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MANAGEMENT BRIEF

Adaptive Spatial Management to Deal with Postflood Inshore Bycatch in a Penaeid Trawl Fishery

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Abstract
Adaptive spatial management provides a way to balance the conservation of bycatch species and the potential economic effects of bycatch-induced closures on a fishery, but implementation can be both data and resource intensive. We present a survey exploring a novel approach to adaptively manage an intermittent bycatch issue in an inshore trawl fishery where Sciaenidae bycatch species (including juvenile Mulloway *Argyrosomus japonicus*, a species of conservation concern) co-occur with large aggregations of a valuable target species (eastern school prawn *Metapenaeus macleayi*), following flood-induced egression from estuarine habitats. Diurnal sampling surveys followed three flood events and targeted permanent inshore closure zones (designed to protect the normally nocturnally harvested eastern king prawn *Melicertus plebejus*) and adjacent inshore nonclosure areas. Sciaenidae abundance was mostly <10 fish/ha trawled, but larger catches generally corresponded with larger catches of eastern school prawn, and these relationships appeared to be steeper within nonclosure zones. There were only minor differences in the size structure of eastern school prawn between zones, and patterns were event and location specific. Negligible eastern king prawn were encountered. The results show that temporarily allowing fishers access to permanent trawl closures following floods may support the exploitation of aggregated target species with reduced interaction with bycatch species of concern. The approach presented here is relevant to the consideration of adaptive spatial management in other trawl fisheries.

Bycatch and interaction with nontarget species is a pervasive issue for all trawl fisheries (Broadhurst 2000). Interaction with nontarget species is particularly problematic when species of conservation concern are encountered and suffer additional mortality as a result of interaction with trawl gear (Beardsall et al. 2013; Gray and Kennelly 2018). Bycatch reduction devices are commonly used to deal with this issue in trawl fisheries (e.g., Brewer et al. 2006); however, closures may also be employed (e.g., Gupta et al. 2020), particularly where the spatiotemporal dynamics of the affected species are well known. Although spatiotemporal closures are likely to be effective in reducing (or preventing) interactions, the removal of fishing effort can come at a significant economic cost to fishers, as access to exploitable stock of target species may be constrained (Broadhurst 2000). Furthermore, this can lead to unforeseen effects in other areas, as effort is displaced (e.g., Abbott and Haynie 2012).

Adaptive spatial management provides a way to balance the conservation of bycatch species with the potential adverse economic effects of bycatch-induced closures on the fishery. However, implementing such an agile approach to management can be both data and resource intensive. Although adaptive management generally has substantial information needs, published examples of research surveys that are intended to inform such decisions are rare. This management brief presents the outcomes of a preliminary survey that was designed to inform the consideration of a novel approach to adaptively manage an

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intermittent bycatch issue within the New South Wales (Australia) Ocean Trawl Fishery (NSW OTF) and convey this practical management experience to readers.

METHODS

Management context and study design.— The NSW OTF targets a large number of primary species, and eastern king prawn *Melicertus plebejus* and eastern school prawn *Metapenaeus macleayi* are two of the most heavily targeted crustaceans. Eastern school prawn have a Type-II penaeid life cycle with an estuarine and oceanic phase whereby they move from estuaries to adjacent inshore habitats to spawn (Racek 1959; Ruello 1977; Glaister 1978b). The movements of eastern school prawn are heavily influenced by rainfall in the catchments of important estuarine nurseries, and high levels of freshwater inflow stimulate episodic emigration from the estuary (Ruello 1973) resulting in large aggregations of high-grade prawns within inshore waters that are adjacent to estuaries. These aggregations are exploited by NSW OTF fishers (Glaister 1978a), with austral autumn (March–May) floods often producing large catches around the Australian Easter holiday period (April), when the market is strong and prices are high for fresh, locally caught eastern school prawn.

The estuarine egression of eastern school prawn is mirrored by juvenile Mulloway *Argyrosomus japonicus*, and co-occurrence of the species in shallow inshore waters means that fishers can encounter high levels of juvenile Mulloway bycatch (as well as bycatch of another oceanic Sciaenidae–Teraglin *Atractoscion aequidens*) while exploiting the abundant eastern school prawn. The New South Wales (NSW) Mulloway population is considered to be depleted (Earl et al. 2020), with a spawning potential ratio <20% of virgin levels (Hughes 2020). Although the effects of inshore bycatch mortality at previously observed levels on the broader Mulloway population is not yet clear, bycatch of this iconic angling species remains an issue of significant public and management interest. The juvenile Mulloway that are encountered are often of a size similar to that of the prawns that are being targeted, which can make typical bycatch-reduction-device grids less effective. Consequently, the bycatch issue is often managed through the implementation of temporary spatial closures in addition to bycatch reduction devices to reduce interaction between trawlers and Mulloway, but this usually includes temporary closure of grounds where eastern school prawn are particularly abundant. Although temporary closures help to minimize potential bycatch-related sustainability issues for the Mulloway stock, such closures have adverse economic and social effects on NSW OTF fishers that are somewhat exacerbated when this scenario occurs during the austral autumn, when prices are buoyant. Other expansive inshore areas adjacent to estuaries are also closed to trawling through a permanent closure network (juvenile eastern king prawn [JEKP] closures, Taylor et al. 2021). It has been suggested that temporarily opening the JEKP closure grounds to daytime trawling for the period when eastern school prawn are abundant in the inshore areas could provide alternate areas where the species can be targeted when other areas are closed due to Mulloway bycatch. The premise behind this idea is that eastern king prawn are usually trawled nocturnally (as they are more nocturnally active), whereas eastern school prawn are usually trawled diurnally in inshore waters following floods, so daytime trawling may not unduly affect the juvenile eastern king prawn that these permanent closures are intended to protect. Such a strategy will only be feasible if areas within JEKP closures support abundant eastern school prawn with limited Mulloway and Teraglin bycatch; however, there is no data to inform the design or suitability of such arrangements.

The trawl survey reported here sought to provide data to support the consideration of the strategy outlined above by examining the distribution, abundance, and size structures of eastern king prawn, eastern school prawn, and Sciaenidae (including both Mulloway and Teraglin) that are encountered during diurnal trawling within JEKP closures and adjacent inshore areas following floods in adjacent estuaries. Specifically, the sampling was designed to compare these variables between JEKP closures (adjacent to the mouths of flooded estuaries) and adjacent inshore areas, with the survey window targeting flood events that occurred between 2017 and 2020.

Sampling was thus undertaken through a daytime trawl survey within the inshore areas (including JEKP closures and adjacent nonclosure areas that are normally trawled for eastern school prawn) adjacent to the Richmond River and Clarence River, the major prawn trawl ports (Ballina and Yamba/Iluka, respectively) within NSW (Figure 1). The surveys were activated and field teams mobilized following floods that approached or exceeded the trigger threshold at which short-term trawling closures would be implemented to minimize Mulloway bycatch (moderate flood level, http://www.bom.gov.au/water/floods/floodWarningServices.shtml). The timing and duration was generally informed by local fishers based on their knowledge of the currents and localized stock movements and prevailing weather conditions (the east-coast low-pressure systems that produce floods in southeastern Australia are often accompanied by extremely challenging ocean conditions).

Sample collection and data analysis.— Single trawls were conducted within randomized 0.3×1 nm grid squares. A numbered grid of squares was applied to the complete survey area at each location (with the exception of known nontrawlable areas), and a set of grid numbers was

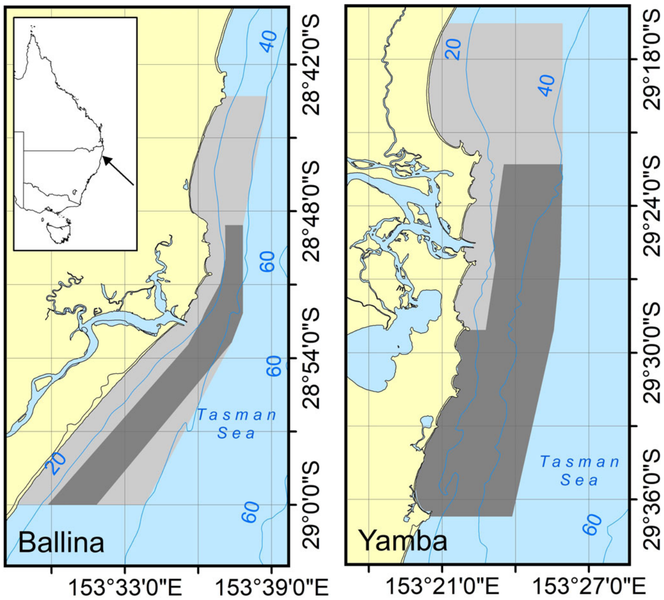

FIGURE 1. Map of management areas investigated, showing JEKP closure (dark gray) and nonclosure (light gray) zones at each location and adjacent estuaries. The bathymetry (m) contours are indicated as light blue lines. The inset in the top left indicates the general location of the study areas relative to the eastern Australian coast.

randomly selected across each survey area (without replacement) for each sampling event to generate a list of coordinates across each strata where the trawls would be conducted. The use of grid squares was simply a way to distribute sampling effort across the survey area, and a grid square was only ever sampled once during a survey event. In the case where the trawl nets fouled during a tow, the sample was excluded, the tow contents were discarded, and the next randomly selected grid was sampled. A 20-min tow of the trawl net was the basal replicate sampling unit, and sampling occurred between 0600 and 1800 hours (i.e., during the day). The GPS coordinates were recorded at the start and end of each tow and used to calculate the distance trawled (trawls were generally conducted in a straight line).

After each trawl, the contents of the port and starboard cod ends were spilled and samples sorted. For each trawl, the total catch of eastern school prawn, Sciaenidae (Mulloway or Teraglin), and eastern king prawn was weighed (0.1 kg precision) and subsampled (<1–2 kg) where necessary before freezing for further processing at the laboratory. At the laboratory, the total sample was weighed and length and weight (0.1 g precision) of each individual was recorded. For prawns, carapace length (CL [mm], measured as the straight-line distance between the base of the eye orbit and the centre of the posterior margin of the carapace) was recorded, whereas total length (TL, mm) was measured for Sciaenidae.

All data exploration and data analysis were undertaken in R v. 4.0.2 (R Core Team 2020). The trawl and biological data were compiled, and the catch data were also standardized by distance towed, net spread, and subsample size. Initial exploration of the data examined the interspecific relationships in abundance between eastern school prawn and eastern king prawn and between Mulloway and Teraglin. The variation in the raw biomass (kilograms for prawns) and abundance (counts for fish) of the main species that were encountered between zones and events was evaluated using generalized linear models (GLMs), with the area that was trawled (ha) by each sample specified as an offset within the model. The models were fitted using the glm or glm.nb functions in the Modern Applied Statistics with S (MASS) package (Venables and Ripley 2002). Error distributions and link functions were selected for each model following the exploration of the data, and the models were of the form *Species* ~ *Zone*-*Event*, where *Species* was the total biomass (for prawns, transformed using a constant [+0.1] to remove zero data) or total abundance (for Sciaenidae) in individual trawls, and parameter coefficients were exponentiated where required. Moran's I test was used to confirm that data were not spatially autocorrelated. For the interaction models, the Akaike information criterion was used to determine the best combination of explanatory variables, using the stepAIC function (MASS package) with forward and backward selection and a criterion for model improvement of 2 Akaike units. Overall goodness of fit was also considered through the ratios of residual deviance to null deviance (higher ratios indicate poorer fitting models). Abundance relationships between eastern school prawn and total Sciaenidae within closure and nonclosure zones were further explored with additional GLMs for each event. The length data were expressed as weighted kernel density distributions for the Ballina and Yamba data, calculated with the density function in the MASS package (Venables and Ripley 2002). The weighting factor that was used in the kernel density distributions was specified against each length measurement through the density function and was calculated to correct for minor differences in the biomass of each subsample that was measured for lengths and differences in the tow biomass that each subsample represented. The length structures of species were compared among zones through inspection of the weighted kernel density distributions and consideration of the *P*-values from Kolmogrov–Smirnov tests.

RESULTS

General Comments and Observations

The project had been planned following feedback from the industry after a number of years when temporary closures (described above) had been implemented. Flood events frequently coincided with inclement weather, usually associated with persistent low-pressure systems along southeastern Australia. The sampling survey proceeded following three "events" (Figure 2), with sampling during each event guided by the advice of experienced trawl operators that it was safe and worthwhile to do so, including that eastern school prawn were present in inshore waters (this informed by expertise of industry and exploratory shots). Consequently, due to differences in the locations

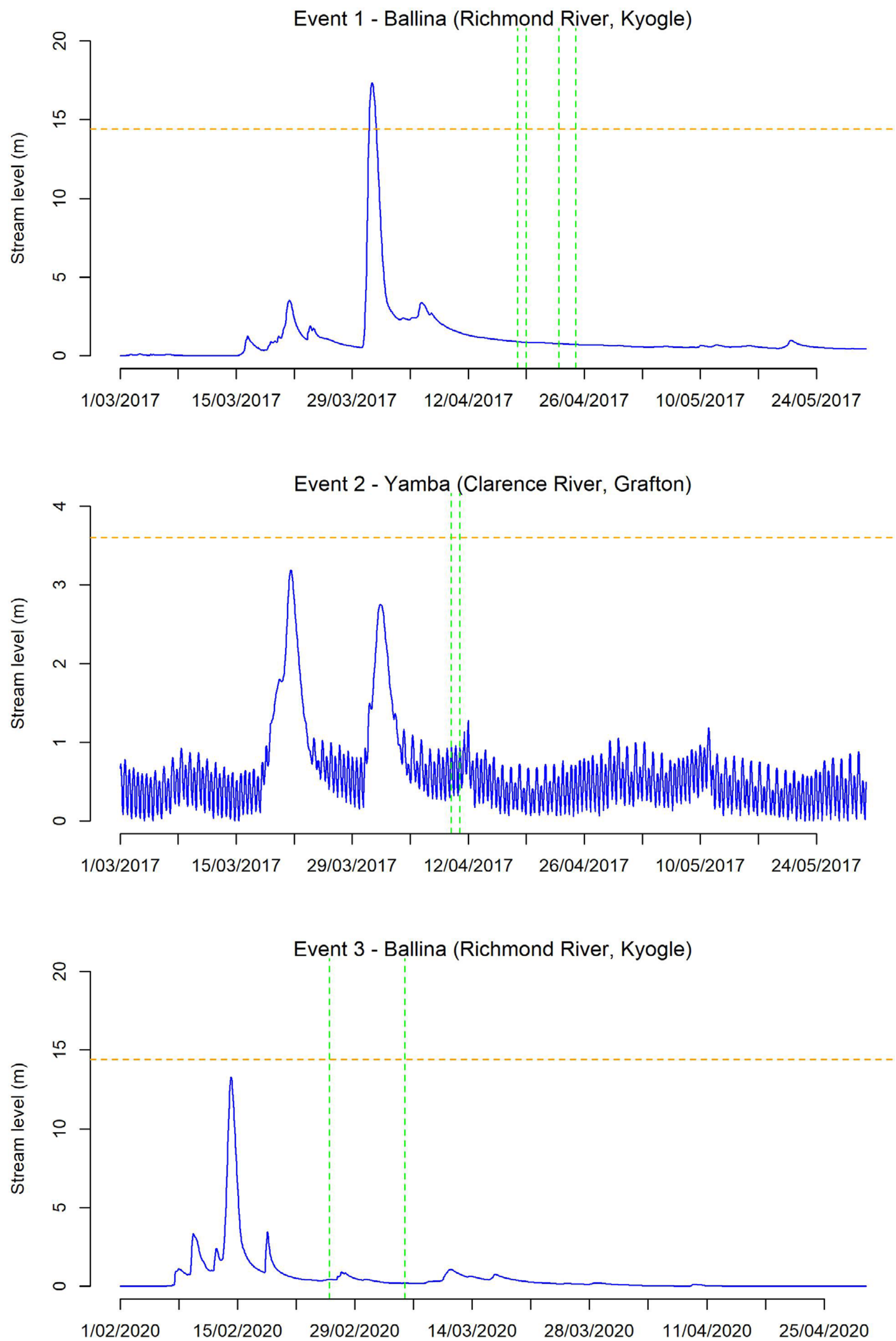

FIGURE 2. Stream-level trace in the estuaries adjacent to the Ballina and Yamba survey areas (Figure 1) for the three events targeted during the survey. The vertical green dashed lines indicate sampling points following each event. The location of the water monitoring station is indicated in the title for each panel. The horizontal orange dashed line indicates the stream level that corresponds to the declaration of "moderate" flood level (as listed for the estuaries and gauging stations above in NSW State Emergency Service, 2018).

and magnitude of each event and differences in the estuaries and catchments involved, there were some differences in the time between the inflow event and sampling campaign that followed (Figure 2). A total of eight trips occurred across these three events (Figure 2), which yielded 67 trawls across the surveyed strata.

Patterns in Animal Abundance and Size Structure.

Eastern school prawn were encountered in ~75% of the samples, at between <1 and 54 kg/ha. Mulloway and Teraglin were encountered in ~40% and ~53% of the samples, respectively, but only at comparatively low abundances (ranging from <1 to 90 individuals/ha, with a mean of ~5 individual/ha). As noted in the Methods section, one of the goals of the survey was to evaluate whether daytime trawling following floods adversely affected eastern king prawn, which were the target of the JEKP closures—eastern king prawn were barely encountered during the sampling program at all, with a maximum biomass of <1 kg/ha and a median biomass approaching zero. There was no evident relationship between eastern school prawn and eastern king prawn catch (Figure 3).

Catches of eastern school prawn, Mulloway, and Teraglin were highly variable between closure and nonclosure zones and flood events, yielding skewed distributions for some strata combinations (Figure 4). There was a large number of trawls where Mulloway and Teraglin were not encountered, but when they were encountered they were often present in similar numbers. A negative binomial GLM comparing abundance data showed a weak relationship between the two species ($\beta = 1.03$, $z = 8.07$, $P < 0.001$; residual: null deviance ratio = 0.68). Eastern school prawn biomass did not show any obvious trends across zones and events, and this was reflected in a GLM (gamma distribution and log link function) and subsequent model selection, with the best model being the intercept-only model (full model residual: null deviance ratio = 0.94). For Sciaenidae, only the Ballina 2017 and Yamba 2017 events were analyzed, as no Sciaenidae were encountered during the Ballina 2020 event. The large number of zeros necessitated a two-step hurdle modeling process, involving an initial binomial logistic GLM of presence/absence data, followed by a negative binomial GLM of abundance in nonzero samples. Following model selection, the best logistic model of total Sciaenidae presence/absence data showed that Sciaenidae were more likely to be encountered within nonclosure zones ($\beta = 6.52$, 95% CI [1.77–29.42], $z = 2.66$, $P = 0.007$; Figure 4), but this model had low explanatory power (residual: null deviance ratio = 0.85). The negative binomial GLM of abundance data for the nonzero samples showed no effect of zone on abundance, with the only nonintercept term in the best model indicating a greater abundance of Sciaenidae during the

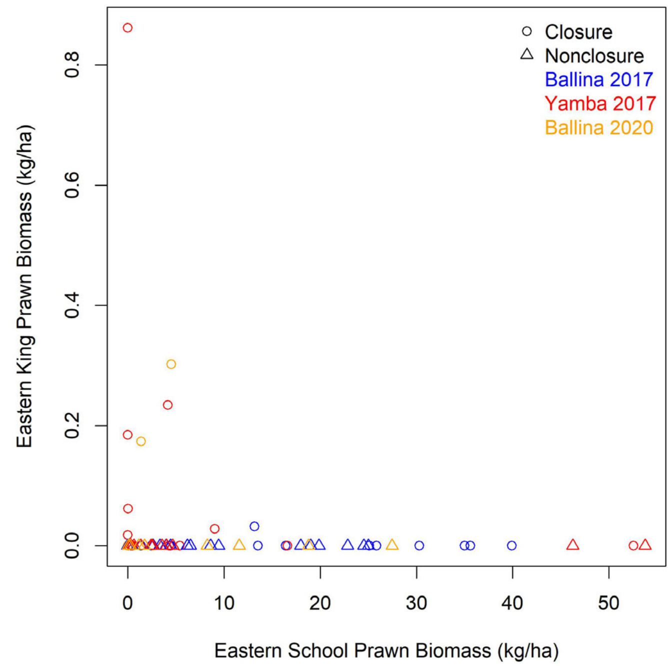

FIGURE 3. Biomass of eastern king prawn encountered during the survey presented against the eastern school prawn biomass captured in the same tow, showing negligible catches of eastern king prawn across the range of eastern school prawn catches encountered. The symbols are coded by sampling strata, including zone (symbol shape) and event (color), as indicated in the legend.

Yamba 2017 event ($\beta = 12.30$, 95% CI [3.91–43.62] $z = 4.19$, $P < 0.001$; Figure 4). This model also had comparatively low explanatory power (residual: null deviance ratio = 0.71).

Larger catches of total Sciaenidae often corresponded with larger catches of eastern school prawn. When evaluated for each event, there was a positive relationship between eastern school prawn biomass and total Sciaenidae abundance across zones for both Ballina (Closure: $\beta = 2.72$, 95% CI [1.91–3.95], $z = 5.37$, $P < 0.001$; Nonclosure: $\beta = 3.34$, 95% CI [2.17–5.38], $z = 5.85$, $P < 0.001$; residual: null deviance ratio = 0.50) and Yamba (Closure: $\beta = 5.47$, 95% CI [1.86–20.64], $z = 3.70$, $P < 0.001$; Nonclosure: $\beta = 10.53$, 95% CI [1.58–52.96], $z = 5.30$, $P < 0.001$; residual : null deviance ratio = 0.73). Although the size of the parameter coefficients indicated that the relationships between eastern school prawn and total Sciaenidae were steeper within nonclosure zones compared with closure zones (suggesting there were fewer Sciaenidae caught per unit eastern school prawn biomass within closure zones), the confidence intervals surrounding these coefficients had considerable overlap.

The size structures showed only minor differences between the closure and nonclosure zones. The most obvious differences were for eastern school prawn, where the

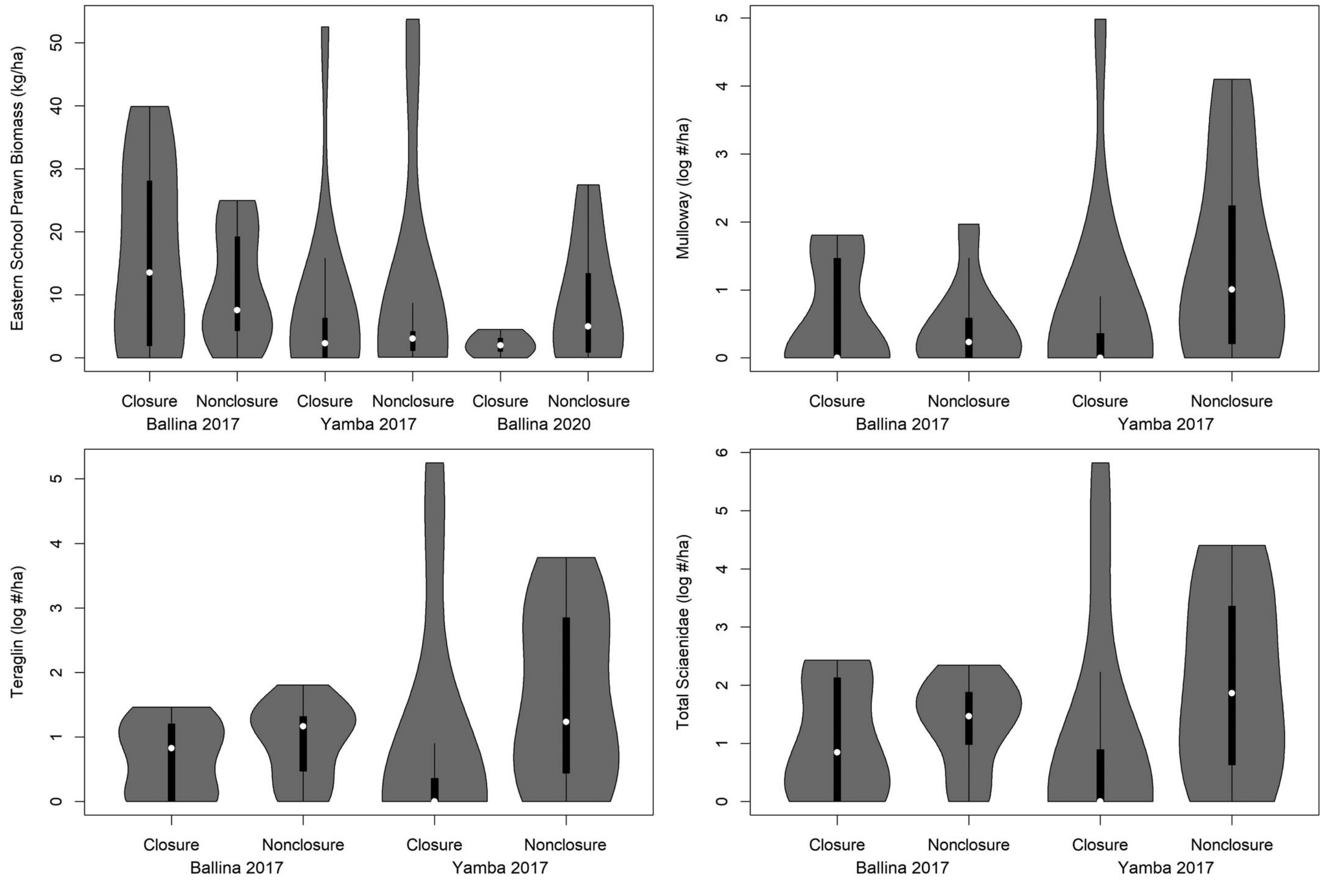

FIGURE 4. Violin plot summarizing the biomass or abundance of the main species captured across strata. The gray shaded area indicates a probability density function that reflects the distribution of the data, and the inlaid box and whisker (within the gray shading) reflect the interquartile range and the range of data, respectively. The white circle indicates the median value.

prawns were larger and bigger size grades were better represented within the closure zone for the Ballina 2017 event (Figure 5). The prawns that were captured during the Yamba 2017 event were generally smaller than in both Ballina events, but larger prawns and better size grades occurred in the nonclosure zone than in the closure zone. There were only minor differences in size structures between zones for Mulloway and Teraglin for both of the 2017 events (Figure 5).

DISCUSSION

Overall, despite the small number of events that occurred during the survey window, the survey provided insight to patterns in occurrence and co-occurrence of the species of interest that were relevant to the management question being considered. Mulloway and Teraglin were often encountered at similar abundances in the same tows, which suggests that juvenile Mulloway share habitats with coastal juvenile Teraglin following their egression from the estuary. It is unknown whether these inshore habitats where Teraglin were encountered represent their usual habitats; certainly neither juvenile Mulloway nor juvenile Teraglin have been regularly encountered in other trawl surveys on these grounds (e.g., Taylor et al. 2020). Teraglin may well be moving into inshore soft-sediment habitats following floods to exploit the pulse of food sources that have washed out of the estuary. Although it is possible that the co-occurrence of Mulloway and eastern school prawn may be driven by predator–prey relationships, prawns are of minimal dietary importance for Mulloway at sizes <100 mm TL (Taylor et al. 2006). Despite being abundant within the survey area (Taylor and Johnson 2020), the comparative lack of eastern king prawn encountered was not surprising as eastern king prawn are normally caught at night.

Implications for Adaptive Management

The survey data indicate that the densities of eastern school prawn that were encountered within JEKP closures were at least comparable to those of adjacent inshore areas that are nominally fished for eastern school prawn.

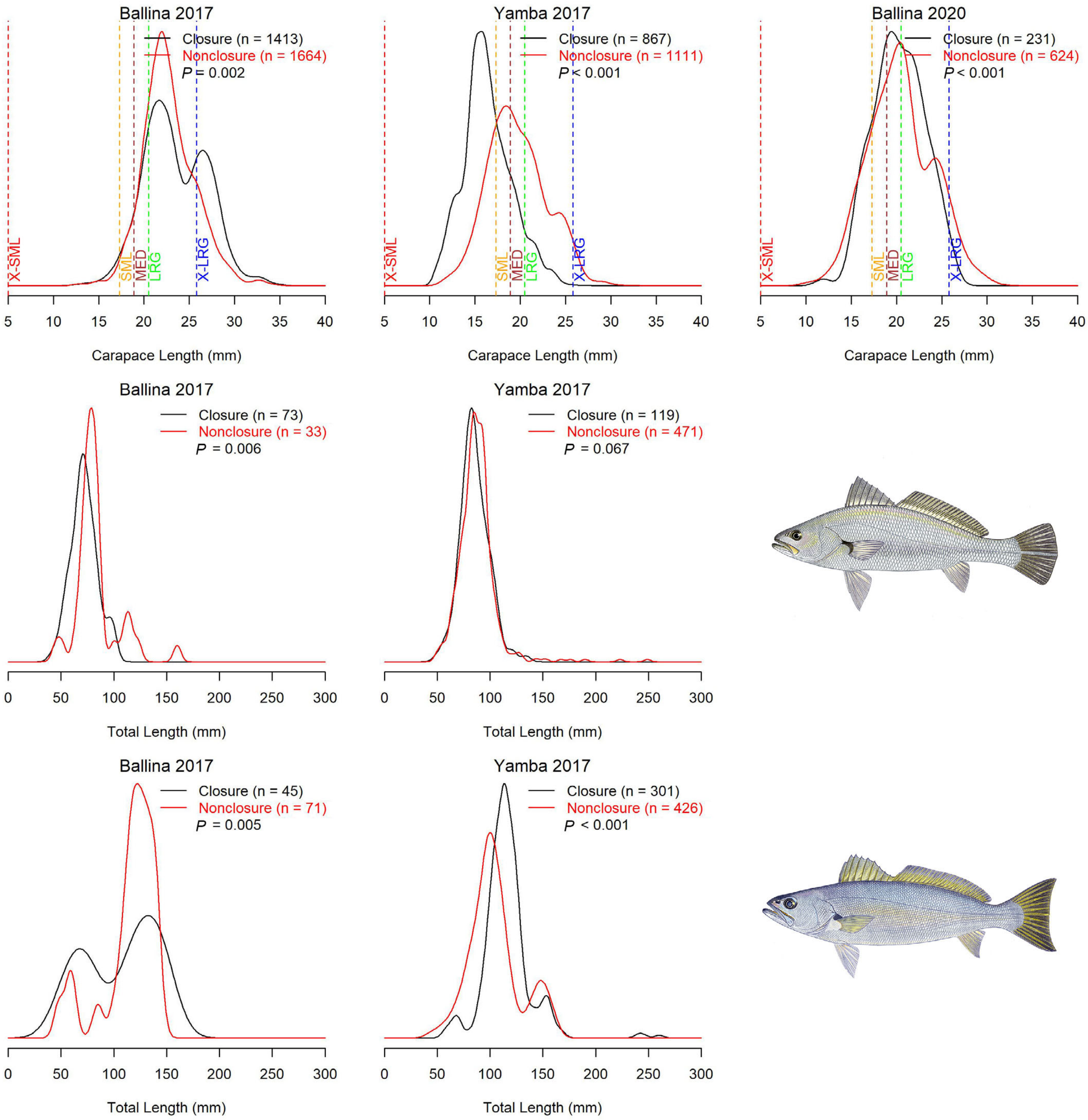

FIGURE 5. Relative size structure of eastern school prawn (top row), Mulloway (middle row), and Teraglin (bottom row) encountered from north coast inshore areas following flood conditions in adjacent estuaries. The values are presented as kernel density distributions for closure (black line) and nonclosure (red line) zones. Each panel title indicates the location and year of each event, and the number of fish (*n*) used in each distribution is indicated in the panel legends, as is the significance value from the Kolmogorov–Smirnov test for differences between the length distributions. Note that there were no Mulloway or Teraglin captured during the Ballina 2020 event. Also indicated are the commercial size-grade data for eastern school prawn (converted from counts) for the Sydney Fish Market (vertical dashed lines indicating “extra small,” “small,” “medium,” “large,” and “extra large”).

In addition, negligible eastern king prawn were encountered, so temporarily allowing daytime trawling within JEKP closures is unlikely to adversely affect juvenile eastern king prawn. Although both Mulloway and Teraglin were still present within the permanent JEKP closures, consideration of simple trends in the data suggested that Sciaenidae bycatch may be lower within closure zones compared with nonclosure zones (for example, see Figure 4). However, the modeling of these patterns suffered from general patchiness and high variability in the abundance of Sciaenidae, which was probably exacerbated by the dynamic environmental conditions during the surveys (which would require substantially increased sampling effort to overcome). Also, comparatively few events were sampled and they were somewhat nuanced—this is often a constraint of event-based studies, particularly where sampling generally coincides with adverse meteorological conditions. Nonetheless, the modeled relationship between eastern school prawn and Sciaenidae bycatch was "shallower" within the JEKP closures, which indicates that the number of Sciaenidae encountered per kilogram of prawns harvested may be lower within the permanent closure areas. Combined with evidence for the comparable densities of similar or better size-grade prawns encountered within the JEKP closures, the above trends suggest that the adaptive management regime that was evaluated warrants further consideration.

Recommendations and Conclusions

Published examples outlining such agile surveys are rare, perhaps due to the logistical challenges posed. Event-based sampling, such as that reported here, generally needs to quickly mobilize staff that are suitably qualified and experienced to operate in challenging conditions. This was possible during our surveys through the deployment of regionally based staff and contractors who are normally engaged in other trawl observer programs. These logistical challenges may be partially addressed in future surveys through the engagement of respected and trusted industry participants in the collection of data to inform adaptive management decisions.

The outcomes from this work will aid future decision making on accessing JEKP closures during the periods following floods if bycatch issues lead to the closure of nominal grounds where eastern school prawn are aggregated following floods. Eastern school prawn were present in "economic" quantities and size grades within the JEKP closures, which suggests that the temporary and partial opening of JEKP closures could be considered as an ameliorative management strategy to dampen the adverse economic consequences that are associated with bycatch-induced short-term closure of other fishing grounds. However, adaptive management is often considered as a hypothesis-testing framework (Williams 2011), so any strategy change is best applied cautiously and accompanied by suitably designed monitoring and evaluation (Hilborn and Sibert 1988). In the case of JEKP closures, implementation may be initially accompanied by "trial" shots to evaluate whether eastern school prawn are present and that Sciaenidae (Mulloway in particular) are encountered in comparatively low abundances (or not present) before trawling is allowed more broadly. If areas of abundant eastern school prawn are encountered, vessels could be permitted to temporarily operate within JEKP closures, but some specific conditions should be considered to ensure that the activity is well managed and temporary arrangements are not abused, including a "move on" rule if elevated levels of bycatch are encountered. This might include the use of vessel monitoring systems to ensure that vessels do not fish outside of designated areas and deployment of observer or electronic monitoring systems to monitor bycatch on vessels that elect to operate within JEKP closures. We also wish to highlight that although the effects of temporarily allowing fishing within JEKP closures on the broader assemblage are difficult to quantify, there is a need to consider these additional elements in any decisions about adaptive spatial management. The general principles outlined here are relevant to the consideration of spatiotemporal adaptive management within other trawl fisheries.

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