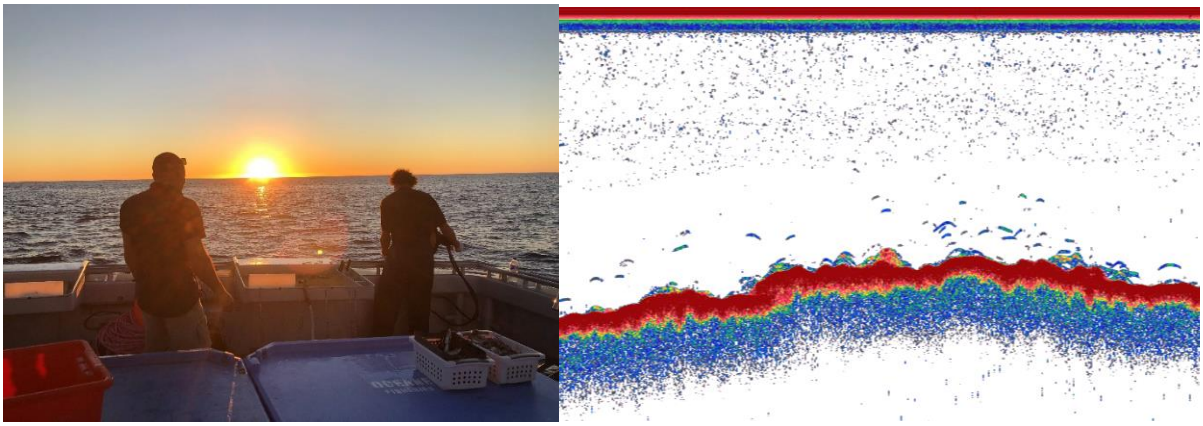
Where did the Snapper go?
Determining factors influencing the recovery of Snapper (*Chrysophrys auratus*) stocks on the West coast of Australia



Gary Jackson, David Fairclough, Emily Fisher, Yasha Hetzel, Mirjam Van Der Mheen, Ben Scoulding, Bronwyn Gillanders, Patrick Reis-Santos, Luciano B. Beheregaray, Jonathan Sandoval-Castillo and Matias Braccini

2023

FRDC Project No 2018-050

© 2023 Fisheries Research and Development Corporation.
All rights reserved.

ISBN 978-1-925415-01-8

Where did the Snapper go? Determining factors influencing the recovery of Snapper (*Chrysophrys auratus*) stocks on the West coast of Australia

FRDC Project 2018-050

2023

Ownership of Intellectual property rights

Unless otherwise noted, copyright (and any other intellectual property rights, if any) in this publication is owned by the Fisheries Research and Development Corporation, Department of Primary Industries and Regional Development Western Australia, University of Western Australia, University of Adelaide, Flinders University and CSIRO Marine Research.

This publication (and any information sourced from it) should be attributed to Jackson, G., Fairclough D.V., Fisher, E.A., Hetzel, Y., Van Der Mheen, M., Scoulding, B., Gillanders, B.M., Reis-Santos, P., Beheregaray, L.B., Sandoval-Castillo, J. and Braccini M., 2023. Where did the Snapper go? Determining factors influencing the recovery of Snapper (*Chrysophrys auratus*) stocks on the West coast of Australia. Final Report on FRDC Project No. 2018-050. Perth, Western Australia.

Creative Commons licence

All material in this publication is licensed under a Creative Commons Attribution 3.0 Australia Licence, save for content supplied by third parties, logos and the Commonwealth Coat of Arms.

Creative Commons Attribution 3.0 Australia Licence is a standard form licence agreement that allows you to copy, distribute, transmit and adapt this publication provided you attribute the work. A summary of the licence terms is available from https://creativecommons.org/licenses/by/3.0/au/. The full licence terms are available from https://creativecommons.org/licenses/by-sa/3.0/au/legalcode.

Inquiries regarding the licence and any use of this document should be sent to: frdc@frdc.com.au

Front cover images as follows:

(Left) Snapper fishing off Koks Island, Shark Bay, Western Australia (photo DPIRD), (Right) echogram of snapper-like demersal fish (image CSIRO).

Disclaimer

The authors do not warrant that the information in this document is free from errors or omissions. The authors do not accept any form of liability, be it contractual, tortious, or otherwise, for the contents of this document or for any consequences arising from its use or any reliance placed upon it. The information, opinions and advice contained in this document may not relate, or be relevant, to a reader's particular circumstances. Opinions expressed by the authors are the individual opinions expressed by those persons and are not necessarily those of the publisher, research provider or the FRDC.

The Fisheries Research and Development Corporation plans, invests in and manages fisheries research and development throughout Australia. It is a statutory authority within the portfolio of the federal Minister for Agriculture, Fisheries and Forestry, jointly funded by the Australian Government and the fishing industry.

Researcher Contact Details
Name: Gary Jackson
Address: Western Australian Fisheries & Marine Research Laboratories
39 Northside Drive
Phone: Hillarys WA 6025
Email: 08 9203 0191
gary.jackson@dpird.wa.gov.au

FRDC Contact Details
Address: 25 Geils Court
Deakin ACT 2600
Phone: 02 6122 2100
Email: frdc@frdc.com.au
Web: www.frdc.com.au

In submitting this report, the researcher has agreed to FRDC publishing this material in its edited form.

Contents

List of Tables ..... **v**

List of Figures ..... **vii**

Acknowledgments ..... **xiii**

Abbreviations ..... **xiv**

Executive Summary ..... **xv**

Overview xv
Background xv
Objectives xvi
Methodology xvi
Results/Key Findings xvii
Implications for relevant stakeholders xviii
Recommendations xviii
Keywords xix

1. Introduction **1**

1.1 Background 1
1.2 Need 3

2. Objectives **4**

3. Genomics to improve understanding of Snapper stock connectivity on the Australian west coast **5**

3.1 Introduction 5
3.2 Methods 5
3.3 Results 6
3.4 Discussion/Conclusion 13

4. Otolith microchemistry to improve understanding Snapper stock connectivity and identify nursery areas in the Gascoyne & West Coast bioregions **14**

4.1 Introduction 14
4.2 Methods 14
4.3 Results 16
4.4 Discussion/Conclusion 19

5. Ocean circulation modelling to investigate Snapper egg and larval dispersal between Gascoyne & West Coast bioregions **20**

5.1 Introduction 20
5.2 Methods 23
5.3 Results 27
5.4 Discussion/Conclusion 50

6. Evaluating the use of active acoustic methods for monitoring the distribution and abundance of Snapper in spawning aggregations 52
6.1 Introduction 52
6.2 Methods 52
6.3 Results 56
6.4 Discussion/Conclusion 60
7. Investigating changes in Snapper biology in the Gascoyne and West Coast bioregions of Western Australia 61
7.1 Introduction 61
7.2 Methods 62
7.3 Results 70
7.4 Discussion/Conclusion 98
8. Conclusions 101
9. Implications 102
10.Recommendations 103
10.1 Further development 103
11.Extension and Adoption 104
11.1 Project coverage 104
12.Project materials developed 105
Appendix 1 - List of Researchers and Project Staff 106
Appendix 2 - References 107
Appendix 3 - Supplementary Information 114
Chapter 3 114
Chapter 4 115
Chapter 5 116
Chapter 7 126

List of Tables

Table 3.1. Levels of genomic variation in *C. auratus* sampled from seven localities in WA based on 15,839 filtered SNPs. For most localities, samples were divided into adults (-A) and juveniles (-J). Other abbreviations are number of individuals genotyped (n), proportion of polymorphic loci (PL%), observed (Ho) and expected heterozygosity (He)........ 6

Table 3.2. Pairwise levels of genomic differentiation based on F_{ST} for *C. auratus* sampled from seven localities in WA. Analysis is based on 15,839 filtered SNPs. For most localities, samples were divided in adults (-A) and juveniles (-J). F_{ST} values are under the diagonal, p values from significance tests are over the diagonal. Bold values are comparisons significant at 5% false discovery rate. Values in red and underlined correspond to comparisons between adults and juveniles from the same locality. Shark Bay (SHB), Kalbarri (KAL), Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS), adults (-A) juveniles (-J). 8

Table 4.1. Juvenile habitat use classification accuracy using edge otolith chemistry of juvenile *C. auratus*. Results show the cross validated correctly classified individuals (%) of juveniles assigned to their location of capture, including all locations within the Mid-West region, as well as by pooling all locations within the Mid-West region (n=227). Gascoyne (GAS), Mid-West (MIW), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS). Note there are no otoliths from juveniles collected in Kalbarri. 17

Table 4.2. Adult habitat use discrimination based on classification accuracy from canonical analysis of principle coordinates (CAP) using edge otolith chemistry of adult *C. auratus*. Results show the cross validated correctly classified individuals (%) of adults to their location of capture, including all locations within the Mid-West region, as well as by pooling locations within the Mid-West region (n=243). Gascoyne (GAS), Kalbarri (KAL), Mid-West (MIW), and locations therein Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB). Note there are no otoliths from adults collected in Cockburn Sound. 18

Table 5.1. Dates of new and full moons in the months of June, July, and August for each of the simulation years. Particles were released hourly on these dates and 2 days before and after these dates. *Note that 2010 and 2019 were only included in the high-resolution Shark Bay model run; **2012 and years before 2010 were only simulated in the regional OzRoms model runs. 24

Table 5.2. Quantitative comparison of model skill between the CWA-ROMS model in Shark Bay where observations of currents and sea level were available from previous field work undertaken by UWA in 2009 and 2011........ 25

Table 6.1. List of aggregating fish species observed by the unbaited remote underwater video cameras. TS-L group refer to the target strength to length relationship applied to each group (see Fig. 2B). Mean fork length (FL in cm, ± 1 SD) was determined from stereo length measurements. N is the number of fish measured. The FL to total weight (TW) equation for Pink snapper took the form of $TW = 2.8416 * log(FL, mm) - 9.8054$ and is based catches made in Shark Bay from 2018-2022 Bay and were taken from the Department of Primary Industries and Regional Development (DPIRD), WA, database. FL-TW for all other species fitted the linear regression equation $\mathrm{TW} = aLW * FLbLW$ with units for length and weight given in the table. Constants for the equations were taken from various sources, 1 = DPIRD database, 2 = Smallwood et al. (2018), 3 = FishBase (accessed November 2021) (Froese & Pauly, 2022), 4 = Al-Marzouqi et al. (2013), and 5 = Parsa et al. (2017). Figure and legend taken from Scoulding et al. (2023). 59

Table 7.1. Estimated mean lengths (mm TL) of female and male *C. auratus* at ages 5, 10, 15 and 20 y in the Gascoyne, Kalbarri and Mid-West, calculated from von Bertalanffy growth parameters estimated from available data for each sex and area. 71

Table 7.2. Estimated von Bertalanffy growth parameters for female and male *C. auratus* in the Gascoyne, based on data for ages 4-25 y sampled across different sampling periods. 72

Table 7.3. Estimated von Bertalanffy growth parameters for female and male *C. auratus* in Kalbarri, based on data for ages 4-25 y sampled across different sampling periods. 75

Table 7.4. Estimated von Bertalanffy growth parameters for female and male *C. auratus* in the Mid-West, based on data for ages 4-25 y sampled across different sampling periods. 78

Table 7.5. Estimates (±95% CLs) of parameters a and b of the linear relationship between the natural logarithms of total length (mm TL) and weight (g) for female and male *C. auratus* in each management area, and for these areas combined... 81

Table 7.6. Estimates (and associated 95% CLs) of the ages and lengths at which 50% and 95% of female and male *C. auratus* have attained maturity in the Gascoyne, based on data from the peak spawning period (June – August) grouped by decadal sampling periods, and combined across these periods................... 87

Table 7.7. Estimates (and associated 95% CLs) of the ages and lengths at which 50% and 95% of female and male *C. auratus* have attained maturity in Kalbarri, based on data from the peak spawning period (June – August) grouped by decadal sampling periods, and combined across these periods. 89

Table 7.8. Estimates (and associated 95% CLs) of the ages and lengths at which 50% and 95% of female and male *C. auratus* have attained maturity in the Mid-West, based on data from the peak spawning period (June – August) grouped by decadal sampling periods, and combined across these periods................... 91

Table 7.9. Numbers of *C. auratus* by length class (cm FL) and cohorts for trawl surveys in Denham Sound (DS) and Outer Bay (OB). 92

Table 7.10. Number of *C. auratus* of 0+ cohort by length class (cm FL) and year born based on growth model of Tapp (2003) for Denham Sound (DS) and Outer Bay (OB). 93

List of Figures

Figure 1.1. Map showing the four fishery bioregions of Western Australia (NCB, North Coast Bioregion, GCB, Gascoyne Coast Bioregion; WCB, West Coast Bioregion; SCB, South Coast Bioregion), and the management areas of the WCB. 2

Figure 3.1. Admixture (structure) plot representing the population genomic structure of *C. auratus* in WA. Analysis was based on 15,839 filtered SNPs. Gascoyne (GAS), Mid-West (MIW), Shark Bay (SHB), Kalbarri (KAL), Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS), adults (-A) juveniles (-J) 9

Figure 3.2. Principal components analysis of *C. auratus* from seven localities in WA. Analysis is based on 15,839 filtered SNPs. The first two PCAs explain 1.2% of the total variation. Shark Bay (SHB), Kalbarri (KAL), Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS). Adults (-A), juveniles (-J). 10

Figure 3.3. Pairwise genomic differentiation based on F_{ST} of *C. auratus* from seven localities in WA. Analysis is based on 15,839 filtered SNPs. F_{ST} values under the diagonal, p values over the diagonal. Bold values are significant at 5% false discovery rate. Values underlined correspond to comparisons between adults and juveniles form the same locality. Shark Bay (SHB), Kalbarri (KAL), Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS). Adults (-A), juveniles (-J). 11

Figure 3.4. Principal components analysis comparing adults (-A) and juveniles (-J) *C. auratus* from five localities in WA. Analysis is based on 15,839 filtered SNPs. Shark Bay (SHB), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS). First two PCAs explain 1.2% of the total variation. 12

Figure 3.5. Spatial autocorrelation analysis of C. auratus in the four regions of Gascoyne (GAS), Mid-West (MIW), Kalbarri (KAL) and Cockburn Sound (COS). The Y axis represents the spatial autocorrelation coefficient (r). Dashed red lines are the 95% CIs around the null hypothesis of randomly distributed genotypes (no autocorrelation), estimated with 1000 permutations. Blue bars are the r values for each region and black whiskers are the r values 95% CIs, estimated with 1000 bootstraps. All estimated r values were significant ($P < 0.05$) 13

Figure 4.1. Ordination plot of the canonical analysis of principle coordinates (CAP) for multivariate elemental composition of the edge of otoliths of juvenile *C. auratus* collected along Gascoyne and the West Coast Bioregions. Analyses were performed with all locations within the Mid-West region (left), as well as by pooling locations within the Mid-West region (right). Gascoyne (GAS), Mid-West (MIW), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS). Classification and overall correctly assigned individuals (%) are summarised in Table 4.1. 17

Figure 4.2. Ordination plot of the canonical analysis of principle coordinates (CAP) for multivariate elemental composition of the edge of otoliths of adult *C. auratus* collected along Gascoyne and the West Coast Bioregions. Analyses were performed with all locations within the Mid-West region (left), as well as by pooling locations within the Mid-West region (right). Gascoyne (GAS), Kalbarri (KAL), Mid-West (MIW), and locations therein Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB). Classification and overall correctly assigned individuals (%) are summarised in Table 4.2. 18

Figure 4.3. Ordination plot of the non-metric multidimensional scaling (nMDS) for the near core multivariate elemental composition of adult *C. auratus* of different cohorts (2012, 2014, and 2016) collected along the Gascoyne and the West Coast bioregions. Locations within the Mid-West region are pooled. Gascoyne (GAS), Kalbarri (KAL), Mid-West (MIW) (locations therein Abrolhos, Geraldton, Dongara, Jurien Bay). 19

Figure 5.1. (a) Overview of particle release sites along the West Australian coast (red dots). Red dots in (b) correspond to known *C. auratus* spawning sites, whilst the particle release sites in (c) and (d) represent potential spawning areas as specific spawning sites are not yet known in those regions. Black outlines show the division of the area into three regions: (b) Shark Bay; (c) Kalbarri; and (d) Mid-West. Shark Bay is divided

into three sub-regions (dashed black outlines). The red outlines show the boundaries used to determine connectivity between the different sites. Grey contours show the depth in meters. The model domain extended along the entire west coast, but all particle trajectories remained with the bounds shown in (a). 21

Figure 5.2. Location map for the high-resolution dispersal model for Shark Bay. The model domain extended along the west coast between NW Cape and Cape Leeuwin. Particle release sites are indicated with red X, blue dots show locations where 0+ and 1+ *C. auratus* are regularly recorded, bounded by black polygons (potential settlement areas) that were used to determine which particles were successful. 22

Figure 5.3. Percentage of particles averaged over all release sites that were 'successful' at reaching the nursery areas inside Shark Bay (polygon shown in Figure 5.2), for different drift duration windows (a-d) for each release around new and full moons (+/- 2days). Particles that passed through the nursery polygon within the temporal window (e.g. between days 15-33) were deemed successful. The 15-33 day window (c) was used for subsequent analysis. Note varying y-axis limits for clarity. 26

Figure 5.4. Mean particle density (for any age particle) over all 6 simulation years for: (a) the entire West coast; (b, c, d) Shark Bay region 1, 2, and 3; (e) Kalbarri region; and (f) the Mid-West region. Excluding particles <15 days showed negligible differences compared to this figure and is not shown. 28

Figure 5.5. Mean drift time for all particles passing through each grid cell over all 6 simulation years for (a) the entire West coast; (b, c, d) Shark Bay region 1, 2, and 3; (e) Kalbarri region; and (f) the Mid-West region. 29

Figure 5.6. Histogram of maximum linear particle advection distance (position after 33 days – release location), showing the probability (y-axis) of particles drifting a specific distance (x-axis) over all sites (a) and from their 11 release locations (k-l) during 2014. Other years (not shown) showed similar results. . 30

Figure 5.7. Connectivity matrix for the 11 *C. auratus* spawning sites for all 6 simulation years (lower resolution OzRoms model) with colour shading representing the percentage of age 15+ day particles passing through connectivity boxes shown in Figure 5.1. The columns (labeled across top of x-axis) show the locations that particles are coming from ("source") and the rows show the locations that particles arrive in ("sinks") (labeled along y-axis). The numbers in each cell show the shortest drift time and the mean drift time for any particles in the Kalbarri Inshore location came from: Turtle Bay (0-5%), Kalbarri Inshore (45+%), and Kalbarri Offshore (0-5%) (shading). Any particles released at Turtle Bay that arrived at Kalbarri Inshore, were at least 11.5 days old with mean drift time of 28.2 days (numbers overlaid on shading). 31

Figure 5.8. Average particle density maps for the high-resolution simulations in Shark Bay for 2011 (left) and 2014 (right) showing the likelihood particles released from each site passed through a given grid cell. Use of all particles decreased bias due to low numbers of particles and highlighted subtle differences between years. Filtering particles to remove young particles did not change overall patterns. 33

Figure 5.9. Average particle density maps for the high-resolution simulations in Shark Bay for 2010 showing the likelihood particles released from each spawning site passed through a given grid cell at any time. Note the higher density of particles outside of the bay compared to Figure 5.8. Black dots indicate corresponding release sites. Use of all particles decreased bias due to low numbers of particles and highlighted subtle differences between years. Filtering particles to remove young particles did not change overall patterns. 34

Figure 5.10. Histogram of linear particle advection distance (position after 33 days – release location), showing the probability (y-axis) of particles drifting a specific distance (x-axis) over all sites (a) and from their 7 release locations (b-h). These data are a composite of all years simulated and are also indicative of individual year patterns as overall drift distances did not vary greatly between years. 35

Figure 5.11. Mean drift time of (any) particles passing through grid cells for 2011 (left) 2014 (right). Black dots indicate corresponding release sites. 36

Figure 5.12. Connectivity matrix for the 7 *C. auratus* particle release sites (age 15-33 day particles) for years: (a) 2010, (b) 2011, (c) 2014, (d) 2019. The columns show the “source” of particles and the rows show where particles arrive to (“sinks”). Boxes defining source/sink sites are shown in Figure 5.2. Colours indicate % of particles arriving in a location (the matrix is row normalized). Transport into settlement areas within the bay are shown in Figures 17-20. 37

Figure 5.13. Tracks of 50 randomly selected particles released from Cuvier that were successful (left) and unsuccessful (right) at reaching the settlement areas defined with the blue and black polygons. 39

Figure 5.14. Tracks of 50 randomly selected particles released from Carmellas1 that were successful (left) and unsuccessful (right) at reaching the settlement areas defined with the blue and black polygons. 40

Figure 5.15. Tracks of 50 randomly selected particles released from Turtle Bay that were successful (left) and unsuccessful (right) at reaching the settlement areas defined with the blue and black polygons. 41

Figure 5.16. GPS Drifter release and trajectory in northern Shark Bay in June 2009 showing northward drift between Naturaliste Channel and Northern *C. auratus* spawning sites (adapted from Kangas et al. 2012). 42

Figure 5.17. Relative percentage of ‘successful’ particles that passed into settlement areas in Shark Bay between 15 and 33 days after release. (a) shows relative success for each of the spawning release sites averaged over the entire spawning season (June-August); (b) shows relative success for each lunar release (within +/-2 days of new/full moon dates) averaged over all 7 release sites. 43

Figure 5.18. Bubble plot showing relative success of particles grouped by release date (x-axis) and release site (y-axis). The size of the circles is proportional to the number of particles that reached settlement areas after 15 days. (a) shows data for 2011 and (b) shows data for 2014. 44

Figure 5.19. Success of particles grouped by release dates in 2011 surrounding new and full moons (+/- 2 days). Arrows show mean daily wind speed and direction from ERA5 model. Low success occurred when winds blew from the east or south and high success occurred when winds were weak or from the north and west. 46

Figure 5.20. Success of particles grouped by release dates in 2014 surrounding new and full moons (+/- 2 days). Arrows show mean daily wind speed and direction from ERA5 model. Low success occurred when winds blew from the east or south and high success occurred when winds were weak or from the north and west. 47

Figure 5.21. Bureau of Meteorology synoptic weather charts showing conditions causing (a) poor success; (b) high success for particles in Shark Bay. The low/high success shown in (c) resulted from persistence of these conditions in the days/weeks following these particle releases. 48

Figure 5.22. Daily mean wind speed (m/s) and direction at Shark Bay from ERA5 model for simulated winters in both low-resolution and high-resolution numerical models. New and full moon dates coinciding with particle release dates are shown. 49

Figure 5.23. Maps of July average mean sea level pressure (MSLP) and wind anomalies for (a) 2010 and (b) 2011 derived from the ERA5 atmospheric reanalysis and calculated against the 1992-2016 climatology. July 2010 experienced stronger more easterly and southerly winds caused by a persistent high pressure to the southwest of the state; July 2011 was characterized by weaker more variable winds and a low pressure anomaly. 50

Figure 6.1. Flow graphic of the analytical methods applied to an *acouptics* survey, moving from raw data sources and types, to combined acoustics and optics species-specific density estimates and habitat information. Figure and legend taken from Scoulding et al. (2023). 54

Figure 6.2. A) the three acoustic categories (snapper-like, probable Yellowtail scad, and unknown small pelagic fish), B) examples frames from neat-concurrent deployments of remote underwater video, and C) the five-target strength (*TS*) to length (*L*) groups used in the interpretation and analysis of the acoustic

data. Group *TS-L* equations are given at 38 kHz, where aTS is the slope and bTS is the intercept. Figure and legend taken from Scoulding et al. (2023). 55

Figure 6.3. Shows processing workflow used to partition acoustic backscatter and estimate biomass of aggregating fish species. Figure and legend taken from Scoulding et al. (2023). 56

Figure 6.4. Map of the survey area (closed fishing area) with integrated backscatter (circles proportional to $\sqrt{s_A}$, scaled to the largest observation of 126,449 m^2 nmi^{-2}) of snapper-like (yellow), unknown small pelagic fish (blue) and probable yellowtail scad (orange) by 50 m intervals along the cruise track during the 2020 *acouptics* survey at 38 kHz. The black lines show the cruise track. The inset maps show Western Australia (right) and Shark Bay (left), with the black rectangles showing Shark Bay and closed fishing area, respectively. Figure and legend taken from Scoulding et al. (2023). 57

Figure 6.5. Map of the closed fishing area in Shark Bay, WA, showing the vessel cruise track (black dotted line) during the *acouptics* survey in July 2020. The survey consisted of broadscale transects (500 m spacing) and a series of fine resolution surveys (20-50 m spacing). The pie charts point to the locations of remote unbaited video stereo camera deployments with the pieces showing the proportions of different aggregating fish species. The black dots show the locations of camera drops used to validate acoustic habitat classification. Grey shading indicates bathymetry to a maximum depth of 70 m. Figure and legend taken from Scoulding et al. (2023). 58

Figure 7.1. Trawl research survey locations in Denham Sound (Western Gulf - DS Prawn sites, Scallop, Leads) and other locations collectively referred to as 'Outer Bay'. Survey locations in Eastern Gulf and Freycinet Estuary (black triangles and diamonds, respectively) were the focus of earlier research on inner gulf *C. auratus* stocks... 66

Figure 7.2. Length frequency of *C. auratus* recorded during trawl surveys conducted in different seasons at outer bay (OB) locations 2002-2021 to show 0+ fish first appearing at around 6 cm FL in spring surveys (e.g. OB-2017, OB-2019)... 68

Figure 7.3. Numbers of 0+ *C. auratus* recorded by month and year born (all survey years combined) from Denham Sound (DS) and Outer Bay (OB) survey areas, indicating peak spawning period May-July.......... 69

Figure 7.4. Lengths (mm TL) at age (4-25 y) of female and male *C. auratus* in each management area, with von Bertalanffy growth curves fitted separately to available data for each sex in the Gascoyne (green lines), Kalbarri (teal lines) and Mid-West (blue lines)... 70

Figure 7.5. Lengths (mm TL) at age (4-25 y) of female and male *C. auratus* in the Gascoyne, with von Bertalanffy growth curves fitted separately to available data for each sex collected in 1991-2000 (red lines), 2001-2010 (orange lines) and 2011-2020 (purple lines). 72

Figure 7.6. Observed lengths (mm TL) of individual cohorts (4-7 y) of female and male *C. auratus* in the Gascoyne for years with adequate sample sizes (>150 fish across both sexes, with at least 10 fish in each cohort/year). The horizontal line in each boxplot denotes the mean length, the box represents the first and third quartiles (25th and 75th percentiles, respectively) and the whiskers show the minimum and maximum values.. 73

Figure 7.7. Lengths (mm TL) at age (4-25 y) of female and male *C. auratus* in Kalbarri, with von Bertalanffy growth curves fitted separately to available data for each sex collected in 2001-2010 (orange lines) and 2011-2020 (purple lines). 75

Figure 7.8. Observed lengths (mm TL) of individual cohorts (4-7 y) of female and male *C. auratus* in Kalbarri for years with adequate sample sizes (>150 fish across both sexes, with at least 10 fish in each cohort/year). The horizontal line in each boxplot denotes the mean length, the box represents the first and third quartiles (25th and 75th percentiles, respectively) and the whiskers show the minimum and maximum values.. 76

Figure 7.9. Lengths (mm TL) at age (4-25 y) of female and male *C. auratus* in the Mid-West, with von Bertalanffy growth curves fitted separately to available data for each sex collected in 2001-2010 (orange lines) and 2011-2020 (purple lines)... 78

Figure 7.10. Observed lengths (mm TL) of individual cohorts (4-7 y) of female and male *C. auratus* in the Mid-West for years with adequate sample sizes (>150 fish across both sexes, with at least 10 fish in each cohort/year). The horizontal line in each boxplot denotes the mean length, the box represents the first and third quartiles (25th and 75th percentiles, respectively) and the whiskers show the minimum and maximum values.......... 79

Figure 7.11. Estimated relationships between the natural logarithms of total length (mm TL) and weight (g) for female and male *C. auratus* in the Gascoyne (green lines) and Mid-West (blue lines) management areas, noting no separate relationship was calculated for Kalbarri due to small sample of fish with known weights. 80

Figure 7.12. Estimated logistic curves of the proportions of mature female and male *C. auratus* at length (mm TL) in each management area during the key spawning period (June – August). The curves were fitted separately to data for each sex from the Gascoyne (green lines), Kalbarri (teal lines) and Mid-West (blue lines). 82

Figure 7.13. Estimated logistic curves of the proportions of mature female and male *C. auratus* at age (y) in each management area during the key spawning period (June – August). The curves were fitted separately to data for each sex from the Gascoyne (green lines), Kalbarri (teal lines) and Mid-West (blue lines). 83

Figure 7.14. Estimated logistic curves of the proportions of mature female and male *C. auratus* at length (mm TL) in the Gascoyne during the key spawning period (June – August). The curves were fitted separately to data for each sex from 1981-1990 (grey lines), 2001-2010 (orange lines) and 2011-2020 (purple lines). 85

Figure 7.15. Estimated logistic curves of the proportions of mature female and male *C. auratus* at age in the Gascoyne during the key spawning period (June – August). The curves were fitted separately to data for each sex from 2001-2010 (orange lines) and 2011-2020 (purple lines). 86

Figure 7.16. Estimated logistic curves of the proportions of mature female and male *C. auratus* at length (mm TL) in Kalbarri during the key spawning period (June – August). The curves were fitted separately to data for each sex from 2001-2010 (orange lines) and 2011-2020 (purple lines). 88

Figure 7.17. Estimated logistic curves of the proportions of mature female and male *C. auratus* at age in Kalbarri during the key spawning period (June – August). The curves were fitted separately to data for each sex from 2001-2010 (orange lines) and 2011-2020 (purple lines). 89

Figure 7.18. Estimated logistic curves of the proportions of mature female and male *C. auratus* at length (mm TL) in the Mid-West during the key spawning period (June – August). The curves were fitted separately to data for each sex from 2001-2010 (orange lines) and 2011-2020 (purple lines). 90

Figure 7.19. Estimated logistic curves of the proportions of mature female and male *C. auratus* at age in the Mid-West during the key spawning period (June – August). The curves were fitted separately to data for each sex from 2001-2010 (orange lines) and 2011-2020 (purple lines). 91

Figure 7.20. Cohorts of *C. auratus* from trawl surveys at Outer Bay locations by survey year and month 2002 to 2021. Individual cohorts are colour coded as indicated. 94

Figure 7.21. Cohorts of *C. auratus* from trawl surveys at Denham Sound locations by survey year and month 2000 to 2021. Individual cohorts are colour coded as indicated. 95

Figure 7.22. Mean nominal catch rates (with 95% CI) for 0+ *C. auratus* for Denham Sound (DS) and Outer Bay (OB), by year born and season during which trawl survey was undertaken. N.B. catch rates here do not include zero counts of 0+ during each trawl shot. 96

Figure 7.23. Relative standardized catch rates for 0+ individuals (with 95%CI) by season for Denham Sound and Outer Bay. Each series has been normalised to a mean score of 1. 97

Figure 7.24. Distribution of environmental variables for the 0+ cohort (all years combined) sampled in Outer Bay survey area only. MSL – mean sea level, SST – sea surface temperature, StartDepth – Leeuwin Current strength, chloro – chlorophyll, wind – wind strength. 98

Acknowledgments

The need for this project resulted from extended discussions with commercial Snapper fishers operating in the Gascoyne and West Coast bioregions of Western Australia from 2014 onwards.

The project was made possible by funding from Fisheries and Development Corporation (FRDC Project 2018-050) with co-investment from Department of Primary Industries and Regional Development (DPIRD) Western Australia, CSIRO, Flinders University, University of Adelaide and University of Western Australia.

We thank the owner, skippers and crew of the FV *Ocean Conquest* and FV *Ada Clara* for their professional and enthusiastic assistance with the at-sea-surveys.

We also thank the following staff from the collaborating organisations for their contributions to this project:

DPIRD – Nick Jarvis, Dion Boddington, Blaine Hodgson, Brett Crisafulli, Adam Eastman, Peter Coulson

Flinders University – Diana Elena-Vornicu

University of Adelaide – Ashleigh Sharrad, Sarah Gilbert

University of Western Australia – Charitha Pattiaratchi, Ivica Janekovic

CSIRO - Candice Untiedt

This report was internally reviewed by Shane Walters (DPIRD) and externally reviewed by Drs Craig Noell and Troy Rogers (SARDI).

This report is dedicated to the memory of Dr Mike Moran, fishery scientist with Western Australian Department of Fisheries who was responsible for Snapper research in the Shark Bay/Gascoyne region between 1980 and 2005. Mike, who was highly regarded within the Australian marine science community, and a mentor and friend too many of us, died in 2016.

Abbreviations

ANOVA	Analysis of Variance
ARC	Australian Research Council
BRUV	Baited Remote Underwater Video
CAP	Canonical Analysis of Principle coordinates
CL	Confidence Limits
CV	Coefficient of Variation
CW	Continuous Wave
DPIRD	Department of Primary Industries and Regional Development
FL	Fork Length
FRDC	Fisheries Research and Development Corporation
FV	Fishing Vessel
GCB	Gascoyne Coast Bioregion
ICP-MS	Inductively Coupled Plasma Mass Spectrometer
MLL	Minimum Legal Length
nMDS	(non-metric) Multi-Dimensional Scaling
PCA	Principal Component Analysis
ROMS	Regional Ocean Modelling System
RUV	Remote Underwater Video
SARDI	South Australian Research and Development Institute
SCB	South Coast Bioregion
SL	Standard Length
SNPs	Single-Nucleotide Polymorphisms
TACC	Total Allowable Commercial Catch
TL	Total Length
TS	Target Strength
WBT	Wideband Transceiver
WCB	West Coast Bioregion
WA	Western Australia

Executive Summary

Overview

This report describes a collaborative project focused on Snapper (*Chrysophrys auratus*) carried out between 2018 and 2021 by researchers from the Western Australian Department of Primary Industries and Regional Development (DPIRD), Flinders University, University of Adelaide, University of Western Australia, and CSIRO. The project was co-funded by the Fisheries Research and Development Corporation and had three key aims, which were motivated by questions raised by commercial fishers in the Gascoyne and West Coast bioregions of Western Australia, about *C. auratus* stock structure in relation to current fishery management boundaries and the methodologies used to assess these Snapper stocks.

Firstly, the biological connectivity of *C. auratus* in waters offshore of Shark Bay (in the Gascoyne Coast Bioregion) and to the south off an area between Kalbarri and Geraldton (in the West Coast Bioregion) were investigated using population genomics, otolith chemistry and larval dispersal modelling. These studies identified, for the first time, nursery grounds inside Shark Bay that are attributable to the Gascoyne oceanic Snapper stock, confirmed the larval transport pathways linking these with known spawning grounds around islands off Shark Bay and commenced the development of a recruitment index for this stock.

Secondly, a novel fishery-independent survey method, combining acoustics (sonar) with underwater cameras, termed acouptics, was trialled for monitoring *C. auratus* stocks off Shark Bay. The study has shown that these active acoustic methods can be used to monitor Snapper aggregations and estimate numbers of fish/biomass, providing a potential addition to the future Snapper assessment toolkit.

Thirdly, this project explored if there had been any changes in the biological characteristics of *C. auratus* in oceanic waters of the Gascoyne Coast Bioregion and northern West Coast Bioregion over the past 30 years. The study demonstrated changes in maturity of Snapper in the Gascoyne, with the updated parameters used to inform the most recent (2022) assessment of this *C. auratus* stock.

The outcomes of this project will provide the basis for a review of stock assessment approaches and management arrangements for *C. auratus* on the West coast of Australia. Outcomes of the acouptics work provides a conceptual basis for application in *C. auratus* assessment research elsewhere in Australia and New Zealand.

Background

Chrysophrys auratus stocks in oceanic waters of the adjacent Gascoyne and West Coast bioregions of Western Australia have been assessed and managed separately, based on available information about stock connectivity and the historical development of fishery management arrangements (Fowler et al. 2020). Previous research had indicated *C. auratus* stocks in oceanic waters off the West coast were related, with recruitment likely coming from multiple nursery areas. In the Gascoyne, a stock assessment in 2017 indicated that the biomass of the oceanic stock was around the limit reference level despite a series of substantial management interventions since 2003. In the West Coast Bioregion, a stock assessment in 2017 did not show acceptable levels of stock recovery following management intervention in 2010.

The lack of recovery of *C. auratus* in the Gascoyne and West Coast bioregions resulted in persistent questions from the commercial sector about the adequacy of available information on stock structure and the data inputs and assessment methods used to determine stock status. The monitoring and assessment of *C. auratus* stocks in Western Australia has primarily been based on fishery-dependent methods that can be uncertain for a range of reasons. As *C. auratus* aggregate to spawn, active acoustic methods can offer an alternative fishery-independent approach for monitoring spatial distribution and abundance of the spawning stock.

Climate change has been recognised as likely to impact temperate species such as *C. auratus* in Western Australia (Caputi et al. 2015). Commercial fishers in the Gascoyne had reported lower abundances of *C. auratus* at spawning locations off Shark Bay between 2014 and 2016 and observed few smaller fish, suggesting a period of weaker-than-average recruitment following the 2011 marine heatwave. In the northern areas of the West Coast Bioregion, catch rates of commercial fishers increased in the years following significant management changes to recover stocks, with industry suggesting this was due to a southward movement of fish from the Gascoyne, possibly in response to changes in environmental conditions.

Objectives

The primary objectives of this project were to:

1. Improve understanding of *C. auratus* stock connectivity between the Gascoyne and West Coast bioregions using high-resolution genomic techniques.
2. Identify evidence of key sources of recruitment to *C. auratus* stocks in the Gascoyne and West Coast bioregions using otolith microchemistry.
3. Quantify *C. auratus* egg and larval dispersal between the Gascoyne and West Coast bioregions using high-resolution ocean circulation modelling.
4. Evaluate the use of active acoustic methods for monitoring the distribution and abundance of *C. auratus* in spawning aggregations.
5. Investigate possible changes in key biological parameters in *C. auratus* in the Gascoyne and West Coast bioregions in relation to changes in environmental conditions and stock abundance.

Secondary objectives of the project were to better understand fish-habitat relationships at the main *C. auratus* spawning locations north of Bernier Island and begin development of a recruitment index for the Gascoyne oceanic stock.

Methodology

Samples of *C. auratus* collected at locations in the Gascoyne and West Coast bioregions were used for genomic and otolith microchemistry studies to investigate stock connectivity and to identify sources of recruitment. We then incorporated information on egg and larval development with the location of spawning grounds and nursery areas in the Gascoyne with larval dispersal modelling to understand potential transport pathways at the finer (within the Shark Bay region) and larger (along the west coast) spatial scales.

A new, fishery-independent survey method combining acoustics and underwater video, was trialled for monitoring the spatial distribution of *C. auratus* spawning aggregations in waters off Shark Bay and providing estimates of abundance.

Available biological data for *C. auratus* sampled from oceanic waters of the Gascoyne and northern areas of the West Coast Bioregion were used to explore any temporal changes in growth and maturity over the past few decades. Estimates of von Bertalanffy growth parameters and logistic length- and age-based maturity parameters were compared across sexes, spatial management areas, and decadal sampling periods. Information on the distribution and abundance of the youngest age classes of *C. auratus* recorded in trawl survey areas in Shark Bay were used to develop 0+ catch rates to explore environmental correlations and develop a recruitment index for the Gascoyne oceanic stock.

Results/Key Findings

Results from the genomics study were consistent with the hypothesis that *C. auratus* is represented by relatively large breeding populations across the study region. No genomic differentiation was detected among samples from the Gascoyne, Kalbarri, and the Mid-West, a result indicative of a single stock of *C. auratus* with high connectivity across that region. The genomic results also point to the existence of low differentiation between samples in these waters (i.e. Gascoyne, Kalbarri, and Mid-West) and samples from Cockburn Sound to the south, confirming the findings of another recent national scale study (Bertram et al. 2022). Snapper from Cockburn Sound appear to be from a different stock of *C. auratus* that shows limited connectivity with the Gascoyne stock. No genomic differentiation was detected between adults and juveniles in each locality. The results were consistent with the hypothesis of local recruitment within each of the sampling areas, i.e. Gascoyne *C. auratus* recruitment derived from local spawning rather than contributions from outside the region.

Analysis of trace elements at the edge of juvenile *C. auratus* otoliths demonstrated high site-level classification accuracy, indicating site fidelity in juvenile habitat use and the occurrence of multiple nurseries. Results were consistent for two different year classes collected from the Gascoyne, indicating repeated differentiation of that bioregion as a source of recruits. Results for the different cohorts showed no clear patterns in the chemical composition of the near core - juvenile section of otoliths of adult *C. auratus* collected across the Gascoyne and the West Coast bioregions. This indicates that adults collected from any one of these locations, and from the different age groups, would be derived from multiple nursery locations.

The application of hydrodynamic and passive particle numerical models to quantify the oceanographic connectivity of the Gascoyne and West Coast bioregions has improved understanding of the egg/larval dispersal of *C. auratus* within and between these regions. Results showed that Shark Bay is only minimally connected to Kalbarri and the Mid-West when using passive particle advection limited by a 33-day drift time. Dispersal was typically north to south, driven by the southward-flowing Leeuwin Current, influenced by the action of eddies, and opposed by prevailing southerly winds. Dispersal from Kalbarri to the Mid-West was more likely, and between inshore and offshore sites, but similar drift distance limits applied throughout the region with most particles not traveling much more than 200 km from the release sites. This essentially matches the findings of genomics and otolith microchemistry, which indicated localised recruitment. Dispersal pathways from Shark Bay spawning sites around the offshore islands were identified. Most particles from northern release sites that were successful at drifting into settlement areas inside the central-eastern portion of Shark Bay followed a direct pathway through northern Geographe Channel that was highly dependent on wind conditions. Another possible, but less efficient pathway consisted of recirculation around the western shore of the islands entering through Naturaliste Channel. Particles released at sites that were inside the bay and closest to settlement areas were consistently the most likely to settle successfully. Particles released outside of Bernier and Dorre Islands or at Turtle Bay (Dirk Hartog Island) resulted in lower, more variable connectivity although particles could still be transported to the settlement areas in the required timeframe.

The trial of the novel acouptics approach to survey *C. auratus* showed that spawning aggregations are easily detected using acoustic methods and that individuals of this species are consistently recorded by unbaited stereo cameras. However, this study has also revealed an unexpectedly complex multi-species environment in waters off Shark Bay. Whilst the methods presented in this report can be used to estimate the abundance of *C. auratus* aggregations, these values should not be incorporated into any form of assessment at this time due to the large number of current unknowns. For the acouptics method to produce reliable estimates of *C. auratus* abundance, it is essential that the target strength of all aggregating fish species is known. In this study we observed 19 aggregating species, of which only two (including *C. auratus*) have measurements of target strength available. Given the difficulty of measuring these species *in situ*, it is therefore recommended that future studies apply a theoretical modelling approach to determine the target strength for all aggregating species in the surveyed area. This would vastly reduce the amount of uncertainty and could lead to the inclusion of biomass estimates determined using acouptics in stock assessments.

Analyses of biological data from the Gascoyne oceanic stock, boosted by recent fishery-independent sampling undertaken to monitor the current fishery closure around Bernier Island, have indicated that individuals are growing faster to a larger size, with a reduction in the estimated age at 50% maturity for females to 3 years compared to the earlier published estimate of 4 years. As the data available to explore any temporal changes in the biological characteristics of *C. auratus* in this study were relatively limited, due to a lack of smaller and younger fish in the mostly fishery-dependent samples, the need to group samples by decadal periods may have led to a smoothing of any real trends in estimates of growth and maturity curves over time across areas. This highlights the need for regular review of biological parameters used in stock assessments, and the importance of fishery-independent sampling to ensure the full age and size range of fish are represented in samples.

The mean lengths of *C. auratus* of selected year classes in each area varied over time, with some of these variations potentially driven by the increase and decrease in abundance of stronger recruitment pulses. Records of 0+ *C. auratus* in prawn trawl research survey data from the northern part of Shark Bay (Outer Bay*)* that had been linked to the spawning grounds around the offshore islands were limited (temporally) and therefore unable to provide the extensive timeseries of 0+ catch rates that had been sought. Mean nominal 0+ catch rates for both Denham Sound and Outer Bay survey locations were low overall and with minimal variation between years (2003-2020), limiting the ability to identify trends in recruitment at the present time. Due to the small sample sizes (trawl records with measured 0+ fish) and relatively small contrast in the values of the environmental variables considered here (wind, sea surface temperature, chlorophyll, sea level, and Leeuwin Current strength), none showed a significant effect on 0+ recruitment.

Implications for relevant stakeholders

The value of this project to the fishing industry and fishery managers is the contemporary understanding of the biological stock structure of *C. auratus* in the Gascoyne and West Coast bioregions that will inform discussion on data inputs to future stocks assessments, the scale of those assessments and a review of future management arrangements. The project also provides value through the first-time development of a recruitment index for Gascoyne oceanic stock that with further research could become a useful addition to future assessments and better inform management. The project has provided new biological information that identified a change in maturity that was incorporated into a recently completed stock assessment for the Gascoyne oceanic stock of *C. auratus*. The project has provided another platform for the continuing proof-of-method work on the application of active acoustic techniques in the assessment of demersal fish stocks in Australia and worldwide.

Recommendations

To ensure the timely application of results of this project, we recommend a review of the spatial scale of the current assessments of *C. auratus* in the Gascoyne and northern areas of the West Coast Bioregion, and the spatial scale at which the current harvest strategies apply to ensure differences in Snapper stock levels in the respective bioregions and within management areas can be considered. Periodic review of stock structure is important for this and other demersal fishery resources, particularly with ongoing environmental change, such as increasing water temperatures.

To ensure that biological inputs to stock assessments of *C. auratus* in WA are appropriate, we recommend that biological sampling is sufficient to periodically (every 10 years) permit review of all the key biological characteristics of snapper (growth, maturity, recruitment).

We recommend that DPIRD continue to collect sufficient information on 0+ *C. auratus* from research trawl surveys, and to consider expanding sampling through regular measurement of larger numbers of fish and revisit recruitment-environment modelling in future when more data are available.

Finally, we recommend continued investment to further evaluate the application of acoustics for fishery assessments in Western Australia and elsewhere.

Keywords

Snapper, *Chrysophrys auratus*, genomics, otolith chemistry, dispersal modelling, stock structure, connectivity, recruitment, Gascoyne Coast Bioregion, West Coast Bioregion, acoustic surveys, acouptics, stock assessment, fisheries management

1. Introduction

1.1 Background

Snapper (*Chrysophrys auratus*) is an important component of scalefish resources across the Gascoyne Coast Bioregion (GCB), West Coast Bioregion (WCB) and South Coast Bioregion (SCB) of Western Australia (WA) (Figure 1.1). The species is targeted by commercial and recreational fisheries in all three bioregions with around 600 t landed annually until quite recently (Fowler et al. 2020). Stocks of *C. auratus* are currently assessed and managed separately within each of these bioregions.

Previous studies have identified spatial differences in age compositions, growth, lengths and ages at maturity and spawning periods in Snapper among the bioregions (Wakefield et al. 2015; 2016). Important Snapper spawning aggregations and associated nursery areas have been identified at Shark Bay (GCB) and Cockburn Sound (WCB) (Wakefield et al. 2015). However, the contributions to recruitment from other locations along the west coast, where spawning also occurs, while possibly substantial, are not well understood.

Analysis of microsatellite DNA data indicated Snapper shows isolation by distance along the west coast but no genetically distinct subpopulations or stocks (Gardner et al. 2022). Otolith microchemistry has indicated adult residency at the scale of management areas in the GCB, WCB and SCB with recruitment likely coming from multiple nursery areas potentially across bioregions (Fairclough et al. 2013). Tagging studies support these findings with the majority of adults tagged at the key spawning locations in the GCB and WCB recaptured within 100 km suggesting evidence of adult philopatry (Moran et al. 2003; Wakefield et al. 2011; Crisafulli et al. 2019).

In the GCB, a stock assessment in 2017 indicated that the Snapper stock was around the limit level (B_{20}). This was despite a series of substantial management interventions since 2003 that reduced the retained catch to below 50% of pre-2003 levels. The commercial fishery had performed poorly since 2014/15: catch rates declined to below the target level and only ~50-60% of the Total Allowable Commercial Catch (TACC) had been taken. In 2018, to meet harvest strategy objectives, additional management action was taken that included a further 80% reduction in TACC (to 51 t) and spatial closures to protect key spawning aggregations. In the WCB, a stock assessment in 2017, indicated that levels of fishing mortality and female spawning potential ratio do not show evidence of stock recovery to acceptable levels, with indications that recovery may be slower in the north (Kalbarri and Mid-West management zones) compared with south (Perth metropolitan and South-west management zones) (Figure 1.1).

In WA, climate change has been recognised as likely to impact temperate species such as Snapper particularly in northern areas of its geographic range (i.e. GCB) (Caputi et al. 2015). In 2014-2016, commercial fishers in the GCB reported lower abundances of Snapper at spawning locations off Carnarvon, which historically sustained high catches over many decades. This was in conjunction with lower catch rates and observations of a lack of smaller Snapper. This suggests poor recruitment and underlies the under-performing fishery, despite substantial management intervention over more than 15 years. In the northern areas of the WCB, higher Snapper catch rates were reported by commercial fishers in years following significant management changes to recover stocks, but also following the 2011 marine heatwave, with suggestions from industry this was due to the southward movement of fish from the GCB, possibly in response to changes in environmental conditions.

Monitoring and assessment of WA Snapper stocks is currently based on fishery-dependent methods that are inherently uncertain for a range of reasons. Active acoustic methods offer an alternative, fishery-independent approach to monitoring spatial distribution and assessing stock abundance that are cost effective and based on statistical survey designs.

The lack of recovery in the GCB, and poor fishery performance after 15+ years of management intervention, and in northern areas of the WCB after 10+ years, resulted in persistent questions from the commercial sector about the adequacy of (1) the current understanding of Snapper stock structure and (2) the data inputs and stock assessment models currently used to determine snapper stock status. Additionally, fishers have suggested a range of potential factors that might have impacted Snapper in the GCB/WCB including the effects of climate change and in particular the higher temperatures experienced on the west coast of WA between 2011 (marine heatwave) and 2013, and long-term warming (Pearce and Feng, 2017; Hobday et al. 2018; Kajtar et al. 2021). It is currently not known how changes in environmental conditions and stock abundance may have affected:

(1) the connectivity and the spatial distribution of *C. auratus* in the GCB and northern areas of WCB, and
(2) key aspects of Snapper biology.

This represents a significant risk to management of snapper across the management units.

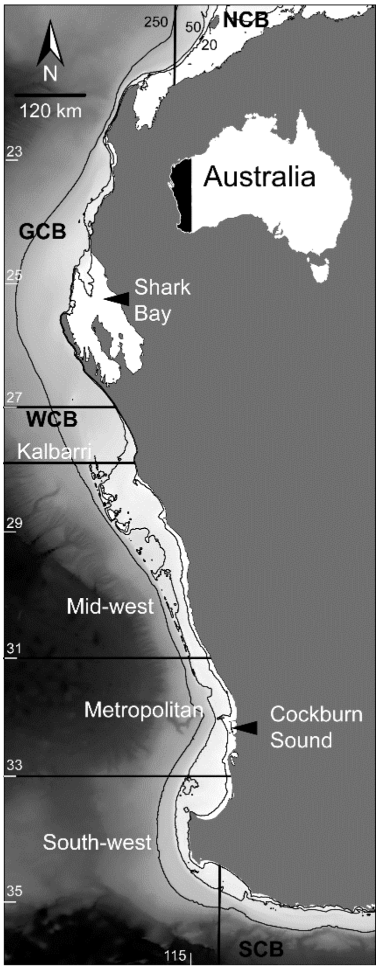


Figure 1.1. Map showing the four fishery bioregions of Western Australia (NCB, North Coast Bioregion, GCB, Gascoyne Coast Bioregion; WCB, West Coast Bioregion; SCB, South Coast Bioregion), and the management areas of the WCB.

1.2 Need

Ensuring that connectivity and stock dynamics are well understood is crucial to determining the appropriate scale for fisheries assessment and management. There is strong industry and management interest in determining the extent to which connectivity and stock dynamics of Snapper along the west coast might have changed over time reflecting changes in environmental conditions and stock abundance. There is a need to reassess the most appropriate scale for management of the Snapper resource in WA under the new Aquatic Resources and Management Act. There is a need to evaluate whether active-acoustic methods can improve capacity to monitor the spatial distribution and abundance of Snapper in key spawning aggregations and whether these methods are complementary to the existing approaches used to assess Snapper stocks in the GCB and WCB and elsewhere in Australia.

2. Objectives

The main objectives of the project were:

1. Improve understanding of *C. auratus* stock connectivity between the GCB and WCB using high-resolution genomic techniques.
2. Identify evidence of key sources of recruitment to *C. auratus* stocks in the GCB and WCB using otolith microchemistry.
3. Quantify *C. auratus* egg and larval dispersal between the GCB and WCB using high-resolution ocean circulation modelling.
4. Evaluate the use of active acoustic methods for monitoring the distribution and abundance of *C. auratus* in spawning aggregations.
5. Investigate possible changes in key biological parameters in *C. auratus* in the GCB and WCB in relation to changes in environmental conditions and stock abundance.

3. Genomics to improve understanding of Snapper stock connectivity on the Australian West coast

Jonathan Sandoval-Castillo and Luciano B. Beheregaray
Molecular Ecology Lab (MELFU), Flinders University

3.1 Introduction

Information from genomics (i.e. data based on 1000s of DNA markers) provides exceptional power to address a comprehensive spectrum of needs and applications relevant to fisheries management. This includes defining the number of demographically distinct management units (i.e. stocks) and the degree of connectivity between them (Bernatchez et al. 2017; Grummer et al. 2019). In this component of the project, we generated and analysed data from thousands of highly resolving DNA markers known as SNPs (single-nucleotide polymorphisms) for Snapper (*Chrysophrys auratus*) sampled from four regions of WA. These regions, which included the Gascoyne, Kalbarri, Mid-West and Cockburn Sound, were represented by samples from seven different localities. Samples from both juveniles and adults were obtained from five of these seven localities (Table 3.1).

Our objectives were to use high-resolution genomic datasets to:

(1) test for genomic differentiation among samples from different localities to infer connectivity and the number of stocks across the four study regions, and
(2) test for genomic differentiation between adults and juveniles separately in each locality to inform about local recruitment. Addressing these two objectives can substantially improve our understanding of the number of *C. auratus* stocks and patterns of connectivity on the west coast of Australia.

3.2 Methods

Details about the molecular methods (e.g. DNA extraction, genomic library preparation, genome sequencing) as well as pipelines and software used for bioinformatics and statistical analyses are provided in Brauer et al. (2016) and Sandoval-Castillo et al. (2018). Briefly, genomic DNA from ethanol-preserved tissue samples of 371 *C. auratus* were extracted using a salting out protocol. Adult *C. auratus* were collected in 2019, whereas juveniles were collected in 2018 and 2019. The quality of the extraction was evaluated using a NanoDrop-2000 (Thermo scientific) spectrophotometer, a Qubit 2.0 fluorometer and electrophoresis agarose gels. Double digest restriction-site associated DNA (ddRAD) libraries were prepared for the 310 samples that passed quality controls, plus 10 replicates to estimate sequencing error rate. The libraries were mixed in pools of 96 samples, each sample in equal concentrations, for sequencing in four lanes of a HiSeq 4000 Illumina machine (150bp PE).

The raw sequence quality was assessed using the software FASTQC (Brown et al 2017). Then, the sequences were demultiplexed, quality trimmed (including barcodes and RAD tags) and quality filtered using STACKS (Catchen et al. 2013). The remaining reads were aligned to the *C. auratus* genome and variants were called using a modification the GATK pipeline (MaKenna et al. 2010). The resulting single nucleotide polymorphisms (SNPs) were then filtered using VCFTOOLS (Danecek et al. 2011).

The genomic variation in the final SNP data set was estimated by locality (as well as by juvenile and adult stage, when applicable) in terms of expected heterozygosity (H_E), observed heterozygosity (H_O), and percentage of polymorphic loci (P) using ARLEQUIN (Excoffier et al 2010). Population genetic structure was assessed using both non model-based Principal Component Analysis (PCA) and model-based Admixture analysis, using the R package ADEGENET (Jombart et al. 2015) and the ADMIXTURE algorithm (Alexander and Lange 2011). Spatial autocorrelation (SAC) analysis of within-population relatedness was used to test for a signal consistent with local recruitment within each region (Gascoyne, Kalbarri, Mid-West and Cockburn Sound). That takes place when individuals from the same sampling region are more closely related to each other than they are to individuals from other regions, a result that generates a significantly positive SAC coefficient *r*. Statistical significance was based on 999 permutations to estimate 95% confidence intervals around the null hypothesis of no SAC, and 1000 bootstrap replications to estimate the 95% confidence interval around *r*. Analyses were ran on GenALEx 6.5 (Peakall and Smouse 2012) and ADEGENET.

3.3 Results

After filtering the initial dataset, we obtained ~3.06 billion DNA sequences with an average of 5.01 million sequences per individual *C. auratus*. After mapping these sequence reads to the high-quality *C. auratus* genome, we obtained ~110,000 SNP markers. These were filtered for low quality variants as well as removing samples with high levels of missing data (>25%). The final high-quality filtered dataset includes data for 271 *C. auratus* individuals for a total of 15,839 SNPs.

3.3.1 Genomic variation

Levels of genome-wide variation were relatively high in all localities (Table 3.1) and very similar between them. These results are consistent with the hypothesis that *C. auratus* is represented by relatively large breeding populations across the study region. Small differences in variation were found between adults and juveniles from the Mid-West, with adults showing higher heterozygosity but fewer polymorphic loci (Table 3.1), although the latter could be a product of differences in sample size.

Table 3.1. Levels of genomic variation in *C. auratus* sampled from seven localities in WA based on 15,839 filtered SNPs. For most localities, samples were divided into adults (-A) and juveniles (-J). Other abbreviations are number of individuals genotyped (n), proportion of polymorphic loci (PL%), observed (Ho) and expected heterozygosity (He).

Region	Locality	n	PL%	Ho	He
Gascoyne	Shark Bay (SHB-A)	27	46.4875	0.2049	0.2103
	Shark Bay (SHB-J)	28	46.7953	0.2047	0.2115
Kalbarri	Kalbarri (KAL-A)	25	46.6827	0.2040	0.2114
Mid-West	Abrolhos (ABR-A)	16	42.7049	0.2255	0.2318
	Geraldton (GER-A)	11	40.1081	0.2578	0.2549
	Geraldton (GER-J)	28	47.2456	0.1994	0.2079
	Dongara (DON-A)	10	38.0667	0.2564	0.2603
	Dongara (DON-J)	29	47.5083	0.2061	0.2098
	Jurien Bay (JUB-A)	13	40.6109	0.2311	0.2411
	Jurien Bay (JUB-J)	30	47.7484	0.1958	0.2057
Cockburn Sound	Cockburn Sound (COS-J)	24	46.1048	0.2042	0.2113
	Cockburn Sound (COS-A)	29	46.6677	0.1972	0.2076

3.3.2 Population genomic structure

Low to nil differentiation among localities

The results of analyses of the genomic dataset pointed to very low to nil population differentiation in the study region, which is indicative of substantial connectivity along the coast. The admixture analysis suggested a single population of *C. auratus* (K=1, likelihood= -2621032.623822) represented by the group with 'red' genetic ancestry in Figure 3.1. However, samples from Cockburn Sound (both juveniles and adults) also have substantial 'blue' genetic ancestry (i.e. ancestry to another population different than 'red'). The latter result suggested low differentiation between Cockburn Sound and all the other localities. This was also supported by the PCA results, which showed low differentiation between two clusters of individual *C. auratus*, one cluster comprising the samples from Gascoyne, Kalbarri, and Mid-West regions, and a second cluster comprising the samples from Cockburn Sound (Figure 3.2). The first two PCAs combined explain only 1.2% of the total variation in the data, indicating low differentiation between the two groups. The Fst results also pointed to either nil or very low differentiation among localities (maximum Fst between localities is 0.005). The pairwise locality comparisons based on Fst supported the two clusters inferred by the PCA, with both adults and juveniles from Cockburn Sound showing low but significant differentiation to other localities (Table 3.2; Figure 3.3). This included the marginally significant comparisons between Cockburn Sound and Dongara *C. auratus* ($p = 0.042$ and 0.046), which were not considered different at a 5% false discovery rate.

To clarify the nature of the 'blue' genetic ancestry in Figure 3.1, we compared the dataset from this FRDC project with an ongoing continental-wide genomic study of *C. auratus* (ARC Linkage project LP180100756, lead CI Beheregaray). This involved calling the SNP dataset again by including samples from South Australia that represent the next distinct stock along the coast (LP180100756, unpublished). This comparison clearly points to the South Australian stock as the source of the Cockburn Sound 'blue' ancestry, likely due to admixture with the South Australian population (Appendix 3 - Supplementary Information, Figure S3.1).

Table 3.2. Pairwise levels of genomic differentiation based on F_{ST} for *C. auratus* sampled from seven localities in WA. Analysis is based on 15,839 filtered SNPs. For most localities, samples were divided in adults (-A) and juveniles (-J). F_{ST} values are under the diagonal, p values from significance tests are over the diagonal. Bold values are comparisons significant at 5% false discovery rate. Values in red and underlined correspond to comparisons between adults and juveniles from the same locality. Shark Bay (SHB), Kalbarri (KAL), Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS), adults (-A) juveniles (-J).

	SHB-A	SHB-J	KAL-A	ABR-A	GER-A	GER-J	DON-A	DON-J	JUB-A	JUB-J	COS-J	COS-A
SHB-A		0.724	0.864	0.589	0.408	0.318	0.660	0.687	0.468	0.036	**0.000**	**0.000**
SHB-J	0.000		**0.001**	0.681	0.715	**0.000**	0.370	0.029	0.358	**0.003**	**0.000**	**0.000**
KAL-A	0.000	0.002		0.065	0.094	0.030	0.887	0.433	0.516	0.339	**0.000**	**0.000**
ABR-A	0.000	0.000	0.002		0.549	0.606	0.604	0.168	0.465	0.166	**0.000**	**0.000**
GER-A	0.000	0.000	0.002	0.000		0.134	0.523	0.286	0.172	0.049	**0.000**	**0.000**
GER-J	0.001	0.002	0.001	0.001	0.002		0.314	0.193	0.005	0.075	**0.000**	**0.000**
DON-A	0.000	0.001	0.000	0.001	0.000	0.001		0.625	0.484	0.630	0.042	0.046
DON-J	0.000	0.001	0.000	0.001	0.001	0.001	0.000		0.461	0.400	**0.000**	**0.000**
JUB-A	0.001	0.001	0.001	0.001	0.002	0.003	0.001	0.001		0.590	**0.002**	**0.000**
JUB-J	0.001	0.002	0.001	0.001	0.002	0.001	0.001	0.001	0.001		**0.001**	**0.000**
COS-J	0.004	0.004	0.004	0.004	0.004	0.003	0.002	0.002	0.004	0.002		0.247
COS-A	0.004	0.005	0.005	0.005	0.004	0.003	0.003	0.002	0.005	0.003	0.001	

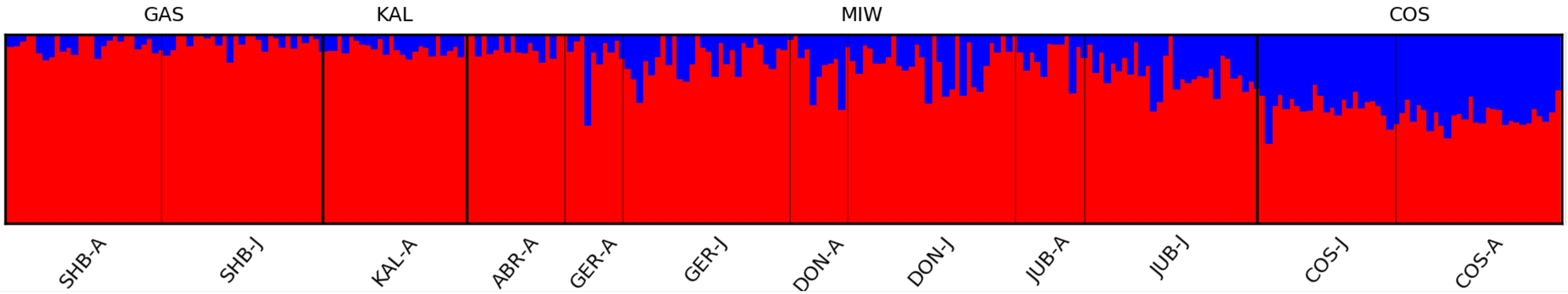


Figure 3.1. Admixture (structure) plot representing the population genomic structure of *C. auratus* in WA. Analysis was based on 15,839 filtered SNPs. Gascoyne (GAS), Mid-West (MIW), Shark Bay (SHB), Kalbarri (KAL), Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS), adults (-A) juveniles (-J)

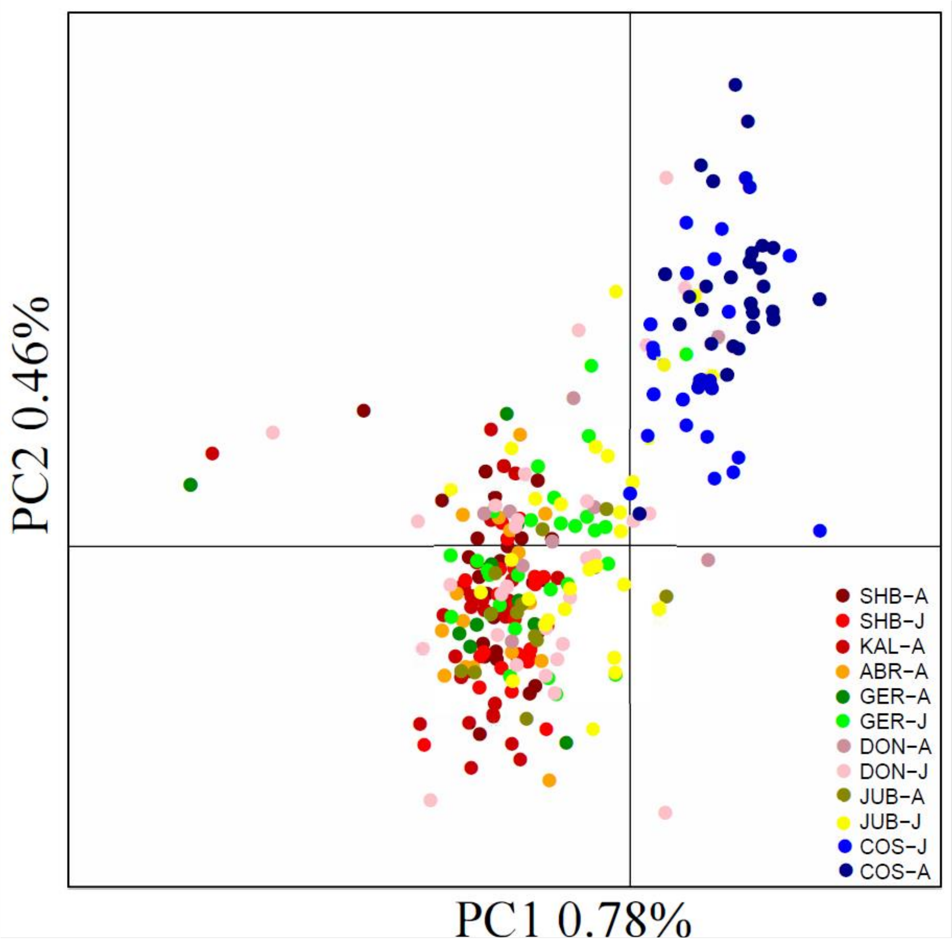


Figure 3.2. Principal components analysis of *C. auratus* from seven localities in WA. Analysis is based on 15,839 filtered SNPs. The first two PCAs explain 1.2% of the total variation. Shark Bay (SHB), Kalbarri (KAL), Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS). Adults (-A), juveniles (-J).

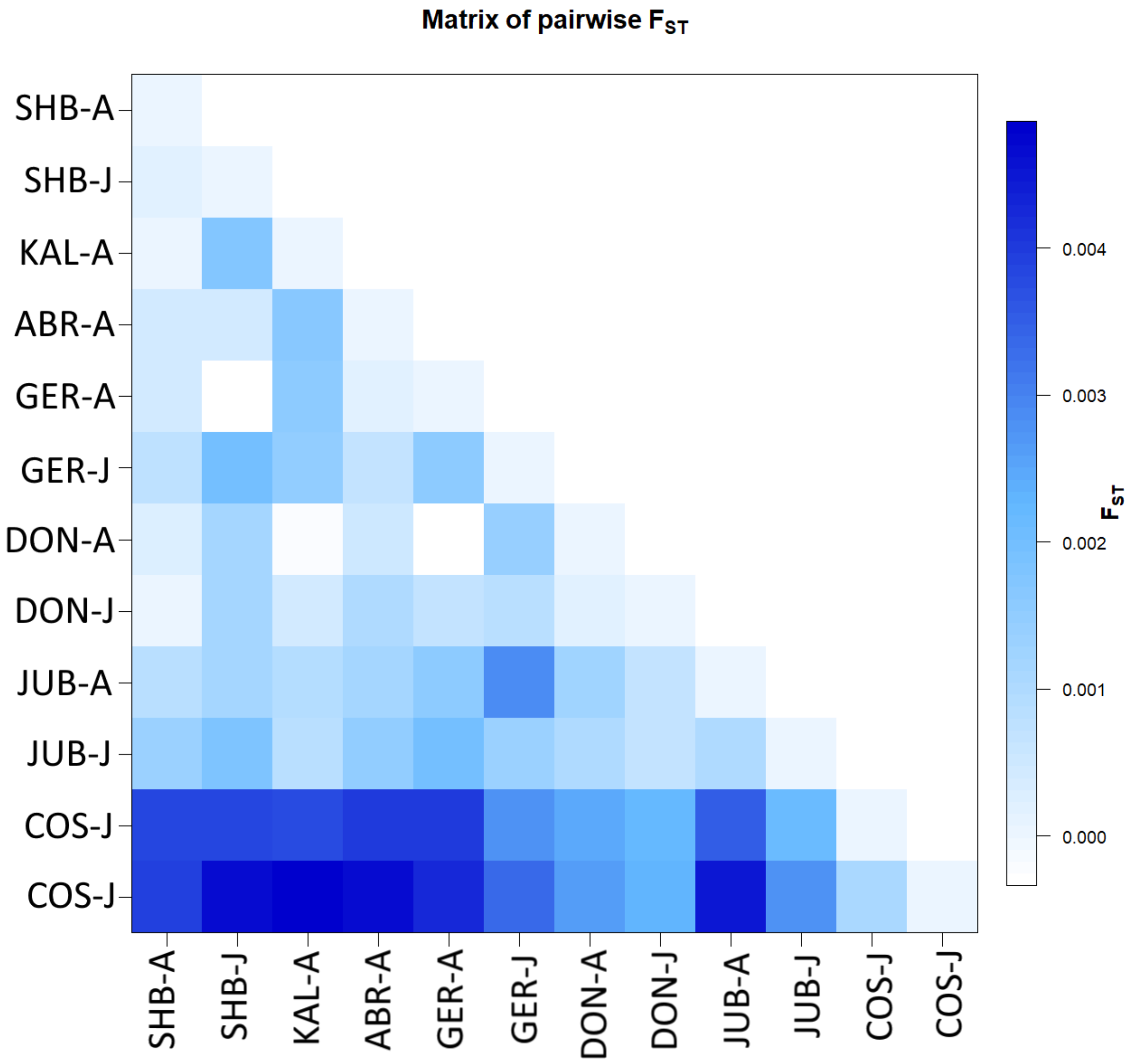


Figure 3.3. Pairwise genomic differentiation based on F_{ST} of *C. auratus* from seven localities in WA. Analysis is based on 15,839 filtered SNPs. F_{ST} values under the diagonal, p values over the diagonal. Bold values are significant at 5% false discovery rate. Values underlined correspond to comparisons between adults and juveniles form the same locality. Shark Bay (SHB), Kalbarri (KAL), Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS). Adults (-A), juveniles (-J).

No genetic differentiation between adults and juveniles in each locality

There was no evidence of genetic differentiation when comparing adults and juveniles from the same locality, a pattern detected for all five localities where samples from these two groups were available (Figure 3.4). This result was observed in all statistical tests carried out; Admixture, PCA and Fst comparisons.

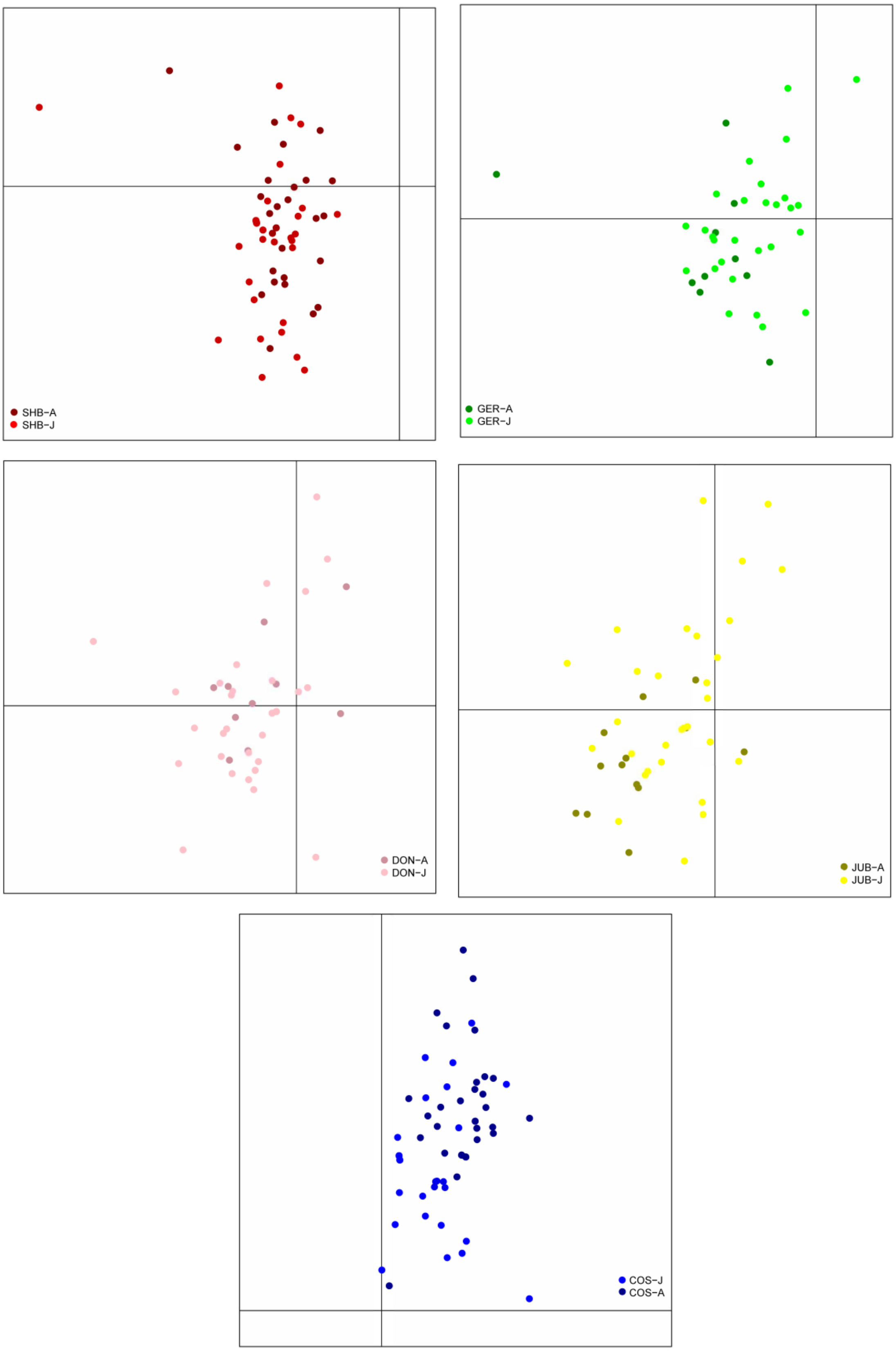


Figure 3.4. Principal components analysis comparing adults (-A) and juveniles (-J) *C. auratus* from five localities in WA. Analysis is based on 15,839 filtered SNPs. Shark Bay (SHB), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS). First two PCAs explain 1.2% of the total variation.

There was significant positive spatial autocorrelation in samples from all four regions (*r* was greater than the upper bound of the null distribution of no spatial autocorrelation, and its 95% confidence intervals represented by error bars did not include zero; Figure 3.5), a result consistent with local recruitment within each region.

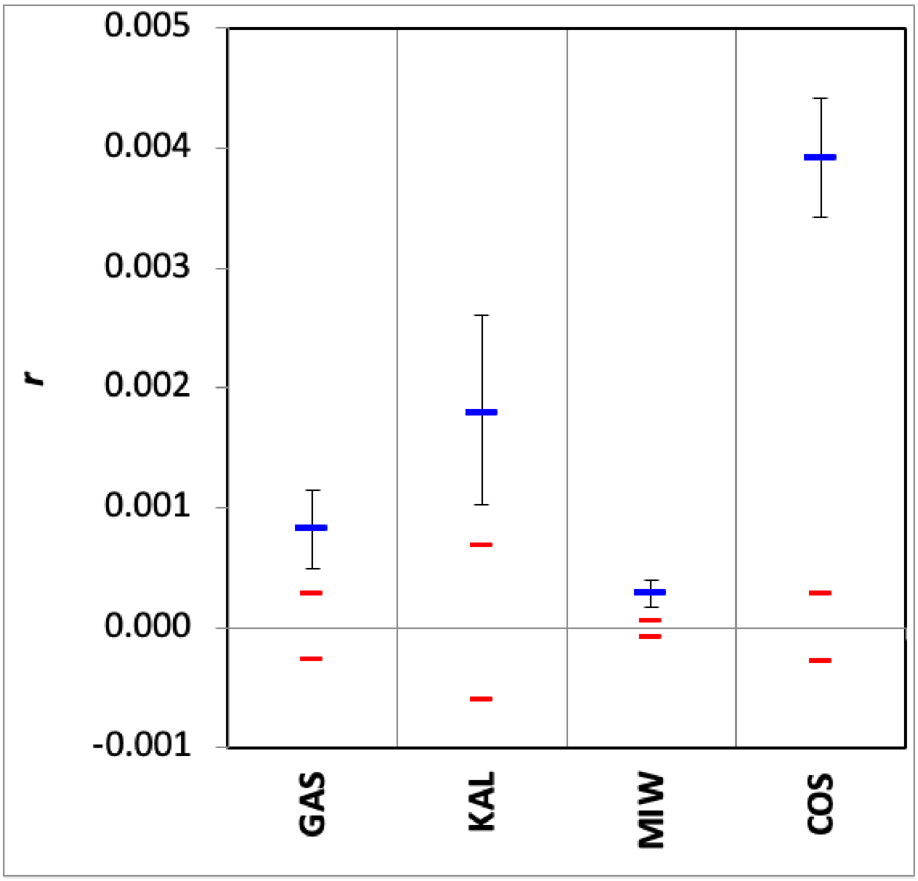


Figure 3.5. Spatial autocorrelation analysis of C. auratus in the four regions of Gascoyne (GAS), Mid-West (MIW), Kalbarri (KAL) and Cockburn Sound (COS). The Y axis represents the spatial autocorrelation coefficient (r). Dashed red lines are the 95% CIs around the null hypothesis of randomly distributed genotypes (no autocorrelation), estimated with 1000 permutations. Blue bars are the r values for each region and black whiskers are the r values 95% CIs, estimated with 1000 bootstraps. All estimated r values were significant ($P < 0.05$)

3.4 Discussion/Conclusion

Nil genomic differentiation was detected among samples from the Gascoyne, Kalbarri and Mid-West areas, a result indicative of a single stock of *C. auratus* with high connectivity across that region. The genomic results also pointed to the existence of low differentiation between samples comprising this northern stock (i.e. Gascoyne, Kalbarri, and Mid-West) and samples from Cockburn Sound on the lower west coast. Cockburn Sound appeared to comprise a different stock of *C. auratus* that showed reduced connectivity with the northern stock.

No genomic differentiation was detected between adults and juveniles in each locality. In addition, individuals sampled in the same region (including juveniles and adults) appeared more related to local snapper than to snapper sampled in other regions. The finding of higher genetic relatedness within than between regions is consistent with the hypothesis of local recruitment within each of the sampling regions, e.g. Gascoyne *C. auratus* recruitment derived from local spawning rather than contributions from outside the sampling area.

4. Otolith microchemistry to improve understanding Snapper stock connectivity and identify nursery areas in the Gascoyne & West Coast bioregions

Patrick Reis-Santos and Bronwyn Gillanders
University of Adelaide

4.1 Introduction

Otolith chemistry has been widely used to investigate natal origin, connectivity and fish stock structure (Fairclough et al. 2013; Tanner et al. 2016; Reis-Santos et al. 2022). The application of otolith chemistry in fisheries science builds on otoliths being calcium carbonate structures that are metabolically inert and grow continuously whilst incorporating elements from the surrounding environment (Campana and Thorrold 2001; Elsdon et al. 2008). As otolith chemical composition is driven by extrinsic factors such as water chemistry, salinity and temperature but also influenced by diet, ontogeny or physiology (Izzo et al. 2018; Reis-Santos et al. 2018; Sturrock et al. 2015), fish that remain in different environments throughout their life histories are expected to have distinct otolith elemental signatures along the otolith matrix (e.g. edge composition represents habitat at the time of collection, and chemical composition near the core represents natal origin). In this context, otoliths are time calibrated archives of the chemical composition of a fish's surrounding environment.

Here we analysed otolith chemical signatures of juvenile (age 0+) and adult (age 3+ to 7+) Snapper (*Chrysophrys auratus*) to investigate habitat use, potential sources of recruitment, and improve understanding of stock connectivity in the GCB and WCB.

4.2 Methods

Otoliths were extracted from 591 juvenile and adult *C. auratus* collected across locations in Gascoyne, Mid-West and Cockburn Sound (Table 4.1), and prepared for Laser ablation – Inductively coupled mass spectrometry (LA-ICP-MS), following Reis-Santos et al (2018b). Briefly, otoliths were embedded in Epofix Resin spiked with Indium (In, at 30ppm) and sectioned transversely through the core using a low-speed saw (Buehler Isomet). Sections were wet polished using 30, 9 and 3 µm lapping paper and ultrapure water, and mounted on glass slides with thermoplastic glue (CrystalBond 509). To finish, slides were sonicated in ultrapure water for 3 min, and triple rinsed with ultrapure water and dried in a laminar flow. All otoliths were stored in sealed plastic bags pending analysis.

Table 4.1. Number of samples of adult and juvenile *Chrysophrys auratus* collected at different locations across the Gascoyne and West Coast Bioregions.

Bioregion	**Management area**	**Location**	**Year class (adults)**	**Adults**	**Year class (juveniles)**	**Juveniles**
Gascoyne	Gascoyne	Gascoyne oceanic	2012	25	2017	57
			2014	25	2018	59
			2016	35		
West Coast	Kalbarri	Kalbarri	2012	34		
			2014	31		
			2016	26		
	Mid-West	Geraldton	2012	14	2018	59
			2014	18		
			2016	26		
		Dongara	2012	4	2018	43
			2014	9		
			2016	15		
		Jurien	2012	13	2018	37
			2014	3		
			2016	8		
	Metropolitan	Cockburn Sound			2018	50

Otolith elemental concentrations of ^{7}Li, ^{24}Mg, ^{55}Mn, ^{65}Cu, ^{66}Zn, ^{88}Sr, ^{137}Ba and ^{208}Pb were analysed using a RESOlution LR 193nm Excimer laser system attached to an Agilent 7900x inductively coupled plasma mass spectrometer (ICP-MS). Ca was used as an internal standard (Yoshinaga et al. 2000), and In was also measured as a marker to distinguish between otolith material and both the spiked resin and CrystalBond. For juvenile and adult *C. auratus* from all locations, 60 µm spots were used to analyse the marginal edge of the otoliths, i.e., recent elemental incorporation representative of time and site of capture. For adult *C. auratus*, spot analyses outside the core, between the primordium and the 1st annulus, were also run. This area was taken to represent the juvenile life period and match the area analysed in juvenile otoliths (Figure 4.1). Laser ablations (5hz, fluence ~3.5 j cm^{2}) occurred in a sealed chamber with resulting analyte transported to the ICP-MS via a smoothing manifold in an argon (Ar) and helium (He) stream. Pre-ablations were done to remove any potential surface contamination. Certified reference material (NIST 612 – National Institute of Standards and Technology) was analysed at the start and end of each session and after every 10 otoliths to correct for mass bias and machine drift. External precision was evaluated on MACS-3 (United States Geological Survey). Recovery % and precision (% relative standard deviation, RSD) of NIST measurements were 100 % and <1 % RSD for all elements, and 97 – 101 % and 3 to 9 % RSD for MACS3, respectively.

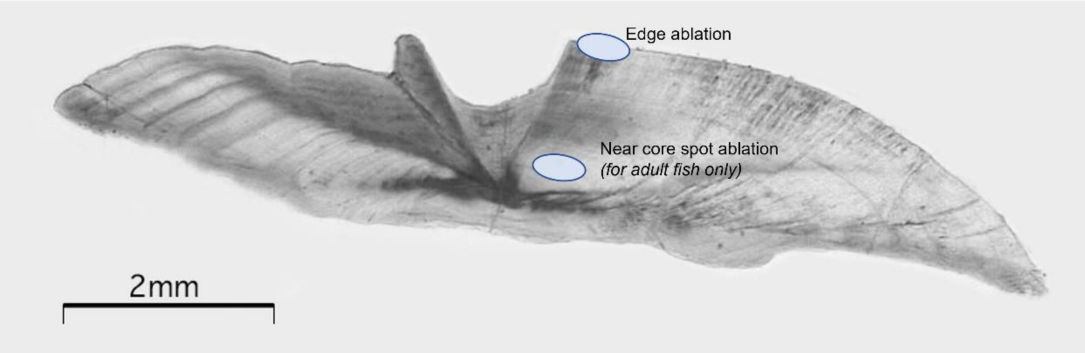


Figure 4.1. Image of a transverse section of an adult *C. auratus* otolith, highlighting the approximate areas for laser ablation in the edge, representative of time and site of capture, as well as the near core area, matching the edge areas analysed in 0+ fish.

Data reduction, including background corrections and mass count to ppm conversions were performed using Iolite (Paton et al. 2011), with any otoliths showing Indium contamination removed from subsequent analysis. After this and outlier checks, we obtained data from 276 juvenile and 243 adult *C. auratus*.

For juvenile and adult otolith edge composition, classification statistics were generated using canonical analysis of principle coordinates (CAP) in Primer v7 (Clarke et al. 2014). This is a constrained ordination for discriminating among a *priori* groups and provides a sound and unbiased measure of how distinct groups are in multivariate space. Here, CAP was used to evaluate the accuracy in determining habitat use of individual fish and the classification success in discriminating collection sites. For the otolith composition of the near core region of adult otoliths, because we cannot assume that all adult fish were spawned or spent their juvenile period in their collection site, we can only use unconstrained statistical methods (Moll et al. 2019; Reis-Santos et al. 2018a; Rogers et al. 2019). Therefore, multivariate data collected from the near core region of adult otoliths were analysed using non-metric multidimensional scaling (nMDS) to identify potential groups and patterns in the chemical signatures of the near core region of adult otoliths from the different collection areas. Analyses were also performed per cohort to safeguard for any bias from potential temporal variations in otolith chemistry (Di Franco et al. 2021; Elsdon et al. 2008; Moll et al. 2019).

4.3 Results

4.3.1 Edge analysis of juvenile otoliths - juvenile habitat use classification accuracy

The multivariate elemental signatures of the otolith edge of juvenile *C. auratus* collected in 2019 (representing the 2018 year class) were successful in discriminating juvenile nursery habitat use. There was an overall high classification accuracy of 76.2%, with classification accuracies per individual site ranging between 88.9 % for Gascoyne juveniles down to 65 % for juveniles collected in the sub region of Dongara (Mid). When pooling across locations within the Mid-West region, and comparing across the three major areas of the Gascoyne, Mid-West and Cockburn Sound, the overall classification accuracy improved to 89.6 %, with correct classification accuracies per region reaching

97.8 %, 83.7 %, 88.9 %, respectively (Table 4.1, Figure 4.1). The inclusion of otoliths from juveniles collected in Gascoyne in 2018 (2017 year class) only slightly reduced classification accuracies, though highlight potential temporal variations in otolith chemistry (Appendix 3 - Supplementary Information, Table S4.1).

Table 4.1. Juvenile habitat use classification accuracy using edge otolith chemistry of juvenile *C. auratus*. Results show the cross validated correctly classified individuals (%) of juveniles assigned to their location of capture, including all locations within the Mid-West region, as well as by pooling all locations within the Mid-West region (n=227). Gascoyne (GAS), Mid-West (MIW), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS). Note there are no otoliths from juveniles collected in Kalbarri.

Edge Analysis – Juveniles Correctly classified individuals (%)			
Region	Locality		
GAS		75.0	83.7
MIW		-	88.9
	GER	73.2	-
	DON	65.0	-
	JUB	80.0	-
COS		88.9	97.8
Overall		76.2	89.6

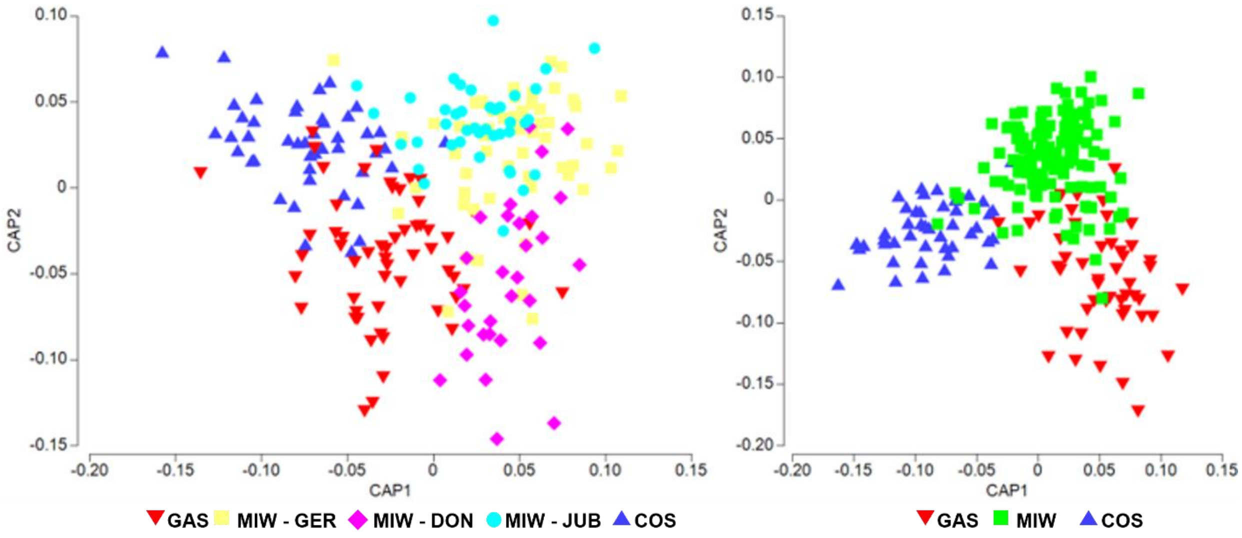


Figure 4.1. Ordination plot of the canonical analysis of principle coordinates (CAP) for multivariate elemental composition of the edge of otoliths of juvenile *C. auratus* collected along Gascoyne and the West Coast Bioregions. Analyses were performed with all locations within the Mid-West region (left), as well as by pooling locations within the Mid-West region (right). Gascoyne (GAS), Mid-West (MIW), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS). Classification and overall correctly assigned individuals (%) are summarised in Table 4.1.

4.3.2 Edge analysis of adult otoliths - adult habit use classification accuracy

Edge otolith composition of adult *C. auratus* collected across the sub regions returned a low overall classification accuracy (34.6 %), with no fish accurately classified to their collection location in Geraldton (Mid-West), and the best discriminated region (Kalbarri) only reaching 44.9 % correct classification. Pooling the Mid-west locations increased overall classification accuracy to 51.9 %, but classifications were still low (Gascoyne 53.5 %, Kalbarri 55.1 %, Mid 47.8%) (Table 4.2, FFigure 4.2). If we compare only the regions that match those where juveniles were collected, classification success for the Gascoyne and Mid-West (Geraldton, Dongara and Jurien) regions reach 67.6 % and 66.0 %, respectively. The lowered classification success using the chemical composition of the edge of adult *C. auratus* otoliths was independent of cohort, as separate analyses of the 2012, 2014 and 2016 cohorts yielded similar results (Appendix 3 - Supplementary Information, Table S4.2). Overall, otoliths of adult *C. auratus* cover a smaller geographical range (did not include Cockburn Sound) and had lower discriminatory power than juveniles collected in the Gascoyne and the West Coast Bioregions.

Table 4.2. Adult habitat use discrimination based on classification accuracy from canonical analysis of principle coordinates (CAP) using edge otolith chemistry of adult *C. auratus*. Results show the cross validated correctly classified individuals (%) of adults to their location of capture, including all locations within the Mid-West region, as well as by pooling locations within the Mid-West region (n=243). Gascoyne (GAS), Kalbarri (KAL), Mid-West (MIW), and locations therein Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB). Note there are no otoliths from adults collected in Cockburn Sound.

Edge Analysis – Adult			
Correctly classified individuals (%)			
Region	Locality		
GAS		36.6	53.5
KLB		44.9	55.1
MIW		-	47.8
	ABR	28.2	-
	GER	0	-
	DON	38.4	-
	JUB	16.7	-
Overall		34.6	51.9

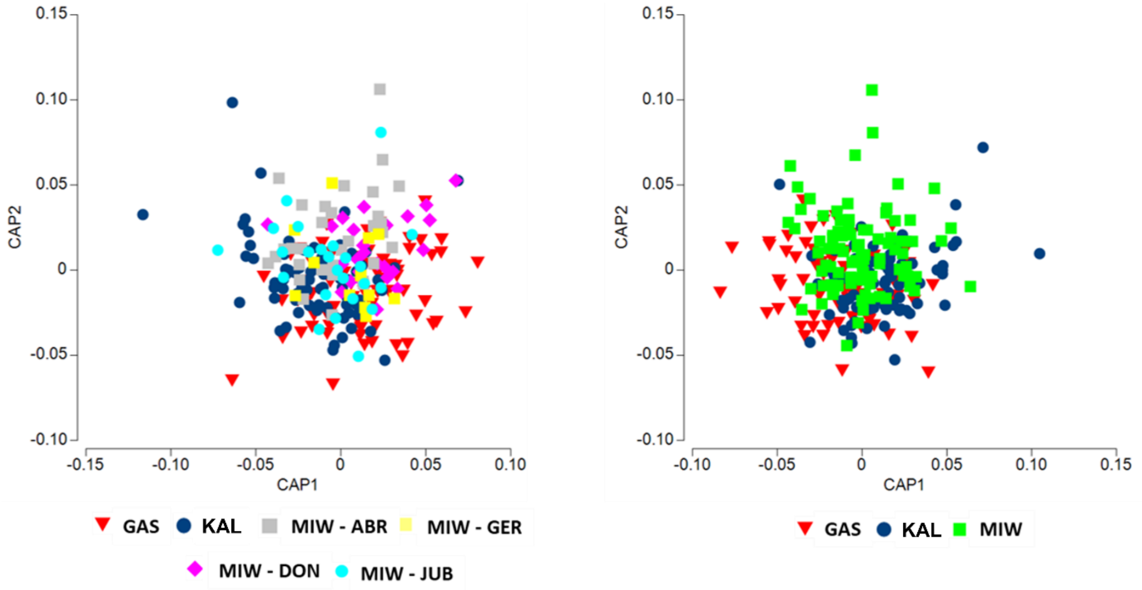


Figure 4.2. Ordination plot of the canonical analysis of principle coordinates (CAP) for multivariate elemental composition of the edge of otoliths of adult *C. auratus* collected along Gascoyne and the West Coast Bioregions. Analyses were performed with all locations within the Mid-West region (left), as well as by pooling locations within the Mid-West region (right). Gascoyne (GAS), Kalbarri (KAL), Mid-West (MIW), and locations therein Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB). Classification and overall correctly assigned individuals (%) are summarised in Table 4.2.

4.3.3 Near core analysis of adult otoliths

The unconstrained nMDS analyses per cohort show no clear patterns in the chemical composition of the near core - juvenile section of otoliths of adult *C. auratus* collected across the GCB and WCB. Across all cohorts there is an overlap in multivariate space of individual otolith signatures (Figure 4.3).

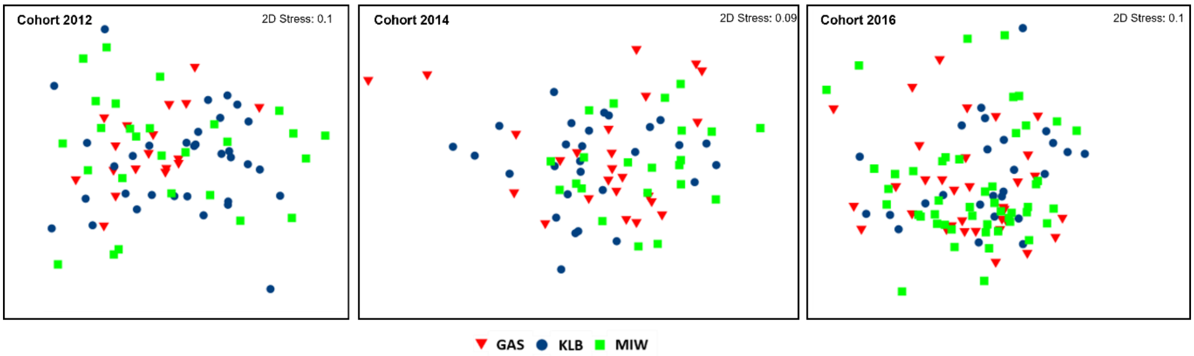


Figure 4.3. Ordination plot of the non-metric multidimensional scaling (nMDS) for the near core multivariate elemental composition of adult *C. auratus* of different cohorts (2012, 2014, and 2016) collected along the Gascoyne and the West Coast bioregions. Locations within the Mid-West region are pooled. Gascoyne (GAS), Kalbarri (KAL), Mid-West (MIW) (locations therein Abrolhos, Geraldton, Dongara, Jurien Bay).

4.4 Discussion/Conclusion

Analyses of the edges of otoliths of juvenile *C. auratus* produced high classification success to the nursery site from which they were collected. This included sites from the Gascoyne, Mid-West (Geraldton, Dongara, Jurien Bay) and Metropolitan (Cockburn Sound) areas. This indicated site fidelity in juvenile habitat use and demonstrated the use of multiple nursery environments for *C. auratus*. Moreover, when these analyses were repeated at the Management Area scale (i.e. Gascoyne, Mid-west, Metropolitan), overall classification success improved to ≥ 89%, with individual regions varying from 83.7 to 97.8%, emphasising the distinction in sources of recruits at that larger scale.

For adult otolith edges, the moderate success of classification to the site of capture suggests that during that life stage there is movement and mixing among locations. This was consistent regardless of the year class considered. Low differences among fish from different locations may also be influenced by low differences in chemical composition of the water column and/or other factors that influence otolith chemistry (Izzo et al. 2018). This finding is consistent with a previous study which found only moderate classification success to the site in otolith edges of adult *C. auratus* (Fairclough et al. 2013). However, while nursery signatures were detected in otoliths of juveniles, the elemental signatures of otolith cores of adults from different management areas (Gascoyne, Kalbarri and Mid-West) overlapped. This pattern was consistent for adults from different year classes and demonstrates that adults from any one location are likely derived from multiple nurseries. Nonetheless, because the differentiation in chemical signatures among juvenile nursery areas for the 2018 cohort was robust, we can build on this information to reconstruct movement and quantify the relative contributions of different nursery areas to adult populations. For this, we will need to compare the signatures from juvenile otoliths to the chemical signatures derived from the juvenile section of adults of the same cohort (Elsdon et al. 2008; Reis-Santos et al. 2022), i.e., we need to analyse the juvenile section of adult otoliths that match the characterised juvenile year class (in this case the 2018 cohort), and/or build libraries of annual juvenile signatures to investigate variations in relative contributions over time.

5. Ocean circulation modelling to investigate Snapper egg and larval dispersal between Gascoyne & West Coast bioregions

Yasha Hetzel and Mirjam Van Der Mheen
Oceans Institute, University of Western Australia

5.1 Introduction

Important spawning aggregations and associated nursery areas for Snapper (*Chrysophrys auratus*) have been previously identified at Shark Bay in the GCB (Figure 5.1) but the connectivity within that region and other sites in the WCB is poorly understood. Here, we used ocean circulation models to force passive particle tracking simulations to better understand how ocean currents influence the dispersal of *C. auratus* eggs and larvae. The relative connectivity between potential spawning and settlement sites, and the environmental drivers, were determined through analysis of >700,000 drift trajectories of passive particles advected by predicted currents across 7 winter spawning seasons.

The analysis focussed on determining connectivity at two main spatial scales:

(1) Between regions: Shark Bay (Figure 5.1b); Kalbarri (offshore/inshore) (Figure 5.1c); and Mid-West (offshore/inshore) (Figure 5.1d) including the Abrolhos Islands and inshore nearer Geraldton.
(2) In Shark Bay between spawning sites around Cape Cuvier, Bernier and Dorre Islands and Dirk Hartog Island and settlement sites in the central part of the bay (Figure 5.2).

Particle release sites for Shark Bay (Figure 5.1) were determined based on where spawning aggregations have been known to occur and have been historically targeted by recreational and commercial fishers. Post processing of particle trajectories aimed to establish the potential connectivity between release sites and into known settlement habitats (within Shark Bay) where juvenile Snapper are commonly found (Figure 5.2). In addition, connectivity between boxes surrounding all regional release sites was calculated in order to determine general connectivity and drift timescales between all areas of interest, since not all spawning and settlement sites are known at present. Specific environmental conditions (currents, wind) were then linked to the relative ‘success’ of particles reaching nursery areas. This approach highlighted physical connectivity mechanisms that may favour or restrict larval connectivity between *C. auratus* stocks and compliments the genomic and otolith chemistry approaches addressed by other objectives in this project.

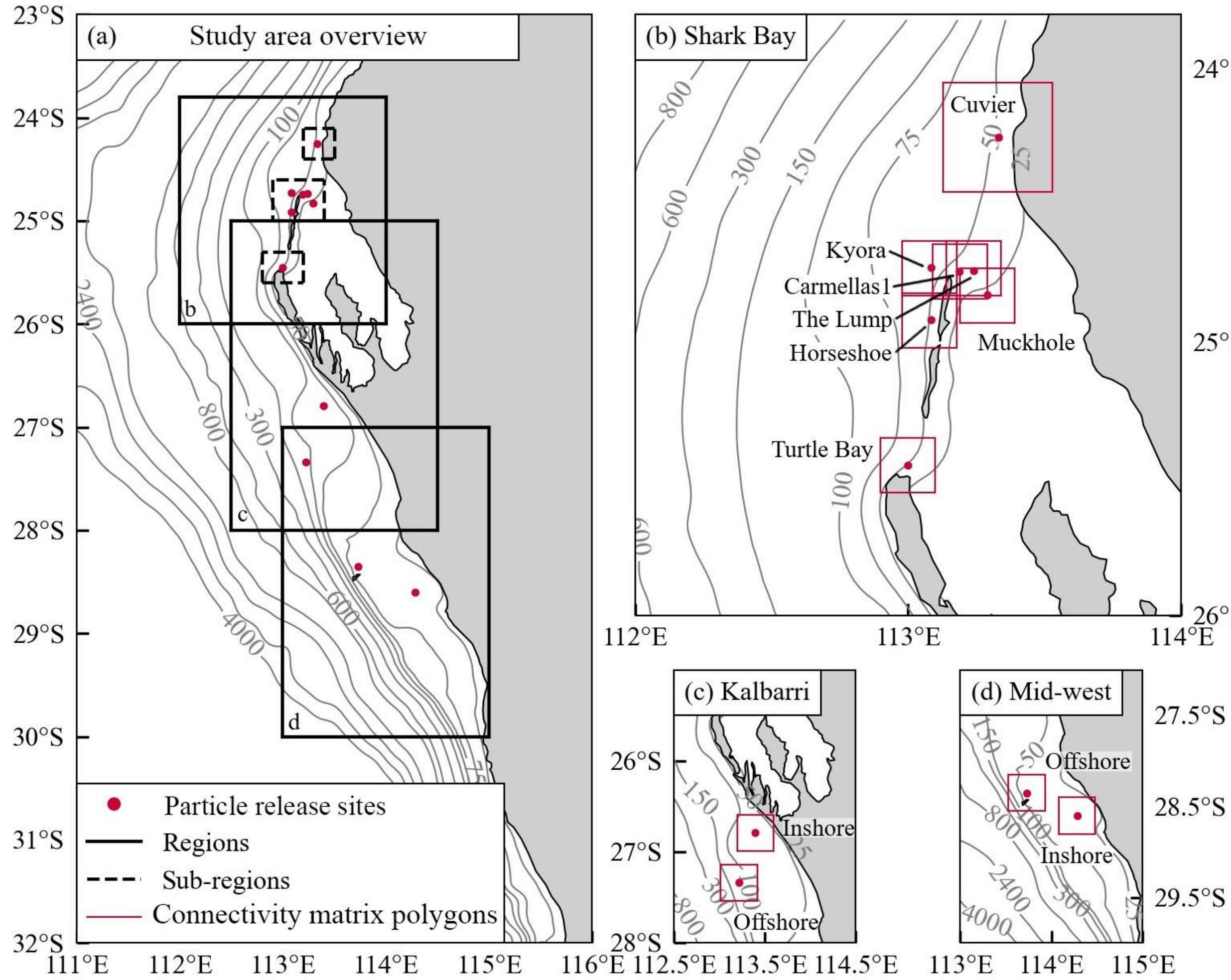


Figure 5.1. (a) Overview of particle release sites along the West Australian coast (red dots). Red dots in (b) correspond to known *C. auratus* spawning sites, whilst the particle release sites in (c) and (d) represent potential spawning areas as specific spawning sites are not yet known in those regions. Black outlines show the division of the area into three regions: (b) Shark Bay; (c) Kalbarri; and (d) Mid-West. Shark Bay is divided into three sub-regions (dashed black outlines). The red outlines show the boundaries used to determine connectivity between the different sites. Grey contours show the depth in meters. The model domain extended along the entire west coast, but all particle trajectories remained with the bounds shown in (a).

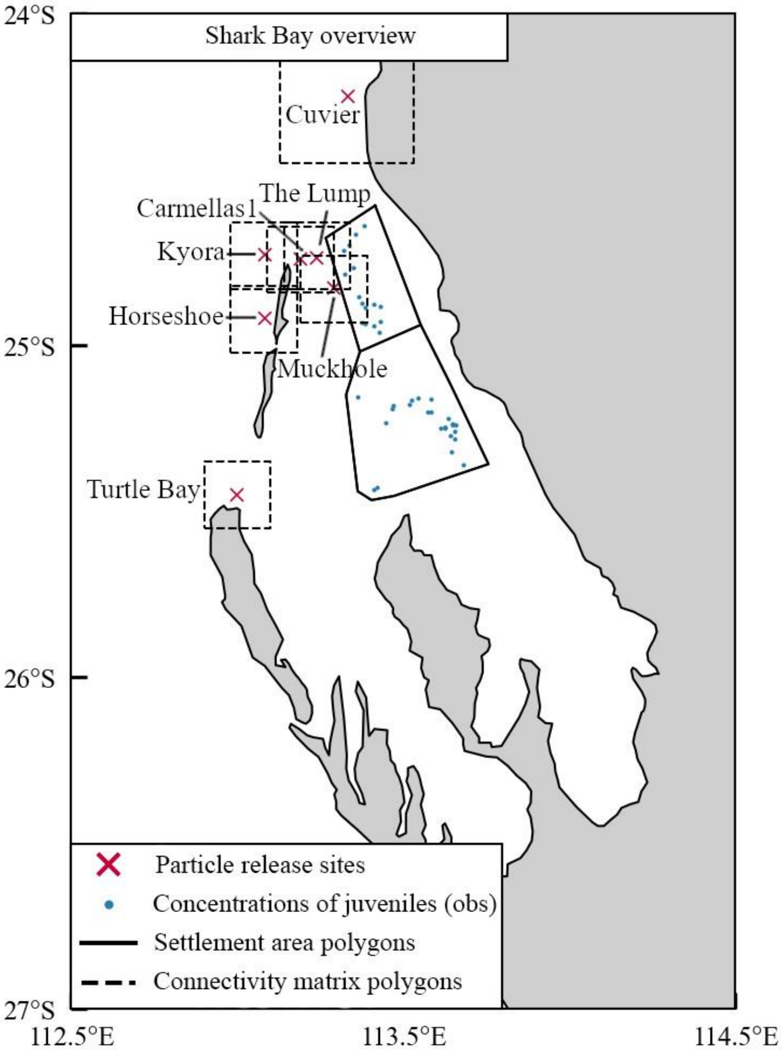


Figure 5.2. Location map for the high-resolution dispersal model for Shark Bay. The model domain extended along the West coast between NW Cape and Cape Leeuwin. Particle release sites are indicated with red X, blue dots show locations where 0+ and 1+ *C. auratus* are regularly recorded, bounded by black polygons (potential settlement areas) that were used to determine which particles were successful.

The main objectives of this work were therefore to:

(1) Identify the main dispersal pathways for known *C. auratus* spawning sites.
(2) Quantify the probability of virtual *C. auratus* egg/larval transport from site to site both within and between the GCB and WCB regions, and from offshore spawning sites into Shark Bay settlement areas.
(3) Determine the distances virtual *C. auratus* larvae are transported by ocean currents during their passive larval life stage.
(4) Identify environmental conditions that favour transport of particles (*C. auratus* larvae) into Shark Bay settlement areas.

5.2 Methods

5.2.1 Particle tracking model

We used Lagrangian particle tracking simulations to determine potential larval dispersal and connectivity between different spawning locations in the GCB and WCB. We used OceanParcels-v2 (Delandmeter & van Sebille, 2019; Lange & van Sebille, 2017) to run particle tracking simulations forced by ocean surface currents from the Regional Ocean Modelling System (ROMS), at two different spatial resolutions to address the objectives outlined above. Both the particle tracking model (https://oceanparcels.org/#peerreviewedarticles) and the ROMS ocean circulation model are extensively used for similar studies globally.

C. auratus larval growth and behaviour have not been studied *in-situ* in this region and it is not known how transferable information on behaviour and growth measured in cooler, shallower, more stratified environments might be. However, other studies (e.g. Francis, 1994; Fowler and Jennings 2003; Sim-Smith et al. 2012) suggest that *C. auratus* have a relatively short larval period (<33 days) and an even shorter duration (i.e. from flexion onwards) where they can influence their dispersal through swimming. Thus, it is proposed that passive particles may provide useful predictions of larval dispersal with this species.

It is commonly accepted that larval behaviour can influence dispersal (e.g. Leis, 2021), however, including behaviour in a particle tracking model (e.g. swimming, vertical migration) needs to be carefully considered as it can introduce uncertainty in results that are difficult to validate. In a related FRDC project (2019/015) studying dispersal of virtual prawn larvae in Shark Bay, particle tracking experiments indicated that dispersal during the first few days after particles were released (when larvae cannot yet swim) was a critical factor determining whether the particles were flushed from the bay, and that wind was the dominant forcing. Further sensitivity studies in the relatively shallow, well-mixed bay indicated that vertical position in the water column did not dramatically alter the trajectories of the particles. Thus, for this Snapper study particles were passive and drifted in the surface layer.

In New Zealand, where water temperatures were 16-21 ° C, Francis (1994) estimated that *C. auratus larvae* settle within 18-33 days and noted that warmer temperatures caused faster growth and earlier settlement. In our study area where water temperatures were warmer due to the southward flowing Leeuwin current (21-24 ° C), it is not known whether this would result in larvae settling earlier than 18 days. To account for this uncertainty, we allowed particles to drift for 33 days and tested the effect of different settlement windows (e.g. Figure 5.3). Choosing 15 or 20 days as the shortest time when particles were allowed to settle did not have a dramatic influence on the results leading us to choose 15-33 days as an appropriate settlement window.

We used a time step of 10 minutes and output particle locations every 4 hours including the ambient water temperature for the position. Particle trajectories were time-stepped using a fourth order Runge Kutta scheme, which is the default setting in OceanParcels We added a constant horizontal diffusion to the velocity fields to account for the effects of turbulence. Following Peliz et al. (2007), the horizontal diffusion was calculated as: $K_h = \varepsilon^{1/3}\Delta x^{4/3},\ where\ \varepsilon = 10^{-9}\ m^2s^{-3},\ and\ \Delta x \approx 3km,\ so\ K_h = 48.3\ m^2s^{-1}$. Particles that interacted with the coastline were allowed to continue drifting when currents changed and advected the particles away or parallel to the shoreline. This behaviour was assigned as the processes that determine beaching of particles require a much higher resolution model then is computationally practical for a domain of this size.

We ran particle tracking simulations for years covering a range of oceanic and atmospheric forcing (e.g. strong/weak Leeuwin Current, winds) (Table 5.1). *C. auratus* are broadcast spawners and are thought to release eggs around the new and full moons. For each of these years, particles were released during the *C. auratus* spawning months from June to August on full/new moon dates +/- 2 days (Table 5.1) . On these dates, we concurrently released 10 positively buoyant particles in the surface layer every hour at each release site (11/7 sites for the regional/Shark Bay models) to minimise bias due to specific tides or winds that vary on short time scales. Thus, for each lunar 'virtual spawning event', 13,200/8400 particles were released, resulting in a total of at least 79,200/50,400 particles for each simulation year (733,200 total trajectories).

Table 5.1. Dates of new and full moons in the months of June, July, and August for each of the simulation years. Particles were released hourly on these dates and 2 days before and after these dates. *Note that 2010 and 2019 were only included in the high-resolution Shark Bay model run; **2012 and years before 2010 were only simulated in the regional OzRoms model runs.

Year	New moons	Full moons
2001	21-Jun; 20-Jul; 19-Aug	06-Jun; 05-Jul; 04-Aug
2007	15-Jun; 14-Jul; 12-Aug	01-Jun; 30-Jun; 30-Jul; 28-Aug
2008	03-Jun; 03-Jul; 01-Aug	18-Jun; 18-Jul; 16-Aug
2010*	12-Jun; 11-Jul; 10-Aug	26-Jun; 26-Jul; 24-Aug
2011	01-Jun; 01-Jul; 30-Jul; 29-Aug	15-Jun; 15-Jul; 13-Aug
2012**	19-Jun; 19-Jul; 17-Aug	04-Jun; 03-Jul; 02-Aug; 31-Aug
2014	27-Jun; 26-Jul; 25-Aug	13-Jun; 12-Jul; 10-Aug
2019*	03-Jun; 03-Jul; 01-Aug; 30-Aug	17-Jun; 17-Jul; 15-Aug

5.2.2 Regional circulation model

The 3-dimensional OzROMS model hindcast (2000-2016) Wijeratne et al. (2018) has been designed specifically to simulate ocean processes on the continental shelf, including tides and atmospheric forcing (ERA-5 reanalysis Hersbach et al. (2020)), and has been successfully validated around Australia. Most previous dispersal modelling studies undertaken in the region have either covered small areas or have used coarse resolution ocean models that do not include tides or resolve important processes that can act to retain larvae near the coast.

Ocean currents from OzROMS are available for all Australian waters for the years 2000-2016 at approximately 3.0 by 4.5 km horizontal resolution and hourly temporal resolution. OzROMS uses a terrain-following sigma-coordinate vertical grid and has a vertical resolution of 30 levels. Currents in the OzROMS surface layer used for the simulations in this study represent ocean currents in approximately the upper 2% of the water column. At the 11 release locations, the water depth varies between approximately 25 to 110 m (Figure 5.1), which means that OzROMS surface currents represent currents in approximately the upper 0.5 to 2 m of the water column.

5.2.3 Shark Bay circulation model

In order to better resolve the hydrodynamics inside Shark Bay, a higher resolution (2km) realistic setup of the ROMS model with 25 vertical layers was used to force the particle tracking simulations. This model is run by the University of Western Australia (UWA coastal oceanography) as a real-time forecast for the central west coast of Australia (CWA-ROMS) (). The model was run in hindcast mode with atmospheric forcing from the ERA5 reanalysis (Herbach et al. 2020), ocean boundaries from the global NEMO ocean model (https://www.nemo-ocean.eu/) and the TPXO9 global tidal solution. Hourly surface current outputs from this model were available as a hindcast covering the period 2010-2020, and the model has since been updated to contain 3 hourly 3-dimensional outputs from 2000 to present. The benefit of CWA-ROMS includes better representation of depths inside the bay (derived from Hetzel et al. (2015)), more accurate tides, and improved hydrodynamics. Simulations were undertaken for 2010,2011, 2014, and 2019. The setup details and ability of this model setup to simulate hydrodynamics along the WA continental shelf is described in Mahjabin et al. (2019); and a more detailed comparison of water levels and currents for Shark Bay was undertaken for the present study. The complete model domain extended from the NW Cape (Exmouth) to Cape Leeuwin (Augusta), however particles remained within the bounds shown in Figure 5.1.

A quantitative comparison with observations at six sites in Shark Bay (Table 5.2) used the measure of "model skill" (Warner et al. 2005), where a value of 1 represents a perfect fit to observations. The comparison showed that the model satisfactorily reproduced currents, with similar skill levels to previously published work (Hetzel et al. 2015).

Table 5.2. Quantitative comparison of model skill between the CWA-ROMS model in Shark Bay where observations of currents and sea level were available from previous field work undertaken by UWA in 2009 and 2011.

Site	Water level	Current velocity
Monkey Mia	0.70	N/A
Denham	0.60	N/A
Naturaliste Channel – Moor1	0.59	0.68
Naturaliste Channel – Moor2	N/A	0.80
Geographe Channel – Moor3	0.76	0.74
Carnarvon	0.75	N/A

5.2.4 Analysis

The trajectories were post-processed to determine the average density of any age particles passing through each grid cell of the model domain on monthly, annual, and multi-year timescales. An equivalent metric was calculated to determine the minimum and mean time for particles to reach given cells. The resulting maps included particles of all ages and are informative to identify drift pathways, connectivity timescales, and temporal variability. Connectivity matrices were then derived to reveal the likelihood that particles released at one spawning site arrived at another site. For the Shark Bay analysis the connectivity between *C. auratus* spawning sites and potential settlement areas was determined by finding which age 15+ day particles drifted into polygons bounding settlement areas identified in trawl surveys, where juvenile *C. auratus* are commonly found in the eastern half of the northern portion of Shark Bay (Figure 5.2).

A sensitivity study was undertaken to determine the effect of drift duration on the particles ability to reach (settle) in the settlement polygons using the high-resolution Shark Bay model. The relative success of particles passing through the polygon during days 0-10; 10-20; 20-33; and 15-33 indicated that the highest rates of particles reaching settlement polygons occurred in early days (i.e. 0-10) and dropped off significantly by 33 days (Figure 5.3). In this respect, the particles in the 0-10 day window behaved differently to the longer drift durations, but the relative 'success' of the longer-drifting particles was not sensitive to the exact time window chosen for settlement. Practically, *C. auratus* larvae are unlikely to develop the capacity to actively arrive in the settlement areas within the first 10 days. Particles that passed into the polygon after 15 days were deemed 'successful'.

The averaging of different releases of many thousands of particles is required in order to make a confident assessment of the connectivity between sites. Any single particle or group of particles would be expected to deviate from the mean of many particles due to the action of specific tides and winds. Whilst each of those individual tracks indicate possible limits, confidence would be low that a specific track would be followed if it did not occur for a range of conditions.

More detailed analysis to determine effects of specific weather conditions was undertaken for the Shark Bay simulations. This was achieved by assessing which particle release dates were more likely to result in particles arriving in nursery areas, e.g. ‘success’. Quantifying ‘success’ for each release site and date allowed us to infer the specific environmental conditions that led to stronger and weaker *C. auratus* recruitment, interpreted here as conditions that favour transport into the nursery areas. A reliable historical index of realised spawning and recruitment is still in development, so reference to specific years as ‘high’ or ‘low’ recruitment years is difficult due to other confounding factors. For example, during 2011 Shark Bay experienced marine heat wave that had devastating ecological effects for the bay, but contrastingly appeared to cause increased transport of particles into the nursery areas (Figure 5.3). The Leeuwin Current also flowed strongly during 2011, thus influencing advection of particles between regions.

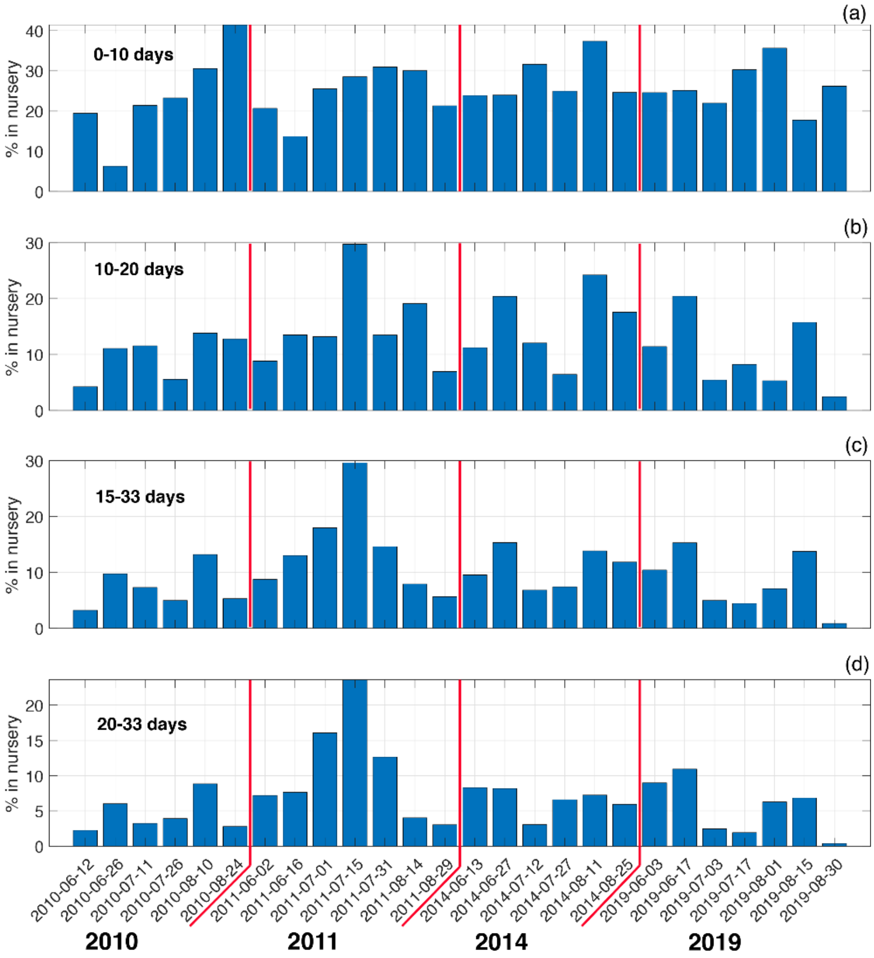


Figure 5.3. Percentage of particles averaged over all release sites that were ‘successful’ at reaching the nursery areas inside Shark Bay (polygon shown in Figure 5.2), for different drift duration windows (a-d) for each release around new and full moons (+/- 2days). Particles that passed through the nursery polygon within the temporal window (e.g. between days 15-33) were deemed successful. The 15-33 day window (c) was used for subsequent analysis. Note varying y-axis limits for clarity.

5.3 Results

5.3.1 Regional particle dispersal and connectivity between Shark Bay, Kalbarri and the Mid-West

Particle density maps derived from all particle releases indicated that the northern sites were well-connected (Figure 5.4). Specifically, particles from Cape Cuvier (SB1) were very likely to reach the northern Shark Bay sites (Kyora, Carmellas, The Lump, Horseshoe, Muckhole) (SB2) (Figure 5.4). The reverse was also true with particles likely to go from SB2 to SB1. Northern particles were also likely to reach Turtle Bay via an offshore pathway to the west of the islands (Figure 5.4b, c). Majority of the particles released at Turtle Bay travelled out of the bay to the south, with a limited number reaching Kalbarri. Another pathway into Shark Bay and to the north was also evident suggesting that particles could reach SB1 and SB2 from Turtle Bay if transported into the bay through the Naturaliste Channel (Figure 5.4d).

Although a few particles reached Kalbarri and the Mid-West from the SB sites and vice-versa, connectivity between the two regions was low (Figure 5.4d, e), with distance south reducing the likelihood of any hydrodynamic connection. Kalbarri and the Mid-West, however, were well-connected.

The mean dispersal time for particles released during all years also indicated that all Shark Bay sites were interconnected within 33 days and generally within 15 days (Figure 5.5). The average drift time between Shark Bay and Kalbarri and Mid-West was >25 days, reducing the likelihood that these areas are connected given the best estimates for pelagic larval drift duration. Short drift times (<15 days) were indicated between Kalbarri and Mid-West sites, with faster movement toward the south. Particles from these regions could drift as far as ~Jurien Bay within 15-33 days.

A histogram describing the distance of particles from their origin after drifting for 33 days (

Figure 5.6) showed that local recruitment (e.g. <200 km range) was most likely for all sites. Sites within Shark Bay were thus unlikely to disperse as far as Kalbarri or the Mid-West. Particles released at sites outside the bay were, not surprisingly, more likely to travel further than those inside the bay. Mid-West (inshore and offshore) showed a broader drift range than Kalbarri (nearshore and offshore).

Connectivity matrices derived from all model runs also indicated that particles aged 15-33 days were mostly retained locally (Figure 5.7). There was some movement from northern sites (Cuvier to Horseshoe) to Turtle Bay, but it was less common in reverse. There were only subtle differences between the years at a few sites, with the patterns described here mostly consistent irrespective of release year.

Southward transport of particles was slightly enhanced during 2011 due to a stronger Leeuwin Current, with marginally broader dispersal patterns possibly related to more variable winds over the region, and enhanced eddy activity outside the bay (not shown). Likewise, transport between Turtle Bay and Kalbarri Inshore; and Kalbarri Offshore and Inshore only occurred during 2011, and thus those values in (Figure 5.7) were derived from the single years.

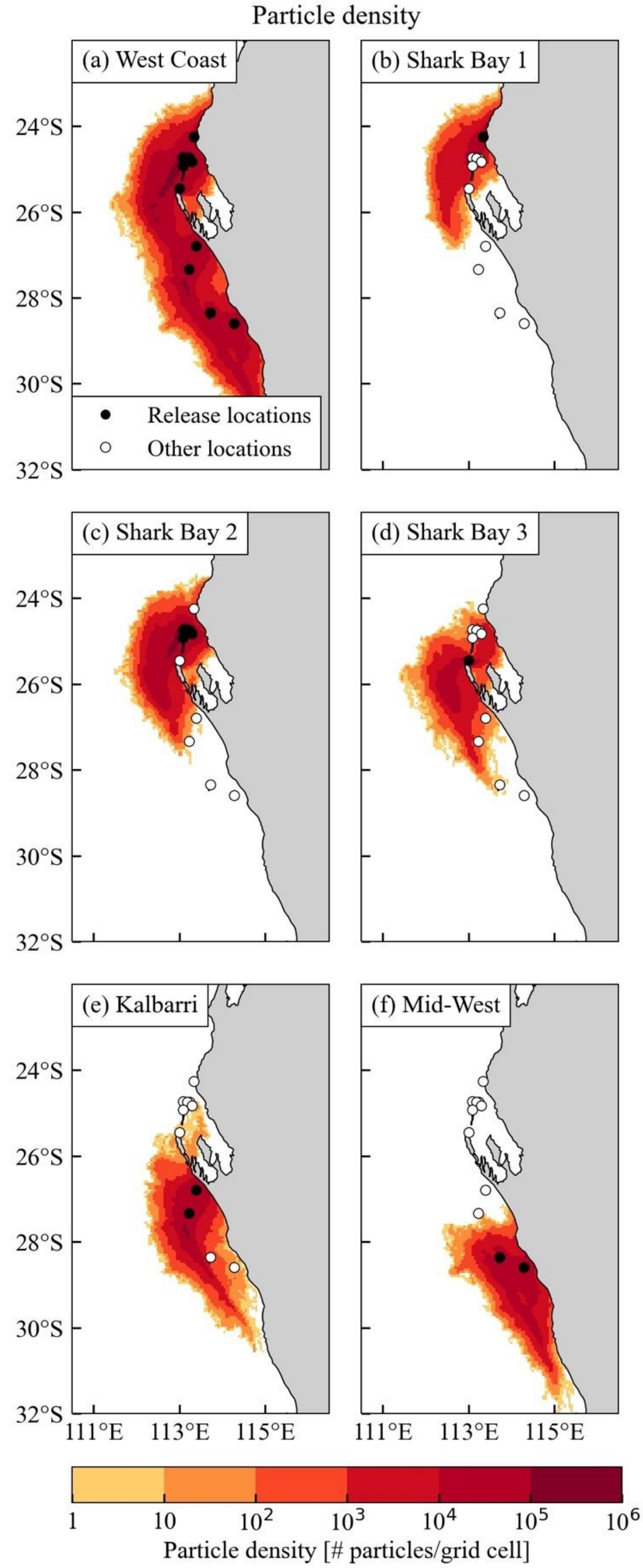


Figure 5.4. Mean particle density (for any age particle) over all 6 simulation years for: (a) the entire West coast; (b, c, d) Shark Bay region 1, 2, and 3; (e) Kalbarri region; and (f) the Mid-West region. Excluding particles <15 days showed negligible differences compared to this figure and is not shown.

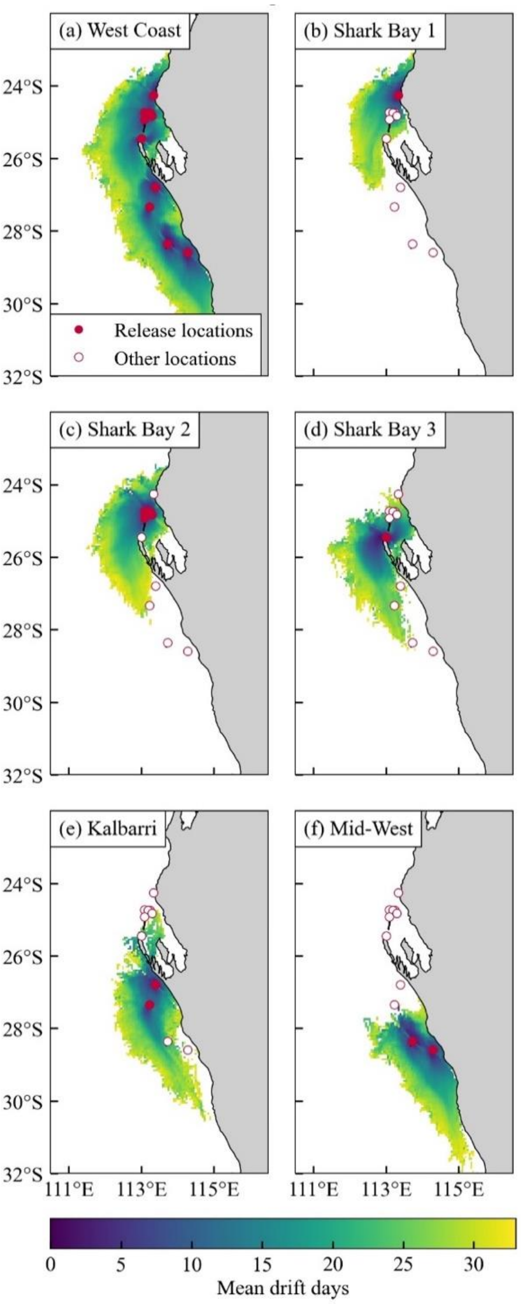


Figure 5.5. Mean drift time for all particles passing through each grid cell over all 6 simulation years for (a) the entire West coast; (b, c, d) Shark Bay region 1, 2, and 3; (e) Kalbarri region; and (f) the Mid-West region.

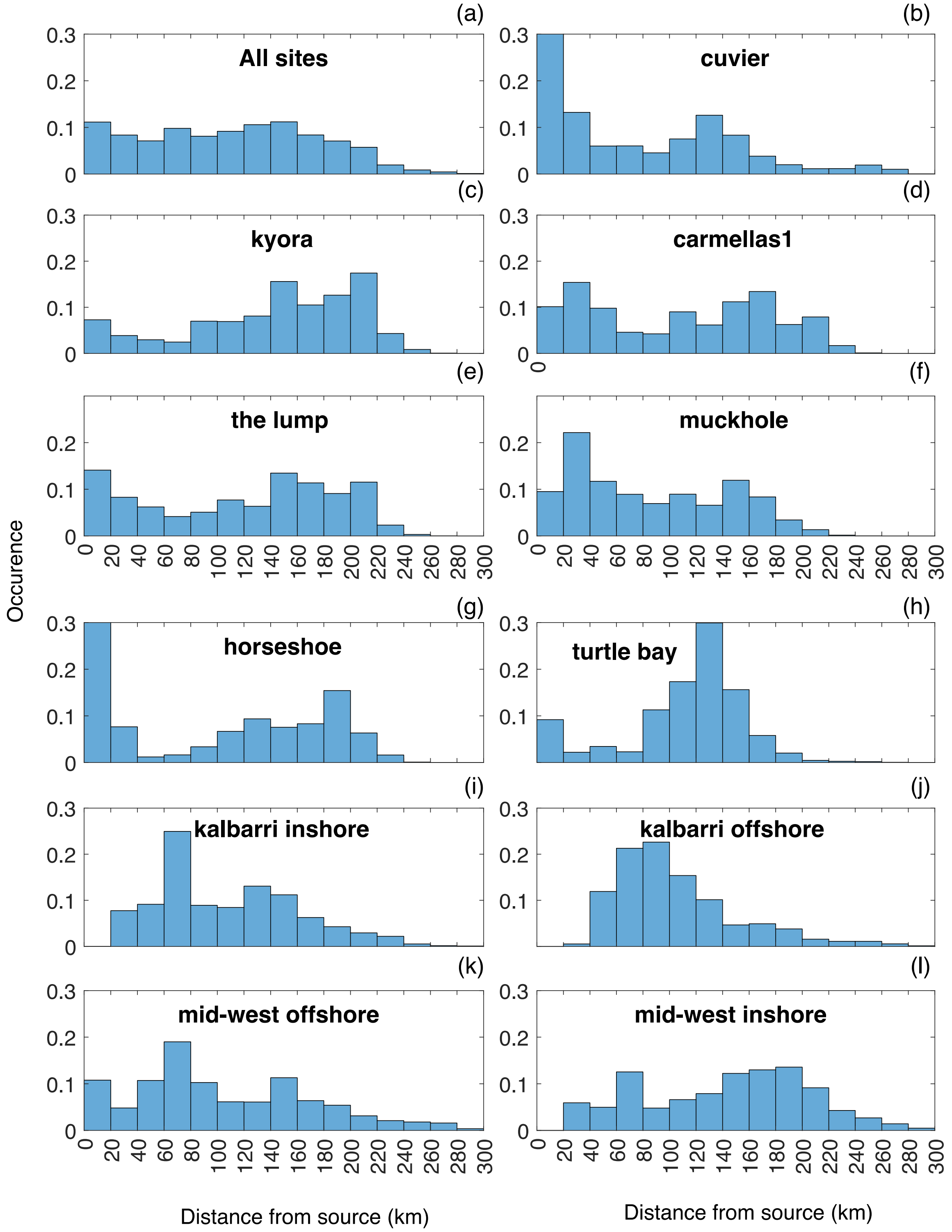
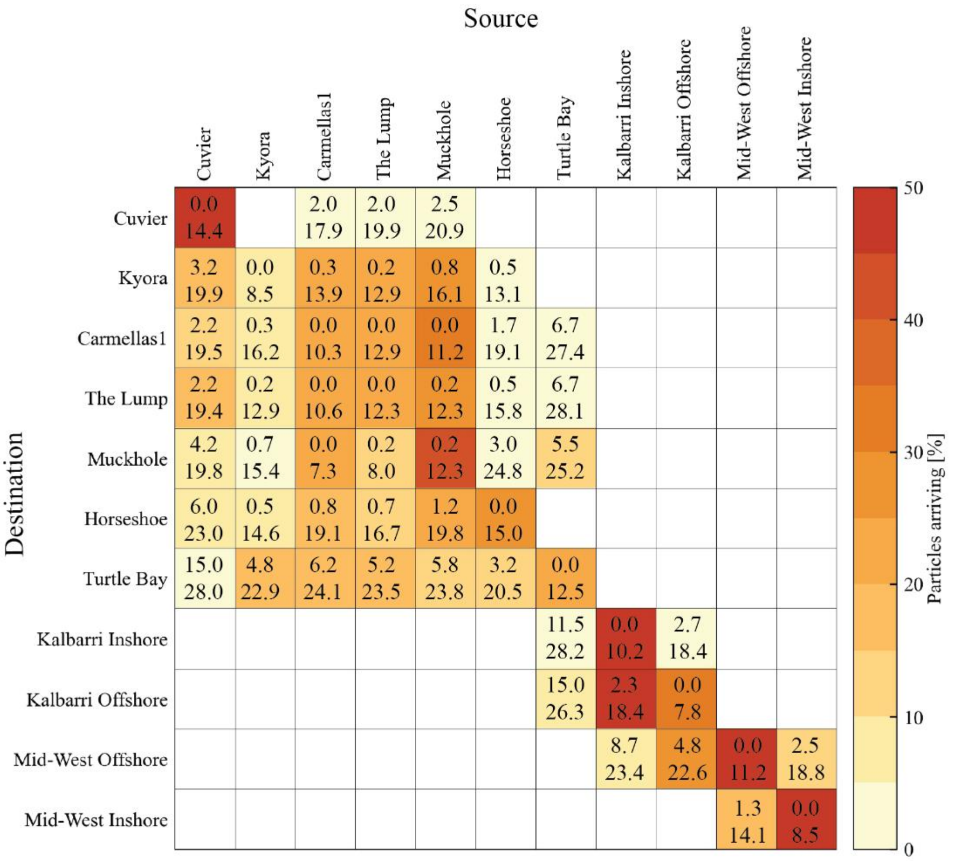


Figure 5.6. Histogram of maximum linear particle advection distance (position after 33 days – release location), showing the probability (y-axis) of particles drifting a specific distance (x-axis) over all sites (a) and from their 11 release locations (k-l) during 2014. Other years (not shown) showed similar results.

The particle tracking results consistently indicated that connectivity was highest between local sites and limited between Shark Bay and Kalbarri and the Mid-West (Figure 5.7). This was a robust finding as all analyses agreed across all six years (not shown). To understand more subtle differences within Shark Bay and interannual variability and their environmental drivers required the use of a higher resolution numerical model and is described in the following Shark Bay section.



	Cuvier	Kyora	Carmellas1	The Lump	Muckhole	Horseshoe	Turtle Bay	Kalbarri Inshore	Kalbarri Offshore	Mid-West Offshore	Mid-West Inshore
Cuvier	0.0 14.4		2.0 17.9	2.0 19.9	2.5 20.9						
Kyora	3.2 19.9	0.0 8.5	0.3 13.9	0.2 12.9	0.8 16.1	0.5 13.1					
Carmellas1	2.2 19.5	0.3 16.2	0.0 10.3	0.0 12.9	0.0 11.2	1.7 19.1	6.7 27.4				
The Lump	2.2 19.4	0.2 12.9	0.0 10.6	0.0 12.3	0.2 12.3	0.5 15.8	6.7 28.1				
Muckhole	4.2 19.8	0.7 15.4	0.0 7.3	0.2 8.0	0.2 12.3	3.0 24.8	5.5 25.2				
Horseshoe	6.0 23.0	0.5 14.6	0.8 19.1	0.7 16.7	1.2 19.8	0.0 15.0					
Turtle Bay	15.0 28.0	4.8 22.9	6.2 24.1	5.2 23.5	5.8 23.8	3.2 20.5	0.0 12.5				
Kalbarri Inshore							11.5 28.2	0.0 10.2	2.7 18.4		
Kalbarri Offshore							15.0 26.3	2.3 18.4	0.0 7.8		
Mid-West Offshore								8.7 23.4	4.8 22.6	0.0 11.2	2.5 18.8
Mid-West Inshore										1.3 14.1	0.0 8.5

Figure 5.7. Connectivity matrix for the 11 *C. auratus* spawning sites for all 6 simulation years (lower resolution OzRoms model) with colour shading representing the percentage of age 15+ day particles passing through connectivity boxes shown in Figure 5.1. The columns (labeled across top of x-axis) show the locations that particles are coming from ("source") and the rows show the locations that particles arrive in ("sinks") (labeled along y-axis). The numbers in each cell show the shortest drift time and the mean drift time for any particles in the Kalbarri Inshore location came from: Turtle Bay (0-5%), Kalbarri Inshore (45+%), and Kalbarri Offshore (0-5%) (shading). Any particles released at Turtle Bay that arrived at Kalbarri Inshore, were at least 11.5 days old with mean drift time of 28.2 days (numbers overlaid on shading).

5.3.2 Particle dispersal and connectivity within Shark Bay

The first objective of the higher resolution Shark Bay simulations was to determine connectivity from known spawning sites around Shark Bay's offshore islands to settlement areas in the central-eastern portion of the bay. The second objective was to better understand which environmental conditions favoured transport of particles into the settlement areas.

5.3.2.1 Dispersal range

Mean particle density maps for 2011, 2014 (Figure 5.8) showed that particles from any release (spawning) site could reach the settlement polygons, but were more likely to reach the northern area, except for Turtle Bay which were more likely to reach the southern polygon. Most particles that were transported out of the bay travelled south with the Leeuwin Current, however a few did travel northward out of the model domain, likely due to periods of strong southerly winds. Particles during 2014 were more dispersed compared to 2011, likely due to stronger winds. Winter months in 2011 experienced weaker and more variable winds compared to 2014.

During 2010 (Figure 5.9) more particles were lost from the bay and drifted south compared to 2011 and 2014. Sites to the east of Bernier Island were most likely to reach the settlement areas due to their proximity. Turtle Bay on the other hand was less connected to the settlement areas compared to 2011 and 2014.

Overall, 75% of particles released around Shark Bay travelled less than 100 kilometres from their release locations in 33 days (Figure 5.10a). The size of northern Shark Bay (~90 km x 70 km) means that the settlement areas were well within reach of the drifting particles, however, mean currents tended to push particles out of the bay and passive particles released outside of the islands required specific conditions to enter the bay. Despite its position on the open coast, Cuvier experienced relatively localised drift trajectories (<80 km) with around 30% of particles remaining within 20 km of the release point (Figure 5.10b). This may be attributed to prevailing southerly winds driving most particles onto land due to the coastline orientation. Most of the other sites showed a bi-modal distribution with up to 10-15% of particles traveling >200 km (Figure 5.10c-h). These particles were considered to be 'lost' from the system, flushed out of the bay and southward into the Leeuwin Current.

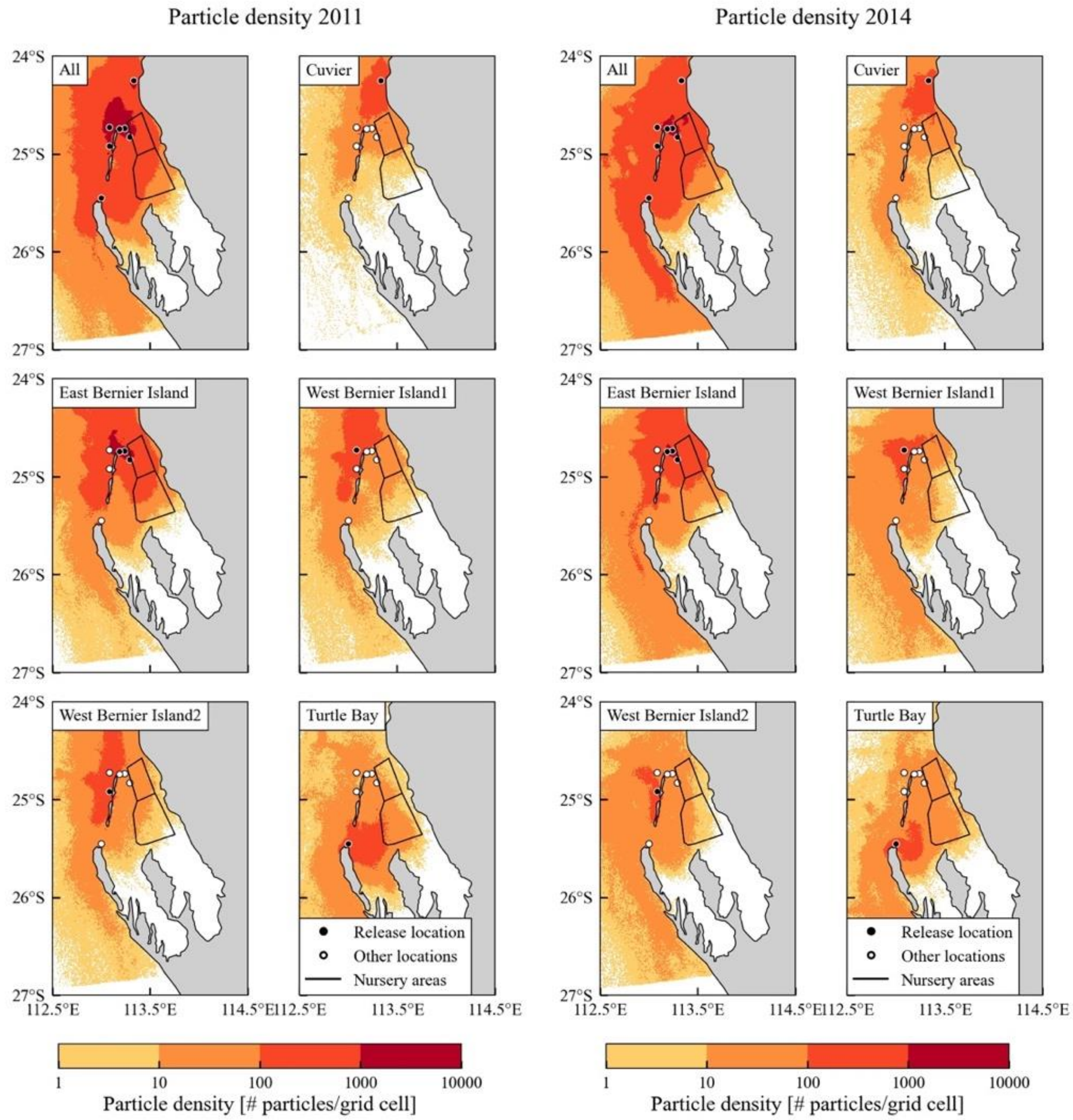


Figure 5.8. Average particle density maps for the high-resolution simulations in Shark Bay for 2011 (left) and 2014 (right) showing the likelihood particles released from each site passed through a given grid cell. Use of all particles decreased bias due to low numbers of particles and highlighted subtle differences between years. Filtering particles to remove young particles did not change overall patterns.

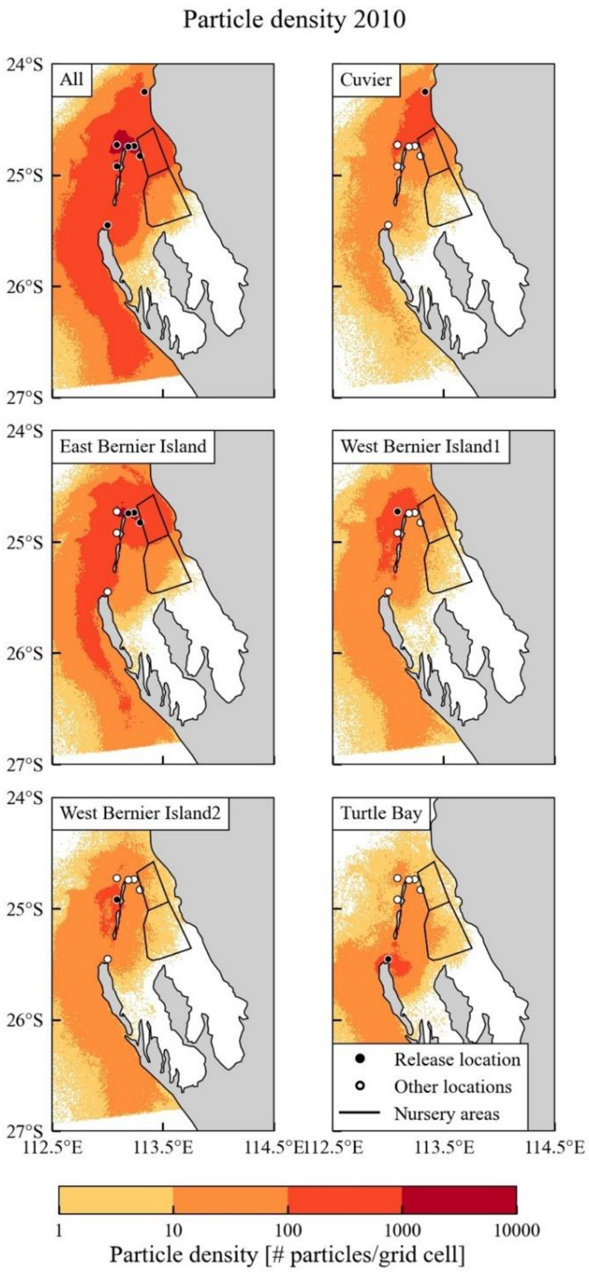


Figure 5.9. Average particle density maps for the high-resolution simulations in Shark Bay for 2010 showing the likelihood particles released from each spawning site passed through a given grid cell at any time. Note the higher density of particles outside of the bay compared to Figure 5.8. Black dots indicate corresponding release sites. Use of all particles decreased bias due to low numbers of particles and highlighted subtle differences between years. Filtering particles to remove young particles did not change overall patterns.

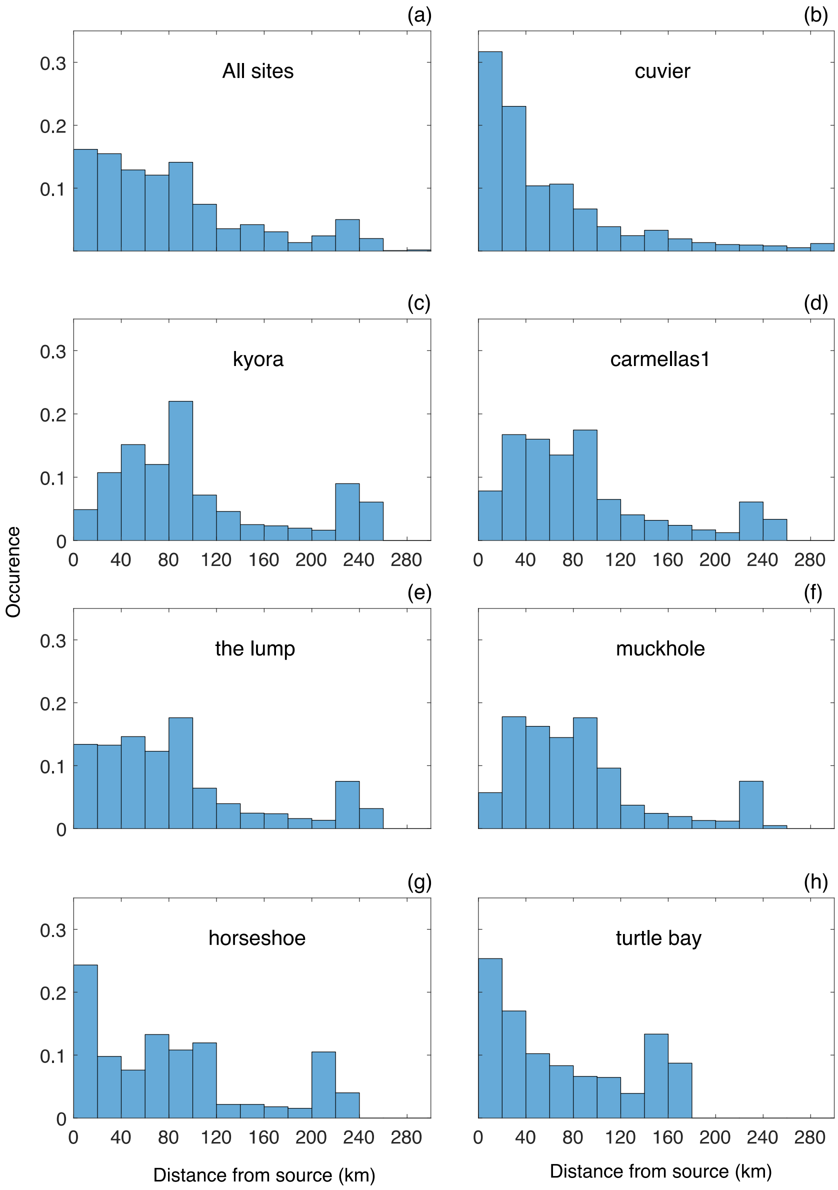


Figure 5.10. Histogram of linear particle advection distance (position after 33 days – release location), showing the probability (y-axis) of particles drifting a specific distance (x-axis) over all sites (a) and from their 7 release locations (b-h). These data are a composite of all years simulated and are also indicative of individual year patterns as overall drift distances did not vary greatly between years.

5.3.2.2 *Dispersal timescales*

Mean drift times into settlement polygons were generally <10 days but exceeded 15 days at the extreme southern end (Figure 5.11). Drift times for particles released outside the bay (e.g. West Bernier or Turtle Bay) were longer (14-20 days).

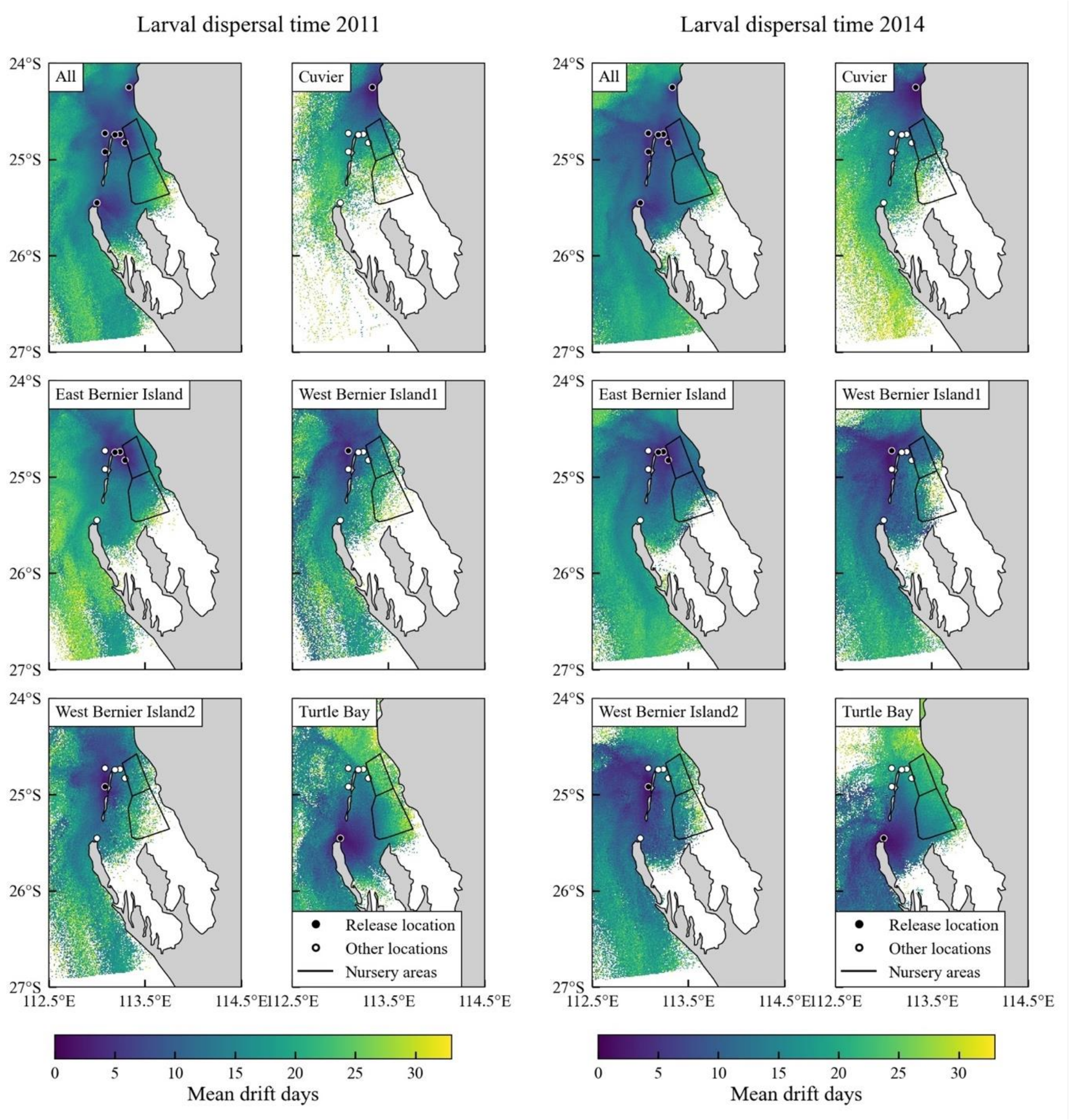


Figure 5.11. Mean drift time of (any) particles passing through grid cells for 2011 (left) 2014 (right). Black dots indicate corresponding release sites.

5.3.2.3 *Shark Bay connectivity between release sites*

Patterns of connectivity between particle release sites were consistent across years with local sources of particles more likely to arrive in each area compared to particles originating further away (Figure 5.12). Carmellas1, The Lump, and Muckhole, located in Geographe Channel on the east side of the islands were well-connected, and from those sites to Kyora, but less so in reverse. This highlighted that particles moved easily out of the bay toward the north but were less likely to enter the bay against mean current flow. Horseshoe and Turtle Bay, further south along the western shore, were less connected to the other sites. Cuvier, despite being relatively close to the other sites, was poorly connected, possibly due to its position north of the bay.

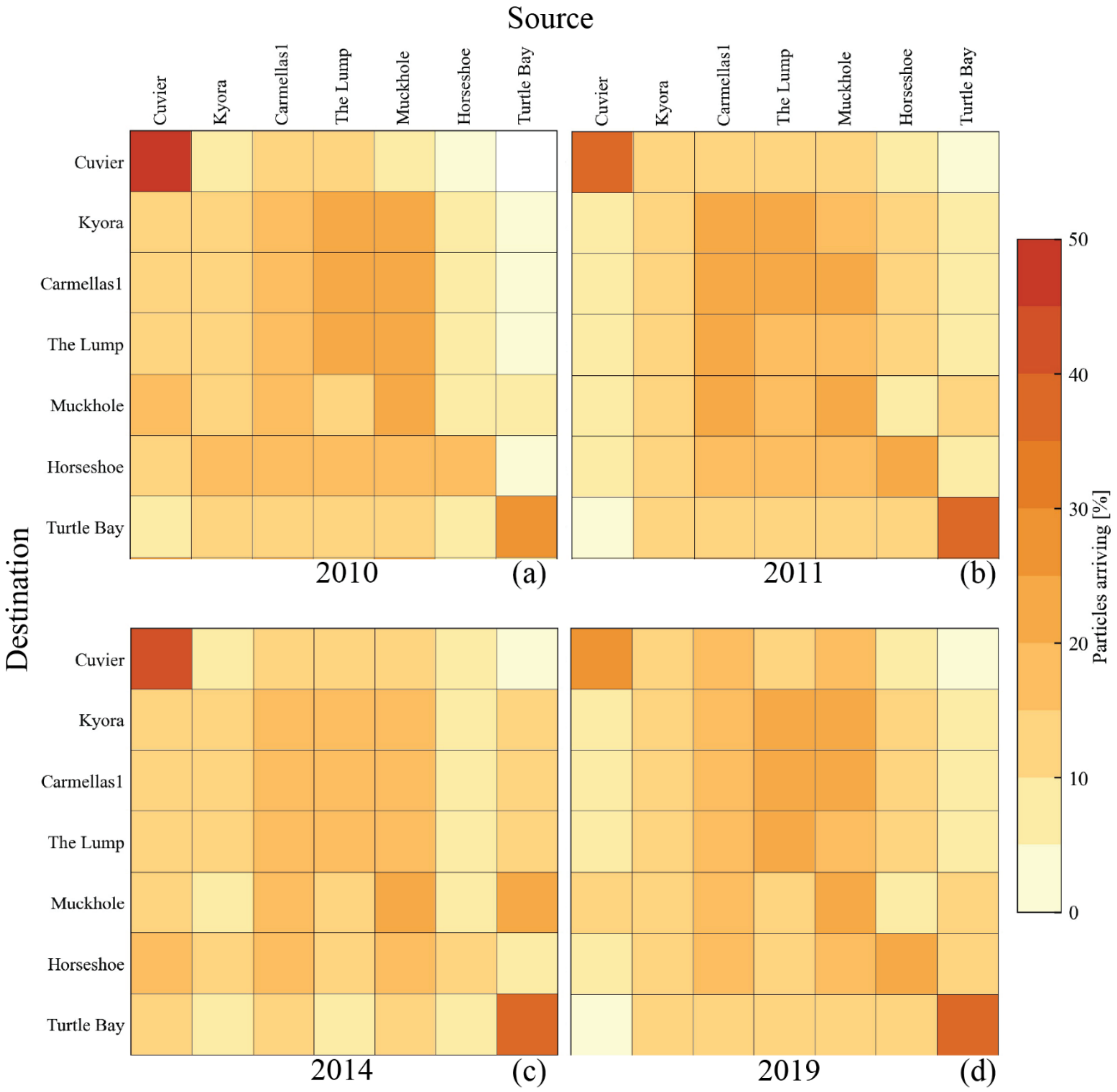


Figure 5.12. Connectivity matrix for the 7 *C. auratus* particle release sites (age 15-33 day particles) for years: (a) 2010, (b) 2011, (c) 2014, (d) 2019. The columns show the “source” of particles and the rows show where particles arrive to (“sinks”). Boxes defining source/sink sites are shown in Figure 5.2. Colours indicate % of particles arriving in a location (the matrix is row normalized). Transport into settlement areas within the bay are shown in Figures 17-20.

5.3.2.4 Transport pathways

The majority of successful particles reaching potential settlement areas within the bay followed direct pathways , south through Geographe Channel, although it was possible for particles to drift offshore and then back into the bay again through Naturaliste Channel and drift north into the settlement areas (e.g. Figure 5.13, Figure 5.14). Successful particles released from Turtle Bay drifted east and northward into the centre of the bay, following the mean flow into Naturaliste Channel and out of Geographe Channel (Figure 5.15). Unsuccessful particles released from Turtle Bay were most likely to be flushed directly out of the bay and drift to the south, however some particles followed the typical pathway to the north but remained to the west of the settlement areas closer to Bernier and Dorre Islands.

Consistent residual northward transport into Naturaliste Channel and out of Geographe Channel presented a challenge for particles (larvae) trying to reach the settlement areas from the northern spawning sites. This required movement contrary to the prevailing current and southerly (blowing south to north) winds to enter the bay. Modelling and field observations of currents suggest, however, that episodic reversal events do occur. These events are discussed in the environmental driver section below.

The findings described here are consistent with previous work targeting Saucer scallop (*Amusium balotti*) larval dispersal in Shark Bay (Kangas et al. 2012); FRDC Project 2007-051) and with virtual prawn larval dispersal (FRDC Project 2019-015). Scallop dispersal modelling suggested close connectivity within northern regions of Shark Bay, but limited connectivity between Denham Sound (near Turtle Bay) and northern regions, particularly in the southward direction. A key difference here, however, is that Turtle Bay and associated Snapper sites are further north than Scallop trawling grounds in Denham Sound and thus are likely more connected to the northern regions and offshore waters. In that study, GPS drifter released in Naturaliste Channel between the islands all drifted north exiting Shark Bay through the northern entrance channel near SB2 (Figure 5.16).

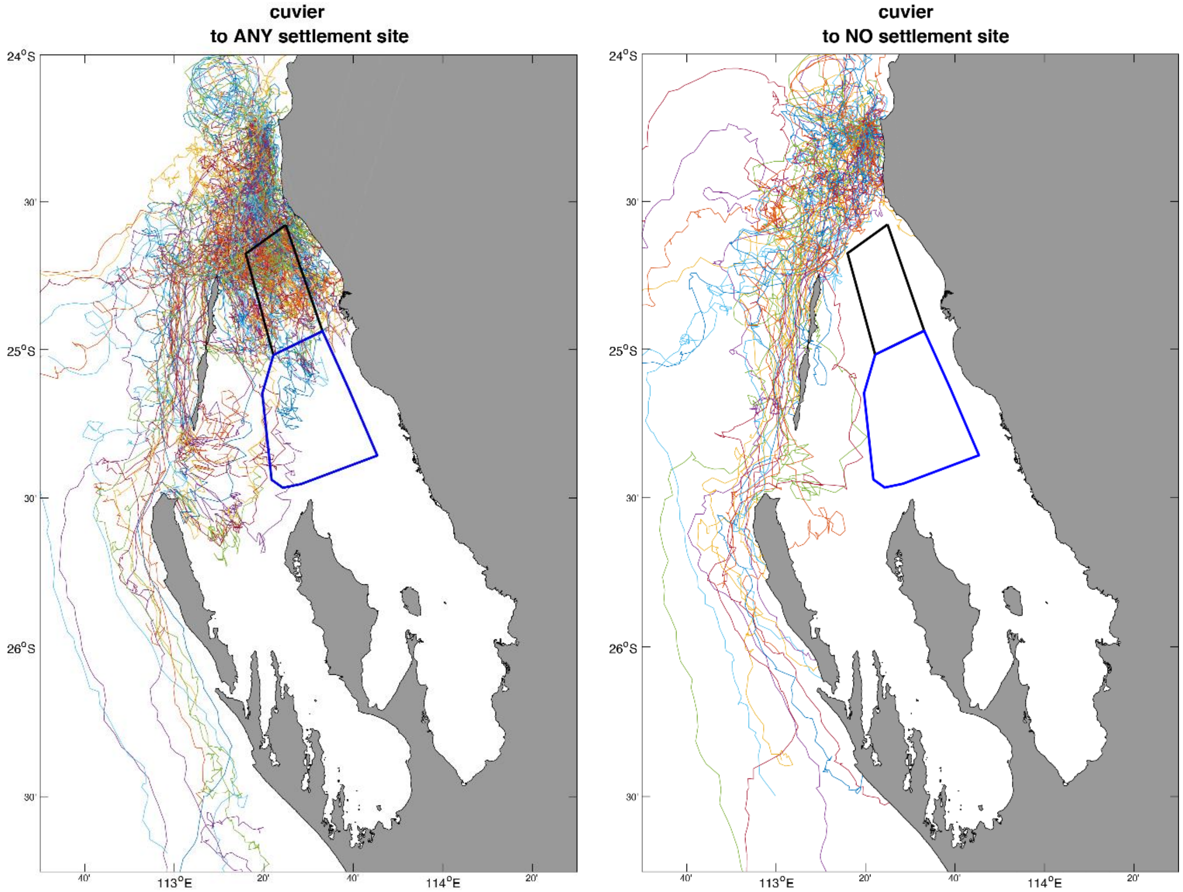
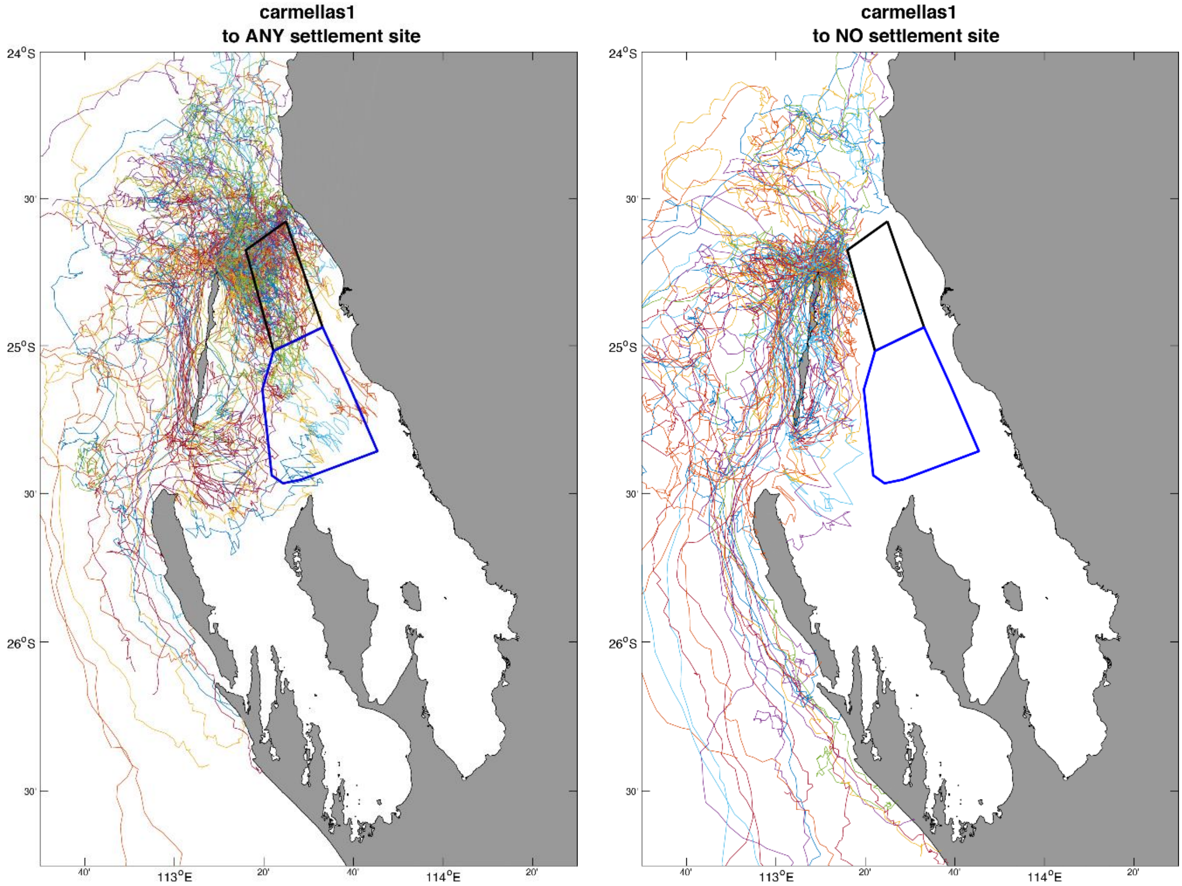


Figure 5.13. Tracks of 50 randomly selected particles released from Cuvier that were successful (left) and unsuccessful (right) at reaching the settlement areas defined with the blue and black polygons.


carmellas1 to ANY settlement site

carmellas1 to NO settlement site

Figure 5.14. Tracks of 50 randomly selected particles released from Carmellas1 that were successful (left) and unsuccessful (right) at reaching the settlement areas defined with the blue and black polygons.

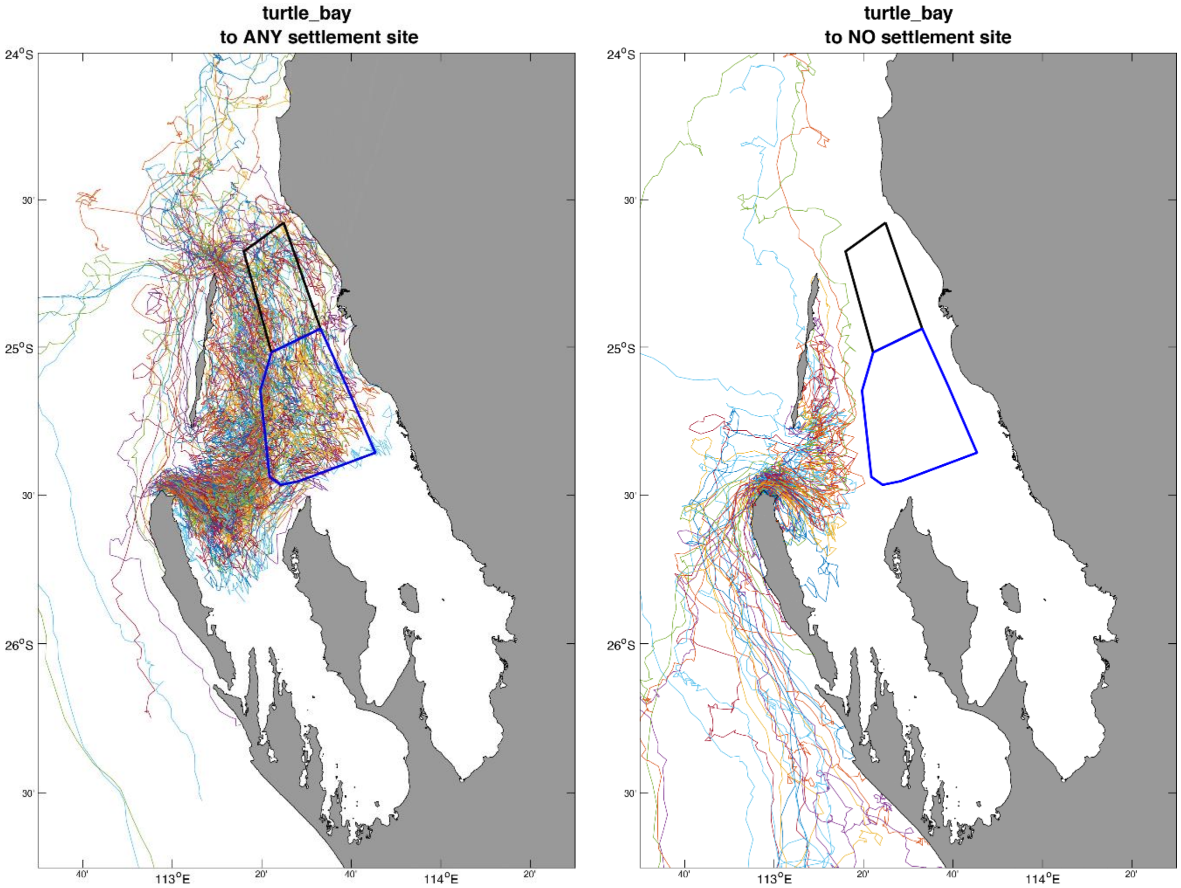


Figure 5.15. Tracks of 50 randomly selected particles released from Turtle Bay that were successful (left) and unsuccessful (right) at reaching the settlement areas defined with the blue and black polygons.

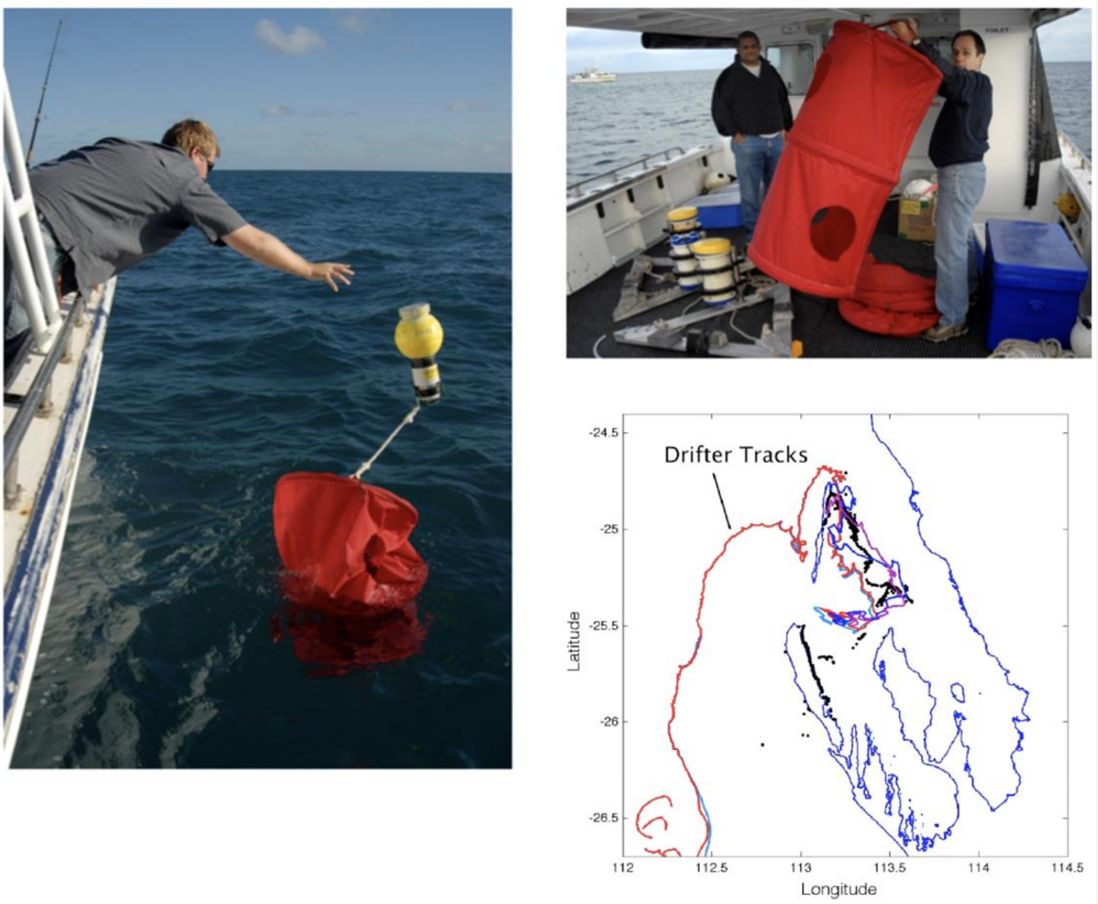


Figure 5.16. GPS Drifter release and trajectory in northern Shark Bay in June 2009 showing northward drift between Naturaliste Channel and Northern *C. auratus* spawning sites (adapted from Kangas et al. 2012).

5.3.2.5 Inter-annual and inter-site variability

Annual average percent success (particles entering the settlement areas after 15 days) ranged between 3% and 23% across all years with highest variability observed between sites compared to inter-annual differences (Figure 5.17a). Carmellas1 and Muckhole were the most successful release sites due to their proximity to the nursery areas. Following that were the Lump and Turtle Bay for 2011, 2014, and 2019. These years were all more ‘successful’ than 2010, with 2011 having highest rates of connectivity. Lowest connectivity occurred for Kyora and Horseshoe which are located on the oceanic side of Bernier Island. 2011,2014, and 2019 had very similar patterns between sites, whilst 2010 showed lower overall connectivity with Cuvier showing its highest rate, and Horseshoe and Turtle Bay having particularly poor connectivity with the settlement areas (Figure 5.17a).

Connectivity rates averaged for all sites showing totals for lunar releases (full/new moons +/- 2days) indicated that variability between lunar releases (Figure 5.17b) was high, with 2011 standing out as a ‘successful’ year albeit mostly based on releases in mid-July where favourable conditions occurred over the month (Figure 5.17b). This suggested that success is highly event-driven. The environmental events favouring transport into the bay and nurseries are examined in the following section.

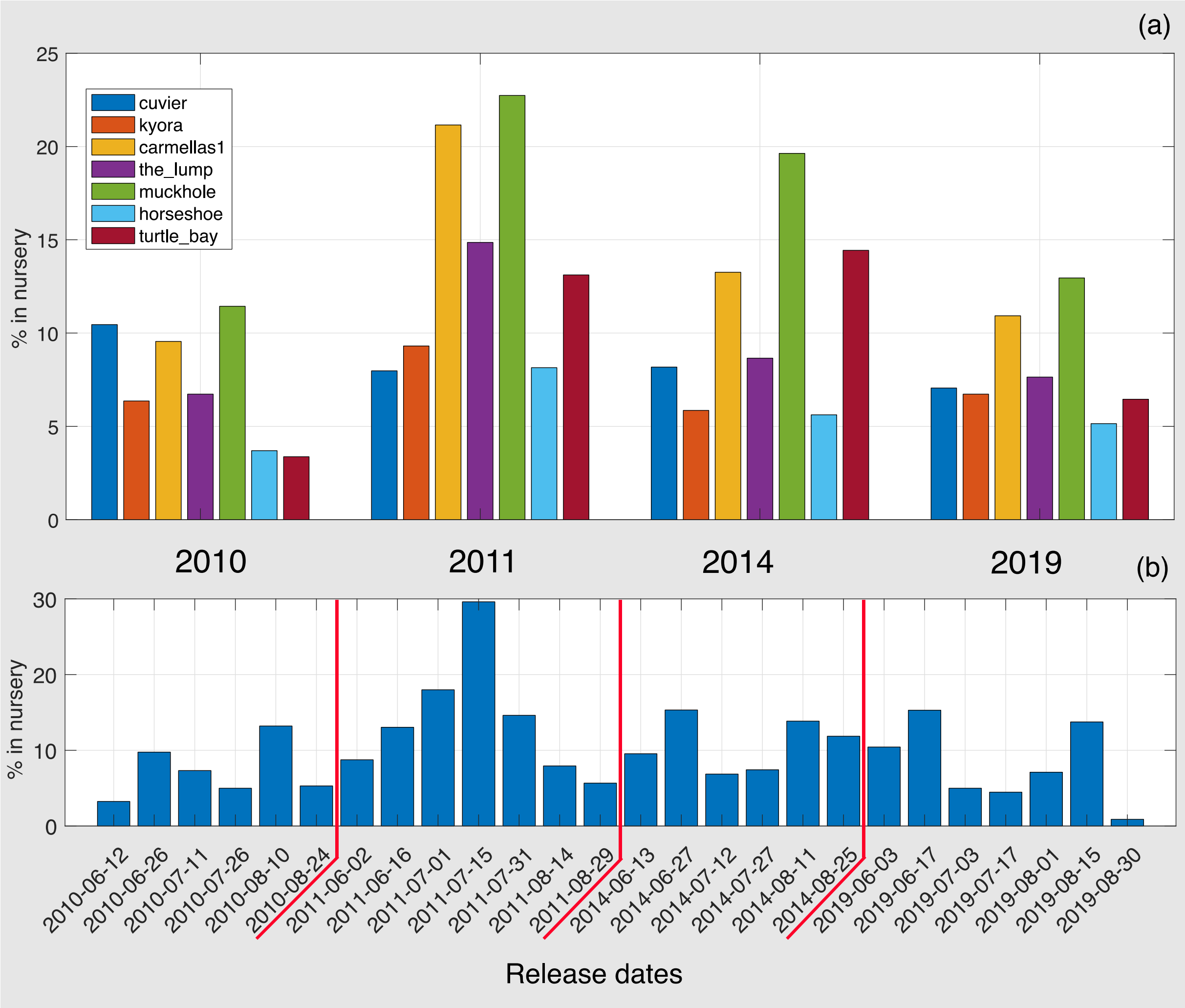


Figure 5.17. Relative percentage of 'successful' particles that passed into settlement areas in Shark Bay between 15 and 33 days after release. (a) shows relative success for each of the spawning release sites averaged over the entire spawning season (June-August); (b) shows relative success for each lunar release (within +/-2 days of new/full moon dates) averaged over all 7 release sites.

Cuvier and Turtle Bay showed high variability with date of release, and other sites such as Horseshoe (outside of bay) required specific conditions for particles to reach settlement areas (Figure 5.18). Cuvier and Turtle Bay at the north and south ends of the bay often had opposite responses—when success was high for Cuvier (e.g. 2011-06-02) it was low for Turtle Bay and vice versa (e.g. 2014-08-25). This corresponded to northerly/southerly wind conditions after particle release.

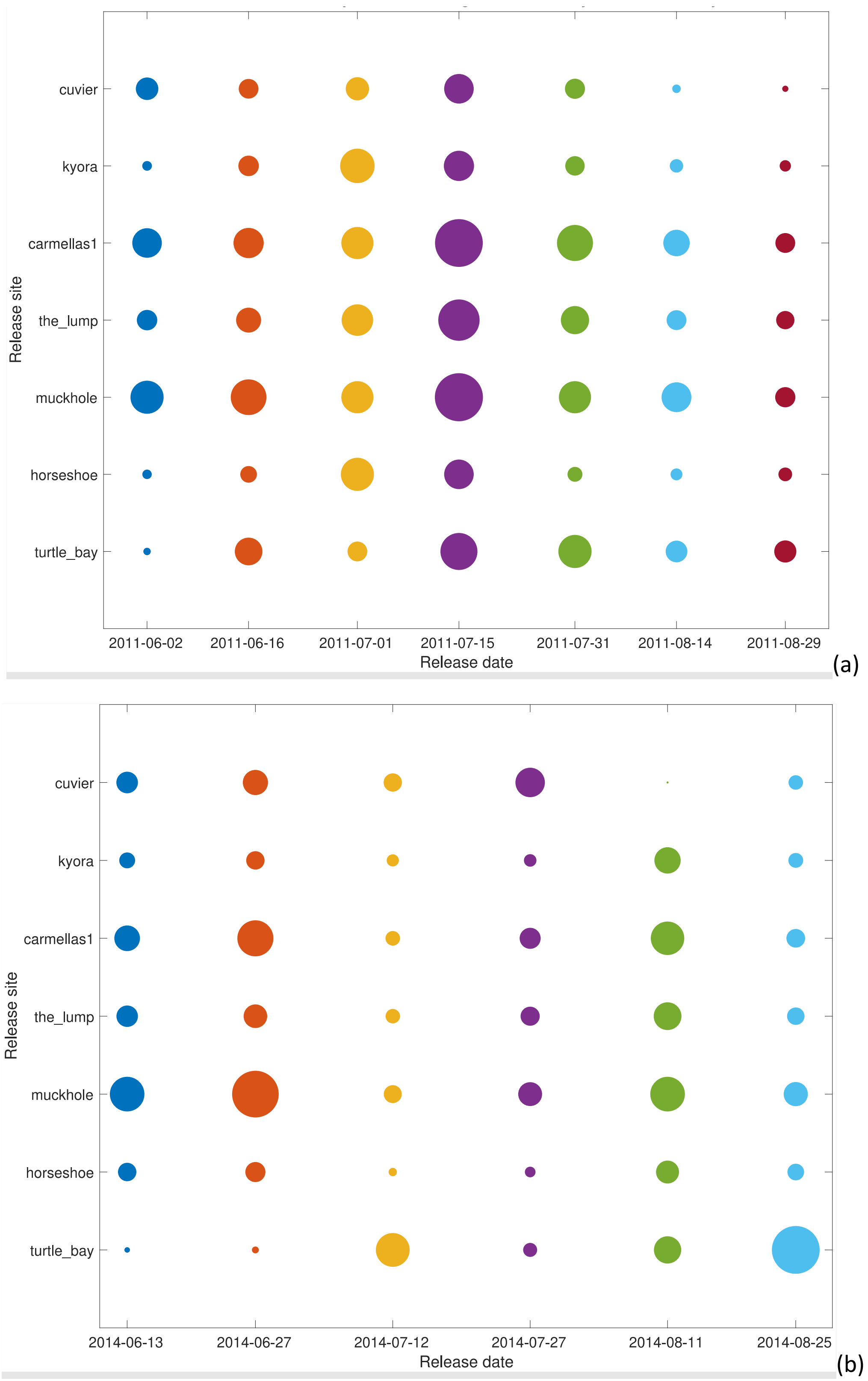


Figure 5.18. Bubble plot showing relative success of particles grouped by release date (x-axis) and release site (y-axis). The size of the circles is proportional to the number of particles that reached settlement areas after 15 days. (a) shows data for 2011 and (b) shows data for 2014.

5.3.2.6 Environmental drivers

Residual currents in the upper water column in Shark Bay are mainly driven by winds and transport of particles into the nursery areas requires favourable winds. Therefore, the relative success of particles varied significantly with each particle release and was highly dependent on weather (wind) conditions.

Passive particles were more likely to be successful if the release date coincided with winds either being weak or blowing from the north and west quadrants, or if those conditions occurred soon after particle release and/or persisted in the weeks following, for example during the second half of July and start of August 2011 (Figure 5.19). In contrast southerly or easterly winds caused particles to be flushed from the bay making those conditions unfavourable, such as happened during mid to late July 2014 (Figure 5.20).

Wind conditions in the region generally vary on a 7-10 day cycle due to the passage of synoptic weather systems (Figure 5.21). When high-pressure (anticyclone) systems pass by winds blow from the south and east. In between high-pressure systems the winds are more likely to be weak or blow from the north (Figure 5.22). If low-pressure (cyclonic) systems (storms) or cold fronts extend as far north as Shark Bay north/west winds occur and can blow over 1-3 days, or longer if the systems stall and multiple low pressures impact the region. Thus, the timing of the particle releases (and full/new moons) in relation to these systems determines the trajectories the particles will follow upon release in the predicted currents.

Low success in 2010 could be attributed to the presence of anomalous high-pressure systems and persistent and strong easterly (offshore) winds (Figure 5.23a). Winds were more variable during 2011 and 2014 resulting in higher rates of connectivity. 2011, a La Niña year had consistently weaker, and more onshore winds blowing toward the coast from the north and west (Figure 5.23b).

Years with more storm events are more likely to result in successful transport of particles from spawning sites into settlement areas. It may be possible to extrapolate these results to other years that were not modelled by looking at historic wind (e.g. Appendix 3 - Supplementary Information, Figure S5.1 – S5.10) and atmospheric pressure (e.g. Appendix 3 - Supplementary Information, Figure S5.11) and identifying which winters had more storm events following new and full moons, but this is out of scope of this project and these plots are presented here for reference in future studies.

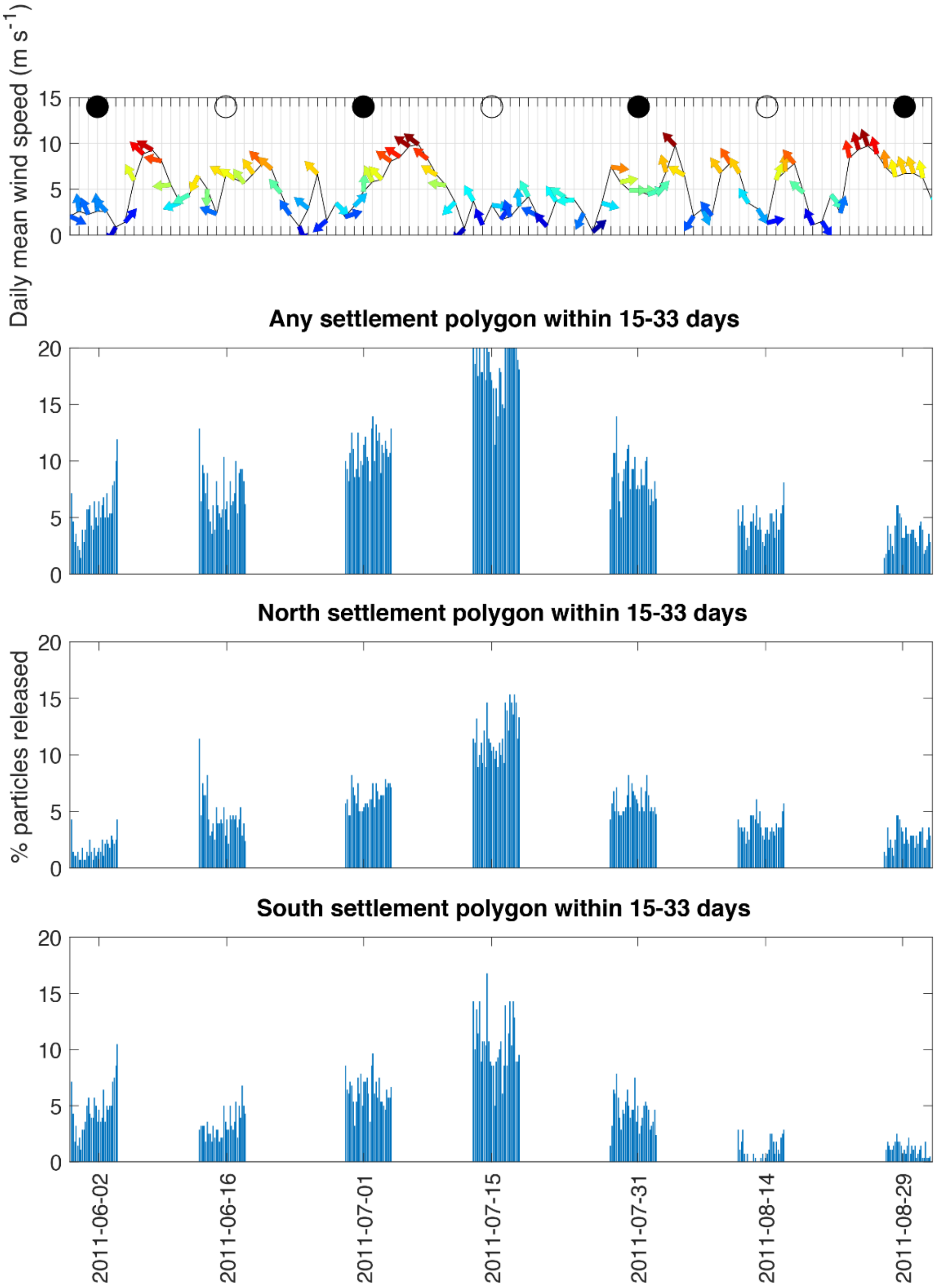


Figure 5.19. Success of particles grouped by release dates in 2011 surrounding new and full moons (+/- 2 days). Arrows show mean daily wind speed and direction from ERA5 model. Low success occurred when winds blew from the east or south and high success occurred when winds were weak or from the north and west.

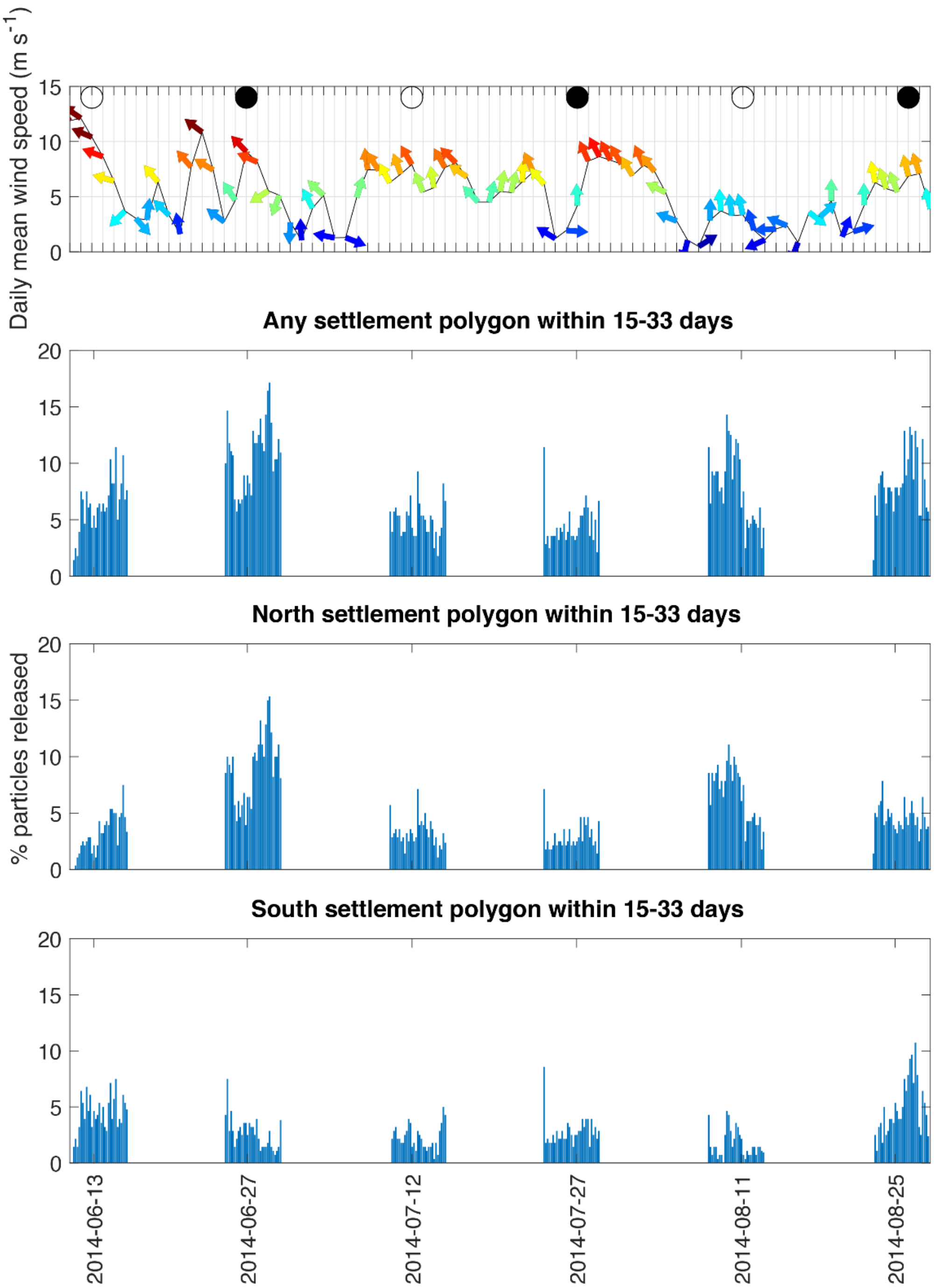


Figure 5.20. Success of particles grouped by release dates in 2014 surrounding new and full moons (+/- 2 days). Arrows show mean daily wind speed and direction from ERA5 model. Low success occurred when winds blew from the east or south and high success occurred when winds were weak or from the north and west.

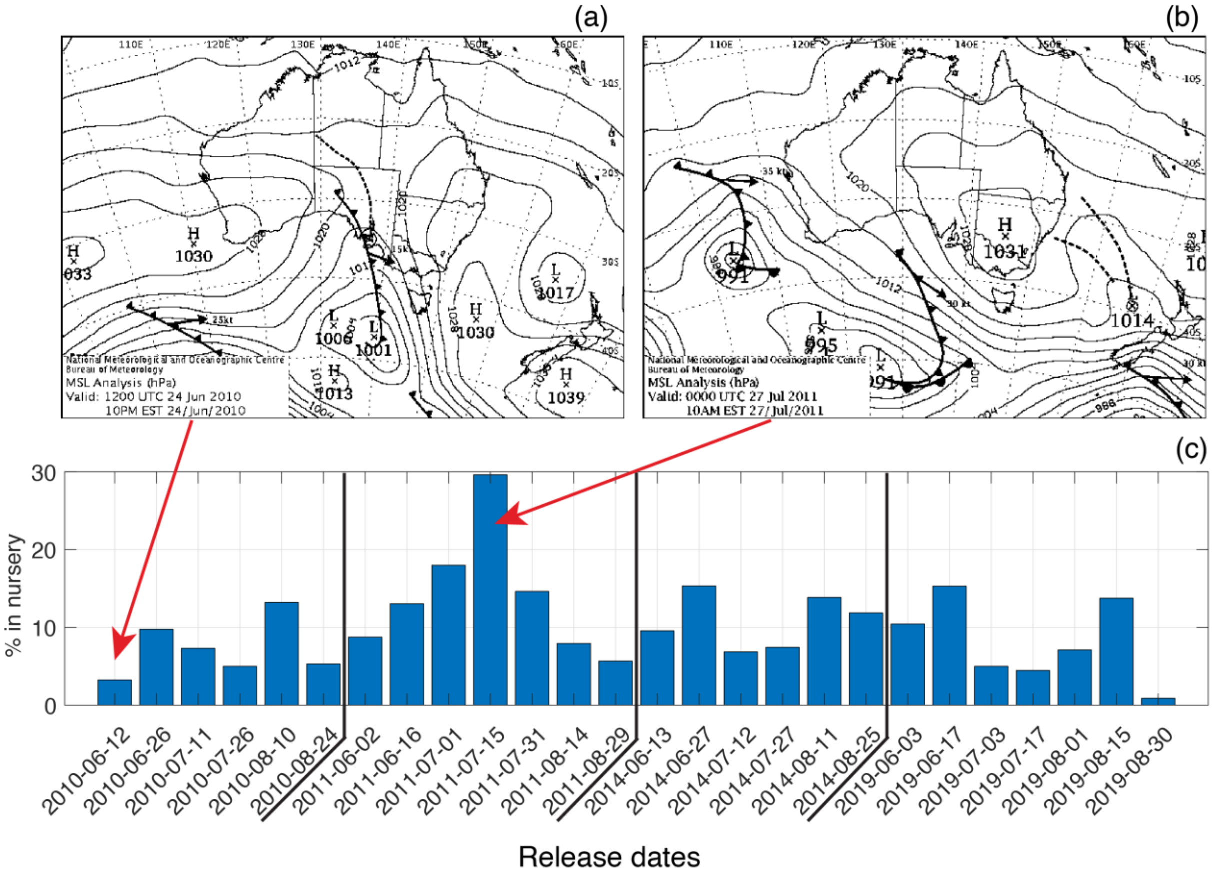


Figure 5.21. Bureau of Meteorology synoptic weather charts showing conditions causing (a) poor success; (b) high success for particles in Shark Bay. The low/high success shown in (c) resulted from persistence of these conditions in the days/weeks following these particle releases.

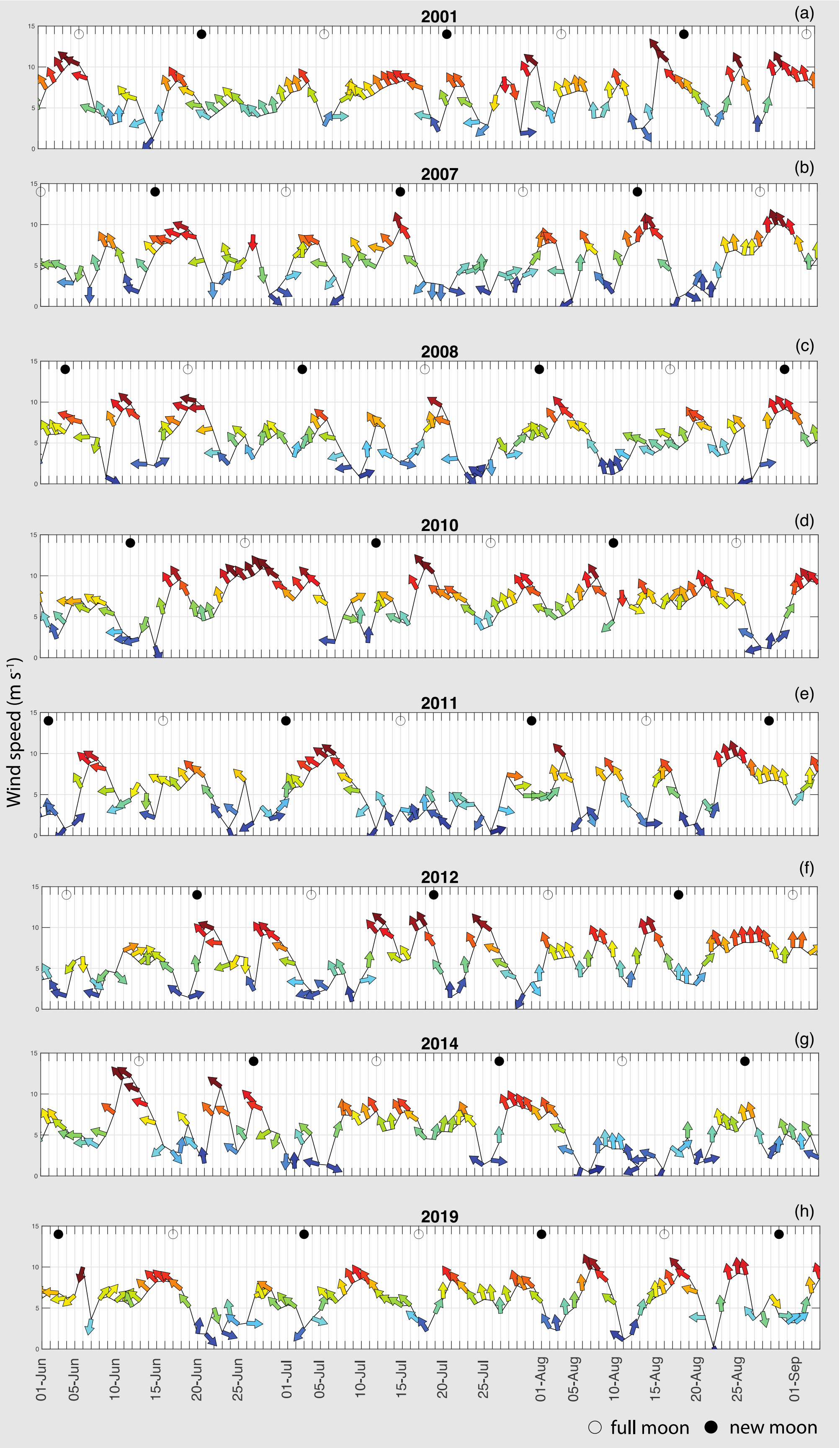


Figure 5.22. Daily mean wind speed (m/s) and direction at Shark Bay from ERA5 model for simulated winters in both low-resolution and high-resolution numerical models. New and full moon dates coinciding with particle release dates are shown.

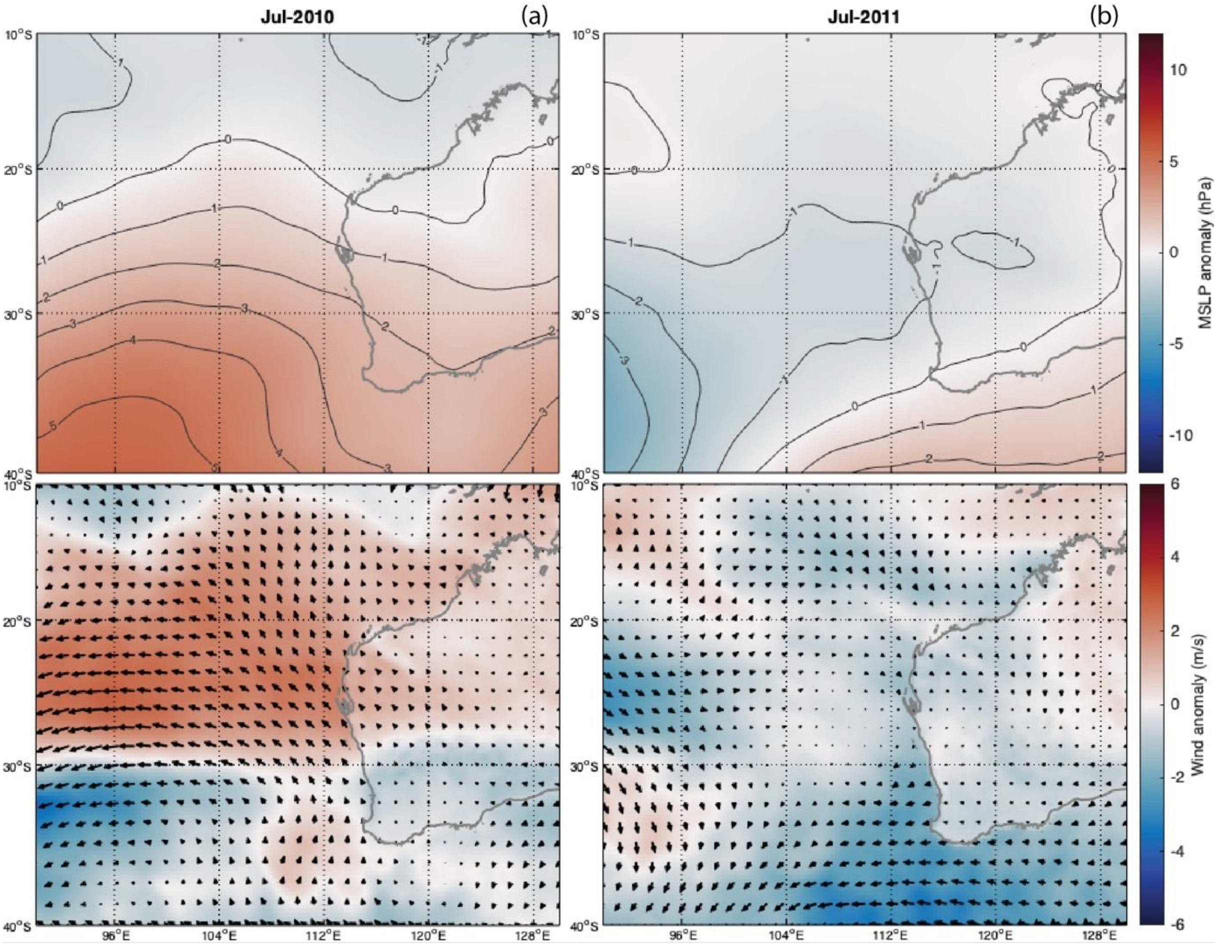


Figure 5.23. Maps of July average mean sea level pressure (MSLP) and wind anomalies for (a) 2010 and (b) 2011 derived from the ERA5 atmospheric reanalysis and calculated against the 1992-2016 climatology. July 2010 experienced stronger more easterly and southerly winds caused by a persistent high pressure to the southwest of the state; July 2011 was characterized by weaker more variable winds and a low pressure anomaly.

5.4 Discussion/Conclusion

The application of hydrodynamic and passive particle numerical models to the GCB and WCB has enabled the quantification of oceanographic connectivity, which will improve understanding of *C. auratus* egg/larval transport within and between the GCB and WCB regions, and from offshore spawning sites into Shark Bay settlement areas.

We found that Shark Bay is only minimally connected to Kalbarri and the Mid-West when using passive particle advection limited by a 33-day drift time. Dispersal was typically north to south, driven by the southward-flowing Leeuwin Current, influenced by the action of eddies, and opposed by prevailing southerly winds. Dispersal from Kalbarri to the Mid-West was more likely, and between inshore and offshore sites, but similar drift distance limits applied throughout the region with most particles not traveling much more than 200km from release sites. Dispersal pathways from Shark Bay spawning sites around the offshore islands were identified. Most particles from northern release sites that were successful at drifting into settlement areas inside the central-eastern portion of Shark Bay followed a direct pathway through northern Geographe Channel. This pathway was highly dependent on wind conditions. Another possible, but less efficient pathway consisted of recirculation around the western shore of the islands entering through Naturaliste Channel. Particles released at sites inside the bay and closest to the settlement areas were consistently the most likely to settle successfully. Particles released outside of Bernier and Dorre Islands or at Turtle Bay (Dirk Hartog Island) featured lower, more variable connectivity but could still be transported to the settlement areas in the required timeframe.

Oceanographic connectivity as determined by passive particle dispersal modelling thus supports the findings of the genomic (this report, Chapter 3) and otolith chemistry analyses (this report, Chapter 4). Drift trajectories and timescales suggest local recruitment dominates and any mixing between regions is more likely to occur during later life stages.

Relative patterns of connectivity described above were similar between most years. However, high variability was observed between the particle releases around full/new moons attributed to varying wind conditions over the season. The main physical feature that particles (larvae) released at the northern sites must overcome is the mean northward current that enters Naturaliste Channel and flows northward exiting the bay though Geographe Channel. This current is driven by inflow of Leeuwin Current water, wind-driven currents as well as density-driven circulation caused by release of hypersaline water from the inner gulfs. Southerly winds enhance the flow making it difficult for particles to enter the settlement areas inside the bay. Reversals in the flow direction caused by northerly winds that occur during passage of low pressure systems or cold fronts were found to be favourable for particle transport into the bay. Likewise, westerly winds that did not necessary reverse the northward current also assisted particle transport toward the east into settlement areas.

The timing of weather systems in relation to particle releases (virtual spawning events) was critical. Extended periods of weak and/or onshore (blowing toward the coast) winds encouraged transport into settlement areas whilst strong easterly (blowing away from the coast) or southerly (shore parallel) winds resulted in poor (virtual) recruitment. Exact timing or duration of wind events that control successful spawning and recruitment cannot be determined without more complete biological data describing Shark Bay *C. auratus* spawning and larval behaviour. However, in any case an extended period of weak or onshore winds associated with low pressure systems is likely to enhance recruitment of *C. auratus* larvae into the settlement areas and enable them to stay long enough to develop swimming abilities. On the other hand, anomalous strong high pressure systems with strong southerly or easterly winds and fair weather will likely act to flush particles and presumably larvae from the bay. Ocean circulation and dispersal variability outside Shark Bay were also dependent on synoptic weather systems, and the strength of the Leeuwin Current.

These underlying drivers of variability are modulated by the El Niño Southern Oscillation (ENSO) and other large scale climate processes like the Southern Annular Mode (SAM) (http://www.bom.gov.au/climate/sam/) or Indian Ocean Dipole (IOD) (http://www.bom.gov.au/climate/iod/). Monitoring of these processes in the future may be relevant to better understand snapper recruitment variability in the region.

Better understanding of larval behaviour, particularly vertical position, drift duration, and timing/frequency/location of spawning events will enhance future understanding of the Snapper connectivity in the GCB and WCB. Other factors influencing the success of larvae such as food availability, influence of temperature on growth / mortality are out of the scope of this project but will likely have an influence on recruitment and could be included in the biophysical dispersal model if they were known. The main conclusions drawn from this work were robust across many different years and incorporated the trajectories of hundreds of thousands of particles encompassing a broad range of conditions. This suggested physically plausible results that agree with findings from the other components of this project.

6. Evaluating the use of active acoustic methods for monitoring the distribution and abundance of Snapper in spawning aggregations

Ben Scoulding
CSIRO Oceans & Atmosphere

This chapter has been submitted to a peer reviewed journal:

Scoulding, B., Gastauer, S., Taylor, J.C, Boswell, K.M, Fairclough, D.V., Jackson, G., Sullivan, P., Shertzer, K., Campanella, F., Bacheler, N., Campbell, M., Domokos, R., Schobernd, Z., Switzer, T.S., Jarvis, N., Crisafulli, B.M, Untiedt, C., Fernandes, P.G. (2022). Estimating abundance of fish associated with structured habitats by combining acoustics and optics: fisheries acouptics. *Journal of Applied Ecology*. 2023.

The following provides a synopsis of the main findings from this publication with the addition of a section on key findings and recommendations. The figures and tables in this chapter have been taken from Scoulding et al. (2023).

6.1 Introduction

The overarching aim of this chapter was to evaluate the use of active acoustic methods for monitoring the distribution and abundance of Snapper (Pink snapper, *Chrysophrys auratus*) in spawning aggregations. The objectives included:

(1) Quantifying the density of *C. auratus* and provide estimates of *C. auratus* biomass from a survey in Shark Bay.
(2) Validating the target strength (TS) for *C. auratus*.
(3) Providing industry, scientist, and fishery managers with an evaluation of the use of active acoustic methods for monitoring the distribution and abundance of *C. auratus* in spawning aggregations.

To meet the key objective of this chapter Scoulding et al. (2023) took advantage of two common fish survey techniques – acoustics and optics – to develop and conduct an integrated acoustic-optical survey method (termed *acouptics*) for estimating the abundance of *C. auratus* within an area closed to fishing north of Bernier Island, Shark Bay. The study focused on a sub-region of the closed area in 20-70 m depth, which produces high catches of *C. auratus* as they migrate inshore to spawn.

6.2 Methods

The *acouptics* survey was conducted during daylight hours from the 14th to 22nd July 2020 onboard the 26.2 m commercial hook and line fishing vessel FV *Ada Clara*. Acoustic data, collected by a calibrated scientific echosounder mounted to the side of the vessel, was interpreted with the help of concurrent observational data via unbaited remote underwater video (RUV). The six RUVs used during this study comprised two Canon LEGRIA HF M52 cameras housed in steel frames. RUV locations were placed at locations of fish backscatter detected by the echosounder. When a suitable aggregation of fish was detected, the vessel immediately returned to the location and the RUVs were deployed. The cameras soaked ≥ 90 mins before retrieval. Geographic position was recorded for each acoustic, video, biological and environmental sample.

Figure 6.1 provides an overview of the processing steps required to get biomass estimates from an acouptics surveys. This is described in full by Scoulding *et al*. (2023) and summarised here. Video analysis was done in SeaGIS EventMeasure. Acoustic data was partitioned using the first 2 minutes of camera recordings. For each 2-minute video recording, fork length (*FL*) was measured for all individuals of each species at the time when the MaxN was observed. Fork length to total weight for all species were taken from reliable sources (Table 6.1). Acoustic data were processed in Echoview software. Fish aggregations, detected using Echoview's school detection algorithm, were manually classified as either: (1) snapper-like (in reference to *C. auratus*); (2) probable yellowtail scad, *Trachurus novaezelandiae;* or (3) unknown small pelagic fish, which includes possible *T. novaezelandiae* (Figure 6.2). Echo-integration was then performed on all aggregations.

Target strength (*TS*), the measure of how much sound an individual fish reflects, was estimated from *ex situ TS* measurements of 10 large *C. auratus* in Cockburn Sound (CS), WA, on 21st November 2019. Recordings were made in a 5 x 5 x 7 m custom-built net-pen located in a sheltered part of CS. All other species were assigned to a representative *TS* to length (*L)* group, based on morphological similarities. These were snapper-like (Lutjanids, Haemulids and Mullidae), trevally-like (Carangids. and the Sciaenid *Argyrosomus japonicus*, i.e., mulloway), cod-like (Epinephelids and Serranids, i.e., rockcod/grouper species), and small-pelagic-like (Carangids, i.e., yellowtail scad). Target strength to length equations for these groups were based on the best available data in the literature (Figure 6.2). Abundance of *C. auratus* was estimated using geostatistical conditional simulations (summarised in Figure 6.3 and described fully in Scoulding et al. 2023).

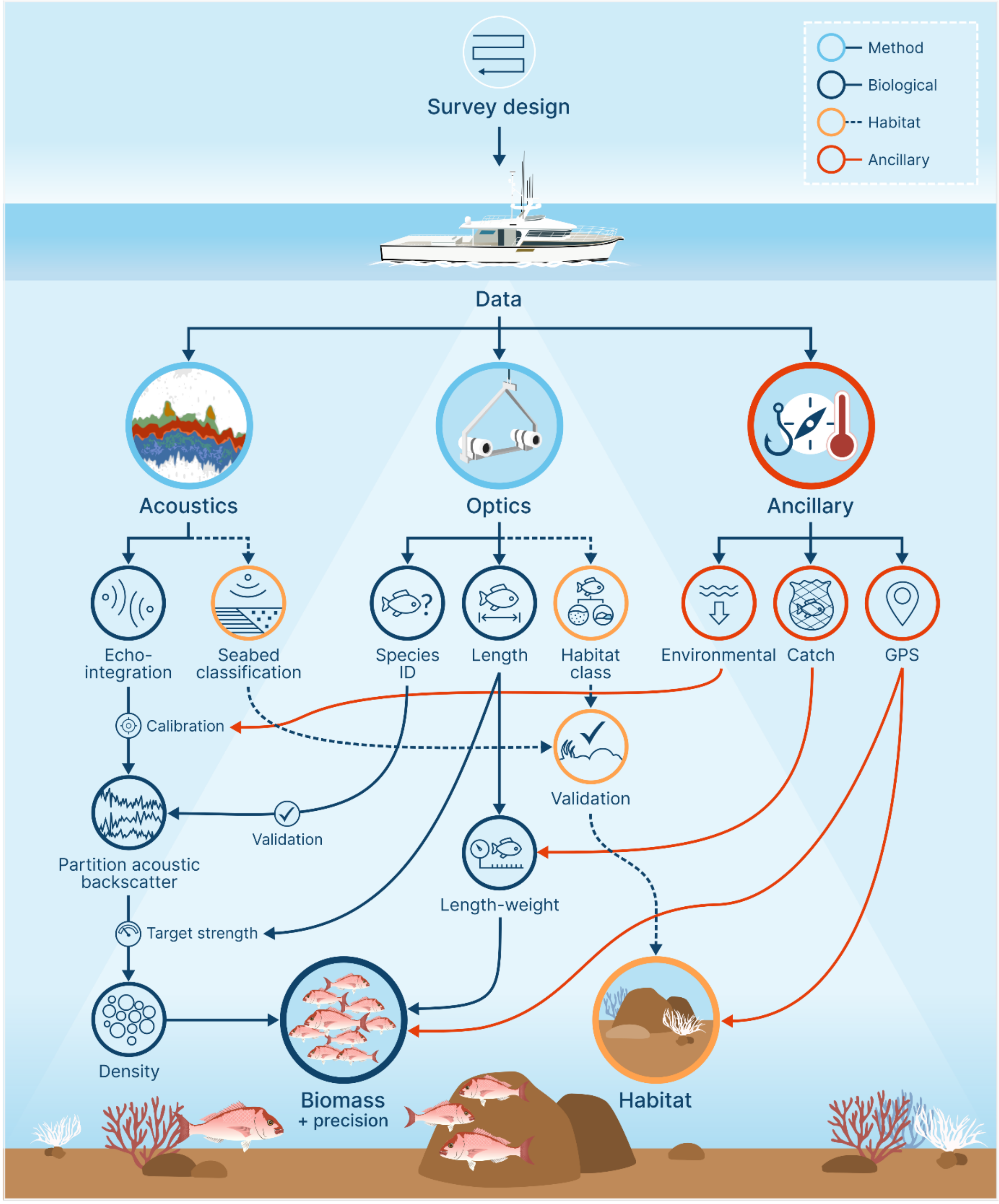


Figure 6.1. Flow graphic of the analytical methods applied to an *acouptics* survey, moving from raw data sources and types, to combined acoustics and optics species-specific density estimates and habitat information. Figure and legend taken from Scoulding et al. (2023).

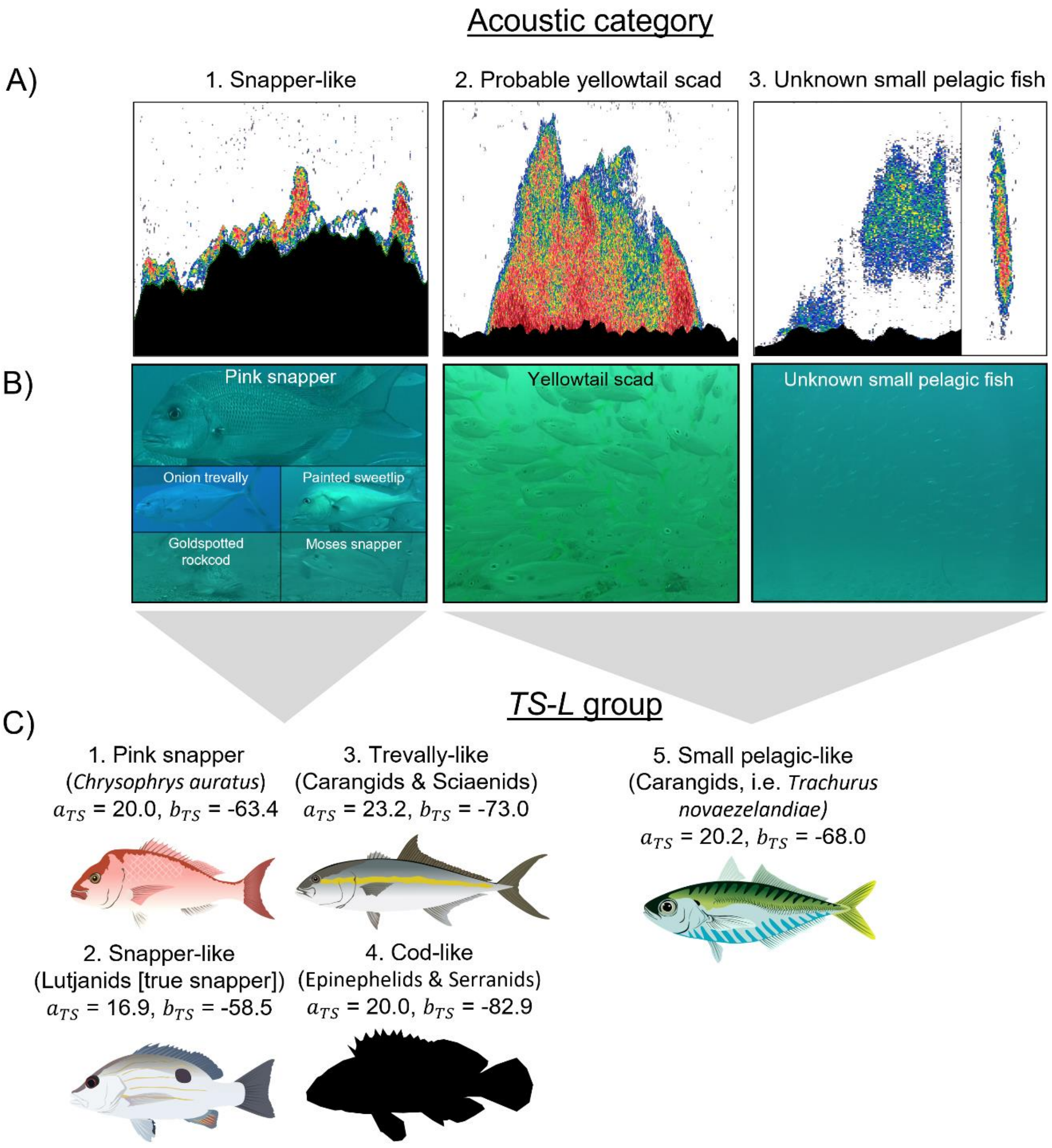


Figure 6.2. A) the three acoustic categories (snapper-like, probable Yellowtail scad, and unknown small pelagic fish), B) examples frames from neat-concurrent deployments of remote underwater video, and C) the five-target strength (*TS*) to length (*L*) groups used in the interpretation and analysis of the acoustic data. Group *TS-L* equations are given at 38 kHz, where a_{TS} is the slope and b_{TS} is the intercept. Figure and legend taken from Scoulding et al. (2023).

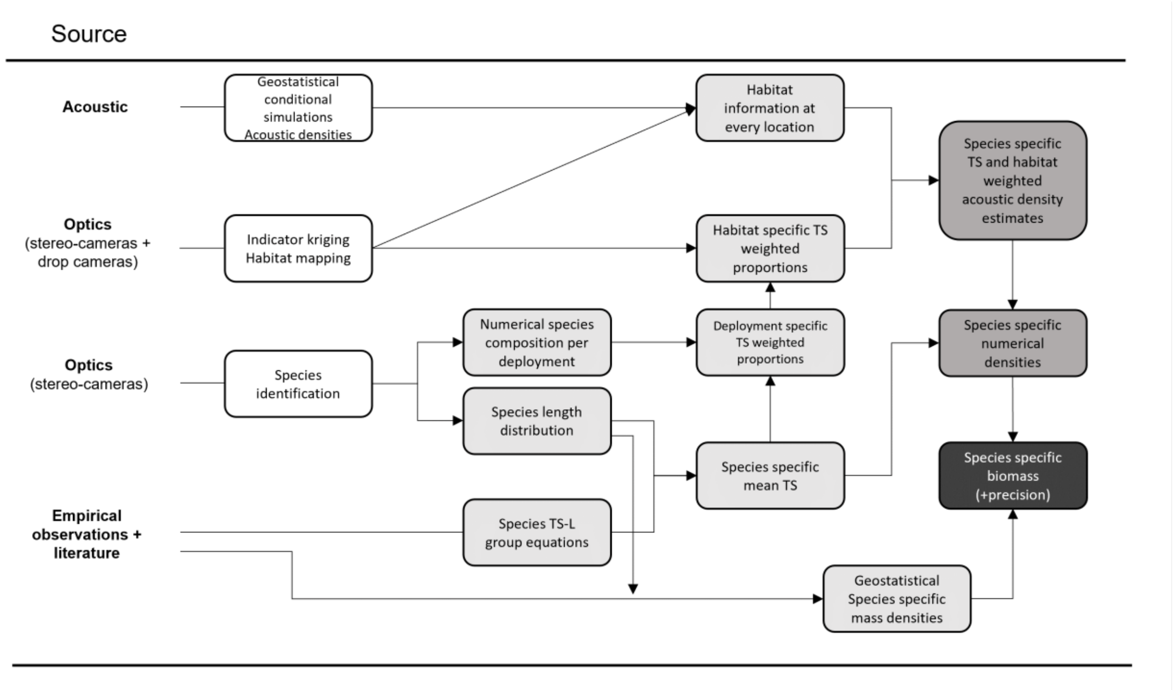


Figure 6.3. Shows processing workflow used to partition acoustic backscatter and estimate biomass of aggregating fish species. Figure and legend taken from Scoulding et al. (2023).

6.3 Results

In total 162 nautical miles of transects were completed over the surveyed area of 182 km^2. The highest Snapper-like concentrations were recorded in the central southern part of the area, whilst the highest probable yellowtail scad concentrations were recorded in the northeast corner (Figure 6.4). Twenty-nine RUVs were successfully deployed during the survey at depths ranging from 28.4 to 66.6 m (Figure 6.5). Eight occurred over sandy substrates, 11 occurred over reef, and 10 occurred over sand with patches of biogenic growth. Eighteen aggregating (Table 6.1) and twenty-four non-aggregating fish species were observed (see supplementary material in Scoulding et al. (2023)).

The five *TS-L* groups, Pink snapper, snapper-like, small pelagic fish, cod-like, and trevally-like, consisted of 1, 7, 3, 1 and 6 species, respectively. Several species of shark and ray, moray eels and a Humpback whale were also observed. All aggregating fish species possessed gas-filled swim bladders. The numerical proportions (in terms of total MaxN) of aggregating species observed varied across the surveyed area. *Chrysophrys auratus* were observed in 19 RUV deployments (66 % of those analysed). Of those deployments, 14 had a *C. auratus* MaxN < 4, indicating this species was mostly loosely aggregated (74% of the time, *C. auratus* were observed). Yellowtail scad and other baitfish species made up ≥50 % of the total number of aggregating fish observed nine times (47%). Other aggregating fish species dominated the other 10 RUV deployments where Pink snapper was observed (53%). *Chrysophrys auratus* were the second most abundant aggregating species observed with a biomass of 18.02 t (CV = 28.49%) (Table 6.1).

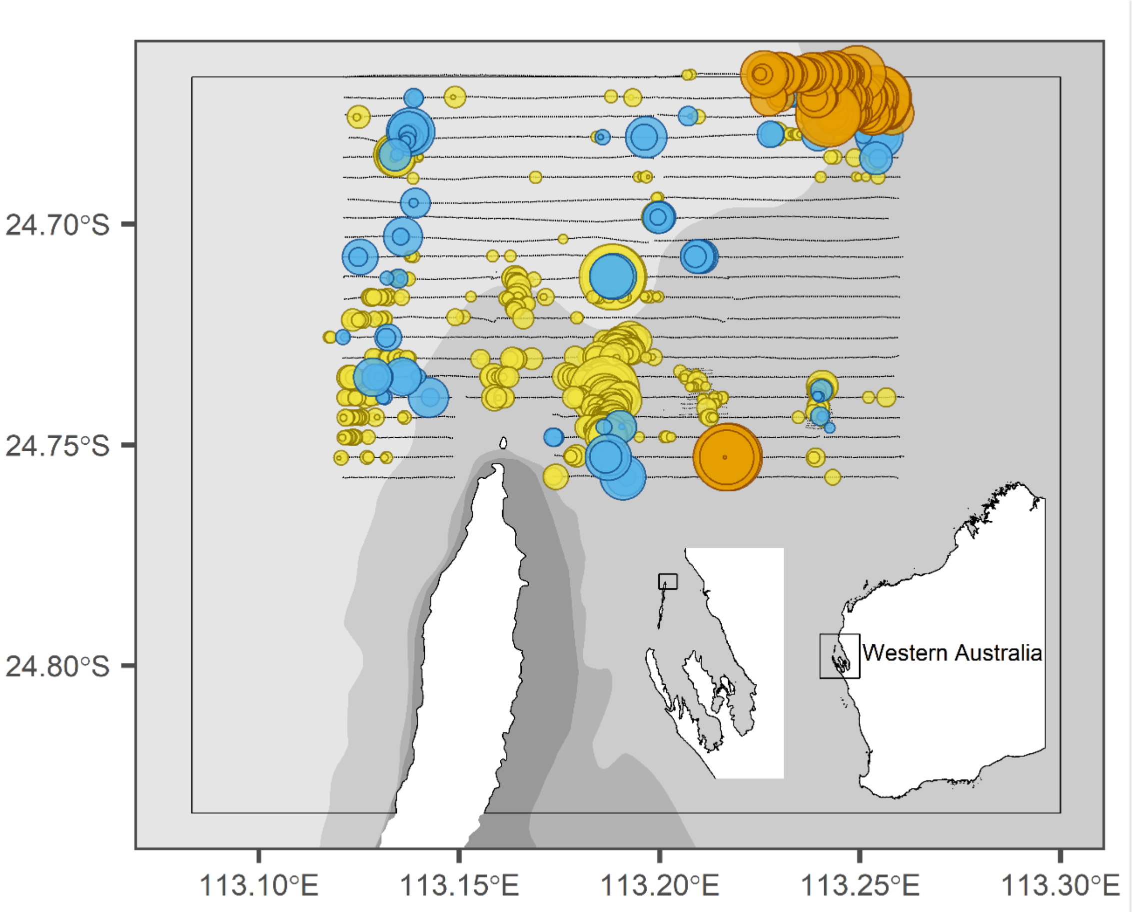


Figure 6.4. Map of the survey area (closed fishing area) with integrated backscatter (circles proportional to √s_A, scaled to the largest observation of 126,449 m^2 nmi^{-2}) of snapper-like (yellow), unknown small pelagic fish (blue) and probable yellowtail scad (orange) by 50 m intervals along the cruise track during the 2020 *acouptics* survey at 38 kHz. The black lines show the cruise track. The inset maps show Western Australia (right) and Shark Bay (left), with the black rectangles showing Shark Bay and closed fishing area, respectively. Figure and legend taken from Scoulding et al. (2023).

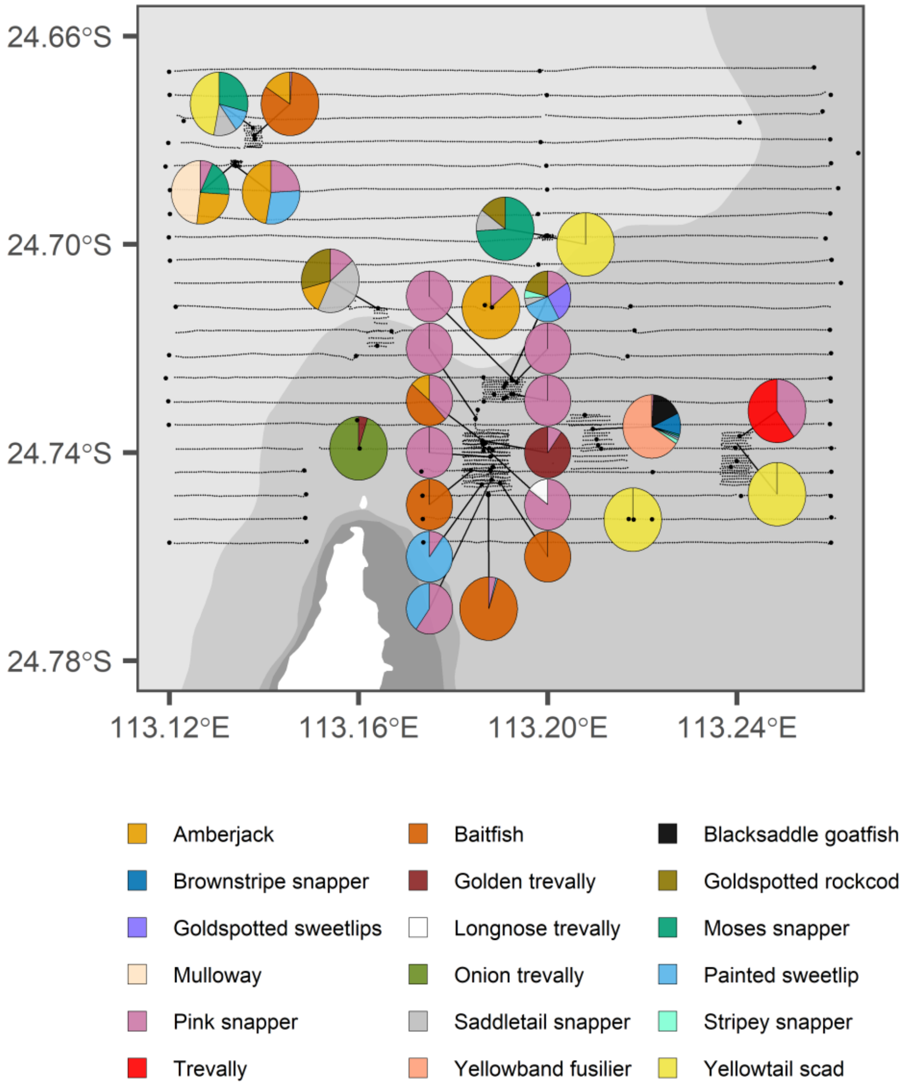


Figure 6.5. Map of the closed fishing area in Shark Bay, WA, showing the vessel cruise track (black dotted line) during the *acouptics* survey in July 2020. The survey consisted of broadscale transects (500 m spacing) and a series of fine resolution surveys (20-50 m spacing). The pie charts point to the locations of remote unbaited video stereo camera deployments with the pieces showing the proportions of different aggregating fish species. The black dots show the locations of camera drops used to validate acoustic habitat classification. Grey shading indicates bathymetry to a maximum depth of 70 m. Figure and legend taken from Scoulding et al. (2023).

Table 6.1. List of aggregating fish species observed by the unbaited remote underwater video cameras. TS-L group refer to the target strength to length relationship applied to each group (see Fig. 2B). Mean fork length (FL in cm, ± 1 SD) was determined from stereo length measurements. N is the number of fish measured. The FL to total weight (TW) equation for Pink snapper took the form of $TW = 2.8416 * log(FL, mm)^{-9.8054}$ and is based catches made in Shark Bay from 2018-2022 Bay and were taken from the Department of Primary Industries and Regional Development (DPIRD), WA, database. FL-TW for all other species fitted the linear regression equation $\mathrm{TW} = a_{LW} * FL^{b_{LW}}$ with units for length and weight given in the table. Constants for the equations were taken from various sources, 1 = DPIRD database, 2 = Smallwood et al. (2018), 3 = FishBase (accessed November 2021) (Froese & Pauly, 2022), 4 = Al-Marzouqi et al. (2013), and 5 = Parsa et al. (2017). Figure and legend taken from Scoulding et al. (2023).

***TS-L* group**	**Common name**	**Species**	**Mean fork length (cm) (± SD)**	**N**	***FL-TW***				**Mean weight (g)**	**Mean TS (dB re 1 m^2)**	**Biomass**	
					a_{LW}	**b_{LW}**	**Units**	**Source**			**Total (t)**	**CV (%)**
Pink snapper	Pink snapper	*Chrysophrys auratus*	44.9 (± 10.6)	306	2.8416	-9.8054	log	1	2157	-30.47	18.02	28.49
Snapper-like	Blacksaddle goatfish	*Parupeneus spliurus*	24.3 (± 4.5)	34	0.000049	2.7885	mm, g	2	245	-34.95	0.18	25.44
	Brownstripe snapper	*Lutjanus vitta*	26.8 (± 1.8)	15	0.00000584	3.1178	mm, g	1	225	-34.30	0.11	16.78
	Goldspotted sweetlips	*Plectorhinchus flavomaculatus*	41.3 (± 5.8)	32	0.001531	2.2459	mm, g	2	1176	-31.15	0.74	13.11
	Moses' snapper	*Lutjanus russellii*	36.1 (± 6.2)	48	0.00001613	2.9976	mm, g	1	855	-31.97	1.43	23.70
	Painted sweetlip	*Diagramma pictum labiosum*	53.3 (± 8.3)	93	0.00001166	3.0214	mm, g	1	2129	-29.33	4.62	23.90
	Saddletail snapper	*Lutjanus malabaricus*	61.8 (± 11.8)	33	0.00002241	2.9352	mm, g	1	3444	-28.37	2.41	22.78
	Stripey snapper	*Lutjanus carponotatus*	35.1 (± 4.9)	17	0.00001089	3.0911	mm, g	1	862	-32.32	0.18	22.38
Small pelagic	Yellowtail scad	*Trachurus novaezelandiae*	19.6 (± 4.8)	132	0.000086	2.5782	cm, g	1	141	-41.73	2.41	35.73
	Yellowband fusilier	*Pterocaesio chrysozona*	9.7 (± 4.0)	56	0.01047	3.12	mm, g	3	9.4	-48.36	0.35	38.87
	Unknown baitfish	*NA*	-	-	0.000086	2.5782	cm, g	2	5	-51.17	6.08	54.19
Trevally-like	Amberjack	*Seriola dumerili*	91.8 (± 28.7)	70	0.000185	2.5596	mm, g	2	7405	-27.32	20.83	9.00
	Golden trevally	*Gnathanodon speciosus*	70.9 (± 15.8)	51	0.000045	2.7756	mm, g	2	4230	-29.66	3.37	15.40
	Longnose trevally	*Carangoides chrysophrys*	65.9 (± 2.6)	9	0.0369	2.7123	cm, g	4	3189	-30.78	1.83	12.85
	Mulloway	*Argyrosomus japonicus*	99.3 (± 5.6)	13	0.000011	2.9541	mm, g	2	7879	-26.67	1.87	14.27
	Onion trevally	*Carangoides coeruleopinnatus*	56.6 (± 5.1)	16	0.024	2.953	cm, g	5	3743	-32.23	10.80	12.05
	Trevally	*Carongoides* sp.	29.4 (± 2.7)	4	0.000044	2.8433	mm, g	2	468	-38.90	1.99	14.48
Cod-like	Goldspotted rockcod	*Ephinephelus coioides*	73.5 (± 13.8)	21	0.000003	3.2342	mm, g	2	6903	-45.18	10.96	24.52

6.4 Discussion/Conclusion

A full discussion of the findings is given in Scoulding *et al*. (2023). Here we summarise it briefly.

This study has shown that aggregations of *C. auratus* are easily detected using acoustic methods and that individuals of this species are consistently seen by unbaited stereo cameras. However, this study has also revealed an unexpectedly complex multi-species environment. Whilst the *acouptics* method described by Scoulding et al. (2023), and summarised here, can estimate the abundance of *C. auratus* in aggregations, we do not recommend that the biomass value for this species (18.02 t) is used as part of any formal assessment owing to the large number of current unknowns. For the *acouptics* method to be produce reliable estimates of *C. auratus* abundance it is essential that the target strength of all other aggregating fish species is known. In this study we observed 18 aggregating species of which only *C. auratus* have *TS* measurements available. It is therefore recommended that future studies focus on obtaining *TS* measurements for all aggregating species in the surveyed area. Given the difficulty of measuring these species *in situ* a theoretically modelling approach will likely be best suited to this task, whereby, individual specimens are scanned (CT or x-ray), and *TS* is estimated using an appropriate model. This will vastly reduce the amount of uncertainty and could lead to the inclusion of biomass estimates determined using the *acouptics* method in stock estimates.

The *TS* of *ex situ* Cockburn Sound *C. auratus* made in this study can be considered a good approximation of *TS* for this species. However, due to these measurements being based on much larger individuals than those commonly found in Shark Bay it is likely that the *TS* values used in this study will not be entirely correct. It is therefore recommended that *ex situ TS* are made of *C. auratus* in Shark Bay following the methods described by Scoulding et al. (2023). These estimates can be supplemented by theoretical scattering models using available CT scans of *C. auratus* in WA.

The method described in this report depend on having appropriate knowledge of the habitat distribution in the survey area. The habitat map was used to determine species specific acoustic densities across the survey area and therefore abundance. In this study habitat was determined visually using a combination of drop cameras and RUV deployments. Given the sparsity of the camera deployments it would be prudent to make further habitat observations in the survey area to better refine the habitat. This will increase the precision of future abundance estimates. In addition to visual observations of the seafloor habitat could be determined from aerial drone surveys, multibeam echosounder surveys, and single beam echosounder surveys.

The analysis performed in this study was time consuming and underwent numerous iterations until we settled on an appropriate approach. Whilst the initial cost of establishing the *acouptics* method was high (labour intensive), future *acouptics* surveys will be far more efficient. Future surveys should consider using compact underwater stereo cameras to collect the necessary validation data. These systems can be built to a budget and suspended on a dropline. When an aggregation is seen on the echogram the vessel can stop and deploy the camera, lowering it slowly to the seafloor and holding for ~5 minutes. This method has the advantage of being affordable, as only one stereo camera is needed, and saves time as the vessel does not need to return to collect the RUVS. Further, more data can be collected as you are not limited by the number of RUVs available. Additionally, as each deployment only lasts five minutes and only the first two minutes of data are analysed, the time and effort spent on video analysis is greatly reduced. In conclusion the methods described in this report have genuine potential for estimating the biomass of *C. auratus*. However, before estimates can be used in stock assessments the following needs to be done:

(1) *Ex situ TS* measurements of *C. auratus* in Shark Bay.
(2) *TS* measurements of other aggregating fish species in the survey area.
(3) Refinement of habitat maps.
(4) Development and deployment of a cost-effective stereo drop camera system.

7. Investigating changes in Snapper biology in the Gascoyne and West Coast bioregions of Western Australia

Gary Jackson, David Fairclough, Emily Fisher and Matias Braccini
Department of Primary Industries and Regional Development

7.1 Introduction

The biology of Snapper (*Chrysophrys auratus*) has been extensively studied in both the GCB and WCB of WA (Wakefield 2006; Jackson 2007; Lenanton et al. 2009; Marriott et al. 2012; Fairclough et al. 2014). Data resulting from those studies have been incorporated into stock assessments of *C. auratus* in the Gascoyne since 2002 (Moran et al. 2005; Jackson et al. 2020) and West Coast since 2007 (Wise et al. 2007; Fairclough et al. 2014; 2021). Several large datasets of biological information for *C. auratus* for these regions of WA are now available, some extending over more than four decades of sample collection. It is important that the biological parameters used as input in stock assessment models are regularly reviewed and updated to ensure assessments are based on the best available information.

While studies of *C. auratus* elsewhere in Australia (Fowler and Jennings 2003; Hamer and Jenkins 2004; Saunders 2009; Bessell-Browne et al. 2020) and New Zealand (Francis 1993; Francis et al. 1995) have identified high levels of inter-annual variation in the abundance of 0+ individuals, monitoring of the recruitment of this species in WA, and potential linkages with stock abundance and environmental drivers has been limited. Moran et al. (2005) investigated recruitment to the Gascoyne oceanic stock indirectly using cohort analysis of age composition data obtained from the commercial fishery over the period 1982-2003. The results from that study indicated that the stock had experienced a period of higher recruitment in the early 1990s, possibly related to cooler water temperatures, followed by lower recruitment through the mid- to late-1990s.

The development of an index of 0+ recruitment of *C. auratus* in the Gascoyne has been attempted in the inner gulfs of Shark Bay using data collected by trawl surveys (Moran and Kangas 2003) and trap surveys (Jackson et al. 2007), with 0+ fish in Denham Sound and the Freycinet Estuary shown to be related to inner gulf stocks and separate from the Gascoyne oceanic stock (Gaughan et al. 2003; Nahas et al. 2003). While much information on the distribution and abundance of 0+ *C. auratus* recorded during fishery-independent trawl surveys in waters outside the inner gulfs was known to exist (Moran and Kangas 2003), further work had not been undertaken to determine the origins of these 0+ fish, nor to develop an index of 0+ recruitment for the Gascoyne oceanic stock. Given that the productivity of fisheries for *C. auratus* has been shown to be largely determined by variable recruitment (Bessell-Browne et al. 2020; Cartwright et al. 2020), early warnings of periods with low levels of recruitment to the Gascoyne oceanic stock would give fishery managers the opportunity to better plan management action 3-5 years in advance, resulting in more stable and less reactive responses than has typically been the case in the past (Jackson et al. 2020). Data sets on recruitment of 0+ *C. auratus* in the Kalbarri and Mid-West management areas are not available due to knowledge of representative nursery areas being restricted to a small number of sites (Fairclough et al. 2013) and limited by resources available to conduct annual recruitment surveys.

Increasing water temperatures and/or extreme events, such as marine heatwaves, associated with climate change, have been recognised as likely to impact temperate species such as *C. auratus* in Australia, particularly in northern areas of its distribution along the West Coast (Caputi et al. 2015). Between 2014 and 2016, commercial fishers in the Gascoyne observed a lack of small *C. auratus*, suggesting a period of lower recruitment attributed to the extreme environmental conditions prior to that time (including a marine heatwave in 2011, followed by warmer than average conditions in 2012 and 2013). In the northern management areas of the adjacent WCB (i.e. Kalbarri and Mid-West areas), higher catch rates of *C. auratus* were reported by commercial fishers in the years following the 2011 marine heatwave, with suggestions this could be due to the southward movement of individuals from the Gascoyne in response to changes in environmental conditions or reflect recruitment from spawning grounds to the north.

While the earlier chapters of this report have focused on stock connectivity and identification of sources of *C. auratus* recruitment in the GCB and upper WCB, the objectives here were to utilise existing biological datasets to:

(1) Investigate potential changes in biological characteristics (growth and maturity) of *C. auratus* in the GCB and northern zones of WCB.
(2) Develop an index of 0+ recruitment for the Gascoyne oceanic stock of *C. auratus* and investigate annual recruitment variation.
(3) Model recruitment indices for the Gascoyne oceanic stock of *C. auratus* with key environmental parameters (sea surface temperature, wind, Leeuwin Current strength).

7.2 Methods

7.2.1 Biological data and analyses

Biological data for *C. auratus* used in these analyses were collated from previous fishery-dependent and fishery-independent sampling regimes. These sampling programs were primarily designed to obtain population age distributions for use in estimating key indicators of stock status, using catch curve and per-recruit analyses and/or integrated assessment models (Wise et al. 2007; Fairclough et al. 2014; 2021; Jackson et al. 2020). In the oceanic waters of the GCB (excluding the inner gulfs of Shark Bay), samples have been collected since the early 1980s, mostly from commercial line fishing catches and some research-based trawl sampling aimed at collecting juveniles. In the northern WCB (Kalbarri and Mid-West management areas), samples have been mostly obtained from commercial and recreational line fishing catches, from 2001 onwards.

Key biological information for *C. auratus* sourced from the historical data sets for these analyses included the age, length, weight, sex and reproductive stage of individual fish, where the latter had been macroscopically determined from gonads using standard criteria (e.g. Wakefield et al. 2011). Depending on the sampling programs, biological characteristics of fish in the data sets were not always complete, for example weights were mostly limited to fishery-independent samples. Therefore, sample sizes vary extensively between the type of analyses undertaken. Consistent with earlier published studies of *C. auratus* in WA (Wakefield et al. 2015; 2017), all length-based analyses used total lengths (TL, mm) of fish. For samples collected from the Gascoyne where only the fork length (FL) had been recorded, they were converted to TL as follows:

$\mathrm{TL} = (1.1789 \times \mathrm{FL}) + 0.7$ (Moran and Burton 1990).

As the biological characteristics of *C. auratus*, such as its growth pattern, differ between females and males (Jackson et al. 2010; Wakefield et al. 2015; 2017), all analyses were undertaken separately for the two sexes. Unsexed fish (mostly juveniles or immature fish <200 mm TL) were randomly categorised as either female or male for analyses. The analyses were also undertaken separately for each management area (Gascoyne, Kalbarri and Mid-West), with earlier studies demonstrating variations in the biology of this species at fine and large spatial scales, including across its latitudinal range (Jackson et al. 2010; Wakefield et al. 2015; 2017). Exploration of temporal patterns in growth and length/age at maturity were conducted by grouping available biological data from each management area into decadal sampling periods. While it is recognised that any changes in biology would likely occur gradually over several years, and thus may not be captured through decadal comparisons, sample sizes were generally too small to allow for smaller temporal groupings, in particular, where models were fitted to these data.

Biological analyses were undertaken in R (R Core Team 2021). Specifically, for analyses where models were fitted to data (e.g. von Bertalanffy growth curves and logistic maturity curves), the R package WAFishBiology was employed (Hesp 2022). Descriptions of these analyses are presented below, with further detail available in the R package vignette.

7.2.1.1 Growth

The range of ages from annual samples of *C. auratus* in each management area (Gascoyne, Kalbarri, Mid-West) varied substantially. Further, size-selectivity of the key sampling method (i.e. line fishing) and the effect of minimum legal lengths (MLLs) for retention typically leads to an under-representation of small and young fish in fishery-dependent sample data (e.g. Gwinn et al. 2010). Therefore, growth curves were fitted to the lengths at age of fish within the same age range, i.e. 4-25 y. A minimum age of 4 y was set as the majority of fish collected over this age were above relevant MLLs for retention in each management area. Ages of fish were thus above the estimated ages at which 50% (A_{50}) of individuals are selected by line fishing in the Gascoyne oceanic waters (3.1 y; DPIRD, 2022, unpublished data) and northern WCB (3.7 y; Fairclough et al. 2021). This ensured that the youngest fish in the analyses were likely to comprise representative length ranges at those ages.

For each management area, the von Bertalanffy growth function was fitted to length at age data for female and male *C. auratus*. The estimated mean lengths at age a, L_a, were calculated as

$$L_a = L_\infty(1 - \exp(-k(a - t_0))),$$

where L_∞ is the asymptotic length (mm TL), k is the growth coefficient (y^{-1}), and t_0 is the hypothetical age (y) at zero length. Growth curves were fitted to data using non-linear regression, employing the nlminb function in R (R Core Team, 2011) to minimise the negative log-likelihood λ. This was calculated as

$$\lambda = \frac{n}{2}[\ln(2\pi) + 2\ln(\hat{\sigma}) + 1],$$

where n is the sample size and $\hat{\sigma}$ is the variance of the data (see Haddon 2011). Estimates of uncertainty around model parameters (L_∞, k, t_0) were calculated from the inverse of the Hessian matrix outputted by nlminb, where the 95% confidence limits (CLs) were approximated as ±1.96 × the asymptotic standard errors derived from this variance-covariance matrix. To characterise the spatial differences in length during the life cycle of *C. auratus* across the Gascoyne, Kalbarri and Mid-West, the predicted mean lengths at ages 5, 10, 15 and 20 y in each area were calculated using the estimated von Bertalanffy growth parameters.

Within each management area, any temporal patterns in growth of *C. auratus* were explored by fitting von Bertalanffy growth curves separately to length at age data (ages 4-25 y) for each decadal sampling period, where the sample size and spread of data across the age range was adequate. This included three periods in the Gascoyne (1991-2000, 2001-2010, and 2011-2020) and two periods in each of the Kalbarri and Mid-West areas (2001-2010 and 2011-2020). To examine the biological significance of any observed temporal differences in the maximum lengths at age of female and male *C. auratus* in each area, the percentage difference in the estimated mean lengths of fish aged 10-25 y (i.e. individuals close to their asymptotic lengths) were calculated. For each of the two sexes, the mean observed lengths of individual cohorts during which most growth occurs (ages 4 to 7 y) were also calculated for each individual year of data with adequate sample sizes (>150 fish, with at least 10 in each of the cohorts) across management areas.

For each management area and relevant sampling period, the relationships for *C. auratus* between the natural logarithms of fish weight (W, g) and total length (L, mm) were described by a linear model:

$$\ln(W) = \ln(a) + (b \ln(L)).$$

Model parameters a and b of this relationship were estimated by linear regression employing the lm function in R, with the predict function used to calculate 95% CLs associated with the line (R Core Team 2011).

7.2.1.2 Maturity

The lengths and ages at which 50 and 95% of *C. auratus* of each sex attain sexual maturity were estimated for each management area (Gascoyne, Kalbarri, Mid-West) using samples collected during the key spawning months of June to August inclusive (Wakefield et al. 2015; DPIRD, 2022 unpublished data). Data were limited to fish samples where the reproductive stage of gonads (ovaries or testes) had been recorded, which were used to categorise fish as either immature (stages I and II) or mature (stages III and above). The proportions of mature females and males at length L, ρ_L, were estimated using the logistic relationship:

$$\rho_L \ = \left(1 \ + \exp\left(-\ln(19)\frac{L - L_{50}}{L_{95} \ - \ L_{50}}\right)\right)^{-1},$$

where L_{50} and L_{95} are the lengths (mm TL) at which 50 and 95% of *C. auratus* attained maturity, respectively. Likewise, the proportions of mature females and males at age a, ρ_a, were estimated as

$$\rho_a \ = \left(1 \ + \exp\left(-\ln(19)\frac{a - a_{50}}{a_{95} \ - \ a_{50}}\right)\right)^{-1},$$

where a_{50} and a_{95} are the respective ages (y) at which 50 and 95% of *C. auratus* have matured.

When fitting the age-based logistic maturity curves to data, the proportions mature at each age were based on the rounded, integer ages of fish. The negative log-likelihood associated with each curve was calculated as

$$\lambda = \textstyle\sum_j X_j\left[\ln\left(\rho_j + \left(1 - X_j\right)\ln(1 - \rho_j)\right],$$

where the jth fish was represented by X=0 if immature and X=1 if mature (e.g. French et al. 2014). Maturity curves were fitted to data for each sex, area and sampling period by minimising λ using the nlminb optimisation function in R (R Core Team 2021). The 95% CLs around each parameter estimate were derived from their associated variance-covariance matrix (refer to method described above for growth analyses).

Data to explore any temporal changes in maturity were more limited than those used in growth analyses due to the few small and young immature fish sampled over time during the key spawning period. In the Gascoyne, small fish have been primarily collected from oceanic waters by dedicated research sampling undertaken in the 1980s and more recently since 2018. Similar sampling programs have not been undertaken in the Kalbarri and Mid-West management areas since the early 2000s. To enable some temporal comparisons to be undertaken across each management area, data from the Gascoyne of all small (<200 mm TL) and immature fish of each sex were therefore borrowed and added to each of the data sets across management areas and sampling periods. The assumption that these fish would be immature irrespective of where and when they were caught was considered reasonable based on previous understanding of maturity of *C. auratus* in WA (e.g. Jackson et al. 2010; Wakefield et al. 2015).

7.2.2 Trawl survey data and analyses

Fishery-independent research trawl surveys have been routinely undertaken in Shark Bay since the early 1990s to monitor recruitment and spawning stock levels of Western king prawns (*Penaeus latisulcatus*), Brown tiger prawns (*P. esculentus*) and Saucer scallops (*Amusium balotti*) (Kangas et al. 2015). These surveys are standardised and undertaken seasonally, typically in spring (October-December), summer (February-March) and autumn (May-July) and involve trawl shots at sites in Denham Sound and the waters to the north of Cape Peron (referred to hereon as the 'outer bay') (Figure 7.1). Surveys are undertaken at night and use twin otter trawls in similar configuration as fished by commercial trawlers in Shark Bay, i.e. prawn trawl nets with 50 mm mesh in the body of net and 45 mm mesh in the cod end (Kangas et al. 2015). Each trawl shot is of 20 minutes duration at a speed of around 3 knots. The trawl gear used also catches a large range of bycatch species (Kangas et al. 2007), including *C. auratus* that have been recorded over a wide range of lengths (40-550 mm FL).

In this study, the trawl research data collected since 1992 were interrogated for information on the distribution and abundance of the youngest age classes of *C. auratus* collected across all the trawl survey areas in Shark Bay. The results of the stock connectivity and dispersal modelling studies reported in Chapters 3-5, based on biological samples of small *C. auratus* (FL = 95-152 mm, i.e. individuals from the 0+ and 1+ age cohorts) collected during trawl surveys at the outer bay locations in 2018 and 2019, confirmed (i) no genetic differentiation between adult *C. auratus* sampled at key spawning grounds for the Gascoyne oceanic stock to the north and west of the offshore islands (Bernier and Dorre Islands) and juvenile *C. auratus* collected at the nursery grounds in the central and eastern regions of the outer bay indicating high levels of local recruitment and (ii) larval dispersal pathways (primarily wind-driven) between the oceanic spawning grounds and inner bay settlement (nursery) areas. The aim here was to interrogate the available trawl research data and based on the records of *C. auratus*, use standardised 0+ catch rates to explore environmental correlations and develop a recruitment index for the Gascoyne oceanic stock.

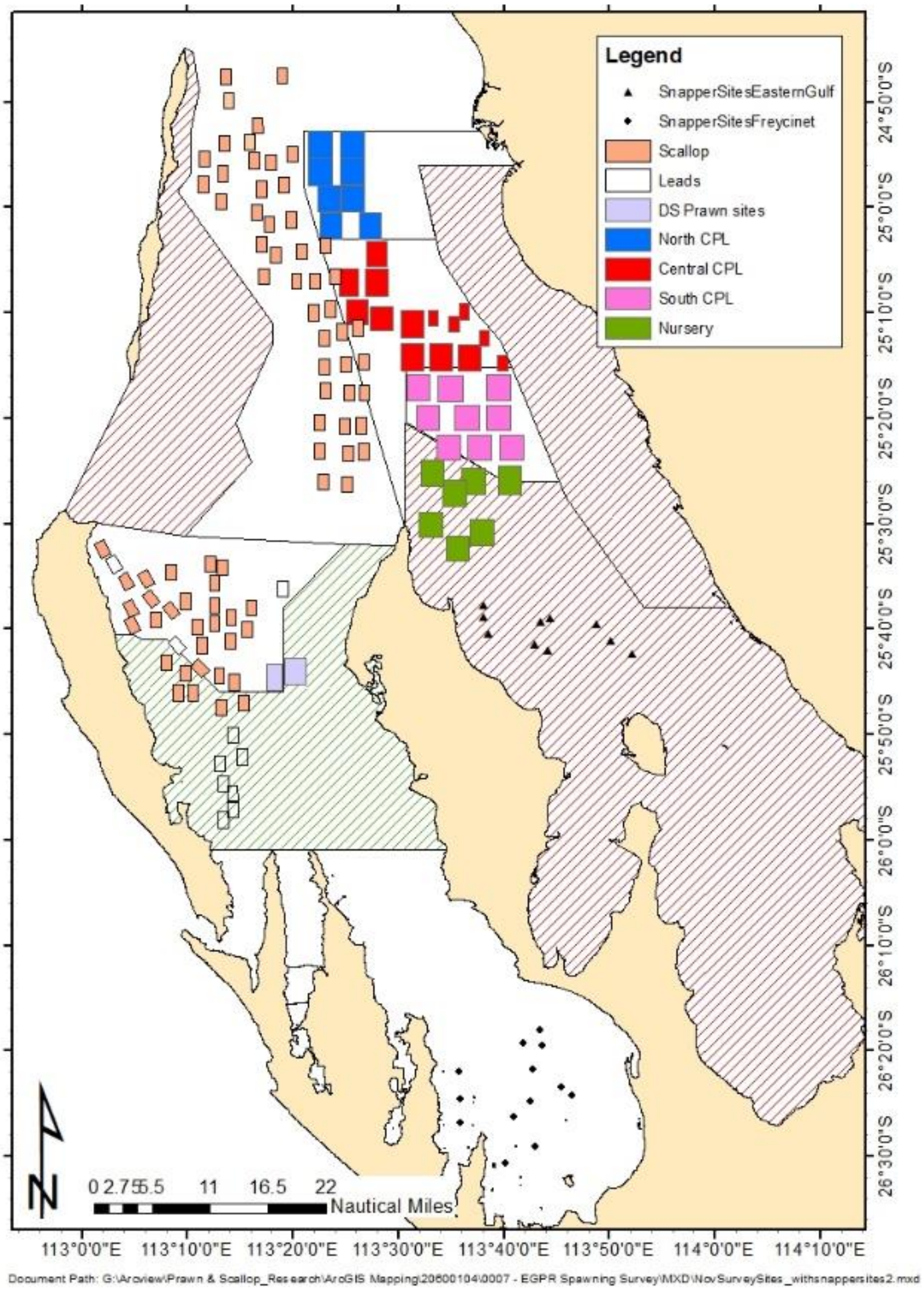


Figure 7.1. Trawl research survey locations in Denham Sound (Western Gulf - DS Prawn sites, Scallop, Leads) and other locations collectively referred to as 'Outer Bay'. Survey locations in Eastern Gulf and Freycinet Estuary (black triangles and diamonds, respectively) were the focus of earlier research on inner gulf *C. auratus* stocks.

7.2.2.1 0+ catch rates

Information on *C. auratus* in the (prawn) trawl databases 1992-present was found to have been inconsistently recorded particularly in the early years and was available in a variety of forms, i.e. presence only, counts only and counts and length measurements (FL, to the nearest 10 mm). Following the merging of the relevant datasets, the trawl survey locations (Figure 7.1) were combined into four broad survey areas as follows: Denham Sound and The Leads = Denham Sound (DS); Eastern Gulf = EG; Freycinet Estuary = FE; North CPL, Central CPL, West CPL, South CPL, East Peron Nursery, Koks, Southern Group, Easter Group = Outer Bay (OB). Sampling months were combined into four seasons as follows: January-March = Summer; April-June = Autumn; July-September = Winter; October-December = Spring.

With the aim here to develop a recruitment index for *C. auratus*, records of individuals larger than 300 mm FL were removed from the analyses (these amounted to <1% of records in total). Records indicating that the trawl shot (port and/or starboard net) had been compromised (reasons including full of weed, shot aborted, trawl caught on reef, trawl damaged) were also removed (amounting to 4.7% of records in total). Given the focus on developing a recruitment index for the Gascoyne oceanic stock (rather that the inner gulf stocks), for the outer bay trawl survey locations (identified as potential nursery areas for this stock) we established that there were many years where *C. auratus* had only been recorded in the form of presence/absence and therefore without length data. Usable information containing the numbers of *C. auratus* and individual lengths for the outer bay locations was available only since 2005. Data for the Denham Sound sites was most usable for the period 2000-2020 and is included here for comparison with outer bay sites. Data for the Freycinet Estuary and Eastern Gulf are not discussed further here.

Preliminary analysis of length-frequencies from trawl surveys in the different months/seasons indicated that smallest *C. auratus* first became vulnerable to the trawl gear and appeared in the trawl survey records in the spring (October-December) at around 60 mm (FL) when fish would be expected to be about 4-6 months of age (assuming a birth date of 1 June for the Gascoyne oceanic stock, Wakefield et al. 2017). This cohort (i.e. fish born in same year) was typically still evident as 0+ in the subsequent summer survey (February-March) and then again as 1+ in the following autumn survey (July-September) (Figure 7.2).

The development of an index of *C. auratus* recruitment, based on standardised 0+ catch rates and modelling the effect of environmental predictors, required the allocation of the smaller length classes of *C. auratus* to specific cohorts and the allocation of specific environmental conditions existing at the time each cohort was born. Typically, in studies such as these, probability-based mixture distribution modelling that accounts for natural variation in length-at-age is used to allocate individual fish to separate cohorts based on their length. This approach was investigated but determined not applicable across all the available survey data, given the very low and unbalanced sample sizes (i.e. numbers of *C. auratus* measured each survey) for many of the survey area-month-year combinations. Alternatively, the approach we used here was for every *C. auratus* recorded in each trawl shot to be allocated to a cohort based on the date of capture and individual length (FL) at capture using the inverse of the growth model developed by Tapp (2003, based on daily increment counts in sectioned otoliths in *C. auratus* from Denham Sound) as follows:

$FL = 0.25 * \text{age (days)} + 40.98$ ($R^2 = 0.67$)

Next, individuals with an estimated age of <365 days since birth were allocated to the 0+ cohort, individuals with estimated ages between 365 and 730 days were allocated to the 1+ cohort, and so on. Based on this, all 0+ *C. auratus* recorded were allocated to the year in which they were born (‘year born’).

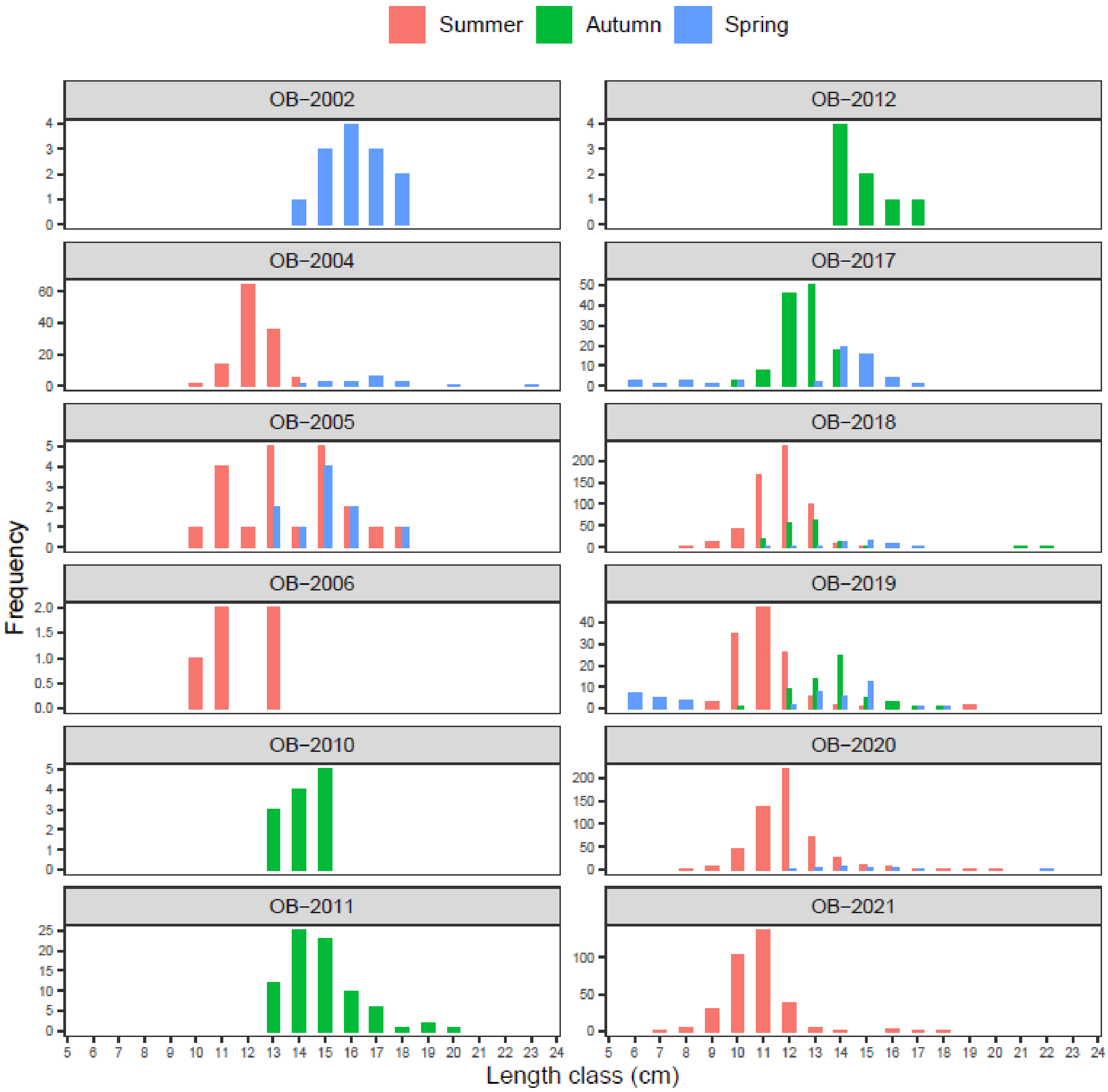


Figure 7.2. Length frequency of *C. auratus* recorded during trawl surveys conducted in different seasons at outer bay (OB) locations 2002-2021 to show 0+ fish first appearing at around 6 cm FL in spring surveys (e.g. OB-2017, OB-2019).

7.2.2.2 Recruitment index

Once the years in which individual 0+ *C. auratus* had been born were determined, the available environmental data (for the Outer Bay - wind speed, sea surface temperature, chlorophyl, sea level, and Leeuwin Current strength; for Denham Sound - sea surface temperature and sea level only) corresponding to the month with the greatest number of 0+ per trawl survey area for the year each cohort was born (Figure 7.3) was used in the modelling process. Data were analysed using general linear models with a negative binomial distribution, where the number of 0+ individuals caught per shot was used as the response variable and year born and relevant environmental variables used as predictors. Preliminary analyses were undertaken to remove highly correlated predictors.

Regardless of the month born, all individuals from a given cohort were allocated to the same environmental conditions. Allocating year- and month-specific environmental conditions was not attempted as it considerably reduced the degrees of freedom and generated a highly unbalanced design. Records with zero catches of 0+ *C. auratus* were excluded from the analyses as these data could not be allocated to any year born nor to past environmental conditions. The recruitment indices (standardised 0+ mean catch rate + 95% CI) were constructed for each survey area and for the summer and spring surveys separately due to considerable differences in sample sizes. All analyses were done using the statistical package R.

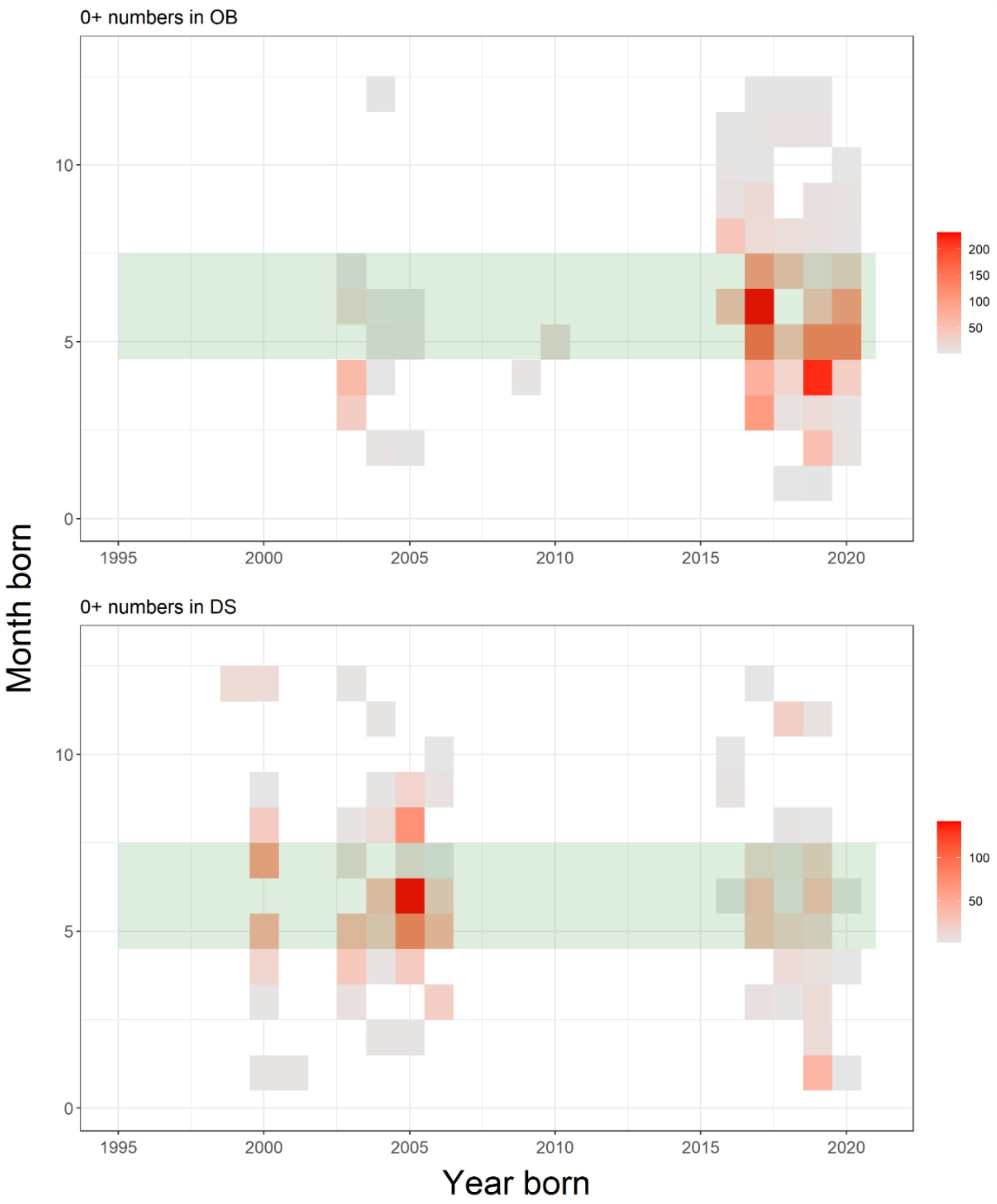


Figure 7.3. Numbers of 0+ *C. auratus* recorded by month and year born (all survey years combined) from Denham Sound (DS) and Outer Bay (OB) survey areas, indicating peak spawning period May-July.

7.3 Results

7.3.1 Growth

The estimated growth patterns for *C. auratus* aged 4-25 y differed between sexes and across management areas, with the largest lengths at age attained by females at higher latitudes (Figure 7.4). While the estimated mean lengths of 5-year-old fish were relatively similar among areas (ranging from 508-524 mm TL for females and 497-517 mm TL for males), the lengths at age of older fish were greater at higher than lower latitudes (Figure 7.4, Table 7.1). For example, the estimated mean length of females increased from 688 mm TL at age 10 y to 840 mm TL at age 20 y in the Mid-West, compared to an increase from 654 mm TL at 10 y to 707 mm TL at 20 y in the Gascoyne (Table 7.1). The estimated lengths of males at 10 and 20 y increased from 661 to 808 mm TL in the Mid-West compared to an increase from 633 to 689 mm TL in the Gascoyne (Table 7.1). For older (>10 y) females and males in Kalbarri, the estimated mean lengths at age lay between those estimated for the Mid-West and Gascoyne areas (Figure 7.4, Table 7.1). The estimated von Bertalanffy growth parameters are presented below within separate subsections for the three management areas.

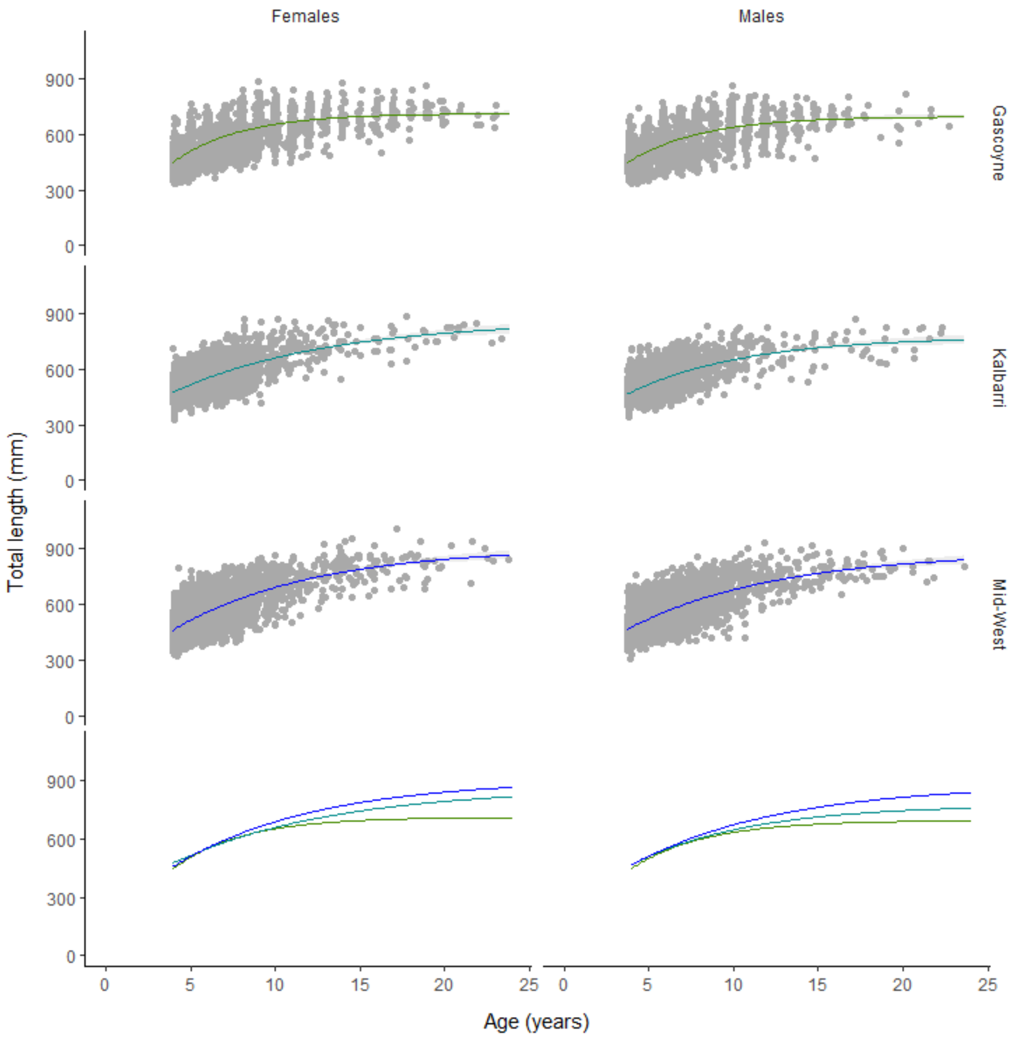


Figure 7.4. Lengths (mm TL) at age (4-25 y) of female and male *C. auratus* in each management area, with von Bertalanffy growth curves fitted separately to available data for each sex in the Gascoyne (green lines), Kalbarri (teal lines) and Mid-West (blue lines).

Table 7.1. Estimated mean lengths (mm TL) of female and male *C. auratus* at ages 5, 10, 15 and 20 y in the Gascoyne, Kalbarri and Mid-West, calculated from von Bertalanffy growth parameters estimated from available data for each sex and area.

	5 y	10 y	15 y	20 y
Females				
Gascoyne	508	654	695	707
Kalbarri	524	667	750	797
Mid-West	510	688	786	840
Males				
Gascoyne	497	633	675	689
Kalbarri	517	653	717	748
Mid-West	500	661	754	808

7.3.1.1 Gascoyne

Comparisons of the growth patterns of female and male *C. auratus* across decadal sampling periods in the Gascoyne suggested only relatively minor changes in the mean lengths at age over time (Figure 7.5, Table 7.2). Differences between curves were more marked for females than males, however, this may be the result of relatively low sample sizes in the first sampling period (1991-2000), particularly for the youngest and oldest fish. For both sexes, point estimates of the von Bertalanffy growth coefficient k were lowest (0.17 y^{-1}) for the 2001-2010 sampling period, compared to 0.27 and 0.29 y^{-1} for females and males, respectively, in 2011-2020. The low estimates of k in 2001-2010 corresponded to relatively low estimates of t_0 for this period (-1.6 for females and -1.87 for males). With the exception of females in 1991-2000, estimates of L_∞ for *C. auratus* in the Gascoyne were relatively similar across periods, ranging from 716-721 mm TL for females and 690-695 mm TL for males (Table 7.2). For each sex, the mean percentage differences between sampling periods of the estimated lengths at each age ranging from 10 to 25 y (i.e. where fish are near their asymptotic size) were less than 5%.

The lengths of individual cohorts of *C. auratus* have fluctuated over time in the Gascoyne, with an increase in the mean lengths observed for cohorts aged 5-8 y from the mid-2000s to 2019 (Figure 7.6). The marked reduction in mean lengths across sexes and cohorts in 2020 coincides with the start of a trial in the commercial fishery in this region to reduce the MLL for retention of *C. auratus* from 410 to 380 mm TL. This would allow selection of a greater relative number of small fish within each of the youngest age classes, driving the reduction in their mean lengths. It is also possible that this is the result of a strong recruitment pulse recently entering the fishery.

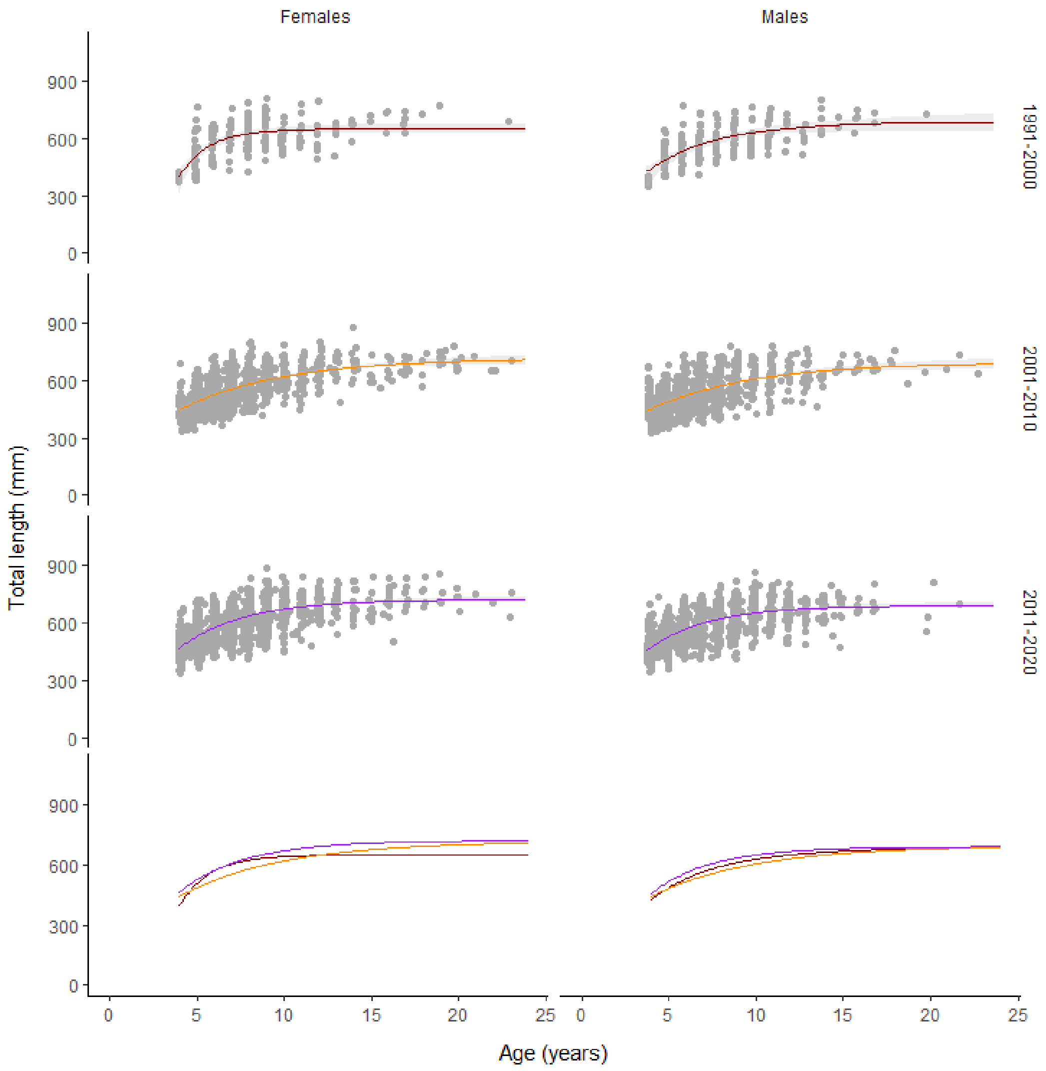


Figure 7.5. Lengths (mm TL) at age (4-25 y) of female and male *C. auratus* in the Gascoyne, with von Bertalanffy growth curves fitted separately to available data for each sex collected in 1991-2000 (red lines), 2001-2010 (orange lines) and 2011-2020 (purple lines).

Table 7.2. Estimated von Bertalanffy growth parameters for female and male *C. auratus* in the Gascoyne, based on data for ages 4-25 y sampled across different sampling periods.

	L_∞ (mm TL)	k (y^{-1})	t_0 (y)
Females			
1991-2000	650 (628-672)	0.59 (0.39-0.88)	2.4 (1.6-3.2)
2001-2010	716 (688-746)	0.17 (0.14-0.22)	-1.6 (-2.6--0.5)
2011-2020	721 (705-737)	0.27 (0.23-0.32)	0.2 (-0.4-0.8)
Combined	712 (699-725)	0.25 (0.22-0.28)	0 (-0.4-0.4)
Males			
1991-2000	691 (634-754)	0.24 (0.13-0.45)	-0.2 (-2.9-2.4)
2001-2010	695 (660-731)	0.17 (0.13-0.23)	-1.9 (-3.1--0.6)
2011-2020	690 (675-706)	0.29 (0.25-0.34)	0.2 (-0.3-0.8)
Combined	695 (680-711)	0.23 (0.21-0.27)	-0.5 (-1.0-0.1)

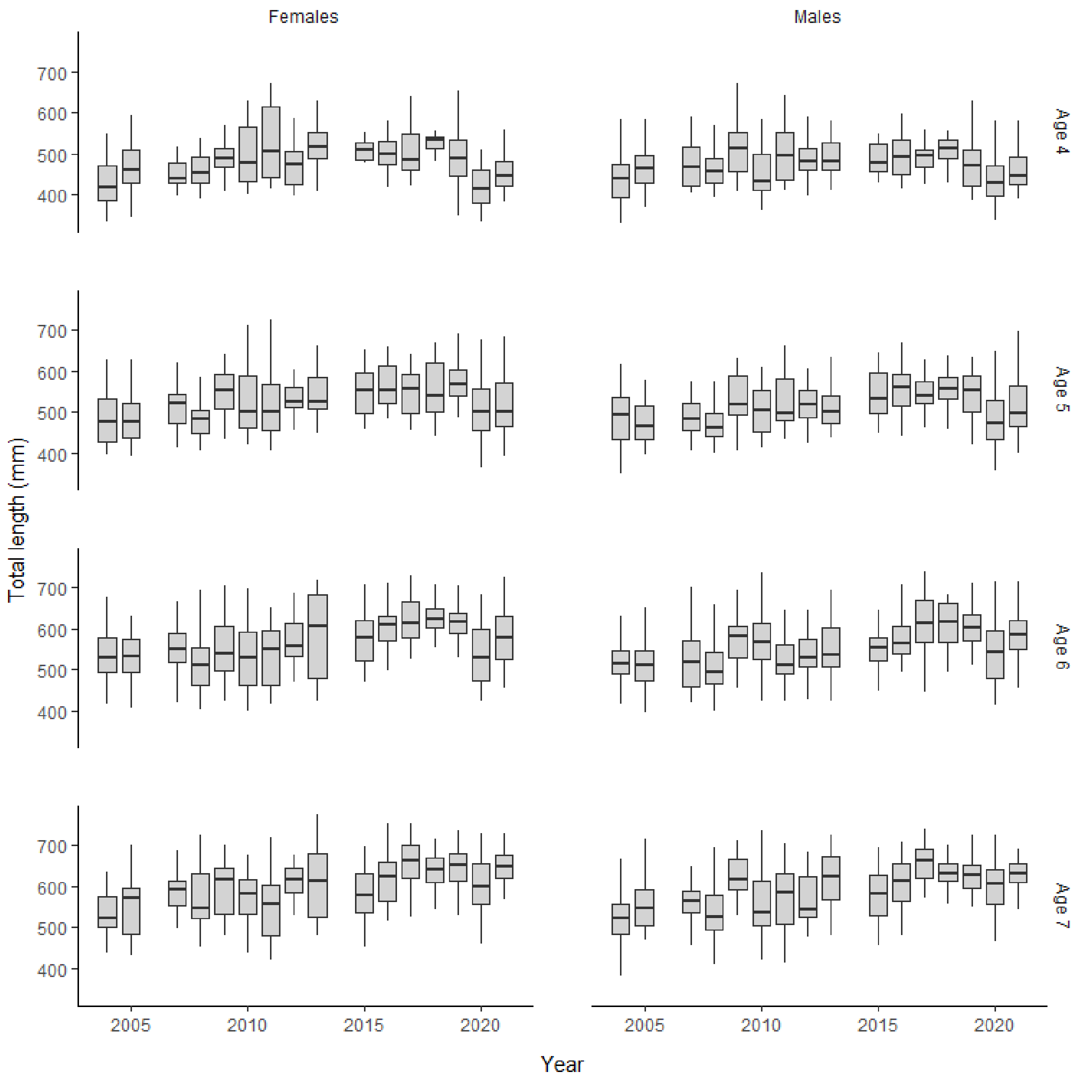


Figure 7.6. Observed lengths (mm TL) of individual cohorts (4-7 y) of female and male *C. auratus* in the Gascoyne for years with adequate sample sizes (>150 fish across both sexes, with at least 10 fish in each cohort/year). The horizontal line in each boxplot denotes the mean length, the box represents the first and third quartiles (25th and 75th percentiles, respectively) and the whiskers show the minimum and maximum values.

7.3.1.2 Kalbarri

For each sex, the estimated mean lengths of *C. auratus* at ages >10-12 y in Kalbarri were higher in 2001-2010 than in 2011-2020, however, these differences are likely the result of limited samples of older fish from the earlier period (Figure 7.7). Compared to the growth parameters estimated for the Gascoyne, point estimates of k were lower (0.09-0.13 y^{-1} for females and 0.10-0.19 y^{-1} for males) and estimates of L_∞ were higher (818-939 mm TL for females and 738-851 mm TL for males) in Kalbarri (Table 7.3). The mean percentage difference in the estimated lengths at each age ranging from 10 to 25 y (i.e. where fish are near their asymptotic size) between the two sampling periods was 5% for females and 4% for males.

The length ranges of fish in individual cohorts (aged 4 to 7 y) sampled in Kalbarri have been relatively consistent over time (Figure 7.8). While low sample sizes in several years (data not shown) makes it challenging to detect any broader trends across these cohorts, a slight increase in the mean lengths observed from around 2012 to 2015 coincides with increasing catch rates of *C. auratus* in Kalbarri over this time, likely resulting from a strong recruitment pulse from 2007 that was observed in the southern part of the West Coast Bioregion (Fairclough et al. 2021).

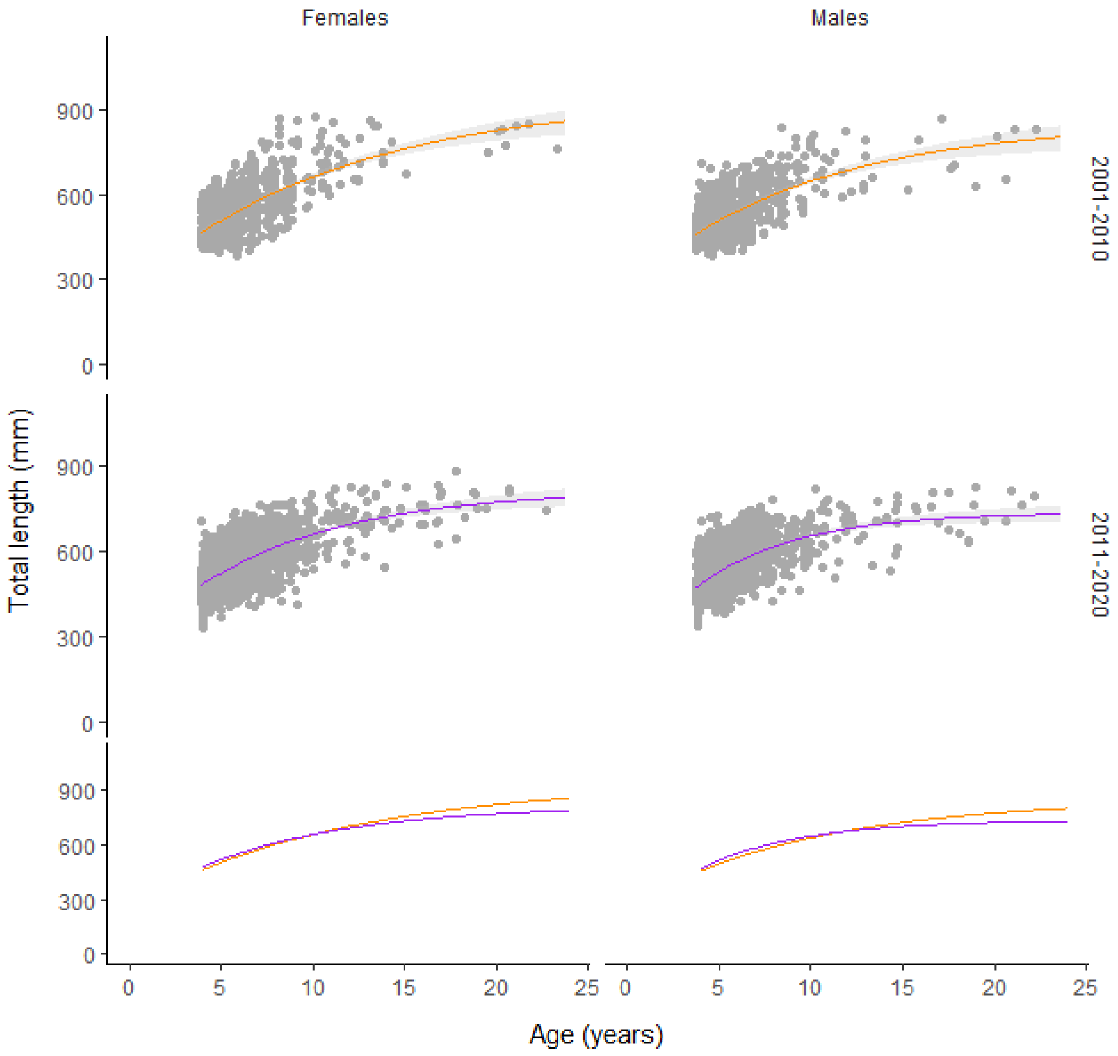


Figure 7.7. Lengths (mm TL) at age (4-25 y) of female and male *C. auratus* in Kalbarri, with von Bertalanffy growth curves fitted separately to available data for each sex collected in 2001-2010 (orange lines) and 2011-2020 (purple lines).

Table 7.3. Estimated von Bertalanffy growth parameters for female and male *C. auratus* in Kalbarri, based on data for ages 4-25 y sampled across different sampling periods.

	L_∞ (mm TL)	k (y^{-1})	t_0 (y)
Females			
2001-2010	939 (842-1048)	0.09 (0.06-0.12)	-3.8 (-5.2--2.4)
2011-2020	818 (766-872)	0.13 (0.10-0.16)	-3.1 (-4.3--1.9)
Combined	863 (814-915)	0.11 (0.09-0.13)	-3.5 (-4.4--2.6)
Males			
2001-2010	851 (766-945)	0.10 (0.07-0.14)	-3.5 (-5.0--2.0)
2011-2020	738 (705-772)	0.19 (0.15-0.23)	-1.6 (-2.5--0.6)
Combined	775 (741-810)	0.15 (0.12-0.18)	-2.3 (-3.1--1.5)

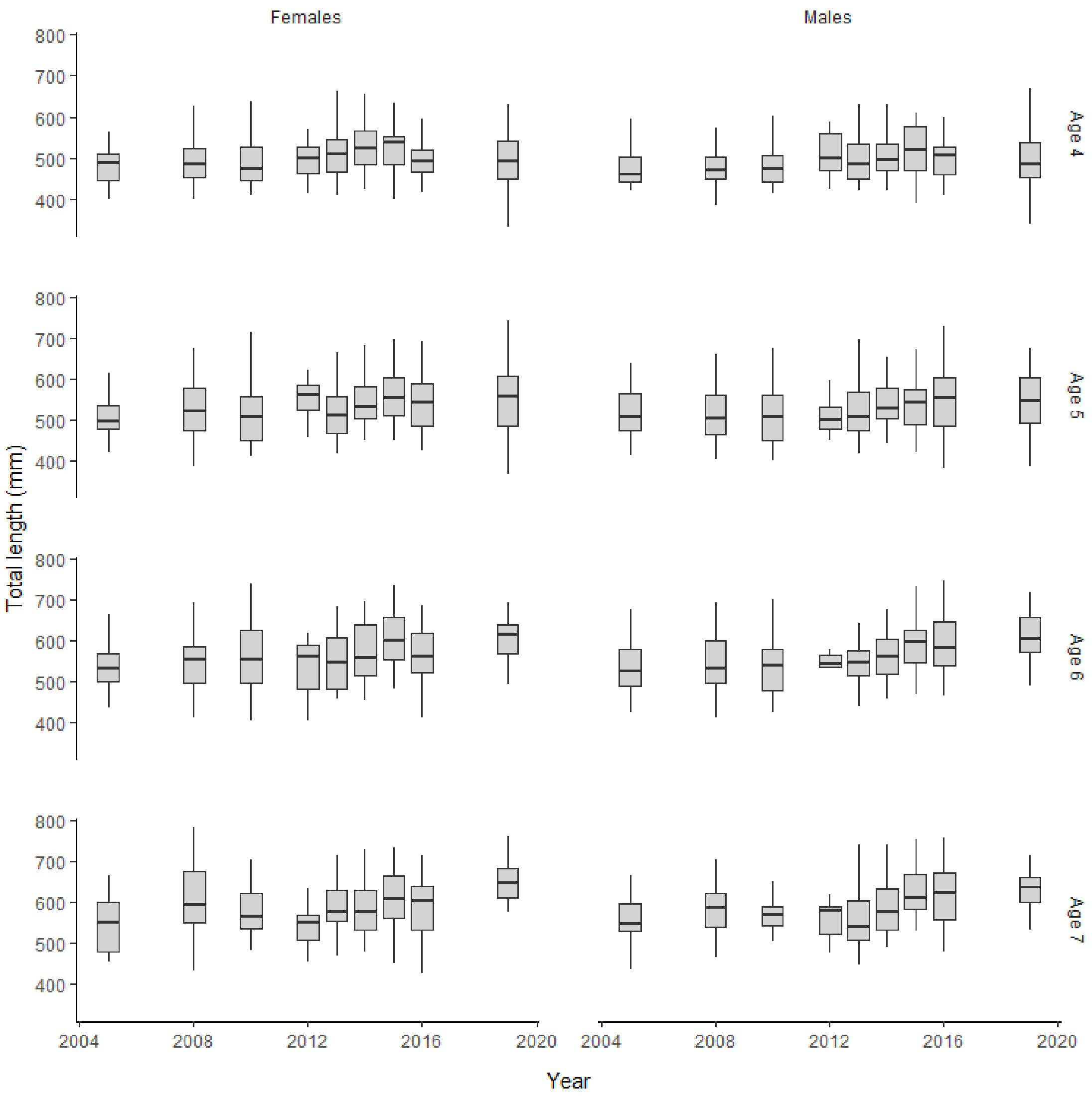


Figure 7.8. Observed lengths (mm TL) of individual cohorts (4-7 y) of female and male *C. auratus* in Kalbarri for years with adequate sample sizes (>150 fish across both sexes, with at least 10 fish in each cohort/year). The horizontal line in each boxplot denotes the mean length, the box represents the first and third quartiles (25th and 75th percentiles, respectively) and the whiskers show the minimum and maximum values.

7.3.1.3 Mid-West

There was no marked difference between sampling periods in the estimated mean lengths of female and male *C. auratus* at ages 4-25 y in the Mid-West (Figure 7.9). Although estimates of the von Bertalanffy growth parameters for each sex were very similar for fish sampled in 2001-2010 and 2011-2020 (Table 7.4), sample sizes of older fish in the earlier period were limited. Point estimates of k for females and males in the Mid-West (0.11-0.13 y^{-1} and 0.10-0.12 y^{-1}, respectively) were similar to those in Kalbarri (and lower than those in the Gascoyne), while point estimates of L_∞ were higher (903-927 mm TL for females and 892-897 mm TL for males) than the two areas to the north. The mean percentage difference, between the two sampling periods, in the estimated lengths at each age from 10 to 25 y (i.e. where fish are near their asymptotic size) was zero for females and 4% for males.

The lengths of individual cohorts (aged 4 to 7 y) of *C. auratus* sampled in the Mid-West fluctuate over time (Figure 7.10), following a pattern typical of a species that exhibits variable inter-annual recruitment (Fairclough et al. 2021). There was a slight decrease observed in the mean lengths at age across cohorts from 2009 to 2011, followed by a period of higher mean lengths at age from 2012 (Figure 7.10). This is consistent with data from the Kalbarri area and provides evidence for a strong cohort spawned in 2007 that would have recruited into the fishery around that time. An increasing trend in the mean lengths at age since 2012 is particularly evident in the 7-year-old cohort (Figure 7.10).

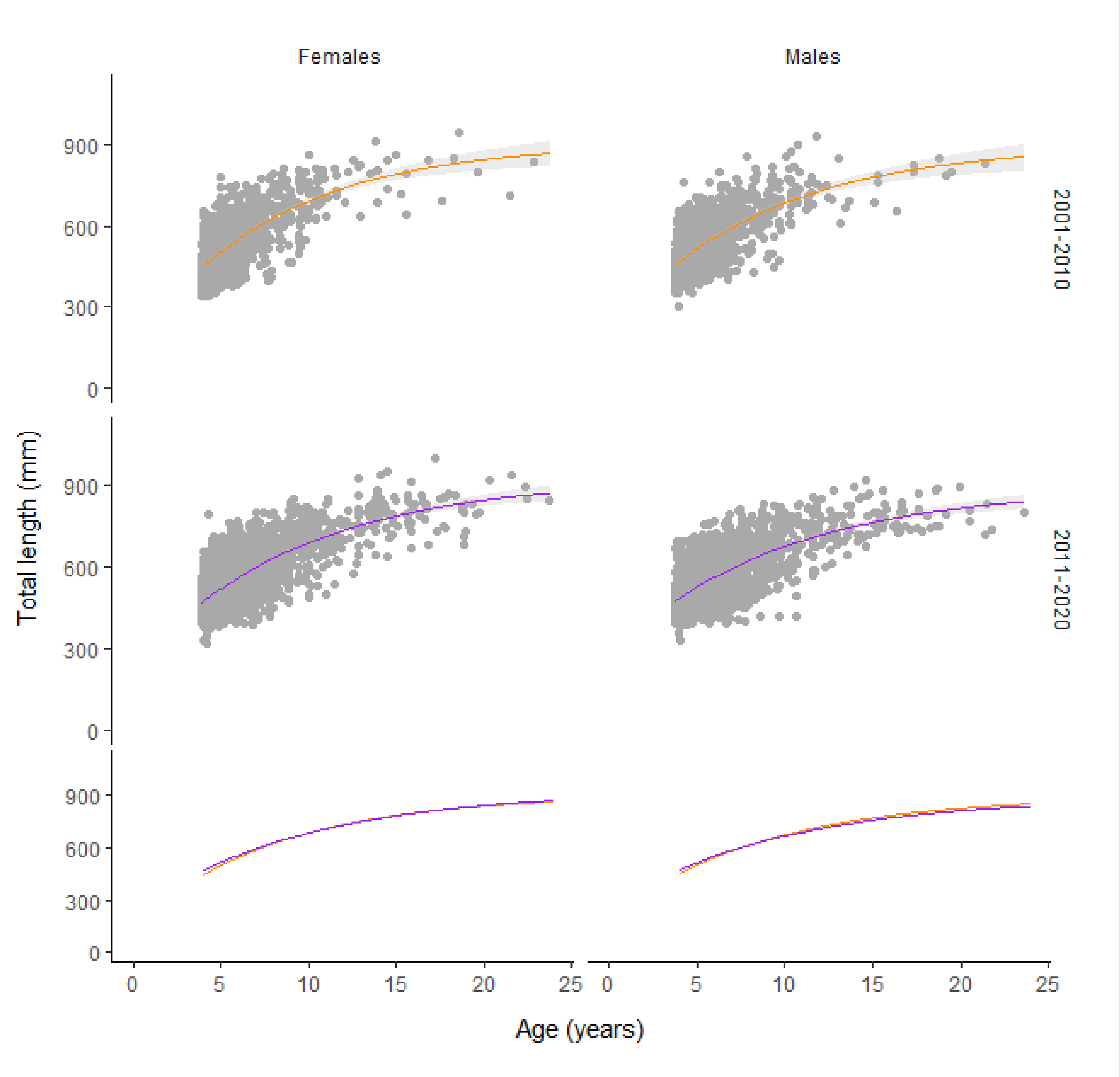


Figure 7.9. Lengths (mm TL) at age (4-25 y) of female and male *C. auratus* in the Mid-West, with von Bertalanffy growth curves fitted separately to available data for each sex collected in 2001-2010 (orange lines) and 2011-2020 (purple lines).

Table 7.4. Estimated von Bertalanffy growth parameters for female and male *C. auratus* in the Mid-West, based on data for ages 4-25 y sampled across different sampling periods.

	L_∞ (mm TL)	k (y^{-1})	t_0 (y)
Females			
2001-2010	903 (831-981)	0.13 (0.10-0.16)	-1.4 (-2.2--0.6)
2011-2020	927 (875-983)	0.11 (0.09-0.13)	-2.7 (-3.4--1. 9)
Combined	906 (867-946)	0.12 (0.11-0.14)	-1.9 (-2.4--1.4)
Males			
2001-2010	897 (813-989)	0.12 (0.09-0.16)	-2.1 (-3.1--1.1)
2011-2020	892 (842-946)	0.10 (0.09-0.13)	-3.3 (-4.2-2.4)
Combined	881 (841-922)	0.11 (0.1-0.13)	-2.6 (-3.3—2.0)

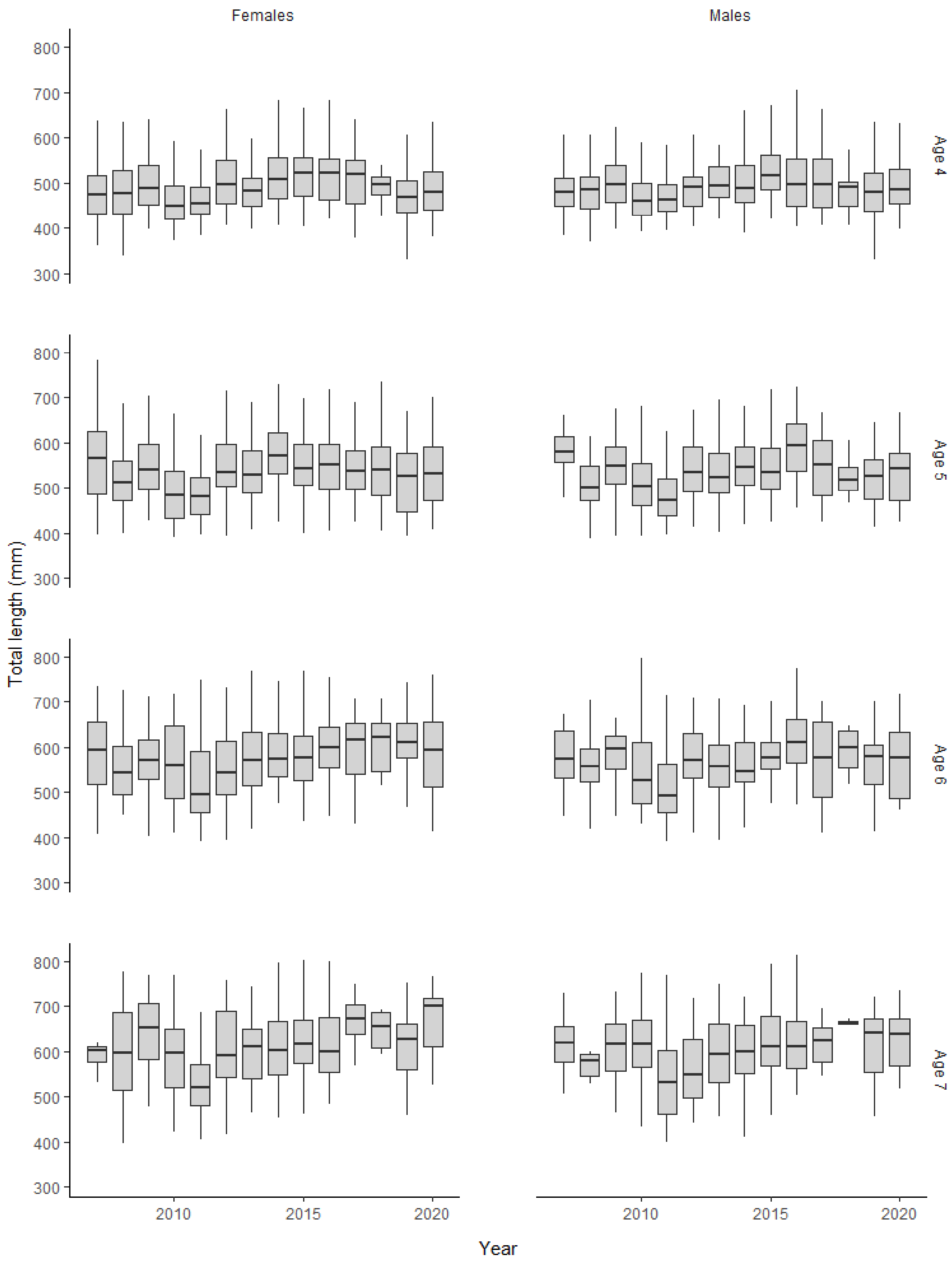


Figure 7.10. Observed lengths (mm TL) of individual cohorts (4-7 y) of female and male *C. auratus* in the Mid-West for years with adequate sample sizes (>150 fish across both sexes, with at least 10 fish in each cohort/year). The horizontal line in each boxplot denotes the mean length, the box represents the first and third quartiles (25th and 75th percentiles, respectively) and the whiskers show the minimum and maximum values.

7.3.1.4 Length-weight relationships

Estimated parameters of the log-linear relationship between total length (mm) and weight (g) of female and male *C. auratus* in the Gascoyne and Mid-West management areas (see Figure 7.11) are provided in Table 7.5. While length and weight samples available for each of these management areas to explore any temporal changes in the length-weight relationship were limited, preliminary analyses did not indicate any marked differences between sampling periods (results not shown). Note that the sample size of fish with records of weight in the Kalbarri area were too low to estimate relationships for this area separately.

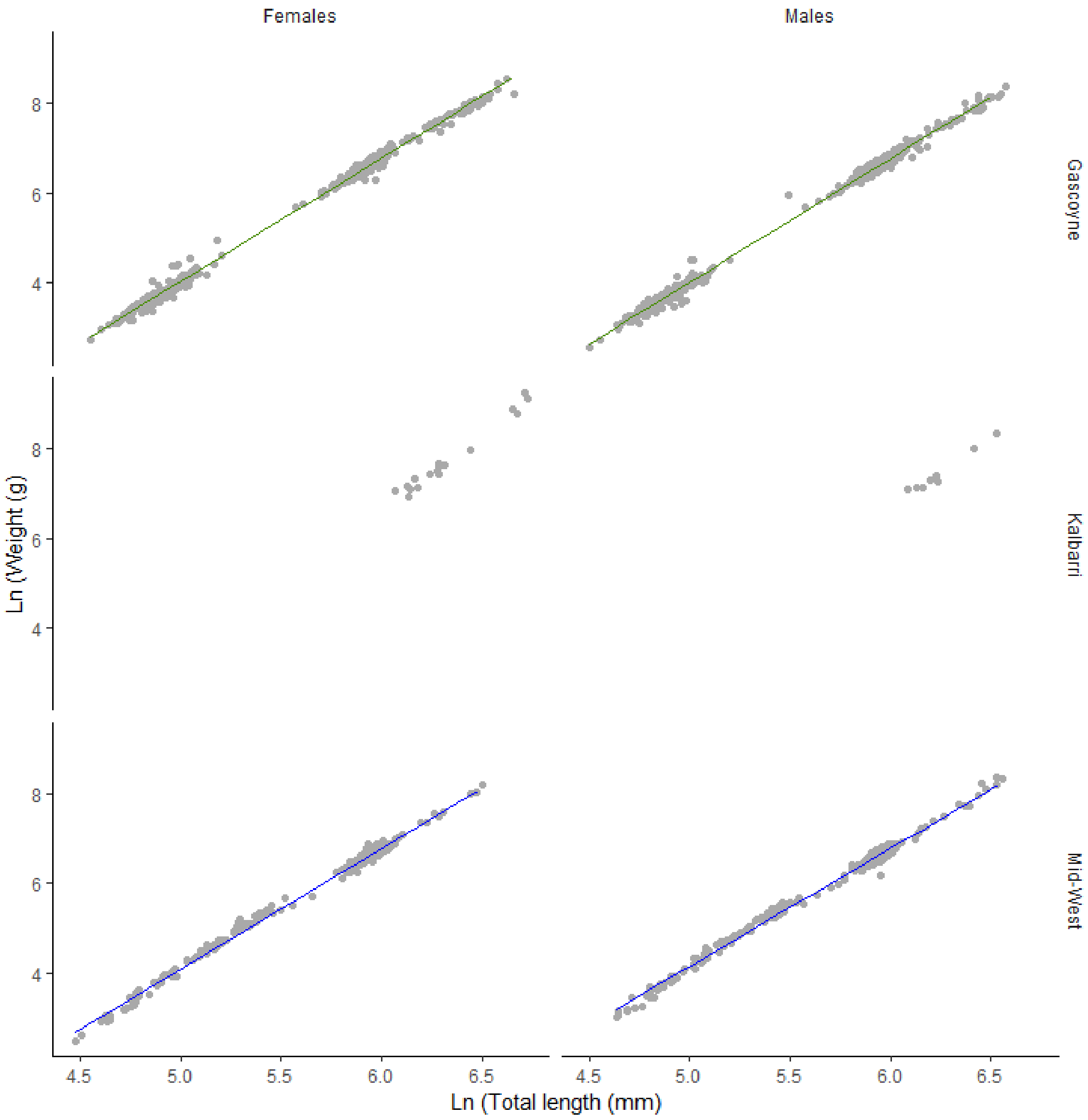


Figure 7.11. Estimated relationships between the natural logarithms of total length (mm TL) and weight (g) for female and male *C. auratus* in the Gascoyne (green lines) and Mid-West (blue lines) management areas, noting no separate relationship was calculated for Kalbarri due to small sample of fish with known weights.

Table 7.5. Estimates (±95% CLs) of parameters a and b of the linear relationship between the natural logarithms of total length (mm TL) and weight (g) for female and male *C. auratus* in each management area, and for these areas combined.

	a	b
Females		
Gascoyne	-9.808 (-9.890--9.726)	2.765 (2.750-2.780)
Kalbarri	Not estimated	Not estimated
Mid-West	-9.237 (-9.354--9.120)	2.671 (2.651-2.691)
Combined areas	-9.741 (-9.807--9.675)	2.755 (2.744-2.767)
Males		
Gascoyne	-9.774 (-9.844--9.704)	2.759 (2.747-2.772)
Kalbarri	Not estimated	Not estimated
Mid-West	-9.139 (-9.247--9.032)	2.655 (2.636-2.673)
Combined areas	-9.623 (-9.684--9.561)	2.735 (2.724-2.746)

7.3.2 Maturity

Estimates of maturity for *C. auratus* showed that females mature at a slightly larger size and older age than males, with the maturity of both sexes occurring earlier at the northern latitudes compared to those further south (Figure 7.12, Figure 7.13). Parameter estimates describing the maturity curves are presented below in the sub-sections for each management area.

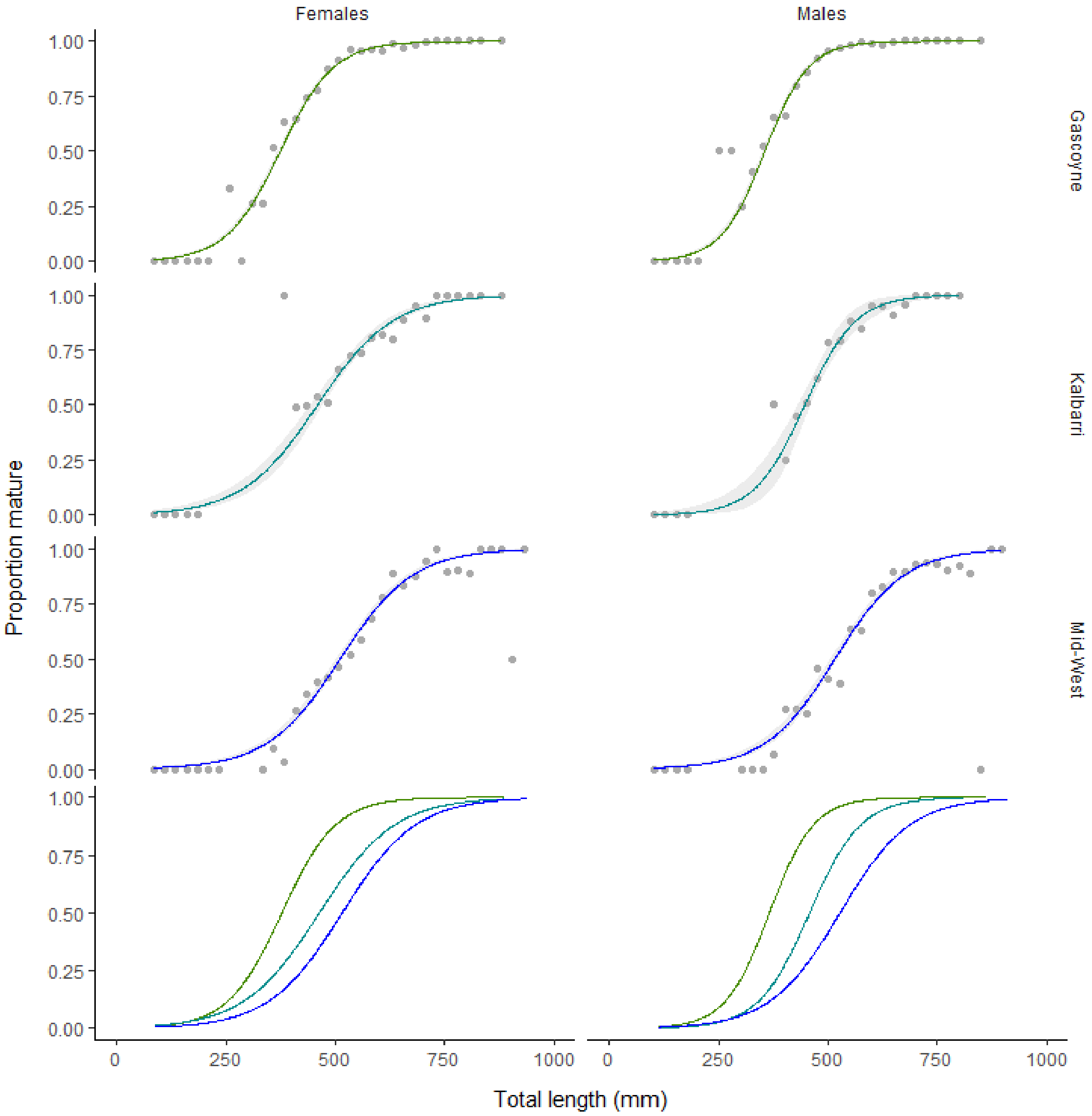


Figure 7.12. Estimated logistic curves of the proportions of mature female and male *C. auratus* at length (mm TL) in each management area during the key spawning period (June – August). The curves were fitted separately to data for each sex from the Gascoyne (green lines), Kalbarri (teal lines) and Mid-West (blue lines).

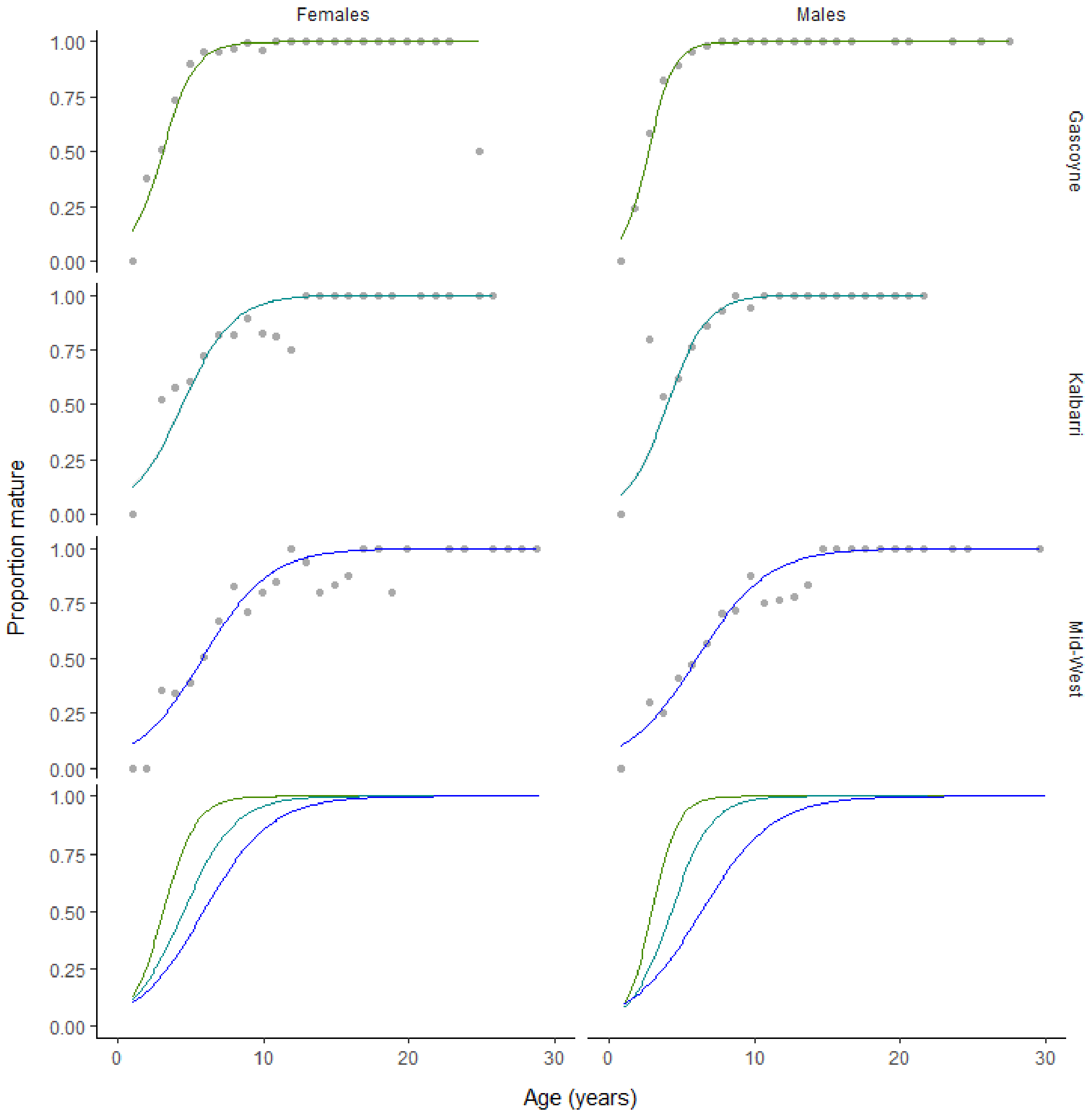


Figure 7.13. Estimated logistic curves of the proportions of mature female and male *C. auratus* at age (y) in each management area during the key spawning period (June – August). The curves were fitted separately to data for each sex from the Gascoyne (green lines), Kalbarri (teal lines) and Mid-West (blue lines).

7.3.2.1 Gascoyne

Estimates of the lengths at which 50% of *C. auratus* mature in the Gascoyne have gradually increased over time across the three decadal sampling periods for which sufficient data were available from the key spawning period (June to August inclusive; Figure 7.14). Point estimates of L_{50} for females increased from 333 mm TL in 1981-1990 to 401 mm TL in 2011-2020, while the L_{50} for males increased from 314 to 385 mm TL over the same sampling periods (Table 7.6). Estimates of L_{95} for both sexes followed this same increasing pattern (Table 7.6).

The estimated ages at which 50% of female and male *C. auratus* attain maturity in the Gascoyne were relatively similar across the two most recent sampling periods (2001-2010 and 2011-2020; Figure 7.15), noting that sample sizes of aged fish from the key spawning period between 1981 and 1990 were too low to estimate separately. Point estimates of A_{50} for females were 3.3 and 3.1 y in 2001-2010 and 2011-2020, respectively, while the A_{50} estimates for males in those sampling periods were 3.1 and 2.9 y (Table 7.6).

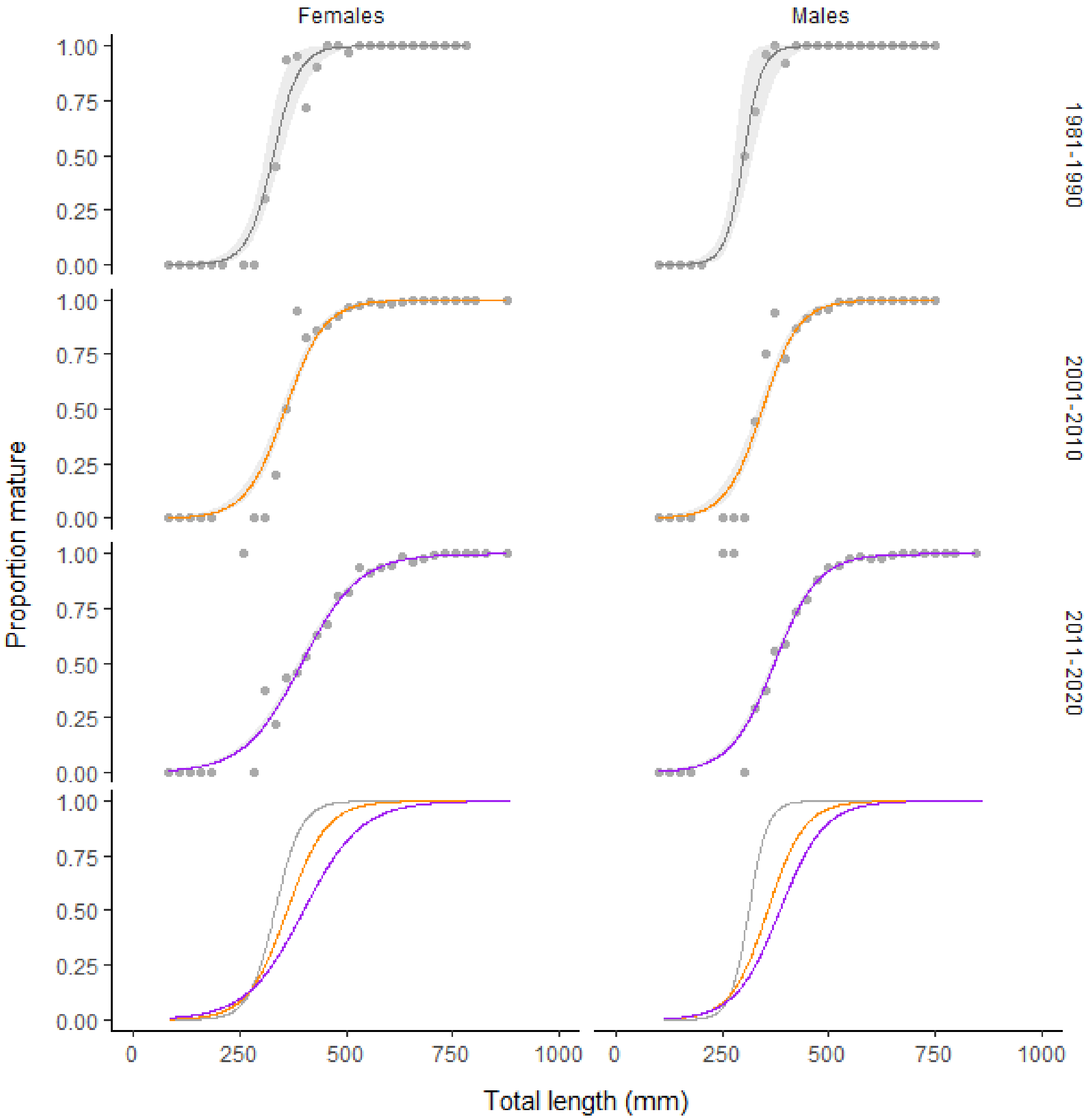


Figure 7.14. Estimated logistic curves of the proportions of mature female and male *C. auratus* at length (mm TL) in the Gascoyne during the key spawning period (June – August). The curves were fitted separately to data for each sex from 1981-1990 (grey lines), 2001-2010 (orange lines) and 2011-2020 (purple lines).

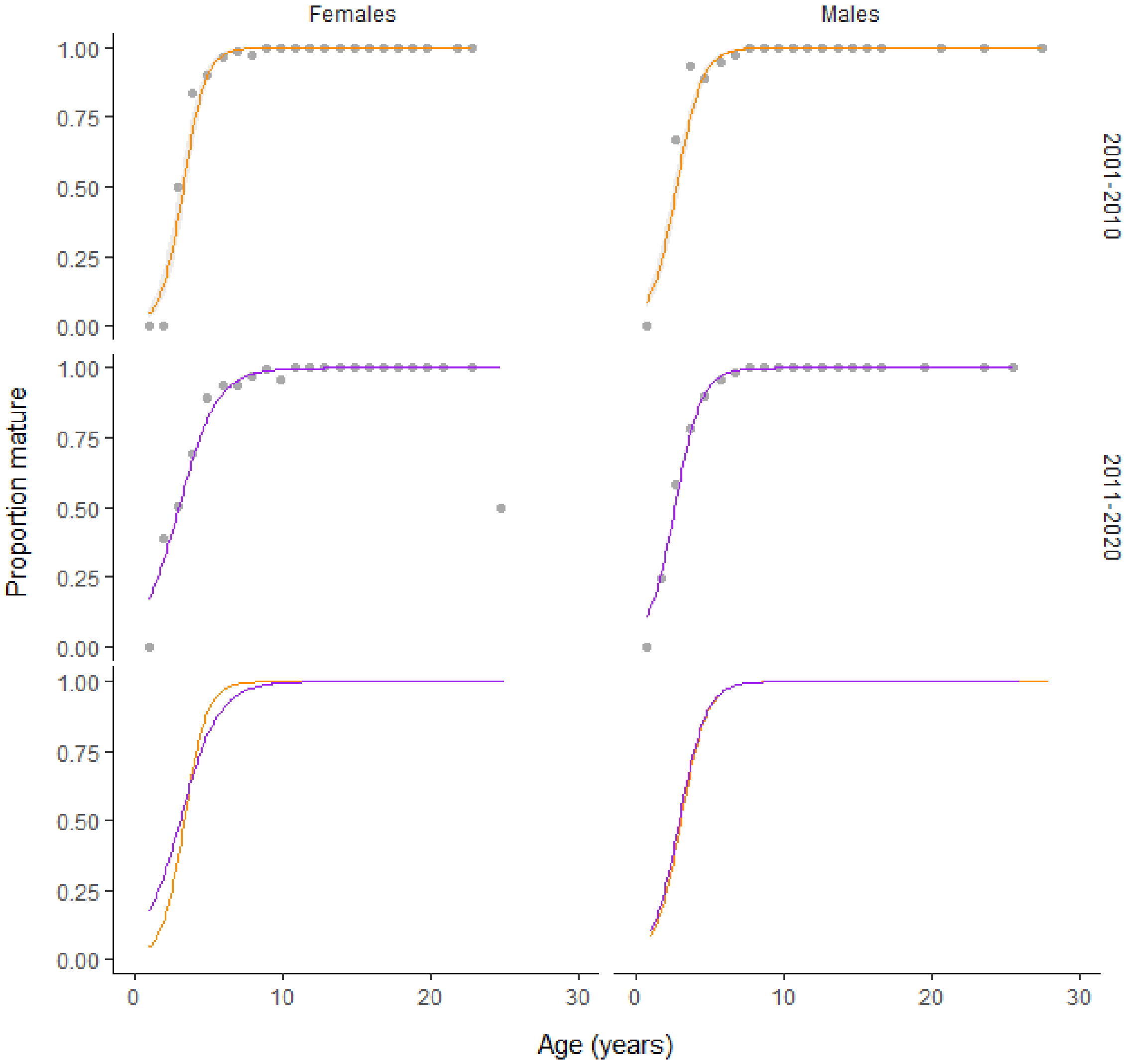


Figure 7.15. Estimated logistic curves of the proportions of mature female and male *C. auratus* at age in the Gascoyne during the key spawning period (June – August). The curves were fitted separately to data for each sex from 2001-2010 (orange lines) and 2011-2020 (purple lines).

Table 7.6. Estimates (and associated 95% CLs) of the ages and lengths at which 50% and 95% of female and male *C. auratus* have attained maturity in the Gascoyne, based on data from the peak spawning period (June – August) grouped by decadal sampling periods, and combined across these periods.

	L_{50} (mm TL)	L_{95} (mm TL)	A_{50} (y)	A_{95} (y)
Females				
1981-1990	333 (312-353)	423 (381-466)	-	-
2001-2010	362 (352-372)	498 (486-511)	3.3 (3.1-3.6)	5.6 (5.4-5.8)
2011-2020	401 (393-408)	598 (591-606)	3.1 (3.0-3.2)	6.9 (6.8-7.0)
Combined	377 (372-383)	558 (552-564)	3.1 (3.0-3.2)	6.4 (6.3-6.5)
Males				
1981-1990	314 (291-337)	375 (324-426)	-	-
2001-2010	356 (346-366)	483 (468-498)	3.1 (2.8-3.3)	5.6 (5.4-5.8)
2011-2020	385 (379-391)	538 (529-546)	2.9 (2.8-3.0)	5.6 (5.4-5.7)
Combined	366 (361-371)	514 (507-521)	3.0 (2.9-3.0)	5.6 (5.5-5.7)

7.3.2.2 Kalbarri

The estimated lengths and ages at which 50% of *C. auratus* sampled during the key spawning period (June to August) in Kalbarri have attained maturity differed between sexes and sampling periods (Figure 7.16, Figure 7.17). However, as the sample sizes for these analyses were very low, results should be treated cautiously. Point estimates of L_{50} for females were 449 mm TL in 2001-2010 and 478 mm TL in 2011-2020, while those estimates for males were 475 and 438 mm TL, respectively (Table 7.7). The corresponding estimates of A_{50} for females in the two sampling periods were the same (4.5 y), while the estimated A_{50} for males was much higher in 2001-2010 (5.2 y) than in 2011-2020 (3.3 y). Maturity estimates based on the combined data from both sampling periods (Table 7.7), which are likely more reliable, showed that *C. auratus* in Kalbarri mature at a larger size and older age than in the Gascoyne.

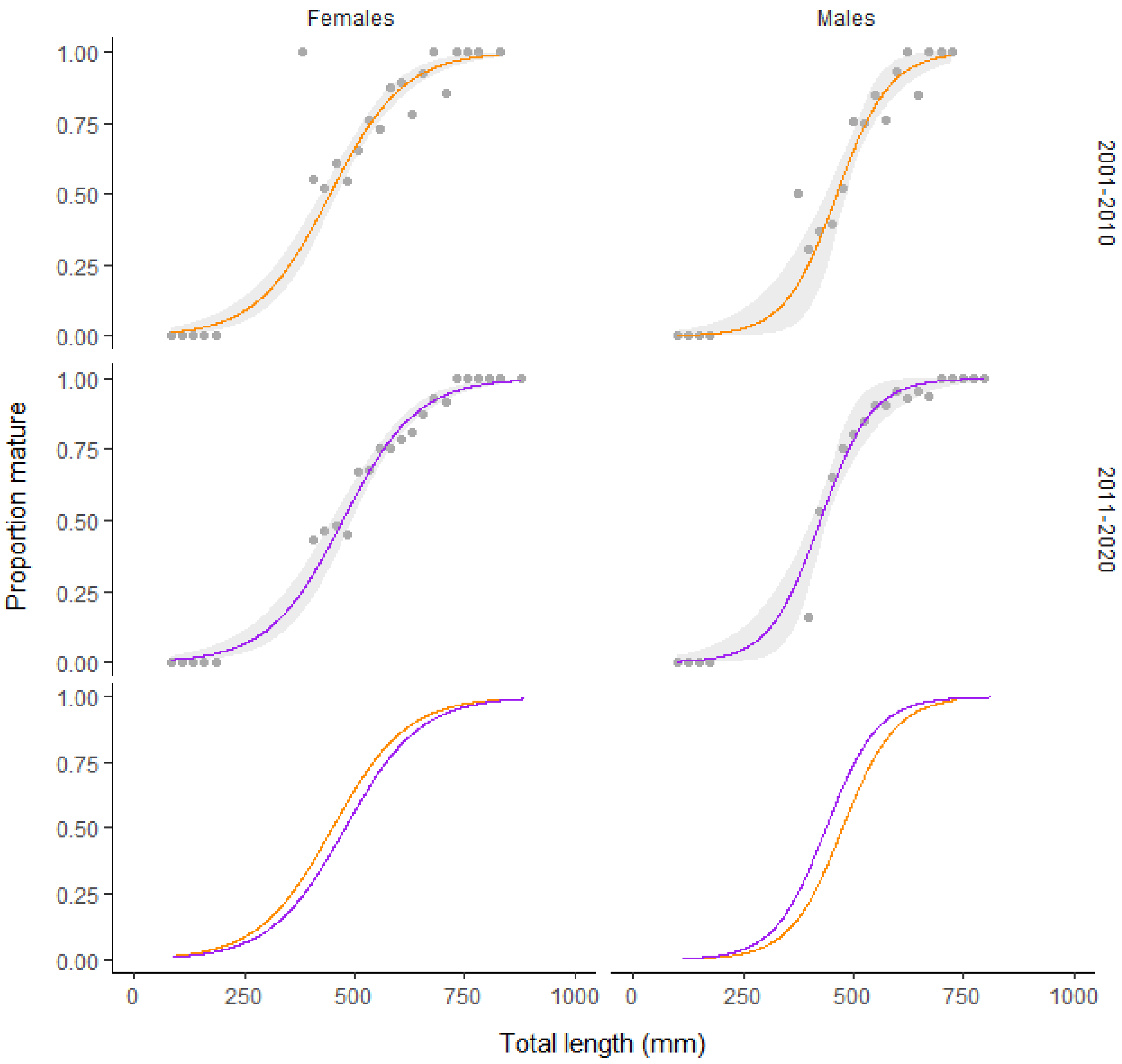


Figure 7.16. Estimated logistic curves of the proportions of mature female and male *C. auratus* at length (mm TL) in Kalbarri during the key spawning period (June – August). The curves were fitted separately to data for each sex from 2001-2010 (orange lines) and 2011-2020 (purple lines).

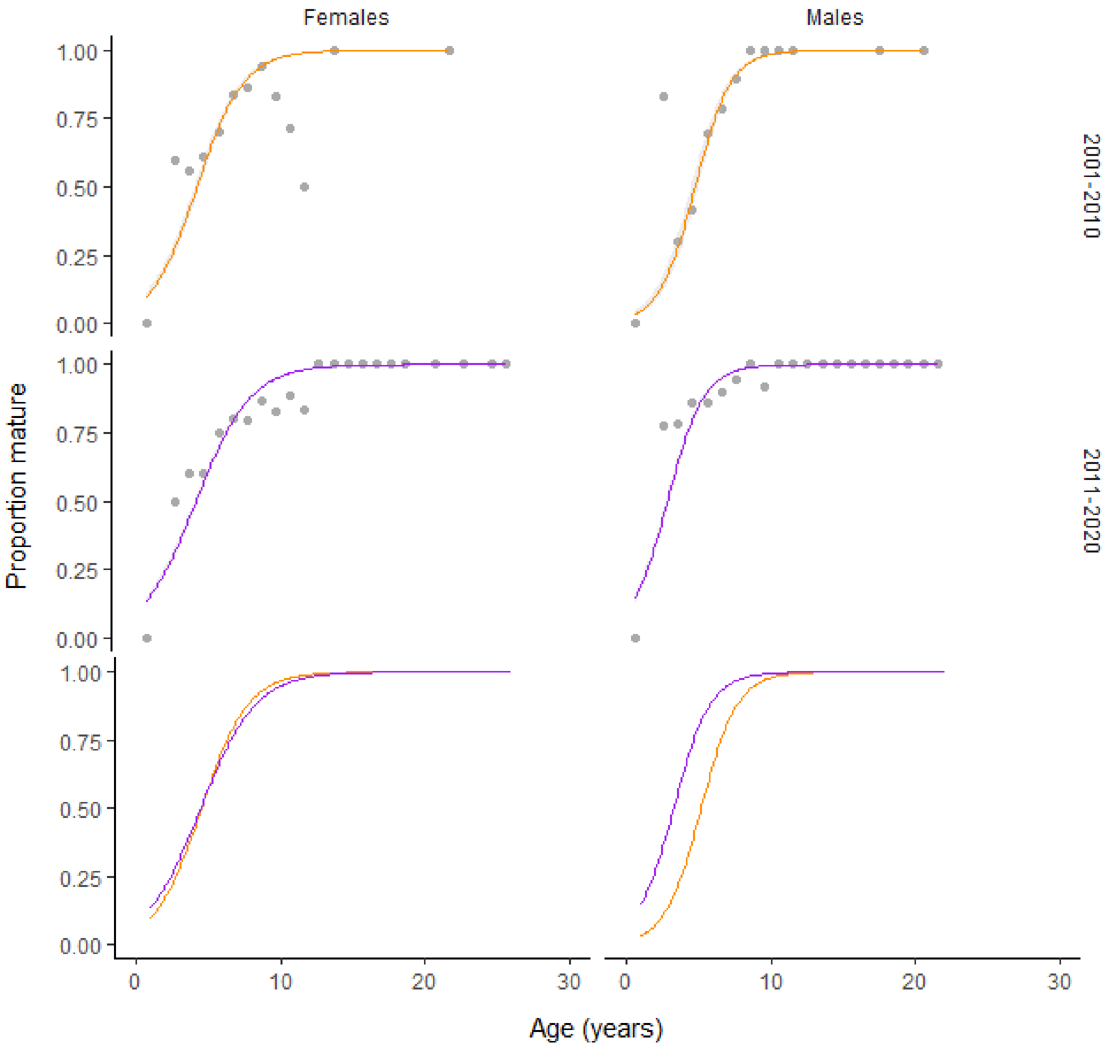


Figure 7.17. Estimated logistic curves of the proportions of mature female and male *C. auratus* at age in Kalbarri during the key spawning period (June – August). The curves were fitted separately to data for each sex from 2001-2010 (orange lines) and 2011-2020 (purple lines).

Table 7.7. Estimates (and associated 95% CLs) of the ages and lengths at which 50% and 95% of female and male *C. auratus* have attained maturity in Kalbarri, based on data from the peak spawning period (June – August) grouped by decadal sampling periods, and combined across these periods.

	L_{50} (mm TL)	L_{95} (mm TL)	A_{50} (y)	A_{95} (y)
Females				
2001-2010	449 (431-467)	697 (654-739)	4.5 (4.3-4.7)	9.3 (9.1-9.4)
2011-2020	478 (456-501)	727 (694-759)	4.5 (4.3-4.6)	10.0 (9.9-10.2)
Combined	463 (449-477)	716 (691-742)	4.5 (4.4-4.6)	9.7 (9.6-9.8)
Males				
2001-2010	475 (452-499)	652 (589-714)	5.2 (4.9-5.4)	8.8 (8.7-9.0)
2011-2020	438 (420-455)	610 (535-685)	3.3 (3.1-3.4)	7.0 (6.8-7.1)
Combined	458 (444-472)	630 (583-676)	4.3 (4.1-4.4)	8.3 (8.2-8.4)

7.3.2.3 Mid-West

As for Kalbarri, the maturity estimates for *C. auratus* in the Mid-West should be treated cautiously given the limited data available from the key spawning period between June and August (Figure 7.18, Figure 7.19). Estimates of the lengths and ages at which 50% of females and males have attained maturity (L_{50} and A_{50}, respectively) in the Mid-West were generally higher than those for the Kalbarri and Gascoyne management areas in the same sampling periods (Table 7.8). In the Mid-West, the estimated L_{50} for both sexes declined between 2001-2010 and 2011-2020, which was also the case for males in Kalbarri but opposite to the trend observed for females in that area, and both sexes in the Gascoyne. Conversely, point estimates of A_{50} for females and males were slightly lower in the more recent sampling period (Table 7.8), as was also the case in Kalbarri (for males, noting estimates for females did not change) and the Gascoyne.

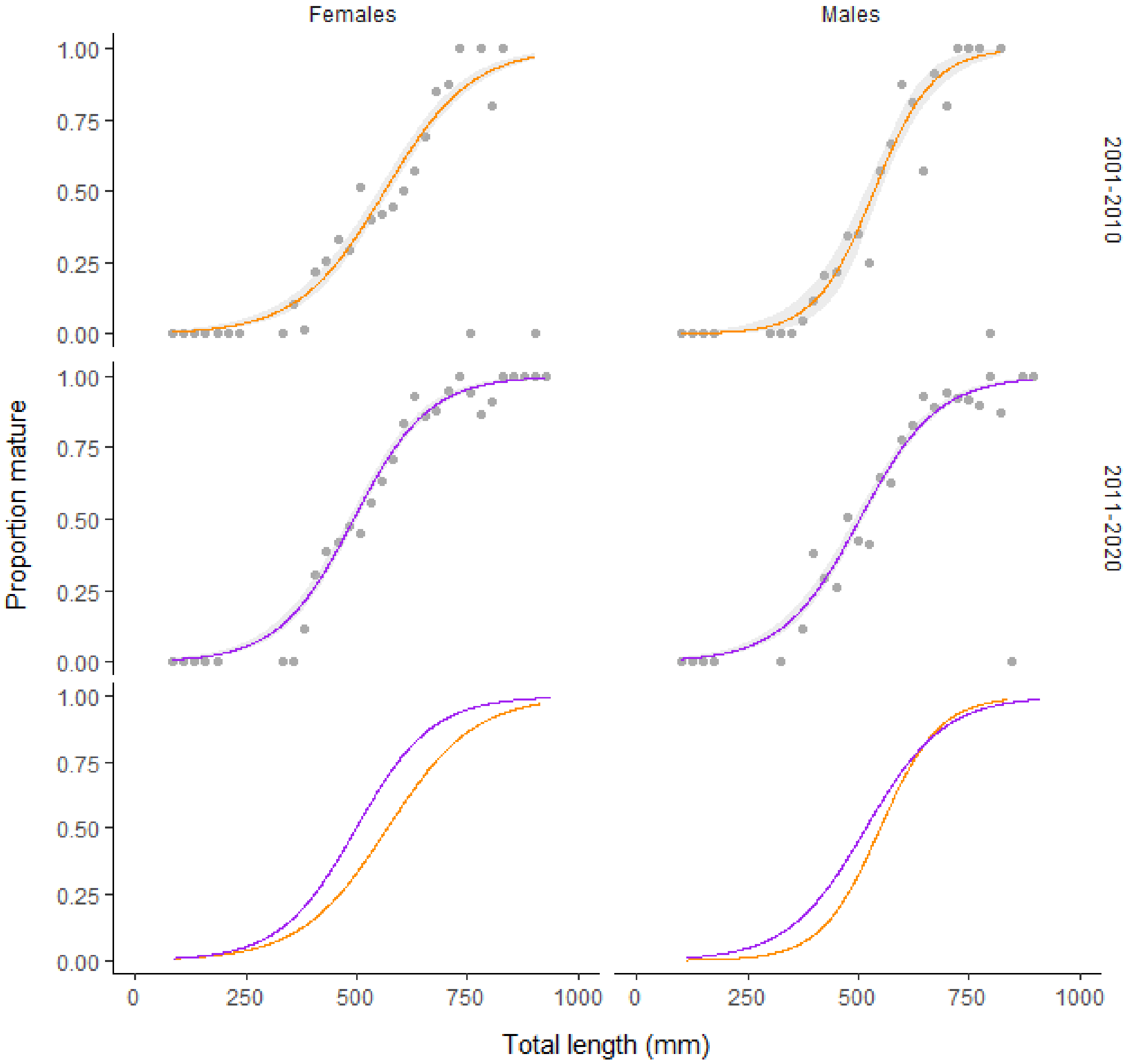


Figure 7.18. Estimated logistic curves of the proportions of mature female and male *C. auratus* at length (mm TL) in the Mid-West during the key spawning period (June – August). The curves were fitted separately to data for each sex from 2001-2010 (orange lines) and 2011-2020 (purple lines).

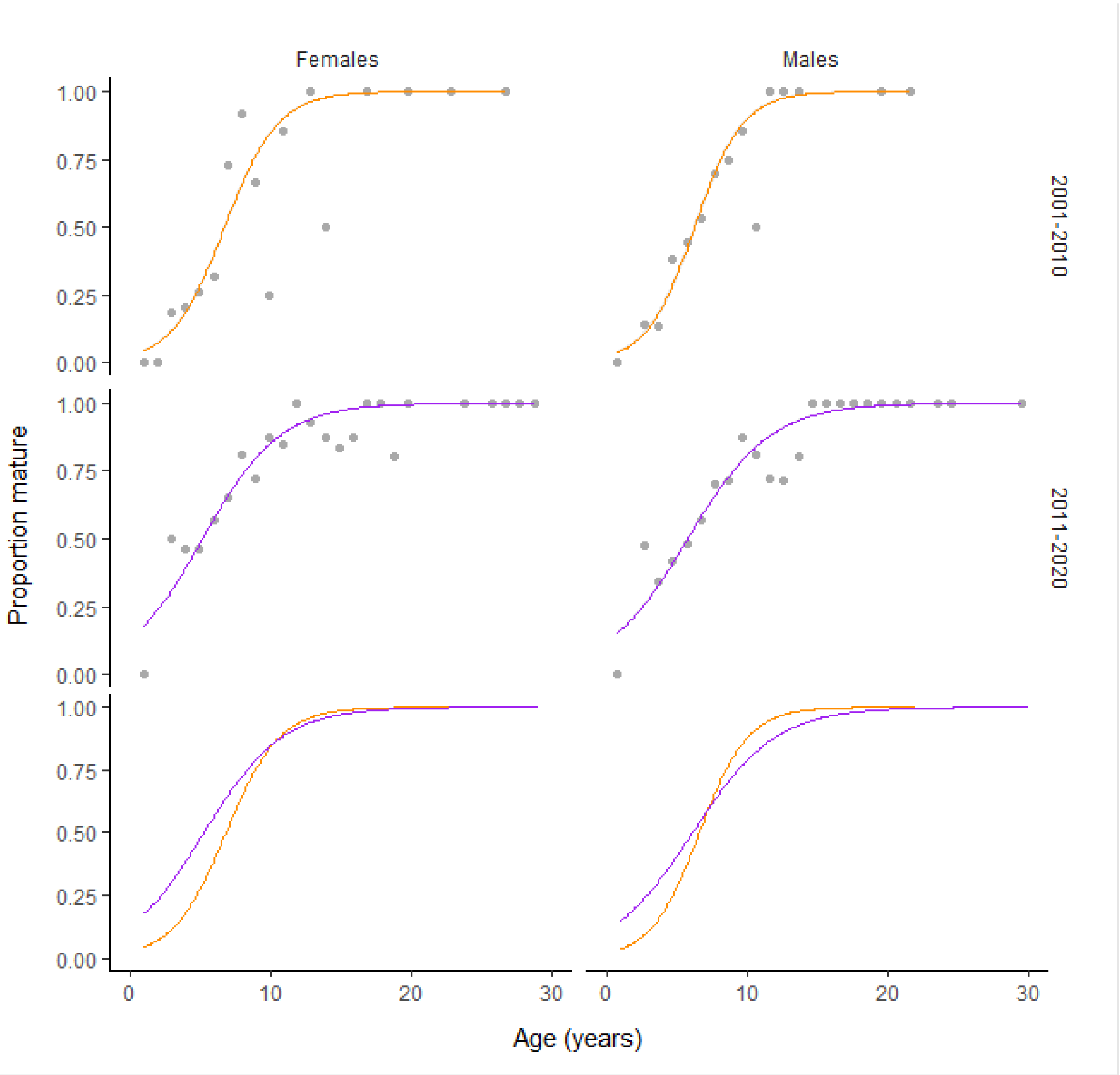


Figure 7.19. Estimated logistic curves of the proportions of mature female and male *C. auratus* at age in the Mid-West during the key spawning period (June – August). The curves were fitted separately to data for each sex from 2001-2010 (orange lines) and 2011-2020 (purple lines).

Table 7.8. Estimates (and associated 95% CLs) of the ages and lengths at which 50% and 95% of female and male *C. auratus* have attained maturity in the Mid-West, based on data from the peak spawning period (June – August) grouped by decadal sampling periods, and combined across these periods.

	L_{50} (mm TL)	L_{95} (mm TL)	A_{50} (y)	A_{95} (y)
Females				
2001-2010	569 (555-583)	857 (826-888)	6.8 (6.7-6.9)	12.4 (12.3-12.5)
2011-2020	498 (489-508)	749 (729-769)	5.2 (5.2-5.3)	13.4 (13.4-13.4)
Combined	515 (507-523)	761 (745-778)	5.9 (5.9-5.9)	12.7 (12.6-12.7)
Males				
2001-2010	549 (532-566)	745 (702-788)	6.6 (6.5-6.7)	11.7 (11.5-11.8)
2011-2020	517 (507-527)	776 (757-796)	6.1 (6-6.2)	14.8 (14.7-14.9)
Combined	527 (519-536)	762 (744-780)	6.4 (6.3-6.4)	13.5 (13.5-13.6)

7.3.3 0+ catch rates

Based on records of *C. auratus* in trawl surveys in Denham Sound (DS) and Outer Bay (OB), individuals of lengths 60-130 mm FL and 140-220 mm FL were allocated to the 0+ and 1+ age groups, respectively (Table 7.9) with 0+ the most abundant age group across all surveys. The peak in numbers of 0+ was in 2005 followed by 2000 and 2019 in DS and in 2017 and 2019 in OB (Table 7.10). Fish from the same cohort (year born) were represented in one to three consecutive trawl surveys in DS and one to five consecutive surveys in OB (Figure 7.20 and Figure 7.21). Information on 0+ *C. auratus* in the trawl survey data that could be used to calculate catch rates was available for the period 2000-2005 and 2015-present for DS but not available for the period 2006-2014, while useful data for OB was only from 2015 onwards.

Mean nominal 0+ catch rates for both DS and OB were low overall, ranging between close to zero and 0.5-0.7 individuals per shot, with lower error associated with the lowest catch rates and higher error associated with the higher catch rates (Figure 7.22). There was no significant difference in the trends in mean nominal catch rates between the year (includes zero counts of *C. auratus*) and year born (no zero counts included) plots. For the limited information available, standardised (relative) 0+ catch rates showed minimal variation between years in both DS and OB (Figure 7.23).

Table 7.9. Numbers of *C. auratus* by length class (cm FL) and cohorts for trawl surveys in Denham Sound (DS) and Outer Bay (OB).

Length class (cm FL)	DS			OB		
	0+	1+	2+	0+	1+	2+
6	5	0	0	10	0	0
7	33	0	0	7	0	0
8	66	0	0	16	0	0
9	115	0	0	58	0	0
10	238	0	0	240	0	0
11	260	0	0	536	0	0
12	207	0	0	699	0	0
13	106	0	0	388	0	0
14	0	141	0	0	184	0
15	0	210	0	0	116	0
16	0	160	0	0	53	0
17	0	76	0	0	28	0
18	0	35	0	0	12	0
19	0	11	0	0	6	0
20	0	6	0	0	3	0
21	0	3	0	0	1	0
22	0	3	0	0	2	0
23	0	0	1	0	0	1
24	0	0	2			
25	0	0	3			
27	0	0	4			
28	0	0	1			
29	0	0	1			
30	0	0	1			

Table 7.10. Number of *C. auratus* of 0+ cohort by length class (cm FL) and year born based on growth model of Tapp (2003) for Denham Sound (DS) and Outer Bay (OB).

Survey area	Year born	Length class (cm FL)									
		4	5	6	7	8	9	10	11	12	13
DS	1999	0	0	0	0	0	0	0	0	0	11
DS	2000	0	0	0	4	1	20	59	42	18	13
DS	2001	0	0	0	0	0	0	0	0	2	0
DS	2003	0	0	0	0	0	3	8	35	27	8
DS	2004	0	0	0	0	2	11	31	22	3	5
DS	2005	0	0	4	12	30	71	124	81	24	3
DS	2006	0	0	0	0	1	4	1	21	39	21
DS	2016	0	0	0	0	0	0	1	3	0	1
DS	2017	0	0	0	0	2	0	6	22	32	9
DS	2018	0	0	0	0	0	0	5	18	12	22
DS	2019	0	0	1	17	30	6	2	16	48	13
DS	2020	0	0	0	0	0	0	1	0	2	0
OB	2003	0	0	0	0	0	0	2	14	64	36
OB	2004	0	0	0	0	0	0	1	4	1	7
OB	2005	0	0	0	0	0	0	1	2	0	2
OB	2009	0	0	0	0	0	0	0	0	0	3
OB	2010	0	0	0	0	0	0	0	0	0	12
OB	2016	0	0	0	0	0	0	3	8	46	52
OB	2017	0	0	3	1	5	15	47	185	292	167
OB	2018	0	0	0	0	0	3	36	48	35	28
OB	2019	0	0	7	5	5	9	46	138	223	75
OB	2020	0	0	0	1	6	31	104	137	38	6

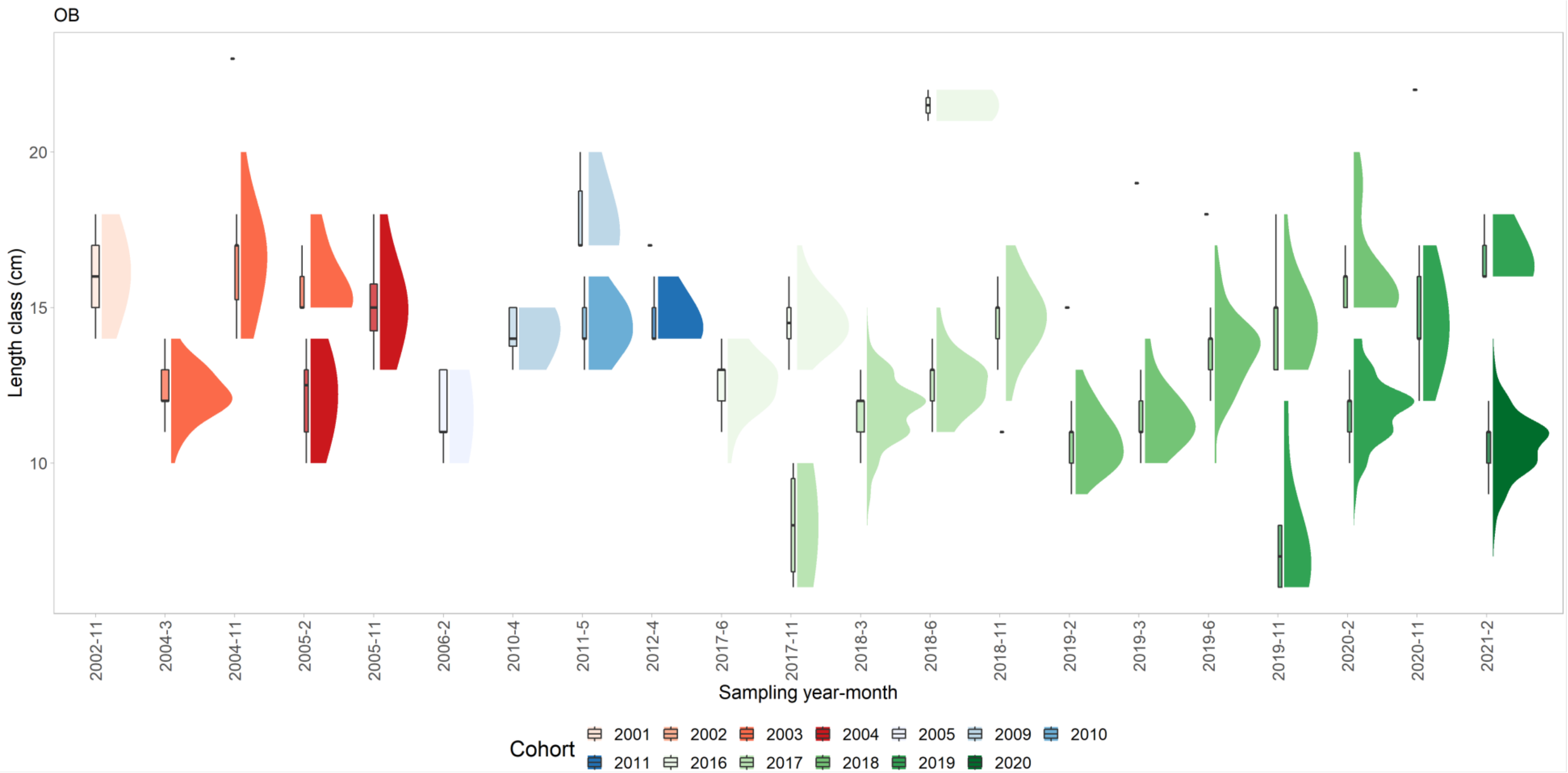


Figure 7.20. Cohorts of *C. auratus* from trawl surveys at Outer Bay locations by survey year and month 2002 to 2021. Individual cohorts are colour coded as indicated.

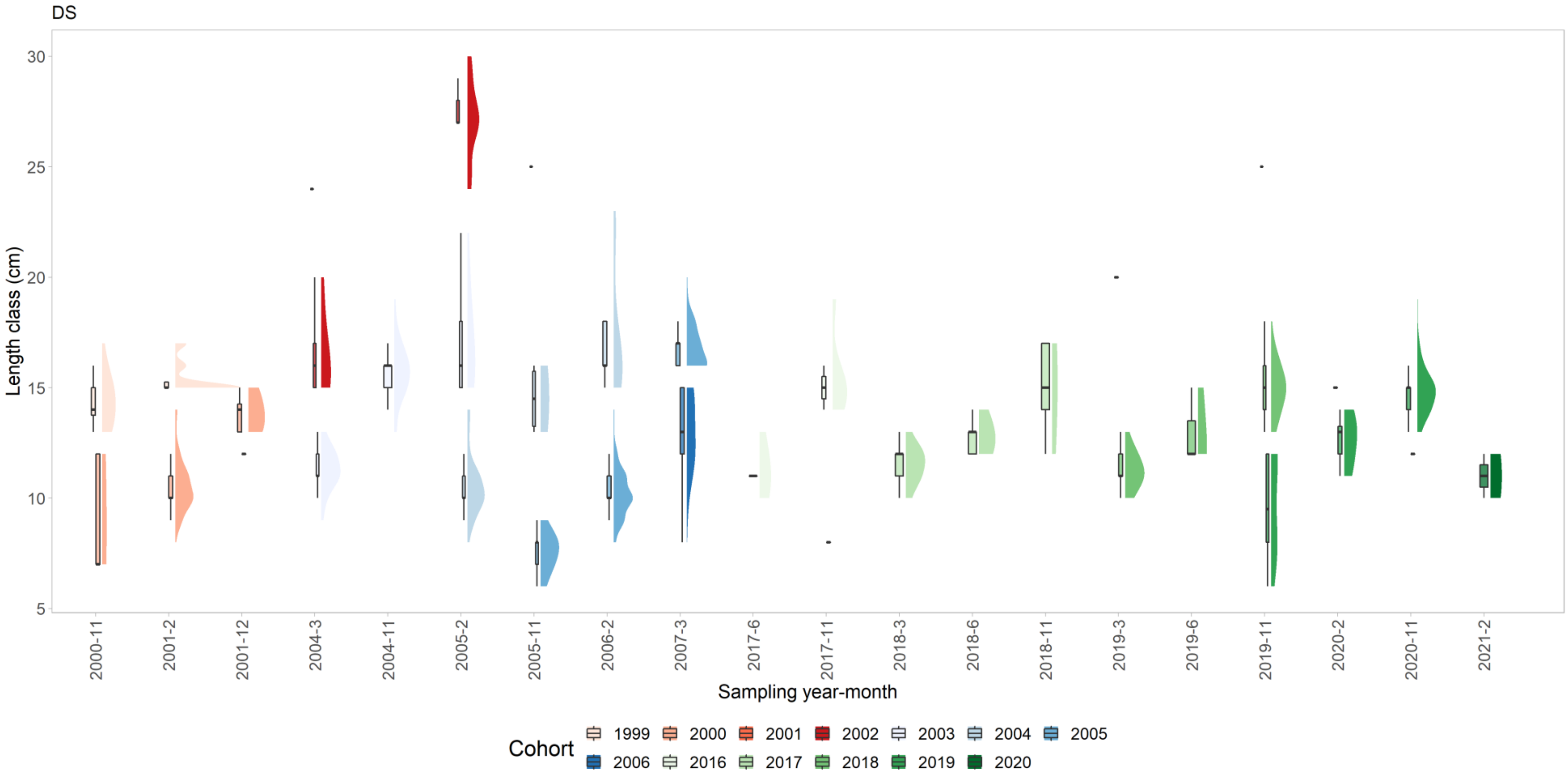


Figure 7.21. Cohorts of *C. auratus* from trawl surveys at Denham Sound locations by survey year and month 2000 to 2021. Individual cohorts are colour coded as indicated.

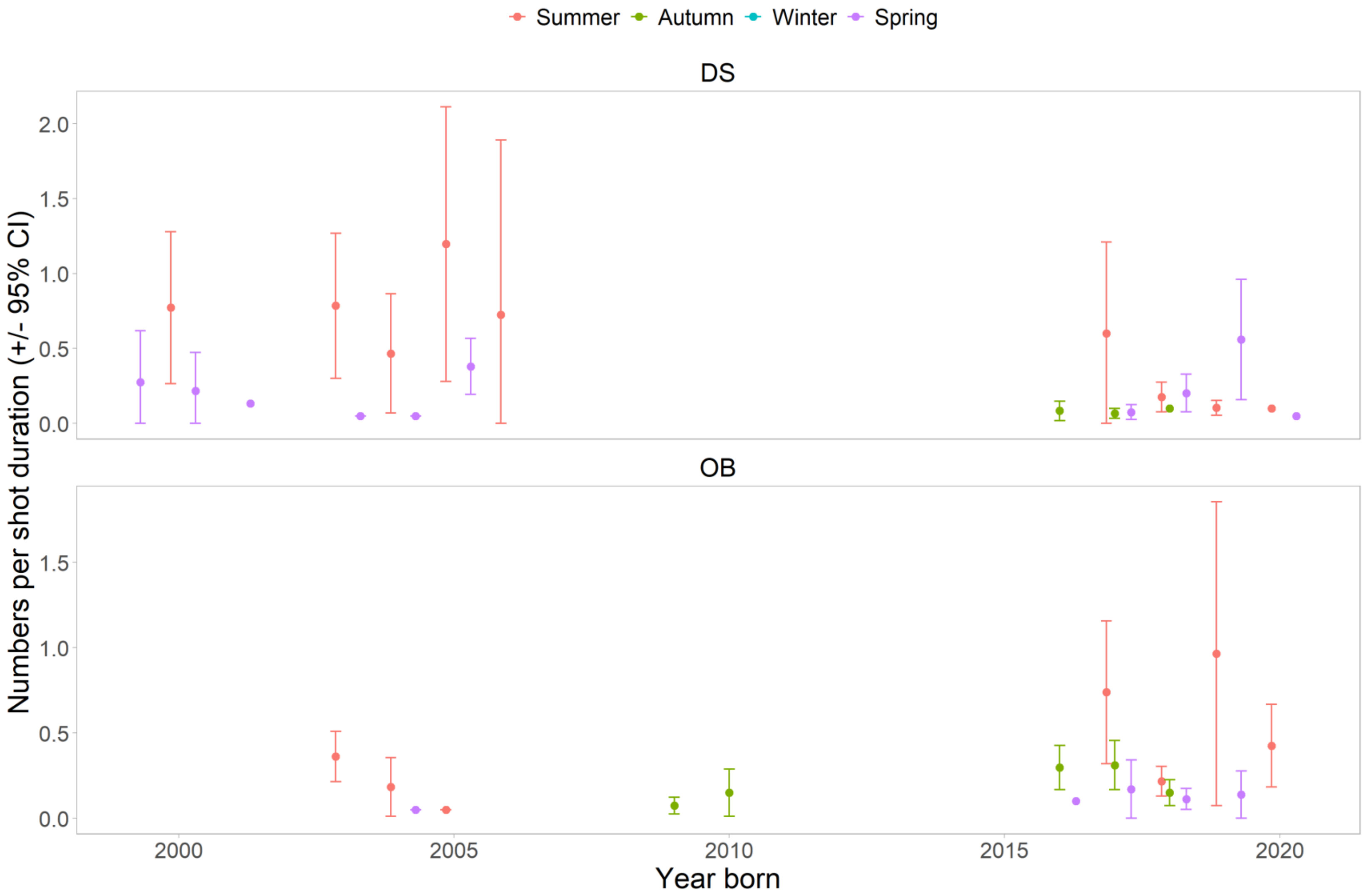


Figure 7.22. Mean nominal catch rates (with 95% CI) for 0+ *C. auratus* for Denham Sound (DS) and Outer Bay (OB), by year born and season during which trawl survey was undertaken. N.B. catch rates here do not include zero counts of 0+ during each trawl shot.

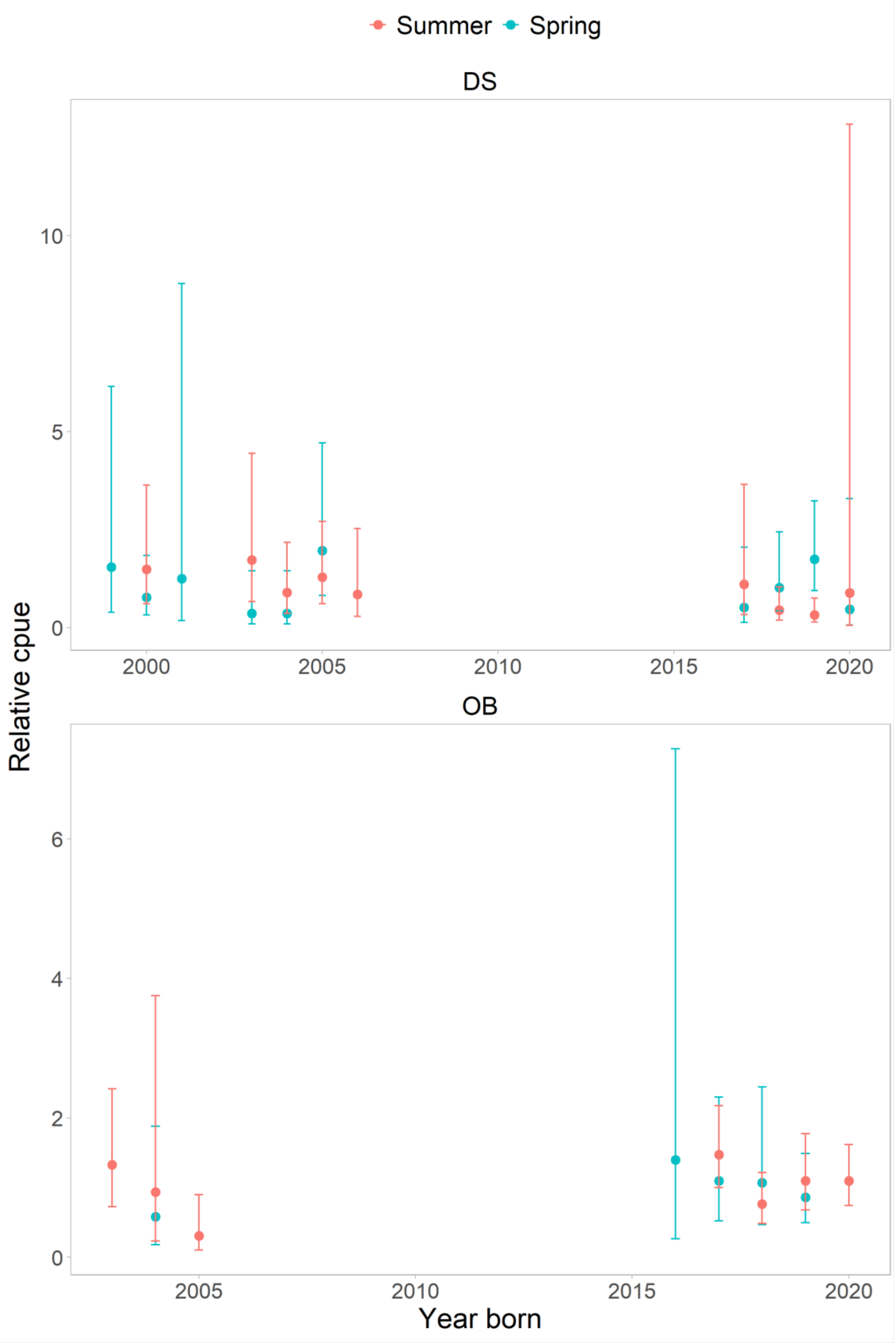


Figure 7.23. Relative standardized catch rates for 0+ individuals (with 95%CI) by season for Denham Sound and Outer Bay. Each series has been normalised to a mean score of 1.

7.3.4 Recruitment index

Due to the small sample sizes (trawl records with 0+ *C. auratus*) and relatively low contrast in the values of the environmental variables considered (Figure 7.24), none of the environmental variables showed a significant effect (see ANOVA results in Appendix 3 - Supplementary Information, Tables S7.1-S7.4).

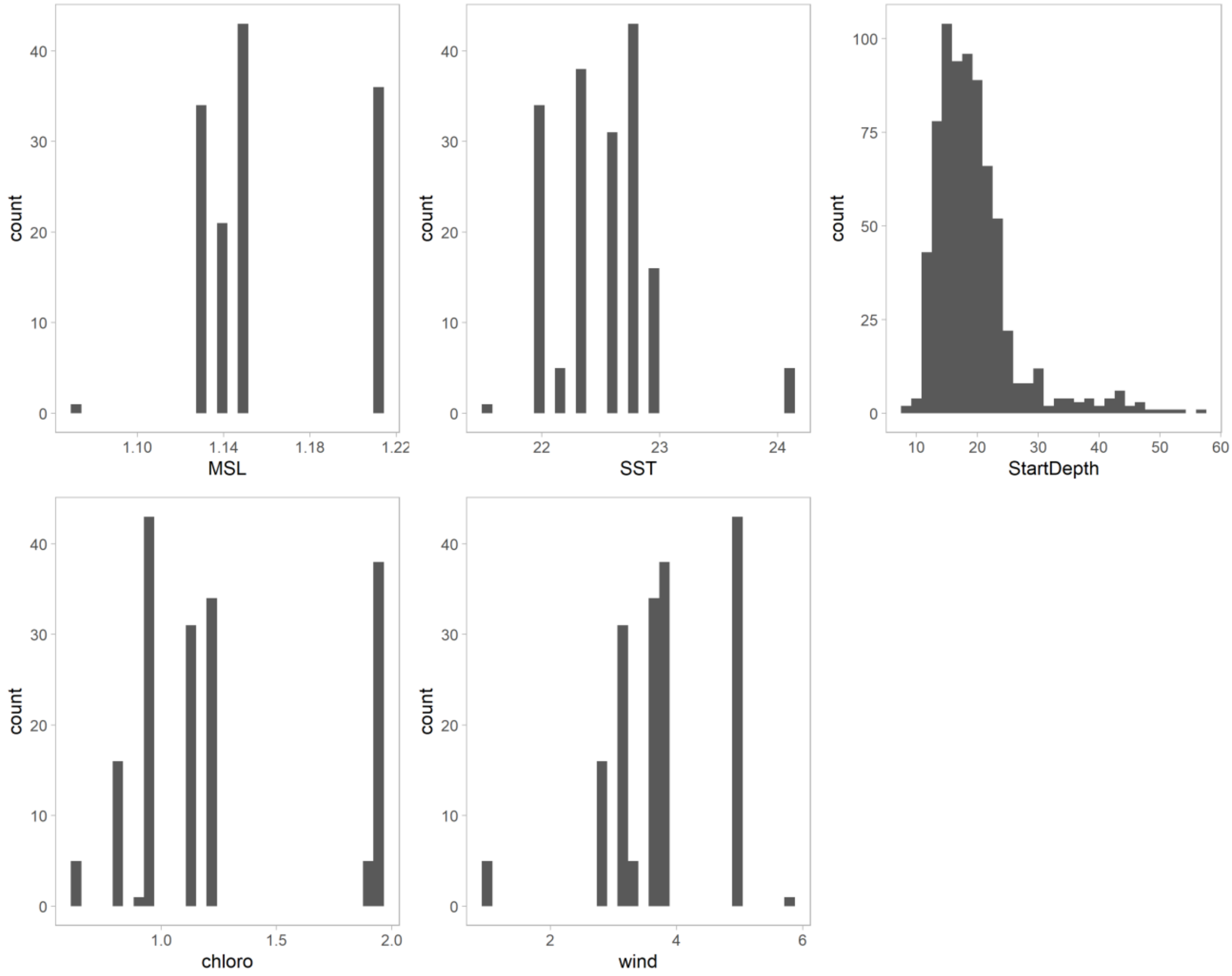


Figure 7.24. Distribution of environmental variables for the 0+ cohort (all years combined) sampled in Outer Bay survey area only. MSL – mean sea level, SST – sea surface temperature, StartDepth – Leeuwin Current strength, chloro – chlorophyll, wind – wind strength.

7.4 Discussion/Conclusion

7.4.1 Understanding spatial and temporal changes in biology

Analyses of the biological characteristics of fish species are dependent on data being representative of the underlying populations. In WA, monitoring of demersal fish species has primarily focused on fishery-dependent sampling of annual age frequencies from recreational and commercial catches, which are critical inputs to stock assessments (e.g. Wise et al. 2007; Fairclough et al. 2014; 2021). It is well recognised that size-selectivity of sampling methods, which in the case of *C. auratus* limits the capture and retention of individuals below the MLL, can bias estimates of biological parameters unless accounted for in analyses (Gwinn et al. 2010; Frater and Stefansson 2020). The approach taken in this current study, to focus growth analyses on the range of age cohorts represented across samples (4-25 y) and borrowing information from available samples of small and immature fish for all maturity analyses, aimed to provide an initial exploration any marked temporal changes in the biology of *C. auratus*. To undertake more thorough periodic reviews of the biological parameters used as input for stock assessments, however, fishery-independent sampling may be necessary to supplement data collection of the smaller and younger individuals.

Independent sampling of *C. auratus* across the full size and age ranges of this species has been conducted during specific projects, e.g. for previous biological and connectivity studies. As a consequence, small and immature fish (below the minimum legal length of 410 mm) have not been sampled repeatedly over time to allow review of biological parameters for this species on the upper west coast in WA. Furthermore, estimates of maturity have been based on samples collected between May and October (Wakefield et al. 2015), when limiting these to data from only the peak spawning months (June to August, as in this study) may be more appropriate to minimise the probability of sexually mature individuals being categorised as sexually immature earlier in the spawning period, when their gonads may not have started developing. While grouping of biological data by decadal sampling periods was necessary in this current study to ensure adequate sample sizes across analyses, it is recognised that this approach could smooth any real changes in the biology of *C. auratus* over time. For example, the mean percentage differences between sampling periods of the estimated lengths at ages above 10 years were ≤5%, suggesting there has been no biologically significant change in growth across the individual management areas. Due to the limitations of available data, more rigorous statistical comparisons between estimated growth or maturity parameters were not attempted in this study. Designing sampling programs specifically for the purpose of periodic reviews of biological parameters, that allow for the capture of smaller fish and ensure sufficient samples from the key spawning period for maturity analyses, would be more appropriate where resources for such sampling is available.

For *C. auratus* in the Gascoyne, where fishery-independent sampling has been undertaken between 2018 and 2022, the biological parameters used for input in the assessment model have recently been re-estimated and compared to those previously published for this stock (Wakefield et al. 2015; 2017). The key findings of that work (Jackson et al. 2023, in prep.), which compared parameter estimates based on data collected around 15 years apart rather than grouped by decadal sampling periods, suggested individuals in this area are growing faster to a larger size, resulting in a reduction in the estimated age at 50% maturity for females from around 4 y to 3 y. This result is not unexpected given the close relationship of this species' biology with water temperature (Wakefield et al. 2015; 2017). As the temperature tolerance range of fish species is typically narrower towards the edges of their range (e.g. Pörtner and Peck 2010), impacts of warming waters on the biology of *C. auratus* are likely to be noticed earlier in the Gascoyne compared to the more southern management areas. The observed temporal change in the growth and maturity of *C. auratus* in the Gascoyne highlights the importance for regular review of biological characteristics to inform stock assessments and management. The updated biological parameters based on recently collected fishery-independent data resulted in a more optimistic assessment of stock status in 2022, with the rebuilding of biomass now predicted to occur well before the 2037 milestone set out in the recovery plan for the stock (DPIRD 2020).

7.4.2 Recruitment index

The work described here is an important first attempt to make use of information on the distribution and abundance of the youngest age classes of *C. auratus* in research trawl surveys in Shark Bay, to commence development of a recruitment index for the Gascoyne oceanic stock. The value of an annual index of recruitment for stock assessment and to support more dynamic management of *C. auratus* stocks is well understood (Cartwright et al. 2020). Recruitment surveys to support stock assessments are routinely undertaken in Queensland (Bessell-Browne et al. 2020), Victoria (Hamer et al. 2011) and South Australia (A. Fowler pers. comm.). Development of such an index for the Gascoyne oceanic stock had not previously been possible in part due to lack of information on the location of nursery grounds. Locations where 0+ *C. auratus* have been regularly recorded at the outer bay locations have now been shown to be oceanographically and genomically linked with offshore spawning of *C. auratus* in Gascoyne oceanic waters at locations to the north and west of the offshore islands (Bernier and Dorre islands). The broad coverage of the well-established fishery-independent trawl surveys allows us to determine the spatial extent of the main nursery areas. In addition, the seasonal nature of the surveys, where individual cohorts have been followed for as much as five separate surveys through a season, gives confidence in the approach to monitor *C. auratus* recruitment using these data.

The annual trawl surveys in Shark Bay that provide important information for the management of valuable invertebrate fisheries have remained relatively consistent since 2000. While it had been hoped that more extensive data on the variation of the abundance of the youngest age classes of *C. auratus* were available we have identified that insufficient data were recorded for *C. auratus* for many years, preventing a better longer-term understanding of interannual recruitment variability. It is recommended that DPIRD trawl surveys in Shark Bay continue to collect information on juvenile *C. auratus* in a consistent manner, such that we can revisit these types of analyses in the future. Also, it would be useful to explore alternative measures of abundance in addition to 0+ catch rates, e.g. abundance of 0+ fish per trawl area as used elsewhere (Bessell-Browne et al. 2020). Juvenile *C. auratus* have been found to occupy a diversity of habitats in nursery areas in Australia and New Zealand and there is a need to better understand associations between 0+ fish and different habitat types at finer spatial scales in the outer bay areas of Shark Bay. It is recognised that while progress has been made in identifying important nursery areas in Shark Bay, there is very limited information on the locations of nursery areas in the northern management areas of the West Coast, i.e. from around Kalbarri (27° S to Lancelin (31°S). Further investigation of such locations is required to be able to design recruitment surveys for this species at locations beyond Shark Bay.

8. Conclusions

This project has met the objective of improving our understanding of *C. auratus* stock connectivity between the Gascoyne and West Coast bioregions. Genomics confirmed no differentiation among samples from the Gascoyne, Kalbarri and Mid-West areas, indicative of a single stock of *C. auratus* with high connectivity across that region. However, the related objective of identifying sources of recruitment via genomics indicated recruitment in the Gascoyne, Kalbarri and Mid-west was mostly derived from local spawning. Otolith chemistry indicated high levels of site fidelity in juvenile habitat use, but that adults in any one location would be derived from multiple nurseries. Overlapping otolith chemistry signatures indicated mixing among adult populations, however, given spatial variation in biological parameters, this could be influenced by low distinction in water chemistry among regions in this study.

The project has met the objective of using oceanographic modelling to improve understanding of the larval dispersal of *C. auratus* within the Shark Bay region and between there and Kalbarri and the Mid-West. Results showed that Shark Bay is only minimally connected to Kalbarri and the Mid-West during passive drift larval life stages with dispersal from Kalbarri to the Mid-West more likely. Dispersal pathways were identified from Shark Bay spawning sites around the offshore islands to settlement areas inside the central-eastern portion of Shark Bay mostly via northern Geographe Channel but also potentially from outside of the islands or at Turtle Bay (Dirk Hartog Island). These results highlight that the hydrodynamics, primarily driven by wind, encourage local recruitment and supports the genomics and otolith chemistry results.

The project has met the objective of trialling a combined acoustics and optical (acouptics) approach, demonstrating that *C. auratus* spawning aggregations can be detected using acoustic methods and that individuals of this species are consistently observed using unbaited stereo cameras. The work also revealed an unexpectedly complex multi-species fish community in the main *C. auratus* fishing grounds off Shark Bay during the peak season (June-August).

The project has met the objective of exploring spatial variation and temporal changes in the biological characteristics of *C. auratus* using DPIRD's extensive biological datasets from the Gascoyne and West Coast bioregions. These analyses provided further evidence for spatial variation in growth and maturity of this species across its latitudinal range. They also showed that individuals in the Gascoyne oceanic stock have been growing faster to a larger size in recent years, resulting in a reduction in the estimated age at 50% maturity for females from 4 to 3 years. While the spatial variation in biological characteristics provide support for adults "settling" in coastal regions, at least at the management area scale, consistent with previous mark-recapture studies, there is presumably enough mixing to contribute to homogeneity of genetic and/or otolith chemistry signatures.

Finally, the project has established that information on 0+ *C. auratus* collected during Shark Bay (prawn) trawl surveys at outer bay locations can used to estimate 0+ catch rates that in turn have potential to be used as a recruitment index for the Gascoyne oceanic stock, with more work required to understand relationships with the key environmental variables (wind, sea surface temperature, chlorophyll, sea level, and Leeuwin Current strength) as more data become available in the future.

9. Implications

This study has highlighted the scales at which connectivity of *C. auratus* occurs along the West coast of Australia, and the need to account for spatial differences in the biology of this species in assessments. Currently, assessment of *C. auratus* in oceanic waters off Shark Bay in the Gascoyne Coast Bioregion are conducted separately to those for *C. auratus* in the Kalbarri and Mid-west areas of the West Coast Bioregion, over a geographic scale of ~800 km, using biological parameters derived from each of those regions. Assessments now allow for incorporation of changes in biology, such as growth over time, more accurately representing changes in productivity (e.g. Fairclough et al. 2021). Each of these regions are exploited to different extents by the commercial and recreational sectors and are managed differently under separate harvest strategies, indicating the need for stock status information at scales relevant to those differences to continue managing exploitation appropriately. This approach contrasts with the last assessment of *C. auratus* along more than 1,000 km of the east coast of Australia, where multiple fisheries operate and differences in growth have also been detected. However, that assessment was conducted at the biological stock level, following microsatellite studies that have indicated that this extensive region comprises a single genetic stock (Wortmann et al. 2018; Stewart et al. 2020; Fowler et al. 2021).

The high-resolution genomic work conducted in this study (FRDC 2018-050) and that of Bertram et al. (2022) support the hypothesis that *C. auratus* are genetically homogeneous across the Gascoyne and northern West Coast bioregions of WA. However, evidence of localised recruitment and spatial variation in biological parameters supports the need to continue monitoring of breeding stock levels at finer spatial scales than that of the broader genetic stock.

10. Recommendations

The results of this study should be used as the basis for a review of the spatial scale of current assessments of *C. auratus* in the Gascoyne and northern areas of the West Coast Bioregion, and of the scale at which the current harvest strategies apply to manage exploitation across the respective bioregions in Western Australia.

10.1 Further development

Acouptics has shown potential for estimating the abundance and distribution of Snapper but there is a need for more investment/industry support before adoption as part of any formal stock assessment.

There is potential for collaboration between co-investigators on this project and SARDI researchers to apply outcomes of the acouptics research to assess Snapper spawning aggregations in the South Australian gulfs.

In Western Australia, a study to evaluate the use of acoustics combined with drone surveys to assess Snapper spawning aggregations in Cockburn Sound is currently underway as part of the WAMSI-Westport Marine Science Program (https://wamsi.org.au/research/programs/wamsi-westport-marine-science-program/). This project is expected to be completed in early 2024.

An Echoview software training course aimed at upskilling DPIRD research staff in the analysis and interpretation of fisheries acoustic data in relation to demersal and pelagic fisheries is planned for mid-2023.

There are plans for DPIRD and SARDI staff to participate in a Snapper stock assessment workshop in mid-2023.

11. Extension and Adoption

Designing an acoustic/optical survey for surveying Gascoyne snapper aggregations, Florida, February 2020 (B Scoulding & D Fairclough). Workshop held with international experts in acoustic survey, optical (video) survey and fisheries stock assessment.

G Jackson gave a presentation on behalf of Ben Scoulding 'Where did the snapper go? An acoustic optical survey of snapper' at the Annual Management Meeting for Gascoyne Demersal Scalefish Managed Fishery, 15 October 2020.

B Scoulding gave a presentation at CSIRO in Hobart in October 2020 titled 'Where did the snapper go? An acoustic optical survey of snapper'.

B Scoulding gave a presentation to DPIRD staff at Hillarys in July 2021 titled 'An acoustic approach to assessing snapper'.

Information on results of connectivity studies (D Fairclough) were presented at the Annual Management Meeting of the West Coast Demersal Scalefish (Interim) Managed Fishery and Management update briefing of Recfishwest, both in September 2022.

Additional presentations to commercial and recreational fishers in the Gascoyne and Westcoast Bioregions will occur in first half of 2023 when this FRDC final report is finalised.

11.1 Project coverage

DPIRD media: Yammer, Media Release at start of project in 2019.

CSIRO media: 'Sounds of the deep – music for sustainable fisheries' https://ecos.csiro.au/sounds-of-the-deep-music-for-sustainable-fisheries/

Article in *Fishing World*, WA Fisheries goes hi-tech to monitor snapper stocks, July 2020.

12. Project materials developed

Scientific papers:

Scoulding, B., Gastauer, S., Taylor, J.C, Boswell, K.M., Fairclough, D.V., Jackson, G., Sullivan, P., Shertzer, K., Campanella, F., Bacheler, N., Campbell, M., Domokos, R., Schobernd, Z., Switzer, T.S., Jarvis, N., Crisafulli, B.M, Untiedt, C., Fernandes, P.G. (2023). Estimating abundance of fish associated with structured habitats by combining acoustics and optics. *Journal of Applied Ecology* http://doi.org/10.1111/1365-2664.14412

Appendix 1 - List of Researchers and Project Staff

Gary Jackson (PI), DPIRD

David Fairclough, DPIRD

Emily Fisher, DPIRD

Matias Braccini, DPIRD

Nick Jarvis, DPIRD

Brett Crisafulli, DPIRD

Dion Boddington, DPIRD

Adam Eastman, DPIRD

Peter Coulson, DPIRD

Blaine Hodgson, DPIRD

Ben Scoulding, CSIRO

Candice Untiedt, CSIRO

Luciano Beheregaray, Flinders University

Jonathan Sandoval-Castillo, Flinders University

Diana Elena-Vornicu, Flinders University

Bronwyn Gillanders, University of Adelaide

Patrick Reis-Santos, University of Adelaide

Ashleigh Sharrad, University of Adelaide

Sarah Gilbert, University of Adelaide

Yasha Hetzel, University of Western Australia

Mirjam Van Der Mheen, University of Western Australia

Chari Pattiaratchi, University of Western Australia

Ivica Janekovic, University of Western Australia

Wally Zorzi, Rosscommon Nominees

Jamie Shaw, Rosscommon Nominees

Jonah Nero, Rosscommon Nominees

Brad van Rongen, Shoreline Marine Fabrications

Appendix 2 - References

Alexander, D. H., & Lange, K. (2011). Enhancements to the ADMIXTURE algorithm for individual ancestry estimation. *BMC Bioinformatics*, 12: 1-6.

Al-Marzouqi, A., Jayabalan, N., Al-Nahdi, A. (2013). Length based growth and stock assessment of the longnose trevally *Carangoides chrysophrys* (Cuvier, 1833) from the Arabian Sea coast of Oman. *Indian J. Fish.,* 60(2): 1-6.

Bernatchez, L., Wellenreuther, M., Araneda, C., Ashton, D.T., Barth, J.M., Beacham, T.D., Maes, G.E., Martinsohn, J.T., Miller, K.M., Naish K.A. (2017). Harnessing the power of genomics to secure the future of seafood. *Trends in Ecology & Evolution* 32: 665-680.

Bertram, A., Fairclough, D., Sandoval-Castillo, J., Brauer, C., Fowler, A., Wellenreuther, M., Beheregaray, L. B. (2022). Fisheries genomics of snapper (*Chrysophrys auratus*) along the west Australian coast. *Evolutionary Applications* 15: 1099-1114.

Bessell-Browne, P., Prosser, A., Garland, A. (2020). Pre-recruit abundance indices for eastern king prawn, blue swimmer carb and snapper in south eastern Queensland. Department of Agriculture and Fisheries, Queensland.

Brauer, C.J., Hammer, M.P., Beheregaray, L.B. (2016). Riverscape genomics of a threatened fish across a hydroclimatically heterogeneous river basin. *Molecular Ecology* 25: 5093–5113.

Brown, J., Pirrung, M., McCue, L.A. (2017). FQC Dashboard: integrates FastQC results into a web-based, interactive, and extensible FASTQ quality control tool. *Bioinformatics 33*(19): 3137-3139.

Campana, S.E., Thorrold, S.R. (2001). Otoliths, increments, and elements: keys to a comprehensive understanding of fish populations? *Canadian Journal of Fisheries and Aquatic Sciences* 58: 30-38.

Caputi, N., Feng, M., Pearce, A., Benthuysen, J., Denham, A., Hetzel, Y., Matear, R., Jackson, G., Molony, B., Joll, L., Chandrapavan A. (2015). Management implications of climate change effect on fisheries in Western Australia, Part 2: Case studies. FRDC Project No. 2010/535. Fisheries Research Report No. 261. Department of Fisheries, Western Australia. 156 pp.

Cartwright, I., McPhail, J., Knuckey, I., Smith, T., Rayns, N., Steer, M. (2020). National Snapper Workshop – Rebuilding our iconic Snapper stocks. Final report to FRDC on Project No. 2019/085. 58 pp.

Catchen, J., Hohenlohe, P.A., Bassham, S., Amores, A., Cresko, W.A. (2013). Stacks: an analysis tool set for population genomics. *Molecular Ecology* 22(11): 3124-3140.

Clarke, K.R., Gorley, R.N., Somerfield, P.J., Warwick, R.M. (2014). Change in marine communities: an approach to statistical analysis and interpretation. 3rd Edition. PRIMER-E, Plymouth.

Danecek, P., Auton, A., Abecasis, G., Albers, C. A., Banks, E., DePristo, M. A., ... & 1000 Genomes Project Analysis Group. (2011). The variant call format and VCFtools. *Bioinformatics* 27(15): 2156-2158.

Delandmeter, P., & van Sebille, E. (2019). The Parcels v2.0 Lagrangian framework: new field interpolation schemes. *Geosci. Model Dev.* 12(8): 3571-3584. https://doi.org/10.5194/gmd-12-3571-2019

Department of Primary Industries and Regional Development (DPIRD). (2020). Gascoyne Demersal Scalefish Resource: Oceanic Pink Snapper Recovery Plan 2018-2037. Fisheries Management Paper No. 298. Department of Primary Industries and Regional Development, Western Australia. 13 pp.

Di Franco, A., Calò, A., De Benedetto, G.E., Ghigliotti, L., Pennetta, A., Renard, M.D.M., Pisano, E., Vacchi, M., Guidetti, P. (2021). Otolith chemical composition suggests local populations of Antarctic silverfish *Pleuragramma antarctica* (Boulenger, 1902) around Antarctica are exposed to similar environmental conditions at early life stages. *Polar Biology* 44: 1979-1991.

Elsdon, T.S., Wells, B.K., Campana, S.E., Gillanders, B.M., Jones, C.M., Limburg, K.E., Secor, D.H., Thorrold, S.R., Walther, B.D. (2008). Otolith chemistry to describe movements and life-history parameters of fishes: Hypotheses, assumptions, limitations and inferences. *Oceanography and Marine Biology: An Annual Review* 46: 297-330.

Excoffier, L., & Lischer, H.E. (2010). Arlequin suite ver 3.5: a new series of programs to perform population genetics analyses under Linux and Windows. *Molecular Ecology resources 10*: 564-567.

Fairclough, D.V., Edmonds, J.S., Jackson, G., Lenanton, R.C.J., Kemp, J., Molony, B.W., Keay, I.S., Crisafulli, B.M., Wakefield, C.B. (2013). A comparison of the stock structures of two exploited demersal teleosts, employing complementary methods of otolith element analysis. *Journal of Experimental Marine Biology and Ecology* 439: 181-195.

Fairclough, D.V., Molony, B.W., Crisafulli, B.M., Keay, I.S., Hesp, S.A., Marriott, R.J. (2014). Status of demersal finfish stocks on the west coast of Australia. Fisheries Research Report No. 253. Department of Fisheries, Western Australia.

Fairclough, D.V., Hesp, S.A., Denham, A., Fisher, E.A., Marks, R., Ryan, K.L., Lek, E., Allen, R., Crisafulli, B.M. (2021). 2021 assessment of the status of the West Coast Demersal Scalefish Resource. Fisheries Research Report No. 316. Department of Primary Industries and Regional Development, Western Australia. 158 pp.

Fowler, A.J., Jennings, P.R. (2003). Dynamics in 0+ recruitment and early life history for snapper (*Pagrus auratus*, Sparidae) in South Australia). *Marine and Freshwater Research* 54: 941-956.

Fowler, A., Stewart, J., Roelofs, A., Garland, A., Jackson, G. (2021). Snapper (*Chrysophrys auratus*). In: Piddocke, T., Ashby, C., Hartmann, K., Hesp, A., Hone, P., Klemke, J., Mayfield, S., Roelofs, A., Saunders, T., Stewart, J., Wise, B., Woodhams, J. (eds.), Status of Australian Fish Stocks Reports 2020. Fisheries Research and Development Corporation, Canberra.

Francis, M.P. (1993). Does water temperature determine year class strength in New Zealand snapper (*Pagrus auratus*)? *Fisheries Oceanography* 2: 65-72.

Francis, M.P., Langley, A.D., Gilbert, D.J. (1995). Snapper recruitment in the Hauraki Gulf. New Zealand Fisheries Assessment Research Document 95/17. 27 pp.

Francis, M. P. (1994). Duration of larval and spawning periods in Pagrus auratus (Sparidae) determined from otolith daily increments. Environmental Biology of Fishes, 39(2), 137-152. https://doi.org/10.1007/BF00004931

Frater, P.N., Stefansson, G. (2020). Comparison and evaluation of approaches aimed at correcting or reducing selectivity bias in growth parameter estimates for fishes. *Fisheries Research 225*. https://doi.org/10.1016/j.fishres.2019.105464

French, B., Potter, I.C., Hesp, S.A., Coulson, P.G., Hall, N.G. (2014). Biology of the harlequin fish *Othos dentex* (Serranidae), with particular emphasis on sexual pattern and other reproductive characteristics. *Journal of Fish Biology* 84: 106-132.

Froese, R., Pauly, D. (eds.) (2000). FishBase 2000: concepts designs and data sources (Vol. 1594). WorldFish.

Gardner, M.J., Chaplin, J.A., Fairclough, D.V., Potter, I.C. (2022). Microsatellite-based assessment of the genetic structure of snapper, *Chrysophrys auratus*, in Australasia. *Estuarine, Coastal and Shelf Science* 274: 107932. https://doi.org/10.1016/j.ecss.2022.107932

Gaughan, D., Moran, M., Ranaldi, M., Watling, J.R. (2003). Identifying nursery areas used by inner bay and oceanic pink snapper (*Pagrus auratus*) stocks in the Shark Bay region, in relation to the effect of prawn trawling on inner bay snapper stocks. FRDC Final Report on Project No. 2001/061. Department of Fisheries, Western Australia. 27 pp.

Grummer, J.A., Beheregaray, L.B., Bernatchez, L., Hand, B., Luikart, G., Narum, S.R., Taylor, E.B. (2019). Aquatic landscape genomics and environmental effects on genetic variation. *Trends in Ecology and Evolution* 34: 641-654.

Gwinn, D.C., Allen, M.S., Rogers, M.W. (2010). Evaluation of procedures to reduce bias in fish growth parameter estimates resulting from size-selective sampling. *Fisheries Research* 105: 75-79.

Haddon, M. (2001). Modelling and quantitative methods in fisheries, 2nd edition. Chapman & Hall, CRC Press. 449 pp.

Hamer, P. A., and Jenkins, G. P. (2004). High levels of spatial and temporal recruitment variability in the temperate sparid *Pagrus auratus*. *Marine and Freshwater Research* 55: 663-673.

Hamer, P.A., Acevedo, S., Jenkins, G.P. and Newman, A. (2011). Connectivity of a large embayment and coastal fishery: spawning aggregations in one bay source local and broad-scale fishery replenishment. *Journal of Fish Biology* 78: 1090-1109.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* 146(730): 1999-2049. https://doi.org/https://doi.org/10.1002/qj.3803

Hesp, A. (2022). WAFishBiology: Collection of methods for analysis of fish biological data. R package version 0.1.0.

Hetzel, Y., Pattiaratchi, C., Lowe, R., Hofmeister, R. (2015). Wind and tidal mixing controls on stratification and dense water outflows in a large hypersaline bay. *Journal of Geophysical Research: Oceans* 120(9): 6034-6056. https://doi.org/10.1002/2015jc010733

Hobday, A.J., Oliver, E.C.J., Sen Gupta, A., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Holbrook, N.J., Moore, P.J., Thomsen, M.S., Wernberg, T., Smale, D.A. (2018). Categorizing and naming marine heatwaves. *Oceanography* 31: 162–173.

Izzo, C., Reis-Santos, P., Gillanders, B.M. (2018). Otolith chemistry does not just reflect environmental conditions: A meta-analytic evaluation. *Fish and Fisheries* 19 (3): 441-454. https://doi.org/10.1111/faf.12264

Jackson, G. (2007). Fisheries biology and management of pink snapper *Pagrus auratus*, in the inner gulfs of Shark Bay, Western Australia. PhD Thesis, Centre for Fish and Fisheries Research, Murdoch University, Western Australia. 254 pp.

Jackson, G., Burton, C., Moran, M., Radford, B. (2007). Distribution and abundance of juvenile pink snapper, *Pagrus auratus*, in the gulfs of Shark Bay, Western Australia, from trap surveys. Fisheries Research Report No. 161. Department of Fisheries, Western Australia. 36 pp.

Jackson, G., Norriss, J.V., Mackie, M.C., Hall, N.G. (2010). Spatial variation in life history characteristics of snapper (*Pagrus auratus*) within Shark Bay, Western Australia. *New Zealand Journal of Marine and Freshwater Research* 44: 1-15.

Jackson, G., Denham, A., Hesp, A., Hall, N., Fisher, E., Stephenson, P. (2020). Resource Assessment Report: Gascoyne Demersal Scalefish Resource. Department of Primary Industries and Regional Development, Western Australia. 158 pp.

Jackson, G., Fisher, E., Denham, A., Hesp, A., Trinnie, F. (2023, in prep.). Resource Assessment Report: Gascoyne Demersal Scalefish Resource. Department of Primary Industries and Regional Development, Western Australia.

Jombart, T., Collins, C. (2015). *A tutorial for discriminant analysis of principal components (DAPC) using adegenet 2.0.0.* London: Imperial College London, MRC Centre for Outbreak Analysis and Modelling.

Kangas, M.I., Chandrapavan, A., Hetzel, Y. L., Sporer, E.C. (2012). Minimising gear conflict and resource sharing issues in the Shark Bay trawl fisheries and promotion of scallop recruitment. Fisheries Research Report No. 229. Department of Fisheries, Western Australia.

Kajtar Jules B., Holbrook Neil J., Hernaman Vanessa (2021) A catalogue of marine heatwave metrics and trends for the Australian region. *Journal of Southern Hemisphere Earth Systems Science* **71**, 284-302.

Lange, M., van Sebille, E. (2017). Parcels v0.9: prototyping a Lagrangian ocean analysis framework for the petascale age. *Geosci. Model Dev.* 10(11): 4175-4186. https://doi.org/10.5194/gmd-10-4175-2017

Leis, J. M. (2021). Perspectives on Larval Behaviour in Biophysical Modelling of Larval Dispersal in Marine, Demersal Fishes. Oceans, 2(1), 1-25. https://www.mdpi.com/2673-1924/2/1/1

Lenanton, R., StJohn, J., Keay, I., Wakefield, C., Jackson, G., Wise, B., Gaughan, D. (2009). Spatial scales of exploitation among populations of demersal scalefish: implications for management. Part 2: Stock structure and biology of two indicator species, West Australian dhufish (*Glaucosoma hebraicum*) and pink snapper (*Pagrus auratus*), in the West Coast Bioregion. FRDC Final Report on Project No. 2003/052. Fisheries Research Report No. 174. Department of Fisheries, Western Australia. 187 pp.

Mahjabin, T., Pattiaratchi, C., Hetzel, Y., Janekovic, I. (2019). Spatial and Temporal Variability of Dense Shelf Water Cascades along the Rottnest Continental Shelf in Southwest Australia. *Journal of Marine Science and Engineering* 7(2): 30. http://www.mdpi.com/2077-1312/7/2/30

Marriott, R., Jackson, G., Lenanton, R., Telfer, C., Lai, E., Stephenson, P., Bruce, C., Adams, D., Norriss, J. (2012). Biology and stock status of demersal indicator species in the Gascoyne Coast Bioregion. Fisheries Research Report No. 228. Department of Fisheries, Western Australia. 210 pp.

McKenna, A., Hanna, M., Banks, E., Sivachenko, A., Cibulskis, K., Kernytsky, A., ... & DePristo, M.A. (2010). The Genome Analysis Toolkit: a MapReduce framework for analyzing next-generation DNA sequencing data. *Genome Research 20*: 1297-1303.

Moll, D., Kotterba, P., Jochum, K.P., von Nordheim, L., Polte, P. (2019). Elemental Inventory in Fish Otoliths Reflects Natal Origin of Atlantic Herring (*Clupea harengus*) From Baltic Sea Juvenile Areas. *Frontiers in Marine Science* 6 (191): 1-11. https://doi.org/10.3389/fmars.2019.00191

Moran, M.J. and Kangas, M. (2003). The effects of the trawl fishery on the stock of pink snapper, *Pagrus auratus*, in Denham Sound, Shark Bay. Fisheries Research Bulletin No. 31. Department of Fisheries, Western Australia.

Moran, M., Stephenson, P., Gaughan, D., Moore, J. (2005). Minimising the cost of future stock monitoring, and assessment of the potential for increased yields from the oceanic snapper, *Pagrus auratus*, stock off Shark Bay. FRDC Final Report on Project No. 2000/138. Department of Fisheries, Western Australia.

Nahas, E.L., Jackson, G., Pattiaratchi, C.B., Ivey, G.N. (2003). Hydrodynamic modelling of snapper (*Pagrus auratus*) egg and larval dispersal in Shark Bay, Western Australia: reproductive isolation at a fine spatial scale. *Marine Ecology Progress Series* 265: 213-226.

Parsa, M., Rahnama, B., Mahmoudi Khoshdarehgi, M. (2017). Length–weight relationships of five fish species from Carangidae family in waters of the northern Persian Gulf, Iran. *Journal of Applied Ichthyology* 33 (5): 1055-1057. https://doi.org/10.1111/jai.13422

Paton, C., Hellstrom, J., Paul, B., Woodhead, J., Hergt, J. (2011). Iolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry* 26: 2508-2518.

Peakall, R., Smouse, P.E. (2012). GenAlEx 6.5: Genetic analysis in Excel. Population genetic software for teaching and research-an update. *Bioinformatics* 28: 2537-2539.

Pearce, A. Feng, M. (2017). Observations of warming on the Western Australian continental shelf. *Marine and Freshwater Research* 58: 914-920.

Peliz, A., Marchesiello, P., Dubert, J., Marta-Almeida, M., Roy, C., Queiroga, H. (2007). A study of crab larvae dispersal on the Western Iberian Shelf: Physical processes. *Journal of Marine Systems* 68(1): 215-236. https://doi.org/https://doi.org/10.1016/j.jmarsys.2006.11.007

Pörtner, H.O. and Peck, M.A. (2010). Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. *Journal of Fish Biology* 77: 1745-1779.

R Core Team. (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Reis-Santos, P., Gillanders, B.M., Sturrock, A.M. et al. (2022). Reading the biomineralized book of life: expanding otolith biogeochemical research and applications for fisheries and ecosystem-based management. *Reviews in Fish Biology and Fisheries.* https://doi.org/10.1007/s11160-022-09720-z

Reis-Santos, P., Tanner, S.E., Aboim, M.A., Vasconcelos, R.P., Laroche, J., Charrier, G., Pérez, M., Presa, P., Gillanders, B.M., Cabral, H.N. (2018a). Reconciling differences in natural tags to infer demographic and genetic connectivity in marine fish populations. *Scientific Reports* 8: 10343.

Reis-Santos, P., Vasconcelos, R.P., Tanner, S.E., Fonseca, V.F., Cabral, H.N., Gillanders, B.M. (2018b). Extrinsic and intrinsic factors shape the ability of using otolith chemistry to characterize estuarine environmental histories. *Marine Environmental Research* 140: 332-341.

Rogers, T.A., Fowler, A.J., Steer, M.A., Gillanders, B.M. (2019). Discriminating Natal Source Populations of a Temperate Marine Fish Using Larval Otolith Chemistry. *Frontiers in Marine Science* 6.

Sandoval-Castillo J., Robinson N., Hart A., Strain L., Beheregaray L. B. (2018). Seascape genomics reveals adaptive divergence in a connected and commercially important mollusc, the greenlip abalone (*Haliotis laevigata*), along a longitudinal environmental gradient. *Molecular Ecology* 27: 1603-1620.

Saunders, R.J. (2009). The reproductive biology and recruitment dynamics of snapper *Chrysophrys auratus.* PhD thesis. School Earth and Environmental Sciences, University of Adelaide. 162 pp.

Scoulding, B., Gastauer, S., Taylor, J.C, Boswell, K.M, Fairclough, D.V., Jackson, G., Sullivan, P., Shertzer, K., Campanella, F., Bacheler, N., Campbell, M., Domokos, R., Schobernd, Z., Switzer, T.S., Jarvis, N., Crisafulli, B.M, Untiedt, C., Fernandes, P.G. (2022). Estimating abundance of fish associated with structured habitats by combining acoustics and optics. *Journal of Applied Ecology*. http://doi.org/10.1111/1365-2664.14412

Sim-Smith, C.J., Jeffs, A.G., Radford, C.A. (2012). Variation in the growth of larval and juvenile snapper, *Chrysophrys auratus* (Sparidae). *Marine and Freshwater Research* 63: 1231-1243.

Smallwood, C.B., Hesp, S.A., Beckley, L.E. (2013). Biology, stock status and management summaries for selected fish species in south-western Australia. Fisheries Research Report No. 242. Department of Fisheries, Western Australia. 180 pp.

Stewart, J., Pidd, A., Fowler, A.M., Sumpton, W. (2020). Latitudinal variation in growth rates and limited movement patterns revealed for east-coast snapper *Chrysophrys auratus* through long-term cooperative-tagging programs. *Marine and Freshwater Research* 71: 653-661.

Sturrock, A.M., Hunter, E., Milton, J.A., Eimf, E., Johnson, R.C., Waring, C.P., Trueman, C.N. (2015). Quantifying physiological influences on otolith microchemistry. *Methods in Ecology and Evolution* 6: 806-816.

Tanner, S.E., Reis-Santos, P., Cabral, H.N. (2016). Otolith chemistry in stock delineation: A brief overview, current challenges and future prospects. *Fisheries Research* 173: 206-213.

Tapp, N. (2003). Do size differences of juvenile snapper (*Pagrus auratus*) in two regions of Shark Bay, Western Australia, reflect different environmental conditions? MSc thesis. Edith Cowan University, Perth.

Wakefield, C.B. (2006). Latitudinal and temporal comparisons of the reproductive biology and growth of snapper, *Pargus auratus* (Sparidae), in Western Australia. PhD thesis. Murdoch University, Western Australia. 162 pp.

Wakefield C.B., Fairclough D.V., Lenanton R.C.J. and Potter I.C. (2011). Spawning and nursery habitat partitioning and movement patterns of *Pagrus auratus* (Sparidae) on the lower west coast of Australia. *Fisheries Research* 109: 243-251.

Wakefield, C.B., Potter, I.C., Hall, N.G., Lenanton, R.C.J. and Hesp, S.A. (2015). Marked variations in reproductive characteristics of snapper (*Chrysophrys auratus*, Sparidae) and their relationship with temperature over a wide latitudinal range. *ICES Journal of Marine Science* 72: 2341-2349.

Wakefield, C.B., Potter, I.C., Hall, N.G., Lenanton, R.C.J. and Hesp, S.A. (2017). Timing of growth zone formations in otoliths of the snapper, *Chrysophrys auratus*, in subtropical and temperate waters differ and growth follows a parabolic relationship with latitude. *ICES Journal of Marine Science* 74: 180-192.

Warner, J.C., Geyer, W.R., Lerczak, J.A. (2005). Numerical modeling of an estuary: A comprehensive skill assessment. *Journal of Geophysical Research: Oceans* 110(C5). https://doi.org/10.1029/2004JC002691

Wijeratne, S., Pattiaratchi, C., Proctor, R. (2018). Estimates of Surface and Subsurface Boundary Current Transport Around Australia. *Journal of Geophysical Research: Oceans* 123(5): 3444-3466. https://doi.org/doi:10.1029/2017JC013221

Wise, B.S., St John, J., Lenanton, R. (eds.) (2007). Spatial scales of exploitation among populations of demersal scalefish: Implications for management. Part 1: Stock status of the key indicator species for the demersal scalefish fishery in the West Coast Bioregion. FRDC Final Report on Project No. 2003/052. Fisheries Research Report No. 163. Department of Fisheries, Western Australia. 130 pp.

Wortmann, J., O'Neill, M.F., Sumpton, W., Stewart, J. (2018). Stock assessment of Australian east coast snapper, *Chrysophrys auratus*. Predictions of stock status and reference points for 2016. Queensland Department of Agriculture and Fisheries.

Yoshinaga, J., Nakama, A., Morita, M., Edmonds, J.S. (2000). Fish otolith reference material for quality assurance of chemical analyses. *Marine Chemistry* 69: 91-97.

Appendix 3 - Supplementary Information

Chapter 3

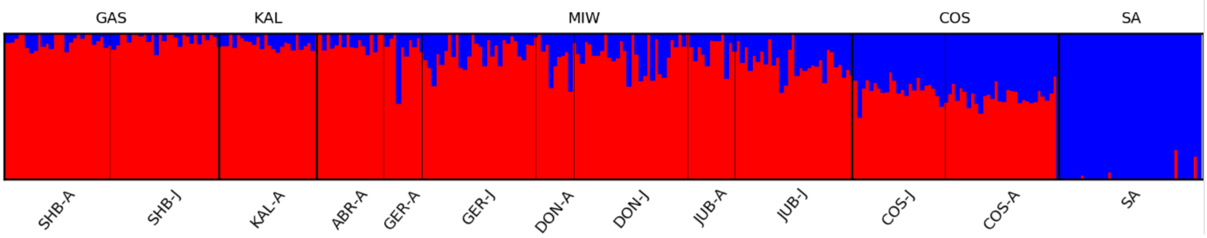


Figure S3.1. Admixture plot representing the population genomic structure of Australasian *C. auratus* from WA and South Australia (SA). Gascoyne (GAS), Mid-West (MIW), Shark Bay (SHB), Kalbarri (KAL), Abrolhos (ABR), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS), adults (-A) juveniles (-J).

Chapter 4

Table S4.1. Juvenile habitat use classification accuracy including fish collected in Gascoyne in both 2018 (2017 year class) and 2019 (2018 year class) to investigate the impact of potential temporal variation in otolith chemical signatures. Results show the cross validated correctly classified individuals (%) of juvenile *C. auratus* to their location of capture, including all locations within the Mid-West region, or pooling location within the Mid-West region (n=276). Gascoyne (GAS), Mid-West (MIW), Geraldton (GER), Dongara (DON), Jurien Bay (JUB), Cockburn Sound (COS). Note there are no otoliths from juveniles collected in Kalbarri.

Edge Analysis – Juveniles
Correctly classified individuals (%)

Region	Locality				
GAS (2018 & 2019)		76.2	78.1	-	-
GAS (2019)		-	-	72.6	73.5
GAS (2018)		-	-	62.5	64.3
MIW		-	85.7	-	85.7
	GER	67.9	-	66.1	-
	DON	73.3	-	67.5	-
	JUB	70	-	66.7	-
COS		93.3	95.6	84.4	86.7
Overall		76.1	84.4	70.7	79.4

Table S4.2. Overall adult habitat use classification accuracy per age cohorts (2012, 2014, 2016). Results show the overall cross validated correctly classified individuals (%) of adult *C. auratus* by age cohorts to their location of capture, including all locations within the Mid-West region, as well as by pooling locations within the Mid-West region. Locations are Gascoyne, Kalbarri, and Mid-West (with location therein Abrolhos, Geraldton, Dongara, Jurien Bay). Note there are no otoliths from adults collected in Cockburn Sound.

Edge Analysis – Adult
Overall Correctly classified individuals (%)

Cohort	All locations	MIW locations pooled
2012	62.7	58.7
2014	20.8	43.1
2016	36.5	61.5

Chapter 5

Historical environmental conditions

Wind

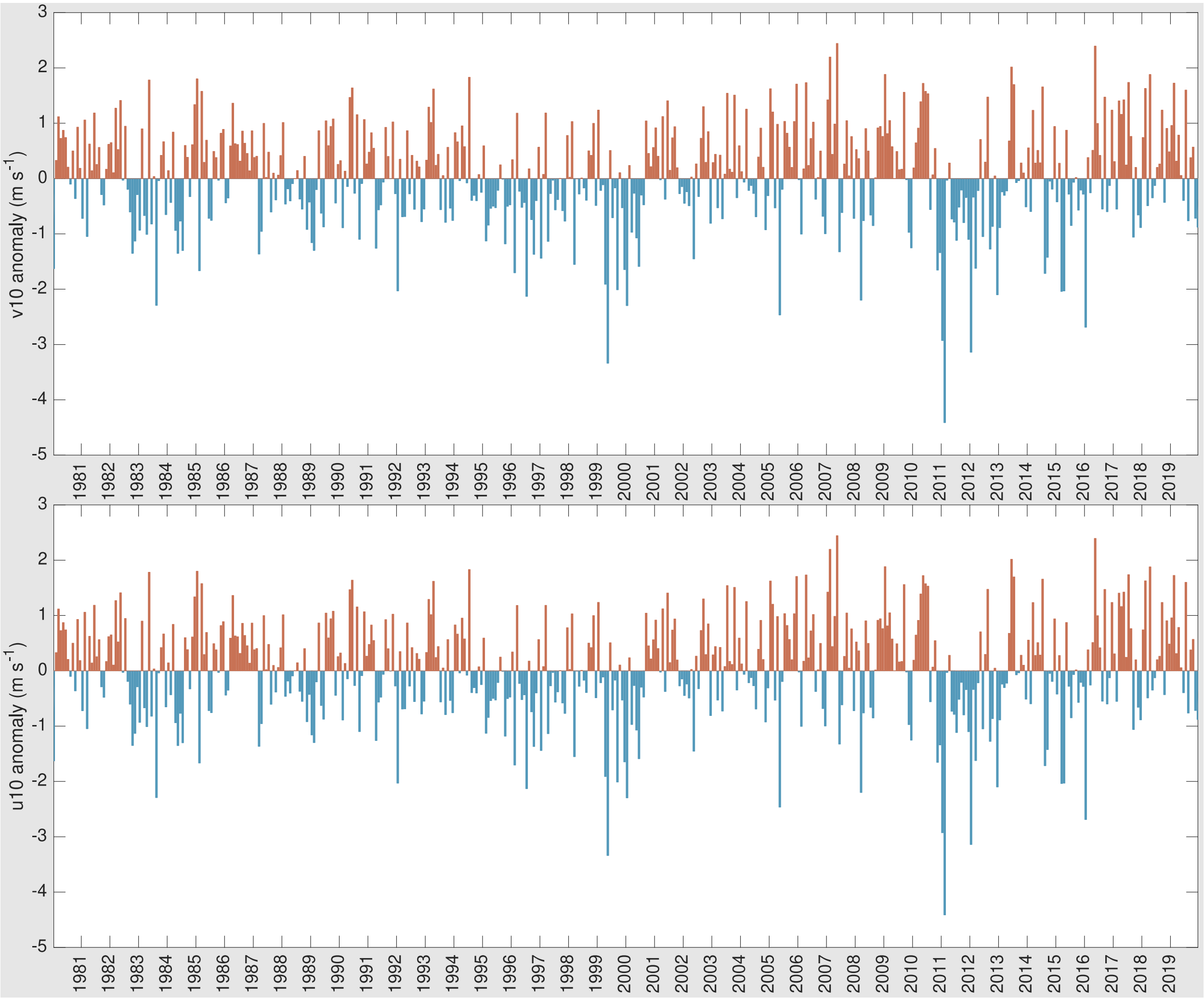


Figure S5.1. Monthly ERA5 wind anomalies (1980-2020) for North (v10) and East (u10) velocity components showing deviations from a 1992-2016 climatology.

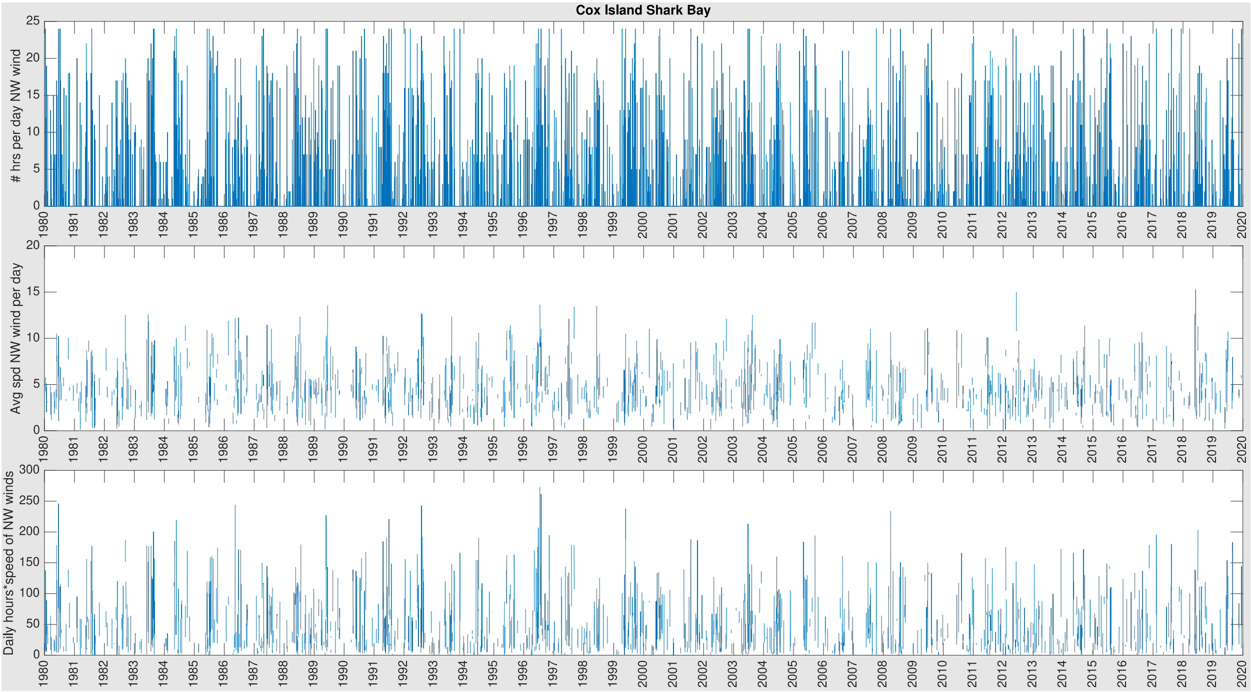


Figure S5.2. Hours of winds blowing from the northwest quadrant at Shark Bay for each month from 1990-2020 based on ERA5 wind data.

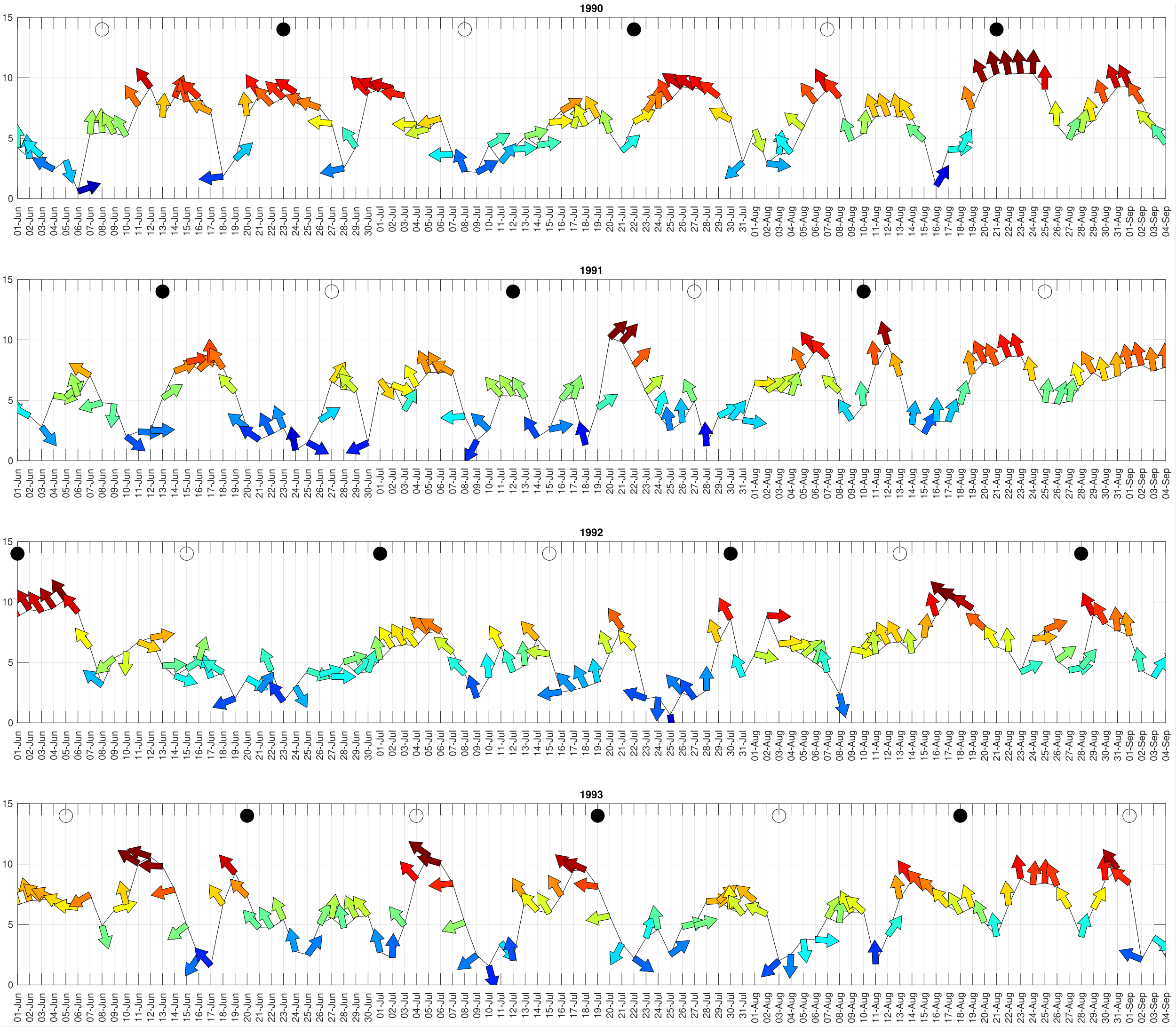


Figure S5.3. Daily winter mean wind speed and direction for 1990-1993 from ERA5 model at Shark Bay showing full and new moons.

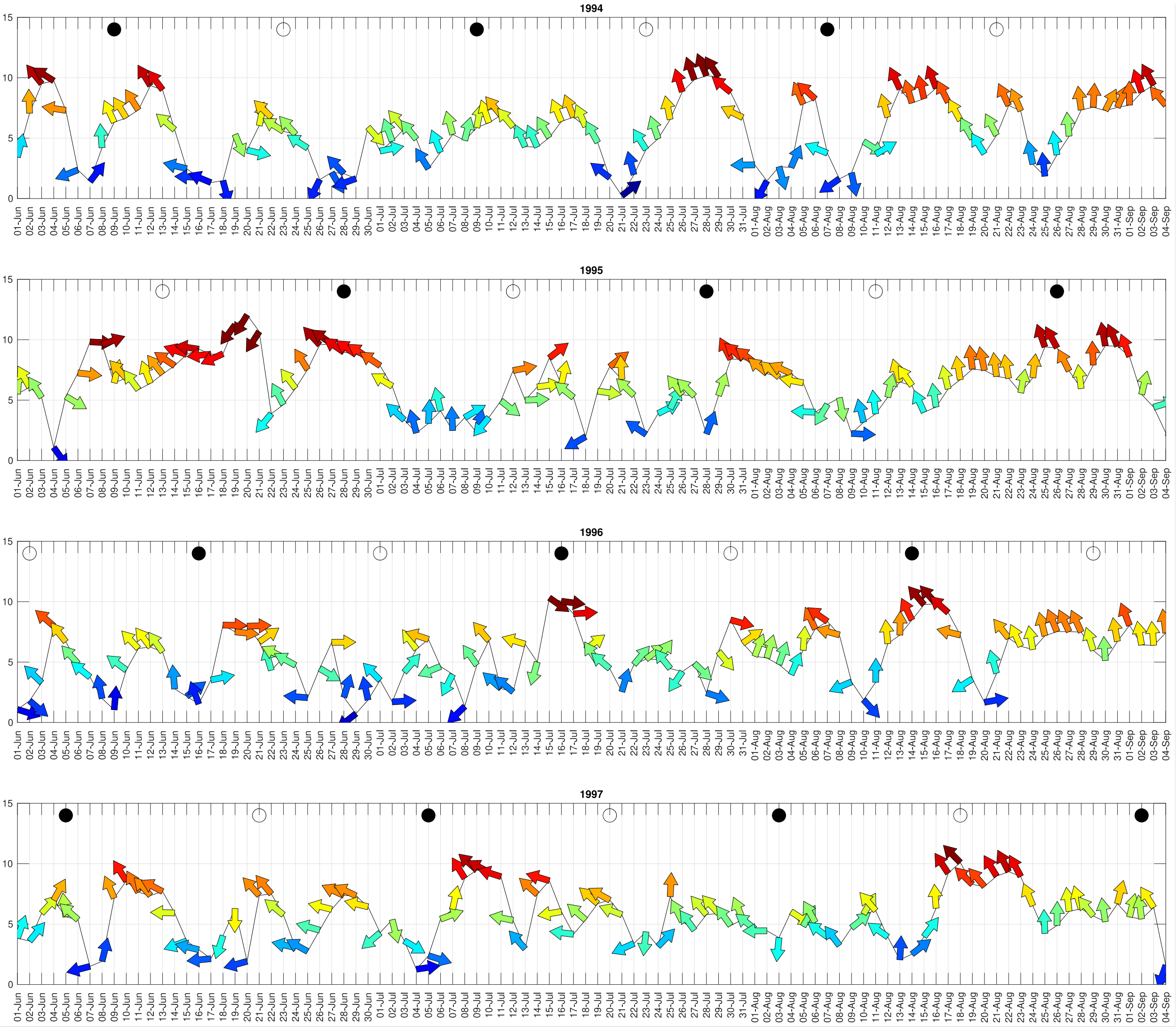


Figure S5.4. Daily winter mean wind speed and direction for 1994-1997 from ERA5 model at Shark Bay showing full and new moons.

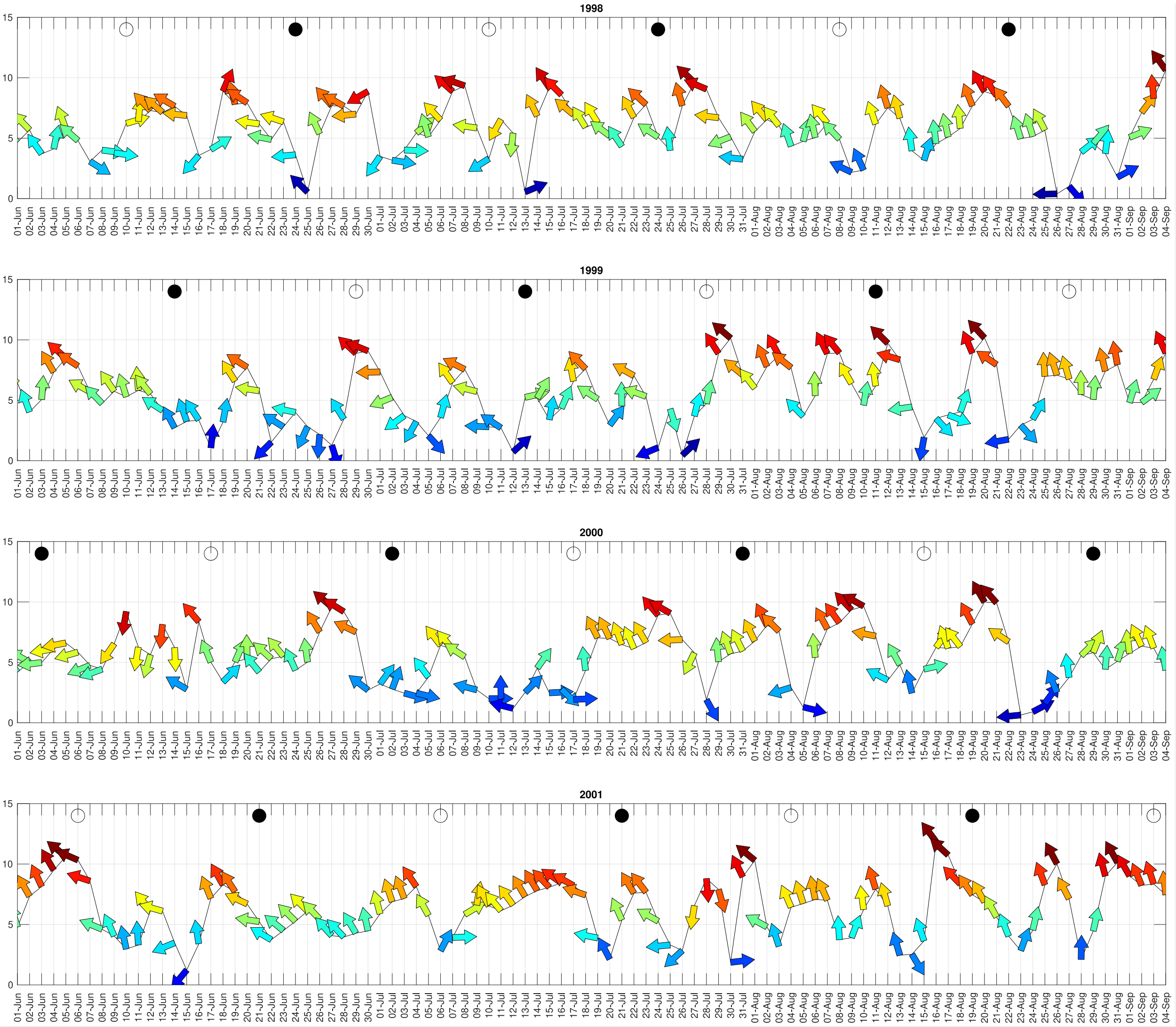


Figure S5.5. Daily winter mean wind speed and direction for 1998-2001 from ERA5 model at Shark Bay showing full and new moons.

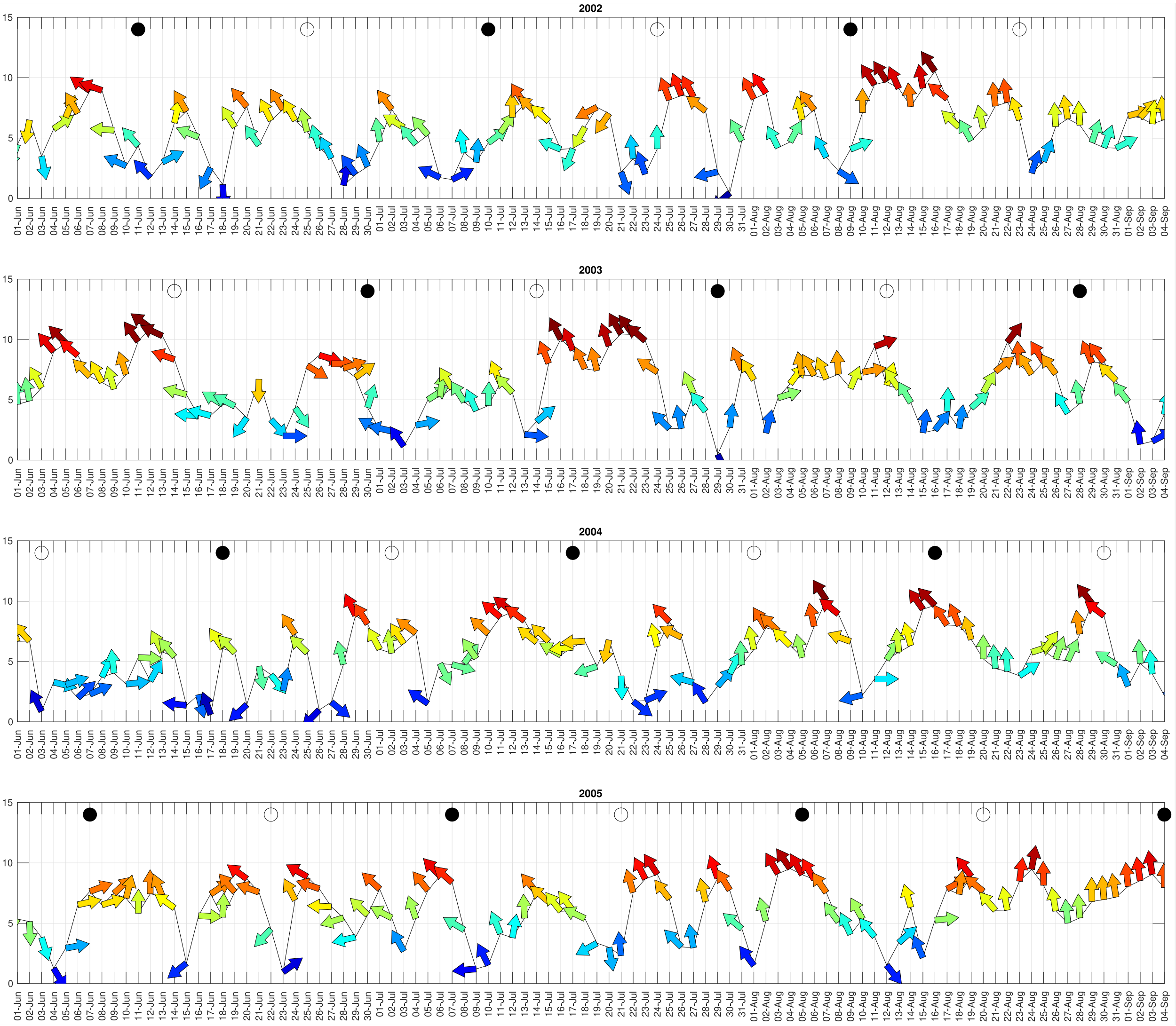


Figure S5.6. Daily winter mean wind speed and direction for 2002-2005 from ERA5 model at Shark Bay showing full and new moons.

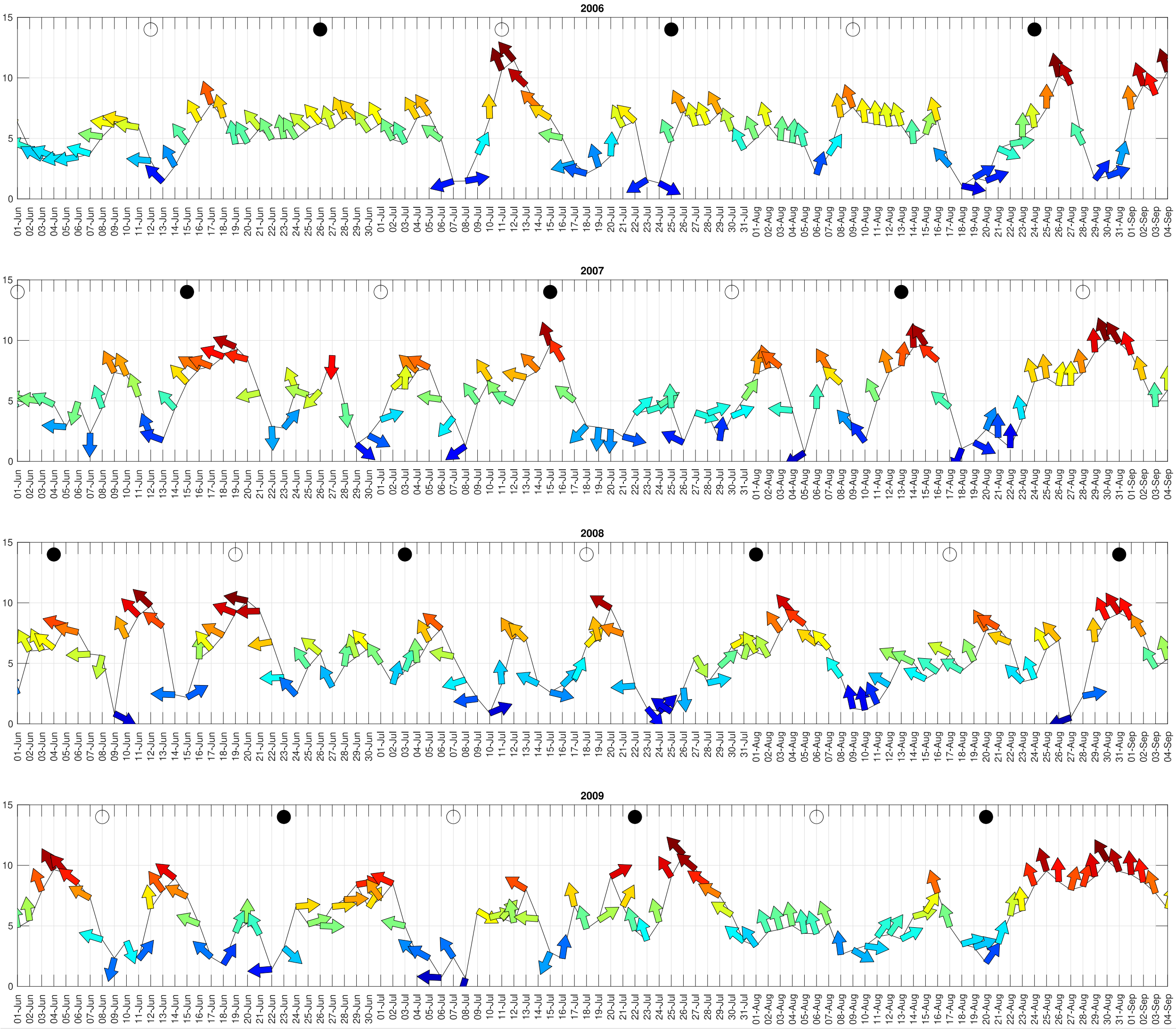


Figure S5.7. Daily winter mean wind speed and direction for 2006-2009 from ERA5 model at Shark Bay showing full and new moons.

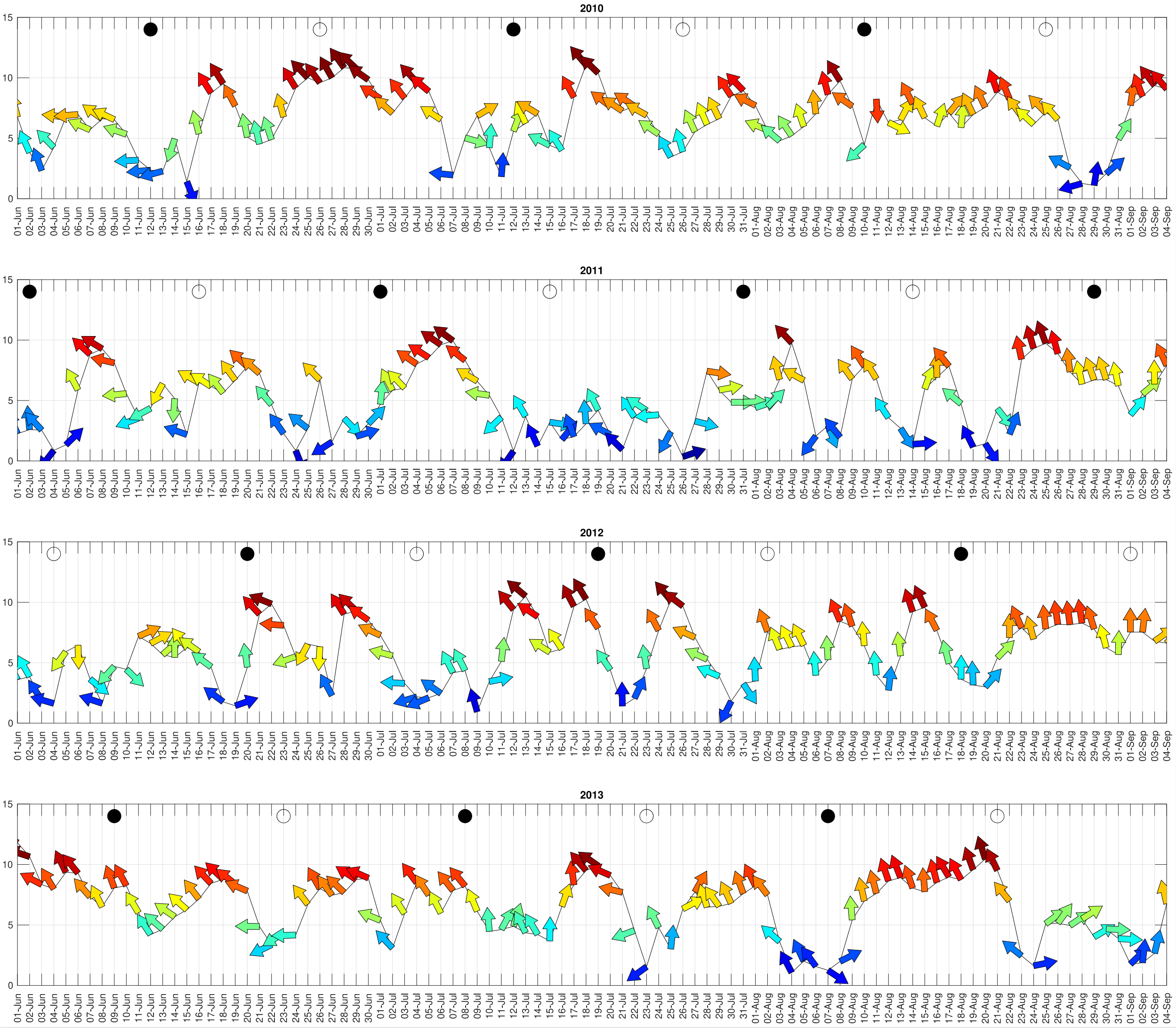


Figure S5.8. Daily winter mean wind speed and direction for 2010-2013 from ERA5 model at Shark Bay showing full and new moons.

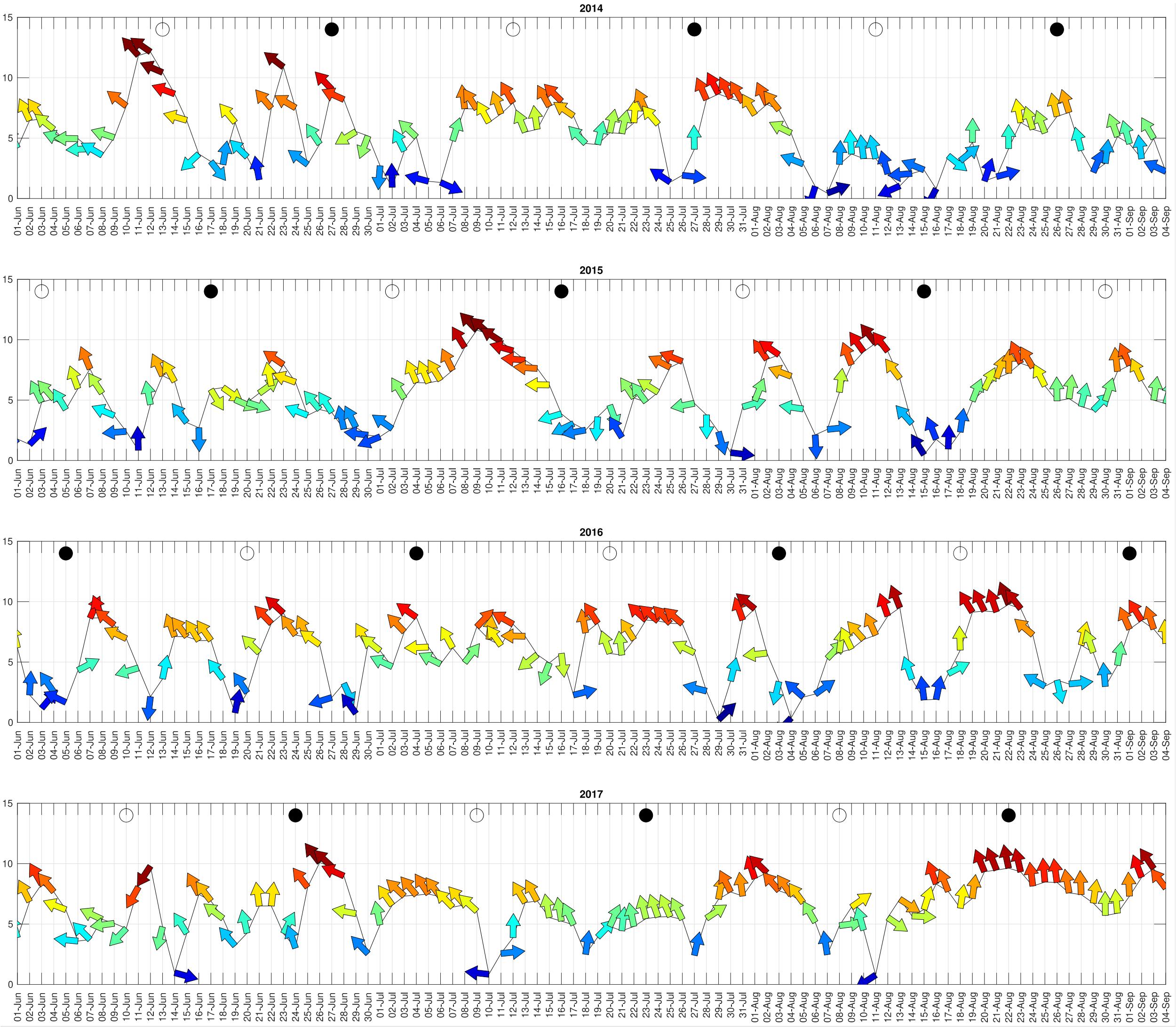


Figure S5.9. Daily winter mean wind speed and direction for 2014-2017 from ERA5 model at Shark Bay showing full and new moons.

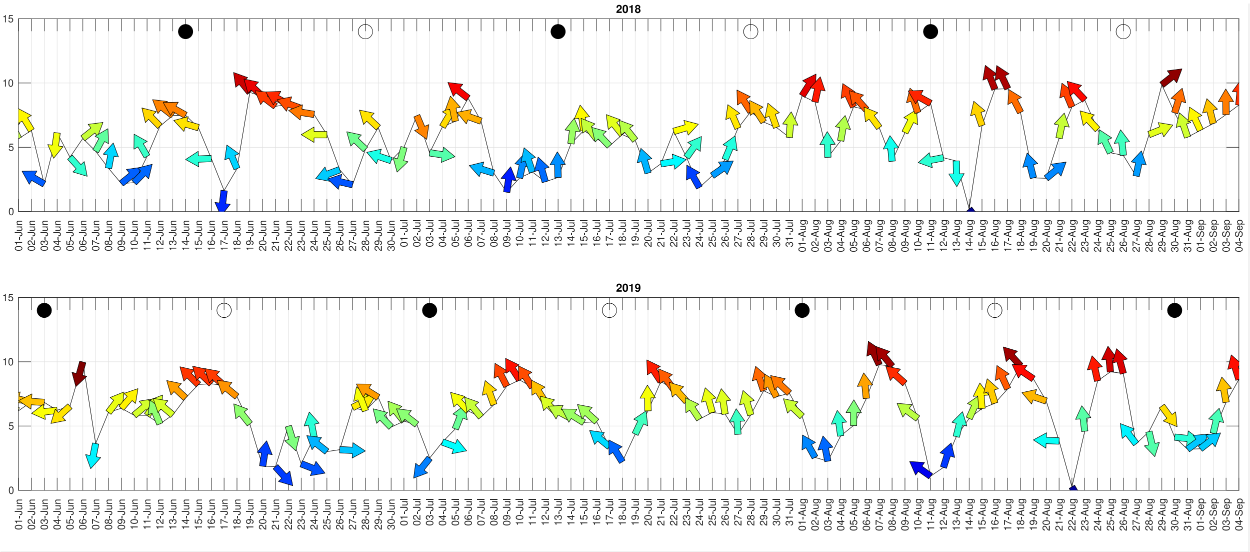


Figure S5.10. Daily winter mean wind speed and direction for 2018-2019 from ERA5 model at Shark Bay showing full and new moons.

Atmospheric pressure

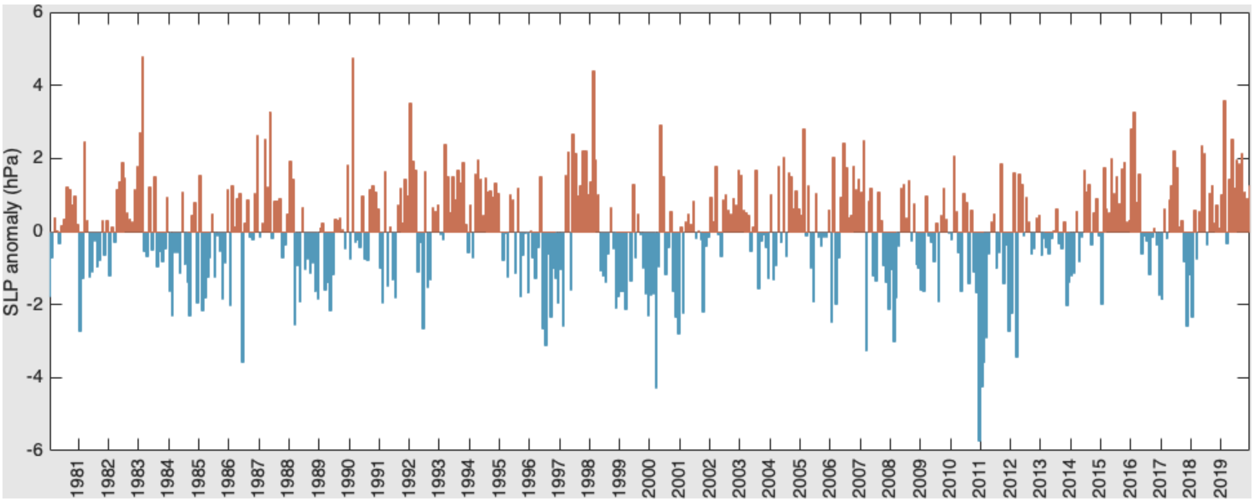


Figure S5.11. Monthly ERA5 mean sea level pressure anomalies (1980-2020) deviations from a 1992-2016 climatology.

Chapter 7

Table S7.1 Summary statistics for the GLM testing the effect of environmental variables (SST, Sea level height) on standardised 0+ mean catch rate, Denham Sound, Spring

	Estimate	Standard Error	z value	Pr(>|z|)	Signif.
(Intercept)	-1.551	0.705	-2.201	0.0372	*
Year.born2000	-0.550	0.834	-0.659	0.5156	
Year.born2001	-0.464	1.220	-0.381	0.7068	
Year.born2003	-1.445	0.996	-1.450	0.1594	
Year.born2004	-1.445	0.996	-1.450	0.1594	
Year.born2005	0.390	0.834	0.468	0.6436	
Year.born2017	-1.099	0.996	-1.103	0.2807	
Year.born2018	-0.268	0.834	-0.321	0.7505	
Year.born2019	0.320	0.772	0.414	0.6821	
Year.born2020	-1.445	1.220	-1.184	0.2474	

*Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05 < '.' < 0.1 < '' < 1*

(Dispersion parameter for gaussian family taken to be 0.9927344)

Null deviance: 39.32 on 34 degrees of freedom

Residual deviance: 24.82 on 25 degrees of freedom

Table S7.2 Summary statistics for the GLM testing the effect of environmental variables (SST, Sea level height) on standardised 0+ mean catch rate, Denham Sound, Summer

	Estimate	Standard Error	z value	Pr(>|z|)	Signif.
(Intercept)	-0.952	0.455	-2.092	0.0405	*
Year.born2003	0.135	0.663	0.203	0.8397	
Year.born2004	-0.513	0.644	-0.797	0.4285	
Year.born2005	-0.112	0.592	-0.189	0.8506	
Year.born2006	-0.613	0.720	-0.852	0.3972	
Year.born2017	-0.382	0.762	-0.502	0.6173	
Year.born2018	-1.191	0.627	-1.899	0.0623	.
Year.born2019	-1.524	0.627	-2.428	0.0181	*
Year.born2020	-1.350	1.439	-0.938	0.3517	

*Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05 < '.' < 0.1 < '' < 1*

(Dispersion parameter for gaussian family taken to be 1.864295)

Null deviance: 139 on 70 degrees of freedom

Residual deviance: 115.6 on 62 degrees of freedom

Table S7.3 Summary statistics for the GLM testing the effect of environmental variables (wind speed, SST, chlorophyl, seal level height and LC strength) on standardised 0+ mean catch rate, Outer Bay, Spring

	Estimate	Standard Error	z value	Pr(>|z|)	Signif.
(Intercept)	-2.996	0.597	-5.020	0.0001	***
Year.born2016	0.693	1.034	0.671	0.5120	
Year.born2017	0.738	0.706	1.045	0.3116	
Year.born2018	0.693	0.731	0.948	0.3570	
Year.born2019	0.524	0.660	0.795	0.4384	

*Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05 < '.' < 0.1 < " < 1*

(Dispersion parameter for gaussian family taken to be 0.7122018)

Null deviance: 12.28 on 20 degrees of freedom

Residual deviance: 11.4 on 16 degrees of freedom

Table S7.4 Summary statistics for the GLM testing the effect of environmental variables (wind speed, SST, chlorophyl, seal level height and LC strength) on standardised 0+ mean catch rate, Outer Bay, Summer

	Estimate	Standard Error	z value	Pr(>|z|)	Signif.
(Intercept)	-1.431	0.306	-4.671	0.0000	***
Year.born2004	-0.549	0.771	-0.712	0.4774	
Year.born2005	-1.564	0.628	-2.491	0.0139	*
Year.born2017	0.133	0.365	0.365	0.7156	
Year.born2018	-0.530	0.387	-1.369	0.1731	
Year.born2019	-0.172	0.392	-0.438	0.6621	
Year.born2020	-0.163	0.365	-0.445	0.6569	

*Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05 < '.' < 0.1 < " < 1*

(Dispersion parameter for gaussian family taken to be 1.502908)

Null deviance: 235.5 on 151 degrees of freedom

Residual deviance: 217.9 on 145 degrees of freedom