



Australian Government

Australian Fisheries Management Authority

UNIVERSITY of TASMANIA



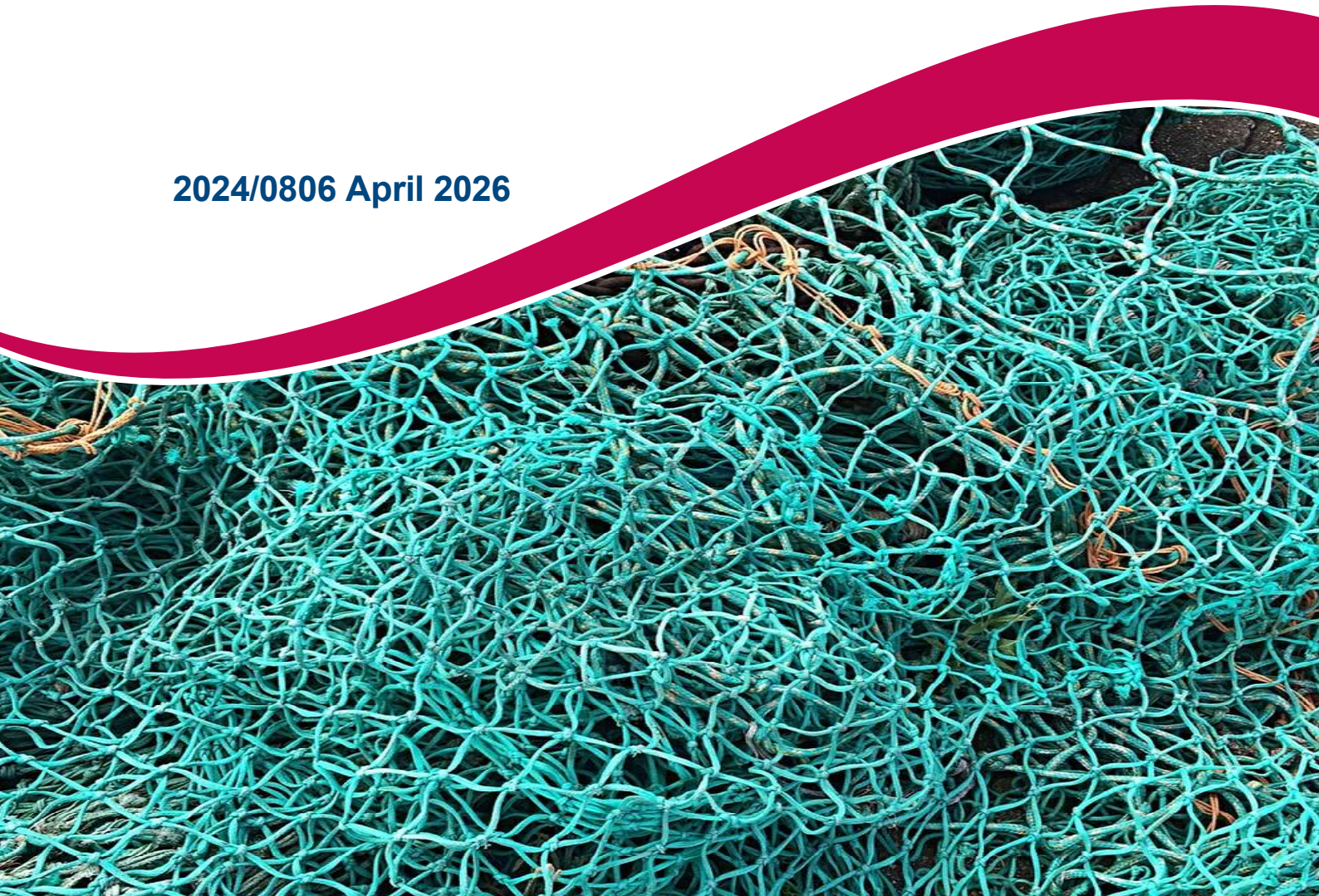
Institute for Marine and Antarctic Studies

Application of the DEPM to Blue Mackerel and Sardine off eastern Australia in 2024

Report to the Australian Fisheries Management Authority

**T.M. Ward, K. Charitonidou, T. Alderson, G. Carlos, A.
Coutts, M. Green, and A.J. Shute**

2024/0806 April 2026



About this document

Ward, T.M., Charitonidou, K., Alderson, T., Carlos, G, Coutts, A., Green, M., and Shute, A. 2026. Application of the DEPM to Blue Mackerel and Australian Sardine off eastern Australia in 2024. Report prepared for the Australian Fisheries Management Authority by the Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, 65 pp

Institute for Marine and Antarctic Studies,
University of Tasmania,
Private Bag 49,
Hobart TAS 7001

Enquiries should be directed to:

Dr. Tim Ward

Institute for Marine and Antarctic Studies

University of Tasmania

Private Bag 49, Hobart, Tasmania 7001, Australia

Email address: timothy.ward@utas.edu.au

Ph. (+61) 0401 126 388

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 circumstance. Opinions expressed by the authors are the individual opinions expressed by those persons and are not necessarily those of the Institute for Marine and Antarctic Studies (IMAS) or the University of Tasmania (UTAS).

© The Institute for Marine and Antarctic Studies, University of Tasmania 2026.

Copyright protects this publication. Except for purposes permitted by the Copyright Act, reproduction by whatever means is prohibited without the prior written permission of the Institute for Marine and Antarctic Studies

Contents

<i>About this document</i>	2
<i>Contents</i>	3
<i>Tables</i>	5
<i>Figures</i>	6
<i>Appendices</i>	8
<i>Acknowledgements</i>	9
<i>Executive Summary</i>	10
1. Introduction	14
1.1 Background	14
1.2 Daily Egg Production Method	15
1.3 Blue Mackerel	16
1.4 Sardine	17
1.5 Need	18
1.6 Objective	18
2. Methods	19
2.1 Total Daily Egg Production	19
2.2 Mean Daily Fecundity	21
2.4 Spawning biomass (<i>SB</i>)	23
2.5 Sensitivity analyses	23
3. Results	25
3.1 Blue Mackerel	25
3.2 Sardine	33
4 Discussion	40
4.1 Blue Mackerel	40
4.2 Sardine	46
4.3 Implications and Recommendations	49
<i>References</i>	50
<i>Appendices</i>	56

Version	Updates	Approver
Draft Final Report	March 2026	Kerrie Bennetts
Final Report	March 2026	Sean Tracey

Tables

Table 1–1. The SPF Harvest Strategy Framework showing maximum exploitation rates (Max ER) and maximum number of fishing seasons (1 May to 30 April) between applications of the DEPM (Max Seasons) for each species at each tier. An Annual Fishery Assessment is required at Tier 1 and Tier 2. A review of available catch and effort data is undertaken at Tier 3. Source: AFMA (2025a). 15

Table 3–1. Estimates of mean spawning fraction (S) at each location in the Eastern Sub-area of the SPF where adult Blue Mackerel were collected 2022, 2023 and 2024. All estimates of S were weighted by sample size (i.e. each individual fish contributed equally to the estimate). 30

Table 3–2. Estimates of adult parameters for the Southern Stock of Australian Sardine obtained from Grammer et al. (2024) that were used to calculate spawning biomass in the present study. 38

Figures

Figure 1–1. The three sub-areas of the Small Pelagic Fishery. Source: AFMA (2025a)	14
Figure 1–2. Years in which DEPM surveys of Blue Mackerel East have been conducted and total annual trawl catch by species in the SPF between 2000/01 and 2024/25. RBT = Redbait, JMK = Jack Mackerel, BMK = Blue Mackerel)	16
Figure 2–1. Map showing sites between southern Queensland and southern New South Wales where plankton samples were collected during 5 to 23 September 2024. At sites marked in black one sample was taken and preserved in formalin. At sites marked in red two samples were collected: one was preserved in formalin and the other in ethanol.....	24
Figure 3–1–1. Map showing egg densities of Blue Mackerel and sea surface temperatures (SST) recorded using the Conductivity Temperature Depth (CTD) profiler during the ichthyoplankton survey conducted during 5–23 September 2024. Red crosses indicate the adult sampling locations.....	27
Figure 3–1–2. Models fitted to egg densities (eggs.m ⁻²) and egg age (hours) of Blue Mackerel egg cohorts from surveys conducted in 2014, 2019 and 2024. Log-linear model (bias corrected), GLM NB with negative binomial error structure and McGarvey-Kinloch (2001) method with assumed values of instantaneous egg mortality (0.2, 0.3, 0.4 and 0.5).	28
Figure 3–1–3. Map showing polygons generated using the Voronoi natural neighbour method and polygons where live Blue Mackerel eggs were present (black) in September 2024.	29
Figure 3–1–4 A) Batch fecundity versus gonad free female weight and B) Relative Fecundity versus total female weight of Blue Mackerel collected off southern Australia in 2002–06. Red circles and lines are for females with hydrated oocytes. Grey circles and lines are estimates for females without hydrated oocytes. Shading around regression slopes are 95% CIs. Source: Ward et al. (2021a).	31
Figure 3–1–5 Sensitivity analysis showing the effects of variation mean daily egg production (P_0), sex ratio (R), relative fecundity (F') and spawning fraction (S) on estimates of spawning biomass (SB) of Blue Mackerel in 2024. Red arrows are values used to estimate SB for 2024. For P_0 , black arrow is the log-linear model and the blue arrow is GLM NB. For S and F' black and blue arrows are the lower and upper 95% CIs. For R black and blue arrows are the mean values obtained by Ward et al. (2009) and Ward et al. (2021a), respectively.	32
Figure 3–2–1. Map showing egg densities Sardine and Sea Surface Temperatures (SSTs) recorded using the Conductivity Temperature Depth (CTD) profiler during the plankton survey conducted during 5–23 September 2024.	35
Figure 3–2–2. Models fitted to egg densities (eggs.m ⁻²) and egg age (hours) of Sardine cohorts from surveys conducted in 2014, 2019 and 2024. Log-linear model (bias corrected), GLM NB1 with negative binomial error structure and McGarvey-Kinloch (2001) method with assumed values of instantaneous egg mortality (0.2, 0.3, 0.4 and 0.5). Three outliers with egg densities	

greater than 1,800 eggs.m⁻² (one collected in 2019 and two collected in 2024) were excluded from the analysis. 36

Figure 3–2–3. Map showing polygons generated using the Voronoi natural neighbour method where live Sardine eggs were present (black) in September 2024. 37

Figure 3–2–4. Sensitivity analysis showing the effects of variation mean daily egg production (P_0), sex ratio (R), relative fecundity (F') and spawning fraction (S) on estimates of spawning biomass of Sardine in 2024. 39

Appendices

Appendix 1. Equations used in the application of the Daily Egg Production Method to estimate the spawning biomass of Blue Mackerel in this study. Adapted from Ward et al. (2021a, b).	57
Appendix 2. Genetic identification of Blue Mackerel eggs	60
Appendix 3. Map showing egg densities of Blue Mackerel and sea surface temperatures recorded using the Conductivity Temperature Depth profiler during the plankton survey conducted during 19 August to 14 September 2014 (Ward et al. 2015) and 4–24 September 2019 (Ward et al. 2021a).	64
Appendix 4. Map showing egg densities of Sardine and sea surface temperatures recorded using the Conductivity Temperature Depth profiler during the plankton survey conducted during 19 August to 14 September 2014 (Ward et al. 2015) and 4–24 September 2019 (Ward et al. 2021a).	65
Appendix 5. Slide presented to the Resource Assessment Group for the Small Pelagic Fishery in December 2025 showing the higher catch-per-unit-effort (CPUE) recorded in trawls conducted off south-eastern Australia in 2023–25 compared to 1993–1996. Source: CSIRO. https://research.csiro.au/sea-mes/species/ and https://research.csiro.au/sea-mes/findings/	66

Acknowledgements

This project was funded by the Australian Fisheries Management Authority (AFMA). The authors gratefully acknowledge the owners, master and crew of the *FV Rubicon* for their professional assistance during the plankton survey. We are grateful to Mr Greg Eden, Mr John Joblin and Mr Tim Hurst, for their assistance collecting samples of adult Blue Mackerel in 2024. We thank Mr Alex Ivey (South Australian Research and Development Institute, SARDI) for providing expert guidance regarding the identification and staging of Blue Mackerel eggs. The Institute for Marine and Antarctic Studies (IMAS) at the University of Tasmania (UTAS) provided a significant in-kind contribution to this project. The report was approved for publication by Professor Sean Tracey (IMAS).

Executive Summary

Background and Need

Estimates of spawning biomass obtained using the Daily Egg Production Method (DEPM) are the primary biological performance indicator for target species in the Small Pelagic Fishery (SPF). Estimates of spawning biomass are used to set Recommended Biological Catches (RBCs) and Total Allowable Catches (TACs) under guidelines outlined in the SPF Harvest Strategy (AFMA 2025a). The Harvest Strategy has three tiers which reflect the number of fishing seasons that have elapsed since the last DEPM survey was conducted.

The DEPM was applied to Blue Mackerel (*Scomber australasicus*) and Australian Sardine (Sardine, *Sardinops sagax*) in the eastern sub-area of the SPF in 2014 and 2019 (Ward et al. 2015, 2021a). Both surveys suggested that the spawning biomass of Blue Mackerel was around 80,000 t. The estimates of the spawning biomass of Sardine obtained from the surveys declined from around 49,600 t in 2014 to around 42,500 in 2019.

The catch of Blue Mackerel in the SPF in 2023/24 was over 11,000 t. The RBC for Blue Mackerel in 2025/26 was set at 16,000 t and the TAC was 15,510 t (AFMA 2025b). Blue Mackerel in Eastern sub-area would have reverted to Tier 2 in 2026/27, reducing the exploitation rate from 20% to 10% and halving the RBC, unless a DEPM survey was undertaken in 2024. The annual catch of Sardine in the SPF has not exceeded 400 t or 5% of the TAC over the last decade.

Objective

To estimate the spawning biomass of Blue Mackerel in the Eastern sub-area and Sardine in the Sardine sub-area in 2024.

Methods

The premise of the DEPM is that the spawning biomass of fish that spawn pelagic eggs can be estimated by dividing the mean number of eggs produced per day throughout the spawning area (i.e., total daily egg production) by the mean number of eggs produced per unit mass of adult fish (i.e., mean daily fecundity).

The equation underpinning the DEPM is:

$$SB = \frac{P_0 A}{R S F'}$$

where SB is spawning biomass, P_0 is mean daily egg production, A is spawning area, R is mean sex ratio, F' is mean relative fecundity and S is mean spawning fraction.

To estimate total daily egg production, ichthyoplankton samples were collected at 262 sites covering 66,790 km² in shelf waters between southern Queensland and central New South Wales from 5 to 23 September 2024. Blue Mackerel and Sardine eggs were identified using standard laboratory procedures. Morphological identifications of Blue Mackerel eggs were confirmed using molecular techniques described in Ward *et al.* (2021a). P_0 was estimated using the loglinear version of the exponential mortality model and a Generalised Linear Model with a negative binomial error structure (GLM NB) where variance increased linearly with the mean. P_0 was also estimated by applying assumed rates of egg mortality (z) to estimates of mean egg density using the method of McGarvey and Kinloch (2001). A was estimated using the Voronoi nearest neighbour method.

To estimate mean daily fecundity, adult sampling of Blue Mackerel was undertaken in 2022–24 at sites located off the New South Wales coast (Tweed Heads, Ballina, Coffs Harbour, Port Macquarie, Port Stephens, Woolongong). Adult sampling of Sardine was not undertaken for this study. Results from adult sampling of Sardine undertaken off South Australia from 1998 to 2024 are used in this report. Adult reproductive parameters of both species, i.e. S , R and F' were estimated using methods described by Ward *et al.* (2021b).

Following the approach developed for Sardine by Ward *et al.* (2021b), estimates of SB for both species were calculated by applying estimates of P_0 , R , S and F' collected over multiple years to the estimates of A obtained from the survey.

Results and Discussion

Blue Mackerel

Live Blue Mackerel eggs ($n = 1,242$) were collected at 122 of the 262 sites (46.6%). Spawning area was estimated to be 31,195 km², which is the highest recorded for the

stock. Mean daily egg production (P_0) was estimated to be 12.9 and 33.4 eggs.day⁻¹.m⁻² using the log-linear model and GLM NB, respectively. The estimate of P_0 obtained using the method of McGarvey and Kinloch (2001) method and a mortality rate (z) of 0.4 was 23.4 eggs.day⁻¹.m⁻². Sex ratio was set at 0.5. Spawning fraction was estimated to be 0.13 from 1,450 mature females collected off eastern Australia in 2022–24. Relative fecundity was estimated to be 140 eggs.g⁻¹ from 57 females with hydrated oocytes collected off South Australia in 2002–06. Based on the estimate of P_0 obtained using the McGarvey and Kinloch (2001) method, the SB of Blue Mackerel in the East sub-area of the SPF in 2024 was estimated to be around 80,000 t. Sensitivity analysis demonstrated the strong influence that uncertainty in the estimate of P_0 had on the estimate of SB .

The DEPM surveys conducted in 2014, 2019 and 2024 each suggested that the SB of Blue Mackerel off eastern Australia was around 80,000 t. However, the expansion in the spawning area from 17,911 km² in 2014 to 31,195 km² in 2024 suggests that the SB may have increased. The similarity of the estimates of SB despite the increase in spawning area reflects the lower estimate of P_0 for 2024 compared to 2019 and 2014. These results highlight the importance of resolving current uncertainties associated with estimating P_0 .

A seven-fold increase in catch rates in trawls conducted in 2023-25 compared to 1993–96 suggests that the abundance of Blue Mackerel off south-eastern Australia may have increased over the last 30 years. There is also evidence to suggest that a large adult biomass occurs off southern NSW, Victoria and eastern Tasmania (where spawning has not been recorded) that is not accounted for in the DEPM surveys. Therefore, estimates of SB obtained in the DEPM surveys are likely to be conservative. There is no evidence to suggest that the SB of Blue Mackerel in the Eastern sub-area of the SPF has declined in response to the large increase in catches over the last decade (e.g. ~12,800 t in 2024/25).

Sardine

Live Sardine eggs ($n = 6,288$) were collected at 64 of the 262 sites (24.5%). Spawning area was 16,215 km². Estimates of P_0 obtained using all three models were similar. Using the log-linear model P_0 was estimated to be 52.1 eggs.day⁻¹.m⁻². Estimates of adult parameters for Sardine were obtained from over 200 samples collected off South Australia

between 1998 and 2024. Relative fecundity was 308 eggs.g⁻¹, spawning fraction was 0.11 and sex ratio was 0.53, The *SB* of Sardine in 2024 was estimated to be around 46,500 t.

The estimate of *SB* for 2024 is similar to the estimates of 49,575 t and 42,724 t obtained in 2014 and 2019, respectively. However, the contraction in spawning area from 22,400 km² in 2014 to 16,215 km² in 2024 suggests that the *SB* of Sardine may have declined. As recent catches have been low (<400 t over the last decade) the potential reduction in *SB* is unlikely to have been caused by fishing pressure. As the reduction in spawning area has coincided with a shift in the main spawning grounds from southern Queensland and northern NSW to central and southern NSW, this reduction could potentially have been driven by climate-related increases in water temperatures and/or phenological changes such as the spawning season occurring earlier in north in 2024 than in 2014. However, it should also be recognised that these differences could reflect natural year to year variability in egg distributions and/or *SB* driven by other factors.

Implications and Recommendations

It is critically important that the next ichthyoplankton survey is extended further south to ensure it covers the entire spawning area of Blue Mackerel off eastern Australia. The number of ichthyoplankton samples taken should also be increased to address uncertainty in the estimate of P_0 . This objective will be partly achieved by extending the survey further south. However, consideration should also be given to reducing the distance between transects and/or sites. Both these changes would increase the cost of future surveys.

Thorough re-analyses of the entire datasets collected in historical DEPM surveys for Blue Mackerel and Sardine off eastern Australia should be conducted before the next survey is undertaken (likely 2029). The primary objectives of this research should be to optimise the statistical methods used to estimate key parameters (including uncertainty) and provide recommendations about how to improve the reliability of future estimates of *SB*. IMAS is currently preparing manuscripts for scientific journals that address these objectives.

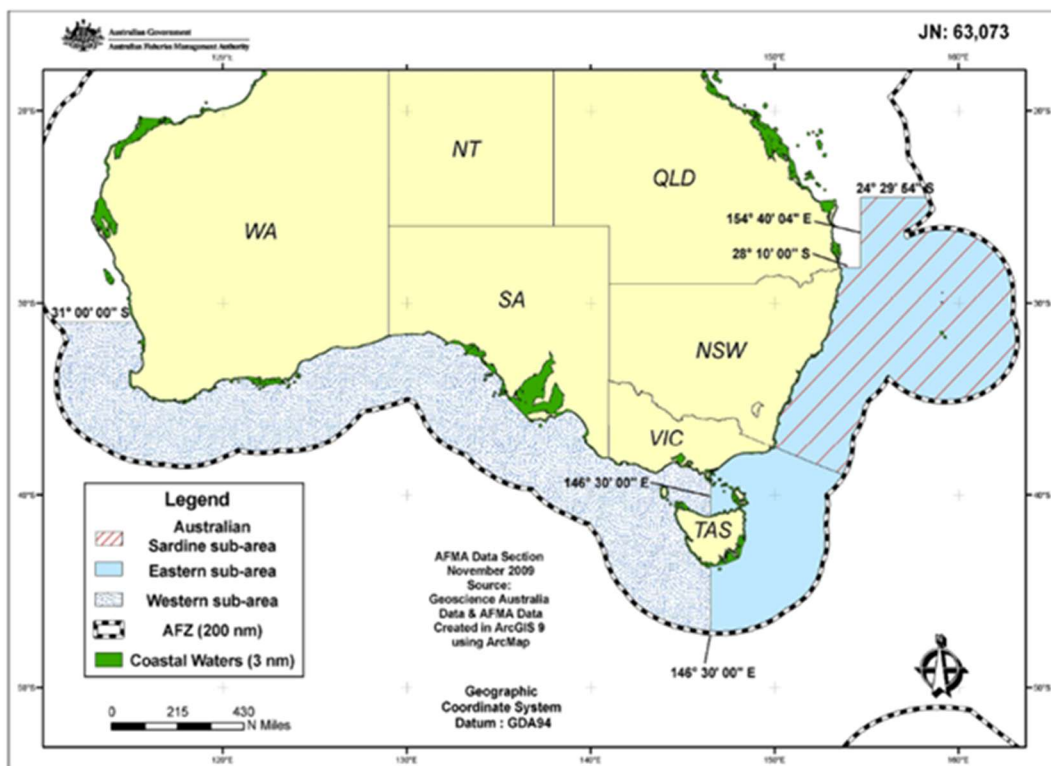
Keywords: Small Pelagic Fishery, Daily Egg Production Method, Spawning Biomass, Jack Mackerel, *Trachurus declivis*, Eastern sub-area

1. Introduction

1.1 Background

The Commonwealth Small Pelagic Fishery (SPF) is divided into the Eastern, Western and Sardine sub-areas (AFMA 2025a, Figure 1–1). The target species are Jack Mackerel (*Trachurus declivis*), Blue Mackerel (*Scomber australasicus*) and Redbait (*Emmelichthys nitidus*) in the Eastern and Western sub-areas and Australian Sardine (*Sardinops sagax*) in the Sardine sub-area (AFMA 2025a).

Figure 1–1. The three sub-areas of the Small Pelagic Fishery. Source: AFMA (2025a)



Estimates of spawning biomass obtained using the Daily Egg Production Method (DEPM) are the primary biological performance indicator for target species. Estimates of spawning biomass are used to set Recommended Biological Catches (RBCs) and Total Allowable Catches (TACs) under guidelines outlined in the SPF Harvest Strategy (AFMA 2025a). The SPF Harvest Strategy has three tiers (Table 1–1). The species-specific exploitation rates at each tier reflect the number of fishing seasons that have elapsed since the last DEPM survey was conducted (Table 1–1).

Table 1–1. The SPF Harvest Strategy Framework showing maximum exploitation rates (Max ER) and maximum number of fishing seasons (1 May to 30 April) between applications of the DEPM (Max Seasons) for each species at each tier. An Annual Fishery Assessment is required at Tier 1 and Tier 2. A review of available catch and effort data is undertaken at Tier 3. Source: AFMA (2025a).

Species Sub-area(s)	Tier 1		Tier 2		Tier 3	
	Max ER	Max Seasons	Max ER	Max Seasons	Max ER	Max Seasons
Sardine Sardine	20%	5 seasons	10%	5 seasons	5%	Indefinite
Blue Mackerel Eastern Western	20% 20%	5 seasons 5 seasons	10% 10%	5 seasons 5 seasons	5% 5%	Indefinite Indefinite
Jack Mackerels Eastern Western	14% 14%	5 seasons 5 seasons	7% 7%	10 seasons 10 seasons	3.5% 3.5%	Indefinite Indefinite
Redbait Eastern Western	12% 12%	5 seasons 5 seasons	6% 6%	10 seasons 10 seasons	3% 3%	Indefinite Indefinite

The total catch in the SPF in 2024/25 was over 28,000 t (Figure 1–2). Over 99% was taken by mid-water trawlers operating in the Eastern sub-area (Ward et al. 2025). The catch of Blue Mackerel in 2024/25 was approximately 12,800 t (Figure 1–2). The annual catch of Sardine in the SPF has not exceeded 400 t or 5% of the TAC over the last decade.

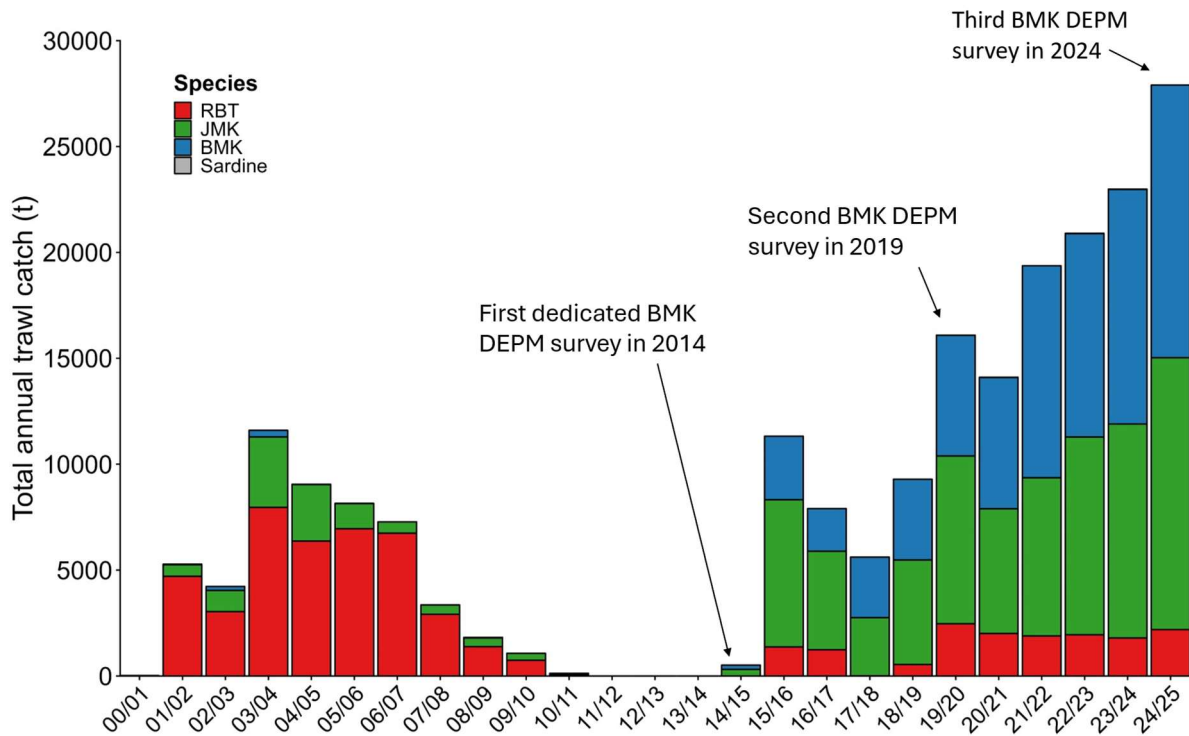
1.2 Daily Egg Production Method

The concept underpinning the DEPM (Appendix 1, Equation 1) is that the spawning biomass of fish that spawn pelagic eggs can be estimated by dividing the mean number of eggs produced per day throughout the spawning area (total daily egg production) by the mean number of eggs produced per unit mass of adult fish (mean daily fecundity; Parker, 1980; Ward et al. 2021). The equations that underpin the DEPM are listed in Appendix 1.

Total daily egg production is calculated from estimates of mean daily egg production (P_0) and spawning area (A) obtained from ichthyoplankton surveys (Appendix 1, Equation 1). Mean daily fecundity is estimated from three adult reproductive parameters: sex ratio by weight (R), spawning fraction (S) and relative fecundity (F' , Appendix 1, Equation 1). The

methods used in this study largely follow the approaches described for Blue Mackerel by Ward et al. (2021a) and for Sardine by Ward et al. (2021b).

Figure 1–2. Years in which DEPM surveys of Blue Mackerel East have been conducted and total annual trawl catch by species in the SPF between 2000/01 and 2024/25. RBT = Redbait, JMK = Jack Mackerel, BMK = Blue Mackerel)



1.3 Blue Mackerel

Blue Mackerel (*Scomber australasicus*, Cuvier 1832; Scombridae) is the only member of its genus that occurs in Australian waters (Gomon et al. 2008). It inhabits coastal and continental shelf waters (mainly in depths up to 200 m) throughout the Pacific Ocean and Indian Ocean. It is likely that there are separate stocks of Blue Mackerel off eastern and south-western Australia (e.g. Bulman et al. 2008; Schmarr et al. 2012), which aligns with the division of the SPF into Eastern and Western sub-areas.

The spawning season of Blue Mackerel off eastern Australia occurs from July to October (Neira and Keane 2008, Rogers et al. 2009). The main spawning areas are shelf waters off southern Queensland and northern and central New South Wales (Ward et al. 2009, 2015, 2021a). Until recently, the reproductive biology, especially the spawning fraction, of Blue

Mackerel off eastern Australia was poorly understood (e.g. Ward et al. 2009, 2015, 2021a, 2025a). However, sampling undertaken in 2022 and 2023 (Ward et al. 2025a) demonstrated that the spawning fraction of Blue Mackerel in key spawning areas such as Port Stephens were similar to estimate of 0.14 that Ward et al. (2009) obtained for southern Australia.

Blue Mackerel is a serial spawner with buoyant, pelagic eggs that make it suitable for the DEPM (e.g. Lasker 1985, Rogers et al. 2009, Ward et al. 2009). A preliminary application of the DEPM in the Eastern sub-area in 2004 suggested that the spawning biomass was at least 30,000 t (Ward et al. 2009). Estimates of spawning biomass obtained in 2014 and 2019 were ~83,300 t (95% CI = 35,100–165,000 t) and 88,265 t (95% CI = 33,320–143,209 t), respectively (Ward et al. 2015, 2021a). The authors of both studies indicated that the results should be interpreted with caution because of uncertainties in estimates of key adult reproductive parameters, especially spawning fraction. The recent acquisition of estimates of spawning fraction in the Eastern sub-area will reduce the uncertainties in future estimates of spawning biomass of Blue Mackerel (Ward et al. 2025a).

1.4 Sardine

Sardine (*Sardinops sagax*, Jenyns 1842, Clupeidae) is found in temperate marine waters from southern Queensland to Western Australia, including northern and eastern Tasmania (Gomon et al. 2008; Ward et al. 2025). Sardine is a metapopulation that is comprised of four separate stocks: Western, Southern, South-eastern and Eastern (Izzo et al. 2017; Sexton et al. 2019). The Eastern stock largely coincides with the Sardine Sub-area of the SPF. However, the northern distribution of the South-eastern stock also extends into waters off southern NSW which are part of the Sardine sub-area.

The peak spawning season of the Eastern Stock extends from July to November (Staunton-Smith and Ward 2000; Ward and Staunton-Smith 2002). The main spawning area is off southern Queensland and northern and central New South Wales (Ward et al. 2015, 2021a). The key adult DEPM parameters of Sardine off eastern Australia, especially spawning fraction and relative fecundity, are likely to be consistent with those that have been reported for this species in Australia and globally (Ward et al. 2025a). The DEPM

was first applied to Sardine in the Eastern sub-area of the SPF in the late 1990s (Staunton-Smith and Ward 2000). The spawning biomass in the Sardine sub-area of the SPF during 2014 and 2019 were estimated to be 49,575 t (95% CI = 24,200–213,300 t) (Ward et al. 2015) and 42,724 t (95% CI = 15,487–69,962 t) (Ward et al. 2021a), respectively.

1.5 Need

Applications of the DEPM to Blue Mackerel in the eastern sub-area of the SPF in 2014 and 2019 suggested that the spawning biomass was around 80,000 t (Ward et al. 2021a). This information underpinned the increase in the catch of Blue Mackerel from less than 300 t in 2014/15 to around 12,000 t in 2024/25 (Figure 1.2, Ward et al. 2025b). The RBC for Blue Mackerel in 2025/26 is 16,000 t and the TAC is 15,510 t (AFMA 2025b). Blue Mackerel in the Eastern sub-area would have reverted to Tier 2 in 2026/27, reducing the exploitation rate from 20% to 10% (Table 1.1) and halving the RBC, unless a DEPM survey was undertaken in 2024.

Sardine catches in the SPF have been less than 400 t over the last five fishing seasons (Ward et al. 2025b; AFMA 2025b). The four-year weighted average catch of NSW vessels operating in the Sardine sub-area was 447 t (AFMA 2025b). The RBC for Sardine in 2025/26 is 8,545 t and the TAC is 8,100 t (AFMA 2025b). Sardine would have reverted to Tier 2 in 2026/27 which would have reduced the exploitation rate to 10% unless a DEPM survey was undertaken in 2024.

1.6 Objective

The objective of this study is to estimate the spawning biomass of Blue Mackerel in the Eastern sub-area and Sardine in the Sardine sub-area in 2024.

2. Methods

2.1 Total Daily Egg Production

2.1.1 Ichthyoplankton survey

During 5–23 September 2024, ichthyoplankton samples were collected from the *FV Rubicon* at 262 sites located on 45 transects between southern Queensland and southern New South Wales (Figure 2–1). Each plankton sample was collected using a paired bongo net made by *Aquatic Research Instruments*. Each net in the pair was made from 500 µm nylon mesh and had internal diameter of 60 cm. Each net was comprised of an initial 100 cm cylindrical section followed by a 200 cm conical section. Detachable plastic cod ends attached to each net each had an internal diameter of 11 cm and 10 lateral apertures covered by 500 µm mesh. The bongo net was deployed within a purpose-built stainless-steel frame that also held a Sea-Bird™ 19+ V2 Conductivity-Temperature-Depth (CTD). The CTD was attached to the lower quarter of the frame to ensure the unit did not interfere with the bongo nets.

The sampling device was deployed to 10 m above the sea floor or to a maximum depth of 200 m and retrieved vertically at $\sim 1 \text{ m}\cdot\text{s}^{-1}$. At each sampling site, plankton collected in the paired net cod-ends were combined into one sample and fixed in a 5% buffered formalin and seawater solution. At every second site, a duplicate sample was collected for genetic validation; the paired cod-ends were combined and preserved in 95% ethanol. Location, sampling date/time, and depth were recorded for each plankton sample.

General Oceanics™ 2030 flow meters with factory calibration coefficients were used to estimate the distance travelled and calculate the volume of water filtered by each net. If there was >5% difference between the two flow meter readings, the relationship between wire length released and flow-meter units was used to determine which meter was more accurate, and that value was used for both nets. If neither flow meter was considered reliable, the linear relationship between wire length and flow-meter units from sites with two reliable flow metre readings was used to calculate the volume of water filtered at that site. Sea surface temperature (SST) was extracted from the CTD profiles at each sampling site by calculating the mean temperature between 2–5 m depth.

2.1.2 Laboratory Processing

Eggs in each ichthyoplankton sample were identified, staged and counted using morphological features identified in published descriptions for Blue Mackerel (Ward et al. 2021a) and Sardine (White and Fletcher 1998). Identifications of Blue Mackerel eggs preserved in ethanol were used to evaluate the morphological identifications of Blue Mackerel in the formalin preserved samples (Ward et al. 2021a, Appendix 2 and 3).

2.1.3 Data Processing and Statistical Analysis

Mean daily egg production (P_0)

The statistical procedures used to estimate P_0 followed the methods described by Ward et al. (2021a, b). Samples with no live eggs were excluded from the estimation of P_0 . Eggs in the first and last stages were also excluded because they have been shown to be under- and over-represented in plankton samples, respectively (Ward et al. 2021a, b; Stratoudakis et al. 2006).

For Sardine, each sample was assigned to one of three temperature bins (i.e. 14–18°C, 18–22°C, and 22–26°C) as per Ward et al. 2021b. For Blue Mackerel, a single bin of 17–23°C was used (Ward et al. 2021a).

Eggs in each sample were aggregated into daily cohorts (i.e. day-0, day-1 and day-2). The weighted mean age of each daily cohort was calculated by weighting estimates of the age of each stage by the number of the eggs in each stage. Zero counts were allocated to samples where a cohort was expected to occur in a sample (based on the water temperature, spawning time and sampling time), but was not found in that sample.

The density of eggs of each daily cohort (i.e. eggs m⁻³) in each sample was calculated by dividing the number of eggs collected by the volume of water filtered (Appendix 1, Equation 2). The number of eggs under one square metre of water (eggs.m⁻²) was calculated by multiplying egg density (i.e. eggs m⁻³) at each site by the depth (m) to which the net was deployed (Appendix 1, Equation 2).

Estimates of P_0 for Blue Mackerel and Sardine were calculated using the log-linear version of exponential egg mortality (Ward et al. 2021a, b; Appendix 1, Equations 3, 4, 5 and 6)

and a Generalized Linear Model with a negative binomial error structure (GLM NB, Appendix 1, Equation 7) which is suitable for over-dispersed data, such as egg density by age (e.g. Ward et al. 2021a, b). GLM NB used a log-link function and variance increased linearly with the mean (Appendix 1 Equation 8). The GLMs were fitted using the glmmTMB 'R' package (NB, Brooks et al. 2017; R Core Team 2022). To evaluate the plausibility of estimates of P_0 obtained from the log-linear model and GLM NB, P_0 was also estimated by applying assumed rates of egg mortality (z) to the estimate of mean egg density using the method of McGarvey and Kinloch (2001 Appendix 1, Equation 9).

Spawning area (A)

A was estimated using the Voronoi natural neighbour method (Watson 1981). The survey area was divided into a series of contiguous polygons centred on each site using the 'deldir' package in the statistical program 'R' (R Core Team 2019, Turner 2016). The area represented by each site (km^2) was calculated. A was defined as the total area of polygons where live eggs were present.

2.2 Mean Daily Fecundity

2.3.1 Adult Sampling and initial processing

In 2022, 2023 and 2024, Blue Mackerel showing evidence of spawning activity were taken by line-fishing at Tweed Heads, Ballina, Coffs Harbour, Port Macquarie, Port Stephens and Wollongong (Figure 2.3) using the methods described by Ward et al. (2023). Fish were dissected at the end of each sampling trip to determine their sex and reproductive status. Ovaries were removed from mature females (Stage III-V) and preserved in a 10% buffered formaldehyde solution. Males, immature females and carcasses of dissected females (individually labelled) were frozen and transported to the Institute of Marine and Antarctic Studies (IMAS, Hobart, Tasmania) for further processing.

Fish taken by the purse-seine vessels operating from Wollongong in 2022 (Figure 2.3) were placed on ice and transported to Sydney Fish Markets. Samples taken from the markets were processed at the Sydney Institute of Marine Science. Ovaries were removed from mature females (Stage III-V) and preserved in 5% buffered formaldehyde solution

(Figure 2.2). Males and immature females were processed as described above. Preserved ovaries of all fish were transported to IMAS for processing.

2.3.2 Laboratory Processing

The estimate of R used to calculate spawning biomass was inferred from the results of studies by Ward et al. (2009) and Ward et al. (2021b).

Histological slides prepared from the ovaries of mature females collected off eastern Australia in 2022, 2023 and 2024 were used to estimate spawning fraction. Ovaries were sectioned and stained with haematoxylin and eosin using standard histological techniques. Several sections from each ovary were examined to determine the presence/absence of post-ovulatory follicles (POFs). POFs were aged according to the criteria developed by Hunter and Goldberg (1980) and Hunter and Macewicz (1985). Details of the methods used to estimate spawning fraction are provided in Ward et al. (2025b).

Few Blue Mackerel with hydrated oocytes were collected during this study. The estimate of relative fecundity (F') obtained from southern Australia in 2002 to 2006 by Ward et al. (2009) was used to calculate spawning biomass. In that study, batch fecundity was estimated from 57 ovaries containing hydrated oocytes using the methods of Hunter and Macewicz (1985). This approach is justified because F' is stable within species (e.g. Ward et al. 2021b). A student project is currently underway to apply methods for estimating batch fecundity that do not rely on the collection of females with hydrated oocytes.

2.3.3 Statistical Analysis

The statistical methods used to estimate adult parameters are described by Ward et al. (2021a, b). R , the ratio of mature individuals (by weight) in each sample and the population were calculated using Equations 10 and 11 (Appendix 1), respectively. S , the mean proportion of females that spawn each night, was calculated for each sample and the population using Equations 12 and 13, respectively (Appendix 1). The 95% confidence intervals for spawning fraction were calculated following the methodology of Picquelle and Stauffer (1985) and ICES (2019), with each haul weighted by the number of sampled mature fish to account for unequal sample sizes. The overall mean, variance, and CV were then computed accordingly. Batch fecundity (F) was estimated from females containing

hydrated oocytes using the gravimetric method described by Hunter et al. (1985). Batch fecundity (F) for females without hydrated oocytes was estimated from the relationship between F and gonad-free female weight derived from females with hydrated oocytes (details outlined in Ward et al. 2021b). F' , the number of eggs produced per gram of total female weight (W), was calculated for each female by dividing F by total female weight (W , Appendix 1, Equation 14).

2.4 Spawning biomass (SB)

Estimates of the SB of Blue Mackerel and Sardine were calculated using the estimate of A obtained from the 2024 ichthyoplankton survey and estimates of P_0 obtained from data collected in the 2014, 2019 and 2024 surveys combined. Estimates of adult parameters for each species were obtained from a variety of sources.

For Blue Mackerel, SB was calculated using the estimate of P_0 obtained using the method of McGarvey and Kinloch (2001) with z set at 0.4, the estimate of S obtained from samples collected off eastern Australian in 2022–24 and the estimate of F' obtained from fish with hydrated oocytes collected off southern Australia in 2002–06. R was set based on studies by Ward et al. (2009, 2021a).

For Sardine, the estimate of P_0 used to calculate spawning biomass was obtained using the log-linear method and adult parameters estimated from samples collected off southern Australia from 1998 to 2024 (Grammer et al. 2024).

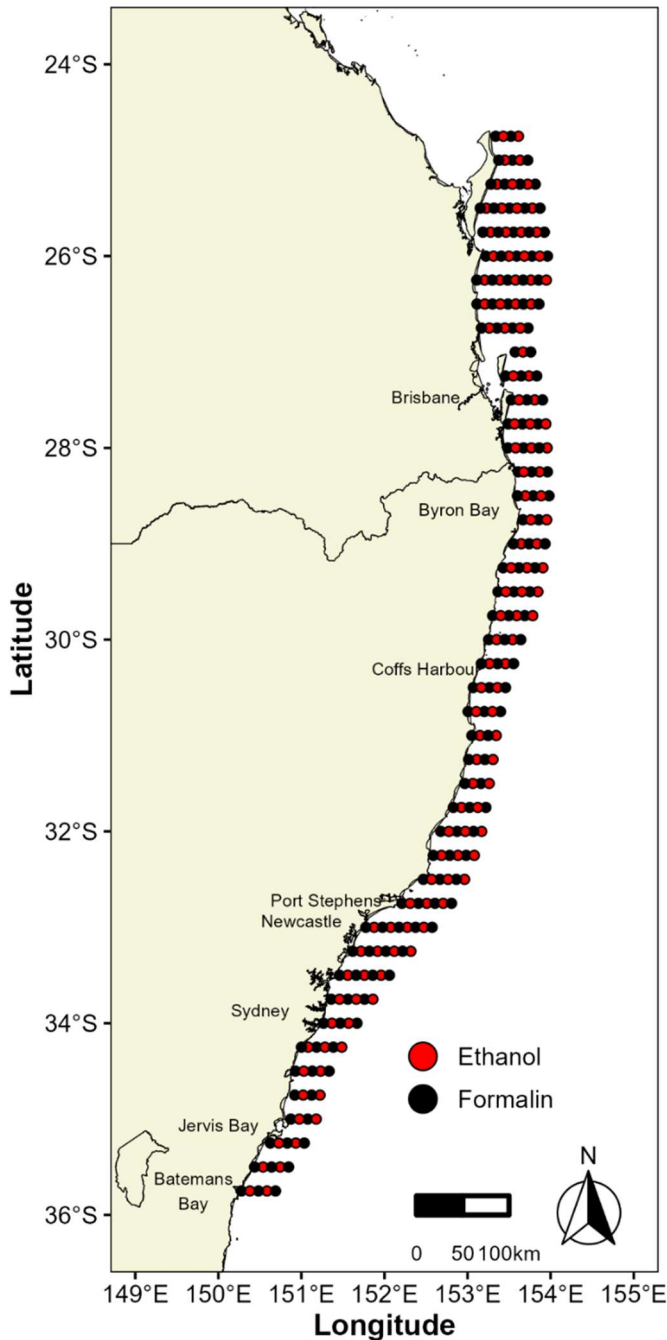
Confidence intervals were not calculated for the estimates of spawning biomass of Blue Mackerel and Sardine because of uncertainties associated with methods used to estimate the mean and/or confidence intervals of individual parameters, especially P_0 and S .

2.5 Sensitivity analyses

Sensitivity analyses were undertaken to assess of the effects of potential variations in P_0 , S , F' and R on estimates of SB . For Blue Mackerel, values of P_0 used in the sensitivity analysis were those obtained using the log-linear model and GLM NB, values of S and F' were the lower and upper 95% CIs, and R were the mean values obtained by Ward et al. (2009) and Ward et al. (2021b), respectively. For Sardine, values of P_0 used in the

sensitivity analysis were those obtained using the McGarvey and Kinloch (2001) method with z set at 0.2 and 0.5 and the lowest and highest values of S , F' and R obtained in individual years by Grammer et al. (2024).

Figure 2–1. Map showing sites between southern Queensland and southern New South Wales where plankton samples were collected during 5 to 23 September 2024. At sites marked in black one sample was taken and preserved in formalin. At sites marked in red two samples were collected: one was preserved in formalin and the other in ethanol.



3. Results

3.1 Blue Mackerel

3.1.1. Egg abundances, distribution and densities

A total of 1,242 live Blue Mackerel eggs were collected at 122 of the 262 (46.6%) sites (Figure 3–1–1). Blue Mackerel eggs were widely distributed throughout the survey area from Sandy Cape, Queensland to Batemans Bay, New South Wales. Most sites with high egg densities (>50 eggs·day⁻¹·m⁻²) were located between Tweed Heads and Coffs Harbour. Blue Mackerel eggs were present at sites with bathymetric depths ranging from 20 m to 1,460 m and SSTs ranging from 17.6°C to 23.9°C.

3.1.2 Mean daily egg production (P_0)

The estimate of P_0 obtained using the log-linear model was 12.9 eggs·day⁻¹·m⁻² and the estimate of z was 0.44 day⁻¹ (Figures 3–1–2). The estimate of P_0 from GLM NB was 33.4 eggs·day⁻¹·m⁻² and z was 0.65 day⁻¹. The estimate of P_0 obtained using the method of McGarvey and Kinloch (2001) with z set at 0.4 was 23.4 eggs·day⁻¹·m⁻² (Figures 3–1–2).

3.1.3 Spawning area (A)

The estimate of A for Blue Mackerel in 2024 was 31,195 km², which was 46.7% of the total area sampled of 66,790 km² (Figure 3–1–3).

3.1.4 Mean sex ratio (R)

Off eastern Australia in 2019, R was 0.56 and estimates for individual samples ranged from 0.43 and 0.69 (Ward et al. 2021a). Off southern Australia during 2002–06, R was 0.46 and estimates for individual samples ranged from 0.31 and 0.76 (Ward et al. 2009). Based on these results R was set at 0.5 for the present study.

3.1.5 Mean spawning fraction (S)

The estimate of S was obtained from 1,450 mature females collected from sites located in the Eastern Sub-area of the SPF during 2022–24 (Figure 3–1–1; Table 3–1–1). The

overall mean S was 0.13 (95% CI = 0.09–0.17). Estimates of S at individual locations ranged from 0.01 (0.00–0.02) at Port Macquarie in 2024 to 0.26 (0.12–0.40) in Port Stephens in 2022 (Table 3–1–1). Annual estimates of S ranged from 0.11 (0.04–0.19) in 2022 to 0.14 (0.06–0.22) in 2024 (Table 3–1–1).

3.1.6 Mean relative fecundity (F')

Few females with hydrated oocytes were collected off eastern Australia in 2022–24, likely because most samples were taken in the morning before the hydration process had begun. During 2002–06, 57 Blue Mackerel with hydrated oocytes were collected from southern Australia (Figure 3–1–4, Ward et al. 2021a). The relationship between batch fecundity and gonad-free female weight was batch fecundity = $186 \cdot \text{gonad-free weight} - 17,795$ ($R^2 = 0.51$). The estimate of F' was 140 eggs.g⁻¹ (95% CI = 136–144). F' was almost constant across the likely range of the total weights of mature females (Figure 3–1–4, Ward et al. 2021a).

3.1.7 Spawning biomass (SB)

The estimate of the SB of Blue Mackerel in the Eastern Sub-area of the SPF in 2024 of 80,216 t was calculated using estimates of $A = 31,195$ km², $P_0 = 23.4$ eggs·day⁻¹·m⁻², $F' = 140$ eggs.g⁻¹, $S = 0.13$, and $R = 0.5$. Confidence intervals were not calculated for the SB of Blue Mackerel due to uncertainties associated with the estimation of P_0 .

3.1.8 Sensitivity analysis

The sensitivity analysis demonstrated the strong influence that method used to estimate P_0 had on the estimate of the SB of Blue Mackerel compared to the other parameters (Figure 3–1–5). Estimates of P_0 obtained using the log-linear model of 12.9 eggs·day⁻¹·m⁻² and GLM NB of 33.4 eggs·day⁻¹·m⁻² provided estimates of SB of 44,221 t and 114,496 t, respectively.

Figure 3–1–1. Map showing egg densities of Blue Mackerel and sea surface temperatures (SST) recorded using the Conductivity Temperature Depth (CTD) profiler during the ichthyoplankton survey conducted during 5–23 September 2024. Red crosses indicate the adult sampling locations.

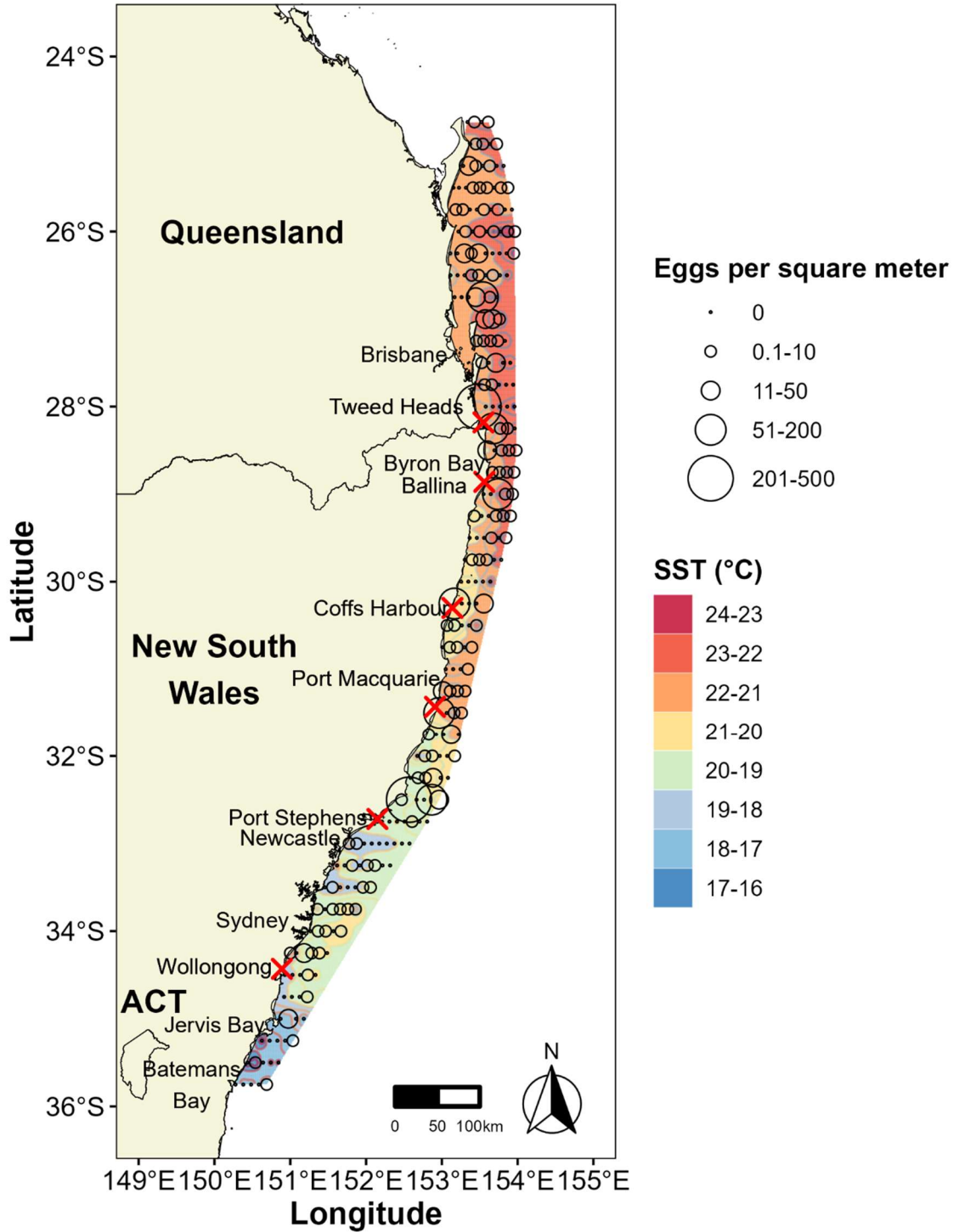


Figure 3–1–2. Models fitted to egg densities (eggs.m⁻²) and egg age (hours) of Blue Mackerel egg cohorts from surveys conducted in 2014, 2019 and 2024. Log-linear model (bias corrected), GLM NB with negative binomial error structure and McGarvey-Kinloch (2001) method with assumed values of instantaneous egg mortality (0.2, 0.3, 0.4 and 0.5).

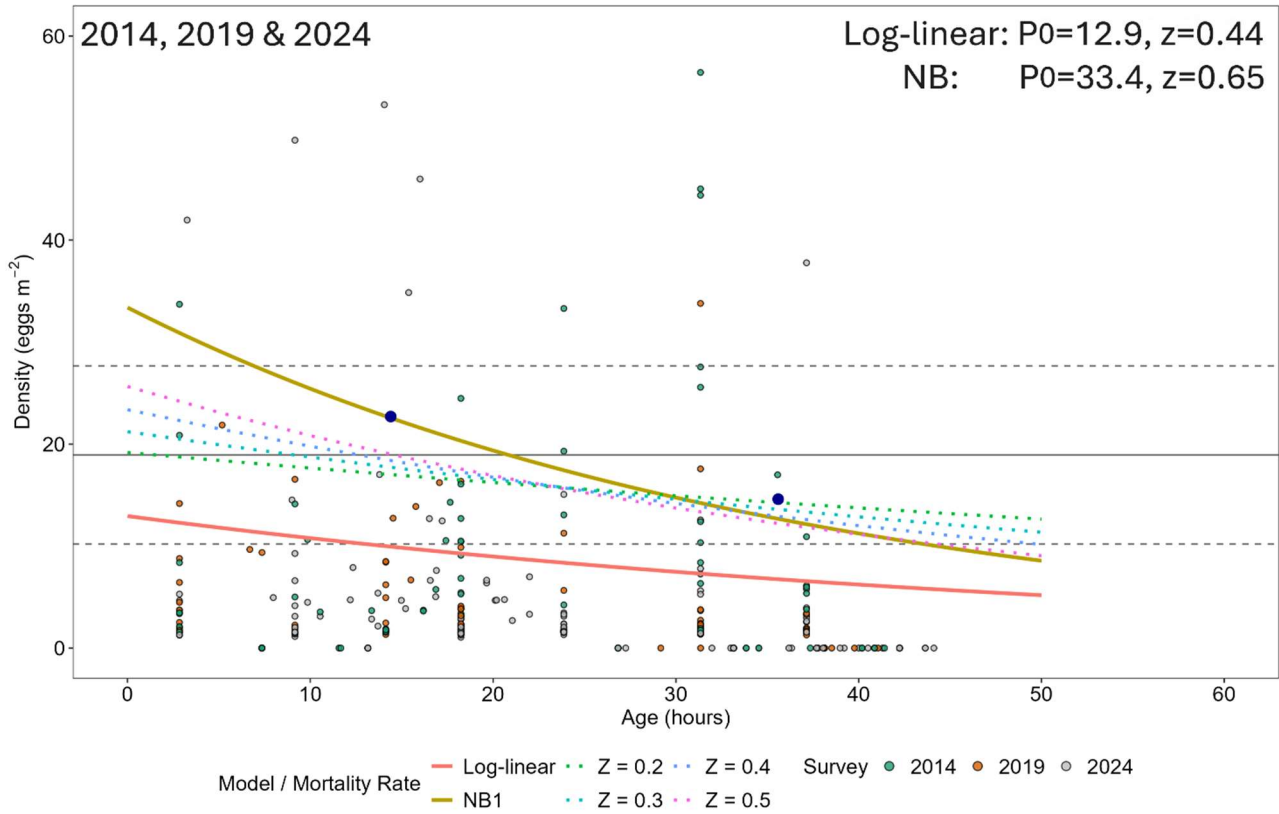
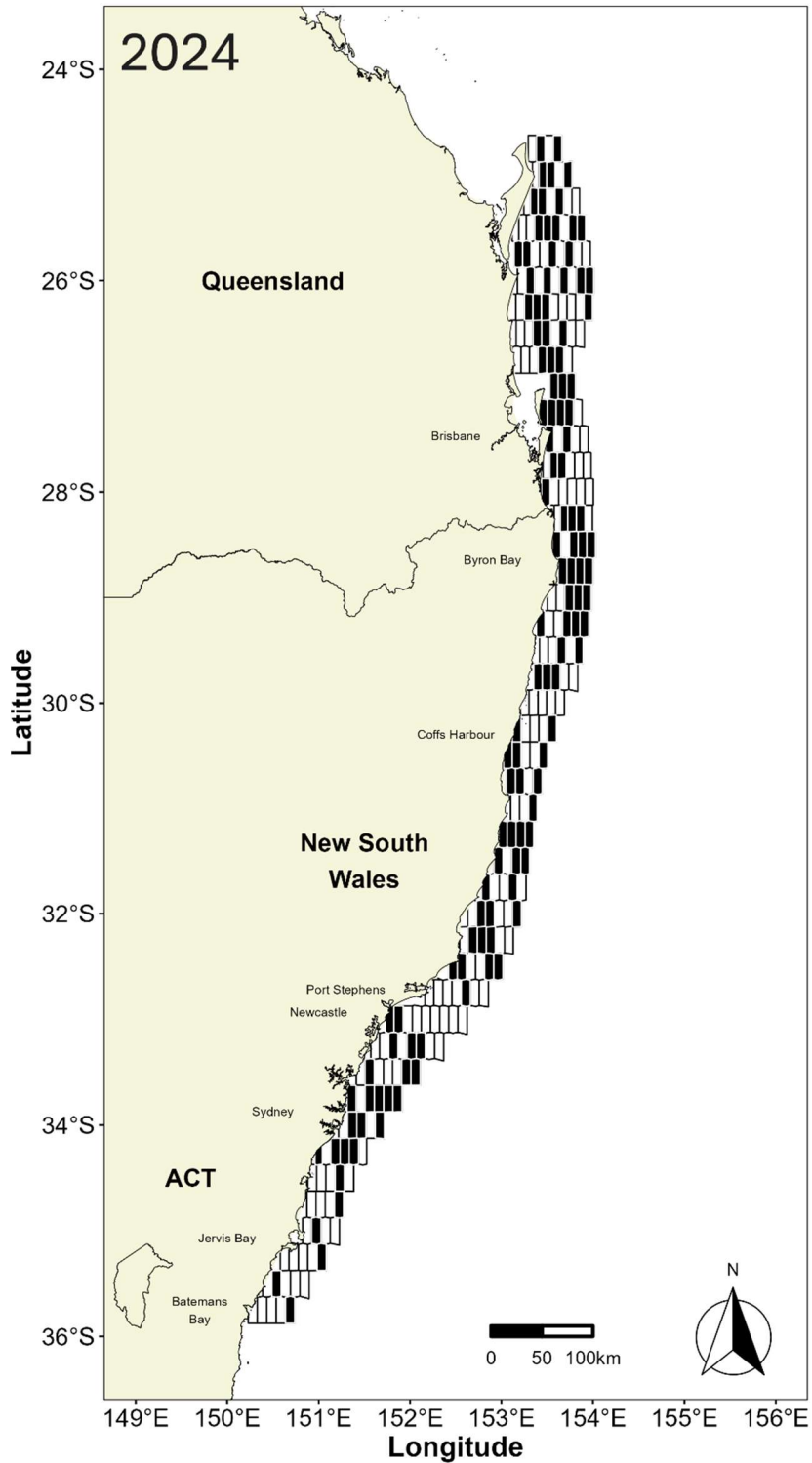


Figure 3–1–3. Map showing polygons generated using the Voronoi natural neighbour method and polygons where live Blue Mackerel eggs were present (black) in September 2024.



Year	Location	No. of samples (N) (mature females, n)	Range	Spawning Fraction (95% Confidence Intervals)
2022	Coffs Harbour	230 (5)	0.00–0.22	0.04 (0.00–0.12)
2022	Port Stephens	163 (4)	0.11–0.36	0.26 (0.06–0.5)
2022	Wollongong	77 (6)	0.00–0.07	0.04 (0.01–0.07)
2022	Total	470 (15)	0.00–0.36	0.11 (0.02-0.22)
2023	Tweed Heads	73 (4)	0.00–0.05	0.04 (0.02–0.06)
2023	Coffs Harbour	315 (6)	0.00–0.32	0.15 (0.04–0.26)
2023	Port Stephens	57 (5)	0.00–0.24	0.12 (0.00–0.41)
2023	Total	445 (15)	0.00–0.32	0.13 (0.06-0.20)
2024	Ballina	70 (3)	0.03–0.26	0.15 (0.0–0.53)
2024	Coffs Harbour	402 (8)	0.02–0.33	0.16 (0.04–0.27)
2024	Port Macquarie	63 (2)	0.00–0.01	0.01 (0.00–0.09)
2024	Total	535 (13)	0.02–0.33	0.14 (0.05-0.22)
2022-24	Grand Total	1,450 (43)	0.00–0.36	0.13 (0.08-0.18)

Table 3–1. Estimates of mean spawning fraction (S) at each location in the Eastern Sub-area of the SPF where adult Blue Mackerel were collected 2022, 2023 and 2024. All estimates of S were weighted by sample size (i.e. each individual fish contributed equally to the estimate).

Figure 3–1–4 A) Batch fecundity versus gonad free female weight and B) Relative Fecundity versus total female weight of Blue Mackerel collected off southern Australia in 2002–06. Red circles and lines are for females with hydrated oocytes. Grey circles and lines are estimates for females without hydrated oocytes. Shading around regression slopes are 95% CIs. Source: Ward et al. (2021a).

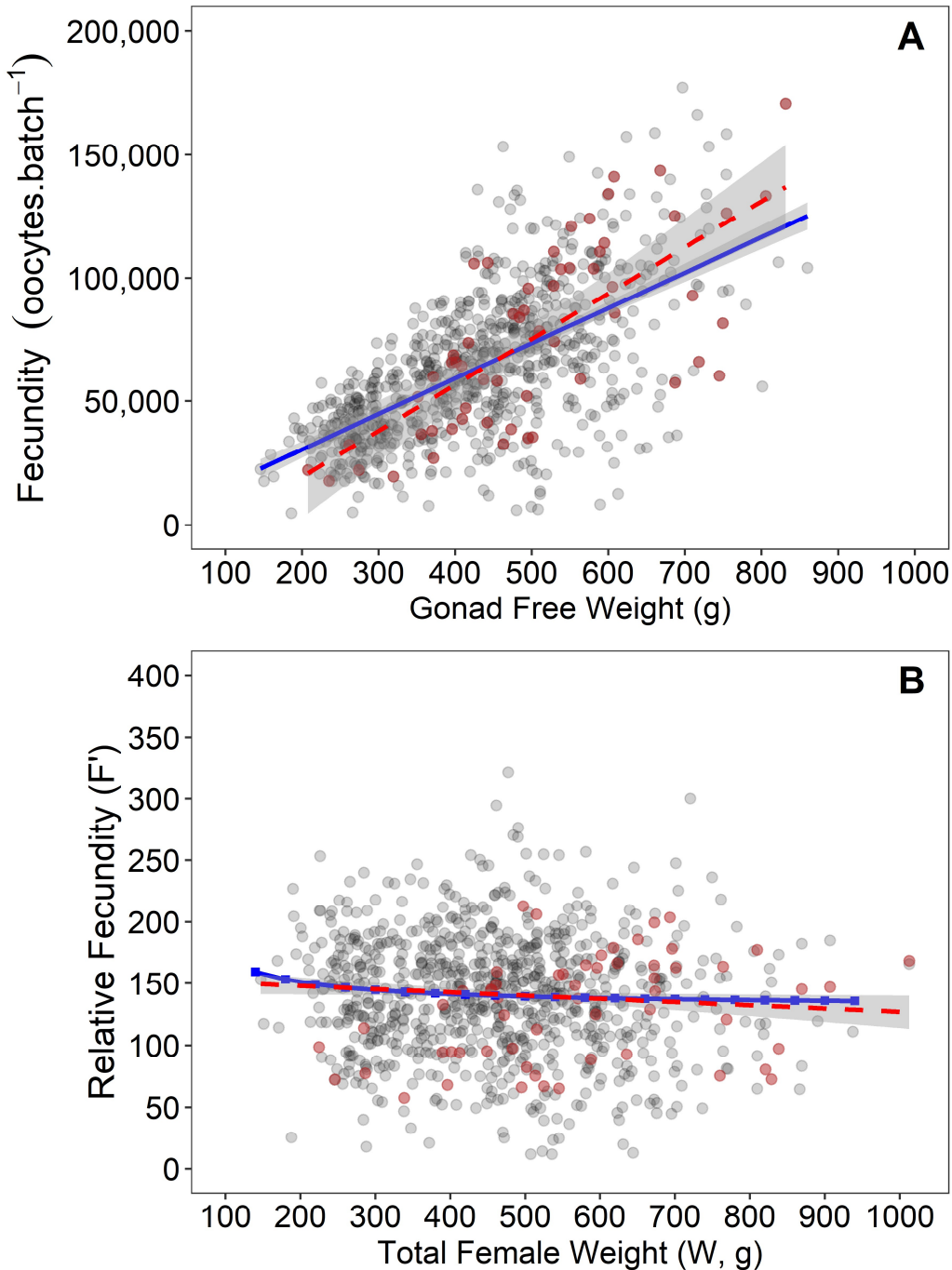
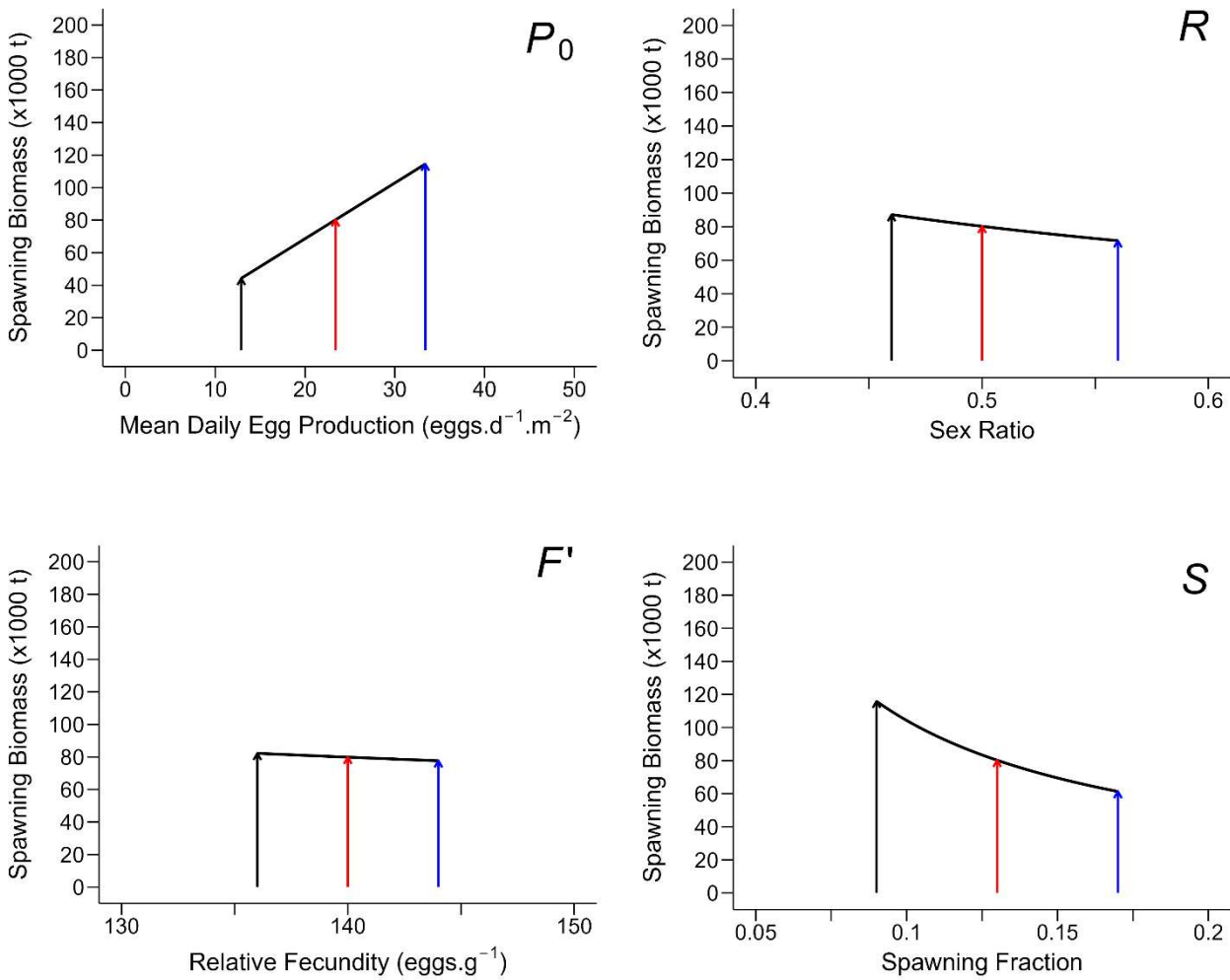


Figure 3–1–5 Sensitivity analysis showing the effects of variation mean daily egg production (P_0), sex ratio (R), relative fecundity (F') and spawning fraction (S) on estimates of spawning biomass (SB) of Blue Mackerel in 2024. Red arrows are values used to estimate SB for 2024. For P_0 , black arrow is the log-linear model and the blue arrow is GLM NB. For S and F' black and blue arrows are the lower and upper 95% CIs. For R black and blue arrows are the mean values obtained by Ward et al. (2009) and Ward et al. (2021a), respectively.



3.2 Sardine

3.2.1 Egg abundances, distribution and densities

A total of 6,288 live Sardine eggs were collected from 64 of the 262 (24.4%) sites (Figure 3–2–1). Two sites contained 46.4% of the total number of eggs collected (2,916 eggs). Few Sardine eggs were collected off southern Queensland. Sardine eggs were collected at sites along the NSW coast, with most were collected off southern NSW between Port Stephens and Batemans Bay. Sardine eggs were present at sites with bathymetric depths ranging from 20 m to 572 m and SSTs ranging from 16.5°C to 23.6°C.

3.2.2 Mean daily egg production (P_0)

Three sites (two in 2024 and one in 2019) had Sardine egg densities greater than 1,800 eggs·day⁻¹·m⁻² (i.e. more than 30 times the mean of other values). These sites were excluded from the analyses because they caused all three models to produce unrealistically inflated estimates of P_0 . Based on the dataset without these values, the estimate of P_0 obtained using the log-linear model was 52.1 eggs·day⁻¹·m⁻² and the mortality rate (z) was 0.53 day⁻¹ (Figures 3–2–2). The estimate of P_0 obtained using GLM NB was 54.5 eggs·day⁻¹·m⁻² and z was 0.33 day⁻¹. Applying the method of McGarvey and Kinloch (2001) with z set at values from 0.2 to 0.5 produced estimates of P_0 ranging from 49.0 to 65.5 eggs·day⁻¹·m⁻².

3.2.3 Spawning area (A)

The estimate of A for Sardine in the Sardine sub-area in 2024 was 16,215 km², which was 24.3% of the total area sampled of 62,790 km² (Figure 3–2–3).

3.2.4 Mean sex ratio (R)

The estimate of R of Sardine off southern Australia during 1998 to 2024 was 0.53 (95% C = 0.36–0.70) (Grammer et al. 2024, Table 3–2–1). Annual estimates of R ranged from 0.36 to 0.70 (Table 3–2–1).

3.2.5 Mean spawning fraction (*S*)

The estimate of *S* for Sardine off southern Australia during 1998 to 2024 was 0.111 (95% CI = 0.100–0.122) (Grammer et al. 2024, Table 3–2–1). Annual estimates of *S* ranged from 0.041 to 0.179 (Table 3–2–1).

3.2.6 Mean relative fecundity (*F'*)

The estimate of *F'* for Sardine off southern Australia during 1998 to 2024 was 308 eggs.g⁻¹ (95% CI = 307–310 eggs.g⁻¹) (Grammer et al. 2024, Table 3–2–1). Annual estimates of *F'* ranged from 298 to 316 eggs.g⁻¹ (Table 3–2–1).

3.2.7 Spawning biomass (*SB*)

The estimate of the *SB* of Sardine in the Eastern Sub-area of the SPF in 2024 of 46,563 t was calculated using estimates of $A = 16,215 \text{ km}^2$, $P_0 = 52.1 \text{ eggs}\cdot\text{day}^{-1}\cdot\text{m}^{-2}$, $F' = 308 \text{ eggs}\cdot\text{g}^{-1}$, $S = 0.111$ and $R = 0.53$. Confidence intervals were not calculated for the *SB* of Sardine due to uncertainties associated with the methods used to estimate the 95% CIs for adult parameters, especially *S*.

3.2.8 Sensitivity analysis

The sensitivity analysis demonstrates the strong influence that estimate and *S* has on estimates of spawning biomass compared to the other parameters. The upper and lower 95% CIs of *S* of 0.179 and 0.041 produce estimates of the *SB* of Sardine in 2024 of 28,874 t and 126,061 t, respectively. `

Figure 3–2–1. Map showing egg densities Sardine and Sea Surface Temperatures (SSTs) recorded using the Conductivity Temperature Depth (CTD) profiler during the plankton survey conducted during 5–23 September 2024.

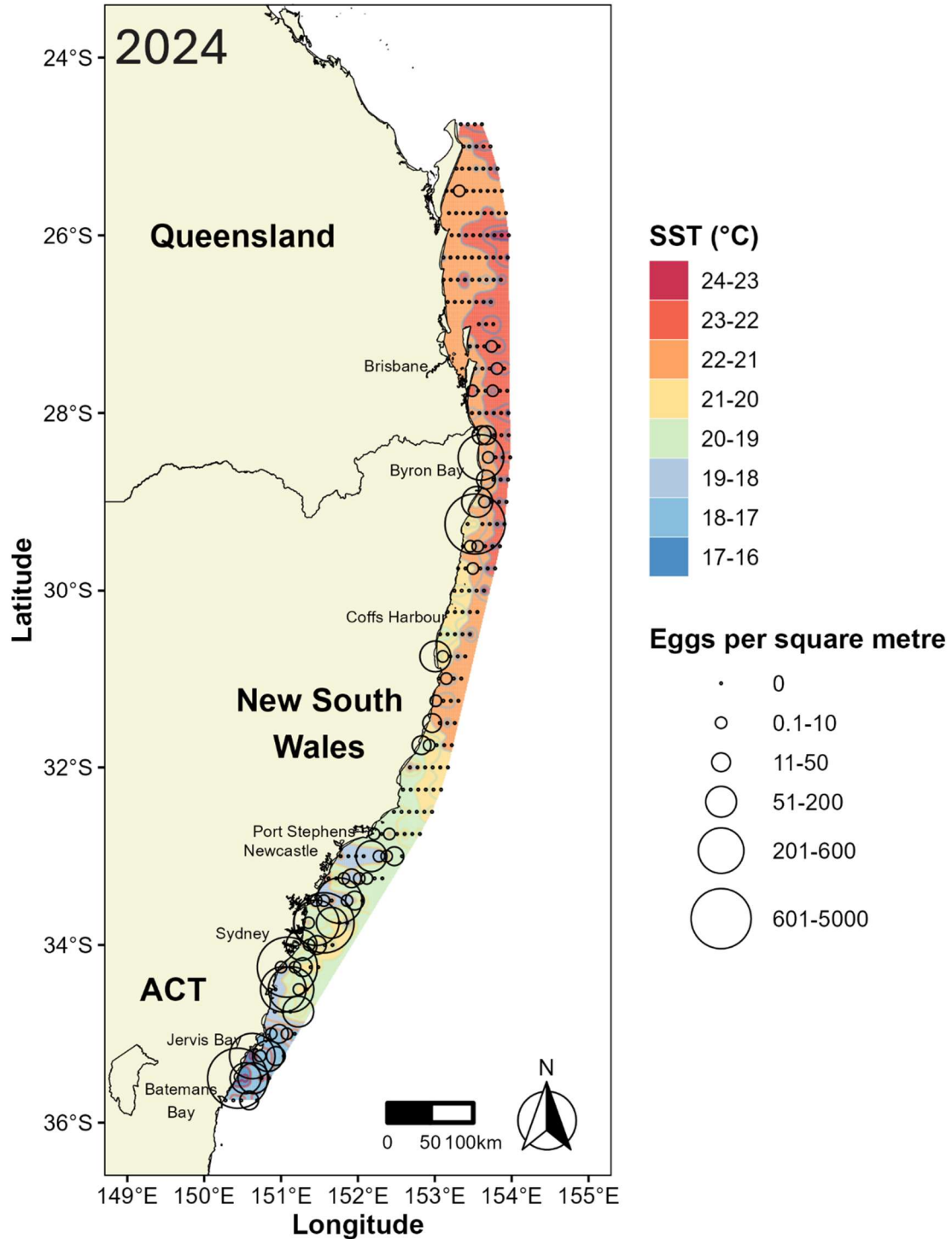


Figure 3–2–2. Models fitted to egg densities (eggs.m⁻²) and egg age (hours) of Sardine cohorts from surveys conducted in 2014, 2019 and 2024. Log-linear model (bias corrected), GLM NB with negative binomial error structure and McGarvey-Kinloch (2001) method with assumed values of instantaneous egg mortality (0.2, 0.3, 0.4 and 0.5). Three outliers with egg densities greater than 1,800 eggs.m⁻² (one collected in 2019 and two collected in 2024) were excluded from the analysis.

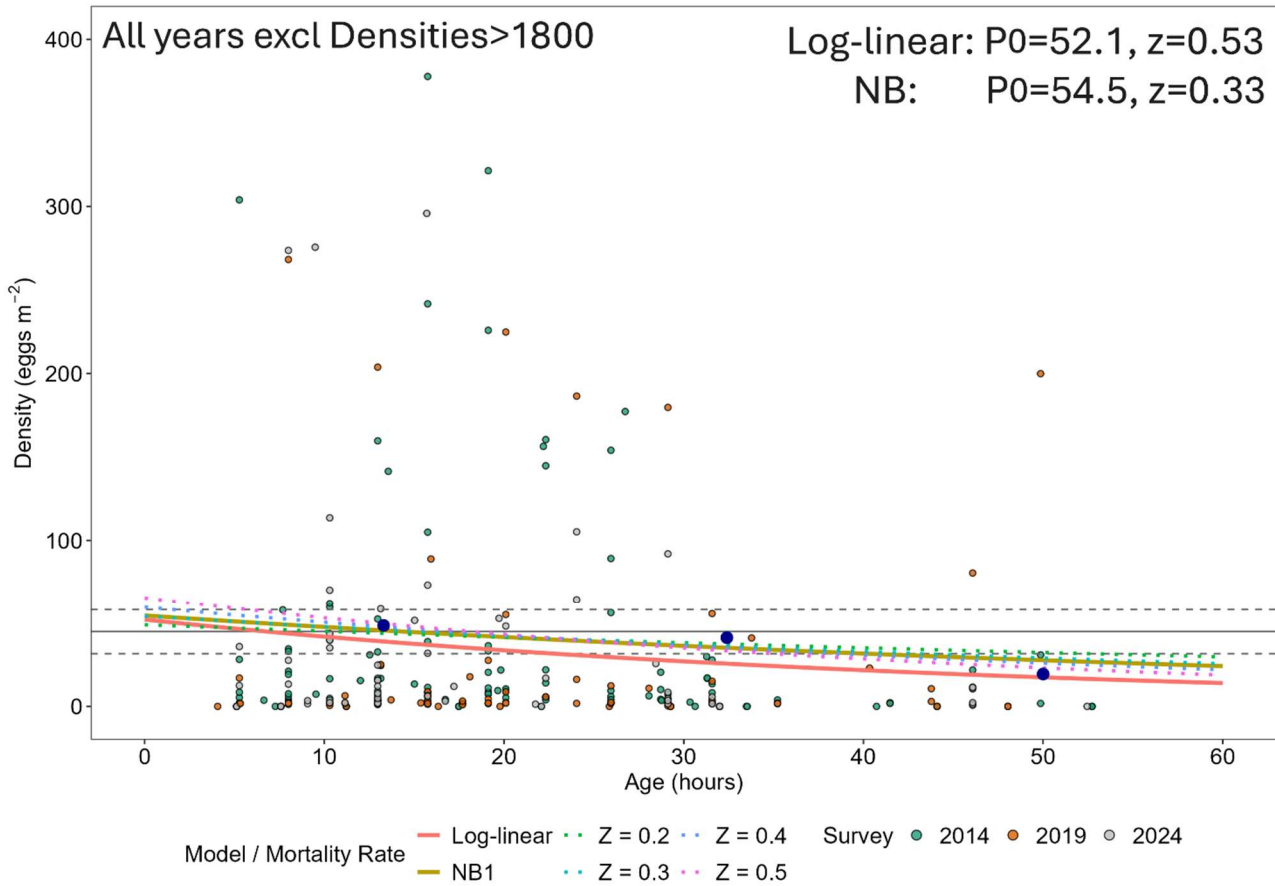
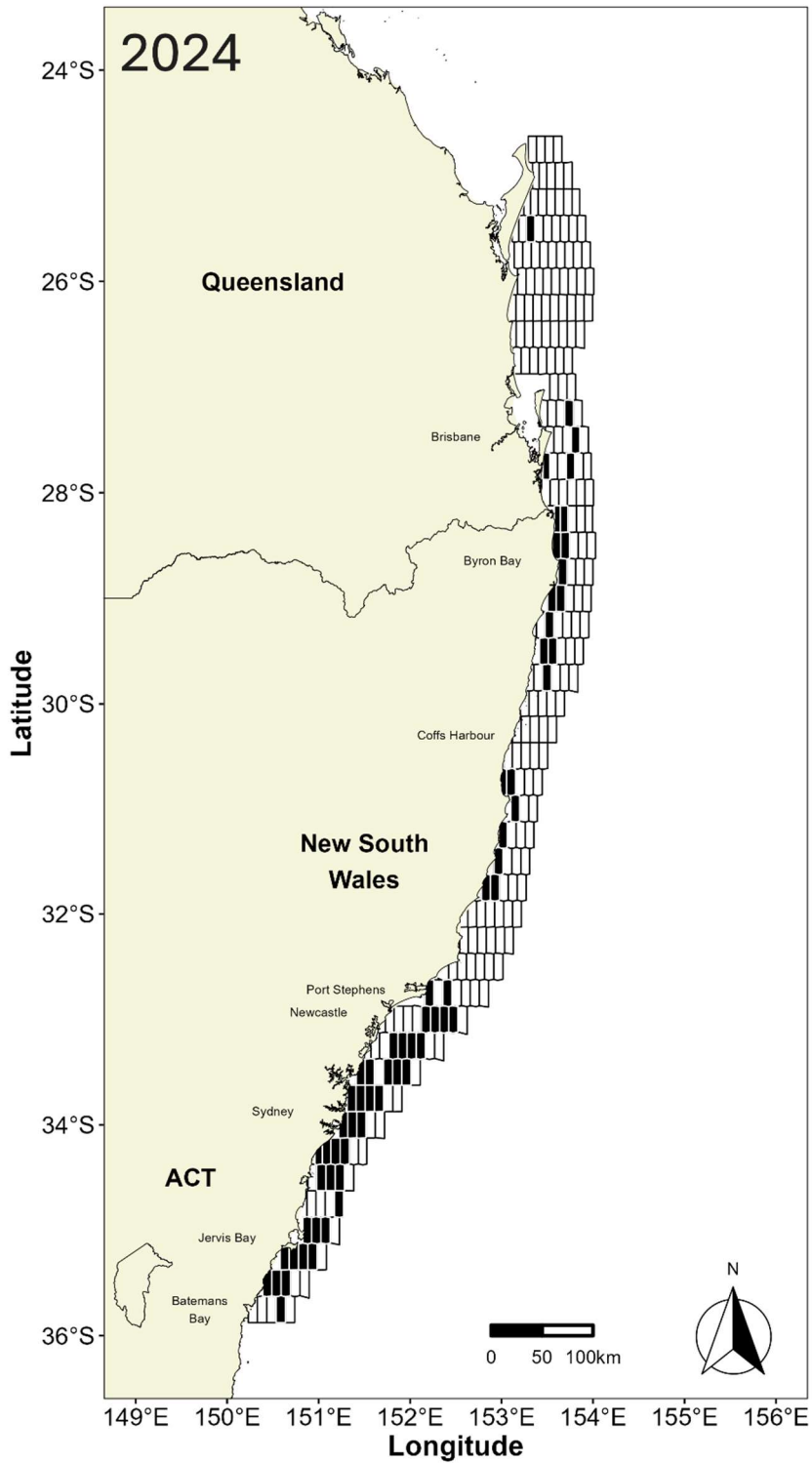


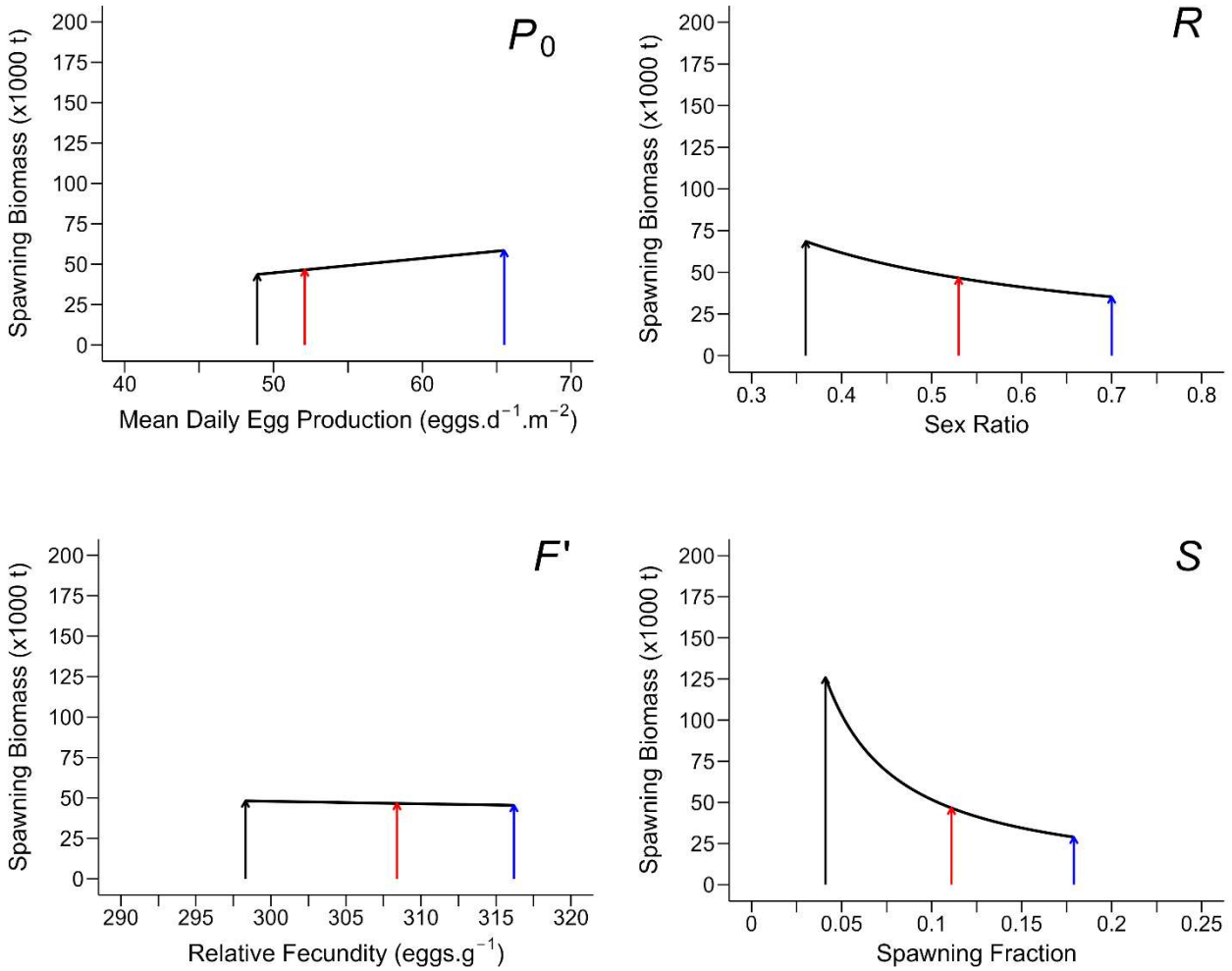
Figure 3–2–3. Map showing polygons generated using the Voronoi natural neighbour method where live Sardine eggs were present (black) in September 2024.



Parameter	Mean	95% Confidence Intervals	Range among years
Spawning Fraction (S)	0.111	0.100–0.122	0.041–0.179
Relative Fecundity (F')	308	307–310	298–316
Sex Ratio (R)	0.53	0.50–0.56	0.36–0.70

Table 3–2. Estimates of adult parameters for the Southern Stock of Australian Sardine obtained from Grammer et al. (2024) that were used to calculate spawning biomass in the present study.

Figure 3–2–4. Sensitivity analysis showing the effects of variation mean daily egg production (P_0), sex ratio (R), relative fecundity (F') and spawning fraction (S) on estimates of spawning biomass of Sardine in 2024.



4 Discussion

4.1 Blue Mackerel

4.1.1. Spawning season and timing of the plankton survey

The timing of ichthyoplankton surveys conducted in 2014 (19 August to 14 September) and 2019 (4–24 September) was informed by monthly gonosomatic indices and macroscopic staging done in the early 2000s that suggested that the spawning season of Blue Mackerel off eastern Australia extended from July to October, with the peak of spawning activity occurring during September (Rogers et al. 2009; Ward et al. 2015; 2021a). However, Rogers et al. (2009) noted that the strength of their conclusions was limited by the relatively small number of mature fish collected during their study and because their macroscopic analyses, especially the classification of fish as spent (Stage V), had not been validated using microscopic criteria (Rogers et al. 2009).

In contrast, the timing of the survey of ichthyoplankton survey conducted during 5–23 September 2024 was informed by a recent study (Ward et al. 2025a) that was based on a large number of mature females ($n = 923$) and involved the use of both macroscopic and microscopic staging techniques. Importantly, data presented by Ward et al. (2025a) were collected in the two spawning seasons immediately preceding the 2024 survey and were therefore likely to reflect the spawning season of Blue Mackerel off eastern Australia in 2024. It is noteworthy, however, that the findings of Ward et al. (2025a) were consistent with those presented by Rogers et al. (2009) and suggested that the spawning season of Blue Mackerel off eastern Australia begins during late July and ends in early November, with peak spawning activity occurring from August to October. There is no evidence to suggest that there has been a major shift in the peak spawning season of Blue Mackerel off eastern Australia over the last two decades.

4.1.2 Survey location and spawning area

The location where the ichthyoplankton surveys were conducted in 2014, 2019 (see Appendix 4) and 2024 was informed by the results of preliminary surveys conducted during 1–7 October 2003 and 20–27 July 2004 (Ward et al. 2009). However, each of the

three most recent surveys extended further south than the area in which eggs were collected during both 2003 and 2004 (i.e. around Newcastle) to ensure that the entire spawning area was sampled. No evidence of spawning was identified south of Sydney in the 2014 and 2019 surveys, but spawning occurred as far south as Batemans Bay in 2024 (i.e. on the southern-most transect). Evidence from the last three ichthyoplankton surveys strongly suggests that the spawning area of Blue Mackerel off eastern Australia has extended southwards over the last decade. Comparisons with the results of the preliminary surveys conducted in 2003 and 2004 suggest that a southward extension in the spawning area may have also occurred during the previous decade (Ward et al. 2009, 2015, 2021a). These results strongly suggest that future ichthyoplankton surveys for Blue Mackerel should extend further south than the last three surveys to ensure that the entire spawning area off eastern Australia is covered. We recommend that future surveys are extended at least as far as south as the southern boundary of the SPF Sardine sub-area (i.e. the NSW Victorian border).

The total area covered by each of the three surveys was similar: 65,528 km² in 2014, 62,467 km² in 2019 and 66,790 km² in 2024. However, the spawning area recorded for Blue Mackerel during the 2024 survey (31,195 km²) was 53% larger than in 2019 (20,387 km²) and 74% larger than in 2014 (17,911 km²). This expansion of the spawning area largely reflected the increase in the number of sites at which eggs were collected in the southern portion of the survey area. As the spawning area of small pelagic fishes, such as Blue Mackerel, is strongly correlated with spawning biomass (Mangel and Smith, 1990; Zenitani and Yamada, 2000; Gaughan *et al.*, 2004, Olafsdottir et al. 2019; Somarakis *et al.*, 2019), this finding suggests that the abundance of Blue Mackerel off eastern Australia may have increased over the last decade despite the large increase in catches by SPF vessels that has occurred over the same period (see Figure 1–2). There is also evidence to suggest that the current biomass is larger than it was in both the 1990s and 2000s. For example, the catch-per-unit-effort (CPUE) of Blue Mackerel recorded in a trawl survey conducted off southern NSW, eastern Victoria and eastern Tasmania in 2023–25 was approximately seven times higher than the level recorded in a comparable trawl survey conducted in 1993–96 (Appendix 6). Similarly, the larger area over which spawning activity was detected in the 2014, 2019 and 2024 surveys compared to the 2003 and 2004

suggests that levels of spawning biomass in the 2010s and 2020s may have been higher than in the 2000s.

4.1.3 Egg abundance and distribution

The distribution of live Blue Mackerel eggs varied among surveys. The expansion in the spawning area described above clearly reflected the progressive increase in the proportion of live eggs collected in the southern portion of the survey area. It is important to note, however, that in both 2019 and 2024 large numbers of eggs were still collected in the northern and central parts of the survey area. This finding strongly suggests that the range of Blue Mackerel off eastern Australia has expanded over the last decade rather than shifted. Supporting this conclusion, live Blue Mackerel eggs were collected at 46.6% (122/262) of sites sampled in 2024 compared to only 32.3% (81/251) in 2014 and 26.7% (70/262) in 2019 (Appendix 5). However, the total number of eggs collected in 2024 (1,242 eggs) was lower than in both 2019 (1,829 eggs) and 2014 (2,330 eggs). This difference in total egg abundances among years largely reflects the presence of large numbers of eggs (i.e. >250 eggs) at two sites in 2014 (931 and 273 eggs) and two sites in 2019 (497 and 287 eggs), whereas no sites in 2024 included >250 eggs. Similarly, egg densities >200 eggs.m⁻² were recorded at only one site in 2024 compared to five sites in both 2014 and 2019. As noted above, the increase in the area over which eggs were collected from the early 2000s to 2024 suggests that the spawning biomass of Blue Mackerel off eastern Australia may currently be at the highest level it has been over the last three decades.

4.1.4 Mean daily egg production (P_0)

The sensitivity analysis conducted in this study shows the strong influence that uncertainty in estimates of P_0 has on estimates of spawning biomass. Because historical uncertainties in the estimates spawning fraction have largely been resolved (e.g. Ward et al. 2025a), and consistent with many DEPM studies worldwide (see Bernal et al. 2012 and Dickey-Collas et al. 2012 for overviews), the key uncertainty associated with the current estimate of spawning biomass of Blue Mackerel relates to the estimation of P_0 . As demonstrated by the analysis of the long-term (20 years) dataset for Sardine off South Australia (Ward et al. 2021b), estimates of P_0 obtained in individual years are highly uncertain with fluctuations among years appearing to be driven more by sampling error than true inter-annual

variability. Following the approach of Ward et al. (2021b), in the present study we addressed this issue by combining data collected over multiple years (i.e. 2014, 2019 and 2024). However, because this combined dataset is comprised of samples from only three surveys the estimate of the overall mean P_0 of Blue Mackerel remains uncertain. The other factor contributing to this uncertainty is the relatively small number of sites that are sampled in each Blue Mackerel survey. For example, only 262 sites were sampled in the 2024 Blue Mackerel survey compared to the 405 sites sampled in the Sardine survey off South Australia in 2024 (Grammer et al. 2024). While this difference in sample size reflects the much larger survey area off South Australia (i.e. 140,900 km²) compared to the current study (66,790 km²) the impact on the uncertainty in the estimate of P_0 is an important issue that needs to be resolved.

The scale of uncertainty in the estimates of P_0 obtained in our study is demonstrated by the large differences in values derived from the log-linear model (i.e. 12.9 eggs·day⁻¹·m⁻²) and GLM NB (i.e. 33.4 eggs·day⁻¹·m⁻²). Consistent with previous studies of Blue Mackerel off eastern Australia (Ward et al. 2015, 2021a), we addressed this issue by estimating spawning biomass using the value of P_0 obtained by applying the method of McGarvey and Kinloch (2001) with z set at 0.4 (i.e. of 23.4 eggs·day⁻¹·m⁻²). While this approach has been a practical short-term solution to the current uncertainty in the estimation of P_0 and could be justified as an acceptable low risk when catches of Blue Mackerel remained well below the TAC (AFMA 2025b), we strongly recommend that future applications of the DEPM to Blue Mackerel off eastern Australia are focused on improving the reliability of the estimate of P_0 . As the Harvest Strategy for the SPF specifies that DEPM surveys only need to be conducted every five years to maintain stocks at Tier 1, the most appropriate way to achieve this goal may be to increase the number of sites that are sampled in future surveys. This outcome will be partly achieved by extending the survey further south as recommended above. However, consideration should also be given to increasing the total number of samples collected during each survey by reducing the distance between transects and/or sites.

Another key uncertainty associated with the estimation of P_0 that needs to be resolved is the method that is used to identify eggs (Appendix 2). Conducting molecular analyses of eggs preserved in ethanol to validate morphological identifications of eggs preserved in

formalin has worked effectively (Ward et al. 2015, 2021a), but other approaches such as the in-situ hybridization (ISH) method (Oxley et al. 2017) developed for Snapper (*Chrysophrys auratus*) should now be evaluated for Blue Mackerel. Alternative statistical methods for estimating P_0 , such as the Bayesian spatially explicit approach developed for anchovy in the Bay of Biscay, (Citores et al. 2024) should also be evaluated, although it needs to be recognised that this approach may not entirely overcome the challenges of estimating P_0 annually. We strongly recommend that prior to the next ichthyoplankton survey research projects are conducted to evaluate the development of the ISH method for Blue Mackerel and assess the potential benefits of using alternative statistical methods to estimate P_0 . A proposal has been developed for an Honours or Masters student at IMAS in 2026 to undertake a research project to begin the process of establishing the ISH method for Blue Mackerel. IMAS is also preparing a manuscript for submission to a scientific journal that includes a reanalysis of data used to estimate P_0 during previous applications of the DEPM to Blue Mackerel off eastern Australia (Ward et al. 2015, 2021a).

4.1.5 Adult reproductive parameters

The adult reproductive parameter with the strongest influence on estimates of spawning biomass is spawning fraction. The sampling program conducted during 2022–24 resolved much of the uncertainty associated with the spawning fraction of Blue Mackerel off eastern Australia (Ward et al. 2025a), which was identified as the key source of uncertainty in previous estimates of spawning biomass (Ward et al. 2015, 2021b). The fact that this parameter appears to be relatively consistent for Blue Mackerel globally (e.g. Rogers et al. 2009; Sinaga et al. 2021) reduces the likely significance of this uncertainty and could potentially reduce the need for extensive adult sampling to be done as part of each future DEPM survey. However, the potential for this parameter to change over the five-year period between DEPM surveys in an environment that is being heavily impacted by climate change (e.g. Fulton et al. 2021; Malan et al. 2021) cannot be discounted. It is recognised, however, that the level of adult sampling undertaken in future surveys is likely to be evaluated in the light of resource constraints associated with the need to address other key uncertainties, especially those associated with the estimation of P_0 .

Estimates of spawning biomass are relatively insensitive to likely variability in estimates of relative fecundity. Therefore, conducting research to reduce the uncertainty in the current estimate of relative fecundity is not a high priority from a stock assessment perspective. However, it is notable that the estimate of this parameter used in the present study was obtained from females with hydrated oocytes collected off southern Australia during 2002–06. As few females with hydrated oocytes were collected off eastern Australia in 2022–2024, this approach could not be applied to samples collected by Ward et al. (2025). However, alternative methods that do not rely on females with hydrated oocytes have been developed to estimate this parameter (e.g. Thorsen and Kjesbu 2001; Saber et al. 2016). A proposal has been developed for an Honours or Masters student at IMAS to undertake a research project to estimate the batch fecundity and relative fecundity of Blue Mackerel off eastern Australia in 2026 using samples collected by Ward et al. (2025a).

The parameter with the least influence on estimates of spawning biomass is sex ratio. However, because sex ratio is likely to be constant among years at 1:1 by number and approximately 0.5 by weight, variations in annual estimates of this parameter provide valuable insights into the difficulty of obtaining reliable annual estimates of other adult parameters, especially spawning fraction (see Ward et al. 2021b). For example, the sex ratio off eastern Australia in 2019 was 0.56 with estimates for individual samples ranging from 0.43 and 0.69 (Ward et al. 2021a). Similarly, the sex ratio off southern Australia between 2002 and 2006 was 0.46 with estimates for individual samples ranging from 0.31 and 0.76 (Ward et al. 2009). These variations among years in estimates of sex ratio are driven by sampling error that may not need to be included in the estimation of spawning biomass. We are currently evaluating the suitability of treating sex ratio as a fixed parameter (i.e. without 95% CIs) with a value of 0.5 (or slightly higher) in future applications of the DEPM to Blue Mackerel (and other species) off eastern Australia.

4.1.6 Spawning biomass

The spawning biomass of Blue Mackerel in the Eastern Sub-area of the SPF in 2024 was estimated to be around 80,000 t, which is similar to the estimates 83,000 t and 88,265 obtained in 2014 and 2019, respectively (Ward et al. 2015, 2021a). These results combined with increase in the spawning area of Blue Mackerel off eastern Australia over

the last decade strongly suggest the spawning biomass has not declined in response to increased fishing pressure from the SPF. The similarity in the estimates of spawning biomass obtained in the three surveys despite the large increase in spawning area in 2024 reflects the lower estimate of mean daily egg production obtained in 2024 compared to the 2014 and 2019. This difference highlights the critical importance of resolving uncertainties associated with estimation of mean daily egg production.

The seven-fold increase in the trawl CPUE reported in the South East Fishery Ecosystem Surveys undertaken in 1993–96 and the South East Australian Marine Ecosystem Surveys (SEA-MES) undertaken in 2023–2025 suggest that the abundance of Blue Mackerel off south-eastern Australia may be higher than it was 30 years ago (Appendix 6). The results of the SEA-MES surveys also suggest that there is a significant adult biomass off southern NSW, eastern Victoria and eastern Tasmania that is not accounted for by the DEPM surveys. Extensive adult sampling undertaken in this area off south-eastern Australia in 2022 and 2023 (Ward et al. 2025a) failed to detect any females with gonad development that would indicate that Blue Mackerel spawn in this region at any time of the year. These findings suggests that a proportion of the Blue Mackerel population off eastern Australia may not spawn every season and that the estimate of spawning biomass obtained in DEPM surveys is likely to be conservative (i.e. lower than the actual adult biomass).

4.2 Sardine

4.2.1 Spawning season and timing of the plankton survey

The ichthyoplankton surveys conducted in 2014, 2019 and 2024 were timed to coincide with the peak spawning season of Blue Mackerel. However, monthly egg densities and gonosomatic indices measured off southern Queensland during 1997 and 1998 indicated that spawning season of Sardine extended from July to November with the peak occurring in August and September (Ward and Staunton Smith 2002), which coincides with spawning season of Blue Mackerel in this region (Rogers et al. 2009; Ward et al. 2015; 2021a, 2025). No information is currently available to evaluate if the peak spawning season of Sardine off eastern Australia has changed over the last two or three decades.

4.2.2 Spawning area

The spawning area of Sardine fell from 22,400 km² in 2014 to 14,281 km² in 2019 and increased to 16,215 km² in 2024. These findings suggest that the spawning biomass of Sardine has fluctuated over the last decade and was likely to have been lower in 2024 than in 2014. Given the relatively small catches of Sardine off eastern Australia in recent years (AFMA 2025b), these potential reductions in spawning biomass are unlikely to have been caused by fishing pressure. The overall reduction in the spawning area has coincided with a shift in the main spawning area from southern Queensland and northern NSW in 2014 (Appendix 4) to central and southern NSW in 2024. This apparent shift in the location of the main spawning grounds could potentially have been driven by climate-related increases in water temperatures throughout the survey area and/or by phenological changes such as the spawning season occurring earlier in the north in 2024 than in the late 1990s (Ward and Staunton Smith 2002) and 2010s (Ward et al. 2015; 2021a, 2025b). However, it should also be recognised that these differences could also reflect natural year to year variability in egg distributions driven by other factors.

4.2.3 Egg abundance and distribution

The percentage of sites where live Sardine eggs were collected fell from 34% (89/262) in 2014 to 23% (58/251) in 2019 then increased slightly to 25% (64/262) in 2024. In contrast, the total number of live eggs collected during the surveys increased from 3,461 eggs in 2014 to 4,667 eggs in 2019 and 6,288 eggs in 2024. These increases in the total egg numbers collected in 2019 and 2024 were mainly driven by the presence of very large numbers of eggs (i.e. >850 eggs) at a few sites. For example, two sites sampled in 2019 had 863 and 1,633 eggs and three sites sampled in 2024 had 867, 946 and 1,970 eggs. Egg densities of >1,800 eggs.m⁻² were recorded at two sites in 2024 (1,820 and 4,164 eggs.m⁻²) and one site in 2019 (1,879 eggs.m⁻²) but were not recorded in any of the samples collected in 2014.

4.2.4 Mean daily egg production (P_0)

Following the approach of Ward et al. (2021b), we estimated P_0 of Sardine using data collected over multiple years (i.e. 2014, 2019 and 2024). However, we excluded the three sites with egg densities >1,800 eggs.day⁻¹.m⁻² (i.e. >30 times the mean of other values)

from the dataset because they caused all three models to produce unrealistically inflated estimates of P_0 . Based on the dataset without these values, the estimate of P_0 obtained using log-linear model and GLM NB were similar: i.e. 52.1 eggs·day⁻¹·m⁻² and 54.5 eggs·day⁻¹·m⁻² respectively. The estimate of P_0 obtained by applying the method of McGarvey and Kinloch (2001) with z set at 0.3 was also similar (i.e. 54.2 eggs·day⁻¹·m⁻²).

4.2.5 Adult reproductive parameters

Using estimates of adult parameters from South Australia to estimate spawning biomass in the present study is justified because these parameters are consistent for *S. sagax* worldwide (Ganias 2014; Somarakis et al. 2019). For example, the estimate of spawning fraction of 0.111 used in this study is similar to the global mean of 0.12 reported for this species by Ganias (2014) and value of 0.14 obtained off eastern Australia in 2014 (Ward et al. 2015). Estimates of relative fecundity (308 eggs·g⁻¹) and sex ratio (0.53) used to estimate spawning biomass in this study are also consistent with values obtained in other studies (e.g. Ward et al. 2015; Somarakis et al. 2019). Consideration should be given to treating sex ratio as a fixed parameter with a value of ~0.53 in future applications of the DEPM to Sardine off eastern Australia.

4.2.6 Spawning biomass

The estimate of the spawning biomass of Sardine in the Eastern Sub-area of the SPF in 2024 of 46,563 t is considered robust because it was obtained using reliable estimates of P_0 and all three adult reproductive parameters. It is also similar to the estimates of spawning biomass obtained in previous DEPM surveys of around 49,600 t in 2014 and 42,500 in 2019 (Ward et al. 2015, 2021a). The reductions in spawning area recorded in 2019 and 2024 compared to 2014 (Appendix 5) also suggest that the spawning biomass may have been lower in 2024 than in 2014 (Ward et al. 2021b). IMAS is currently preparing a manuscript for submission to a scientific journal that reanalyses and synthesises data obtained in historical DEPM surveys of Sardine off eastern Australia.

4.3 Implications and Recommendations

It is critically important that the next ichthyoplankton survey is extended further south to ensure that it covers the entire spawning area of Blue Mackerel off eastern Australia. The number of ichthyoplankton samples taken should also be increased to address uncertainty in the estimate of P_0 . This objective will be partly achieved by extending the survey further south. However, consideration should also be given to increasing the number of samples taken by reducing the distance between transects and/or sites. Both these changes would increase the cost of future surveys.

Thorough re-analyses of the entire datasets collected in historical DEPM surveys for Blue Mackerel and Sardine off eastern Australia should be conducted before the next survey is undertaken (likely 2029). The primary objectives of this research should be to optimise the statistical methods used to estimate key parameters (including uncertainty) and provide recommendations about how the reliability of future estimates of SB can be improved. IMAS is currently preparing manuscripts for submission to scientific journals that address these objectives.

References

- AFMA 2025. Small Pelagic Fishery Harvest Strategy. Canberra: Australian Fisheries Management Authority.
- AFMA 2025. Small Pelagic Fishery. Species Summaries 2024. Canberra: Australian Fisheries Management Authority.
- Bernal, M., Somarakis, S., Witthames, P.R., van Damme, C.J.G., Uriarte, A., Lo, N.C.H. and Dickey-Collas, M. 2012. Egg production methods in marine fisheries: An introduction. *Fisheries Research*, 117, 1–5.
- Brooks, M.E., Kristensen, K., van Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Mächler, M. and Bolker, B.M. 2017. glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *R Journal*, 9, 378–400.
- Dickey-Collas, M., Somarakis, S., Witthames, P.R., van Damme, C.J.G., Uriarte, A., Lo, N.C.H. and Bernal, M. 2012. Where do egg production methods for estimating fish biomass go from here? *Fisheries Research*, 117-118, 6–11.
- Fulton, E.A., Melbourne-Thomas, J., Ogier, E., Dutra, L.X.C., Thomas, L., van Putten, E.I. and CSIRO. 2024. Applying the Fisheries Climate Adaptation Handbook to Australia's State Fisheries. Hobart: CSIRO.
- Ganias, K. 2014. *Biology and Ecology of Sardines and Anchovies*, Oakville, Canada, Apple Academic Press Inc.
- Gaughan, D.J., Leary, T.I., Mitchell, R.W. and Wright, I.W. 2004. A sudden collapse in distribution of Pacific sardine (*Sardinops sagax*) off southwestern Australia enables an objective re-assessment of biomass estimates. *Fishery Bulletin*, 102, 617–633.
- Gomon, M., Bray, D. and Kuitert, R.H. 2008. *Fishes of the Australia's South Coast*, New Holland Publishers (Australia).
- Grammer, G.L., Ivey, A.R. and Cheesman, C. 2024. Spawning biomass of Sardine,

Sardinops sagax, in Australian waters. Adelaide: South Australian Research and Development Institute (Aquatic and Livestock Sciences).

Hunter, J.R. and Goldberg, S.R. 1980. Spawning incidence and batch fecundity in northern anchovy, *Engraulis mordax*. *Fishery Bulletin*, 77, 641–652.

Hunter, J.R. and Lo, N.C.H. 1997. The daily egg production method of biomass estimation: Some problems and potential improvements. *Ozeanografika*, 2, 41–69.

Hunter, J.R. and Macewicz, B.J. 1985. Measurement of spawning frequency in multiple spawning fishes. National Marine Fisheries Service, NOAA.

Izzo, C., Ward, T.M., Ivey, A.R., Suthers, I.M., Stewart, J., Sexton, S.C. and Gillanders, B.M. 2017. Integrated approach to determining stock structure: implications for fisheries management of sardine, *Sardinops sagax*, in Australian waters. *Reviews in Fish Biology and Fisheries*, 27, 267–284.

Keane, J.P. and Neira, F.J. 2008. Larval fish assemblages along the south-eastern Australian shelf: linking mesoscale non-depth-discriminate structure and water masses. *Fisheries Oceanography*, 17, 263–280.

Lasker, R. 1985. An egg production method for estimating spawning biomass of pelagic fish: Application to the Northern Anchovy, *Engraulis mordax*. National Marine Fisheries Service, NOAA.

Malan, N., Roughan, M. and Kerry, C. 2021. The Rate of Coastal Temperature Rise Adjacent to a Warming Western Boundary Current is Nonuniform with Latitude. *Geophysical Research Letters*, 48, e2020GL090751.

McGarvey, R. and Kinloch, M.A. 2001. An analysis of the sensitivity of stock biomass estimates derived from the daily egg production method (DEPM) to uncertainty in egg mortality rates. *Fisheries Research*, 49, 303–307.

Olafsdottir, A.H., Utne, K.R., Jacobsen, J.A., Jansen, T., Oskarsson, G.J., Nottestad, L., Elvarsson, B.T., Broms, C. and Slotte, A. 2019. Geographical expansion of Northeast Atlantic mackerel (*Scomber scombrus*) in the Nordic Seas from 2007 to

2016 was primarily driven by stock size and constrained by low temperatures.

Deep-Sea Research Part II-Topical Studies in Oceanography, 159, 152–168.

Oxley, A.P.A., Catalano, S.R., Wos-Oxley, M.L., Westlake, E.L., Grammer, G.L. and Steer, M.A. 2017. Using in situ hybridization to expand the daily egg production method to new fish species. *Molecular Ecology Resources*, 17, 1108–1121.

Parker, K. 1980. A Direct Method for Estimating Northern Anchovy, *Engraulis mordax*, Spawning Biomass. *Fishery Bulletin*, 78, 541–544.

Picquelle, S. and Stauffer, G. 1985. Parameter estimation for an egg production method of anchovy biomass assessment. National Marine Fisheries Service, NOAA.

Rice, J.A. 1995. *Mathematical Statistics and Data Analysis*, Belmont, California, Duxbury Press.

Rogers, P.J., Ward, T.M., McLeay, L.J., Lowry, M., Saunders, R.J. and Williams, D. 2009. Reproductive biology of blue mackerel, *Scomber australasicus*, off southern and eastern Australia: suitability of the Daily Egg Production Method for stock assessment. *Marine and Freshwater Research*, 60, 187–202.

Saber, S., Macias, D., de Urbina, J.O. and Kjesbu, O.S. 2016. Contrasting batch fecundity estimates of albacore (*Thunnus alalunga*), an indeterminate spawner, by different laboratory techniques. *Fisheries Research*, 176, 76–85.

Schmarr, D.W., Whittington, I.D., Ovenden, J.R. and Ward, T.M. 2012. Discriminating stocks of blue mackerel using a holistic approach: a pilot study. *Advances in Fish Tagging and Marking Technology*. Bethesda: American Fisheries Society.

Sexton, S.C., Ward, T.M., Stewart, J., Swadling, K.M. and Huveneers, C. 2019. Spawning patterns provide further evidence for multiple stocks of sardine (*Sardinops sagax*) off eastern Australia. *Fisheries Oceanography*, 28, 18–32.

Shiraishi, T., Ketkar, S.D., Katoh, Y., Nyuji, M., Yamaguchi, A. and Matsuyama, M. 2009. Spawning frequency of the Tsushima Current subpopulation of chub mackerel *Scomber japonicus* off Kyushu, Japan. *Fisheries Science*, 75, 649–655.

- Smith, P.E. and Richardson, S.L. 1977. Standard techniques for pelagic fish egg and larva surveys. Food and Agriculture Organization.
- Somarakis, S., Tsoukali, S., Giannoulaki, M., Schismenou, E. and Nikolioudakis, N. 2019. Spawning stock, egg production and larval survival in relation to small pelagic fish recruitment. *Marine Ecology Progress Series*, 617, 113–136.
- Staunton Smith, J. and Ward, T.M. 2000. Stock assessment of small pelagic fishes in southern Queensland, with particular reference to pilchards (*Sardinops sagax*). FRDC.
- Stratoudakis, Y., Bernal, M., Ganias, K. and Uriarte, A. 2006. The daily egg production method: recent advances, current applications and future challenges. *Fish and Fisheries*, 7, 35–57.
- Team, R.C. 2022. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.
- Thorsen, A. and Kjesbu, O.S. 2001. A rapid method for estimation of oocyte size and potential fecundity in Atlantic cod using a computer-aided particle analysis system. *Journal of Sea Research*, 46, 295–308.
- Turner, R. 2015. deldir: Delaunay Triangulation and Dirichlet (Voronoi) Tessellation.
- Venables, W.N. and Ripley, B.D. 2002. Random and mixed effects. *Modern applied statistics with S-PLUS*. Springer.
- Ward, T., Carroll, J., Grammer, G., James, C., McGarvey, R., Smart, J. and Ivey, A. 2018. *Improving the precision of estimates of egg production and spawning biomass obtained using the Daily Egg Production Method*, University of Tasmania.
- Ward, T. and Staunton-Smith, J. 2002. Comparison of the spawning patterns and fisheries biology of the sardine, *Sardinops sagax*, in temperate South Australia and sub-tropical southern Queensland. *Fisheries Research*, 56, 37–49.
- Ward, T.M., Burch, P., McLeay, L.J. and Ivey, A.R. 2011. Use of the Daily Egg Production

Method for Stock Assessment of Sardine, *Sardinops sagax*; Lessons Learned over a Decade of Application off Southern Australia. *Reviews in Fisheries Science*, 19, 1–20.

- Ward, T.M., Carlos, G. and Stewart, J. 2023. Estimating the spawning fraction of Blue Mackerel off eastern Australia: Stage 1 Developing a sampling method(s) and identifying sampling locations. Hobart: Institute for Marine and Antarctic Studies, University of Tasmania.
- Ward, T.M., Charitonidou, K., Stewart, J. and Carlos, G. 2025. Estimating the spawning fraction of Blue Mackerel off eastern Australia: Stage 2 Spatiotemporal variability in spawning patterns and implications for future DEPM surveys. Hobart: Institute for Marine and Antarctic Studies, University of Tasmania.
- Ward, T.M., Charitonidou, K., Wolfe, B.W., Alderson, T., Carlos, G. and Couslon, P. 2025. Fishery Assessment Report for the Small Pelagic Fishery: Fishing Seasons 2021–22, 2022–23 and 2023–24. Hobart: Institute for Marine and Antarctic Studies, University of Tasmania.
- Ward, T.M., Grammer, G.L., Ivey, A., Carroll, J., Keane, J., Stewart, J. and Litherland, L. 2015. Egg distribution, reproductive parameters and spawning biomass of Blue Mackerel, Australian Sardine and Tailor off the east coast during late winter and early spring, November. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).
- Ward, T.M., Grammer, G.L. and Ivey, A.R. 2021. Spawning biomass of Blue Mackerel (*Scomber australasicus*) and Australian Sardine (*Sardinops sagax*) in the East sub-area of the Small Pelagic Fishery. Adelaide: South Australian Research and Development Institute (Aquatic Sciences).
- Ward, T.M., Grammer, G.L., Ivey, A.R., Smart, J.J. and McGarvey, R. 2021. Increasing the precision of the daily egg production method; 2020's remix of a 1980's classic. *Ices Journal of Marine Science*, 78, 1177–1195.
- Ward, T.M., Rogers, P.J., McLeay, L.J. and McGarvey, R. 2009. Evaluating the use of the

daily egg production method for stock assessment of blue mackerel, *Scomber austrasicus*. *Marine and Freshwater Research*, 62, 112–128.

Watson, D.F. 1981. Computing the N-Dimensional Delaunay Tessellation with Application to Voronoi Polytopes. *Computer Journal*, 24, 167–172.

White, K.V. and Fletcher, W.J. 1998. Identifying the developmental stages for eggs of the Australian pilchard, *Sardinops sagax*. Fisheries Western Australia.

Wood, S.N. 2006. Low-rank scale-invariant tensor product smooths for generalized additive mixed models. *Biometrics*, 62, 1025–1036.

Yamada, T., Aoki, I. and Mitani, I. 1998. Spawning time, spawning frequency and fecundity of Japanese chub mackerel, *Scomber japonicus* in the waters around the Izu Islands, Japan. *Fisheries Research*, 38, 83–89.

Zenitani, H. and Yamada, S. 2000. The relation between spawning area and biomass of Japanese pilchard, *Sardinops melanostictus*, along the Pacific coast of Japan. *Fishery Bulletin*, 98, 842–848.

Appendices

Appendix 1. Equations used in the application of the Daily Egg Production Method to estimate the spawning biomass of Blue Mackerel in this study. Adapted from Ward et al. (2021a, b).

Calculation	Equation	Equation Number	Parameters	Reference
Spawning biomass	$SB = \frac{P_0 A}{R S F'}$	1	<p>SB: Spawning Biomass <i>P</i>₀: mean daily egg production <i>A</i>: total spawning area <i>R</i>: mean sex ratio <i>F'</i>: mean relative fecundity <i>S</i>: mean spawning fraction</p>	Parker (1980) Ward et al. (2021b)
Egg density (sample)	$P_s = \frac{C D}{V}$	2	<p><i>P</i>_s: density of eggs in a sample <i>C</i>: number of eggs of each age in each sample <i>V</i>: volume of water filtered (m³) <i>D</i>: depth (m) of net cast</p>	Smith and Richardson (1977)
Exponential egg mortality model (<i>P</i> ₀)	$P_t = P_0 e^{-z t}$	3	<p><i>P</i>_t: egg density at age <i>t</i> <i>z</i>: the instantaneous rate of daily egg mortality</p>	Picquelle and Stauffer (1985)

Non-linear least squares regression	$nls(P_t \sim P_0 e^{-z t})$	4	P_t : egg density at age t z : the instantaneous rate of daily egg mortality	Picquelle and Stauffer (1985)
Log-linear model. Negatively biased estimate of P_b	$\ln P_b = \ln(P_{i,t} + 1) - Zt$	5	P_b : negatively biased P_0 $P_{i,t}$: density of eggs of age t at site i z : instantaneous rate of daily egg mortality	Ward et al. (2021b)
Log-linear model. Bias corrected estimate of P_0	$P_0 = e^{(\ln P_b + \sigma^2/2)} - 1$	6	P_b : negatively biased estimate of daily egg production σ^2 : variance of P_b estimate	Ward et al. (2021b)
Generalised Linear Model with negative binomial error structure	$E[P_0] = g^{-1}(-zt + \varepsilon)$	7	$E[P_0]$: expected value of P_0 g^{-1} : inverse-link function zt : the instantaneous rate of daily egg mortality at age t ε : error term	Ward et al. (2021b)
Variance of the GLMs increases linearly with the mean	$\sigma^2 = \mu^*(1 + \varphi)$	8	M : the model estimate, σ^2 : model variance φ : over-dispersion parameter	Ward et al. (2021b)
Estimate of P_0 using assumed values of mortality	$P_0 = \frac{\bar{P} Z}{1 - e^{-2Z}}$	9	P_0 = Initial egg density \bar{P} = measured mean egg density Z = Instantaneous rate of daily egg mortality	McGarvey and Kinloch (2001)
Sex Ratio: sample (\bar{R}_i)	$\bar{R}_i = \frac{F_i}{F_i + M_i}$	10	\bar{R}_i : mean sex ratio of each sample i	Lasker (1985)

			<p>F_i: total weight of mature females in each sample i</p> <p>M_i: total weight of mature males in each sample i</p>	
Sex Ratio: population (R)	$R = \left[\frac{\overline{R_i n_i}}{N} \right]$	11	<p>$\overline{R_i}$: mean sex ratio of each sample i</p> <p>n_i: number of fish in each sample n_i</p> <p>N: total number of fish collected in all samples and</p>	Lasker (1985)
Spawning Fraction: sample ($\overline{S_i}$)	$\overline{S_i} = \frac{d0 + d1 + d2}{3 n_i}$	12	<p>$d0, d1$ and $d2$: the number of mature females with post-ovulatory follicles (POFs) aged day 0, 1 or 2 in each sample i</p> <p>n_i: is the total number of females within a sample.</p>	Lasker (1985)
Spawning Fraction: population (S)	$S = \left[\frac{\overline{S_i n_i}}{N} \right]$	13	<p>$\overline{S_i}$: mean spawning fraction of each sample i</p> <p>n_i: mean number of fish in each sample i</p> <p>N: total number of mature fish collected in all samples</p>	Lasker (1985)
Relative Fecundity (F')	$F' = \overline{F} / \overline{W}$	14	<p>F': Relative Fecundity</p> <p>\overline{F}: Mean Fecundity</p> <p>\overline{W}: Mean Weight</p>	Parker (1980)

<p>Ratio estimator (e.g. F')</p>	$Var(F') = \frac{1}{n_{fish}} \cdot \frac{1}{\bar{W}^2}$ $\cdot \{(F')^2 \cdot \sigma_W^2 + \sigma_F^2 - 2 \cdot F' \cdot cov(F, W)\}$	<p>15</p>	<p>F': relative fecundity \bar{W}: mean weight σ_F^2 and σ_W^2: variances of \bar{F} and \bar{W} $cov(F, W)$: covariance of F and W</p>	<p>Rice (1995)</p>
---	--	-----------	---	--------------------

Appendix 2. Genetic identification of Blue Mackerel eggs

A molecular approach for mitochondrial DNA (mtDNA) extraction, amplification, and sequencing for *Scomber* spp. was applied to identify eggs of Blue Mackerel (*Scomber australasicus*) following laboratory methods detailed in Neira et al. (2014). Briefly, DNA was extracted from eggs identified morphologically using the QIAamp DNA Micro Kit (QIAGEN, USA) following the manufacturer's tissue extraction protocol. DNA concentrations were quantified using a Qubit 4 Fluorometer with the High Sensitivity (HR) Assay (Thermo Fisher Scientific, USA).

Barcode amplification by PCR (Polymerase chain reaction) targeted a ~655 bp fragment of the CO1 gene using general fish primers FishF2 (5'-TCG ACT AAT CAT AAA GAT ATC GGC AC-3') and FishR2 (5'-ACT TCA GGG TGA CCG AAG AAT CAG AA-3') (Ward et al. 2005). An additional primer pair, FishF1 (5'-TCA ACC AAC CAC AAA GAC ATT GGC AC-3') and FishR1 (5'-TAG ACT TCT GGG TGG CCA AAG AAT CA-3') (Ward et al. 2005, was tested on a subset of eggs for comparison. Polymerase chain reactions (PCRs) were performed using MyTaq HS™ mastermix (Bioline, UK), and PCR products were purified and sequenced bi-directionally by Macrogen Inc. (Seoul, Republic of Korea) following Neira et al. (2014). Sequences were compared against reference data in the National Center for Biotechnology Information (NCBI) database using the Basic Local Alignment Search Tool (BLAST) to confirm species identity (Altschul et al. 1990). Species IDs were assigned when query sequences were at least 98% similar to the closest database match.

Both primer sets produced consistent results. In total, 50 eggs collected from 28 stations were analysed to confirm species identity. Of these, 17 eggs from 12 stations were tested for Blue Mackerel confirmation; 15 were identified as *S. australasicus*, while had inconclusive results due to low quality amplicon. Two additional eggs at early developmental stages were tested, with one confirmed as Blue Mackerel. Early developmental stage and ethanol preservation often masked morphological features, complicating identification. For negative confirmation, 20 eggs from 19 stations were analysed and all were verified as other species (Table 1A2).

In conclusion, molecular analysis successfully validated eggs identified morphologically as Blue Mackerel and confirmed the presence of this species across the survey area (Figure

1A2). The results highlight the difficulty of distinguishing Blue Mackerel eggs from morphologically similar eggs of other species (e.g., *Lepidotrigla* spp., *Saurida* spp.) and the limitations imposed by ethanol preservation. Molecular identifications were used to inform the classification of formalin-preserved eggs.

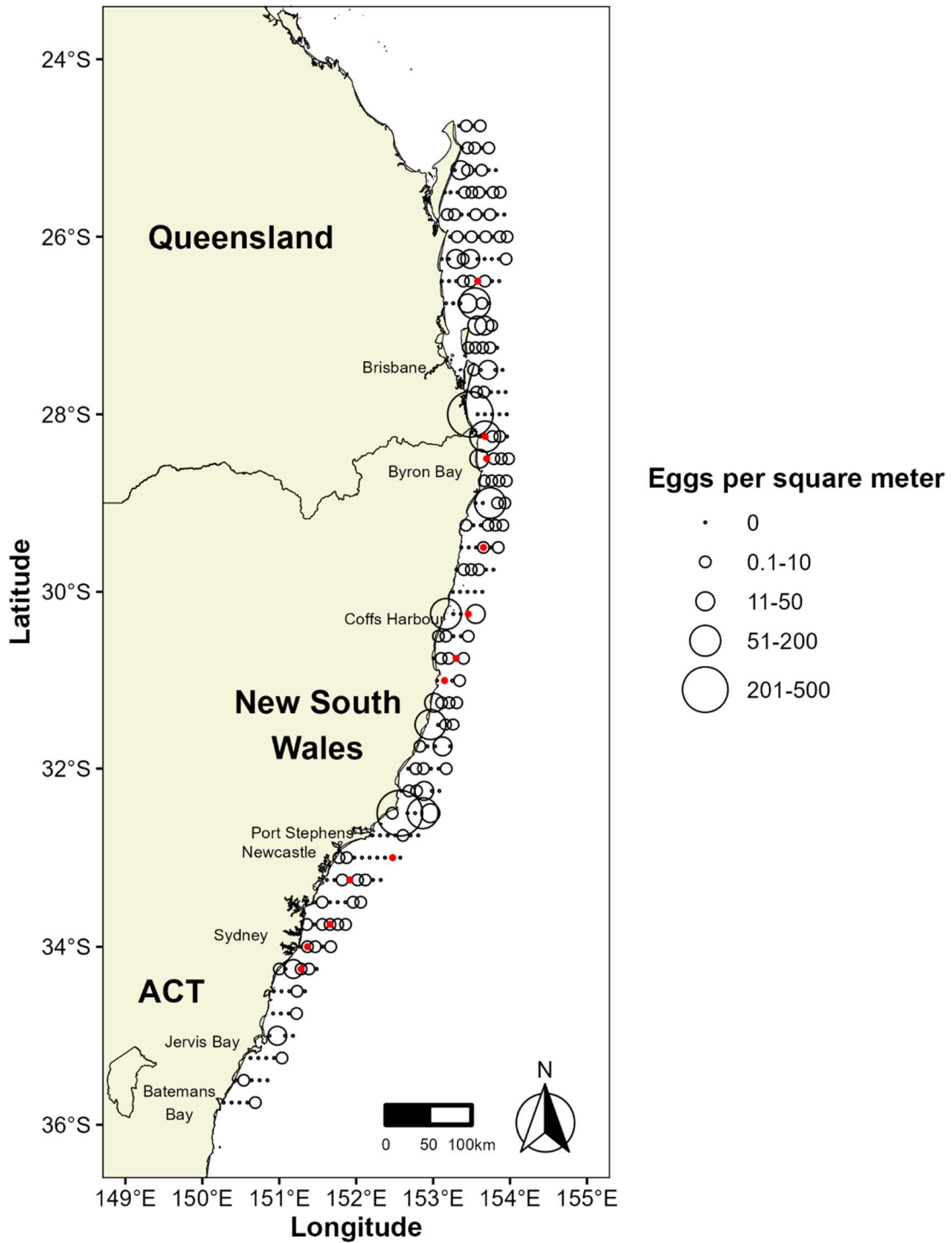
References

- Hall, T.A. 1999. BioEdit: A user-friendly biological sequence alignment editor and analysis program for Windows 95/98/NT. *Nucleic Acids Symposium Series* 41: 95-98.
- Neira, F. J., R. A. Perry, C. P. Burrige, J. M. Lyle, and J. P. Keane. 2014. Molecular discrimination of shelf-spawned eggs of two co-occurring *Trachurus* spp. (Carangidae) in southeastern Australia: a key step to future egg-based biomass estimates. *ICES Journal of Marine Science: Journal du Conseil* 72:614-624.
- Ward, R.D., Zemlak, T.S., Innes, B.H., Last, P.R., and Hebert, P.D. 2005. DNA barcoding Australia's fish species. *Philosophical transactions of the royal society B: biological sciences*, 360(1462), 1847-1857.

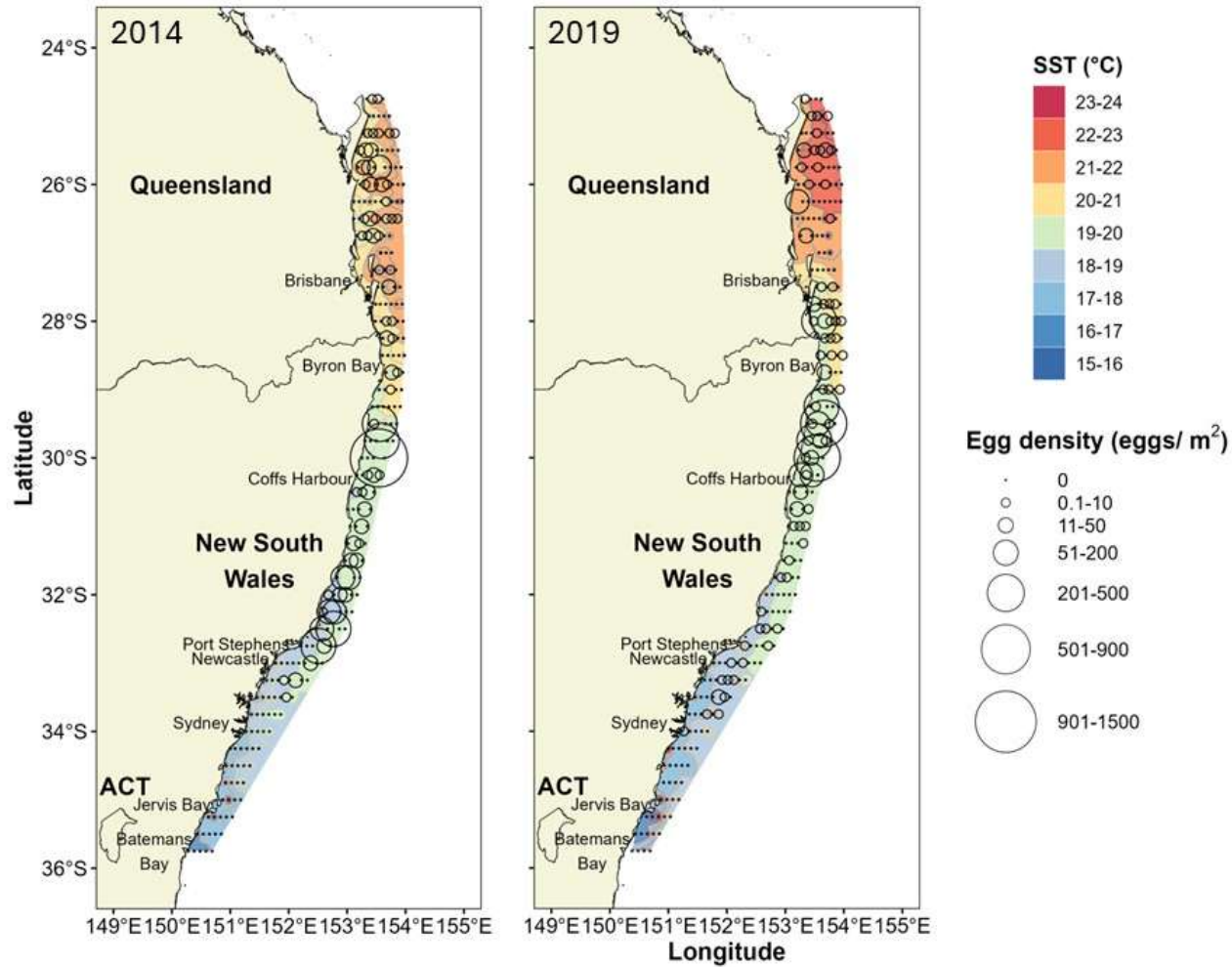
Morphological identification	No. eggs	DNA Identification			Other Species
		BMK confirmed	Other species	Insufficient DNA	
BMK confirmation	17	15	2	0	
Negative confirmation	20	0	18	2	<i>Parapercis allporti</i> (n=1) <i>Champsodon</i> spp. (n=3) <i>Lepidotrigla mulhalli</i> (n=4) <i>Lepidotrigla argus</i> (n=2) <i>Paraulopus oblongus</i> (n=1) <i>Emmelichthys nitidus</i> (n=1) <i>Seriola lalandi</i> (n=2) <i>Optivus agastos</i> (n=3) <i>Etrumeus</i> spp. (n=1)
No clear BMK characteristics	5	0	4	1	<i>Saurida undosquamis</i> (n=1) <i>Hydrolagus trolli</i> (n=1) <i>Lepidotrigla argus</i> (n=2)
Early stages eggs: BMK Confirmation	2	1	1	0	<i>Onigocia grandisquama</i> (n=1)
Early stages eggs: Negative confirmation	6	0	6	0	<i>Lepidotrigla mulhalli</i> (n=1) <i>Parapercis allporti</i> (n=1) <i>Etrumeus</i> spp. (n=1) <i>Trachinocephalus myops</i> (n=2) <i>Optivus agastos</i> (n=1)

Table A2T1. Genetic identification of Blue Mackerel eggs and verification of other species. Species detected by molecular analysis are shown in the 'Other Species' column.

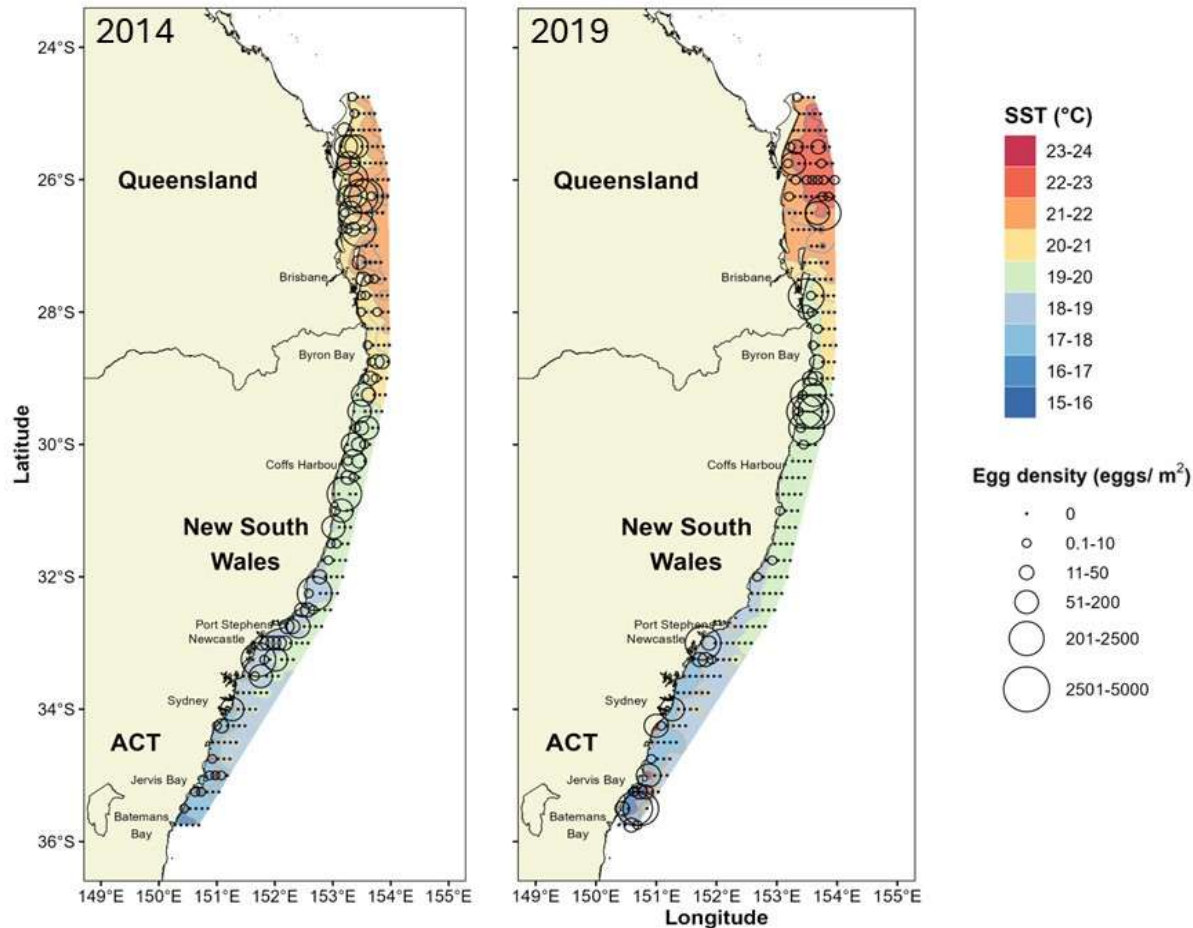
Figure A2F1. Distribution and Densities of live Blue mackerel eggs between Sandy Cape, Queensland and southern New South Wales during September 2024. Ret dots: Blue mackerel eggs confirmed by genetic analysis.



Appendix 3. Map showing egg densities of Blue Mackerel and sea surface temperatures recorded using the Conductivity Temperature Depth profiler during the plankton survey conducted during 19 August to 14 September 2014 (Ward et al. 2015) and 4–24 September 2019 (Ward et al. 2021a).



Appendix 4. Map showing egg densities of Sardine and sea surface temperatures recorded using the Conductivity Temperature Depth profiler during the plankton survey conducted during 19 August to 14 September 2014 (Ward et al. 2015) and 4–24 September 2019 (Ward et al. 2021a).



Appendix 5. Slide presented to the Resource Assessment Group for the Small Pelagic Fishery in December 2025 showing the higher catch-per-unit-effort (CPUE) recorded in trawls conducted off south-eastern Australia in 2023–25 compared to 1993–1996. Source: CSIRO. <https://research.csiro.au/sea-mes/species/> and <https://research.csiro.au/sea-mes/findings/>

