutchins & Swainston 1999).

Larval distributions of two pelagic fish species also displayed affinities with the sheltered waters of the marine embayments. Early stage larvae of *E. australis* exhibited the highest concentrations of all taxa collected and were most prominent in Cockburn Sound and, to a lesser extent, Owen Anchorage. The reproductive period of this pelagic species peaks during the austral summer (January to March) throughout its temperate and subtropical distribution (Hoedt & Dimmlich 1995; Ward *et al.* 2003; Dimmlich *et al.* 2004). The spatial distribution of larvae of another clupeiform species, *S. sagax*, was restricted to Warnbro Sound, and thus segregated from *E. australis* larvae. Larvae of *S. sagax* are found year-round in shelf waters off southwestern Australia and the influence of the Leeuwin Current with respect to growth rates and larval abundance of this species has been investigated (Muhling *et al*. 2008b). In South Australia, the spawning locations of these two clupeiform species are discreet between shelf and gulf waters, where *E. australis* appears to compete unsuccessfully with *S. sagax* for optimal upwelling zones in shelf waters (Ward *et al.* 2001; Dimmlich *et al.* 2004). Dimmlich *et al.* (2004) identified the northern waters of Spencer Gulf and Gulf St Vincent, where egg and larval retention is maximised, to be the centres of anchovy spawning activity in South Australia. *Engraulis australis* commonly spawns in protected nearshore areas across temperate Australia (Neira & Sporcic 2002), which appears to be a common trait among this genus globally (Yoklavich *et al.* 1992; Allain *et al.* 2003; Takasuka *et al.* 2003).

The distributions of some of the larval fishes in this study appeared ubiquitous across all four locations with the most abundant of these being larvae of *Callionymus goodladi*, Monacanthidae and Sillaginidae. Larvae of *C. goodladi* have been recorded consistently in other larval fish studies at coastal and estuarine locations off southwestern Australia (Gaughan *et al.* 1990; Jonker 1993; Kendrick 1993). The broad spatial distribution of larvae of Monacanthidae probably reflects the diverse habitats occupied by the large number of species (>25) that occur in temperate Western Australian waters (Hutchins & Swainston 1999). Larvae of Sillaginidae were one of the few taxa to occur in moderate concentrations at stations along Five Fathom Bank and in Cockburn and Warnbro Sounds. King George whiting (*Sillaginodes punctatus*) is a species known to use Mangles Bay in southern Cockburn Sound as a nursery area (Hyndes *et al.* 1998), but as this species spawns from winter to early spring in southwestern Australia, the preflexion whiting larvae identified in this study were not likely to be *S. punctatus*. Myomere counts indicated that they were probably from the genus *Sillago* (Neira *et al.* 1998). Species within this genus spawn from late spring to early autumn with only *Sillago schomburgkii* spawning in nearshore areas, suggesting that the larvae found in this study were likely to belong to this species (Hyndes & Potter 1997).

Northwestern Owen Anchorage had moderate larval fish concentrations with a high proportion of these larvae originating from demersal eggs. The variety of benthic habitats including seagrass meadows and subtidal reefs adjacent to Owen Anchorage may provide appropriate substrates for attachment of their demersal eggs (Department of Environmental Protection 1996). Demersal eggs would be expected to limit the offshore dispersal of early life history stages and Muhling *et al.* (2008a) found Marmion lagoon (40 km north of Owen Anchorage) to be dominated by larvae of small, inshore reef- and seagrass-inhabiting fishes such as the Tripterygiidae, Clinidae, and Gobiidae and Monacanthidae that produce demersal eggs or are live-bearers. Larvae of Pomacentridae sp. 1, which were specific to Owen Anchorage were most likely to belong to the genus *Parma*. Kendrick (1993) noted that larvae of this taxon exhibited a discrete distribution pattern around sites off Rottnest Island and Carnac Island (southwestern Owen Anchorage). Pomacentridae generally produce demersal eggs and commonly the male will exhibit brooding care for up to a week (Gladstone 2007; Curley & Gillings 2009).

At the deeper stations, west of Five Fathom Bank, larvae of the slender sandburrower, *Creedia haswelli* were found. Similarly, Muhling *et al.* (2008a) found *C. haswelli* to only make significant contributions to larval assemblages in southwestern Australian shelf waters at stations in 40 m and 100 m depths rather than their shallower nearshore station (18 m). Larvae of the broad duckbill, *Enigmapercis reducta* (Percophidae), also occurred in greatest abundances at stations along the deeper western margin of Five Fathom Bank.

The inherent vulnerability of a species increases markedly when a particular life history stage is restricted to a specific area or limited habitat which may be affected by anthropogenic disturbance. In the marine environment, disturbance is commonly encountered within protected bays as their sheltered nature benefits many anthropogenic activities (e.g. ports, industry, aquaculture, fishing, mining, naval defence operations). In southwestern Australia, P. *auratus* forms spawning aggregations in the few sheltered marine embayments along the essentially linear southwest coast during a short annual spawning period (Wakefield 2006). The importance of these embayments in contributing to cohorts of exploited adult stocks of *P. auratus* warrants further investigation. Although the biology is poorly known for most of the other teleost species with larvae recorded in this study, those with larval distributions similar to *P. auratus* could also have a higher inherent vulnerability, given the paucity of nearshore marine embayments along the coast of southwestern Australia and increasing anthropogenic activities in these areas.

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Appendix 1 Total counts and mean larval fish concentration (m^{-3}) for each taxon at each location.

Larval fish taxa	Owen Anchorage		Five Fathom Bank		Cockburn Sound		Warnbro Sound		Overall	
	Total	Mean	Total	Mean	Total	Mean	Total	Mean	Total	Mean
Clupeidae										
Sardinops sagax	1	0.0014	11	0.0041	0	0	245	0.4276	257	0.0405
Spratelloides robustus	9	0.0123	5	0.0018	15	0.0052	0	0	29	0.0043
Hyperlophus vittatus	0	0	1	0.0004	0	0	0	0	1	0.0001
Unidentified	0	0	0	0	0	0	44	0.0837	44	0.0076
Unidentified (ys)	0	0	0	0	0	0	20	0.0352	20	0.0032
Engraulidae										
Engraulis australis	240	0.3349	5	0.0021	6587	2.1594	1	0.0016	6833	0.9714
Engraulis australis (ys)	7	0.0096	6	0.0024	2631	0.8938	0	0	2644	0.388
Synodontidae										
Synodontid sp.	0	0	0	0	0	0	1	0.002	1	0.0002
Syngnathidae[b]										
Stimatopora nigra	5	0.0064	1	0.0004	3	0.0009	5	0.0057	14	0.0018
Syngnathid sp.	0	0	0	0	2	0.0008	0	0	2	0.0003
Pegasidae										
Pegasus volitans	1	0.001	1	0.0004	40	0.0131	8	0.0148	50	0.0073
Scorpaenidae										
Gymnapistes marmoratus	3	0.004	1	0.0004	1	0.0003	0	0	5	0.0007
Scorpaenid sp.	0	0	2	0.0008	0	0	0	0	2	0.0003
Triglidae										
Lepidotrigla papilio	1	0.0015	3	0.0011	8	0.0024	10	0.0176	22	0.0032
Lepidotrigla spp.	0	0	0	0	4	0.0013	2	0.0028	6	0.0008
Unidentified	0	0	2	0.0007	0	0	1	0.0019	3	0.0004
Platycephalidae										
Platycephalus speculator	0	0	1	0.0004	2	0.0006	1	0.002	4	0.0006
Platycephalid sp.1	0	0	0	0	1	0.0004	0	0	1	0.0002
Platycephalid sp.2	0	0	0	0	1	0.0004	0	0	1	0.0002
Unidentified	0	0	1	0.0004	0	0	2	0.0033	3	0.0004
Serranidae										
Epinephelinae sp.	0	0	1	0.0003	0	0	0	0	1	0.0001
Unidentified	1	0.0013	0	0	0	0	0	0	1	0.0001
Plesiopidae[d]										
Paraplesiops sp.	0	0	0	0	1	0.0003	0	0	1	0.0001
Terapontidae										
Pelates octolineatus	0	0	0	0	0	0	6	0.0103	6	0.0009
Pelates sexlineatus	0	0	1	0.0004	1	0.0004	8	0.0129	10	0.0015
Pelates sp.	0	0	0	0	1	0.0003	1	0.0019	2	0.0003
Unidentified	0	0	0	0	1	0.0004	3	0.0056	4	0.0007
Sillaginidae										
Sillago bassensis	0	0	5	0.002	0	0	0	0	5	0.0007
Sillago spp.	0	0	7	0.0028	33	0.0114	16	0.0286	56	0.0085
Unidentified	0	0	1	0.0004	0	0	1	0.002	2	0.0003
Carangidae										
Pseudocaranx sp.	2	0.0028	1	0.0004	13	0.0041	20	0.0324	36	0.0052
Sparidae										
Pagrus auratus	10	0.0141	1	0.0004	124	0.0405	105	0.1811	240	0.0357
Rhabdosargus sarba	0	0	0	0	17	0.0052	0	0	17	0.0023
Unidentified	7	0.0096	2	0.0008	37	0.0118	37	0.0632	83	0.0122
Pomacentridae[d]										
Pomacentrid sp.1	202	0.2844	11	0.0048	0	0	1	0.0011	214	0.0342
Pomacentrid sp.2	0	0	0	0	1	0.0004	0	0	1	0.0002
Mugilidae										
Mugilid sp.	0	0	2	0.0007	0	0	0	0	2	0.0003
Labridae										
Labrid sp.1	3	0.0043	8	0.003	0	0	12	0.0168	23	0.0031
Labrid sp.2	0	0	7	0.0025	0	0	17	0.0244	24	0.0031
Labrid sp.3	0	0	0	0	0	0	2	0.0028	2	0.0003

Appendix 1 (cont.)

Larval fish taxa	Owen Anchorage		Five Fathom Bank		Cockburn Sound		Warnbro Sound		Overall	
	Total	Mean	Total	Mean	Total	Mean	Total	Mean	Total	Mean
Labrid sp.4	0	0	0	0	0	0	3	0.0054	3	0.0005
Unidentified	0	0	4	0.0015	2	0.0006	23	0.0368	29	0.0042
Odacidae										
Odax cyanomelas	2	0.0027	1	0.0004	0	0	4	0.0072	7	0.0011
Haletta semifasciata	0	0	0	0	1	0.0003	0	0	1	0.0001
Siphonognathus argyrophanes	0	0	0	0	0	0	1	0.0014	1	0.0001
Odax sp.	0	0	1	0.0004	0	0	0	0	1	0.0001
Percophidae										
Enigmapercis reducta	12	0.0168	102	0.0376	14	0.0046	3	0.0041	131	0.0179
Pinguipedidae										
Parapercis haackei	2	0.0028	2	0.0008	152	0.049	1	0.0017	157	0.0219
Creediidae										
Creedia haswelli	0	0	18	0.0064	0	0	1	0.0011	19	0.0024
Tripterygiidae[d]										
Tripterygiid sp.1	3	0.0043	11	0.0041	5	0.0016	5	0.0083	24	0.0034
Tripterygiid sp.2	8	0.0109	9	0.0037	29	0.0102	1	0.0011	47	0.0071
Blenniidae[d]										
Parablennius postoculomaculatus	4	0.0054	0	0	3	0.0011	1	0.0011	8	0.0012
Gobiidae[d]										
Gobiid spp.	15	0.0207	9	0.0033	120	0.0404	7	0.0122	151	0.0221
Gobiesocidae[d]										
Gobiesocid sp.1	2	0.0028	3	0.0012	4	0.0014	45	0.0531	54	0.0062
Gobiesocid sp.2	2	0.0027	1	0.0004	0	0	3	0.0041	6	0.0008
Gobiesocid sp.3	0	0	0	0	0	0	1	0.0014	1	0.0001
Gobiesocid sp.4	0	0	1	0.0005	0	0	0	0	1	0.0002
Alabes sp.	0	0	1	0.0004	0	0	0	0	1	0.0001
Unidentified	4	0.0051	5	0.0021	0	0	1	0.002	10	0.0015
Callionymidae										
Callionymus goodladi	58	0.074	37	0.0144	953	0.3064	160	0.2736	1208	0.1708
Bothidae										
Bothid sp.	0	0	0	0	1	0.0004	0	0	1	0.0002
Paralichthyidae										
Pseudorhombus jenynsii	4	0.0056	6	0.0022	19	0.0064	35	0.0597	64	0.0096
Monacanthidae[d]										
Monacanthid spp.	46	0.0641	80	0.0308	244	0.0803	29	0.0473	399	0.0575
Tetraodontidae[d]										
Tetraodontid spp.	0	0	0	0	2	0.0006	0	0	2	0.0003
Unidentified/Damaged	10	0.0121	46	0.0168	100	0.0327	120	0.2102	276	0.0407

The number of stations sampled at each location was: Owen Anchorage (10), Five Fathom Bank (32), Cockburn Sound (38) and Warnbro Sound (8). Families known to produce demersal eggs or brood are indicated by superscript d or b, respectively.

ys, yolk sac larvae.