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Technical Note

Using their heads - A novel, collaborative approach between industry and scientists to monitor a commercial mullet fishery as a result of COVID-19 restrictions

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A R T I C L E   I N F O

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A B S T R A C T

The COVID-19 global pandemic-related restrictions during 2020 severely impacted the Australian seafood industry, including essential scientific monitoring to support stock assessment and to demonstrate sustainability. Here we detail a novel, collaborative monitoring program between scientists and the seafood industry to generate length and age compositions that were representative of one of the largest, most valuable, and controversial fisheries along eastern Australia, the pre-spawning ocean run fishery for Sea Mullet Mugil cephalus that is predominantly a roe fishery. The standard approach to monitoring this fishery has been to base trained scientific staff at the major processing facility for M. cephalus, where they access whole fish from entire catches to generate representative length and age compositions during the peak season, April to May. Covid-19 restrictions prevented this approach for 2020 in eastern Australia. In recognition that in addition to the high-value roe, all components of the female fish are utilized (heads and guts for bait, bodies for human consumption), a multi-stage, spatially stratified sampling design was investigated. Female heads were retained from randomly selected catches from each of the three major fishing zones and transported to the New South Wales Department of Primary Industries fish laboratory based in Sydney. Head lengths (HLs) were measured and converted to Fork Lengths (FLs) using a HL to FL relationship. The resulting fish length compositions from each catch were subsequently combined based on: (i) relative catch size of females within an ocean zone, and; (ii) the relative reported landings of females in each ocean fishing zone. Otoliths were randomly collected from heads sampled from each ocean zone and used to estimate age. The resulting ocean zone to age matrix was combined with the relative reported landings of female fish in each ocean fishing zone to generate a total female age composition for the fishery. The estimated age composition of females were typical in being mainly between ages 3 and 6, with a strong presence of 4-year olds. This stronger cohort was present as 3-year olds in 2018/19 and 5-year olds in 2020/21, thus providing confidence that our sampling was representative of the fishery. The study reinforces the positive outcomes that can be generated through co-management between scientists and the seafood industry.

1. Introduction

Extractive wild fisheries globally have been severely impacted by the COVID-19 pandemic, due to restrictions in markets and trade (FAO, 2021; Love et al., 2021; Villasante et al., 2021). Less well described have been the impacts on seafood sustainability monitoring and assessments due to COVID-19 restrictions. Directives for people to isolate or maintain social distance measures have resulted in the cancellation of both data collection programs and stock assessments (FAO, 2021). The lack of current monitoring and stock assessment leads to increased uncertainty surrounding stock sizes, with an associated difficulty in setting sustainable fishery management rules, such as Total Allowable Catches (FAO, 2021). Long time-series of data can be vital to stock assessment (Cadrin and Dickey-Collas, 2014), and many fisheries rely on sustainability reporting to justify their social licence to fish (Kelly et al., 2017). This can be particularly the case for highly visible, commercial net fisheries (Cullen-Knox et al., 2017; Murphy-Gregory, 2018).

Australia’s wild-capture fisheries are diverse (Smith et al., 2021), are

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monitored regularly and their sustainability reported through a nationally standardized approach (Flood et al., 2016, www.fish.gov.au). These assessments are then used to maintain Australia’s fisheries social licence to operate and to inform Australia’s progress against UN Sustainable Development Goal 14.4.1, “proportion of fish stocks within biologically sustainable levels”. During large parts of 2020 and 2021 Australian fisheries were substantially affected by COVID-19 related restrictions (Ogier et al., 2021). In addition to the social and economic impacts, data collection and monitoring was limited by an inability to access fishery landings.

One of the largest and most controversial commercial fisheries along eastern Australia targets flathead mullet *Mugil cephalus* (Linnaeus 1758). Colloquially known as Sea Mullet, the species supports large fisheries worldwide with landings in the order of 100,000 t p.a. (Whitfield et al., 2012). The Australian state of New South Wales (NSW) supports the largest *M. cephalus* fishery in the country (Stewart et al., 2021), and within NSW this fishery is amongst the largest and most valuable (Stewart et al., 2015). Approximately 65% of the total catch of *M. cephalus* in NSW is landed during the species annual northerly pre-spawning migration during April and May each year (Stewart et al., 2018, NSW DPI Unpublished data). This pre-spawning fishery operates on ocean beaches, generally during daylight hours, and is highly visible. Observations of fishers using large nets and hauling substantial quantities of fish onto public beaches can result in highly emotive conflict with other fishers and the broader community. In addition the primary commodity from the fishery is the roe, that is generally exported for a high value, and fishing pre-spawning aggregations is contentious amongst many of the general public as it is perceived as unsustainable. Such conflict, which threatens the social licence to continue fishing, is a major concern for the fishery (NSW Fisheries, 2003).

The Eastern Australian biological stock of *M. cephalus* is classified as a sustainable stock (Stewart et al., 2021), based largely on the results of an age-structured population model (Lovett et al., 2018). Despite this sustainable status, the commercial fishery and associated seafood industry require regular evidence that the fishery is closely monitored and that indices support the ongoing sustainable status, so as to refute claims to the contrary from opposing sections of the community. This evidence is also required to obtain government approval to export (Department of the Environment and Energy, 2018). To service these industry needs collaboration between fisheries scientists and the major seafood processing facility has been ongoing for more than 25 years (Smith and Duguara, 2002). Scientific monitoring staff access landed catch at the processing facility during April and May each year and collect data on the catch composition in terms of sizes, ages and sex ratios. These data are used directly in the stock assessment, and also in demonstrating the processed female fish are sold for recreational bait. The aim of this and female bodies are generally sold for food, and the guts and heads of the processed female fish are sold for recreational bait. The aim of this work was to utilize the normal processing system in a novel way, to be able to generate representative size and age compositions of the female component of the landed catch.

2. Methods

The NSW coast is divided in 10 ocean zones, with each zone corresponding to one-degree of latitude, that are utilized for reporting, assessment and management purposes (Fig. 1). Landings of *M. cephalus* have historically (during the last decade) been taken mainly from ocean zones 3 (20%) 4 (22%) and 5 (31%). A stratified sampling design was developed in an attempt to gain representative samples of female *M. cephalus* from each of the major fishing zones. Staff at the main seafood facility (Markwell Fisheries) were asked to save the heads from processed female fish from each ocean zone and from as many catches that could be sampled during a four-week period between the end of April and the end of May 2020. Three 8 kg boxes of heads were retained from each catch and the date, fisher, location and catch size split by males and females recorded.

The resulting 81 boxes of frozen fish heads were transported to the fish processing laboratory where further processing occurred. We measured the head length (HL) (Fig. 2) of every head sampled (N = 2499) using digital calipers to the nearest 0.01 cm, and extracted the sagittal otoliths for age estimation from a randomly selected subsample of each catch. We aimed to randomly sample 120 pairs of otoliths from each ocean zone using the assumption that there are generally fewer than 12 age classes represented in the fishery, with the vast majority being aged between three and eight years old (Stewart et al., 2018), and that sampling 10 times the number of age classes should produce a distribution with an acceptable CV (Gerritsen and McGrath, 2007). The number of otolith pairs sampled from each catch within an ocean zone was determined based on the relative total weight of each catch.

Following determination of the relationship between HL and fork length (FL, see below) we estimated the FL of each fish sampled. A fishery-wide estimate of the length frequency distribution of landed

![Fig. 1. Map of the New South Wales coast showing the 10 ocean zones used for reporting commercial fishery landings, with the total beach haul fishery landings of *Mugil cephalus* for the decade 2010/11–2019/20.](image1)

![Fig. 2. *Mugil cephalus* showing measurement of head length (HL) and fork length (FL).](image2)
female *M. cephalus* was made by combining the lengths measured from each catch within an ocean zone, with the relative weighting applied to each catch distribution being determined by the size of the female catch. The resulting length distributions for each ocean zone were then combined, with the relative weighting based on the reported commercial landings of females for each zone. These were estimated from the reported commercial landings and the observed sex ratio during sampling at Markwell Fisheries for each ocean zone.

The age of each fish was estimated by counting annuli in sectioned otoliths according to the validated methodology of Smith and Deguara (2003). The result was a matrix of age class by ocean zone for female *M. cephalus* landings. The age composition for the total landings of female *M. cephalus* was calculated using the reported commercial landings of ocean caught *M. cephalus* by ocean zone, and partitioning it into males and females using the observed sex ratio in catches sampled at Markwell Fisheries for each ocean zone (see Table 1). The relative sizes of the landings of females in each ocean zone were used to weight the relative contribution of the age composition in each zone to the total age composition for the fishery.

2.1 Morphometrics

During 2021 a respite in COVID infections in NSW enabled monitoring staff to return to the Markwell Fisheries seafood facility for normal sampling of the fishery. During that time the HL to FL relationship for the eastern Australian biological stock of *M. cephalus* was established. Linear regression was used to describe the relationship between HL and 1 cm FL bin (rounded down) and to test for differences between the sexes. Visual inspection of the model residuals was used to assess for non-linear patterns, and assess the assumptions of homogeneity and normality of the variance using the plot() command in R.

3. Results

Between the 28th April and the 26th May 2020, the Markwell Fisheries seafood facility processed 27 catches of *M. cephalus* from which random samples of female heads were collected for analysis (Table 1). Landings totaling 172,778 kg were sampled of which 84,335 kg were females. We measured the HL of 2499 *M. cephalus* and extracted otoliths from 480 fish with 120 from each ocean zone sampled (Tables 1 and 2).

3.1. Morphometrics

Three hundred and eighty fish had measurements of HL and FL taken, being 190 males and 190 females, from eight separate catches with fish ranging between 30 and 59 cm FL. Multiple linear regression analyses indicated a significant interaction between the categorical variable of sex and HL (Table 3), indicating different linear relationships between the sexes (Fig. 3). Therefore, the relationship between HL and FL for females only was applied to the head measurements for the 2019/20 season.

The converted and weighted length frequencies of female *M. cephalus* during 2019/20 were similar to those estimated from direct sampling of whole fish in other years (Fig. 4). Female *M. cephalus* ranged in length generally between 30 and 50 cm FL, and were roughly normally distributed with a peak around 40 cm FL.

Landed female *M. cephalus* were dominated by age 3-year old fish in ocean zone 1, and by age 4-year old fish in ocean zones 3, 4 and 5 (Table 2). The fishery-wide age composition of landed female *M. cephalus* as estimated through our modified sampling regime for 2019/20 was roughly normally distributed with a peak at 4 years old (Fig. 5). The age composition in 2019/20 indicated a strong cohort of 4-year old fish, consistent with observed strong cohorts of 3-year old fish in 2018/19 and 5-year old fish in 2020/21 (Fig. 5).

4. Discussion

The novel approach of sampling the female heads of *M. cephalus* - a by-product of the usual roe extraction process of a major seafood processing facility, produced results that were consistent with sampling years based on the traditional sampling design for this fishery. The estimated length composition of female fish during 2019/20, derived

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Table 1
Sample data for *Mugil cephalus* catches sampled during 2019/20.

| Sample Number | Catch Date | Ocean Zone | Total Catch Weight (kg) | Male Catch Weight (kg) | Female Catch Weight (kg) | Proportion Females | Otoliths sampled | Heads measured |
|---------------|------------|------------|--------------------------|------------------------|--------------------------|--------------------|-----------------|----------------|
| 1             | 28/04/2020 | Zone 4     | 14214                    | 7655                   | 6559                     | 0.46               | 31              | 112            |
| 2             | 30/04/2020 | Zone 5     | 10965                    | 5405                   | 5560                     | 0.51               | 17              | 113            |
| 3             | 30/04/2020 | Zone 5     | 6008                     | 2840                   | 3168                     | 0.53               | 9               | 105            |
| 4             | 30/04/2020 | Zone 5     | 4775                     | 2344                   | 2431                     | 0.51               | 7               | 101            |
| 5             | 1/05/2020  | Zone 5     | 10436                    | 5801                   | 4635                     | 0.44               | 14              | 115            |
| 6             | 2/05/2020  | Zone 4     | 23473                    | 12998                  | 10475                    | 0.45               | 49              | 114            |
| 7             | 2/05/2020  | Zone 5     | 10758                    | 4610                   | 6148                     | 0.57               | 18              | 88             |
| 8             | 2/05/2020  | Zone 5     | 2765                     | 1241                   | 1524                     | 0.55               | 5               | 80             |
| 9             | 5/05/2020  | Zone 4     | 5307                     | 3505                   | 1802                     | 0.34               | 8               | 94             |
| 10            | 5/05/2020  | Zone 5     | 4764                     | 1817                   | 2947                     | 0.62               | 9               | 71             |
| 11            | 5/05/2020  | Zone 5     | 1450                     | 480                    | 970                      | 0.67               | 3               | 73             |
| 12            | 11/05/2020 | Zone 3     | 3712                     | 2075                   | 1637                     | 0.44               | 17              | 89             |
| 13            | 11/05/2020 | Zone 4     | 13070                    | 7765                   | 5305                     | 0.41               | 25              | 85             |
| 14            | 11/05/2020 | Zone 5     | 10422                    | 4410                   | 6012                     | 0.58               | 18              | 79             |
| 15            | 12/05/2020 | Zone 5     | 4665                     | 2030                   | 2635                     | 0.56               | 46              | 79             |
| 16            | 12/05/2020 | Zone 5     | 5434                     | 1584                   | 3850                     | 0.71               | 11              | 76             |
| 17            | 13/05/2020 | Zone 4     | 3189                     | 1729                   | 1460                     | 0.46               | 7               | 87             |
| 18            | 14/05/2020 | Zone 3     | 8586                     | 4574                   | 4012                     | 0.47               | 41              | 87             |
| 19            | 15/05/2020 | Zone 3     | 3673                     | 2016                   | 1657                     | 0.45               | 17              | 89             |
| 20            | 16/05/2020 | Zone 1     | 348                      | 169                    | 179                      | 0.51               | 3               | 101            |
| 21            | 20/05/2020 | Zone 1     | 4555                     | 2557                   | 1998                     | 0.44               | 35              | 100            |
| 22            | 22/05/2020 | Zone 3     | 6274                     | 3641                   | 2633                     | 0.42               | 27              | 94             |
| 23            | 23/05/2020 | Zone 5     | 5424                     | 2422                   | 3062                     | 0.55               | 9               | 96             |
| 24            | 24/05/2020 | Zone 1     | 697                      | 264                    | 433                      | 0.62               | 8               | 101            |
| 25            | 25/05/2020 | Zone 1     | 2321                     | 1365                   | 956                      | 0.41               | 17              | 90             |
| 26            | 25/05/2020 | Zone 3     | 4212                     | 2427                   | 1694                     | 0.41               | 18              | 87             |
| 27            | 26/05/2020 | Zone 1     | 1372                     | 719                    | 653                      | 0.48               | 11              | 93             |
| TOTALS        |            |            | 172778                   | 84335                  | 88443                    |                     | 480             | 2499           |
from sampling head lengths, was consistent with observations during the past 15 years, approximated by a roughly normal distribution, ranging between 30 and 50 cm FL, with an average of approximately 41 cm FL (Stewart et al., 2018, Fig. 4).

The estimated age composition of female *M. cephalus* within the landed catch indicated the majority (95%) were aged between 3 and 6 years, with a strong peak at age class 4. This stronger cohort was present as 3-year olds in 2018/19 and 5-year olds in 2020/21 (Fig. 5), thus providing confidence that our novel sampling approach during 2019/20 did produce results that were representative of the fishery.

The use of partial length measurements for monitoring is not new, particularly for species that are processed (e.g., headed, filleted) before being delivered to market (Holden and Raitt, 1974). The linear relationship between the HL and FL for *M. cephalus* differed between males and females in the present study. Similarly, a study on body morphometrics of *M. cephalus* in Mexico also reported significant differences in the body length to head length ratio between the sexes (Ibáñez Aguirre and Lleonart, 1996). This simply reinforces that any key to convert partial to total lengths should be developed from the population, or part thereof, being studied (Holden and Raitt, 1974). We have demonstrated the utility of applying body morphometric relationships for species that cannot be accessed as whole fish for monitoring. Our positive results could potentially lead to further investigations into monitoring fishery landings of species that are processed at sea, and consequently have been viewed as requiring relatively expensive onboard monitoring (via trained scientific observers). Candidate species include Monacanthids and elasmobranchs that are beheaded at sea (Miller and Stewart, 2009; Braccini et al., 2006; Huveneers et al., 2007).

A novel sampling approach that used the routine processing and marketing practices from a large-scale processing facility for *M. cephalus* to achieve required monitoring was successful. It was fortunate that the marketing of female fish heads for bait, following roe extraction, facilitated both length monitoring and also age monitoring as the otoliths remained within the heads when removed. Despite the success, there were several limitations when compared to the traditional monitoring, whereby trained scientific staff are based directly at the seafood facility to access whole fish from entire catches. One obvious limitation is that we were only able to monitor the female portion of the landed catch, as male fish were sold-on whole. This may not be a major concern as the fishery is mainly focussed on female fish as they bring a greater economic return. However, male fish tend to recruit to the pre-spawning run fishery one year earlier than females (Stewart et al., 2018), meaning that any strong (or weak) age classes would remain unseen for an extra year if only females could be monitored. Another potential negative from this novel sampling approach was a reliance on untrained staff at the seafood facility to put aside head samples. This was overcome through a carefully designed, well described sampling protocol with oversight of the facility manager. However, related to this was an increase in responsibility, and so time, of the collaborating seafood facility staff.

Table 2
Summary of the age classes of *Mugil cephalus* sampled from each ocean zone during 2019/20. The age samples from separate catches within each zone were weighted according to the relative catch sizes.

| Age Class | Zone1 | Zone2 | Zone3 | Zone4 | Zone5 | Zone6 | Zone7 | Zone8 | Zone9 | Zone10 | TOTALS |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|--------|
| 0         | 1     |       |       | 1     |       |       |       |       |       |        | 120    |
| 1         | 8     | 1     |       | 6     | 2     | 2     |       |       |       |        | 20     |
| 2         | 65    | 25    | 25    | 19    | 26    |       |       |       |       |        | 120    |
| 3         | 23    | 62    | 62    | 64    | 52    |       |       |       |       |        | 24     |
| 4         | 16    | 20    | 20    | 30    | 24    |       |       |       |       |        | 46     |
| 5         | 7     | 5     | 5     | 5     | 14    |       |       |       |       |        | 38     |
| 6         | 1     | 1     | 1     |       | 1     |       |       |       |       |        | 2      |
| 7         |       |       |       |       |       |       |       |       |       |        |        |
| 8         |       |       |       |       |       |       |       |       |       |        |        |
| 9         |       |       |       |       |       |       |       |       |       |        |        |
| 10        |       |       |       |       |       |       |       |       |       |        | 2      |
| TOTALS    | 120   | 0     | 120   | 120   | 120   | 120   | 120   | 120   | 120   |         | 120    |

Table 3
Multiple linear regression model outputs for fork length (FL) against head length (HL) and sex for *Mugil cephalus*.

| Model   | Coefficient | Estimate | SE | P      | R² |
|---------|-------------|----------|----|--------|----|
| FL      | Intercept   | -0.10    | 1.83 | NS    | 0.85 |
| HL      | 4.78        | 0.20     | < 0.01 |
| Sex (male) | 4.99     | 2.51     | < 0.05 |
| HL-Sex  | 0.75        | 0.29     | < 0.05 |

Fig. 3. Linear relationships between Head Length (HL) and Fork Length (FL) (1 cm bin) for female and male *Mugil cephalus*.

Despite these limitations, there were also significant benefits through our novel sampling during 2019/20. The major benefit was in being able to demonstrate the ongoing sustainability of this fishery and in maintaining its social licence to continue. In addition, there were substantial savings through a reduction in time that trained scientific monitoring staff had to be in the field, based at the seafood facility for several weeks. These extended trips are often hampered when rough seas or other detrimental factors mean that fish are not being caught, resulting in paid staff having nothing to monitor. Such non-productive days were not an issue with the novel sampling design. In fact, during 2019/20 we were able to sample approximately 2500 fish for length monitoring, compared to the more typical number of around 1500 (Stewart et al., 2018, Fig. 4). Enabling the seafood industry to have increased ownership of the monitoring, and resultant fishery assessment, increases trust and collaboration between the industry and regulatory authorities. As commercial fisheries in NSW transition to more modern management regimes, including formal harvest strategies and cost-sharing arrangements, an increased focus on industry-based data collection and co-management is expected. The novel approach used here could be used as a case study when developing future monitoring programs.
CRediT authorship contribution statement

John Stewart: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. James Craig: Formal analysis, Investigation, Data Curation, Writing – original draft, Visualization, Project administration. Chantelle Clain: Investigation, Writing – original draft, Visualization. Anne-Marie Hegarty: Investigation Writing – original draft, Visualization, Project administration. Nick Meadows: Investigation, Writing – original draft, Visualization. Antony Gould: Investigation, Writing – original draft, visualization. Caitlin Young: Investigation, Writing – original draft, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Fig. 4. Fishery-wide estimates of the length composition of landed female Mugil cephalus in New South Wales 2017/18–2020/21.

Fig. 5. Fishery-wide estimates of the age composition of landed female Mugil cephalus in New South Wales 2018/19–2020/21.
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