Development of indicators for assessing Black Bream health in the Vasse-Wonnerup Wetlands

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Contents

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Summary

This study was commissioned to develop indicators for assessing Black Bream health in the Vasse-Wonnerup Wetlands. The study is an extension of the Revitalising Geographe Waterways' Integrated Ecological Monitoring Study (IEM). The overarching aim of which is to better understand the relationships between water regime, food sources and abundance of benthic macroinvertebrates, fish and birds utilising the range of habitats (regions) present in the Vasse-Wonnerup (see https://rgw.dwer.wa.gov.au/applying-science/vasse-wonnerup-science/).

The study aims to develop indicators for i) the body condition of adult Black Bream in the Wonnerup Inlet and Deadwater and ii) the recruitment of juvenile Black Bream in the Vasse-Wonnerup and to use these indicators to assess the health Black Bream over the period 2011/12 to 2020/21. Black Bream is an iconic species, with individuals completing their life cycle within the wetlands. These fish have 'plastic' biological characteristics that respond to environmental changes in a predictable way and are often severely impacted by fish kills in the system. This species is therefore an ideal indicator that can be used as a proxy for the health of the broader fish community of the Vasse Wonnerup Wetlands.

Key findings

- A body condition index based on the weight of Black Bream at a standardized length of 250 mm was developed using reference conditions from a range of estuaries throughout south-western Australia.
- Body condition was rated as *Very good* in 2013, and *Good* in 2014, but fell to *Very poor* in 2018 and *Poor* in 2020. This could be related to the availability of food and/or occurance of low oxygen events.
- A dolphin was recorded during sampling in February 2018 and in both surveys conducted during the current study (2020) and may have predated on some of the larger Black Bream with better body conditions contributing to the lower scores in these seasons.
- An index of recruitment was developed for juvenile Black Bream (0+; < 160 mm total length) using data collected from seine nets from November 2011 onwards.
- Recruitment was rated as *Very poor* after the 2013 fish kill before increasing to *Poor* and *Fair* in the next two years. Values in typically fell the *Poor* to *Fair* range for the next four years except for 2018 when recruitment was rated as *Good*.

Recommendations

- Determine a baseline estimate of the population size of adult Black Bream in the Vasse-Wonnerup using capture-mark-recapture techniques.

- Continue to monitor both juvenile recruitment and the abundance of adult Black Bream population in the Deadwater, Wonnerup Inlet in November and February and calculate the Body Condition Index
- Use Black Bream indicators to contrite to annual report cards for the Vasse Wonnerup wetlands.
- Better understand the drivers of Black Bream movement around the fish gate in relation to environmental conditions. This will involve tagging more Black Bream with Passive Integrated Transponder tags and analysing the patterns of fish passage that have occurred subsequent to fish gate operation periods since 2018.

1. Introduction

The Vasse-Wonnerup Wetland and its catchment, like many estuaries on the lower-west coast of Western Australia, has been subjected to human activities and is regarded as "extensively modified" (Commonwealth of Australia, 2002; Tweedley et al., 2017b). These modifications have a long history dating back over 100 years and include land clearing, the creation of extensive drainage networks, the diversion of rivers that once flowed into the system, and the construction of surge barriers (Wetland Research & Management, 2007; Tweedley et al., 2017a). Moreover, the Vasse-Wonnerup is the "*most grossly enriched major wetland system known in Western Australia*" (McAlpine et al., 1989), with some of the highest ammonia, total phosphorous and chlorophyll *a* concentrations of any estuary in south-western Australia, including the Peel-Harvey at its height of eutrophication before the construction of the Dawesville Cut (Brearley, 2005; Potter et al., 2021). In addition to human-induced stressors, the fish living within the estuary also experience natural stress (Warwick et al., 2018). Being located in a Mediterranean climate, rainfall and thus freshwater discharge from rivers are highly seasonal (Hallett et al., 2018). Moreover, when combined with the wide and shallow basin, considerable changes in salinity can occur from < 1 ppt during winter and spring to over 130 ppt following dry summer and autumns (Tweedley et al., 2014).

These anthropogenic and natural pressures have had numerous impacts on the ecological health of the Vasse-Wonnerup including, in recent times, several large fish kills (Lane et al., 1997; Tweedley et al., 2014). Fish kills, in particular, occur regularly in the Vasse-Wonnerup, with reports of such events dating back to 1905, with the causes ranging from low oxygen, high temperatures, macroalgal blooms and toxic phytoplankton both in isolation or combination (Lane et al., 1997; Hart, 2014). A fish kill event in April 2013 caused the mortality of an estimated 30,000 fish, primarily adult Sea Mullet (*Mugil cephalus*), Yelloweye Mullet (*Aldrichetta forsteri*) and Black Bream (*Acanthopagrus butcheri*, Department of Water and Environmental Regulation). These three species are the target of commercial fishers, while the vast majority of recreational fishers who utilise the Vasse-Wonnerup target Black Bream, which is an iconic recreational fish species in estuaries across southern Australia (Kailola et al., 1993; Potter et al., 2015b). In addition periods of hypersalinity can influence the abundance and distribution of fish species and their invertebrate prey and can result in non-lethal effects such as declines in fish growth (Whitfield et al., 2006; Tweedley et al., 2019d; Krispyn et al., 2021).

Of the fish that were most prevalent in previous fish kills, both the Sea and Yelloweye mullets are marine estuarine-opportunists, i.e. adult fish spawn in the ocean and their offspring enter the estuary as juveniles. Therefore, stocks of these species can be replenished from Geographe Bay (Potter et al., 2015a; Whitfield et al., 2022). On the other hand, Black Bream is a solely estuarine species, with individuals completing their life cycle within their natal estuaries, which they seldom leave (Cottingham et al., 2018a). Not only has this life history strategy resulted in populations of Black Bream in different estuaries being genetically distinct from one another (Chaplin et al., 1998). Given the history of large fish kills in the Vasse Wonnerup Wetlands and impact on Black Bream ongoing monitoring and management of Black Bream is a priority.

Black Bream is a relatively long-lived (30 years) and large growing (>500 mm and 3 kg) estuarine fish species native to southern Australia (Morison et al., 1998; Potter et al., 2008). As its individuals seldom leave the estuary in which they were born throughout their life, Black Bream are subjected to any deleterious changes that occur within that system (Cottingham et al., 2016). Due to this affinity to their natal estuary, if a population becomes depleted, it cannot be naturally replenished from outside sources (Cottingham et al., 2015a; 2020). This can be problematic for some populations, particularly in stocks that have episodic recruitment or experience regular fish kills.

Black Bream also possess many of the required characteristics to act as an indicator species and are thus useful for monitoring the health of an estuary. Such indications are exemplified by changes in certain biological characteristics, e.g. recruitment, growth and body condition, which respond, in predictable ways, to changing environmental conditions (Cottingham et al., 2014). Furthermore, as Black Bream are typically abundant in estuaries throughout southern Australia (Chuwen et al., 2009; Valesini et al., 2009), where they are among the most targeted finfish species by commercial and recreational fishers (Ryan et al., 2015). Due to this, an extensive database on their biological characteristics exists, thereby allowing the establishment of appropriate reference conditions (Morison et al., 1998; Sarre and Potter, 1999, 2000; Jenkins et al., 2010; Williams et al., 2013; Jenkins et al., 2015).

Monitoring changes in fish growth can provide implicit information on the environmental conditions of an estuary and also the nutrition value/availability of prey, which are typically available in a 'healthy' ecological functioning system (Cottingham et al., 2014; 2018a). The assessment of growth, however, requires the removal of otoliths (ear stones) resulting in death of the fish, which may be counterproductive in populations whose abundances have been reduced (Cottingham et al., 2015b; 2019). In contrast, body condition indices require data on only mass (weight) and length and thus can be undertaken with minimal stress on the fish. Furthermore, the factor(s) regulating the growth of Black Bream are closely linked to body condition and any tendency for body condition to decline will be accompanied by a reduction in energy reserves that could be used for growth (Cottingham et al., 2018a; 2019). Thus, tracking changes in body condition of Black Bream is an effective and non-lethal approach to detecting environmental changes in an estuary.

The aim of this study was to develop indicators for the condition and recruitment of Black Bream in the Wonnerup Inlet and Deadwater, which could be considered as a proxy for the broader fish community in the Vasse-Wonnerup using 'historical' data from 2012 to 2019 from previous studies, and data collected during November 2020 and January 2021 in the current study.

2. Materials and methods

2.1. Sampling regime for the Black Bream indices

Eight sites in both the shallow, nearshore (< 1.5 m) and deeper, offshore (> 1.5 m) waters of Wonnerup Inlet and the Deadwater regions of the Vasse-Wonnerup were sampled (Fig. 1). Fish in these two regions of the Vasse-Wonnerup were sampled as, in a previous two-year seasonal study across the entire system, 99.8% of the Black Bream recorded were found in Wonnerup Inlet and the Deadwater (Tweedley et al., 2014). This recruitment occurs (Beatty et al., 2018; 2021). Thus, sampling these downstream areas allows more representative catches of Black Bream to be obtained, rather than targeting them in areas where catches would be lower and far more variable. However, as interpretation was also supported by a more recent fish survey (Tweedley et al., 2021a). Moreover, tracking studies have shown that Black Bream in the Vasse-Wonnerup are highly mobile with adults swimming, on average, a minimum of 3 km per day and maximum of 45 km (Beatty et al., 2018). Furthermore, they utilise areas upstream and downstream of the surge barriers but congregate in downstream areas for spawning and this is where juvenile the strength of the spawning stock and consequently recruitment is influenced by population size, deleterious factors affecting the fish in other areas of the system (e.g. fish kills) would be able to be detected.

Sampling was designed to occur after the Black Bream have spawned, which in the Vasse-Wonnerup, typically takes place between July and October (Beatty et al., 2018) and the larval fish had reached at least 10 mm in total length (the size at which they start to be caught in 21.5 m seine nets). As spawning may occur at slightly different times of year depending on water temperature, sampling occurred in both spring (usually November) and summer (February). Sampling took place in November and February of each year between 2012 and 2018 and also in February 2019, November 2020 and January 2021 (Beatty et al., 2014; Tweedley et al., 2014; Cottingham et al., 2015b; Tweedley et al., 2016a; Cottingham et al., 2018c, b).

Fish (mainly juveniles, i.e. < 160 mm total length) which are present in the nearshore waters were sampled using a seine net that was 21.5 m long, consisted of two 10 m long wings (6 m of 9 mm mesh and 4 m of 3 mm mesh) and a 1.5 m long bunt made of 3 mm mesh. The seine net, which was laid parallel to the shore at a depth of 1.5 m and then hauled onto the beach, swept an area of 116 m^2. Two replicate samples were collected at eight sites, on each sampling occasion (Fig. 1). Adjacent offshore waters were sampled using a sunken composite multifilament gill net. It comprised eight 20 m long panels, each with a height of 2 m and containing a different stretched mesh size, i.e. 35, 51, 63, 76, 89, 102, 115 or 127 mm. Gill nets were set for one hour, to minimise any fish deaths and allow the release of fish alive to the water (Grixti et al., 2010). All fish were identified to species, counted, measured to the nearest 1 mm total length and weighed to the nearest gram before being released. The weight of each Black Bream was measured from samples collected previously in 2013-2015 and 2018 and 2019 taken from Cottingham et al. (2015b) and Cottingham et al. (2019), respectively.

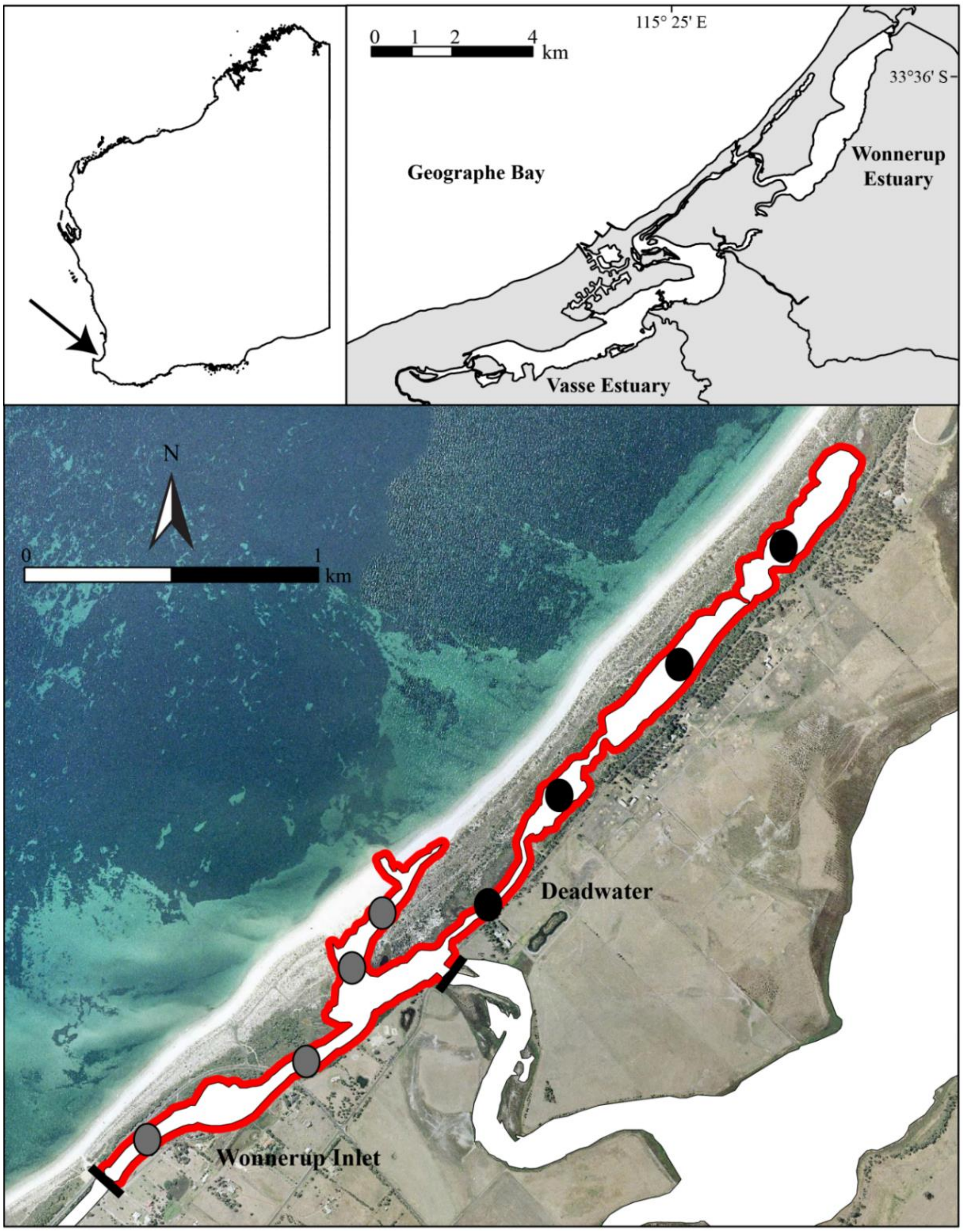

Fig. 1. Map showing the location of the eight sites in Wonnerup Inlet and the Deadwater at which fish were sampled in the shallow, nearshore (< 1.5 m) and deeper, offshore waters (> 1.5 m). Insets (top left) show the location of the Vasse-Wonnerup in Western Australia and (top right) the location of Wonnerup Inlet and the Deadwater within the Vasse-Wonnerup.

2.2. Calculation of body condition

The expected mass of adult Black Bream in the Vasse-Wonnerup Estuary, at a standardized length of 250 mm (the minimum legal length of fish able to be retained by recreational and commercial fishers), was calculated using ten randomly-selected fish from each of three length categories, <160, 180–220, >240 mm, and a reparameterized form of the mass-length relationship ($\ln M = \ln M_{250\ mm}\ a + b\ln[L/L_{250\ mm}]$). The equation, where ln is the natural logarithm, M and L are the estimated body mass (g) and total length (mm) of fish, respectively, and *a* and *b* are constants, was fitted using least squares regression. For more details of this approach see Cottingham et al. (2018a). This process was conducted using fish caught in each year where data are available. Note that although sampling extends across a calendar year, e.g. November 2020 and January 2021, the year referred to in the results is the former year, in this example 2020.

Reference conditions*,* a benchmark against which current and future trends in health measures are compared to, were derived from data compiled by Cottingham et al. (2018a) for six south-western Australian estuaries (i.e. Moore, Swan-Canning, Peel-Harvey, Walpole-Nornalup, Wilson and Wellstead) in 2013–15 and for four of those estuaries in 1993–96, using the same approach. The distribution of the expected mass of Black Bream at a total length of 250 mm were then divided into five grades. The five grades determined were grade *Excellent* (A; > 266.5 g), *Good* (B; 258.6-266.5 g), *Moderate* (C; 252.1-258.5 g), *Poor* (D; 241.1-252.0 g), and *Very poor* (E; < 241.1 g), with grade thresholds set at unequal quintiles of the data points (i.e. 12.5%, 37.5%, 62.5%, 87.5%; Hallett, 2014). This is the same methodology used by Cronin-O'Reilly et al. (2023) to develop an index for assessing the condition of the Vasse-Wonnerup using benthic invertebrates only using a single metric rather than multimeric approach. Note that as similar approach was not conducted from the fish community like that used in the Swan-Canning and Peel-Harvey estuaries (Tweedley et al., 2021b; 2022) on the recommendation of Tweedley et al. (2021a). These authors considered that the low diversity of fish species in regions above the surge barriers combined with the muddy sediment present during the warmer months lowering fishing efficiency would cause any index scores to be incorrect and/or highly-variable, potentially masking the true trend in health of the estuary.

2.3. Recruitment index

The mean density of juvenile (0+; < 160 mm total length) Black Bream (i.e. fish 100 m^{-2}) from 21.5 m seine net samples collected from the nearshore waters of the Wonnerup Inlet and Deadwater regions of the Vasse-Wonnerup in spring (typically November) and summer (typically February) between 2012 and 2021 were square-root transformed and used to construct a Euclidean distance matrix. This was, in turn, subjected to a two-way Permutational Analysis of Variance (PERMANOVA; Anderson et al., 2008) test to identify whether the density of Black Bream differed among Sampling occasion (season and year; 17 levels) and Region (2 levels). Both Sampling occasion and Region were considered fixed and the null hypothesis of no significant differences was rejected when the *P*-value was < 0.05. The percentage contribution made to the total value for the mean squares in each PERMANOVA test by the mean square for each factor and for each interaction between factors was calculated to provide an estimate of the relative importance of each factor and interaction (Crisp et al., 2018). When a significant difference in any main effect or interaction term was detected, a pairwise PERMANOVA test was conducted to identify the particular pairwise comparison(s) that were responsible for the difference. This was supplemented by examining back transformed plots of the marginal means.

Recruitment of fish including Black Bream is known to be naturally variable among years and estuaries. Thus, establishing reference conditions for a Black Bream population requires a long time series of data from the population in the estuary of interest. While such data are available in the Vasse-Wonnerup, i.e. 384 samples undertaken at the same suite of sites using an identical methodology across 24 seasons of data between February 2012 and January 2021 (e.g. Cottingham et al., 2019; current study), there are a number of reasons why all samples cannot be used. Firstly, seven of those samples were obtained in May (autumn) or August (winter) and 14 of the spring and summer samples were collected after a major fish kill in March 2013.

The replicate samples of the abundance of juvenile Black Bream in February 2012, November 2012 and February 2013 were each resampled 100 times using bootstrapping. The recruitment strength in each year (November and February combined to account for differences in the timing of spawning) was then assigned a health grade based on the same unequal quintiles of the data (12.5%, 37.5%, 62.5%, 87.5%) as used for the body condition index. These were *Excellent* (A; > 50.1 Black Bream 100m^{-2}), *Good* (B; 35.2-50.1 Black Bream 100m^{-2}), *Moderate* (C; 19.1-35,1 Black Bream 100m^{-2}), *Poor* (D; 7.3-19.0 Black Bream 100m^{-2}) and *Very poor* (E; < 7.3 Black Bream 100m^{-2}). Note that as with the body condition index, sampling was conducted in November of one year and January of the following year. However, as the adult fish would have spawned during the in the several months before November sampling, index scores are given for the year spawning occurred. Thus, the recruitment index score for 2020 is based on the results of sampling in November 2020 and January 2021.

3. Results

3.1. Body condition index

The average values for the weight of Black Bream at a total length of 250 mm (body condition index) throughout south-western Australia (i.e. the reference conditions) ranged from a minimum of 237 g in Wellstead Estuary in the 1990s to a maximum of 283 g in Swan-Canning Estuary in the 1990s. In the Vasse-Wonnerup, body condition was greatest in 2013 (263 g) and 2014 (261 g), with the corresponding grades of *Very good* (A) and *Good* (B), respectively (Fig. 4). In contrast, body condition index in 2018 fell to *Very poor* (E) with the weight of 234 the lowest of any Black Bream population assessed in south-western Australia. The average weight increased to 242g in 2020 resulted in the body condition index rising to *Poor* (D; Fig. 4).

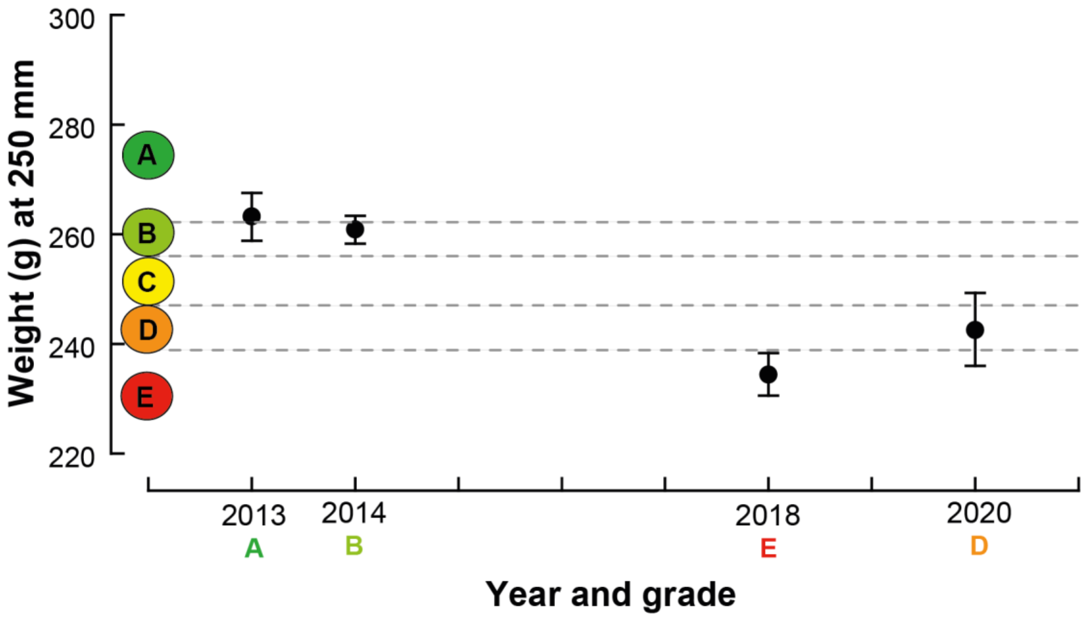

Fig. 4. Average body condition index scores (and 95% confidence interval) for Black Bream in the Vasse-Wonnerup between 2013 and 2020. Colour shading depicts the thresholds for each condition grade (*Excellent*, A to *Very poor,* E). Note that data were not available for all years.

3.2. Recruitment index

The abundance of juvenile Black Bream in the downstream areas of the Vasse-Wonnerup between January 2012 and February 2021 was found to differ between Regions (i.e. Wonnerup Inlet and the Deadwater) and over time (Table 1). The lack of an interaction the two main effects indicates that the temporal trends were fairly consistent in both regions (Table 1).

Juvenile Black Bream were almost twice as abundant in the Deadwater than Wonnerup Inlet, i.e. 13.14 *vs* 7.56 fish 100 m^{-2} (Fig. 5a). Densities changed markedly over time (Table 2), being greatest in February 2012 and 2013, i.e. 37 and 28 fish 100 m^{-2}, respectively, with a lower value in November 2012 (Fig. 5b). There was a large fish kill in April 2013, where an estimated 30,000 fish perished of which Black Bream were a major component. Recruitment was extremely limited in the two years afterwards with almost no juvenile Black Bream recorded in November 2013 or February 2014 and slightly greater densities in the following year (Fig. 5b). Densities increased in the subsequent seasons but varied from a maximum of 18, 17 and 16 fish 100 m^{-2} in the Novembers of 2015 and 2018 and February 2019, respectively, with lowest values of 2-6 fish 100 m^{-2} recorded in November 2018, February 2018 and the two sampling periods in the current study (November 2020 and January 2021; Fig. 5b).

When these data were used to produce the recruitment index scores, 2011/12 was *Very good* (A), declining slightly to *Good* (B) in 2012/13 (Fig. 6a). *Very poor* (E) scores were recorded in 13/14 following the fish kill, after which scores were *Poor* (D) or *Fair* (C) in all years except 18/19 when they were rated as *Good*.

Table 1. Mean squares (MS), percentage contribution of mean squares to the total mean squares (%MS), *pseudo-F* ratios (*pF*) and significance levels (*P*) from a two-way PERMANOVA test on the density of juvenile Black Bream recorded from 21.5 m seine nets in the shallow, nearshore waters of the Wonnerup Inlet and Deadwater regions of the Vasse-Wonnerup in February and November in most years between 2012 and 2021. *df* = degrees of freedom. Significant differences ($P < 0.05$) highlighted in bold.

Source	df	MS	%MS	*pF*	*P*
Season and year	**16**	**24.33**	**23.71**	**4.70**	**0.001**
Region	**1**	**64.98**	**63.32**	**12.54**	**0.001**
Season and year × Region	16	8.13	7.92	1.57	0.079
Residual	238	5.18	5.05		

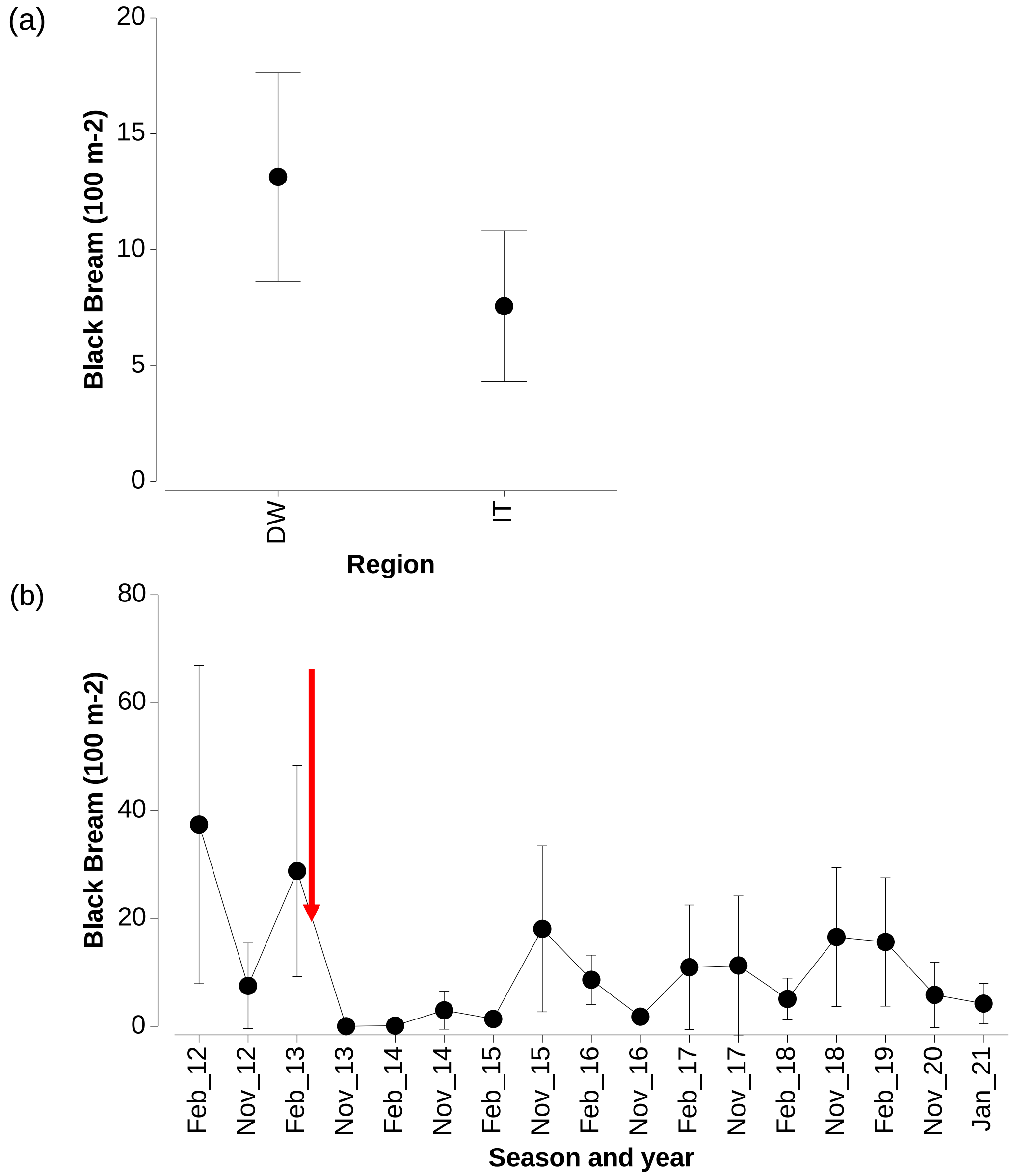

Fig. 5. Mean density of juvenile Black Bream (fish 100 m^{-2}) and 95% confidence intervals recorded from 21.5 m seine nets in the shallow, nearshore waters of the Wonnerup Inlet and Deadwater regions of the Vasse-Wonnerup in February and November in most years between 2012 and 2021. Red arrow denotes the approximate time at which the large fish kill occurred in April 2013.

Table 2. Pairwise *t*-statistic values and significance levels (*P*) for a pairwise PERMANOVA test on the density of juvenile Black Bream recorded from 21.5 m seine nets in the shallow, nearshore waters of the Wonnerup Inlet and Deadwater regions of the Vasse-Wonnerup in February and November in most years between 2012 and 2021. Significant pairwise comparisons ($P < 0.05$) are highlighted in grey.

		2012		2013		2014		2015		2016		2017		2018		2019	2020
		Feb	Nov	Feb	Nov	Feb	Nov	Feb	Nov	Feb	Nov	Feb	Nov	Feb	Nov	Feb	Nov
2012	Nov	1.516															
2013	Feb	0.331	2.753														
	Nov	2.997	3.060	5.660													
2014	Feb	2.926	2.882	5.520	1.000												
	Nov	2.217	1.248	4.104	2.691	2.374											
2015	Feb	2.479	1.819	4.644	2.543	2.078	0.715										
	Nov	0.599	1.325	1.295	3.976	3.841	2.516	3.005									
2016	Feb	1.082	0.906	2.212	5.282	5.014	2.619	3.465	0.671								
	Nov	2.238	1.307	4.266	4.112	3.518	0.063	0.972	2.609	2.871							
2017	Feb	1.275	0.327	2.309	3.043	2.895	1.489	1.991	0.958	0.462	1.545						
	Nov	1.102	0.677	2.107	3.768	3.598	1.989	2.568	0.705	0.123	2.092	0.308					
2018	Feb	1.660	0.166	3.131	3.842	3.575	1.308	2.068	1.585	1.252	1.423	0.513	0.919				
	Nov	0.608	1.498	1.379	4.786	4.613	2.933	3.553	0.022	0.788	3.095	1.073	0.803	1.832			
2019	Feb	0.503	1.654	1.221	4.924	4.754	3.092	3.708	0.171	0.965	3.259	1.223	0.961	1.999	0.164		
2020	Nov	1.600	0.086	2.980	3.525	3.299	1.305	1.988	1.475	1.099	1.397	0.428	0.812	0.085	1.691	1.855	
2021	Jan	1.824	0.437	3.532	4.991	4.525	1.220	2.225	1.894	1.737	1.404	0.778	1.246	0.315	2.234	2.408	0.387

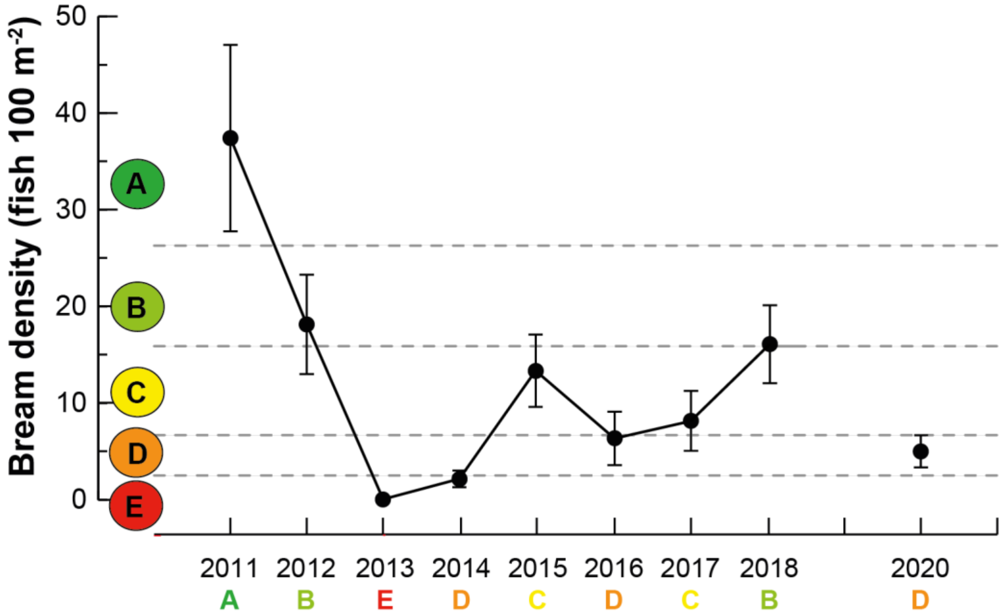

Fig. 6. Average recruitment index scores ± standard error for the abundance of juvenile Black Bream in the Vasse-Wonnerup between 2011/12 and 2020/21. Colour shading depicts the thresholds for each health grade from *Very good* (A) to *Very poor* (E). Note that data were not available for 2019.

4. Discussion

This study had aimed to use ‘historical’ data from 2012 to 2019 and data collected during the current study (November 2020 and January 2021) to develop indicators for i) the body condition of adult Black Bream and ii) the recruitment of juvenile Black Bream in the Vasse-Wonnerup, which could be considered as a proxy for health of the broader fish community.

4.1. Black Bream indices

As Black Bream typically remain within their natal estuary throughout life and contain ‘plastic’ biological characteristics that respond to environmental changes in a predictable way they are an ideal indicator species (Cottingham et al., 2014; Cottingham et al., 2018a). Moreover, while some biological parameters require individuals to be euthanised, acquiring data for body condition indices is non-lethal, can be measured in the field and so is an appropriate method for fish populations whose abundances have been reduced, e.g. due to fish kills, such as occurred in the Vasse-Wonnerup.

The current body condition indices for Black Bream (2020) was *Poor*, but this represents an increase from 2018 when it was *Very poor* and in fact, has the lowest body condition of any Black Bream population for which data has been acquired in south-western Australia (see Appendices 1,2). The low scores in recent years could indicate that the population has not been in good body condition for several years, however, it was encouraging that in 2013 and 2014 the body condition of Black Bream was rated as *Very good* and *Good*, respectively. Thus, current trends are not fixed. Moreover, although not truly representative as the ages of fish used in the body condition index were not measured as this results in their death, around 30% of the Black Bream that died in the June 2021 fish kill were spawned prior to 2013 and so would have been present in the system during each time body condition was measured (Tweedley, unpublished data).

Body condition is essentially the wet weight of the fish at a given length (250 mm) with higher weights being better. Thus, fish at a lower weight are deemed to be less healthy, which reflects the broader environment. Hypoxia is known to reduce the body condition of Black Bream, as they avoid deeper waters and congregate in the normoxic shallower waters and the increased density of fish increases competition for food resources (Cottingham et al., 2018a). In addition to altering the spatial distribution of Black Bream, hypoxia can negatively impact the abundance of invertebrate prey, thus directly impacting fish resources (Tweedley et al., 2016b; 2019a).

With respect to the Vasse-Wonnerup, protracted hypoxic conditions were not typically recorded during daylight hours in Wonnerup Inlet and the Vasse Exit Channel, the areas of the system most utilised by Black Bream (Tweedley et al., 2014; Beatty et al., 2018) during the three years of the Integrated Ecological Monitoring program (July

2017 to March 2020; Tweedley et al., 2019c; 2019b, 2021a). However it is likely that conditions were hypoxic for short periods (several hours) especially just before dawn, due to respiration from phytoplankton/macroalgae and diurnal cycles of dissolved oxygen concentrations in the 50 cm of water below the logger and in the sediments. (Lane et al., 1997; Tweedley et al., 2019a). While such conditions would likely not be persistent enough to preclude the presence of Black Bream, they may lower the abundance of their invertebrate prey. It is thus relevant that during their calculation of the Wetland Benthic Community Index (Cronin-O'Reilly et al., 2023) noted that the presence of azoic benthic samples (i.e. those without any benthic macroinvertebrates) was far higher in the Vasse Exit Channel that any other region of the system. Furthermore, average densities of benthic macroinvertebrates in the Vasse Exit Channel and Wonnerup Inlet (46 and 66 individuals 100 cm^{-2}, respectively) are considerably less than in the Swan-Canning and Peel-Harvey estuaries (96 to 319 individuals 100 cm^{-2})(Wildsmith et al., 2009; 2011). Thus, low prey availability may be a factor contributing to the current poor condition of Black Bream. Hypoxia is thought to have caused shifts in the diet and habitat use of Black Bream in the Swan-Canning Estuary between the 1990s and 2010s lowering body condition (Cottingham et al., 2018a).

This cannot be the only contributing factor, however, as a study in 2014 and 2015, when body conditions were *Good* to *Very good*, demonstrated that 82% of the diet of Black Bream (an opportunistic feeder; Whitfield et al., 2022) comprised macroalgae (Cottingham et al., 2015b; 2019). This food is of relatively low calorific and nutritional value when compared with molluscs and crustaceans, which are consumed far more regularly by Black Bream in other south-western Australian estuaries (Sarre et al., 2000; Chuwen et al., 2007; Cottingham et al., 2019). One potential additional explanation for the lower size of Black Bream could be predation. An Indo-Pacific Bottlenose Dolphin (*Tursiops aduncus*) was recorded during February 2018 and in both surveys in the current study (November 2020 and February 2021). This corresponds with lower catches of Black Bream and a decrease of 12 to 23 mm in mean length of fish (Cottingham et al., 2015b). This phenomenon was recorded in February of both 2017 and 2018 was also present for Sea Mullet and Yelloweye Mullet, and likely reflects the fact that dolphins are ectotherms (warm-blooded), have high metabolic rates and need to consume relative large quantities of fish (Fahlman et al., 2018). It seems that they preferentially target larger fish, which would have a better body condition.

An example of the relatively large impact dolphin predation can have on fish populations is provided by Nicholson et al. (2021) in the Peel-Harvey Estuary. These authors estimated that an adult dolphin (179 kg) would consume 9.3 – 11.3 kg of fish on a daily basis, with the 64 resident dolphins (39 adults and 25 juveniles) in that system consuming ~250,000 kg of fish annually, exceeding that removed by commercial fishers.

Trends in recruitment strength (i.e. the density of juvenile Black Bream) varied markedly among years, being far greater prior to the April 2013 fish kill. That fish kill is considered to have had a substantial effect on the juvenile (0+) and adult Black Bream populations as recruitment for the next two years (2013 and 2014) was very low. Seine netting showed that this coincided with a loss of the juvenile fish and although the adult population was not sampled prior to the event, the loss of a large number of adult fish would have reduced egg production. Recruitment increased in the years since (2015 to 2020) but will likely decline in future as a result of the most recent fish kill event in June 2021.

The data on the density of juvenile Black Bream provide evidence that recruitment occurs in most years in the Vasse-Wonnerup which is not true of all systems, with populations in the Blackwood River, Peel-Harvey Estuary (Murray River) and Gippsland Lakes in Victoria all having episodic recruitment (Potter et al., 2015b; Cottingham et al., 2020). Differences in the recruitment strength in the Vasse-Wonnerup between years not directly linked to a fish kill event are likely due to differences in the water temperature and freshwater flow, but it was beyond the scope of this study to investigate these.

4.3. Future directions

A suite of recommendations for future research with supporting rationales are outlined below.

1) *Estimate population size of adult Black Bream using capture-mark-recapture techniques.*

   Given the loss of substantial numbers of adult Black Bream in several large fish kills there is a need to estimate the size of the population in the Vasse-Wonnerup to facilitate understanding of the magnititude of the fish kills and help guide fisheries management. Intrepretation of the effects of the April 2013 fish kill on subsequent recruitment have been greatly facilitated by the collection of data before the event. However, monitoring of adult Black Bream only commenced after that event, thus estimating population size is the best approach to predicting what the population was like before.

2) *Monitor both juvenile recruitment and adult Black Bream population.*

   The seine and gill netting regime in the Deadwater and Wonnerup Inlet (see Cottingham et al., 2019) should be reestablished with sampling occuring in both November and February to match existing data. As recruitment was low for two years after that event, monitoring should continue for three years at least. This should include measuring the wet-weight of the Black Bream to allow calculation of the Body Condition Index and track this over time as this may be influenced by a reduction in abundance.

3) *Better understand the drivers of Black Bream movement around the fish gate in relation to environmental conditions.*

In 2017, 322 Black Bream were tagged with a Passive Integrated Transponder (PIT) tags (i.e. the same as used when microchipping pets) and a monitoring system installed in the fish gate on the Vasse surge barrier. Many of these fish tagged four years earlier would have died prior to the fish kill (e.g. from predation etc), but four of the remaining fish did travel form the Vasse Exit Channel (the site of the fish kill) through the fish gate into Wonnerup Inlet. Results from 2017 and 2018 are described in Beatty et al. (2021).

The study revealed that Black Bream passage was strongly influenced by hydrology and they favoured passage when the water velocity in the fish gate chute were lowest, which occurred when the water levels upstream and downstream of the surge barrier were relatively similar. When the dissolved oxygen upstream of the surge barrier was good, fewer fish passaged downstream to the Wonnerup Inlet but this was a relatively weak effect and it remains unclear as to the dissolved oxygen trigger values for passage. As the PIT tags last for 20 years, there is a need to similarly analyse the patterns of fish passage that have occurred during subsequent fish gate operation periods of 2018-19, 2019-20 and 2020-21 (when the fish kill occurred). Moreover, by tagging more Black Bream and other species that are found upstream and downstream of the surge barrier, longer term drivers of fish passage can also be quantified. This will further help to refine the management of the fish gates to help facilitate fish passage during periods of poor water quality such as developing triggers for fish gate opening.

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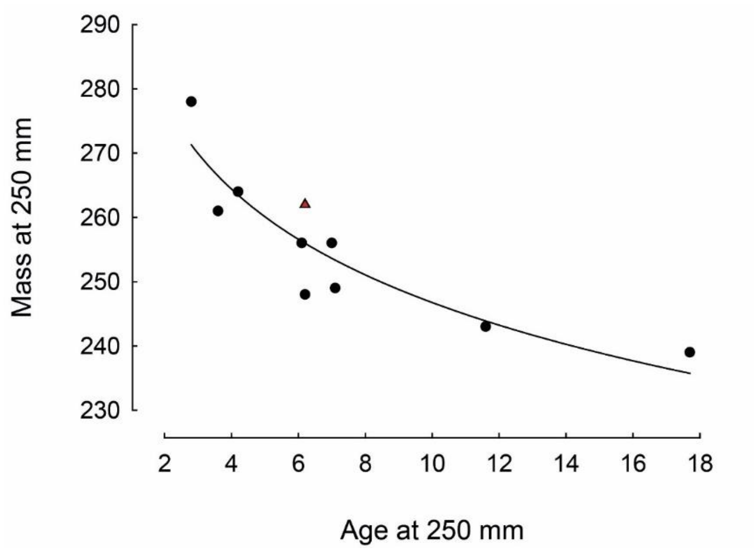
6. Appendices

Appendix 1. Body condition index (weight at a total length of 250 mm) of Black Bream in estuaries on the west and south coasts of south-western Australia in the 1990s and 2010s.

Estuary	2010s Weight (g) at 250 mm	1990s Weight (g) at 250 mm
Moore River	243	256
Swan-Canning Estuary	256	278
Peel-Harvey Estuary	264	No data
Blackwood Estuary	238	No data
Walpole-Nornalup Estuary	239	248
Wellstead Estuary	249	237



Appendix 2. Relationship between growth (age at 250 mm) and body condition (weight at 250 mm) of Black Bream in various estuaries in south-western Australia.