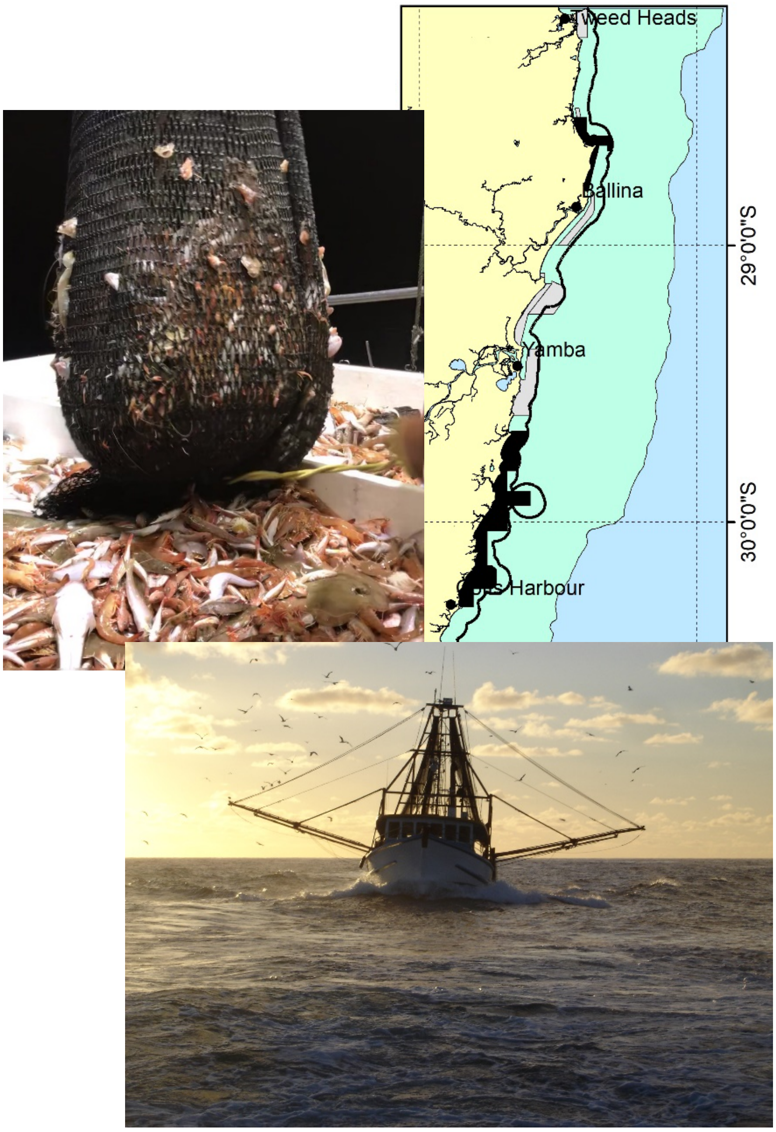
Spatial management within the NSW Ocean Trawl Fishery



Matthew D. Taylor

Daniel D. Johnson

Darren Hale

Edward V. Camp

Bronwyn M. Gillanders

Angela Russell

Tom Barnes

June 2021

FRDC Project No **2016/020**

ISBN 978-1-76058-482-5

Spatial management within the NSW Ocean Trawl Fishery
2016/020

2021

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

Researcher Contact Details
Name: Matthew D. Taylor
Address: Port Stephens Fisheries Institute
Taylors Beach Rd, Taylors Beach,
NSW, 2316
Phone: 02 4916 3937
Email: matt.taylor@dpi.nsw.gov.au

FRDC Contact Details
Address: 25 Geils Court
Deakin ACT 2600
Phone: 02 6285 0400
Fax: 02 6285 0499
Email: frdc@frdc.com.au
Web: www.frdc.com.au

Contents

Tables

Figures

Acknowledgments

We would like to thank the personnel from various organisations who contributed to this project, including J. Silburn, T. Barnes, D.J. Booth, M. Harrison, T. New, M. Burns, J. McLeod, A. Pidd, A. Creese, M. O'Sullivan, L. Bidgood, and B. Leach. In addition, we would like to acknowledge the skippers and crews of the fishing vessels that assisted in survey work over the course of the project, and Eastern King Prawn fishers across NSW and Queensland for assisting with tag recaptures. We also thank the Professional Fishers Association for support in developing this project.

Executive Summary

New South Wales (NSW) DPI-Fisheries reports on the outcomes of a 4-year trawl survey (2017-2020) aimed at evaluating spatial management provisions within the NSW Ocean Trawl Fishery, and the potential for these to be adapted to deal with tactical challenges associated with Eastern School Prawn (*Metapenaeus macleayi*) harvest and Mulloway (*Argyrosomus japonicus*) bycatch following floods in northern NSW. A combination of trawling, tagging, and modelling was used to examine the abundance and distribution of key species in and around the Juvenile Eastern King Prawn (JEKP) closure network, connectivity with the Eastern King Prawn (EKP) fishery, impact of the network on EKP harvest, and to better define source-sink dynamics in Mulloway, which is an important bycatch species. The JEKP closure network functioned effectively in the protection of small EKP, but the overall impact on harvest magnitude in the contemporary EKP fishery was comparatively low. However, the network also provided significant protection for a suite of other quota-managed and bycatch species. Eastern School Prawn were sampled in economic quantities within the closure zones, suggesting that these areas may provide viable grounds for episodic harvest of Eastern School Prawn following coastal floods, when other grounds are closed due to bycatch issues. This is the first evaluation of one of the most extensive closure networks used in a penaeid trawl fishery, and highlights the hitherto unquantified impact of other inshore spatial management arrangements within NSW (e.g. Marine Protected Areas) on species that trawl fisheries interact with.

Background and objectives – The New South Wales (NSW) Ocean Trawl Fishery (OTF) targets a large number of species, however the penaeid species Eastern King Prawn (*Penaeus* [*Melicertus*] *plebejus*) and Eastern School Prawn (*Metapenaeus macleayi*) are the two most heavily targeted crustacean species, and the sillaginids Stout Whiting (*Sillago robusta*) and Eastern School Whiting (*Sillago flindersii*) are the two most heavily targeted fish species (collectively known as "Trawl Whiting"). Targeted spatial management is employed within the fishery, including an extensive network of inshore closures that are primarily targeted at protecting small juvenile EKP from fishing mortality following their emigration from the estuarine nursery (called the Juvenile Eastern King Prawn [JEKP] closure network). Juvenile Eastern King Prawn closures are found immediately adjacent to estuarine nurseries, and the network is unique in terms of its design, extent, and in that the design and implementation was spearheaded by NSW OTF fishers, with the assistance of government. Despite the size and scale of the JEKP closure network, and the length of time that it has been in place, no targeted research has yet been undertaken on these closures.

Large catches of Eastern School Prawn mostly occur within inshore waters following floods in adjacent estuaries. High levels of freshwater inflow stimulates episodic emigration from the estuary, which results in large aggregations of high-grade prawns within inshore waters adjacent to estuaries following these rainfall and flood events. These aggregations are exploited by NSW OTF fishers, with seasonal autumn floods often producing large catches around the Easter period, when prices are high. The estuarine egression of Eastern School Prawn is mirrored by other species, including juvenile Mulloway (*Argyrosomus japonicus*), an imperilled species in south-eastern Australia. Bycatch of this species often leads to temporary closure of Eastern School Prawn grounds, causing substantial economic impacts on the fishery. As large areas of inshore waters adjacent to estuaries are permanently closed to trawling through the JEKP closure network, it has been suggested that temporarily opening JEKP closure grounds to daytime trawling could provide alternate areas where Eastern School Prawn can be targeted when other areas are closed to limit Mulloway bycatch. This will only be feasible if areas within JEKP closures support abundant Eastern School Prawn without Mulloway bycatch. At present there is no data to inform the implementation of such arrangements, or their consequences for EKP harvest or other species. This project sought to: 1) quantify the abundance and size-structure of Eastern King Prawn, Eastern School Prawn, juvenile Mulloway and other species within JEKP closure and non-closure zones, under normal conditions, and following floods; 2) Provide additional context to the Mulloway bycatch issue by

assessing source-sink dynamics in the Mulloway stock; and 3) Provide recommendations based on new data and modelling to inform the future management of access to inshore trawl grounds.

The study conducted a regular trawl survey targeting EKP and other primary and non-target species, which covered three permanently closed inshore areas within the JEKP closure network, located between ~28.5°S and ~33°S. The Ballina survey area spanned waters south and north of the mouth of the Richmond River. The Yamba survey area spanned waters south and north of the mouth of the Clarence River. The Newcastle survey area spanned waters south and north of the mouth of the Hunter River. The regular trawl survey was complemented by an irregular trawl survey targeting Mulloway and Eastern School Prawn, which was activated following floods in estuaries adjacent to the survey areas that approached or exceeded the threshold at which short-term trawling closures would be implemented to minimise Mulloway bycatch (moderate flood level). The irregular trawl surveys followed the same protocol and targeted the same survey areas as for the regular trawl survey, but trawling was conducted during the daytime (which is when Eastern School Prawn are generally targeted after floods). These trawl surveys were further complemented by discrete projects that informed the objectives above, including a prawn tagging program within JEKP closures (with recaptures across the broader fishery), targeted collection of Mulloway for otolith chemistry analysis, and modelling of the impact of JEKP closures on the broader fishery.

Eastern King Prawn and JEKP closures – There was substantial spatial variation in EKP biomass among survey areas, fished and non-fished zones, and sampling periods, with patterns driven by depth, temperature and distance to the adjacent estuarine nursery. Size-structure varied among closures and sampling periods, and differed inside and outside closure zones, however in many cases the majority of prawns that were protected within closure zones were consistently smaller than the estimated size at first capture for optimal yield per recruit. Tagging work revealed that the majority of EKP originating from the JEKP closure network tended to be recaptured from deeper waters adjacent to, or directly north of, the closure zones, but tagging location and release timing influenced recapture patterns. Cohorts tagged early in the growth season showed lower recapture rates, but were larger on average at recapture, and had migrated further. Prawns reached the fishery in the adjacent jurisdiction (Qld) within 54 days-post tagging, but for most cohorts the majority of recaptures were within NSW. Overall, there was good connectivity between JEKP closures and the NSW fishery, and tagged prawns also reached the Qld spawning areas. Despite EKP being abundant within closure zones and there being good connectivity with the fishery, modelling revealed that the impact of the closure network on NSW EKP harvest was comparatively minor, thus suggesting that, given the parameter estimates provided to the model, and the observation and process error occurring within the system, it is unlikely that the JEKP closures are making a detectable difference to the *overall* harvest of EKP across either NSW or Queensland, under current effort regimes.

Other species within JEKP closures – JEKP closures had some impact on the abundance and diversity of other primary species for the NSW OTF, and non-target species. Latitude was a key variable that was driving differences in the taxonomic assemblage among locations. Within locations, there were inconsistent impacts for different non-target species in different trawl closure zones. Length distributions showed size truncation of two abundant non-target species in fished areas, relative to JEKP closures. While the impact of JEKP closures varied among species, it was clear that the spatial management in the fishery provided some refuge for a diversity of non-target species, observed in patterns of species richness, abundance and population size-structure. Juvenile Eastern King Prawn closures in northern NSW were clearly providing some protection from fishing mortality for Eastern School Whiting and Stout Whiting, although the degree of protection varied spatially and also appeared to be influenced by the varying depth distributions of the two species. There were some differences in size-structure observed between closure and non-closure zones for Stout Whiting.

Eastern School Prawn and Mulloway bycatch within JEKP closures – New South Wales experienced a protracted drought throughout the course of this project, so post-flood sampling opportunities were limited. Eastern School Prawn were encountered in ~75% of samples within the irregular sampling program, at between <1 – 54 kg ha^{-1}. Mulloway and Teraglin (*Atractoscion atelodus*, another sciaenid bycatch species) were encountered in ~40% and ~53% of samples (respectively), but only at comparatively low abundances (ranging from <1 – 190 individuals ha^{-1} with a mean of ~ 5 individuals ha^{-1}). Eastern King Prawn were barely encountered during the irregular sampling program. Larger catches of sciaenid species generally corresponded with larger catches of Eastern School Prawn, but these relationships were much steeper in non-closure zones than closure zones, and more juvenile sciaenids appeared to be captured for each kilogram of Eastern School Prawn landed in Yamba, than Ballina. Analysis of size-structures showed that Eastern School Prawn were larger and bigger size grades were better represented within the closure zone at Ballina, compared to the adjacent non-closure zone.

Mulloway source-sink dynamics – Overall, otolith chemistry in post-recruit Mulloway suggested widespread mixing within the geographical area evaluated. Analyses suggested that a reasonable proportion of post-recruit Mulloway could not be reliably classified to the putative nursery estuaries that were sampled. Classification of post-recruit Mulloway among putative nursery estuaries was biased toward two estuaries, which does not concur with the degree of among-estuary connectivity observed in previous tag-recapture studies. It is possible that these estuaries represent important nurseries for the species, however there is a substantial degree of uncertainty in the analysis which mean that strong conclusions were not possible from the dataset. The work completed, however, does provide a strong foundation for future work in this area.

Implications and recommendations – The JEKP closure network was implemented at a time when the NSW OTF fleet was much larger, expending up to 20,000 nights effort per year in the fishery (compared to the current ~5-6,000 nights), and when the stock was growth overfished. Today, the number of vessels in the fishery and overall effort levels are much lower, and tend to be concentrated in deeper waters targeting larger, more valuable prawns. As a result of this, recent catch rates are much higher, but the size-structure within the commercial harvest is also larger than it was historically (Helidoniotis *et al.* 2020). These changes in the fishery may mean that the scope and nature of benefits derived from the spatial management network for EKP are likely to have altered since their implementation, and JEKP closures do not currently appear to have a major impact on the overall productivity of the fishery for EKP. However, while not specifically intended in their implementation, the JEKP closure network provides considerable protection from fishing mortality for the broader assemblage of species which are impacted by the activities of the NSW OTF. Coupled with the fact that the closures were spearheaded by industry, this adds to the sustainability credentials for the fishery, and the social license which supports its operation.

With respect to the adaptive management scenario being considered to deal with Mulloway bycatch while targeting Eastern School Prawn, our evaluation suggests that under current effort scenarios, allowing trawling within JEKP closures is likely to have a minimal impact on EKP yields in NSW and Queensland, but there could be minor impacts on the ex-vessel value derived from expected yields if trawling within JEKP closures impacts EKP. The lack of flood events and associated sampling during this study does not really support strong conclusions regarding the comparative abundance of Eastern School Prawn and Mulloway (and sciaenids more broadly) within closure zones. The data suggested that Eastern School Prawn were present in "economic" quantities within JEKP closures, and there was some evidence for comparatively lower numbers of sciaenids being encountered, but the limited number of events sampled, the overall variability in the data, and general patchiness limited the conclusions that could be drawn. Considering the information above, temporary and partial opening of JEKP closures could be considered as an ameliorative management strategy where other Eastern School Prawn grounds are closed due to Mulloway bycatch. Such a strategy would best be applied cautiously, with implementation accompanied by "trial" shots to evaluate whether Eastern School Prawn are present, and confirming that Mulloway are encountered in comparatively low abundances, before trawling is allowed. While the impacts of temporarily allowing daytime fishing within JEKP closures on the broader assemblage are difficult to predict, there is a need to consider these additional elements in any decisions on adaptive spatial management.

Keywords – Ocean trawling; Penaeid trawling; Bycatch; Eastern King Prawn; Eastern School Prawn; Stout Whiting; Spatial management; Adaptive management

Introduction

The New South Wales Ocean Trawl Fishery

The New South Wales (NSW) Ocean Trawl Fishery (OTF) is one of the largest fisheries in NSW. The fishery spans the length of the NSW coast and is divided into inshore (<3 nm from the coast) and offshore zones, and includes both prawn trawl and fish trawl sectors. Within the NSW OTF, holders of prawn trawl shares can use specified prawn trawl nets to fish inshore ocean waters along the length of the NSW coastline, and offshore ocean waters north of Barrenjoey Headland (~34.6°S). Holders of fish trawl shares can only use specified fish trawl nets to fish inshore and offshore ocean waters north of Barrenjoey Headland. The Southern Fish Trawl also targets fish in inshore waters south of Barrenjoey Headland, and the Deepwater Prawn Trawl targets Royal Red Prawn in deeper offshore waters.

The NSW OTF targets a large number of primary species, however the penaeid species Eastern King Prawn (*Penaeus* [*Melicertus*] *plebejus*) and Eastern School Prawn (*Metapenaeus macleayi*) are the two most heavily targeted crustacean species, and the sillaginids Stout Whiting (*Sillago robusta*) and Eastern School Whiting (*Sillago flindersii*) are the two most heavily targeted fish species (collectively known as “Trawl Whiting”). Other primary species for the fishery include Royal Red Prawn (*Haliporoides sibogae*), Balmain Bug (*Ibacus* spp.), Cuttlefish (*Sepia* spp.), Southern Calamari (*Sepioteuthis australis*), Tiger Flathead (*Neoplatycephalus richardsoni*), Sand/Bluespotted Flathead (*Platycephalus caeruleopunctatus*), Silver Trevally (*Pseudocaranx dentex*), Shovelnose Rays (*Aptychotrema rostrata*) and various species within the Family Octopoidae.

The NSW OTF is subject to a range of different input and output controls, dealing with permitted gear, share-linked quotas, and spatial management arrangements. Quotas were only recently (2019) introduced to the fishery, and include unitised effort quota for the prawn trawl sector, catch quotas for Tiger Flathead, Sand/Bluespotted Flathead and Silver Trevally, as well as a joint “mixed bag” catch quota for Trawl Whiting. Targeted spatial management is also employed within the fishery, and includes specific arrangements for each sector (outlined in **Figure 1**). For the fish trawl sector, all waters north of Smoky Cape (~30.9°S) are permanently closed to the use of fish trawl nets. For the prawn trawl sector, there is an extensive network of inshore closures that are primarily intended to protect juvenile Eastern King Prawn from fishing mortality (the Juvenile Eastern King Prawn [JEKP] closure network, outlined below). Broader Marine Estate management arrangements also include inshore spatial management provisions that influence the operations of participants within the NSW OTF, including Habitat Protection Zones (HPZs) and Sanctuary Zones (SZs) within Marine Protected Areas (MPAs). Consequently, spatial management has a major influence on the operations of fishers within the NSW OTF, and creates a considerable expanse of inshore habitats that are protected from fish trawling, prawn trawling, or both.

Eastern King Prawn, and the Juvenile Eastern King Prawn (JEKP) closure network

Eastern King Prawn (EKP) is the most important crustacean species harvested with the NSW OTF, by catch volume. The species also supports the most valuable penaeid fishery in south-eastern Australia, generating revenue at first-point-of-sale that usually exceeds AUD40 million per year (O'Neill *et al.* 2014). Fishing for EKP spans the two jurisdictions adjacent to NSW; Queensland and Victoria (**Figure 1**), and while some EKP are captured within estuaries (e.g. within the NSW Estuary General Fishery [EGF] and the NSW Estuary Prawn Trawl Fishery [EPTF]), the species is primarily harvested from ocean waters. Harvest is asymmetrically distributed among jurisdictions, with the majority taken in Queensland waters, and only negligible and highly episodic harvest occurring within Victorian waters (Prosser and Taylor 2019).

Eastern King Prawn has a Type-II penaeid life-cycle (Dall *et al.* 1990) with an estuarine phase and a migratory oceanic phase. Spawning mostly occurs in the north of the species' range, off northern NSW and south-eastern Queensland (Montgomery *et al.* 2007). Larvae disperse coastward (in Queensland, Rothlisberg *et al.* 1995) or southward in the East Australian Current (EAC, Everett *et al.* 2017), and recruit into estuarine nurseries within NSW (Young 1978; Taylor *et al.* 2017b). Prawns reside within estuarine habitats before emigrating to the inshore zone (<30 m depth), where they rapidly grow (Racek 1959), and generally pass through the inshore zone during the warmer months of the year (Taylor and Johnson 2020). Following this inshore phase, prawns migrate eastward and northward towards the spawning grounds. It is during this migratory phase that most exploitation occurs. Because of the migratory nature of the species, different life history stages can span multiple jurisdictions.

Within NSW, an extensive permanent inshore spatial management network is implemented under the current *Fisheries Management (Ocean Trawl Share Management Plan) Regulation 2006*. A large proportion of this area is comprised of the inshore JEKP closure network. As noted above, EKP emigrate from estuarine nurseries to reside within inshore sandy and soft sediment habitats for at least a month, before commencing their migration to deeper waters, and northward. Consequently, JEKP closures are found immediately adjacent to estuarine nurseries, and are specifically intended to protect smaller size classes of EKP during this inshore growth phase. This closure network is unique in terms of its design, its extent, and in that the design and implementation was spearheaded by NSW OTF fishers, with the assistance of government. These closures have been in place for several decades, and due to the fish trawl closure north of Smoky Cape (outlined above), JEKP closures north of ~30.9°S are effectively closed to all forms of trawling. Juvenile EKP closures south of ~30.9°S are closed only to prawn trawling, with fish trawling effort allowed through the NSW OTF (north of ~34.6°S) and the SFT (south of this latitude). Despite the size and scale of the JEKP closure network, and the length of time that it has been in place, no targeted research has yet been undertaken on these closures.

Eastern School Prawn emigration and Mulloway bycatch within the New South Wales Ocean Trawl Fishery

As noted above, Eastern School Prawn are a primary species for the NSW OTF, and are periodically targeted in inshore waters. Like EKP, Eastern School Prawn have a Type-II penaeid life cycle with an estuarine and oceanic phase, however their life cycle lacks the extensive coastal migrations that are undertaken by EKP. Eastern School Prawn juveniles use estuarine nurseries, but as they mature they move to inshore habitats adjacent to estuaries, where they spawn, and their progeny tend to undergo localized dispersal, recruiting back into nearby estuaries (Racek 1959; Ruello 1977; Glaister 1978b). Eastern School Prawn are primarily harvested within estuaries by the EPTF and EGF (Taylor and Creighton 2018), but are periodically abundant within inshore waters adjacent to estuaries and are targeted in these waters by NSW OTF fishers. The movements of Eastern School Prawn are heavily influenced by rainfall in the catchments of important nurseries, and the associated freshwater inflow to these estuaries. High levels of freshwater inflow stimulates episodic emigration from the estuary (Ruello 1973), which results in large aggregations of high-grade prawns within inshore waters adjacent to estuaries following these rainfall and flood events. These aggregations are exploited by NSW OTF fishers (Glaister 1978a), with seasonal autumn floods often producing large catches around the Easter period, when prices are high for fresh Eastern School Prawn.

The estuarine egression of Eastern School Prawn is mirrored by other species, including juvenile Mulloway (*Argyrosomus japonicus*). Mulloway are a predatory fish species that also have an estuarine nursery phase, and their movements and productivity are closely linked to freshwater inflow into estuaries (Taylor *et al.* 2014; Stewart *et al.* 2020). Eastern School Prawn are important prey for juveniles (primarily for fish between 200 - 500 mm total length [TL]Taylor *et al.* 2006a). Mulloway support some commercial harvest and the species is an iconic target for anglers, but historic fishing pressure and persistent droughts (which are important for spawning, recruitment and productivity) have impacted the population biomass over the past 20 years, with the NSW stock now considered depleted (Earl *et al.* 2021).

The comparatively depleted state of the NSW Mulloway stock means that Mulloway bycatch is an issue of significant public and management interest. The co-emigration of Mulloway with Eastern School Prawn, and the co-occurrence of the species in inshore waters adjacent to estuaries, means that NSW OTF fishers exploiting abundant and valuable Eastern School Prawn within inshore waters following floods, often encounter high levels of Mulloway bycatch (as well as bycatch of the oceanic sciaenid Teraglin, *Atractoscion atelodus*). This bycatch issue is ultimately managed through the implementation of spatio-temporal trawling closures that prevent trawling within certain inshore waters, where Eastern School Prawn are abundant (called “short-term trawling closures”). While this helps to minimise potential bycatch-related sustainability issues for the Mulloway stock, these closures have significant economic and social impacts on NSW OTF fishers, which are somewhat exacerbated when this scenario occurs during autumn when prices are buoyant.

Spatio-temporal co-occurrence of juvenile Mulloway and Eastern School Prawn within inshore waters following floods have not yet been quantified (outside of observations made during normal fishing operations) since *FRV Kapala* sampled some inshore waters following floods in the early 1990s (Graham *et al.* 1993). As large areas of inshore waters adjacent to estuaries are permanently closed to trawling through the JEKP closure network, it has been suggested that temporarily opening JEKP closure grounds to daytime trawling could provide alternate areas where Eastern School Prawn can be targeted when other areas are closed due to Mulloway bycatch. This will only be feasible if areas within JEKP closures support abundant Eastern School Prawn without Mulloway bycatch. However, such adaptive management arrangements represent a significant departure from spatial management provisions that have been in place for several decades, and at present there is no data to inform the design of such arrangements, or their consequences for EKP harvest. Several pieces of information would be useful in considering and implementing such adaptive management arrangements, and understanding their impacts, including: 1) spatio-temporal patterns in biomass and size-structure of EKP within JEKP closures and adjacent inshore areas, and connectivity with the broader fishery; 2) Distribution, abundance, and size-structure of Mulloway and Eastern School Prawn within JEKP closures and adjacent inshore areas, following floods in adjacent estuaries; and 3) the potential impact of trawling in JEKP closures on the broader fishery.

While Mulloway bycatch in inshore waters can lead to the mortality of many juveniles, consideration of the impacts of periodic extraneous fishing mortality on any species (such as bycatch species) should be contextualised within the metapopulation dynamics of the broader population. While telemetry and tagging studies have revealed some level of connectivity among estuaries and coastal zones for Mulloway within NSW, potential source-sink dynamics in the stock is unknown. This creates some uncertainty regarding the implications of episodic bycatch mortality for the broader Mulloway population, and the broader fishery for the species. In particular, it is important to understand whether the estuarine nurseries within the northern rivers of NSW (where inshore bycatch issues most commonly occur) are likely to affect the productivity and population health of Mulloway in other areas of the state, or whether new recruits may be supplied from elsewhere into the discrete geographic regions where Mulloway are affected by bycatch. Consequently, resolving connectivity, and in particular any potential source-sink dynamics in the Mulloway population, will aid consideration of the environmental, social, and economic issues surrounding Mulloway bycatch within inshore waters, and any management actions that are implemented in response to this (such as implementation of short term spatio-temporal closures to project juvenile Mulloway in inshore waters). Coupled with the points raised in the previous paragraph, these knowledge gaps underpin some of the core research objectives that were addressed in this project (outlined in the Objectives section below).

Other primary and non-target species and inshore spatial management arrangements within New South Wales

While the JEKP closure network was implemented to achieve a specific objective for EKP, it is highly likely that these spatial management arrangements provide partial refuge for populations of species that generally reside within inshore habitats. Such additional benefits are likely to contribute to the overall sustainability credentials for the fishery, and may also provide spawning or recruitment subsidies for other target or non-target species that are exploited within NSW OTF. However, in the absence of targeted surveys there is no data to evaluate this, and consequently the nature and quantum of these additional benefits is uncertain. Information on species abundance, diversity, and size-structure within inshore habitats more generally will also be useful to inform appraisal of broader inshore spatial management arrangements, such as MPAs. Such additional putative benefits are rarely examined or considered in the context of trawl closures.

While the broader patterns in the diversity, biomass, and size-structure of non-target species (i.e., species *other than* NSW OTF primary species, as listed above) that are protected within JEKP closures is of interest, inshore spatial management arrangements along NSW are likely to provide benefits to other heavily exploited species within the NSW OTF. In particular, inshore soft sediments are important Stout Whiting and Eastern School Whiting habitats, with both species inhabiting inshore coastal waters for the majority of their life history, and the bulk of population biomass for these species found at depths shallower than 60 m (Gray *et al.* 2014b). Quantifying the distribution, abundance and size-structure of “protected” whiting is important for understanding the additional impacts of spatial management arrangements on Trawl Whiting species, so populations in non-fished areas can be considered in quota-setting decisions, and also to properly understand the true value of inshore spatial management arrangements.

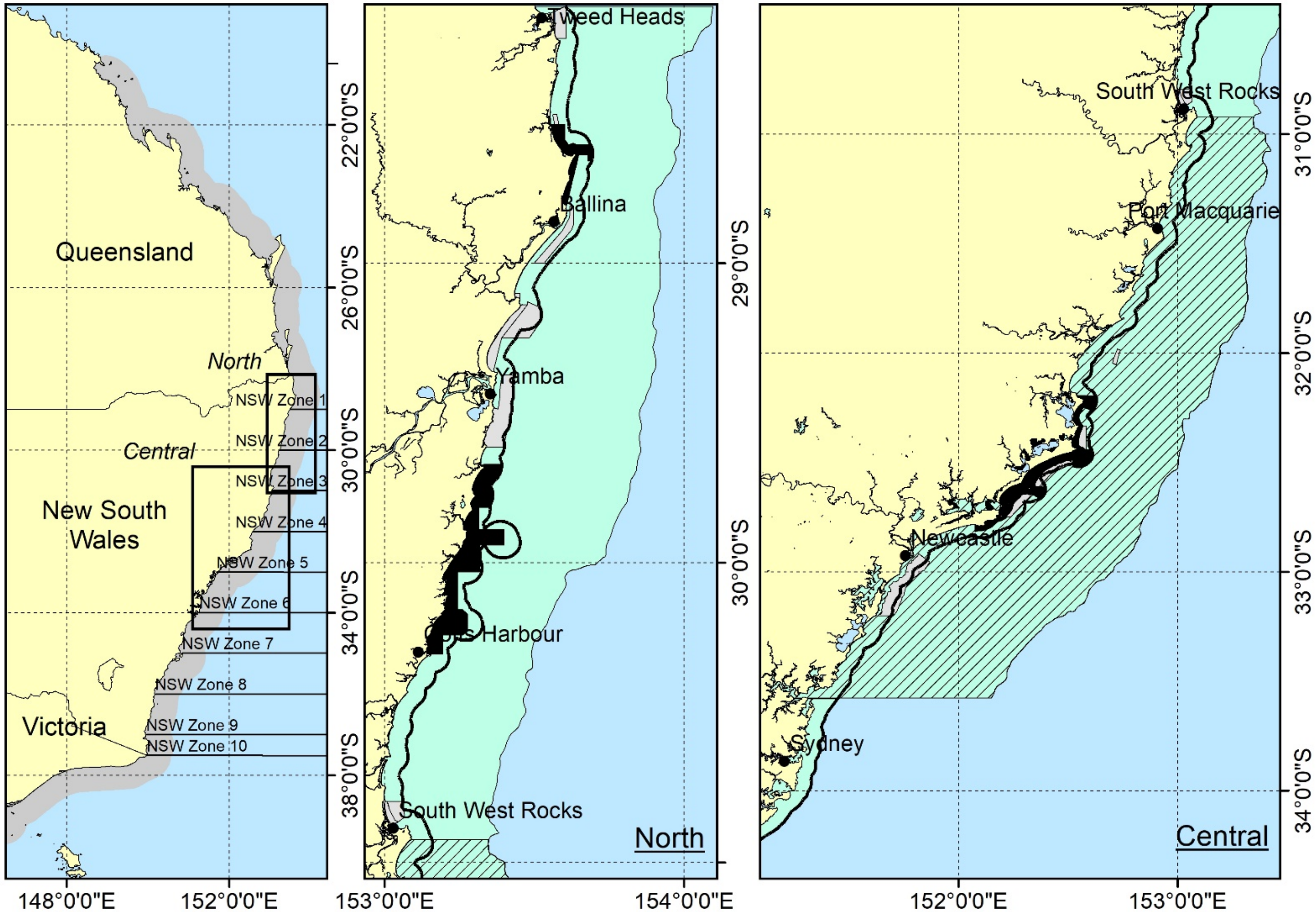


Figure 1 Broad map of eastern Australia (left panel) showing the geographic range of Eastern King Prawn across three jurisdictions (grey shading), and catch reporting zones (otherwise known as ocean zones) within New South Wales. The central and right panel show Eastern King Prawn closures within the northern and central New South Wales coast (grey polygons), as well as Habitat Protection Zones and Sanctuary Zones within Marine Protected Areas (black polygons). The dark line shows inshore waters, green shading indicates prawn trawl waters, and 45° hatching indicates fish trawl waters. Insets of central and right panel are indicated on the left panel.

Objectives

The broad objectives initially outlined for the project were:

1. Apply existing survey techniques to quantify the abundance and size-structure of juvenile Mulloway, School Prawn, and Eastern King Prawn, within current inshore closure and adjacent non-closure zones, under normal conditions and following floods;
2. Quantify connectivity of Mulloway between key estuaries, current inshore closure and non-closure zones, and inshore and offshore trawling grounds, and the contribution of these areas to commercial and recreational landings (as a proxy for the overall stock);
3. Provide recommendations based on scientific data to inform the future management of access to inshore prawning grounds.

Given the contextual background presented in the Introduction, these broad objectives were distilled down into more specific objectives to inform each component of the analysis of the data generated throughout the various surveys conducted:

1. Evaluate the biomass and size-structure of EKP within the JEKP closure network (alongside adjacent reference areas open to fishing), in the context of protecting juvenile prawns from fishing mortality;
2. Examine connectivity between JEKP closure zones and the broader EKP fishery, through evaluation of spatio-temporal patterns in recaptures of tagged prawns, and their length structures, following emigration from closure zones;
3. Examine the diversity, biomass and size-structure of non-target species within the JEKP closure network (alongside adjacent reference areas open to fishing);
4. Examine Trawl Whiting biomass and size-structure within the JEKP closure network (alongside adjacent reference areas open to fishing), and interpret these findings in the context of protection offered by JEKP closures for these species;
5. Evaluate abundance and size-structure of Eastern School Prawn and juvenile Mulloway across inshore areas following heavy rainfall in coastal catchments;
6. Apply otolith chemistry techniques to evaluate the contribution of putative nursery estuaries to post-recruited Mulloway;
7. Model the potential consequences of allowing fishing within JEKP closures, to inform consideration of adaptive management of JEKP closures to support continued harvest of Eastern School Prawn following coastal floods.

Method

General sampling plan and outline

The main kernel of the sampling design was a regular trawl survey targeting EKP, which covered three permanently closed inshore areas within the JEKP closure network, located between ~28.5°S and ~33°S (**Figure 2**). The Ballina survey area spanned waters south and north of the mouth of the Richmond River. The Yamba survey area spanned waters south and north of the mouth of the Clarence River. The Newcastle survey area spanned waters south and north of the mouth of the Hunter River. As noted above, waters north of ~31°S are closed to fish trawling, and as prawn trawling is prohibited within JEKP closures, no trawling is permitted within the Ballina and Yamba JEKP closures. Conversely, while prawn trawling is prohibited within the Newcastle JEKP closure, fish trawling is permitted, so this JEKP closure still experiences some trawling activity. These survey areas encompass the latitudes that experience the greatest fishing effort for EKP and Trawl Whiting within NSW-managed waters.

For trawl surveys, commercial trawlers rigged with standard prawn trawl gear were chartered within each location (Ballina, Yamba and Newcastle). The three vessels chartered and used in this research project varied slightly. The vessel used within the Yamba survey area was 15.24 m in length and powered by a 220 Kw engine, whereas a 13.21 m vessel powered by a 175 Kw engine was used within the Ballina survey area; and a vessel 13.10 m in length and powered by a 112 Kw engine was used in the Newcastle survey area. All vessels were triple-rigged with Florida-flyer trawls made from 42 mm mesh (Kennelly *et al.* 1993) with a total headline length of ~42 m and net spread of ~75%, and 2 m x 0.8 m otter boards (180 kg weight). Code-ends were 45-mm diamond mesh configured with an upward facing composite 55 cm x 70 cm square-mesh BRD panel, ~1.5 m from the drawstring (representing standard prawn trawling gear used in New South Wales waters). The cod-end of the middle net was not fished (following Silburn *et al.* 2020), and net spread was quantified for each vessel using a NOTUS Trawlmaster sensor system (NOTUS Electronics, Newfoundland, Canada).

For the regular trawl survey, commercial trawlers rigged with standard prawn trawl gear (described above) were chartered within each survey area for 3 nights per month from January to April, in 2017, 2018 and 2019 (the Newcastle survey area was only sampled in 2017 and 2018).

The regular trawl survey was complemented by an irregular trawl survey primarily targeting Eastern School Prawn (and incidental catches of Mulloway), which was activated following floods in estuaries adjacent to the survey areas that approached or exceeded the threshold at which short-term trawling closures would be implemented to minimise Mulloway bycatch (moderate flood level). The irregular trawl surveys followed the same protocol and targeted the same survey areas as for the regular trawl survey, but trawling was conducted during the daytime (which is when Eastern School Prawn are targeted immediately following flood events), and the timing and duration was generally informed by local fishers based on their knowledge of currents and localised stock movements, and prevailing weather conditions (the east-coast low pressure systems that usually produce floods are usually accompanied by extremely challenging ocean conditions).

These trawl surveys were complemented by discrete projects that addressed the other objectives. This included a prawn tagging program within JEKP closures (with recaptures across the broader fishery), targeted collection of Mulloway for otolith chemistry analysis, and development of a simulation model to investigate the potential impact of JEKP closures on contemporary EKP harvest within the NSW OTF. These projects are described in more detail below.

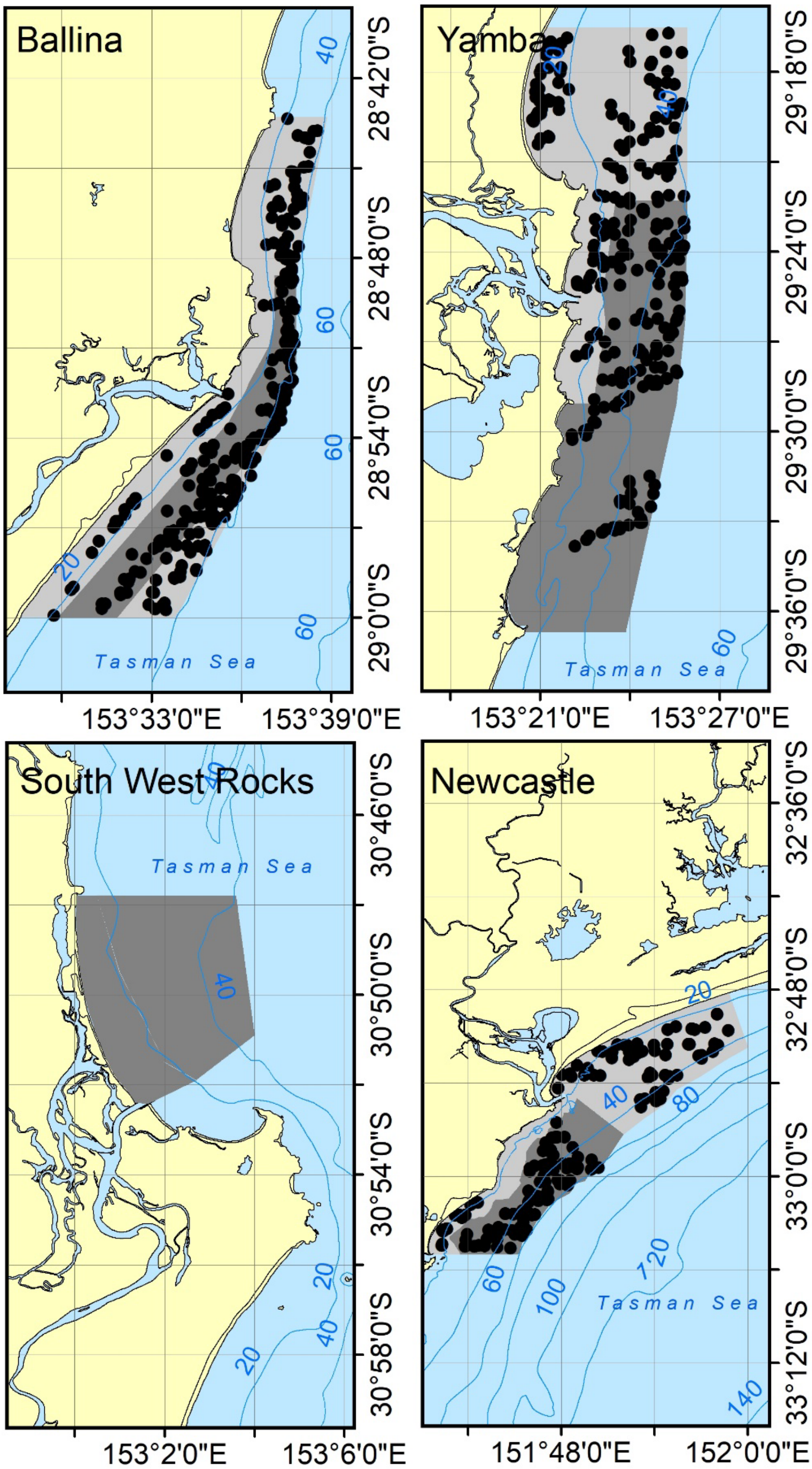


Figure 2 Detail map showing locations that were targeted for the trawl surveys (Ballina, Yamba and Newcastle), and the tagging study (Ballina, Yamba and South West Rocks). Black dots indicate trawls undertaken during the regular trawl survey. Dark grey polygons indicate JEKP closures, and light grey polygons indicate adjacent non-closure zones which were also sampled during the trawl surveys. Bathymetry contours are shown in blue (depth in metres). The absence of black dots within survey areas indicates areas that are not suitable for trawling, or where research trawling is not permitted.

Trawl survey

Sample collection

Multiple trawls were conducted in randomised 0.3 x 1 nm grid squares during each night of sampling. A numbered grid of squares was applied to the complete survey area at each location (with the exception of known non-trawlable areas), and a set of grid numbers was randomly selected across each survey area (without replacement) for each month of sampling. In the case where trawl nets fouled during a tow, the grid was excluded and the tow discarded, and the next grid sampled. Each grid was sampled using 20-minute tows, and sampling occurred between the hours of 20:00 and 06:00 hrs (i.e. at night), which enabled up to 36 samples to be collected per location, per month of sampling. 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).

Sample processing

After each trawl, the contents of the port and starboard codends were spilled onto the sorting tray and representative samples collected to describe catch composition. Samples were sorted into target (commercial) and non-target components. For each replicate trawl, the total catch of EKP, Stout Whiting, Eastern School Whiting, Eastern School Prawn, or Mulloway 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 the sex (M, F, juvenile), 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 fork length (FL, mm) was measured for Trawl Whiting species and total length (TL, mm) was measured for Mulloway.

To address Objective 3, non-target species were sorted and processed, although this was only undertaken for surveys in 2017. Cod-ends were spilled, and catch was partitioned as noted above. Any larger non-target species (e.g., elasmobranchs) were immediately identified, measured, and returned to the water. The total weight of non-target species was measured, and the entire sample frozen. For larger catches (noting that tows were relatively short), 10-kg subsamples were retained (Silburn *et al.* 2020), which represented an average subsample size of 42 ± 2% (mean ± SE). Samples were transported to the laboratory for further processing. At the laboratory, samples were thawed and the contents initially grouped by species, and then each individual species was counted and weighed. For species with abundances deemed sufficiently large, subsamples of 50 individuals were counted and weighed, and average individual weight was used to estimate the total number in the samples. Two common bycatch species, Cocky Gurnard *Lepidotrigla modesta* and Longspine Flathead *Platycephalus grandispinis* (previously *Platycephalus longispinis*) were selected for comparison of size-structures between JEKP closure zones, and these species were also measured for TL (lengths of up to 100 individuals were measured from each sample strata, equating to >600 samples).

Data handling and analysis

Data handling

Trawl catch and effort information and prawn biological data, were compiled in a Microsoft Access relational database, and all statistical analysis was undertaken in R v 3.5.2 (R Core Team 2020). Start and stop GPS coordinates for each trawl were used to calculate distance travelled, and this was used alongside net spread measurements to determine the areal coverage of each tow. This was then used to standardise biomass values to a relative estimate of kilogram-per-hectare-trawled (kg ha^{-1}, i.e. no catchability estimate was applied).

Biological evaluation of Eastern King Prawn within inshore closures and adjacent fished zones

The variables EKP biomass, prawn size (CL, mm), and somatic condition (outlined below), were evaluated to explore the patterns among locations, zones and months, using a number of different approaches. To initially examine the fine-scale spatial distribution of EKP across the survey areas, and sampling periods, a spatially continuous surface reflecting EKP biomass across the survey area within each sampling period was calculated by kriging log-transformed EKP biomass data, using the autoKrige function in R package "automap" (Hiemstra *et al.* 2009). EKP biomass data was then compared across location (Ballina, Yamba and Newcastle), zone (closure and non-closure) and month (January, February, March, April) using an analysis-of-variance (ANOVA), followed by Tukey's post-hoc comparisons of significant main effects and interaction terms. Length data was initially expressed as weighted (weighting factor reflecting EKP biomass [kg ha^{-1}] for each tow, and subsample amount) kernel density distributions (kdd) for Ballina and Yamba data, calculated using the density function in the MASS package (Venables and Ripley 2002). Kernel distributions were used to calculate proportional size distribution (PSD) exceeding the optimal size at first capture (length data for sexes were pooled). The optimal size at first capture (L_{YPR}) was calculated based on optimal ages at first capture (0.55 y for males, and 0.56 y for females) reported in Courtney *et al.* (2014), from which corresponding lengths were calculated at -29.5° latitude using the latitudinal/seasonal EKP growth model of Lloyd-Jones *et al.* (2012). Male and female L_{YPR} estimates were averaged, and the proportion of individuals exceeding this threshold was compared among zone and month using ANOVA, for each location. Finally, somatic condition of prawns was expressed as the standardised residuals of a fitted model between log(CL) and log(weight), and compared between locations and among months using ANOVA.

Evaluation of non-target and bycatch species within inshore closures and adjacent fished zones

A simple two-factor ANOVA was used to compare both total biomass (of non-target species, in this case kilograms per kilometre trawled [kg km^{-1}], as net spread data was not available at the time of this analysis) and species richness (total number of species) across location and zone. Species were then grouped into distinct taxonomic categories of: 1) fish (abbreviated as FISH); 2) non-penaeid decapod crustaceans (abbreviated as DECA); 3) penaeid decapod crustaceans (abbreviated as PENA), and multivariate analyses undertaken using package vegan (Oksanen *et al.* 2017). A Bray-Curtis dissimilarity matrix was calculated for each taxonomic category, and a non-metric multi-dimensional scaling ordination (nMDS) used to identify broad patterns among locations and areas within each of the taxonomic groupings. In addition, an envfit (Oksanen *et al.* 2017) analysis was used to explore the influence of broad-scale environmental factors in driving patterns in the ordination, and a SIMilarity PERcentages (SIMPER) analysis conducted to evaluate the species within each taxonomic grouping that were primarily responsible for driving the variation among locations. Following this, species assemblages were compared between zones for each taxonomic grouping and each location, using a single-factor PERMutational ANalysis Of VAriance (PERMANOVA, Anderson 2001). A SIMPER analysis was again used to identify which species were driving the differences between zones. Lengthfrequencies were compared among zones at each location using weighted kdd's and K-S tests as described for EKP.

Evaluation of trawl whiting within inshore closures and adjacent fished zones

Data was analysed as described for EKP, with the exception that kernel distributions were used to calculate proportional size distribution (PSD) exceeding the length-at-maturity (L_{50}) for each species reported in Gray *et al.* (2014b). Male and female L_{50} estimates were averaged for each species.

Evaluation of School Prawn and juvenile Mulloway across inshore areas following heavy rainfall in coastal catchments

Data collected during the irregular trawl survey following flood events were compiled in an MS Excel workbook. Initial exploration of the data included examining interspecific relationships in abundance between Eastern School Prawn (kg ha^{-1}) and 1) Eastern King Prawn (kg ha^{-1}); 2) Mulloway (# ha^{-1}); 3) Teraglin (# ha^{-1}); and 4) Total Sciaenidae (# ha^{-1}). A linear regression was used to evaluate the retaionship between Mulloway and Teraglin (log-transformed) abundance. Average abundances of key species (Eastern School Prawn, Mulloway, Teraglin and Total Sciaenidae) were compared across strata (zone and event) using a two-factor ANOVA. Further, length structure of key species were compared among strata using weighted KDD's and K-S tests, as described for EKP.

Prawn tagging

Sampling rationale and design

Within NSW, oceanic trawl effort in NSW is categorised into 10 ocean zones corresponding to each degree of latitude (**Figure 1**). The fishery for EKP occurs primarily between 28°S and 33°S (zones 1-5), with the majority of catch and effort occurring from waters north of 31°S (zones 1-3). Three inshore closures north of this latitude were selected to undertake tagging activities (**Figure 2**): 1) Ballina closure zone; 2) Yamba closure zone; and, 3) South West Rocks (SWR) closure zone (adjacent to the mouth of the Macleay River). The SWR closure zone is a spatio-temporal closure rather than a permanent closure, and is closed to prawn trawling on an annual basis from November to February in the following year (inclusive). Tagging surveys were undertaken in the closure zones, "early" and "late" in the period during which prawns would be moving through the inshore region (November to May, although prawns can be abundant as late as June, Racek 1959), in 2018 and 2019 respectively. In Yamba, prawns were only tagged during the "early" period. Data from an earlier tagging study in the Ballina closure zone (2016) was also re-analysed as part of the main data set in this study (see Taylor and Johnson 2020). In addition, we compared the recapture patterns in the current tagging program with historical data from 5,754 prawns tagged within the SWR closure zone during November 1991 and January 1992. These data were collected by the NSW Department of Primary Industries (formerly NSW Fisheries) during the period of historic peak fleet size in NSW, and previously reported as part of the migration model of Gordon *et al.* (1995).

Prawn capture, tagging and recapture

Each tagging event involved capturing, tagging and releasing prawns over 2 nights, following the methodology outlined here. A commercial trawler equipped with standard commercial prawn trawl gear was chartered, and conducted short tows within the closure zone. Once the net was retrieved, the catch was immediately sorted, and live prawns were placed directly into a flow-through holding tank.

Tagging methodology has previously been developed for EKP (Montgomery and Gray 1991; Montgomery *et al.* 1995; Courtney *et al.* 2014), and our technique closely followed this earlier work. Individually numbered polyethylene streamer tags (PST, size 12P) were used with 38 mm applicator needles (Hallprint, South Australia) for tagging. Tags were inserted through the first abdominal segment between the ventral nerve chord and the dorsally-located gut and gonads, and sex and carapace length (CL, mm) were recorded against each tag number. Prawns were released around the location of capture using a specially designed release cage. While the vessel was stationary, prawns were placed in the cage and it was lowered to the substratum, where the door was opened, and the cage inverted. All releases were nocturnal and occurred over sandy substratum at depths between 20 and 40 m.

A communication program was implemented as tagging commenced, to alert fishers of the project, to provide program administration contacts, and outline how to return tagged prawns. Notices about the program were posted through Facebook, or physically mailed to fishers, fishing co-operatives and processing facilities in NSW and Queensland. Kits containing instructions on recording recapture data, measuring prawn CL, and containing waterproof data sheets and Vernier calipers, were also distributed to fishers. As tagged prawns were recaptured, fishers measured prawns and recorded the date, time and location of capture, and communicated these details back to the program administrators. Fishers were reminded of the program throughout the season, and were rewarded with a program T-shirt when they returned prawn recapture data.

Data handling and analysis

Tagging and recapture information was compiled in a Microsoft Access database, and all data handling, manipulation, and statistical analysis undertaken in R v3.5.2 (R Core Team 2020). Initially, metrics relating to tag recaptures (growth [difference in CL at tagging and recapture], days-at-liberty, distance travelled, and movement rates) were compared qualitatively across locations and tagging cohorts. Recapture patterns were visualised spatially using ArcMap v. 10.2.2 (Environmental Science Research Institute, California, USA), and recaptures were mapped to the spatial zones in NSW and Queensland that are used in catch reporting and species stock assessment (see Courtney *et al.* 2014; O'Neill *et al.* 2014; Camp *et al.* 2020). Size-at-tagging (CL, within trawl closure zones), and following emergence from trawl closure zones and appearance in the fishery (size-at-recapture) were compared against L_{YPR} (calculated as outlined above). Statistical comparison of total distance moved before recapture (the Euclidian distance between release and recapture) and size-at-recapture were compared for the factors 1) release timing (early and late), and 2) tagging location (Ballina and SWR) using a two-factor ANOVA. Two-factor ANOVA was also used for statistical comparisons between total distance moved before recapture, and size-at-recapture, for prawns tagged during “early” and “late” releases within the South West Rocks trawl closure zone for the 1991/92 tagging period, and the 2018/19 tagging period. Finally, for all tagging periods and cohorts, the proportional tag recaptures within NSW waters were related with the total fishing effort across the geographic areas through which prawns had migrated, using a simple linear regression of the total proportional recaptures within NSW with $\log_{10}$-transformed total effort. Total effort was calculated for each cohort by summing the total nights trawl effort for 5 months post-tagging (reflecting the longest period prawns were present in NSW waters, Taylor and Johnson 2020), for the ocean zones through which prawns from each tagged cohort would pass (effort data was obtained from the NSW Commercial Catch Statistics database).

Mulloway sampling and otolith chemistry analysis

Sampling design and fish collection

Current knowledge of Mulloway life-history suggests that juveniles settle in estuaries and increasingly migrate between estuaries and inshore areas as they grow and mature (Griffiths 1996; Cowley *et al.* 2008). Consequently, individuals harvested in estuaries may not have initially recruited as early juveniles to the estuary in which they were captured (see Barnes *et al.* 2019). Furthermore, the comparative importance of specific estuaries contributing to Mulloway populations found in inshore coastal areas is also unknown. We applied otolith chemistry techniques (Elsdon and Gillanders 2003a) to investigate source-sink population dynamics and fine-scale population structuring of the Mulloway stock in eastern Australia. This experiment attempted to use similarities in otolith chemistry during early life history to assign animals back to their juvenile nursery, as well as exploring factors that might drive variation in otolith chemistry.

This was achieved using a multi-part experimental design, aimed at providing samples to 1) measure the otolith edge chemical fingerprint in Mulloway from juveniles captured in major putative estuarine nurseries; and 2) measure the juvenile chemical fingerprint in the otoliths of larger, post-recruit Mulloway captured through commercial and recreational fisheries. The edge signature of juveniles still in their estuarine nursery phase was then compared with the sub-yearling signature in the otolith of post-recruited size classes, for which the capture location was known, but the estuarine nursery they inhabited as juveniles was unknown. For part 1) of the design, 5-30 juvenile fish (< 45 cm) were collected from 8 putative estuarine nurseries distributed across the species range in New South Wales (**Figure 3**), during summer/autumn 2017-2018 (while the species range extends along the entire coast, animals are most abundant north of 35°S and therefore sampling efforts focused on this area). The otolith edge signatures were analysed (as described in Russell *et al.* 2021); edge signatures reflect the most recently incorporated material into the otolith surface and therefore can reasonably be assumed to correspond with the location of capture. For part 2) of the design, post-recruit Mulloway (> 45 cm, noting that the minimum size at which the species can be retained by commercial fishers increased during our research program) were collected from commercial fisheries in estuaries and coastal zones across this region during summer/autumn 2017 and 2018, with sample numbers (**Table 1**) stratified among locations roughly in proportion to the relative biomass of harvest in these regions in recent years, to ensure a representative sample of the fishery was obtained. Fish in this latter group had chemical fingerprints in their juvenile (sub-yearling region) region analysed (**Figure 4**) to compare with the fingerprints collected in part 1), but also had their otolith edges analysed to explore broader spatial patterns in the otolith chemistry of post-recruit Mulloway. Sample collections were complemented by samples captured from the recreational fishery, and from fisheries independent mesh net sampling.

To further aid in the interpretation of the patterns derived using otolith chemistry, we also collated a summary of historic tag-recapture data for Mulloway collected by researchers within NSW Department of Primary Industries (from data held within an internal database). These data were previously reported in a different form in West (1993), and have been summarised in a highly aggregated form by Silberschneider and Gray (2008).

Figure 3 Map of the New South Wales (NSW) coast, Australia, showing the estuaries and ocean zones targeted for Mulloway collection. Also indicated is Lake Conjola, which was included in the historic tag-recapture data for Mulloway.

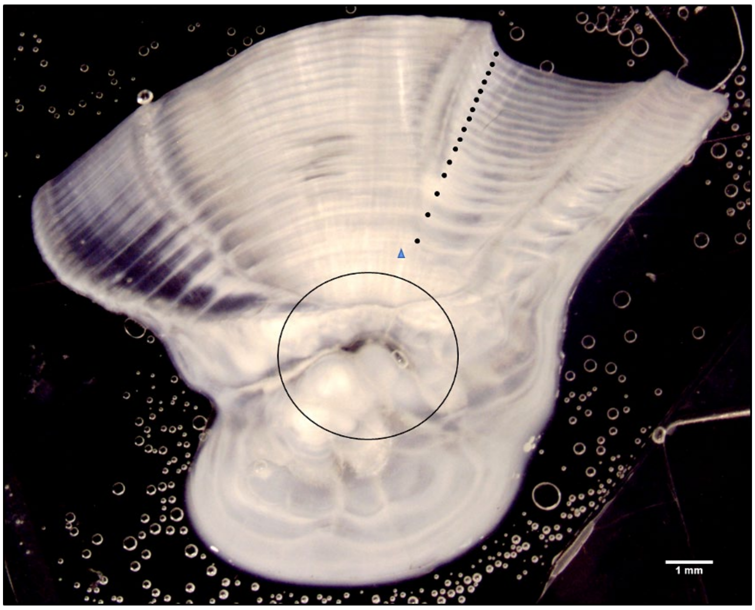


Figure 4 Photomicrograph showing the location of otolith ablation from a post-recruit Mulloway aged 17 years. The primordium (core) is shown within the large ring and yearly annuli (growth rings) are indicated by the small dots. The ablation spot (shown as a triangle), is positioned between the primordium and first annuli, within the region of the first year of growth.

Table 1 Summary of post-recruit Mulloway collected during spring/summer (November to April) 2015-2018, showing the number of samples collected (*N*), and the number for which chemical data were suitable for analysis after QA/QC (*n*). Sample numbers were geographically stratified roughly in proportion to the harvested biomass from each location, however this was not possible for all locations.

Estuary	2015 Sample Size (*N*)	2016 Sample Size (*N*)	2017 Sample Size (*N*)	2018 Sample Size (*N*)	Total Sample Size (*N*)	Chemical Data (Sub-yearling Region *n*)	Chemical Data (Edge Region *n*)	Total Length (range, cm)	Age Range (years)
Richmond River	-	-	-	19	19	19	9	64 – 105	1 – 3
Clarence River	-	-	32	42	74	67	32	45 – 101	1 – 27
Macleay River	3	-	8	7	18	15	11	45 – 105	1 – 21
Hastings River	13	-	2	1	16	13	12	47 – 65	1 – 6
Camden Haven River*	-	-	-	1	1	1	1	80	4
Manning River	-	-	11	18	29	28	20	45 – 100	1 – 8
Wallis Lake	-	-	7	11	18	15	15	45 – 94	2 – 8
Port Stephens	-	-	11	32	43	36	35	45 – 110	1 – 5
Hunter River	-	1	-	28	29	29	17	49 – 100	2 – 17
Tuggerah Lakes*	-	-	-	5	5	6	4	48 – 61	3 – 5
Hawkesbury River	-	-	21	19	40	33	28	46 – 126	2 -8
Myall Lakes*	-	-	-	1	1	1	1	48	2
Georges River	-	-	-	22	22	22	19	45 – 59	2 – 6
Lake Illawarra*	-	-	1	-	1	0	1	46	2
Shoalhaven River	-	-	27	24	51	45	40	45 – 110	2 – 26
Ocean Zone 1*	-	2	1	1	4	2	1	81 – 128	2 – 2
Ocean Zone 2*	-	4	-	1	5	1	2	86.5 – 120	6 – 11
Ocean Zone 3	-	-	7	9	16	14	7	74 – 126	4 – 6

Estuary	2015 Sample Size (*N*)	2016 Sample Size (*N*)	2017 Sample Size (*N*)	2018 Sample Size (*N*)	Total Sample Size (*N*)	Chemical Data (Sub-yearling Region *n*)	Chemical Data (Edge Region *n*)	Total Length (range, cm)	Age Range (years)
Ocean Zone 4	-	-	7	3	10	6	9	73 – 105	1 – 5
Ocean Zone 5	-	-	6	15	21	21	14	71 – 102.6	1 – 6
Ocean Zone 6*	-	2	-	-	2	0	1	84	3
Ocean Zone 7*	-	2	-	1	3	1	1	83 – 131	4 – 9

* Samples from these locations were excluded from PERMANOVA, cluster analysis and CVA due to small sample sizes

Sample preparation and analytical methods

Sagittal otoliths were removed from each fish, cleaned in ultra-pure deionised water (Milli-Q), air-dried overnight and stored in paper envelopes. An otolith from each fish was embedded in two-part epoxy resin (Struers Epofix) spiked with indium (~ 40 ppm), before being sectioned transversely (~300-µm-wide) through the primordium (perpendicular to the long axis) using a low-speed saw (Buehler Isomet) and dual diamond blades. During this process, Milli-Q water was used to lubricate the blades. The resulting sections were affixed to standard glass microscope slides in random order using indium-spiked (~200 ppm) thermoplastic glue (Crystalbond 509) and polished sequentially with various grades of lapping paper (30, 9, and 3 µm). Slides with mounted otoliths were then sonicated for 5 min (Unisonics Australia FXP4) with Milli-Q water to remove any surface contaminants. Once dried overnight in a laminar flow positive pressure fume hood, the slides where individually stored in clean, sealed plastic bags; awaiting trace element analysis using laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS).

Transverse sections of Mulloway otoliths (total n = 428) were analysed at Adelaide Microscopy (University of Adelaide) using a NewWave UP-213-nm laser ablation system connected to an Agilent 7500cs inductively coupled plasma-mass spectrometer (LA-ICP-MS). The ICP-MS instrument was run at a frequency of 5 Hz and fluency of 10 J cm^{-2}, using a spot size of 60 µm. The sample to be analysed was placed in the ablation chamber and viewed remotely on a computer screen. The laser was focused on the intended spot position then fired through the microscope objective lens. Resultant ablated material was entrained by argon and helium gas for analysis of ^{25}Mg, ^{55}Mn, ^{88}Sr, ^{138}Ba, ^{7}Li, ^{44}Ca, and ^{115}In isotopes by ICP-MS. ^{115}In was analysed to detect any contamination from resin or the thermoplastic glue, and calcium was the internal standard used to correct for any variations in ablation yield. Before each sample ablation, elemental background concentrations were determined by analysis of the chamber gases without any sample present. After 20 to 30 s of the blank counts, a single 60 µm spot was ablated. For samples of unknown estuarine nursery (part 2), the ablation position was within the sub-yearling region of the otolith, between the distal edge of the primordium (core) and before the first annual growth ring. This spot location was selected as it is comprised of the material incorporated into the otolith surface, during the individuals' juvenile phase and was therefore the most useful composition to characterise the estuary of origin. Certified reference materials (glass standard NIST 612 and carbonate standard MACS-3) were analysed every 10 to 12 samples and a linear interpolation between the 2 consecutive sets of NIST 612 standards were made to correct for instrument drift, calibrate elemental concentrations, correct mass bias and assess external precision. Between each ablation, a 30 s washout delay was used to purge the chamber and prevent each sample from cross-contamination.

Background counts lasting 60 s were collected at the start and end of each day of analysis, with the variation among these counts used to calculate the limits of detection. In the few cases where data fell below the limit of detection, raw data values were used; since substituting values with an arbitrary number has been shown to bias data owing to non-random patterns in the distribution of small values (Helsel 2006; Schaffler *et al.* 2014; Lazartigues *et al.* 2016). As outlined by Yoshinaga *et al.* (2000), calcium concentration was assumed from the stoichiometry of calcium carbonate as 38.8% and the concentration of other elements (above the limits of detection) were estimated against the Ca concentration. Mean estimates of precision (%RSD, relative standard deviation) based on a NIST 612 standard being treated as an unknown were: 100% (^{25}Mg, ^{7}Li, ^{115}In) and 99.95% (^{44}Ca, ^{88}Sr, ^{138}Ba, and ^{55}Mn). Raw elemental count data were processed using the Iolite software plugin (Paton *et al.* 2011) for IgorPro (Wavemetrics) and sample measures were expressed as ratios to ^{44}Ca (in µmol mol^{-1}) to account for fluctuations in the ablation yield. For each session, baseline values were subtracted (step-forward integration) and 0.5s was cropped from the start and finish of each measurement. Where the indium marker was detected (indicating ablation of the mounting material), individual measurements were further cropped. Output measurements were calibrated against the NIST612 measurements (Spline Smooth 7 integration) over the period of the run. Data (counts s^{-1}) were then converted to concentrations and expressed as ratios to ^{43}Ca (in mmol mol^{-1}) manually, in Microsoft Excel, using the equation of Ludden *et al.* (1995).

Data handling and analysis

Trace elements ^{88}Sr, ^{138}Ba, ^{25}Mg, ^{55}Mn and ^{7}Li were selected for statistical analyses since these consistently produced concentrations above detection limits (LOD), provided the best precision (based on %RSD) and the best accuracy (percent recovery). Furthermore, the selected suite of elements are all indicators of environmental change (although also influenced by intrinsic factors) and are thus informative for environmental history reconstructions (Campana 1999). Prior to analyses, all raw data were checked for errors and outliers using Cleveland dot plots and box plots according to Zuur *et al.* (2010) and any erroneous data caused by spiked indium levels or machine error were removed (see **Table 1**).

Analysis of the two-part experimental design involved modelling and classifying the putative nursery source of post-recruit Mulloway (part 2) based on similarity of their sub-yearling chemical fingerprints with those of juveniles of "known" origin collected for part 1. The premise underlying this comparison is that the majority of important putative nursery sources were accounted for in the collection of "known" samples, which should be evident in overlapping chemical fingerprints between the sample data for part 1 and part 2. This was assessed quantitatively following a modified application of the point-in-polygon technique (Smith *et al.* 2013; Taylor *et al.* 2016). First, multivariate chemical data for both datasets were reduced to two primary principal components using the 'prcomp' function in R (Abdi and Williams 2010). These bivariate data (PC1 and PC2) were subsequently incorporated in a point-in-polygon analysis using the functions developed by Smith *et al.* (2013). Any adult samples that lay outside the 90% contour of the simulated "mixing region" were excluded from the subsequent classification analysis.

To predict the likely nursery areas of post-recruit Mulloway (*n* = 217 after data reduction), multinomial logistic regression (MLR) and non-parametric permutational-ANOVA (PERMANOVA) were used to analyse the multivariate elemental data in R v. 3.2.1. An initial base model was created using samples (*n* = 277) from part 1 of the experimental design (see Russell *et al.* 2021). The multivariate sub-yearling chemical signatures for post-recruited Mulloway were used with this model (and the 'predict' function) to classify each sample to one of the eight *a priori* putative estuarine nurseries. Predictions of natal origins of post-recruit Mulloway were tested at the capture location level. Following this, the null hypothesis of no difference among multivariate sub-yearling chemical data for each location was tested by PERMANOVA (Anderson and Robinson 2003; Anderson and Willis 2003) on a Euclidian distance similarity matrix. The centroid for each location was the centre-point of all samples allocated to that location, in multi-dimensional space (referred to as a multivariate mean in MANOVA; Queen *et al.* 2002). Matrices of the distances among centroids of each location for sub-yearling otolith signatures in post-recruit fish were derived from Euclidean distance similarity matrices of the elemental composition data, and plotted using Canonical Variates Analysis (CVA) to visualise the predicted origins of post-recruit individuals.

To explore broader spatial patterns in the otolith chemistry of the exploited component of the stock, a *K*-means cluster analysis was applied to the standardized multi-elemental data from all capture locations (locations with less than 5 samples were excluded), using Euclidean distance measures (see Kaufman and Rousseeuw 2009). Cluster identities of post-recruit Mulloway were determined for (i) edge signatures (signifying the chemical fingerprint for post-recruit fish at the location of capture); and, (ii) sub-yearling signatures (signifying the chemical fingerprint during the estuarine nursery stage). To determine the optimal number of clusters the average silhouette method was used on *K*-

means generated by 25 initial configurations (Rousseeuw 1987). Following a dispersion test for homogeneity of variance ($P > 0.05$) a non-parametric PERMANOVA was used on each multivariate elemental dataset to evaluate if there were geographic differences in the elemental chemistry of the edge and sub-yearling regions of the post-recruit Mulloway otoliths, based on their capture locations. Post-hoc pairwise comparisons were used where significant effects were found, to further explore variation in multi-elemental fingerprints. Canonical Variates Analysis (CVA) plots were produced from the matrix in order to visualise results.

Modelling the consequences of adaptive closure management for Eastern King Prawn

As discussed above, adaptive management of JEKP closures to temporarily allow trawling for Eastern School Prawn following floods may dampen the economic impacts of spatio-temporal closures implemented to avoid Mulloway bycatch, but this may also lead to unforeseen impacts on the EKP stock. Noting that the JEKP closure network has not been evaluated since it was implemented, this leads to two immediate questions: 1) is the closure network having a substantial impact on the overall harvest of EKP in NSW and Queensland; and, 2) do waters inside JEKP closures allow access to Eastern School Prawn without high levels of Mulloway bycatch. A model was developed to partially addresses this knowledge gap by addressing 1) above. Specifically, we consider this question for JEKP closures in the northernmost part of the NSW fishery (NSW ocean zone [OZ] 1, and OZ 2, **Figure 5**) where the productivity of the stock is greatest, but also where the Mulloway bycatch problem is most prevalent.

Modelling approach

To evaluate the potential impact of the NSW OZ 1 and 2 closures, we developed a spatially explicit, quantitative EKP population model generally following the approach of Camp *et al.* (2020). The population model was an age-structured, discrete-time (with a monthly time step), sex-general model, which represented the entire spatial range of the EKP stock, from Victoria in the south to southern Queensland in the north (**Figure 5**). This structure allowed explicit representations of all major processes and dynamics in the fishery, including spatial movement of sub-adults and adults, dispersal of eggs and larvae, density-dependent recruitment processes mediated by habitat availability, and spatial dynamics of fishing effort (detailed below).

We approached the question of closure impact on the fishery in its current state, by evaluating the expected effects of removing these closures and allowing prawn trawling in currently closed areas. The model was parameterised using recent stock assessments (O'Neill *et al.* 2014; Helidoniotis *et al.* 2020), current fisheries data (harvest and effort), and statistical estimation of catchability parameters to scale the model so that it well represented current spatial patterns in harvest. This type of parameterisation represents a statistically “tuned” model, rather than an explicit stock assessment. Thus, the model is useful for making directional and proportional inferences from the results, but it is not intended to replace, nor should it be mistaken for, a full stock assessment. All parameters (estimated and fixed) used are provided in **Table 2**, **Table 3** and **Table 4**, and model equations are described in **Table 5**. While nearly all critical model dynamics or processes are similar to Camp *et al.* (2020), they are summarised below for completeness.

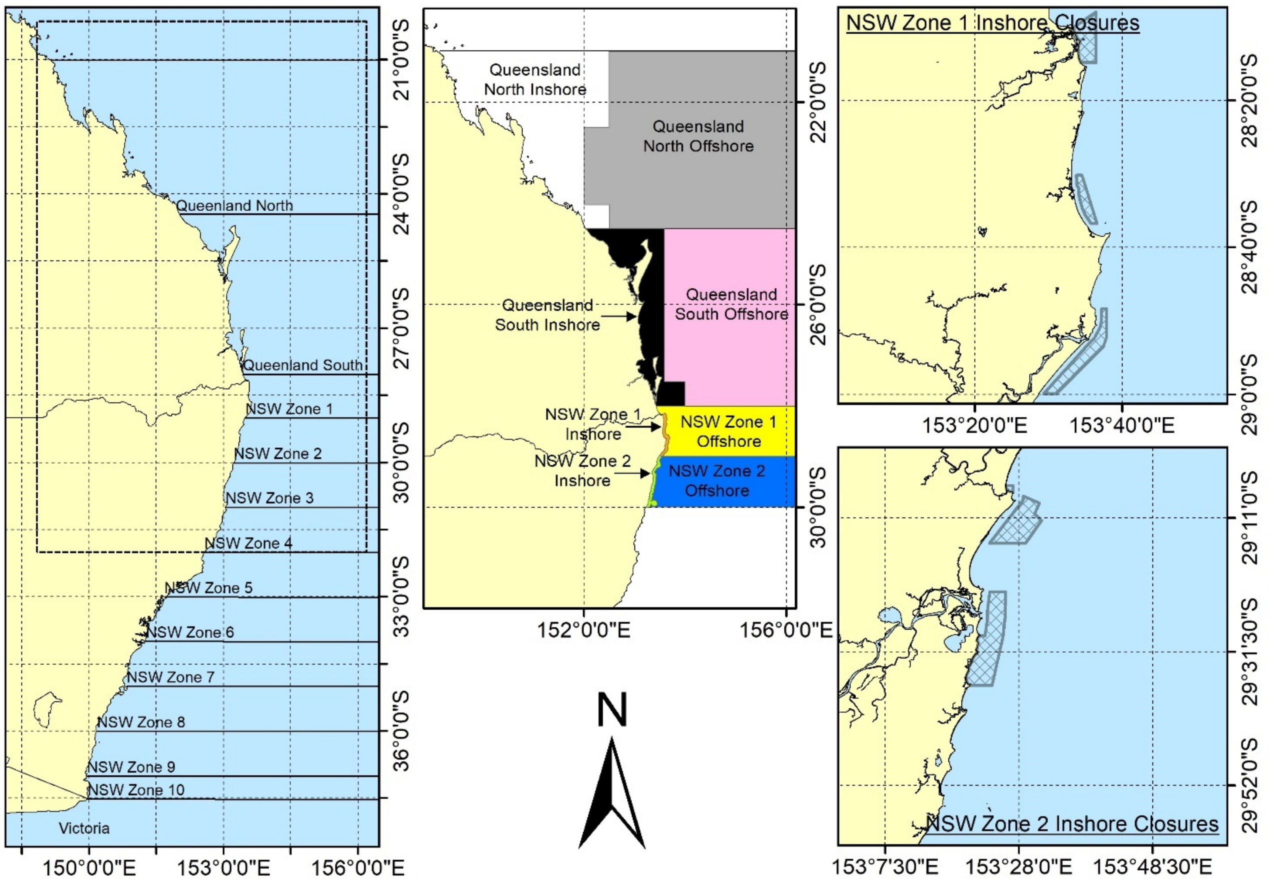


Figure 5 Map showing spatial strata used in the simulation model, including: 1) the various latitudinal ocean zones across the multi-jurisdictional Eastern King Prawn fishery (shown on the left panel, the grey dashed line shows the inset for the middle panel); 2) a detail map showing the main region of interest for the model simulations (middle panel), including the four Queensland zones and northernmost NSW ocean zones; and, 3) the inshore JEKP closure zones on the right panels (grey hatched boxes) for NSW Ocean Zone 1 and 2.

Table 2 Description of parameters and parameter values in the spatial model to estimate impact of habitat restoration for the Eastern King Prawn fishery ("*" preceding parameter indicates value estimated). Symbols relate to the information presented in **Table 3** and formulae outlined in **Table 5** and the text.

Symbol	Description	Units	Value	Source
$\bar{R}_k$	Recruitment at unfished conditions at zone $_k$	fish	Variable, see Table 2	O'Neill *et al.* (2014)
L_∞	Asymptotic length, carapace	mm	55	Courtney *et al.* (2014)
K	von-Bertalanffy metabolic parameter	$month^{-1}$	0.20	Courtney *et al.* (2014)
t_0	Age at length=0	$month^{-1}$	0.00	Expert opinion
w_a	Weight-length constant	g	0.0006	Courtney *et al.* (2014)
w_b	Weight-length exponent	g	3.09	Courtney *et al.* (2014)
α_f	Fecundity alpha parameter		0.199	O'Neill *et al.* (2014)
β_f	Fecundity beta parameter		4.753	O'Neill *et al.* (2014)
L^T	Length at 50% maturity	mm	39	O'Neill *et al.* (2014)
σ^T	Standard deviation of maturity		0.05	O'Neill *et al.* (2014)
M	Instantaneous mortality at L_m	$month^{-1}$	0.20	O'Neill *et al.* (2014)
L_m	Reference carapace length for mortality	mm	25	Expert opinion
C_l	Allometric exponent of length-mortality relationship	constant	1.0	Expert opinion
A_m	Maximum age	months	18	
Ω	Recruitment compensation parameter	ratio	6	Courtney *et al.* (2014)

Symbol	Description	Units	Value	Source
L^c	Carapace length at 50% vulnerability to capture	mm	20	Courtney *et al.* (2014)
σ^c	Standard deviation of length-specific vulnerability to capture		$0.075 * L^c$,	Courtney *et al.* (2014)
$A_{\mathrm{l}}^{\mathrm{m}}$, $A_{\mathrm{u}}^{\mathrm{m}}$	Ages at 50% probability of moving	month	4, 11	Expert opinion
$\sigma_{\mathrm{l}}^{\mathrm{m}}$, $\sigma_{\mathrm{u}}^{\mathrm{m}}$	Standard deviation of age-specific movement probability		$0.18 * A_{\mathrm{l}}^{\mathrm{m}}$, $0.09 * A_{\mathrm{u}}^{\mathrm{m}}$	
E	Total fishing effort, entire fishery (Queensland, NSW, Victoria)	Days per month	1571.99	NSW Department of Primary Industries–Fisheries Commercial Catch and Effort Reporting System
E_k	Zone specific effort	month^{-1}	Variable, see Table 2	
$*q_N^o$	Catchability coefficient scaling parameter for New South Wales, Offshore	rate	5.962e-05	Estimated
$*q_N^i$	Catchability coefficient scaling parameter for New South Wales, Inshore	rate	9.415e-05	Estimated
$*q_Q^o$	Catchability coefficient scaling parameter for Queensland, Offshore	rate	5.435e-05	Estimated
$*q_Q^i$	Catchability coefficient scaling parameter for Queensland, Inshore	rate	3.481e-04	Estimated
H_k	Zone-specific proportion of habitat suitable for recruitment	Proportion	Variable by zone, see Table 2	
c^*	Logical parameter for whether larval are assumed to be capable of locating recruitment habitat (1) or not (0)	Unitless	0	Walters *et al.* (2007)

Symbol	Description	Units	Value	Source
$Y_{k,k}$	Matrix of probabilities of dispersal from zone *k* to zone *k*	Proportion	Variable, see Table 3	Everett *et al.* (2017)
V_a	Age-specific vulnerability to movement	Proportion	Variable, see Figure 2	Expert opinion
p^i	Probability of staying at inshore zones, used to create movement matrix	Proportion	0.6	Braccini et al. 2019
p^o	Probability of staying at offshore zones, used to create movement matrix	Proportion	0.8	Braccini et al. 2019
e_3^n, e_4^n	New fishing effort that redistributed to NSE inshore zones 1 & 2 (*k*=3,4 respectively) from adjacent offshore zones	Proportion	Variable	
r_3, r_4	Total area of NSW inshore zones 1 & 2, respectively	ha	74,951 and 62,347 respectively	NSW Department of Primary Industries
o_3, o_4	Total closed area to be opened of inshore zones 1 & 2, respectively	ha	10,182 and 23,658 respectively	NSW Department of Primary Industries

Table 3 Zone-specific (subscript *k*) parameter values. Parameter symbols are defined in **Table 2**.

Symbol	Queensland North Inshore	Queensland South Inshore	NSW OZ 1 Inshore	NSW OZ 2 Inshore	NSW OZ 3 Inshore	NSW OZ 4 Inshore	NSW OZ 5 Inshore	NSW OZ 6 Inshore	NSW OZ 7 Inshore	NSW OZ 8 Inshore	NSW OZ 9 Inshore	Victoria Inshore
$\bar{R}_k$	2.942×10^8	2.942×10^8	0.044×10^8	1.097×10^8	2.150×10^8	0.668×10^8	0.668×10^8	0.001×10^8	0.001×10^8	0.001×10^8	0.001×10^8	0.001×10^8
E_k	9.335	428.698	17.217	7.850	2.550	0	1.683	0	0	0	0	0.208
$H_{t,k}$	0.176	0.176	0.176	0.223	0.221	0.535	0.4	0.7	0.8	0.95	0.95	0.95
$\bar{R}_k$	0	0	0	0	0	0	0	0	0	0	0	0
E_k	289.367	481.700	59.516	148.500	81.517	0	43.433	0	0	0	0	0.417
$H_{t,k}$	0	0	0	0	0	0	0	0	0	0	0	0

Table 4 Dispersal probability matrix, indicating the probability of eggs spawned in each zone dispersing throughout the region. For example, it is assumed that 10% of eggs spawned in Queensland North disperse to Queensland North, whereas 95% of eggs spawned in Victoria disperse to Victoria. Shown here is the dispersal matrix for eggs spawned in offshore zones dispersing to inshore zones, and identically, from inshore zones to inshore zones. There is assumed no dispersal to offshore zones.

	QLD N	QLD S	NSW OZ 1	NSW OZ 2	NSW OZ 3	NSW OZ 4	NSW OZ 5	NSW OZ 6	NSW OZ 7	NSW OZ 8	NSW OZ 9	Victoria
QLD N	0.1	0	0	0	0	0	0	0	0	0	0	0
QLD S	0.1	0.2	0	0	0	0	0	0	0	0	0	0
NSW OZ 1	0.2	0.2	0.2	0.2	0.01	0.01	0	0	0	0	0	0
NSW OZ 2	0.2	0.2	0.2	0.2	0.05	0.01	0.01	0	0	0	0	0
NSW OZ 3	0.15	0.15	0.2	0.2	0.2	0.06	0.02	0.01	0	0	0	0
NSW OZ 4	0.1	0.1	0.15	0.15	0.2	0.2	0.02	0.02	0.01	0	0	0
NSW OZ 5	0.05	0.05	0.1	0.1	0.2	0.2	0.2	0.02	0.02	0.01	0	0
NSW OZ 6	0.05	0.05	0.1	0.1	0.15	0.2	0.2	0.2	0.02	0.02	0.01	0
NSW OZ 7	0.02	0.02	0.02	0.02	0.1	0.1	0.2	0.2	0.2	0.02	0.02	0.01
NSW OZ 8	0.02	0.02	0.02	0.02	0.05	0.15	0.15	0.2	0.2	0.2	0.02	0.02
NSW OZ 9	0.01	0.01	0.005	0.005	0.02	0.05	0.15	0.15	0.2	0.2	0.2	0.02
Victoria	0	0	0.005	0.005	0.02	0.02	0.05	0.2	0.35	0.55	0.75	0.95

Table 5 Description of model components and equations used in the spatial model to estimate the impact of removing NSW OZ 1 and OZ 2 JEKP closures on the EKP fishery. Parameter symbols are defined in **Table 2**.

Eqn.	Component	Equation
Life History Characteristics of Stock		
Eq. 1	Length (mm) *L* at age $_a$	$L_a = L_\infty(1 - \mathrm{e}^{-K(a-t_0)})$
Eq. 2	Mass (kg) *W* at age $_a$	$W_a = w_a {L_a}^{w_\mathrm{b}}$
Eq. 3	Fecundity *f* at age $_a$	$f_a = 10^{(\alpha_f L_a + \beta_f)}$
Eq. 4	Maturity *T* at age $_a$	$T_a = (1 + \mathrm{e}^{-(L_a - L^T)\sigma^T L^T})^{-1}$
Eq. 5	Survival (year^{-1}) *S* at age $_a$	$S_a = \mathrm{e}^{(-(M L_\mathrm{m} {L_a}^{-1}))^{C_1}}$
Eq. 6	Survivorship *l* at age $_a$	$\begin{array}{r\|l} l_a = 1 & a = 1 \\ \hline l_a = l_{a-1} S_{a-1} & a = 2{:}\,Amax \end{array}$
Eq. 7	Eggs per recruit φ_e	$\varphi_\mathrm{e} = \sum_a f_a T_a l_a$
Eq. 8	General Beverton-Holt *a* parameter	$a = \Omega {\varphi_\mathrm{e}}^{-1}$
Eq. 9	Zone-specific Beverton-Holt b_k parameter	$b_k = (\Omega - 1)(\bar{R}_k \varphi_\mathrm{e})^{-1}$
Eq. 10	Beverton-Holt *a* parameter modified by zone $_k$ and time $_t$ specific recruitment habitat $H_{t,k}$	$a^H_{t,k} = a {H_{t,k}}^{c^*}$
Eq. 11	Beverton-Holt *b* parameter modified by zone $_k$ and time $_t$ specific recruitment habitat $H_{t,k}$	$b^H_{t,k} = {H_{t,k}}^{c^*} b_k (H_{t,k})^{-1}$

Eqn.	Component	Equation
Movement Characteristics of Stock		
Eq. 12	Age-specific probability p at age $_a$ to moving (^{m}) for inshore zones	$p_a^{\mathrm{m}_i} = 1 - (1 - p^i)V_a$
Eq. 13	Age-specific probability p at age $_a$ to moving (^{m}) for offshore zones	$p_a^{\mathrm{m}_o} = 1 - (1 - p^o)V_a$
Eq. 14	Array of movement from zone $_k$ to zone $_k$, by age $_a$	$M_{k,k,a} = f(p_a^{\mathrm{m}_i}, p_a^{\mathrm{m}_o})$
Initialization		
Eq. 15	Recruitment at unfished conditions per zone $_k$ in initial time period $_{(t=1)}$	$\bar{R}_{t=1,k} = (a_{t=1,k}^{H}\varphi_{\mathrm{e}} - 1)(b_{t=1,k}^{H}\varphi_{\mathrm{e}})^{-1}$
Eq. 16	Numbers at age $_a$, zone $_k$ in initial time period ($_{t=1}$)	$N_{t=1,a,k} = \bar{R}_{t=1,k} l_a$
Eq. 17	Eggs at zone $_k$ in initial time period ($_{t=1}$)	$G_{t=1,k} = \sum_a f_a T_a N_{t=1,a,k}$
Eq. 18	Recruits at zone $_k$ in initial time period ($_{t=1}$)	$G_{t=1,k} = \bar{R}_{t=1,k}$
Time Dynamics		
Eq. 19	Exploitation rate U at time $_t$, zone $_k$	$U_{t,k} = 1 - \mathrm{e}^{qE_{t,k}}$
Eq. 20	Larvae at zone $_k$ in time period $_t$	$L_{t,k} = \sum_k G_{t-1,k} Y_{k,1:k}$

Eqn.	Component	Equation
Eq. 21	Recruits at zone $_k$ in time period $_t$	$R_{t,k} = aL_{t,k}(1 + bL_{t,k})^{-1}$
Eq. 22	Updating numbers at time $_t$, age $_a$ and zone $_k$ following movement from previous time step	$N_{t,a,k} = N^{M}_{t-1,a,k}$
Eq. 23	Numbers at time $_t$, age $_a$, zone $_k$ that survive each time period	$N^{S}_{t,a,k} = N_{t-1,a-1,k}S_{a-1}(1 - v^{\mathrm{c}}_{a-1}U_{t-1,k})$
Eq. 24	Eggs at zone $_k$ at time period t	$G_{t,k} = \sum_{a} f_a T_a N_{t,a,k}$
Eq. 25	Numbers at time $_t$, age $_a$ and zone $_k$, following movement	$N^{M}_{t,a,k} = \sum N_{t,a,k}\, M_{k,1:k,a}$

Fishery Characteristics

Eq. 26	Vulnerability *v* at age $_a$ to capture (^{c})	$v^{\mathrm{c}}_{a} = (1 + \mathrm{e}^{-(L_a - L^c)\sigma^{c^{-1}}})^{-1}$
Eq. 27	Total catch C_t in year $_t$ at zone $_k$	$C_{t,k} = U_t v^{\mathrm{c}}_{a} N_{t,a,k}$
Eq. 28	Catch per unit effort per time period $_t$ and zone $_k$	$y_{t,k} = C_{t,k}{E_{t,k}}^{-1}$

Effort redistribution dynamics

Eq. 29	Proportion of increased fishing area in inshore zones, *k*=3*, k*=4	$i_k = o_k {r_k}^{-1}$
Eq. 30	Additional new fishing effort in inshore opened area *k=3, k=4*	$n_k = E_k i_k e_k$

Eqn.	Component	Equation
Eq. 31	Effort redistributed to inshore zones (*k*=3, *k*=4) from offshore zones (*k* =15, *k*=16)	$r_k = E_k i_k (1 - e_k)$
Eq. 32	Updated fishing effort in inshore zones (*k*=3, *k*=4)	$E_k^u = E^k + n_k + r_k$
Eq. 33	Updated fishing effort in offshore zones adjacent to inshore zones (*k* =15, *k*=16)	$E_k^u = E^k - r_k$

Conceptual model

Spatial representation

The spatial structure of the model spanned the spatial range through which EKP is currently exploited (**Figure 5**). There were 24 total zones within a 12 x 2 matrix (12 cells north-to-south by 2 cells east-to-west, with the 12 north-south zones including one zone for Victoria, nine for NSW, and two for Queensland, which aligned closely to the zones in which the stock is currently assessed and managed, and against which catch is reported (Prosser and Taylor 2016; Helidoniotis *et al.* 2020). While the closures evaluated in this work are fully within inshore waters within NSW, accurate representation of the NSW EKP fishery requires accounting for larval dispersal, sub-adult and adult movement, and fisheries removals of EKP beyond NSW. The two east-west zones: 1) account for spatial separation of the fishery, employing fishery data that is reported inshore and offshore within the NSW OTF; 2) makes explicit the offshore movement of EKP as they mature (Braccini *et al.* 2012); and, 3) allows for explicitly representing the lifting of closures which exist in inshore wares. The inshore and offshore zones are used to represent the sub-adult and adult recruited EKP (i.e., individuals no longer undergoing density-dependent mortality). Since EKP are believed to undergo recruitment processes in estuaries, rather than the inshore zones, recruitment is explicitly represented such that density-dependent processes occur in estuaries, with surviving recruits matriculated to longitudinally adjacent inshore zones.

Growth, survival, and fecundity

We modeled EKP growth, survival, and fecundity identically to Camp *et al.* (2020). Growth was described in terms of carapace length (CL, mm), body weight (g), and age months), following their original description in Courtney *et al.* (2014). Carapace length-at-age was modelled using a von Bertelanffy growth function (L_a, Eq. 1, **Table 5**), and corresponding body weight modelled as an allometric function of length (W_a, Eq. 2, **Table 5**). Sub-adult and adult (i.e. post-recruit) EKP survival (S_a, Eq. 5, **Table 5**) was modelled using a Lorenzen-type mortality function that assumes instantaneous natural mortality decreases with increasing body size. Fecundity-at-age was specified as a function of maturity and weight (f_a, Eq. 3, **Table 5**), with average weight-at-maturity (W_m, **Table 2**) calculated from the corresponding length at maturity of 42 mm CL following Glaister (1983). This specification of fecundity is relative in that it represents spawning biomass rather than absolute numbers of eggs, relying on the parameterisation of the stock-recruit function (specifically the Beverton-Holt *a* parameter, Eq. 7, **Table 5**) to scale spawning biomass to appropriate numbers of recruits. Each of growth, survival and fecundity was assumed to be invariant among the spatial compartments represented in the model.

Dispersal

Eastern King prawn aggregate and reproduce offshore, with eggs and subsequent larvae dispersing to estuarine areas via active transportation in advective ocean currents. Estuarine areas in the model are implicitly represented adjacent to each of the 12 inshore zones by the recruitment dynamics. Thus, to account for different estuarine zones receiving relatively different amounts of eggs and larvae, we explicitly described the dispersal processes. Similar to Camp *et al.* (2020), we accounted for dispersal using a matrix of probabilities giving the proportions of eggs spawned at a given zone that disperse to all other zones (**Table 4**), derived from recent modelling (Everett *et al.* 2017). In the current model we assume no dispersal of eggs from inshore zones, which amounts to assuming all spawning occurs in offshore zones. As is common with fisheries population models, the mortality associated with the multiple biological processes between eggs being spawned and juveniles exiting density dependent mortality (i.e., recruiting) is subsumed within the recruitment function (Eq. 21, **Table 5**).

Recruitment

We represent recruitment processes via a Beverton-Holt stock-recruit relationship that has been previously used for EKP (O'Neill *et al.* 2014), but with *a* (Eq. 10, **Table 5**) or *b* (Eq. 11, **Table 5**) parameters modified according to the amount of habitat suitable for recruitment which is believed to currently exist in a recruitment area (Walters *et al.* 2007; Camp *et al.* 2020). While habitat suitable for recruitment, presumably a function of a two-or-three dimensional spatial measurement of usable habitat, may be difficult to quantify, substantial research on EKP recruitment habitat has been previously completed, and spatially explicit stock assessments provide information regarding estimated EKP recruitment at unfished conditions in different regions of the EKP range (O'Neill *et al.* 2014). Following Camp *et al.* (2020), in this work we calculated the *a* parameter of the Beverton-Holt stock recruitment function, (Eq. 7, **Table 5**) as a function of the compensation ratio (Ω, **Table 2**) and eggs-per-recruit (φ_{e}, Eq. 6, **Table 5**), making the *a* parameter identical across recruitment zones. The *b* parameter of the Beverton-Holt function is, in addition to Ω and φ_{e}, also a function of recruitment at unfished conditions ($\bar{R}_k$, **Table 3**). Since recruitment and unfished conditions was assumed to differ across zones (O'Neill *et al.* 2014), this results in zone-specific *b* values (b_k, Eq. 8, **Table 5**). The current work differs slightly from previous work in that it splits the recruitment at unfished conditions $\bar{R}_k$ (**Table 3**) for Queensland provided in O'Neill *et al.* (2014) into two equal amounts for the North and South Queensland zones described in this model. Since the current work does not explore any modifications to recruitment habitat (e.g., restoration), the importance of this specific recruitment process is to ensure the most realistic representation of the current state of the EKP population and fishery.

Movement

The movement of EKP, both from the inshore to the offshore zones, as well as among the offshore zones, is especially important for this study. Movement patterns determine the proportion of EKP that remain vulnerable to the inshore and offshore fishery, and thus could directly alter the effect of removing the inshore closures. While previous research has established that EKP move more offshore and northward as they mature (Montgomery 1990; Courtney *et al.* 2014; Taylor *et al.* 2016), no estimates exist that correspond to all of the explicit management zones described here. Thus, we used the most fine-scale estimates available (Braccini *et al.* 2012) and modified them slightly based on expert opinion to produce a matrix of probabilities of movement from each zone to each other zone. This matrix was then modified by age-specific probabilities of movement (V_a) for EKP, resulting in a three-dimensional array of movement probabilities. Given both the importance, and also uncertainty of movement, we simulated the effects of closures under a range of different movement scenarios.

Fishery

The EKP commercial fishery is represented in the model in a spatially explicit, zone-specific context. We represented zone-specific differences in harvest rate ($U_{t,k}$, Eq. 19, **Table 5**) via input of zone-specific fishing effort (E_k, **Table 3**). The values for effort in each zone were calculated as the average monthly effort reporting through compulsory log books for both New South Wales and Queensland, averaged over the past 5 years.

Model simulations

Parameterisation and operationalisation

The objective of this work, assessing the likely impacts of removing closures located within the two northernmost NSW OZs, requires the model to represent reasonably well the current state and dynamics of the EKP population and fishery. This means the “baseline” model, prior to any representation of closure removal, must predict zone-specific catches similar to those recently observed under current zone-specific fishing efforts. To accomplish this, we estimated four different catchability scaling parameters (**Table 2**), reflecting different catchability scaling for each of the Queensland offshore, Queensland inshore, NSW offshore, and NSW inshore areas within the fishery. This was achieved by minimizing a negative log-normal likelihood comparing the predicted zone-specific harvest to the observed zone-specific harvest.

To operationalise the model for evaluating the effect of opening of specific closures, we altered the effort dynamics according to several scenarios. We did this by assuming the proportional increase in overall fishing would be no more than commensurate with the increase in fishing area. We calculated the increase in fishing area as a ratio, for NSW OZ 1 and OZ 2, of the currently closed area to the total zone area (closed/zone). This assumption is suggestive that the areas closed would be neither desirable nor undesirable to fish. Alternative assumptions (i.e., closed areas are in reality especially good or bad places to fish) are partially accounted for with alternative effort allocations, and are dealt with in greater detail in the Discussion.

Effects of effort allocation

One of the uncertainties surrounding changes in fisheries management provisions is how fishing effort will respond to the yet-unimplemented rules (Parnell *et al.* 2010; Abbott and Haynie 2012). In this case, we do not know how overall effort and spatial effort may change if closures were to be lifted. At the extreme, it is possible that there would be no change whatsoever in the fishing effort, at least at the spatial scale this model represents. This would occur if fishers simply chose not to fish the previously closed areas, due to the prawns within these areas being smaller and less valuable, or perhaps if some or all of the habitat was unsuitable for trawling. However, there is no need to quantitatively assess such a scenario as it would be identical to the baseline, current scenario. What should be assessed is how the effort may or may not redistribute from historically open areas to previously closed areas. Complete redistribution from offshore (historically open) to inshore (previously closed) areas would mean no net change in overall effort. At the other end of the spectrum, no redistribution of effort would allow for an increase in effort in the inshore zone proportional to the increase in fishing area. To address this, we have represented three “bookend” scenarios: 1) a proportional increase in effort in the inshore zone, and no redistribution from the offshore zone; 2) 50% of proportional increase in effort in the inshore zone, with the remaining 50% redistributed from the adjacent offshore zone; and, 3) a proportional increase in effort in the inshore zone that is wholly a redistribution from the offshore zone. This rough characterization permits inference of how fisher behavior might influence results of the management action being assessed.

Addressing uncertainty associated with EKP movement

To account for uncertainty in movement probabilities, we parameterized the model (i.e., estimated the four catchability scaling parameters) under several different movement probability assumptions. We characterised individual cell-to-cell movement as a series of equations which would reproduce the full movement matrix when supplied with two parameters—the probability of staying at an inshore zone (p^i, **Table 2**) and the probability of staying at an offshore zone (p^o, **Table 2**). Thus, changing these two parameters allowed us to represent alternative assumptions (e.g., greater, less movement) in a systematic fashion.

Addressing uncertainty associated with EKP fishing effort

The primary analyses implicitly assume that the fishery will continue to operate as it has for the last five years with respect to fishing effort. However, the NSW OTF has undergone a large reduction in fishing effort over the last two decades (Helidoniotis *et al.* 2020). Recent estimates of fishing effort within NSW average around 5-6,000 vessel-days of fishing effort, whereas historic effort exceeded 19,000 vessel-days of fishing. The decreases have been attributed to several factors, including various industry reform packages, natural attrition from the fishery, changes in EKP prices, margins (with increased fuel and labour costs) and the profitability of international trade (O'Neill *et al.* 2014) as affected by lower cost, farm-raised alternative product from southeast Asia into the Australian market, leading to diminished demand. It is possible that future altered environmental or economic conditions or shifting consumer demand could result in greater demand and/or price, and thus increased fishing effort in NSW. To consider this we re-ran the model results assuming overall NSW effort equal to the average of the greatest 5-year peak, from 1999-2003 (average effort of 19,082 d y^{-1}). Total annual effort was converted to monthly effort and allocated into zones following current proportional distributions.

Results

Biological evaluation of Eastern King Prawn within inshore closures and adjacent fished zones

Overall, 667 trawl shots were undertaken across all locations and strata through the 3 years of the survey program. Approximately 97,000 EKP were captured, equating to ~1.8 tonnes in biomass, and 26,656 prawns were processed for length and weight. There were some temporal gaps in data collection, with inclement weather preventing surveys in Ballina in April 2017 (**Figure 6**) and Yamba in March 2017 (**Figure 7**), and the Newcastle vessel was not available for charter in January 2017 (**Figure 8**).

Patterns in biomass

There was substantial spatial variation in EKP biomass across locations, zones and sampling periods. Biomass appeared greatest in Yamba (**Figure 7**) and lowest in Newcastle (**Figure 8**). Categorical analysis of mean biomass using ANOVA provided an indication of the magnitude of variation, with significant main effects for location ($F_{2,643}$ = 136.48, P << 0.001), zone ($F_{1, 643}$ = 108.80, P << 0.01), and month ($F_{3, 643}$ = 8.07, P << 0.001), but with a significant location x zone interaction ($F_{2, 643}$ = 31.32, P << 0.001, **Figure 9**). Overall biomass in Ballina and Yamba was much greater than in Newcastle, and Tukey's multiple comparisons indicated that the source of the interaction was significantly greater average biomass occurring within the closure zones for Ballina (P = 0.003) and Yamba (P << 0.001), but no difference between zones for Newcastle (P = 0.991, **Figure 9**). Broad temporal patterns across months were generally consistent among locations, with the biomass of EKP moving through the inshore area increasing from January to March, and declining slightly in April (**Figure 9**).

The distribution across the survey area relative to the adjacent estuary, and temporal variation therein, was somewhat different among locations. In Ballina, biomass appeared to be greater in the southern part of the survey area earlier in the sampling period, but biomass increased in the northern part of the survey area as the season progressed (**Figure 6**). In Yamba, the greatest biomass tended to occur in the areas directly outside the mouth of the adjacent estuary (Clarence River) earlier in the sampling period (**Figure 7**). However, in contrast to Ballina, biomass appeared greater in the southern part of the survey area during March and April. In Newcastle (**Figure 8**), where there was much lower biomass, spatial trends across months were less evident. For Ballina and Yamba (Newcastle was not included in the analysis), a linear model revealed relationships between log-transformed EKP biomass (R^2 = 0.50, $F_{3,509}$ = 170.3, P << 0.001) and log-transformed distance to the adjacent estuary (β = 0.15, t = 2.17, P = 0.033), temperature (β = 0.13, t = 4.71, P << 0.001), and depth (β = 0.16, t = 21.55, P << 0.001). Patterns evident in the kriging analysis show that, during some periods, biomass appears to increase rapidly over the areas close to the estuary, and with depth, before plateauing out. Depth had the largest influence on biomass, while temperature also correlated with greater biomass.

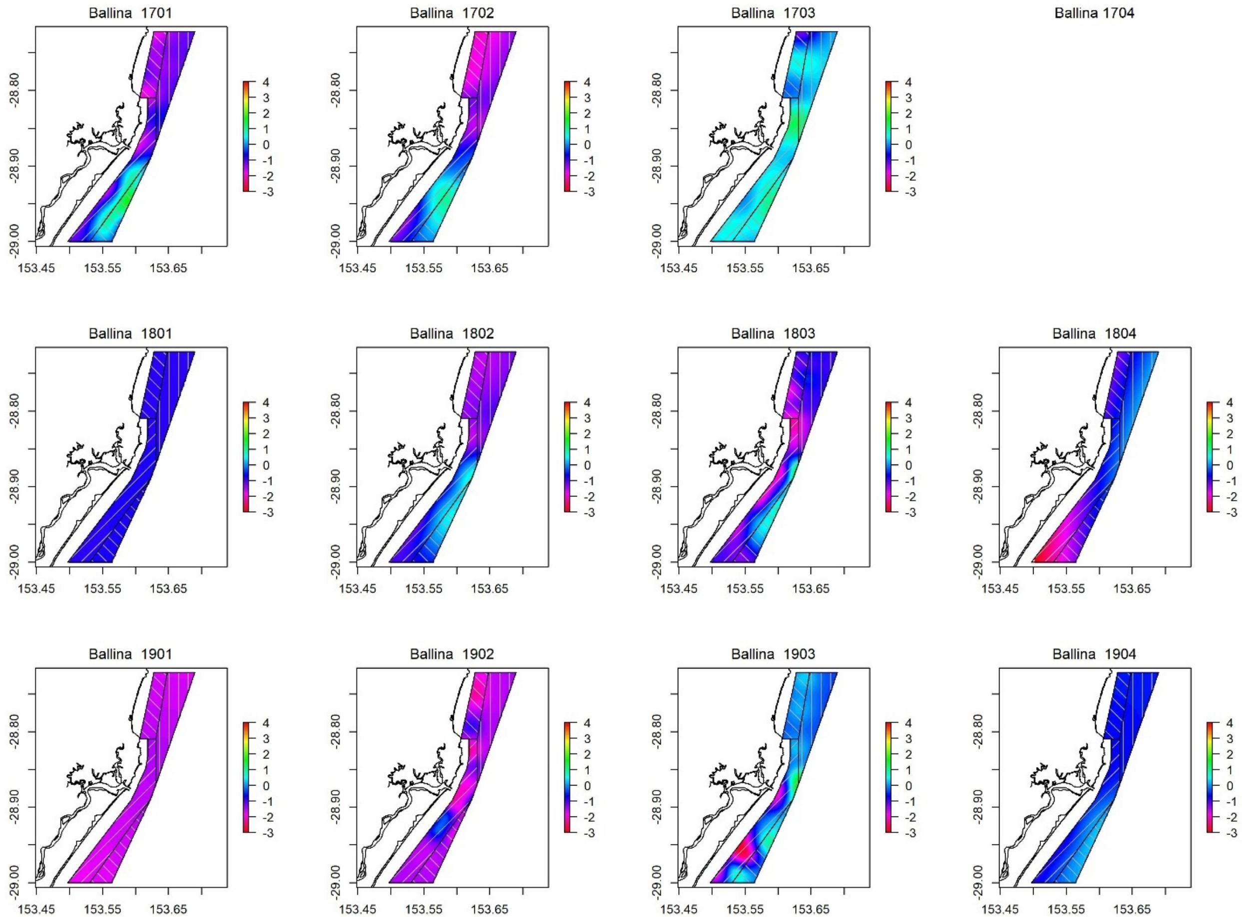


Figure 6 Interpolated Eastern King Prawn biomass (log[kg EKP ha^{-1}]) for the Ballina survey location, for each year (rows) and each month (columns) of the survey. Each panel title indicates the location and period (YYMM) of the survey, and the colourbar legend indicates the relative biomass estimated across the survey area. Closure zones are indicated by 45° hatching, and non-closure zones are indicated by 90° hatching. Note that no survey work was conducted during April 2017 (1704) due to inclement weather.

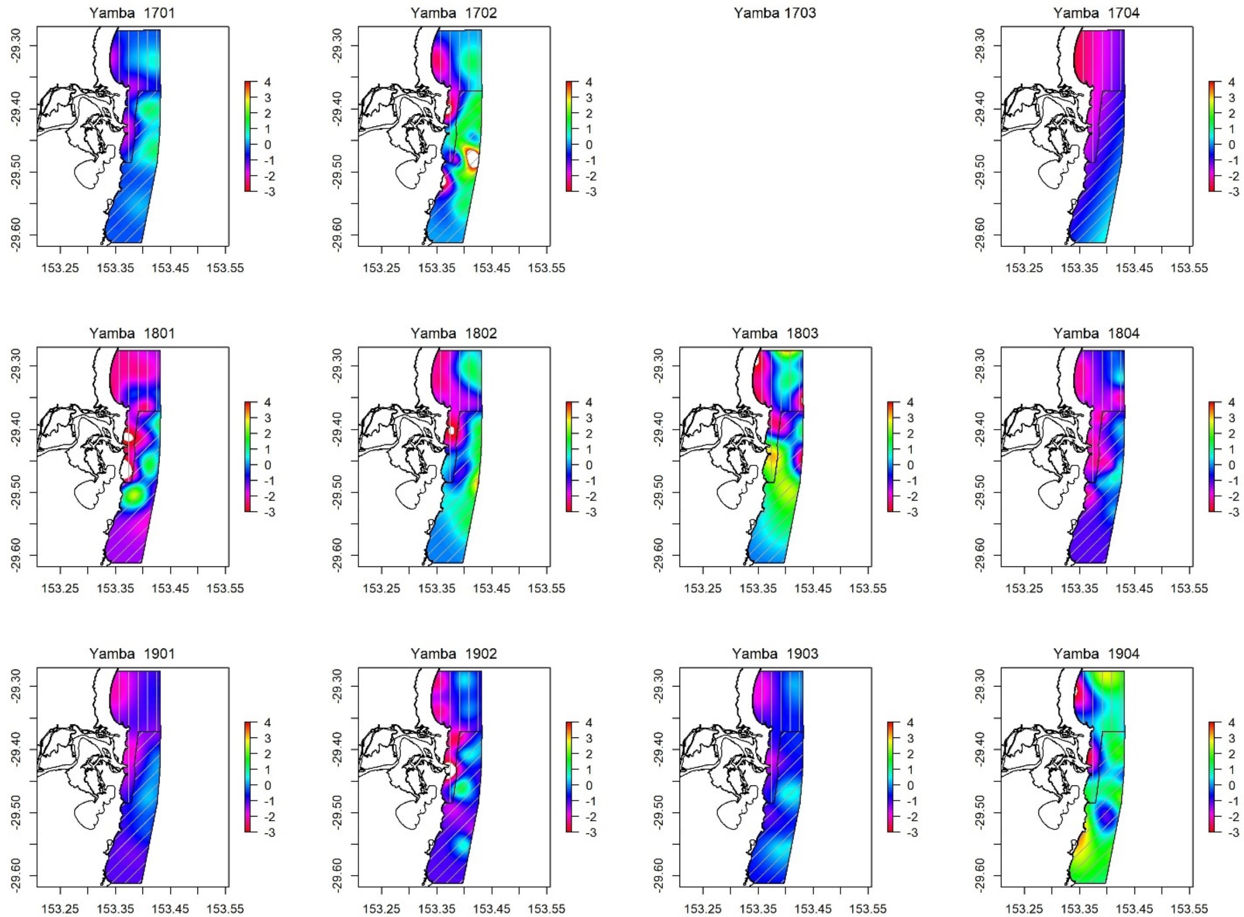


Figure 7 Interpolated Eastern King Prawn biomass (log[kg EKP ha^{-1}]) for the Yamba survey location, for each year (rows) and each month (columns) of the survey. Each panel title indicates the location and period (YYMM) of the survey, and the colourbar legend indicates the relative biomass estimated across the survey area. Closure zones are indicated by 45° hatching, and non-closure zones are indicated by 90° hatching. White colouring within the interpolated areas indicate interpolated densities that exceeded the highest measured density for that location. Note that no survey work was conducted during March 2017 (1703) due to inclement weather.

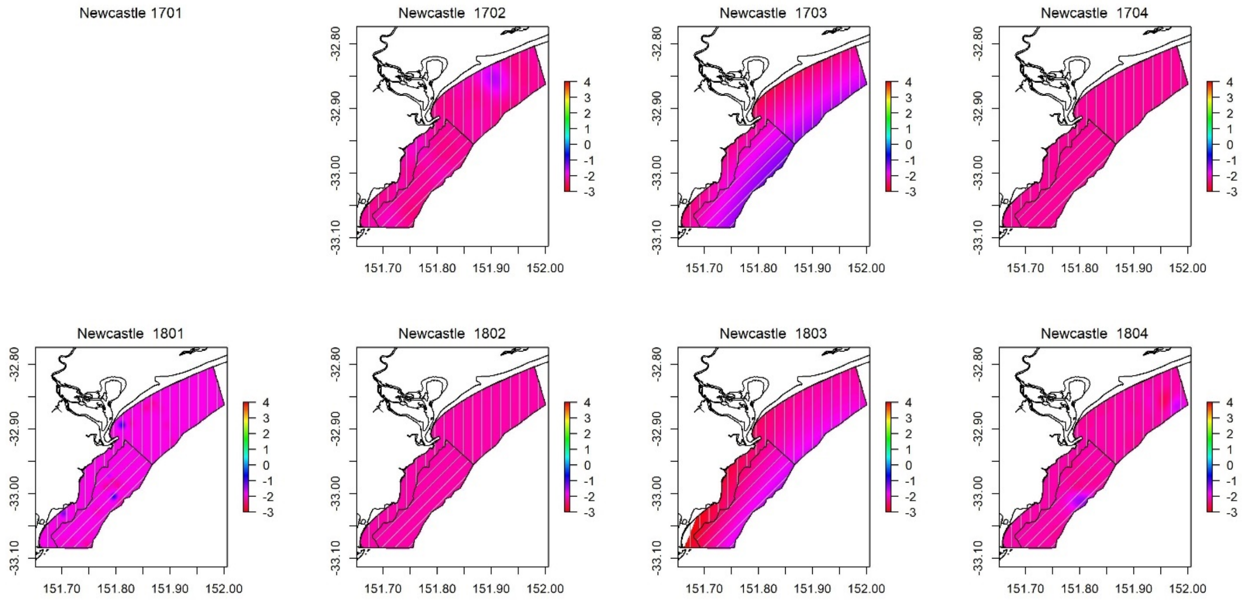


Figure 8 Interpolated Eastern King Prawn biomass (log[kg EKP ha^{-1}]) for the Newcastle survey location, for each year (rows) and each month (columns) of the survey. Each panel title indicates the location and period (YYMM) of the survey, and the colourbar legend indicates the relative biomass estimated across the survey area. Closure zones are indicated by 45° hatching, and non-closure zones are indicated by 90° hatching. Note that no survey work was conducted during January 2017 (1701) as the vessel was not available for charter.

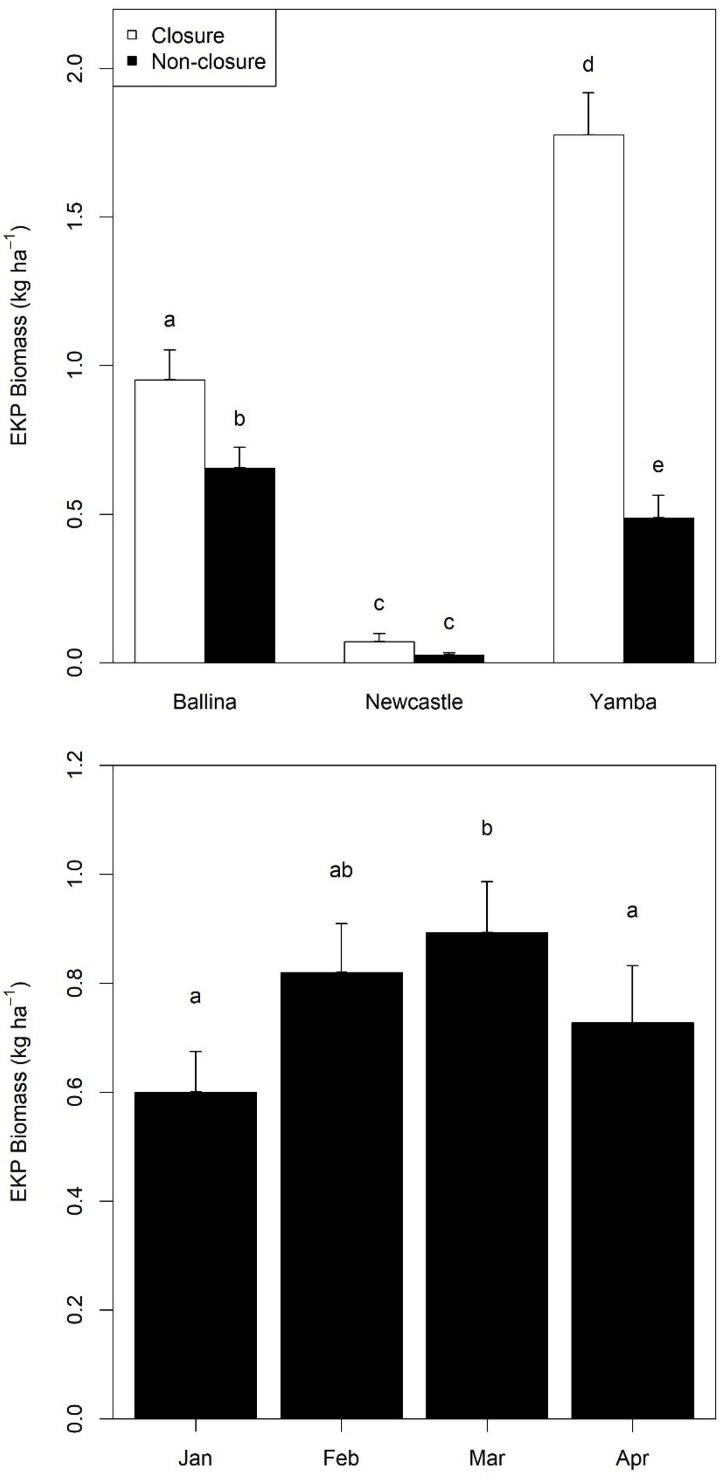


Figure 9 Eastern King Prawn biomass captured across locations and closure strata (upper panel), and across months (lower panel). On each panel, different letters denote significant differences as determined from Tukey's post-hoc test.

Patterns in size-structure and condition

Relative size-structure for the Ballina (**Figure 10**) and Yamba (**Figure 11**) survey area showed divergent trends in terms of size modes and alignment between closure and non-closure zones for these two areas. The proportion of prawns exceeding L_{YPR} varied through time, and there were negligible prawns captured within the inshore survey areas that exceeded the estimated L_{50} for EKP. In the Ballina area, there was close alignment in the size-structure within closure and non-closure zones for the duration of the survey period, although some of these minor differences were still statistically significant (**Figure 10**). In addition, size-structures appeared to predominantly consist of a single mode, with the exception of 2019 where multiple modes were evident. In contrast, the size-structure within the Yamba survey area appeared multi-modal throughout the majority of the sampling period (**Figure 11**). Furthermore, the size-structure of prawns appeared to be larger within the non-closure zone, for the majority of 2017 and 2018. In 2019, size-structures in the two zones aligned more closely than other years, except in February, but were still significantly different.

These patterns were also evident in the ANOVA comparison of the proportion of prawns exceeding L_{YPR} (**Figure 12**). For the Ballina survey area, on average >40% of prawns exceeded L_{YPR}, but there were no significant differences between closure and non-closure zones ($F_{1,175}$ = 2.05, P = 0.154, **Figure 12**). There was, however, a significant difference between months, with a greater proportion of prawns exceeding L_{YPR} during March and April, compared with January and February ($F_{3,175}$ = 18.19, P << 0.001, **Figure 12**). Fewer prawns (on average) exceeded L_{YPR} for the Yamba survey area, and in contrast to Ballina, proportions exceeding L_{YPR} were considerably lower within the closure zones ($F_{1,177}$ = 47.92, P << 0.001, **Figure 12**). However, differences between months indicated that prawns were more likely to exceed L_{YPR} as summer and autumn progressed ($F_{3,177}$ = 15.30, P << 0.001, **Figure 12**). There were some finer-scale spatial patterns in size-structure relative to L_{YPR} (**Figure 13** and **Figure 14**). Within the Ballina survey area, the closure zone and the southern non-closure zone tended to support a greater proportion of prawns that were smaller than L_{YPR}, but this was temporally variable, for example in April 2018, when these regions supported the greatest proportion of prawns exceeding L_{YPR}. (**Figure 13**). It is possible that the larger prawns that periodically appeared within the southern part of the survey area may be originally emigrating from the next nursery to the south, the Evans River (**Figure 1**). The northern part of the Yamba closure zone consistently supported populations which were smaller than L_{YPR}., especially the areas immediately adjacent to the estuary mouth (**Figure 14**). The seasonal trend through summer and autumn was also evident in these spatial patterns.

Finally, prawns captured in the Ballina survey area were of greater somatic condition (i.e. greater weight per unit length) than prawns captured within the Yamba survey area ($F_{1,386}$ = 32.45, P << 0.001, **Figure 15**). Overall, somatic condition increased through time in a consistent fashion between locations ($F_{3,386}$ = 4.93, P = 0.002), with prawns in best condition during March and April (**Figure 15**).

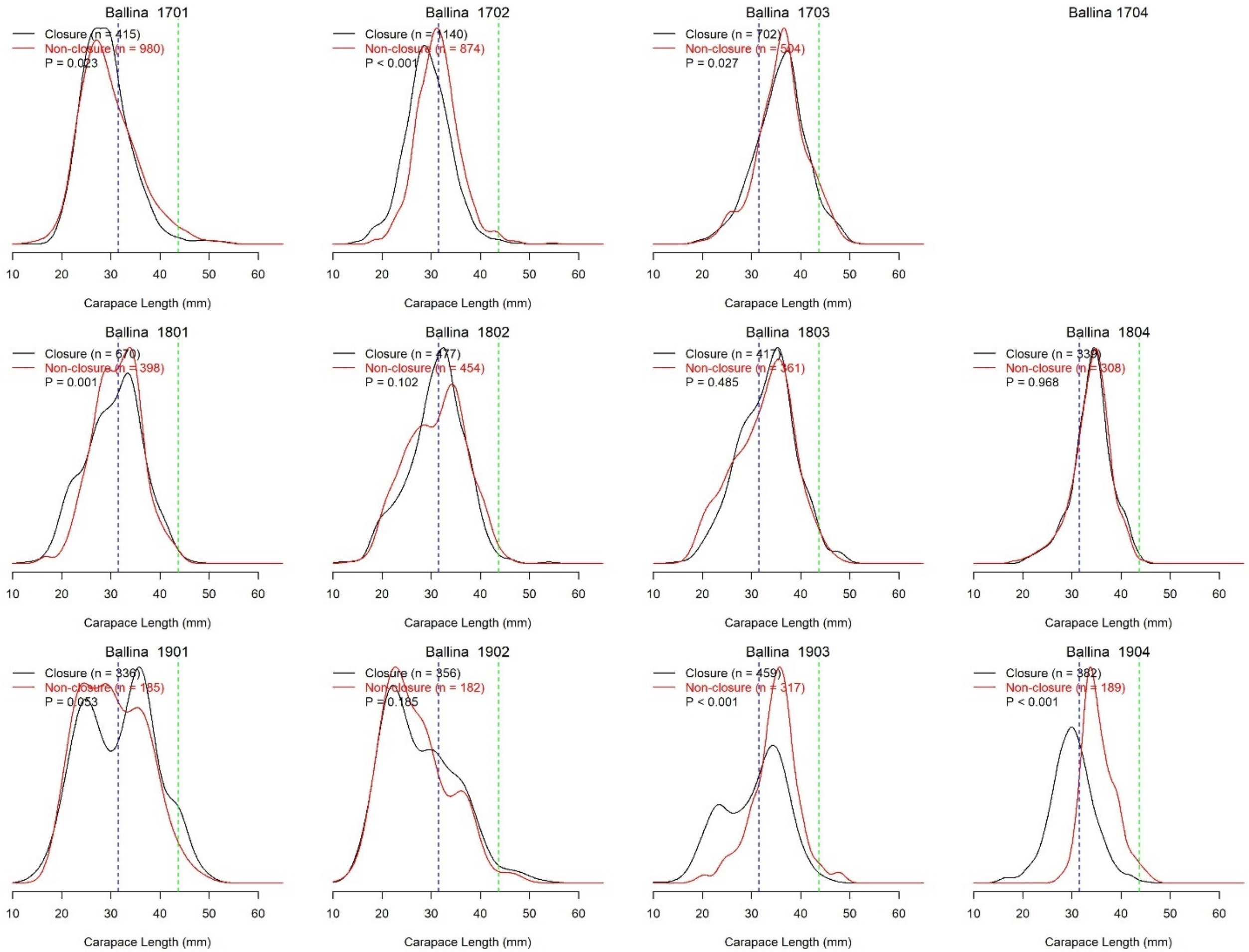


Figure 10 Relative size-structure of Eastern King Prawn within the Ballina survey location for each year (rows) and month (columns) of the survey, presented as kernel density distributions for closure (black line) and non-closure (red line) zones. Each panel title indicates the location and period (YYMM) of the survey, and the number of prawns (n) used in each distribution is indicated in the panel legends, as is the significance value from K-S test between the length structures. Also indicated is the optimal length at first capture (L_{YPR}, vertical blue dashed line, described in the text) and an estimate of length at maturity (L_{50}, vertical green dashed line) derived from data presented in Montgomery *et al.* (2007).

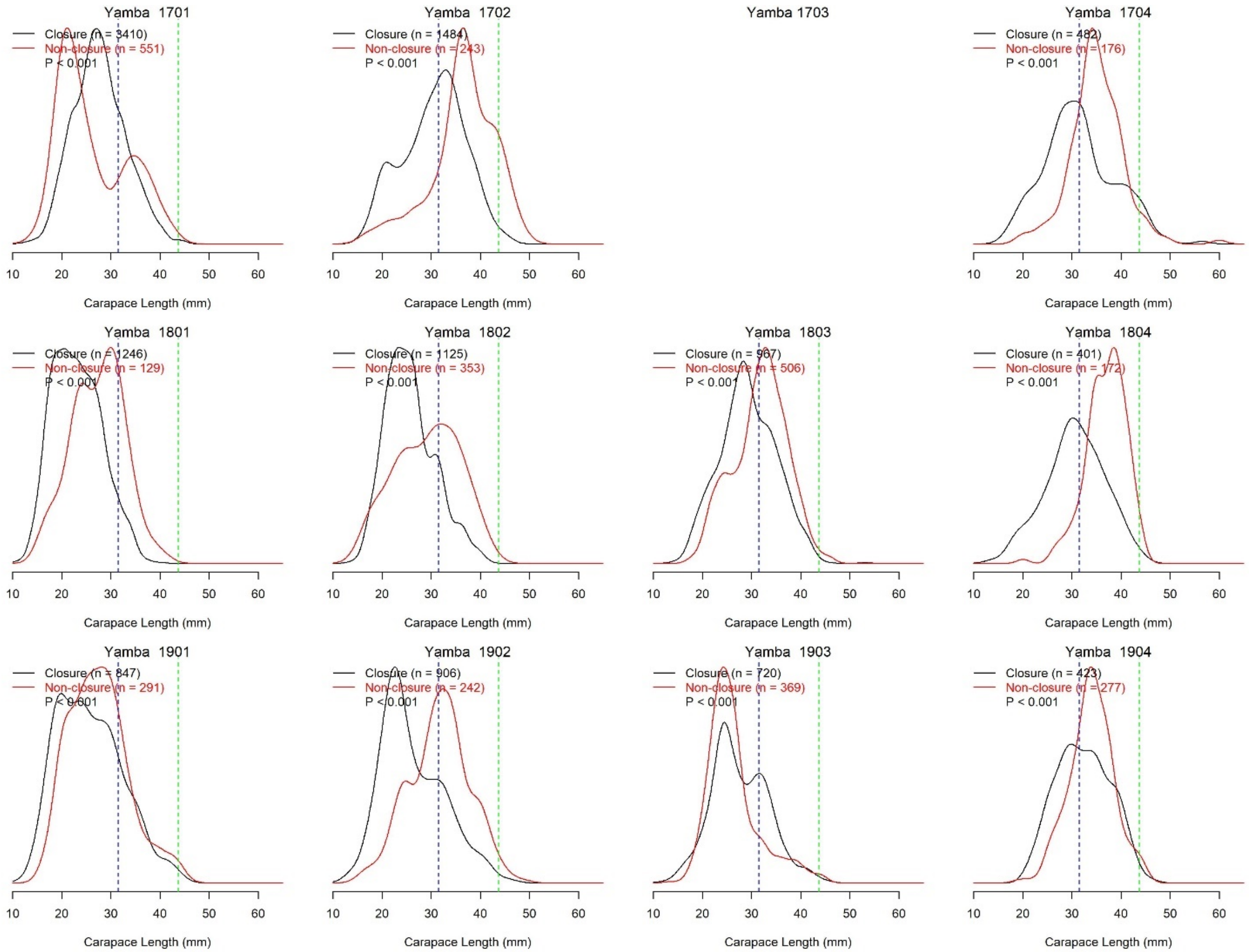


Figure 11 Relative size-structure of Eastern King Prawn within the Yamba survey location for each year (rows) and month (columns) of the survey, presented as kernel density distributions for closure (black line) and non-closure (red line) zones. Each panel title indicates the location and period (YYMM) of the survey, and the number of prawns (n) used in each distribution is indicated in the panel legends, as is the significance value from K-S test between the length structures. Also indicated is the optimal length at first capture (L_{YPR}, vertical blue dashed line, described in the text) and an estimate of length at maturity (L_{50}, vertical green dashed line) derived from data presented in Montgomery *et al.* (2007).

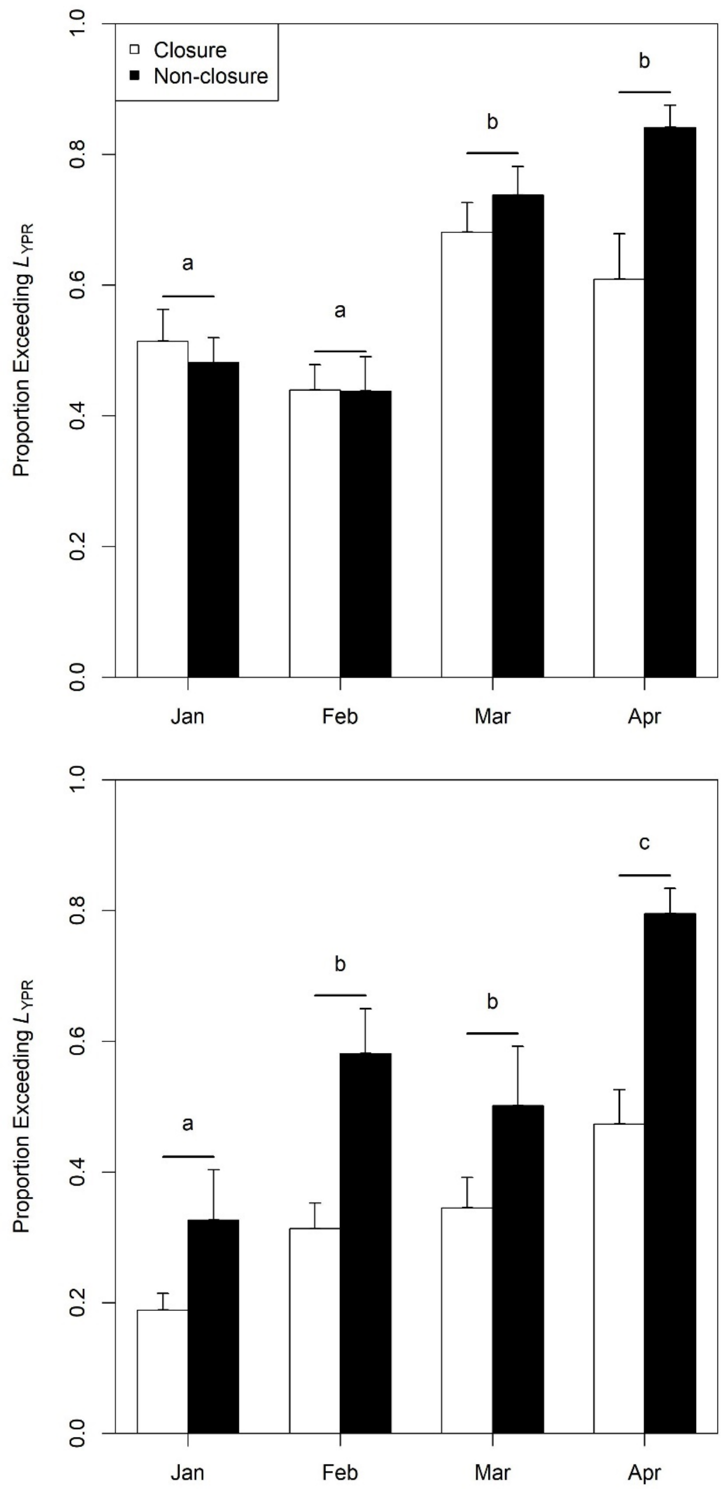


Figure 12 Eastern King Prawn mean (± SE) proportional representation of size classes across closure strata and months relative to the optimal size-at-first-capture estimated from yield-per-recruit analyses (L_{YPR}), for the Ballina survey location (upper panel) and the Yamba survey location (lower panel). The proportion of prawns exceeding L_{YPR} was significantly greater in the non-closure than closure zones in the Yamba survey location, whereas there was no significant effect of closure strata for Ballina. On each panel, different letters denote significant differences among months, as determined from Tukey's post-hoc test.

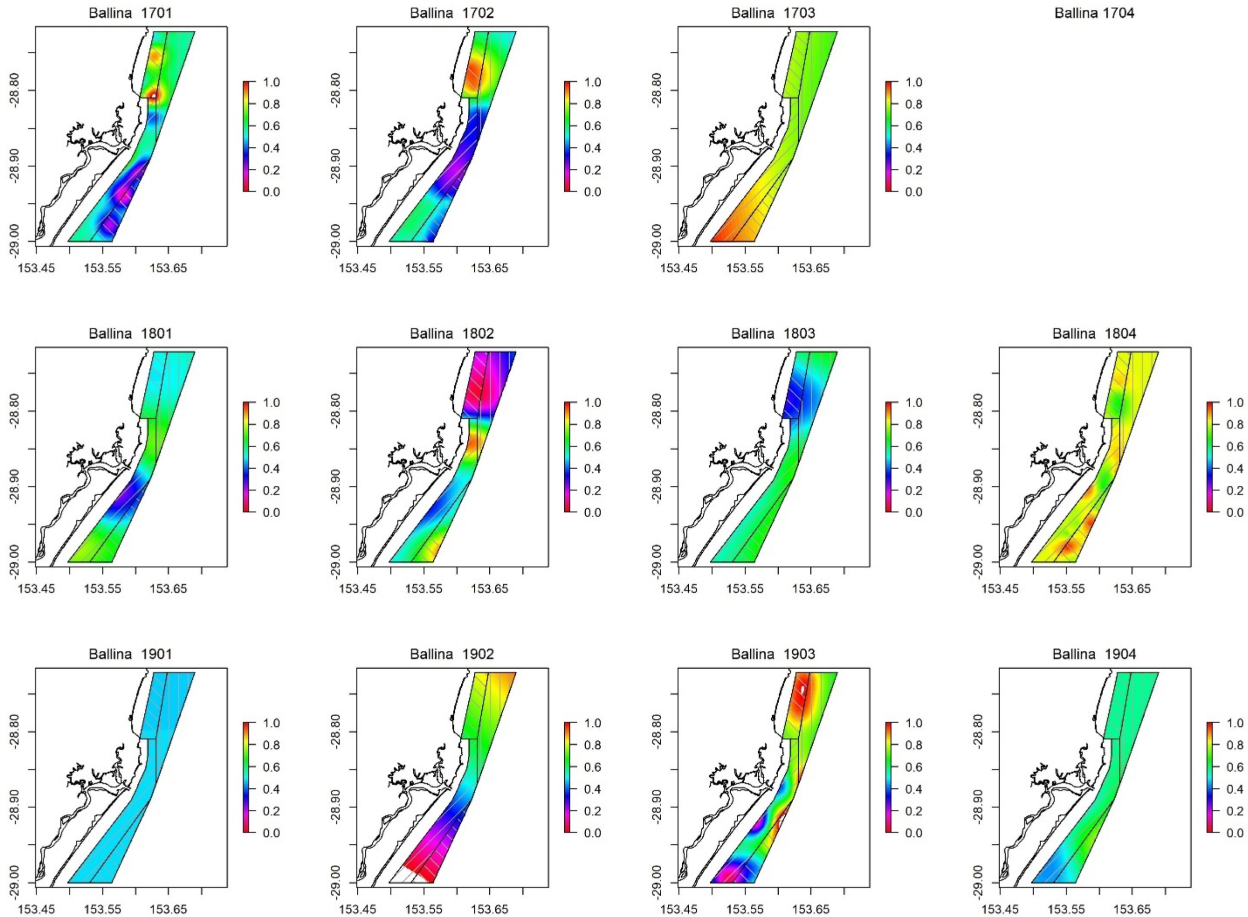


Figure 13 Interpolated surface depicting the proportion of Eastern King Prawn exceeding L_{YPR} across the Ballina survey location, for each year (rows) and each month (columns) of the survey. Each panel title indicates the location and period (YYMM) of the survey, and the colourbar legend indicates the relative biomass estimated across the survey area. Closure zones are indicated by 45° hatching, and non-closure zones are indicated by 90° hatching.

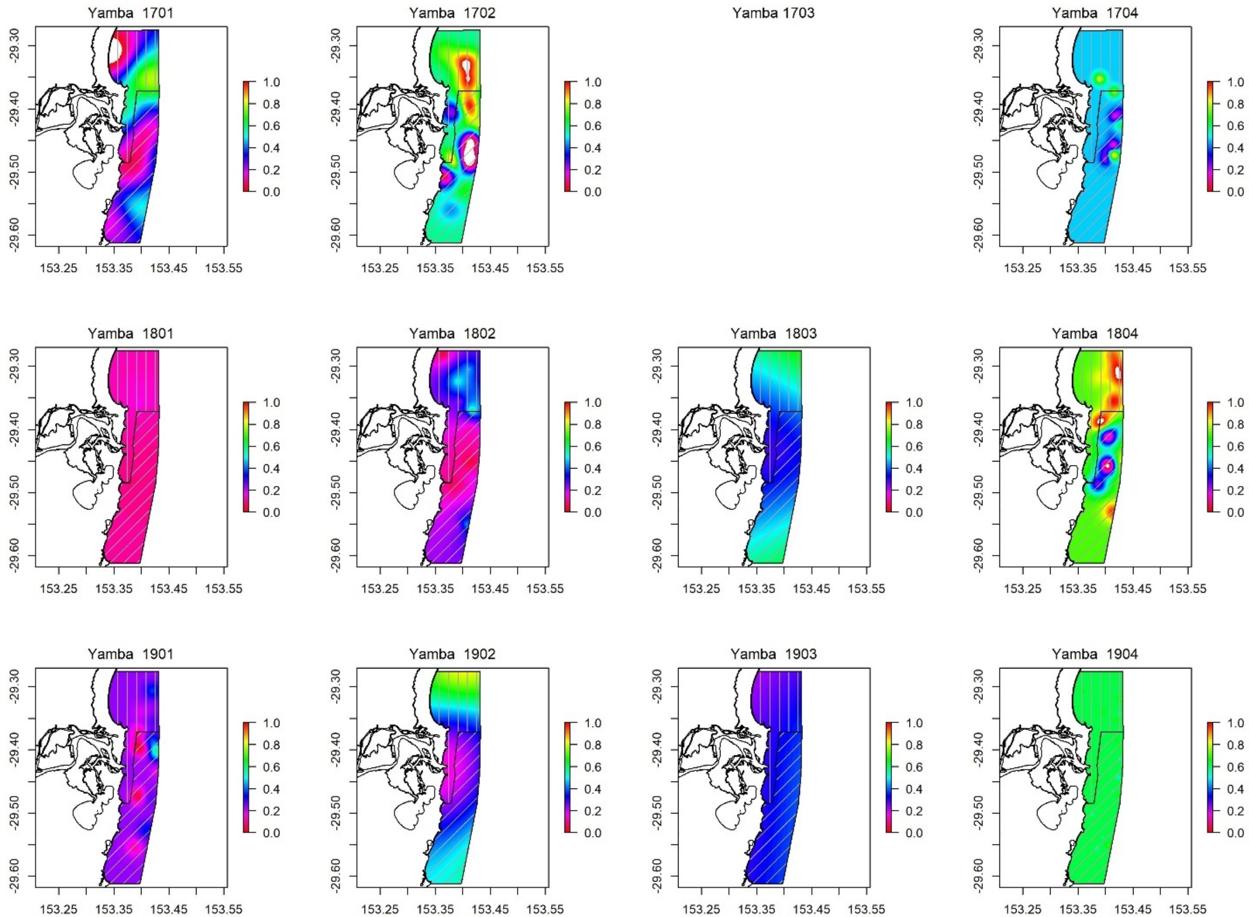


Figure 14 Interpolated surface depicting the proportion of Eastern King Prawn exceeding L_{YPR} across the Yamba survey location, for each year (rows) and each month (columns) of the survey. Each panel title indicates the location and period (YYMM) of the survey, and the colourbar legend indicates the relative biomass estimated across the survey area. Closure zones are indicated by 45° hatching, and non-closure zones are indicated by 90° hatching.

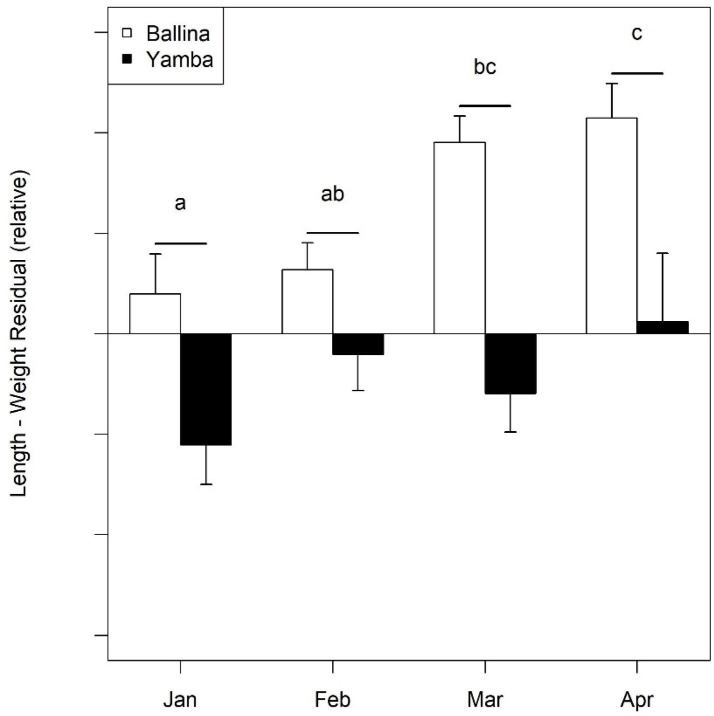


Figure 15 Eastern King Prawn mean (± SE) relative somatic condition expressed as the residuals of the relationship between log(CL [mm]) and log(weight [g]) across locations and months. Overall, somatic condition was significantly greater in the Ballina, than Yamba, and different letters denote significant differences among months, as determined from Tukey's post-hoc test.

Connectivity between Juvenile Eastern King Prawn closures and the broader Eastern King Prawn fishery

Over 7,500 prawns were tagged during 2016-2019, and 786 were recaptured, which equated to a total recapture rate across the program of 10.5%. Both sexes were tagged roughly in proportion to their abundance in the catch, which created some inconsistency in the sex ratio between some tagging events (**Table 6**). There were minor differences in the mean carapace length (CL) of tagged prawns among the different tagging events, with the largest tagged cohorts occurring in the Ballina closure zone and the smallest in the SWR closure zone (**Table 6**). Most tagged prawns from each cohort were captured between 20 and 200-days following tagging, with the maximum time being 626 days (**Table 6**). There were no consistent patterns in the distribution of days-at-liberty among tagging locations, or between early and late periods. Not surprisingly, those cohorts that travelled greater distances tended to have slightly greater movement rates. Growth of tagged prawns at recapture ranged from >0 mm and 37 mm CL.

Recapture patterns within and between jurisdictions

There was considerable variation in both the overall recapture percentage and the geographic location of the tag recaptures, by both tagging period and location (**Table 6**). Cohorts tagged early in the season within the Yamba and SWR closure zone showed lower recapture rates of 3 and 4% respectively, and a similar pattern was also observed in the historical “early” cohort tagged within the SWR closure in 1991 (**Table 6**). Other cohorts had comparatively high recapture rates ranging from 12-15%. Recaptured prawns tagged at Ballina appeared within the Queensland fishery as early as 54 days following tagging, however prawns in “early” cohorts tended to have a much longer period before they arrived in that jurisdiction (**Table 6**). Recaptures of prawns tagged in the Yamba closure zone showed unique patterns, with very few prawns recaptured in Queensland waters (**Table 6**, **Figure 16**). Statistical analysis showed divergent patterns in the distance moved by early and late tagged cohorts from the Ballina and SWR closure zones (**Figure 17**), which was reflected in a significant interaction between release timing and tagging location ($F_{1,695} = 99.75$, $P << 0.01$). In SWR, prawns that were tagged in the early cohort moved further than those tagged in the late cohort, but the opposite pattern was evident in Ballina (**Figure 17**).

These patterns were evident in the distribution of recaptures among fishery zones across NSW and Queensland (**Figure 18**). For most cohorts, the majority of prawns tended to be recaptured from the offshore zones directly adjacent to, or directly north of, the zones in which tags were released. This meant that for most cohorts, the majority of recaptures were in NSW zones. The exception was the late cohort released from Ballina in 2016, for which the majority of prawns were recaptured in Queensland waters, particularly in the Queensland Offshore South zone, in water depths generally ranging from 130-180 m.

Table 6 Summary of tagging and recapture information for each event (values are mean ± SE). *CL* indicates carapace length (mm) at tagging, *Days-at-liberty* indicates that maximum days at liberty for the cohort, *Qld. (d)* indicates the days-at-liberty when prawns **first** appeared in Queensland, and *NSW (d)* indicates the average days-at-liberty within NSW (with the maximum days-at-liberty within NSW included in parentheses), *Distance (km)* indicates the average distance moved by each sex.

Tagging Location	Date	# (♂; ♀)	CL (mm)	Recapture Days-at-liberty	# (♂; ♀)	Recaptures	Qld (d)	NSW (d)	Distance (km) ♂; ♀
Ballina	02/2016 (Late)	1289 (668; 621)	33.1 ± 0.2	221	195 (116; 79)	15.1 %	67	48 (139)	201; 239
	11/2018 (Early)	1120 (688; 432)	38.8 ± 0.2	496[#]	157 (100; 57)	14.0 %	183	67 (295)	42; 27
	05/2019 (Late)	1467 (1072; 395)	35.2 ± 0.1	626[#]	195 (140; 55)	13.3 %	54	30 (156)	76; 127
Yamba	11/2018 (Early)	1136 (615; 521)	34.9 ± 0.2	292	36 (18; 18)	3.0 %	171	87 (291)	119; 273
South West Rocks	11/2018 (Early)	1144 (421; 723)	31.0 ± 0.2	313	43 (15; 28)	4.0 %	154	135 (301)	92; 125
	03/2019 (Late)	1351 (377; 974)	32.4 ± 0.1	255	160 (40; 120)	12.0 %	106	49 (255)	86; 83
	11/1991 (Early)[$]	2942	25.9 ± 0.3	623^	84	2.9 %	228	71 (623^)	86
	01/1992 (Late)[$]	2812	27.9 ± 0.2	215	415	15.0 %	178	61 (190)	33

[$] Denotes historic data from Gordon *et al.* (1995), excluding prawns recaptured within the SWR closure zone (during survey work) during the closure period. Sex-specific information is not available for these samples.

[#] Note that these numbers were updated after results analyses were completed (additional prawns from these cohorts were captured at 424, 452, 481, 496 and 626 days following release).

^ One individual was recaptured at 623 days, and another at 433 days; the remaining recaptures were <320 days.

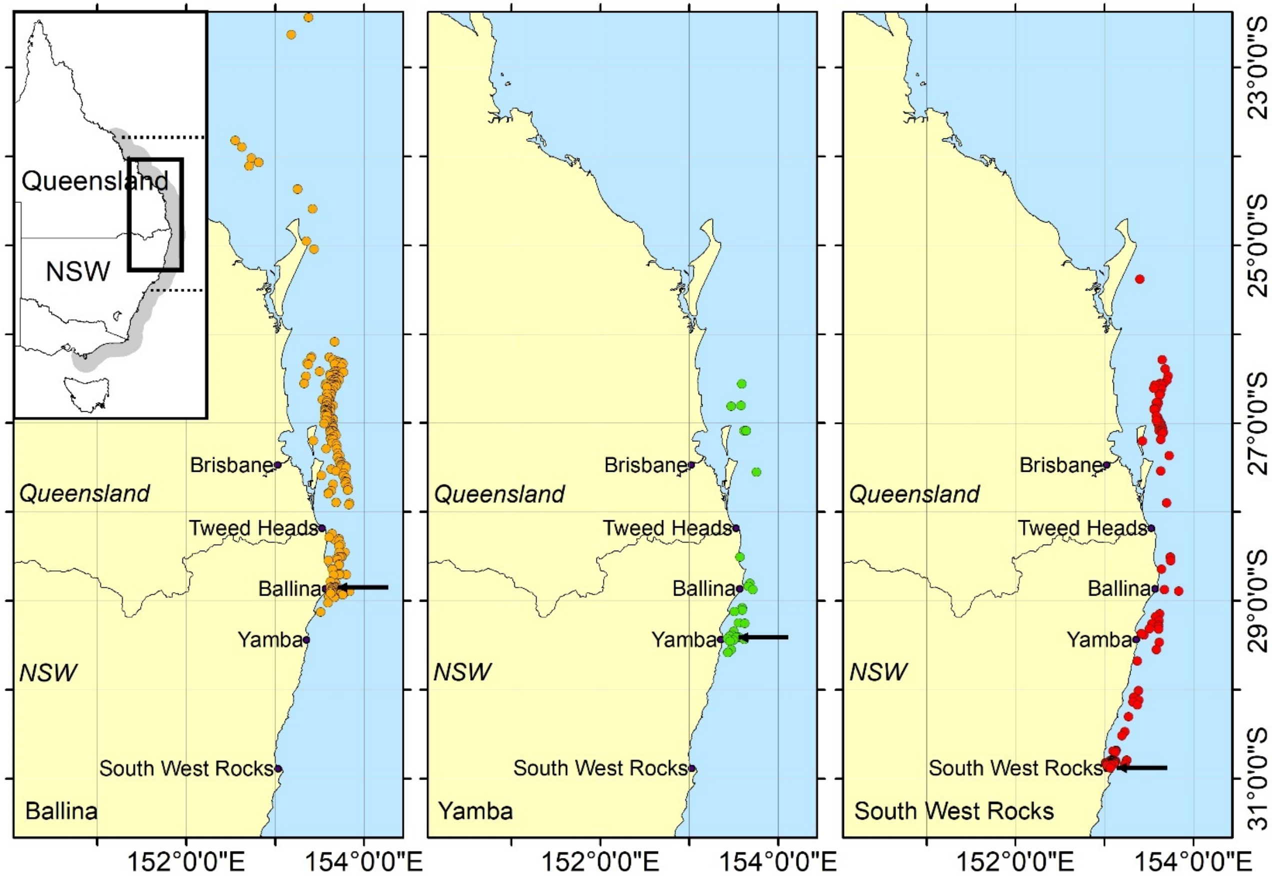


Figure 16 Overall distribution of recaptures originating from each closure zone (indicated with an arrow on each figure).

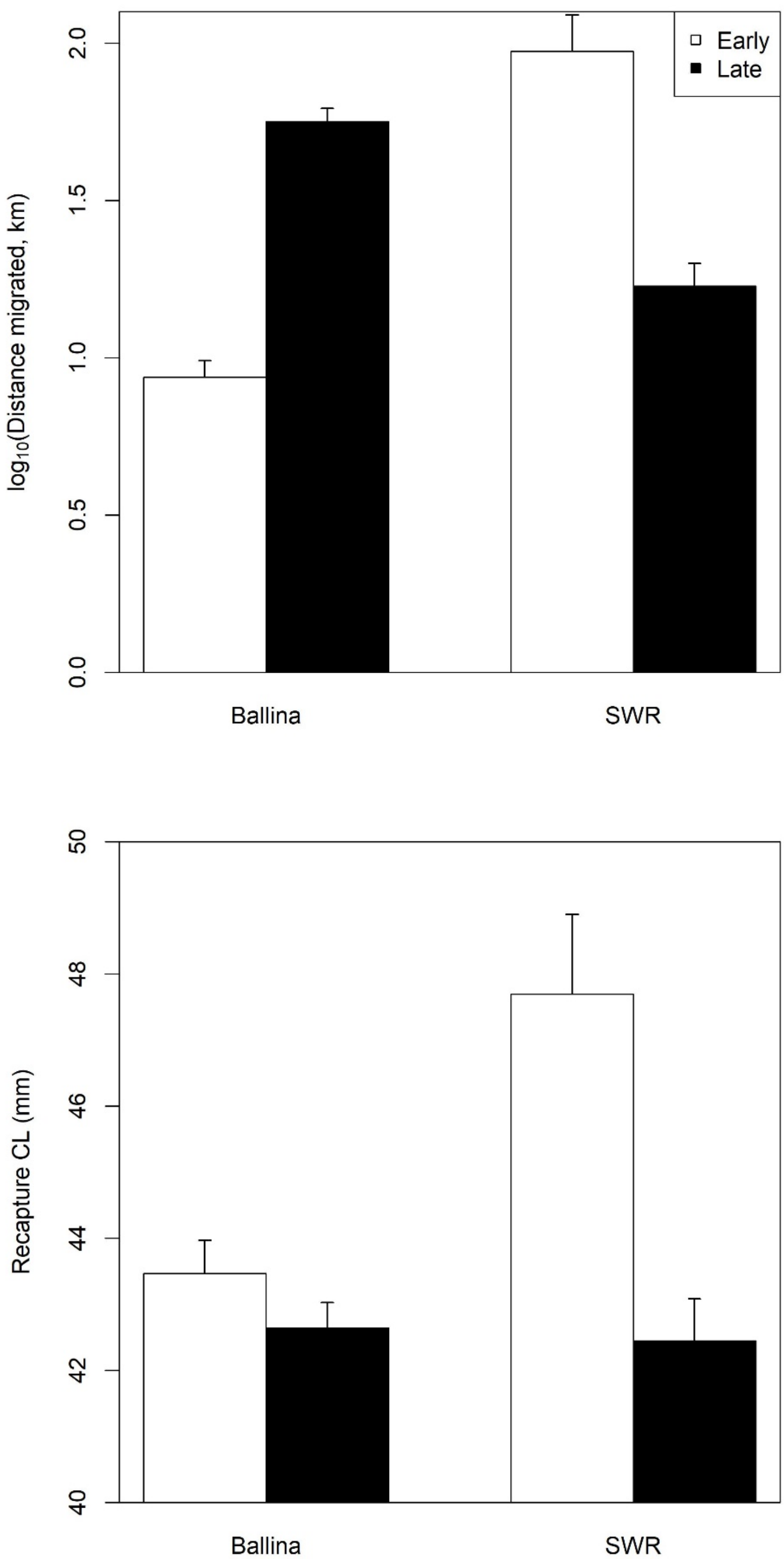


Figure 17 Comparison of $\log_{10}$ transformed mean (+SE) distance migrated (upper panel), and size-at-recapture (carapace length [CL], lower panel) of prawns tagged in early and late cohorts within the Ballina and South West Rocks (SWR) closure zones.

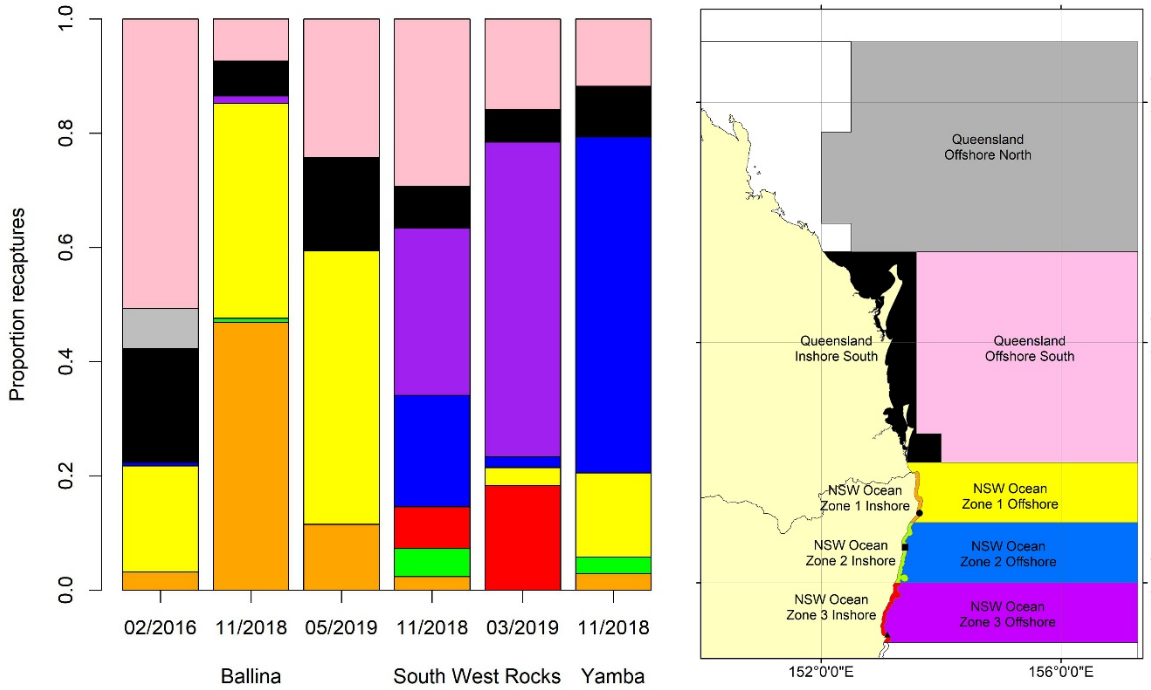


Figure 18 Proportion of recaptures for each tagging event by fishery zone. Stacked bars are colour coded to the corresponding spatial areas presented on the right of the figure.

Size-structure and yield-per-recruit

There was substantial variation in the length-frequency composition of tagged prawns among release locations and between release periods (**Figure 19**). Not surprisingly, the cohorts tagged at the southern closure zone (South West Rocks) were generally smaller in size than those at the northern locations. For the Yamba and South West Rocks tagged cohorts, the majority of prawns were below L_{YPR}, when they were tagged within the closure zone, but recaptured prawns had mostly exceeded L_{YPR}, regardless of cohort timing or recapture jurisdiction (**Figure 19**). The largest recaptured prawns from all cohorts were caught in Queensland waters.

The effect of release timing and tagging location on size-at-recapture was evaluated between early and late releases at Ballina and South West Rocks using the same model as for distance migrated. Modelling revealed an interactive effect of release timing and tagging location on size-at-recapture ($F_{1,644}$ = 8.51, P < 0.01, **Figure 17**). Tukey's post-hoc analyses indicated there were no differences in recapture CL between release events for Ballina (P = 0.67), but prawns released in the South West Rocks closure early cohort had a significantly greater size-at-recapture than all other treatment combinations (P << 0.01).

Comparison with historic data

Recapture patterns for prawns tagged in the South West Rocks trawl closure zone showed substantial variation between current and historical tagging programs (**Figure 20**). During the 1991/92 tagging program, >50% of tags were recaptured within NSW Ocean Zone 3 Inshore (i.e. the zone which contained the SWR trawl closure), and the majority of other tag recaptures were made in the offshore ocean zones adjacent to, and to the north of this area (**Figure 20**). In comparison, recaptures within NSW Ocean Zone 3 Inshore were <20% during the 2019/20 tagging program, with most recaptures occurring within NSW Ocean Zone 3 Offshore. For the latter tagging program, up to 35% of recaptures occurred in Queensland waters, compared to <5% during the 1991/92 program. These differences were evident when distance moved was compared between programs, alongside the timing of release (**Figure 21**), which revealed that prawns released in the 2018/19 program were able to migrate further prior to capture than those released in the 1991/92 program ($F_{1,694}$ = 22.73, P << 0.01, **Figure 21**). However, for both tagging programs, prawns released during the early tagging period tended to migrate much greater distances before capture than those released during the late tagging period ($F_{1,694}$ = 70.25, P << 0.01, **Figure 21**). Size-at-recapture showed similar differences, with prawns from the early tagging period being larger on average at recapture ($F_{1,662}$ = 116.38, P << 0.01, **Figure 21**), and prawns also larger at recapture for the 2018/19 tagging program ($F_{1,662}$ = 148.38, P << 0.01).

Relationship with fishing effort

Linear regression revealed that there was a significant positive relationship between the ($\log_{10}$ transformed) fishing effort that each cohort was exposed to during the migration window, and the proportion of recaptures from that cohort that occurred within NSW waters ($F_{1,6}$ = 6.20, P < 0.05); fishing effort described ~50% of the variation in proportional recaptures within NSW.

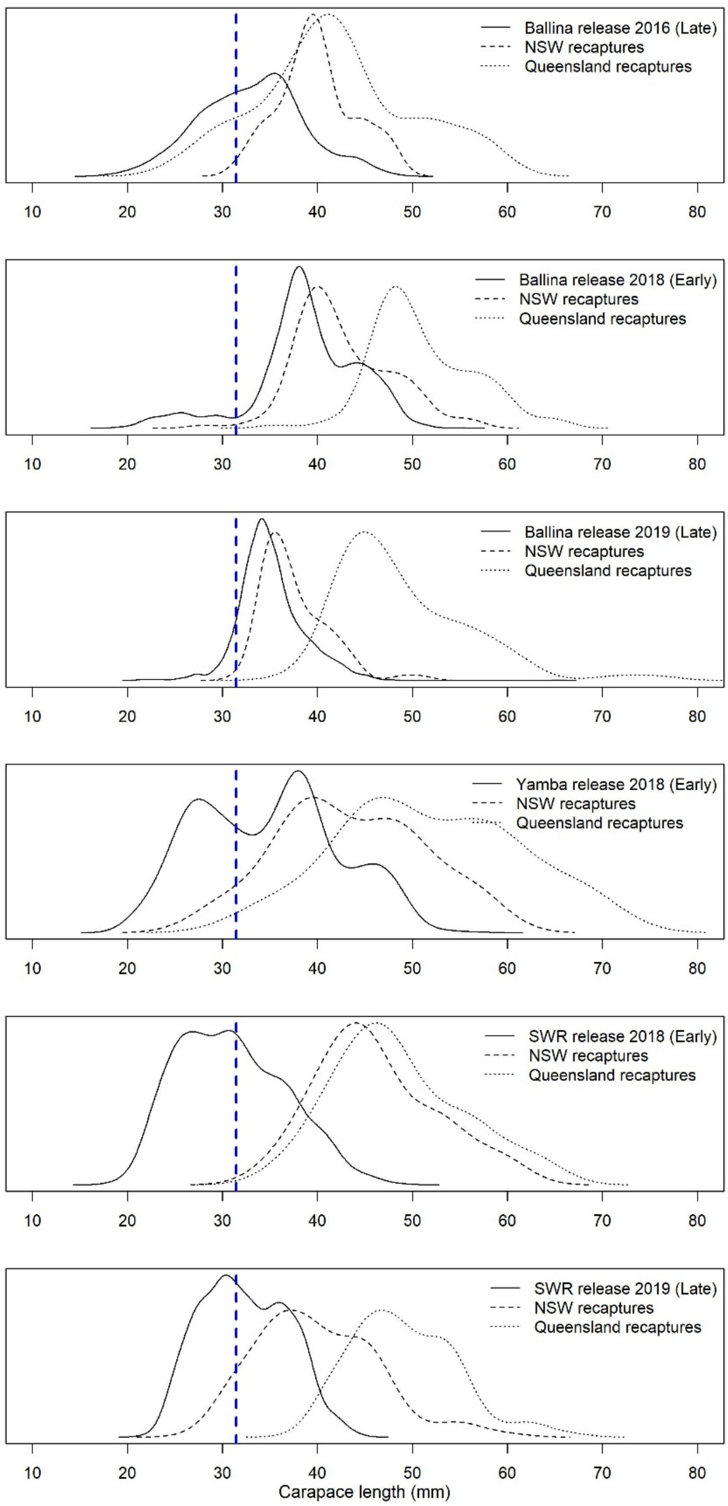


Figure 19 Distribution of prawn sizes expressed as kernel density estimates, including sizes of prawns at each tagging event, and for recaptures in NSW and Queensland (see legend). Vertical dashed lines indicate the estimates of L_{YPR} (dashed blue line).

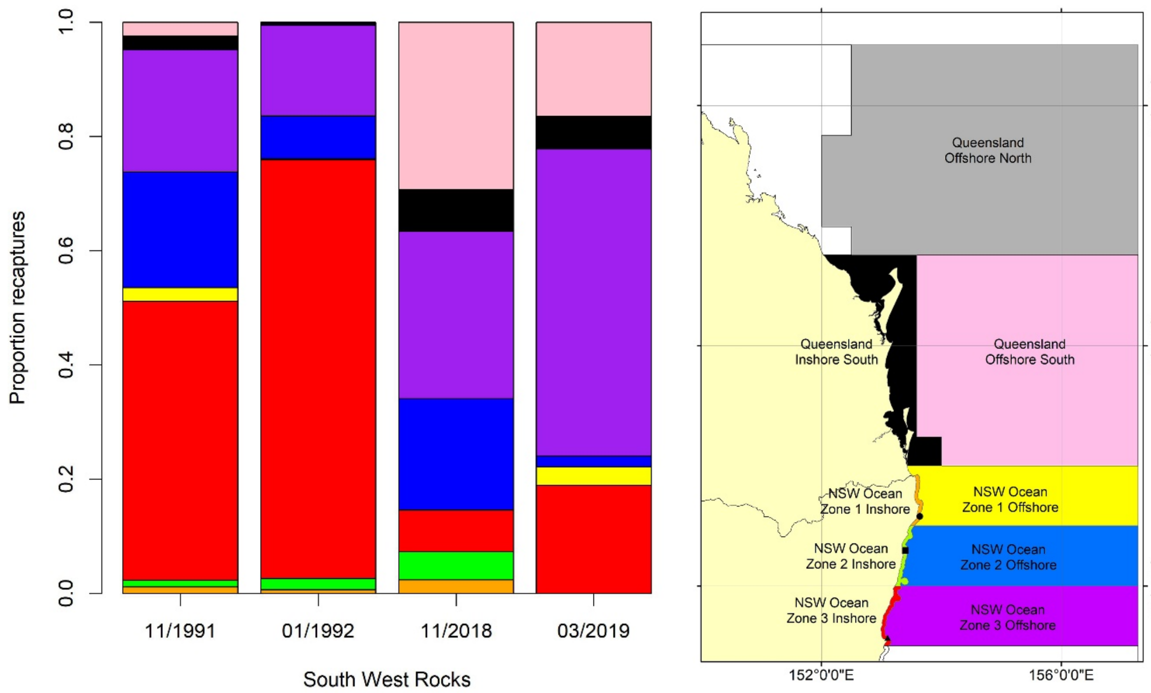


Figure 20 Temporal and spatial comparison of recaptures for South West Rocks, showing proportion of recaptures for each tagging event by fishery zone for historical data (from Gordon *et al.* 1995) and data collected in the present study.

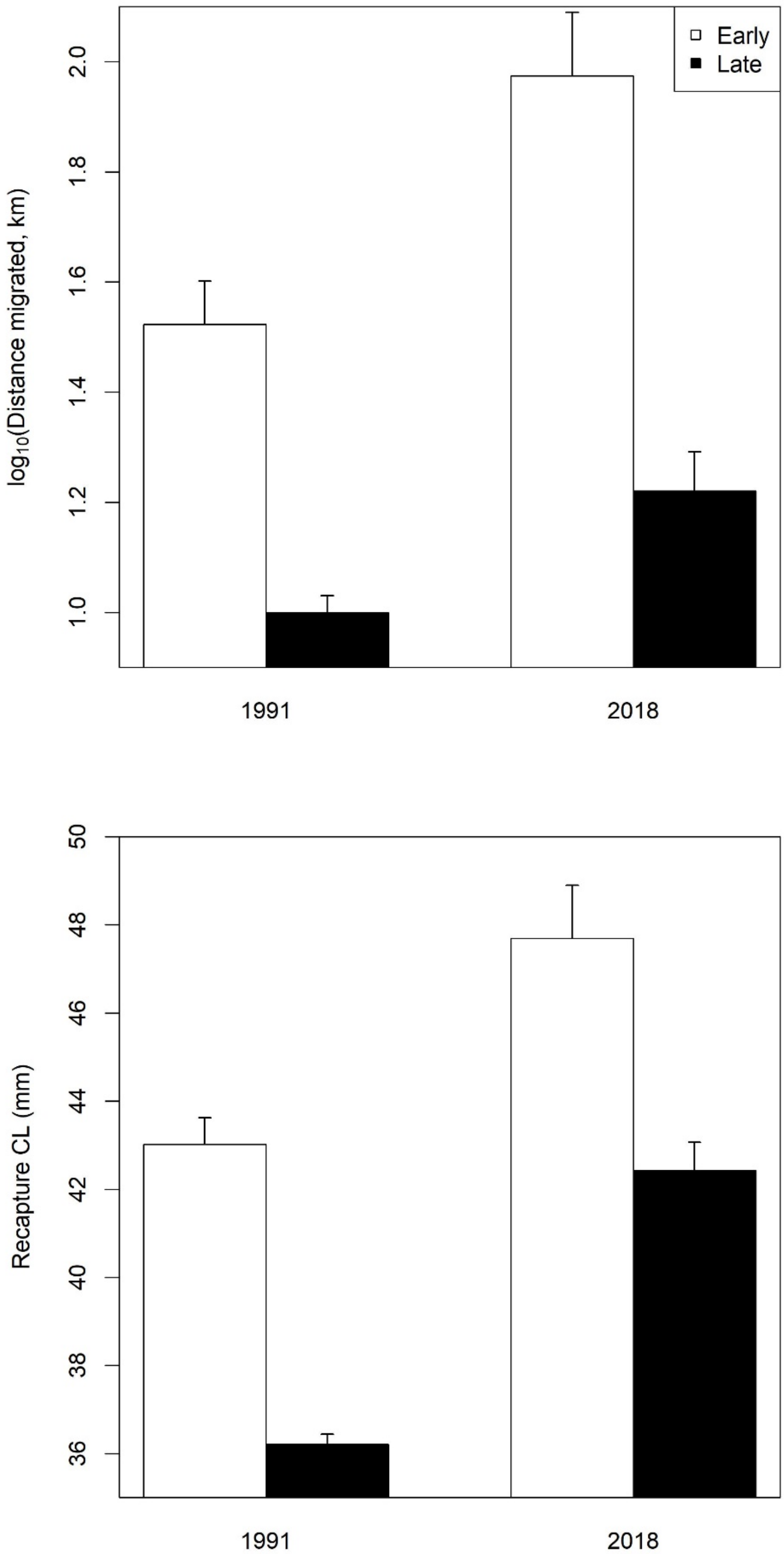


Figure 21 Comparison of $\log_{10}$ transformed mean (+SE) distance migrated (upper panel) and size-at-recapture (carapace length [CL], lower panel) of prawns tagged in early and late cohorts within the South West Rocks (SWR) closure zone, during 1991/92 (historical data from Gordon *et al.* 1995) and 2018/19.

Evaluation of non-target and bycatch species within inshore closures and adjacent fished zones

Broad spatial patterns in trawl catches

Overall, 209 tows were undertaken during the first year of the survey, for which the entire catch was processed. Over 72,000 animals were identified across 216 taxa. For total biomass, there was a significant difference between zones ($F_{1,201}$ = 4.03, P = 0.04), but no difference among locations ($F_{2,201}$ = 2.69, P = 0.07); however, there was a significant location x zone interaction ($F_{1,201}$ = 10.04, P << 0.01; **Figure 22**). Tukey's post-hoc test identified the source of this interaction was a significant difference between zones for Newcastle (P << 0.01, with greater total biomass within the closure zone) that was not detected for the other locations. For species richness, there was a significant difference between zones ($F_{1,201}$ = 4.01, P = 0.04) but no difference among locations ($F_{1,201}$ = 52.32, P << 0.01); however, there was a significant location x zone interaction ($F_{1,201}$ = 5.92, P < 0.01; **Figure 22**). Tukey's post-hoc test identified that the source of this interaction was a significant difference between zones for Yamba (P << 0.01, with greater species richness within the closure zone) that was not detected for the other locations.

Patterns in the taxonomic assemblage

Latitude explained much of the variation observed among locations in the nMDS ordination for the three taxonomic groups: Fish (R^2 = 0.64, P < 0.001); Decapods (R^2 = 0.52 , P < 0.001); and, Penaeids (R^2 = 0.82 , P < 0.001; **Figure 23**). The SIMPER analysis revealed that for each taxonomic group, 3 taxa tended to explain the majority of this variation. The differences in relative abundances among locations for these taxa are evident in **Figure 24**.

For each location, PERMANOVA showed that there were significant differences between closure and non-closure zones for fish at all locations, and for decapods at Yamba and Newcastle (**Table 7**). There were no differences between zones for penaeids at any location (**Table 7**). A SIMPER analysis identified that different taxa were important in driving these differences at different locations (**Figure 25**). For fish, gurnards (*Lepidotrigla* sp.) were more abundant within closure zones at both Ballina and Newcastle, as were Ocean Jacket (*Nelusetta ayraud*) in the Newcastle trawl closure zone, and Longspine Flathead (*Platycephalus longispinus*) in the Yamba trawl closure zone (**Figure 25**). In contrast, Red Bigeye (*Priacanthus macracanthus*) and Tounguefish (Cynoglossidae) were more abundant in the non-closure zone at Ballina and Yamba respectively (**Figure 25**). For decapods, the sand crab species *Portunus sanguinolentus* and *Ovalipes australiensis* were more abundant in the Yamba and Newcastle non-closure zones respectively, whereas stomatopods and brachyuran crabs were more abundant within the closure zones (**Figure 25**). For penaeids, there was a large amount of variability and inconsistent patterns between zones at all locations.

Closures and length structure of common species

Length distributions were significantly different between closure and non-closure zones for all locations, for both Cocky Gurnard and Longspine Flathead (as evaluated using a Kolmogorov-Smirnov test, P << 0.001, **Figure 26**). Length distributions showed obvious size truncation in both species at all locations in non-closure zones. This truncation meant that Cocky Gurnard larger than 100 mm (**Figure 26**), and Longspine Flathead larger than 150 mm (or 175 mm for Yamba; **Figure 26**), were uncommon outside of closure zones.

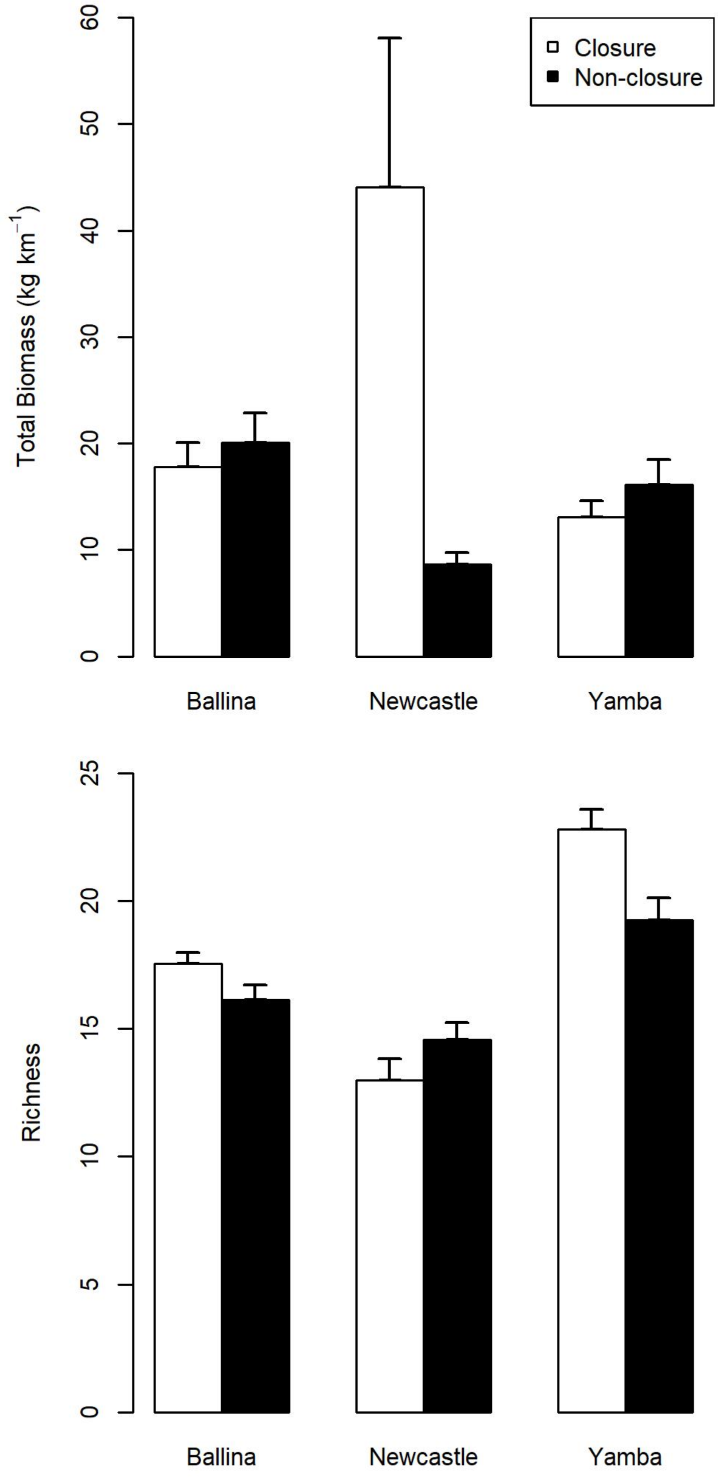


Figure 22 Mean + SE total biomass (upper panel) and species richness (lower panel) of non-target species across locations and areas.

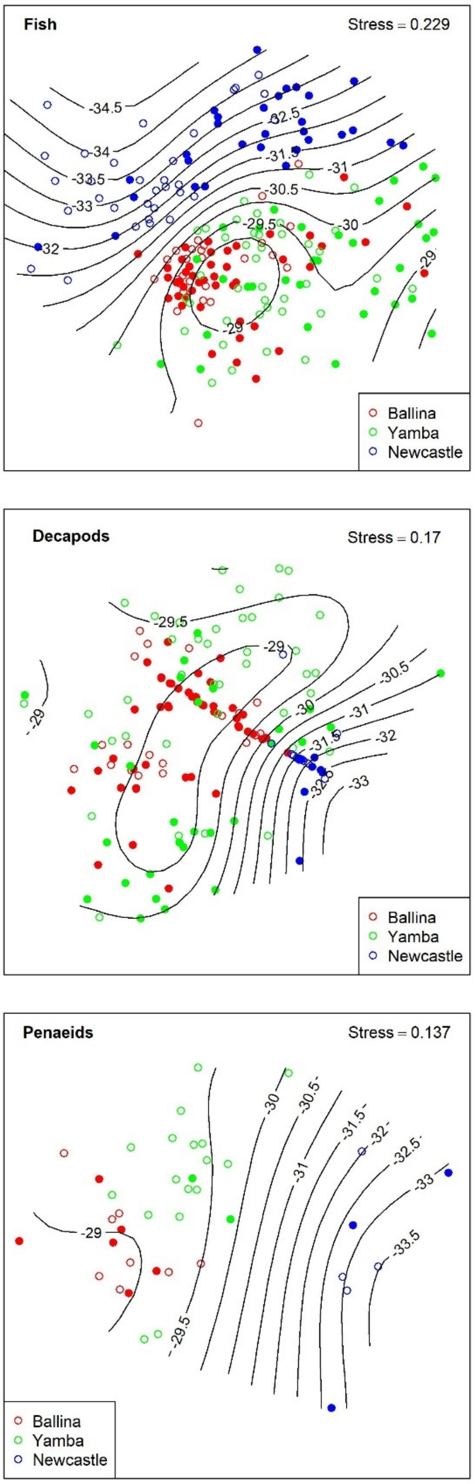


Figure 23 Non-metric multi-dimensional scaling ordination of assemblage data for taxonomic groups fish (upper panel), decapods (middle panel) and penaeids (lower panel). Samples from each location are coloured (see legend), and trawl closure and non-closure zones indicated as unfilled and filled symbols respectively. Contours are included on the plot to indicate the latitudinal scale on the ordination.

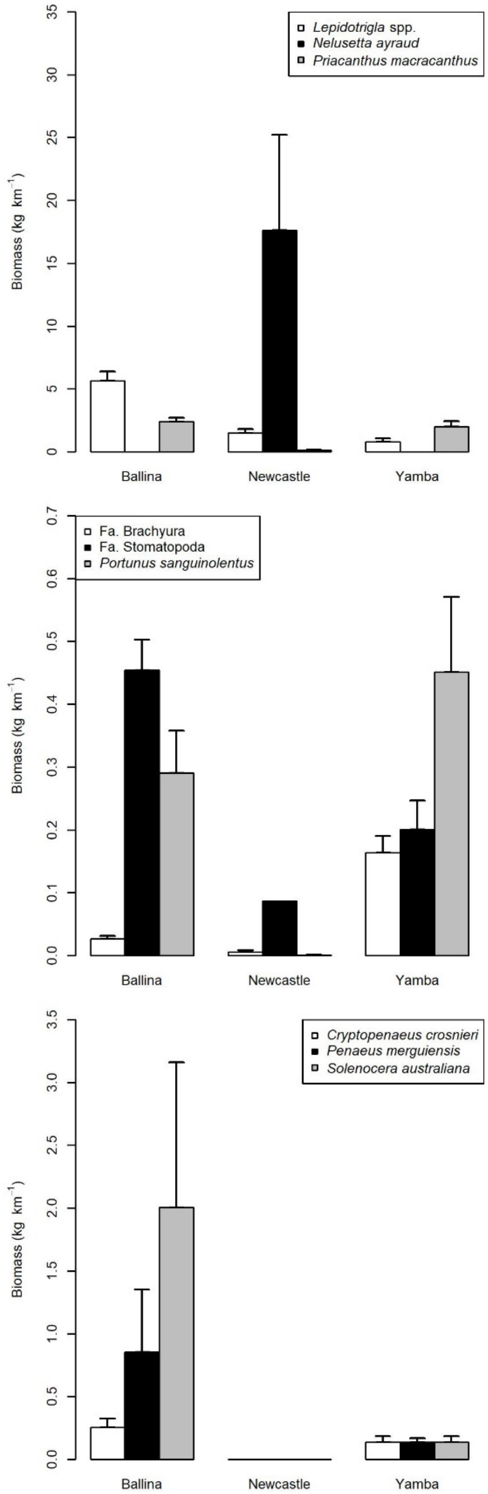


Figure 24 Relative biomass of the three taxa that most contributed to assemblage differences across latitudes for taxonomic groups fish (upper panel), decapods (middle panel) and penaeids (lower panel).

Table 7 Results of PERMANOVA comparisons between closure and non-closure zones at each location of the three taxonomic groups.

Location	FISH		DECA		PENA	
Ballina	$F_{1,69}$ = 2.231	P = 0.039	$F_{1,69}$ = $^{\#}$	P = $^{\#}$	$F_{1,13}$ = 0.273	P = 0.891
Yamba	$F_{1,70}$ = 5.632	P = 0.005	$F_{1,70}$ = 9.405	P = 0.005	$F_{1,17}$ = 0.804	P = 0.572
Newcastle	$F_{1,62}$ = 9.609	P = 0.005	$F_{1,62}$ = 2.818	P = 0.039	$F_{1,17}$ = $^{\#}$	P = $^{\#}$

$^{\#}$ indicates that the PERMANOVA test produced negative components of variation

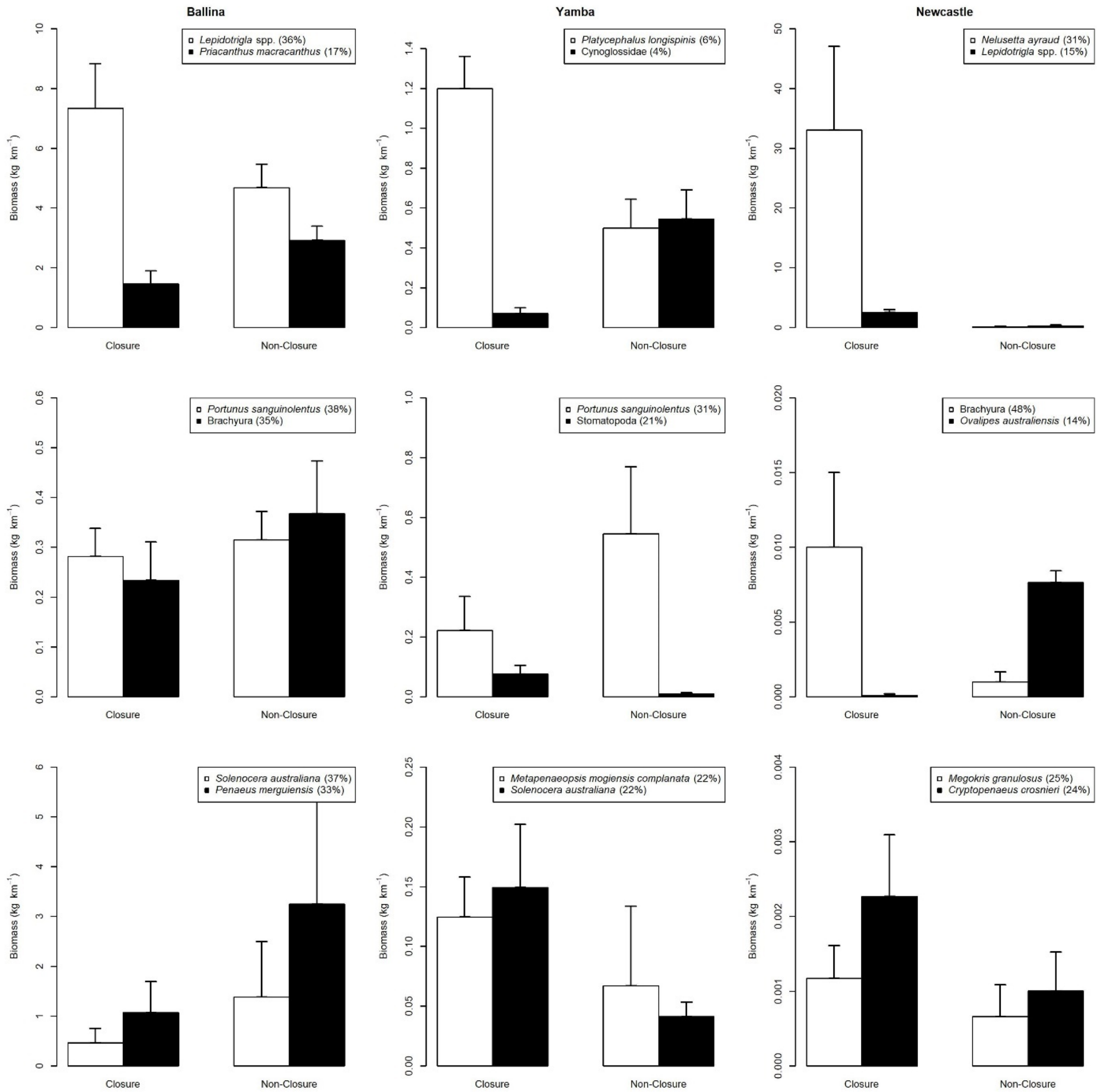


Figure 25 Relative biomass of the top two taxa that most contributed to assemblage differences between trawl closure and non-closure zones for each location, for taxonomic groups fish (upper panels), decapods (middle panels) and penaeids (lower panels). Note that biomass data for Decapods in Ballina, and Penaeids for all locations is included for information only, as there were no significant differences between trawl closure and non-closure zones for these treatment and taxa combinations.

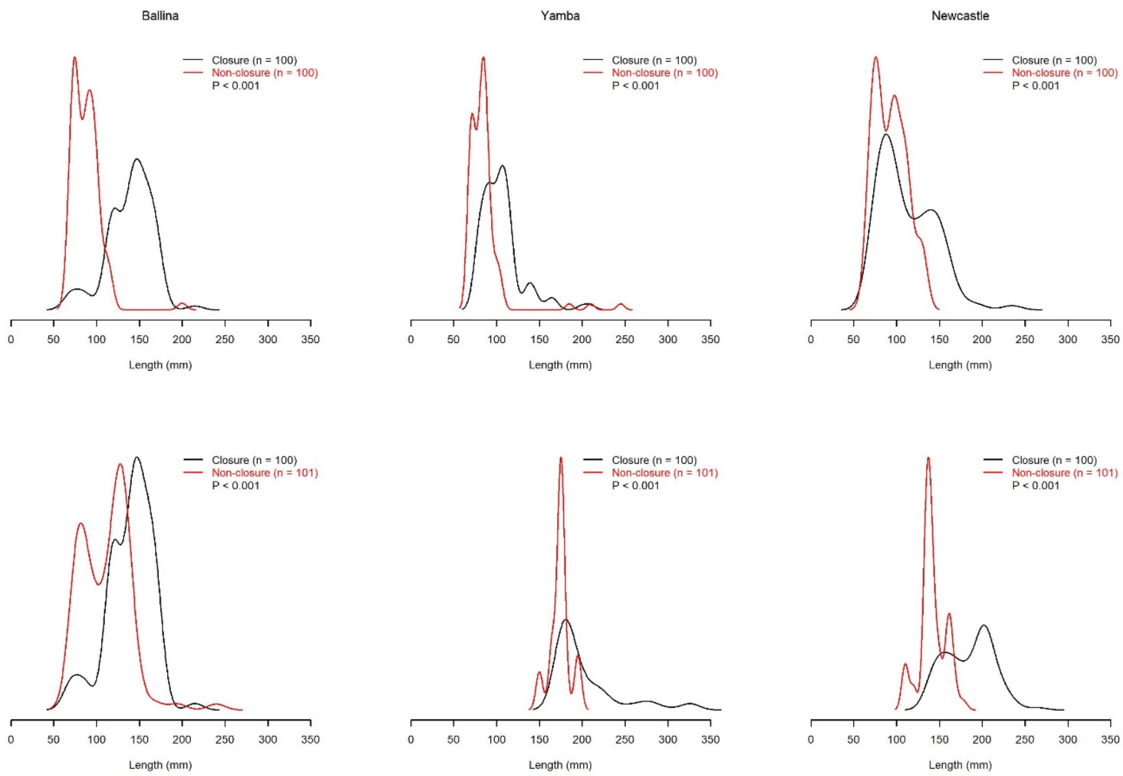


Figure 26 Relative size-structure of Cocky Gurnard (top row) and Longspine Flathead (bottom row) within the Ballina (left panels), Yamba (middle panels) and Newcastle (right panels) survey areas, presented as kernel density distributions for closure (black line) and non-closure (red line) zones. The number of fish (n) used in the each distribution is indicated in the panel legends, as is the P-value from K-S tests between the length structures.

Evaluation of trawl whiting within inshore closures and adjacent fished zones

Over the 667 trawl shots undertaken, a total of ~126,000 Stout Whiting, and 6,945 Eastern School Whiting were captured. As outlined above, inclement weather prevented surveys in Ballina in April 2017 (**Figure 27**) and Yamba in March 2017 (**Figure 28**), and the Newcastle vessel was not available for charter in January 2017 (**Figure 29**).

Patterns in biomass

Spatial and temporal patterns in biomass showed divergent trends across locations, zones and sampling periods. For Stout Whiting in the Ballina survey area, spatial distribution was comparatively homogenous in most months, although pockets of low fish density were periodically evident in deeper waters, and to the south of the survey area (**Figure 27**). Similarly, biomass was comparatively homogenous within the Yamba survey area, with pockets of low fish density appearing in shallower non-closure waters, including directly adjacent to the estuary mouth (**Figure 28**). There was much more spatial variation across the Newcastle survey area, with the greatest biomass occurring closer to shore, but spatial patterns in biomass were comparatively consistent among months (**Figure 29**). Categorical analysis of mean biomass using ANOVA reflected differences in the magnitude of variation, with significant main effects for location ($F_{2,643}$ = 161.6, P << 0.001) and month ($F_{3, 643}$ = 7.65, P << 0.001). There was no significant main effect for zone, but a significant location x zone interaction ($F_{2, 643}$ = 16.5, P << 0.001) and subsequent Tukey's post-hoc test (P << 0.001) indicated that there were significant differences between closure and non-closure zones for Newcastle only, with greater biomass in the non-closure zone (**Figure 30**). Stout Whiting biomass was greatest in January, and lowest in March (P < 0.001), and these differences were consistent across locations.

For Eastern School Whiting, biomass was comparatively low at the Ballina and Yamba survey areas, but at Newcastle, where the biomass was greater, there was a substantial degree of variation across the survey area (**Figure 31**), with biomass appearing to be greatest within the closure zone. ANOVA detected significant differences among locations ($F_{2,643}$ = 193.5, P << 0.001), between zones ($F_{1,643}$ = 35.8, P << 0.001), and among months ($F_{3,643}$ = 9.7, P << 0.001), however there was a significant interaction between these three factors ($F_{6,643}$ = 3.9, P << 0.001). This was interpreted as a greater biomass within the closure zone for Newcastle only, for all months except April (**Figure 31**). For the Newcastle survey area, there was also evidence for an inverse relationship between the biomass of Stout Whiting and Eastern School Whiting, with Stout Whiting more associated with shallower depths (**Figure 31**).

Patterns in size-structure

Relative size-structure for Stout Whiting showed minor, but significant, differences between closure and non-closure zones for most sampling periods in both the Ballina (**Figure 32**) and Yamba (**Figure 33**) survey areas. In most cases, this was due to a greater representation of larger size classes within closure zones compared with non-closure zones (**Figure 32** and **Figure 33**). When size composition data was expressed relative to the length-at-maturity (L_{50}), the proportion of fish exceeding this threshold was consistently greater within closure zones for both the Ballina ($F_{1,202}$ = 5.8, P = 0.017) and Yamba ($F_{1,232}$ = 21.2, P << 0.001) survey areas (**Figure 30**), with patterns consistent across months. Low sample sizes meant that length comparisons were not undertaken for Stout Whiting within the Newcastle survey area. However, patterns were similar for Eastern School Whiting within the Newcastle survey area, with some evidence for larger fish within the closure zone during most sampling periods (except January and February in 2018; **Figure 34**). However, these patterns were not evident when comparing L_{50} among zones (**Figure 31**), and there were no significant main effects on this variable detected for zone ($F_{1,45}$ = 2.0, P = 0.165) or month ($F_{2,45}$ = 2.7, P = 0.070).

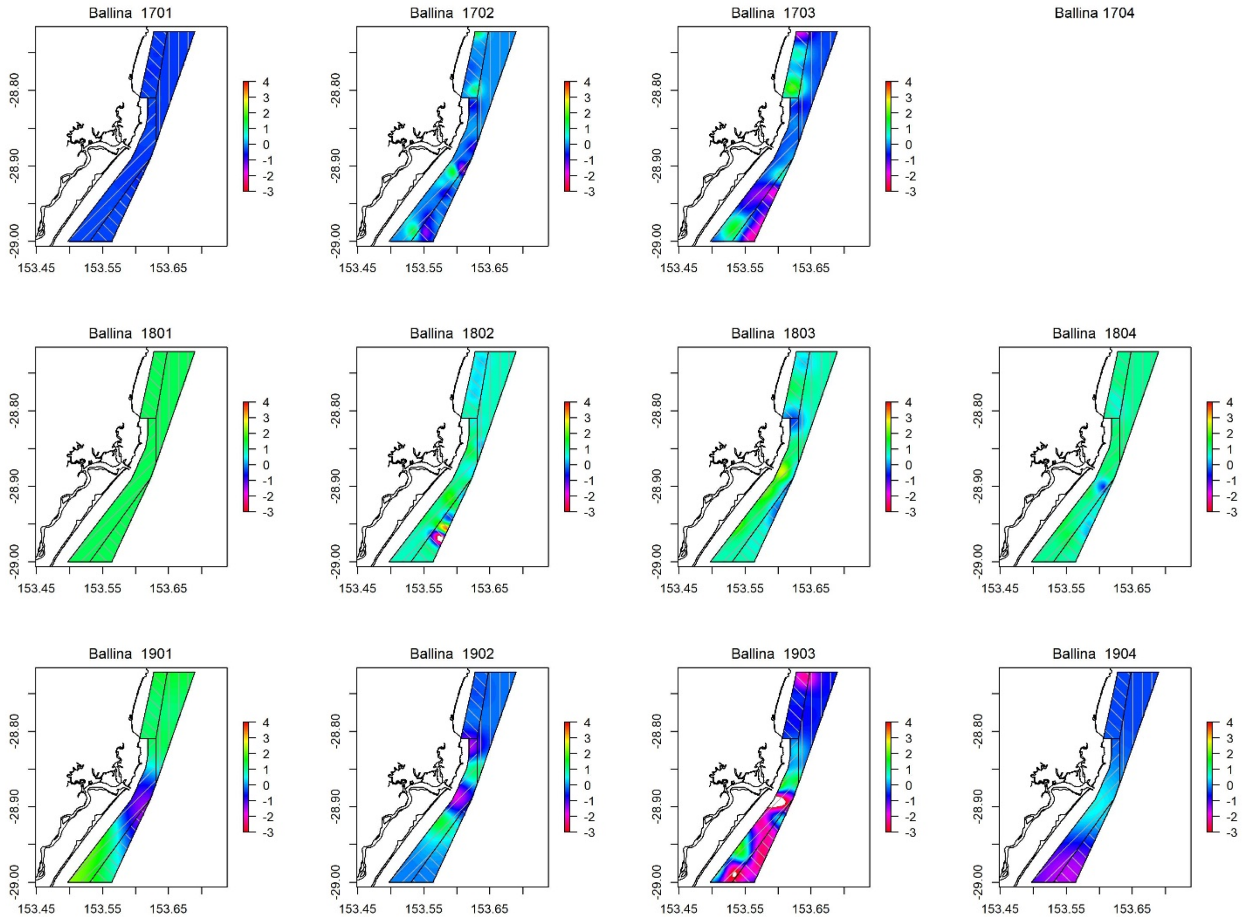


Figure 27 Interpolated Stout Whiting biomass (log[kg ha^{-1}]) for the Ballina survey location, for each year (rows) and each month (columns) that were surveyed, with closure and non-closure zones indicated by 45° and 90° hatching respectively. The title at the top of each panel indicates the location and period (YYMM) for that panel, and the legend indicates the relative biomass estimated across the spatial extent of the survey area. No survey work was conducted during April 2017 (1704) due to inclement weather.

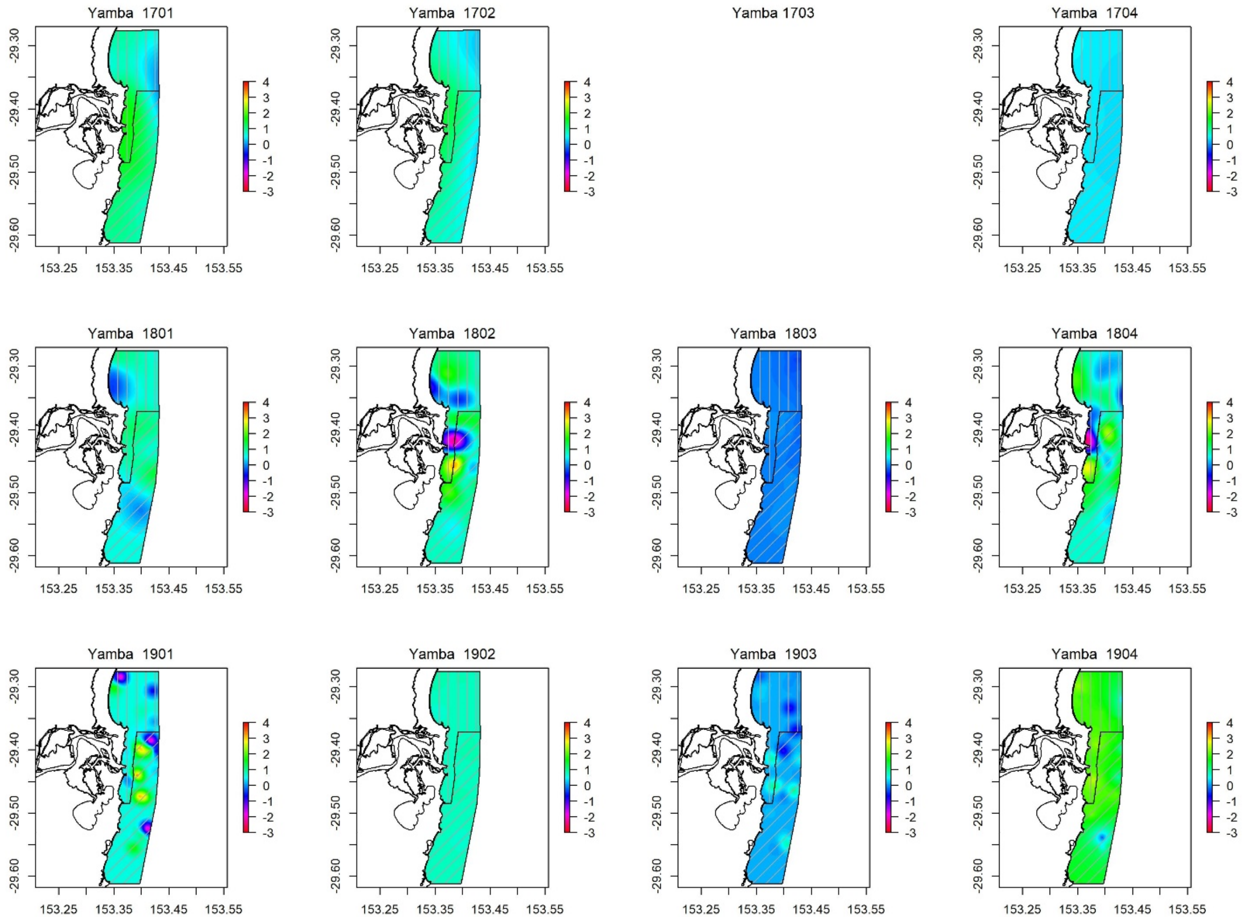


Figure 28 Interpolated Stout Whiting biomass (log[kg ha^{-1}]) for the Yamba survey location, for each year (rows) and each month (columns) that were surveyed, with closure and non-closure zones indicated by 45° and 90° hatching respectively. The title at the top of each panel indicates the location and period (YYMM) for that panel, and the legend indicates the relative biomass estimated across the spatial extent of the survey area. No survey work was conducted during March 2017 (1703) due to inclement weather.

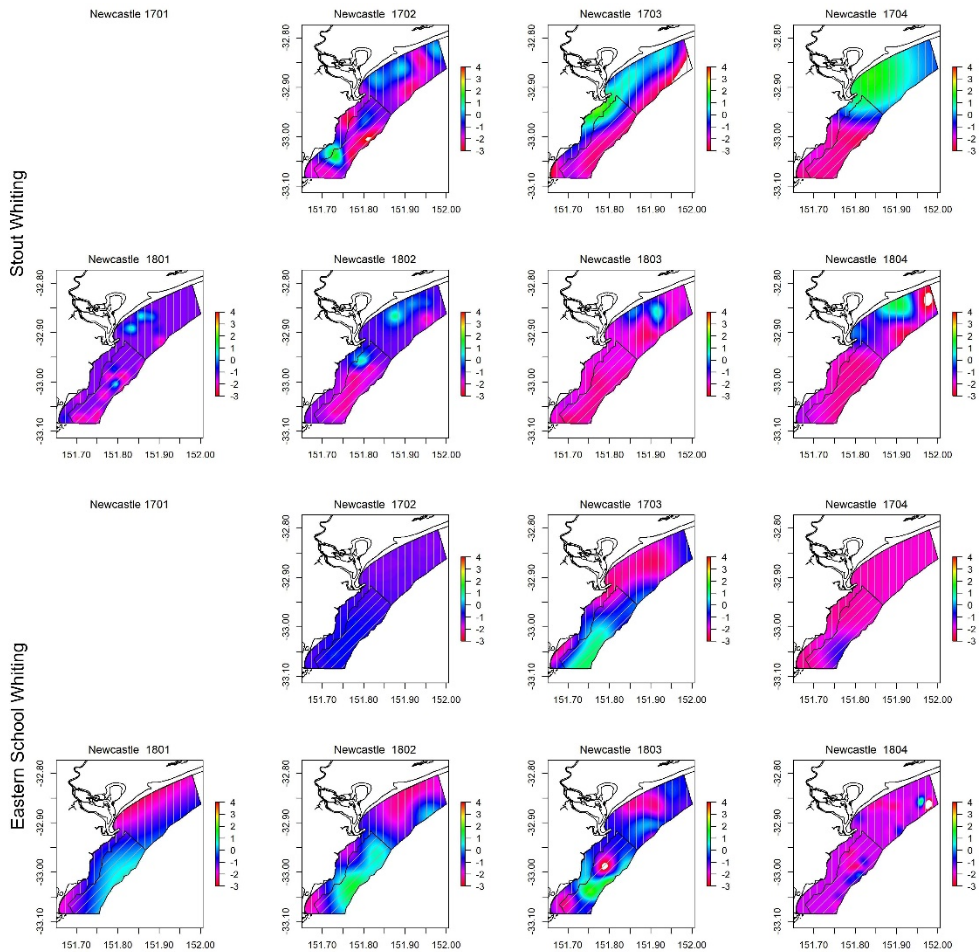


Figure 29 Interpolated Stout Whiting (upper panels) and Eastern School Whiting (lower panels) biomass (log[kg ha^{-1}]) for the Newcastle survey location, for each year (rows) and each month (columns) that were surveyed, with closure and non-closure zones indicated by 45° and 90° hatching respectively. The title at the top of each panel indicates the location and period (YYMM) for that panel, and the legend indicates the relative biomass estimated across the spatial extent of the survey area. No survey work was conducted during January 2017 (1701) as the vessel was not available for charter.

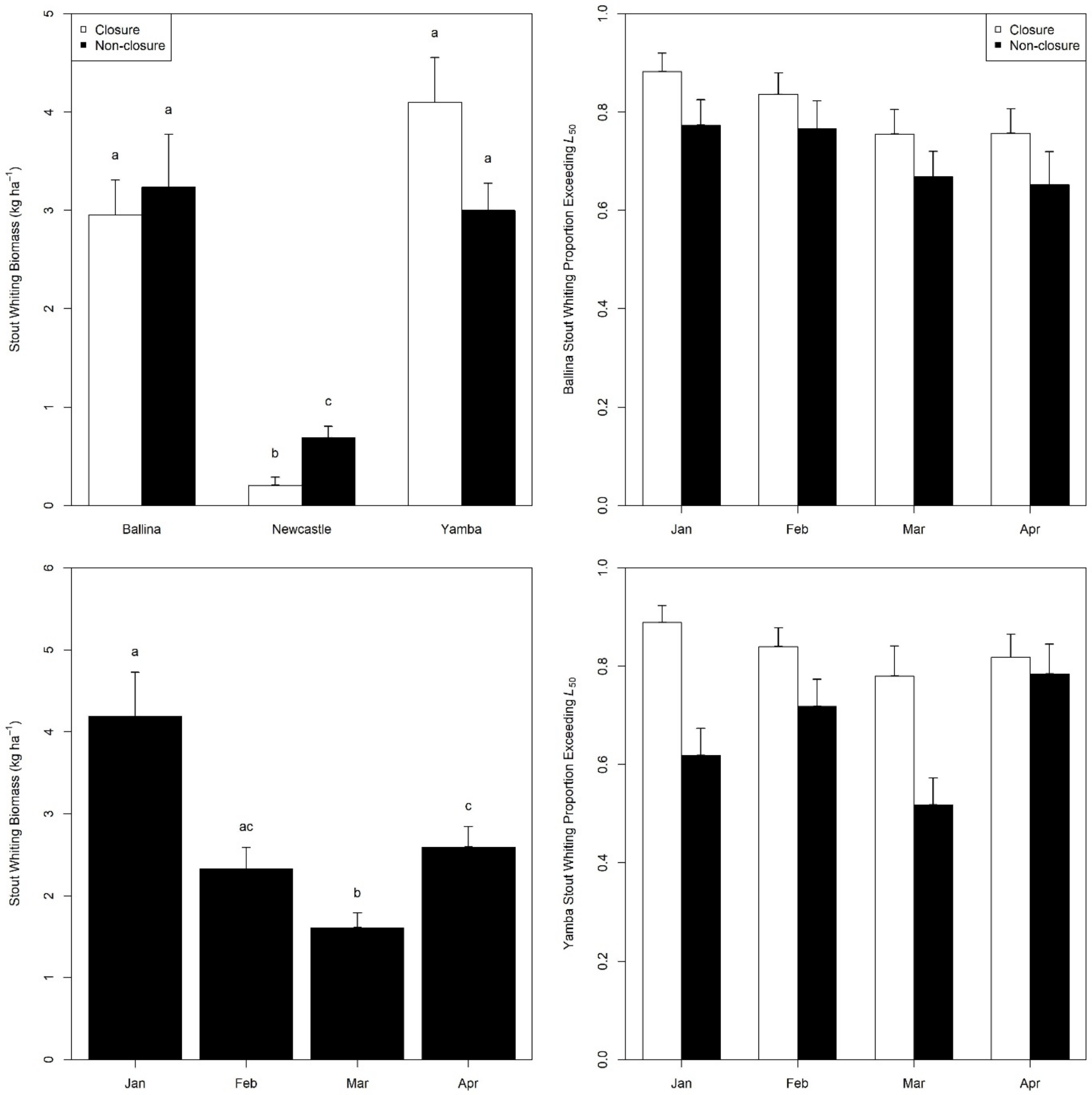


Figure 30 Categorical summary of Stout Whiting biomass (mean ± SE) across locations and closure strata (upper left) and month (lower left). Also indicated is the proportion of Stout Whiting exceeding L_{50} for the Ballina (upper right) and Yamba (lower right) survey locations. On the left panels, different letters denote significant differences, as determined from Tukey's post-hoc test.

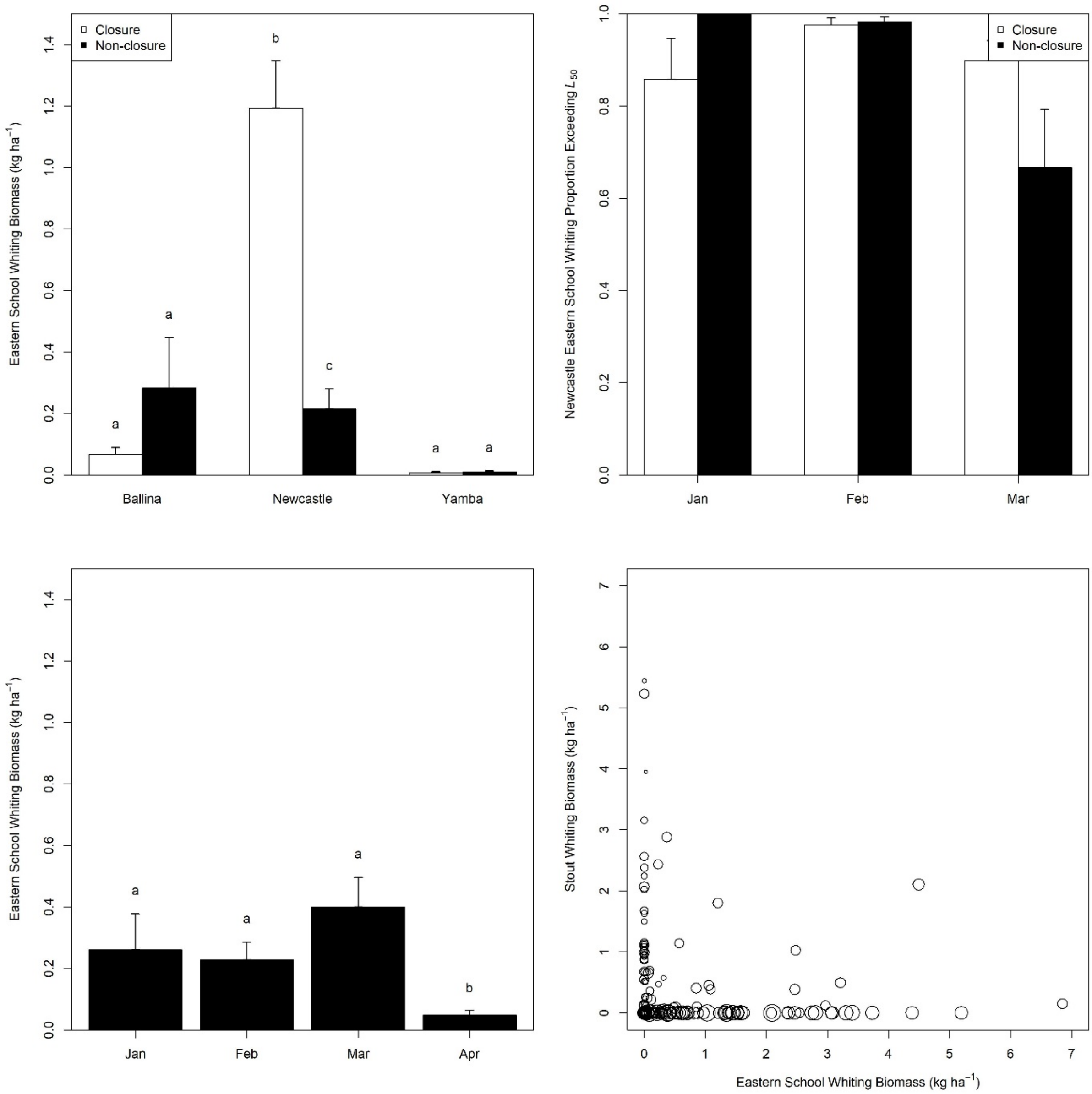


Figure 31 Categorical summary of Eastern School Whiting biomass (mean ± SE) across locations and closure strata (upper left) and month (lower left; different letters denote significant differences, as determined from Tukey's post-hoc test). Also indicated is the proportion of Eastern School Whiting exceeding L_{50} for the Newcastle survey area (upper right), and the relationship between biomass of Stout Whiting and Eastern School Whiting captured at this location (lower right; symbols are sized to provide a relative indication of the depth of each tow).

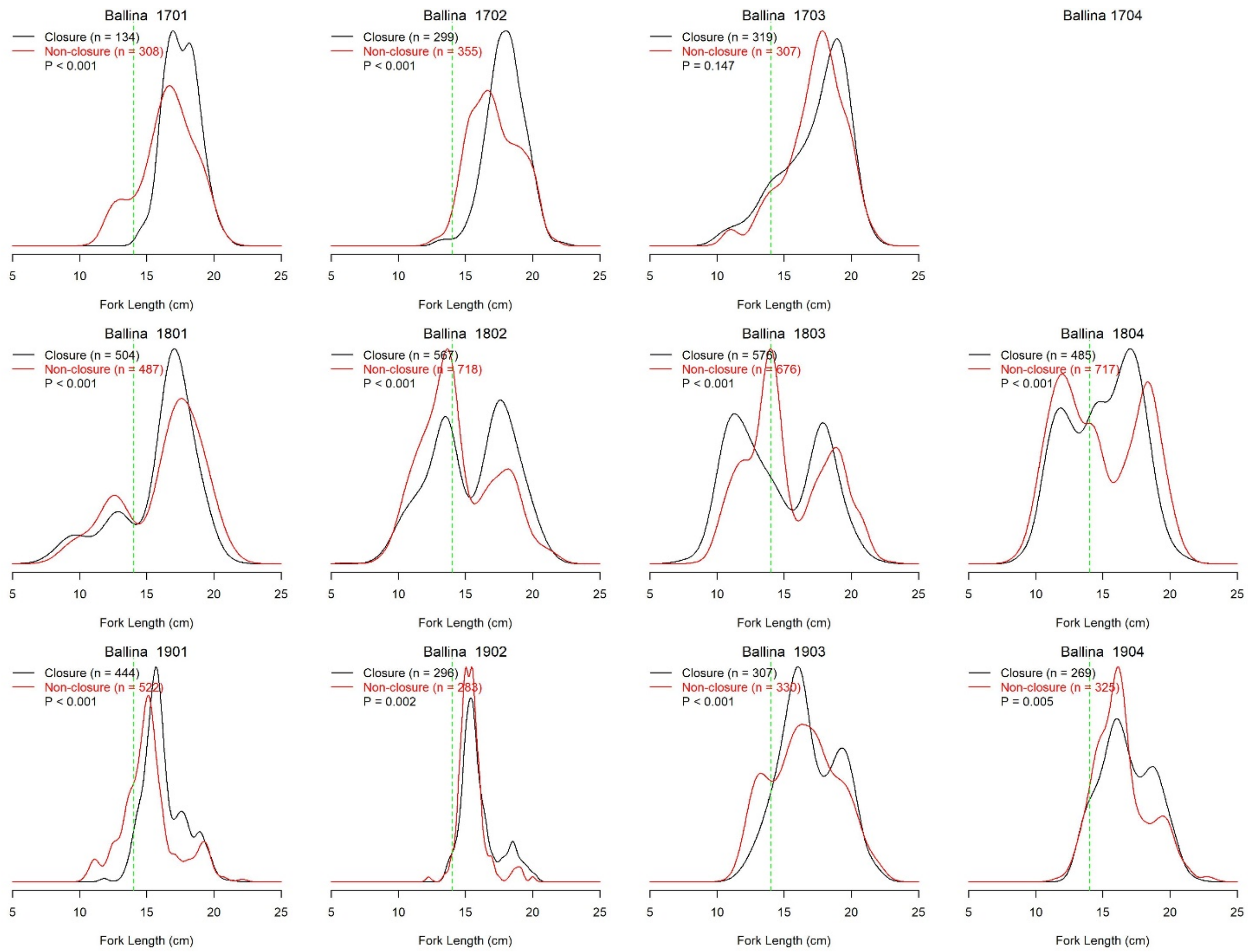


Figure 32 Relative size-structure of Stout Whiting captured within the Ballina survey location for each year (rows) and month (columns) of the survey, presented as kernel density distributions for closure (black line) and non-closure (red line) zones. Each panel title indicates the location and period (YYMM) of the survey, and the number of fish (n) used in each distribution is indicated in the panel legends, as is the significance value from K-S test between the length distributions. Also indicated is an estimate of length-at-maturity (L_{50}, vertical green dashed line) from Gray *et al.* (2014b).

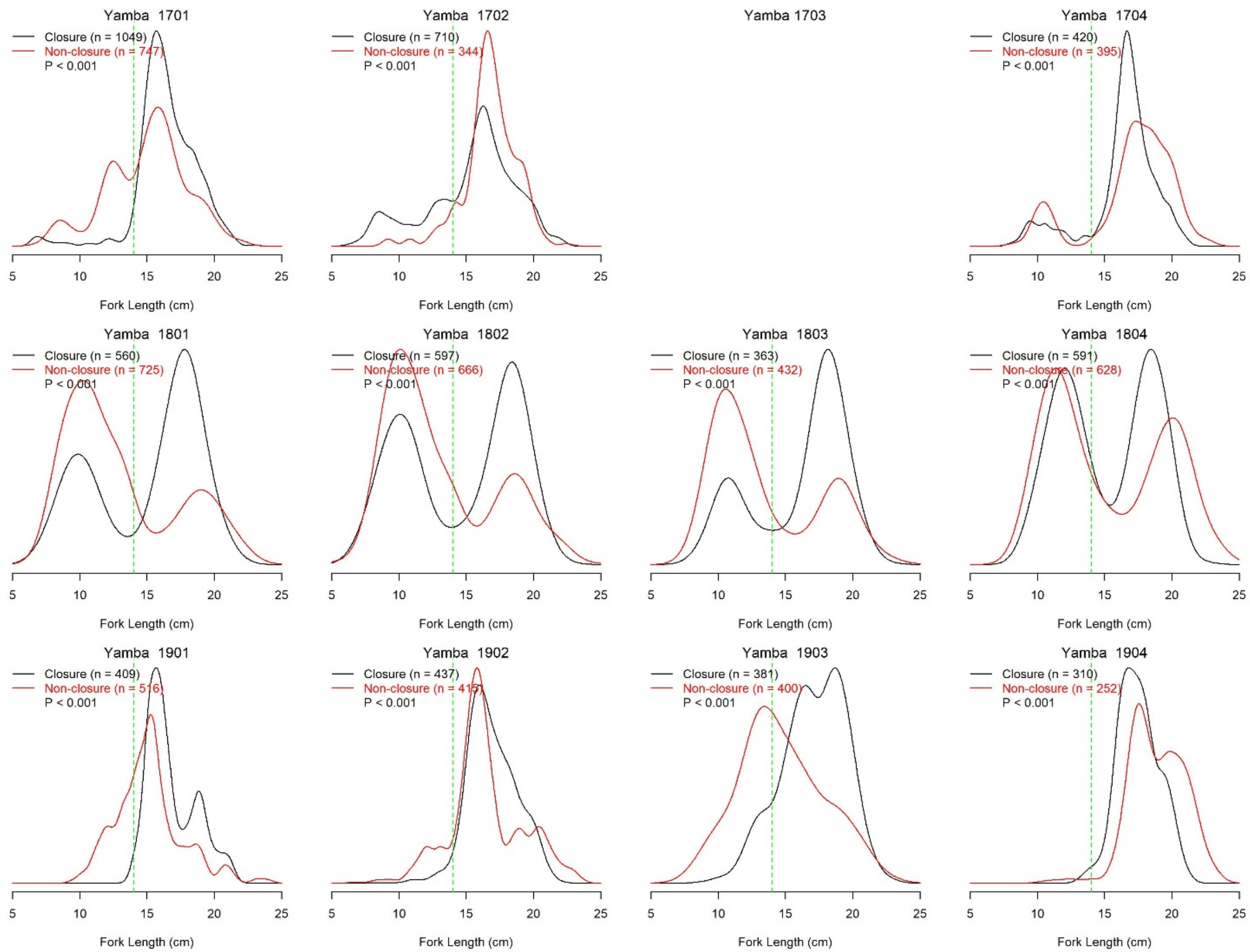


Figure 33 Relative size-structure of Stout Whiting captured within the Yamba survey location for each year (rows) and month (columns) of the survey, presented as kernel density distributions for closure (black line) and non-closure (red line) zones. Each panel title indicates the location and period (YYMM) of the survey, and the number of fish (n) used in each distribution is indicated in the panel legends, as is the significance value from K-S test between the length distributions. Also indicated is an estimate of length-at-maturity (L_{50}, vertical green dashed line) from Gray *et al.* (2014b).

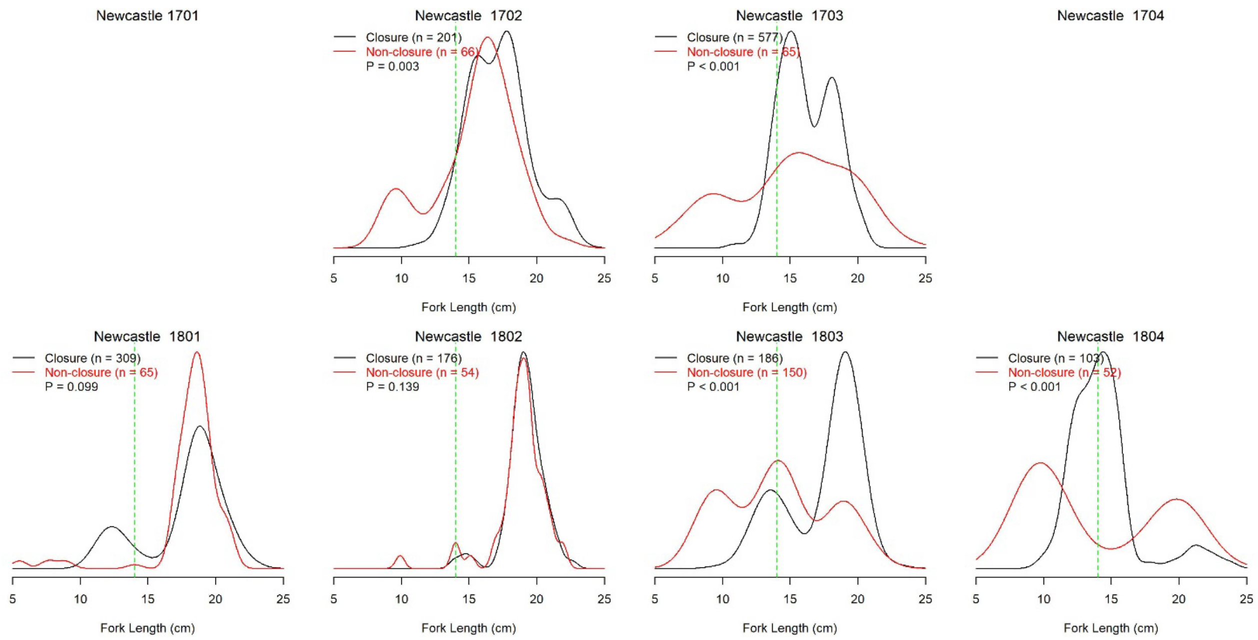


Figure 34 Relative size-structure of Eastern School Whiting captured within the Newcastle survey location for each year (rows) and month (columns) of the survey, presented as kernel density distributions for closure (black line) and non-closure (red line) zones. Each panel title indicates the location and period (YYMM) of the survey, and the number of fish (n) used in each distribution is indicated in the panel legends, as is the significance value from K-S test between the length distributions. Also indicated is an estimate of length-at-maturity (L_{50}, vertical green dashed line) from Gray *et al.* (2014b).

Evaluation of School Prawn and juvenile Mulloway across inshore areas following heavy rainfall in coastal catchments

New South Wales experienced a protracted drought throughout the course of this project. While floods occurred during the first season of the project, this meant that few floods could be sampled during the latter part of survey period. Not surprisingly, flood events frequently coincided with inclement weather, usually associated with persistent low-pressure systems along south-eastern Australia. Sampling these events was challenging, as heavy seas and strong winds made ocean-going trips unsafe. This limited the number of days that could be sampled, and these were further limited by the need to work around other fishing activities being carried out by the chartered vessels. Nonetheless, the sampling survey proceeded in some form following three events (**Figure 35**), with sampling of each event commencing on advice of trawl operators, that it was safe and worthwhile (i.e. Eastern School Prawn were present in inshore waters) to do so. There were a total of eight trips occurring across these three events (**Figure 35**), which yielded 67 successful shots across the surveyed strata.

Eastern School Prawn were encountered in ~75% of samples, at between <1 – 54 kg ha^{-1}. Mulloway and Teraglin were encountered in ~40% and ~53% of samples (respectively), but only at comparatively low abundances (ranging from <1 – 190 individuals ha^{-1} with a mean of ~ 5 individuals ha^{-1}). Eastern King Prawn were barely encountered during the irregular sampling program (**Figure 36**), however there were relationships between Eastern School Prawn and Mulloway, Teraglin and Total Sciaenidae, and a significant relationship between Mulloway and Teraglin abundance (β = 0.904, t = 17.8, P << 0.001, R^2 = 0.75; **Figure 37**). Larger catches of sciaenid species generally corresponded with larger catches of Eastern School Prawn, but these relationships were much steeper in non-closure zones than closure zones for both Ballina (Closure: β = 0.040 , t = 3.9, P < 0.001; Non-closure: β = 0.074 , t = 4.7, P << 0.001, R^2 = 0.48) and Yamba (Closure: β = 0.236 , t = 3.5, P = 0.002; Non-closure: β = 0.892 , t = 5.3, P << 0.001, R^2 = 0.64, note outliers [Eastern School Prawn biomass > 45 kg ha^{-1}] were removed from this regression; **Figure 36**). The relationships were also much steeper in Yamba than Ballina, indicating that more juvenile sciaenids were captured for each kilogram of Eastern School Prawn landed in Yamba, than Ballina (**Figure 36**). No sciaenids were encountered during the Ballina 2020 event.

Categorical representation of the biomass and abundance of key species suggested that Eastern School Prawn were more abundant within closure zones for Ballina, and that sciaenids were more abundant in non-closure zones for Yamba (**Figure 38**). However, ANOVA of differences between events (Ballina 2017 and Yamba 2017 only for sciaenids) and zones (Closure and Non-closure) indicated that none of these differences were statistically significant. Analysis of size-structures showed only minor differences between closure and non-closure zones. The most obvious differences were for Eastern School Prawn, where prawns were larger and bigger size grades were better represented within the closure zone for the Ballina 2017 event (**Figure 39**). Prawns captured in the Yamba 2017 event were generally smaller than both Ballina events, however there was a converse relationship between zones, with large prawns and better size grades in the non-closure zone. There were only minor differences in size-structures between zones for Mulloway and Teraglin, for both the 2017 events (**Figure 39**).

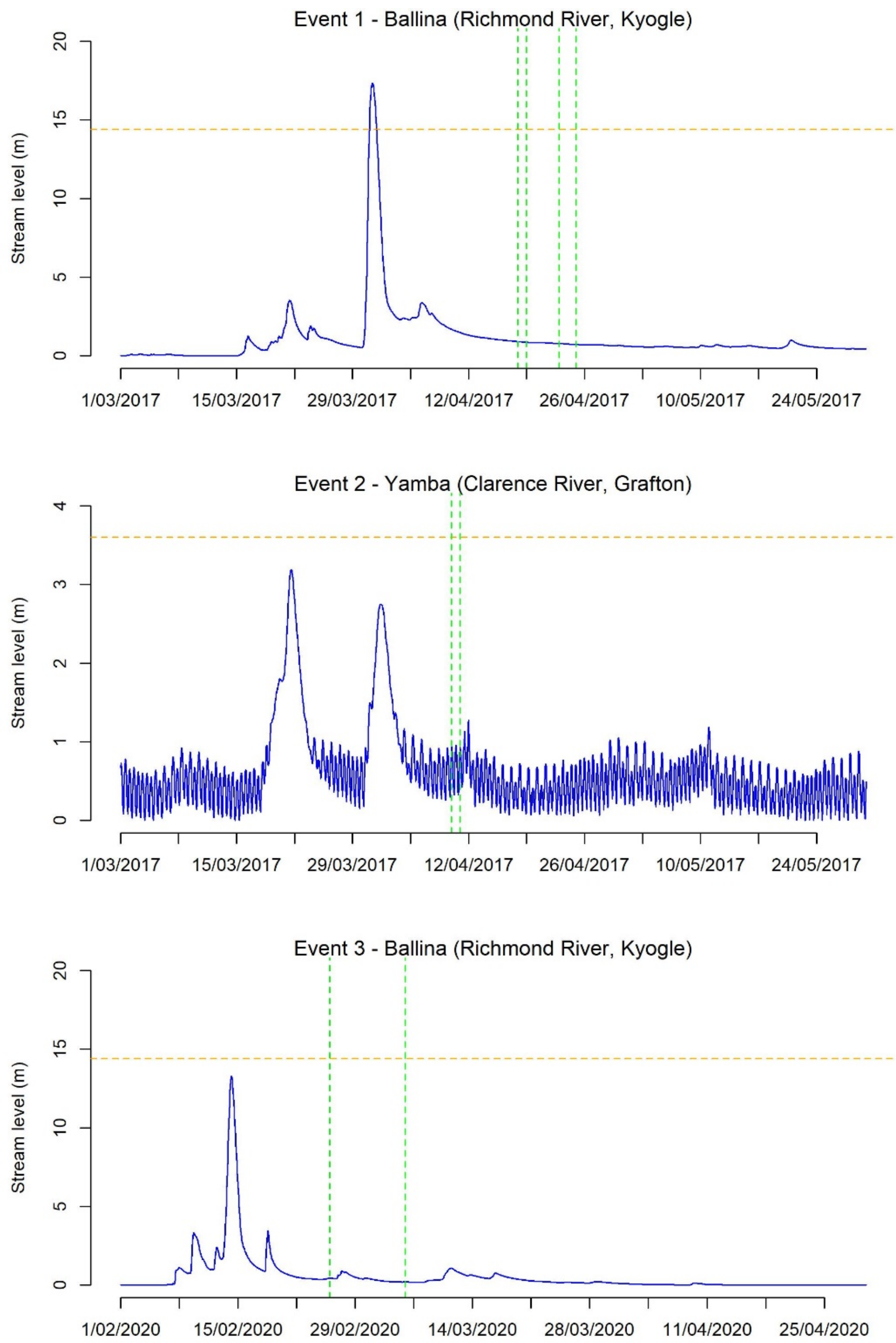


Figure 35 Stream level trace in the estuaries adjacent to the Ballina and Yamba survey areas (**Figure 2**) for the three events targeted during the irregular survey program. Vertical green dashed lines indicate sampling points following each event. The location of the water monitoring station is indicated in the title for each panel. The horizontal orange dashed line indicates the stream level which corresponds to the declaration of “moderate” flood level (as listed for the estuaries and gauging stations above in NSW State Emergency Service 2018).

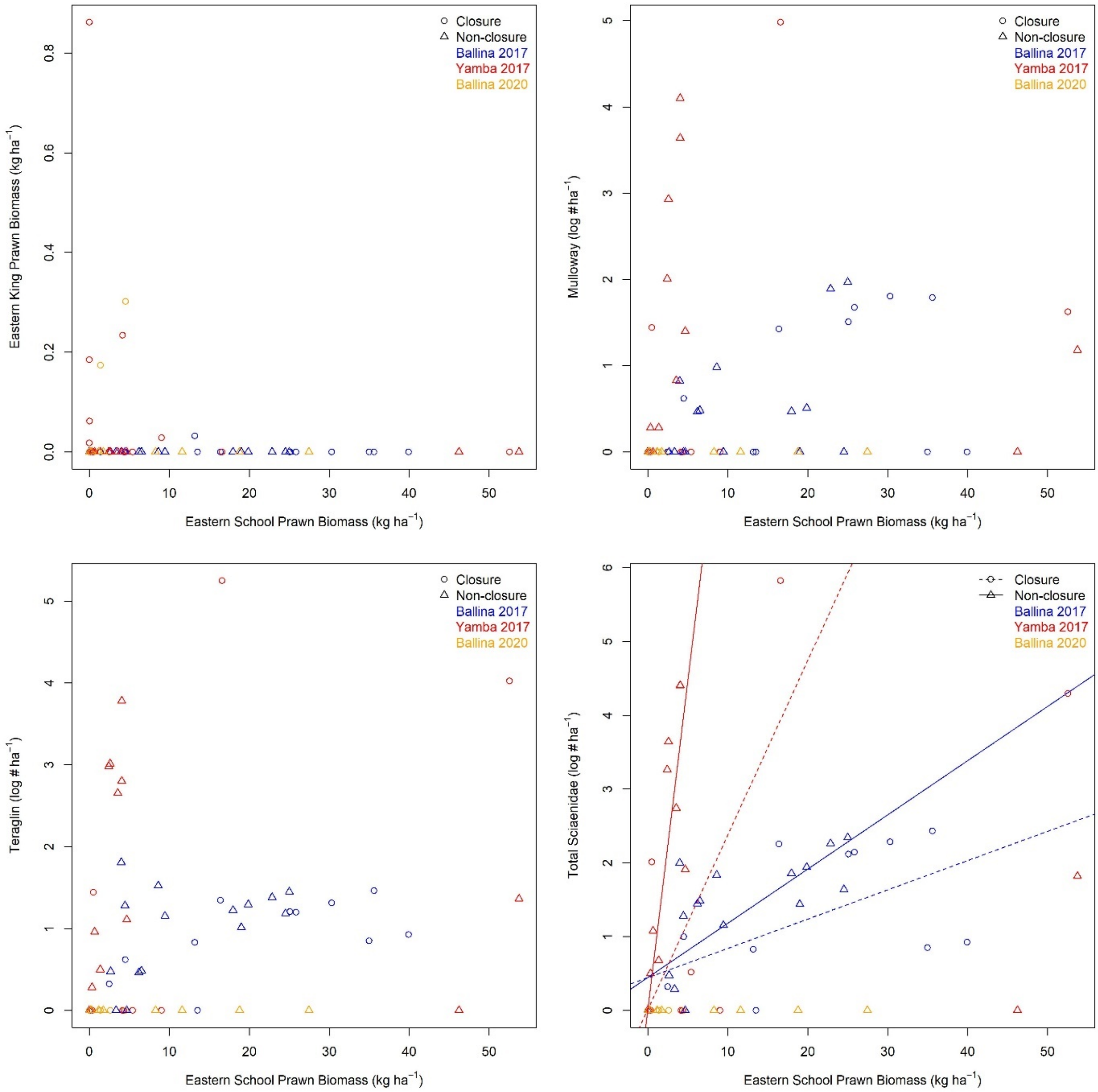


Figure 36 Relationships between biomass (prawn species) and abundance (fish species) of key species encountered during the irregular survey program. Symbols are coded by sampling strata, including zone (symbol shape) and event (colour), as indicated in the legend.

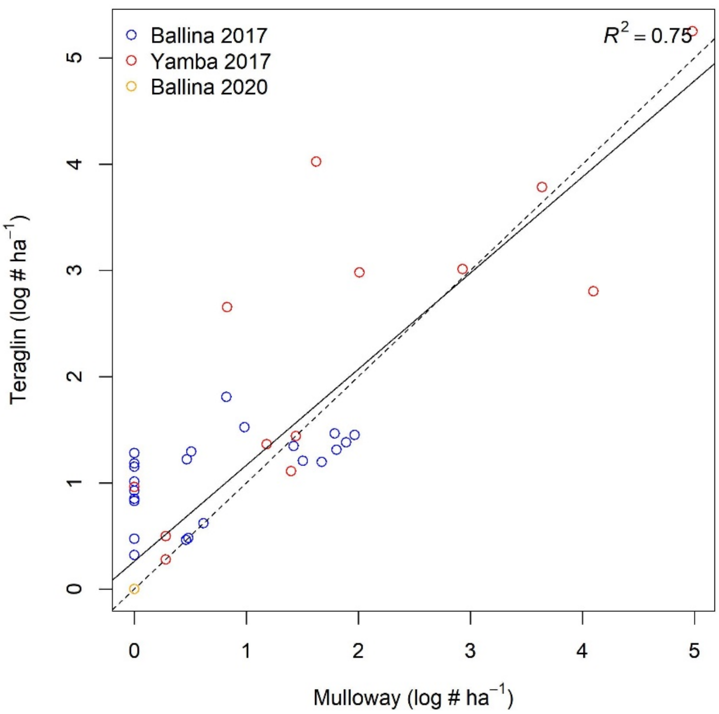


Figure 37 Relationship between Mulloway and Teraglin abundance in samples collected from north coast inshore areas following flood conditions in adjacent estuaries. The linear model between the variables is included as a solid black line (and R^2 indicated on the plot). A 1:1 line between the variables is also shown for comparison.

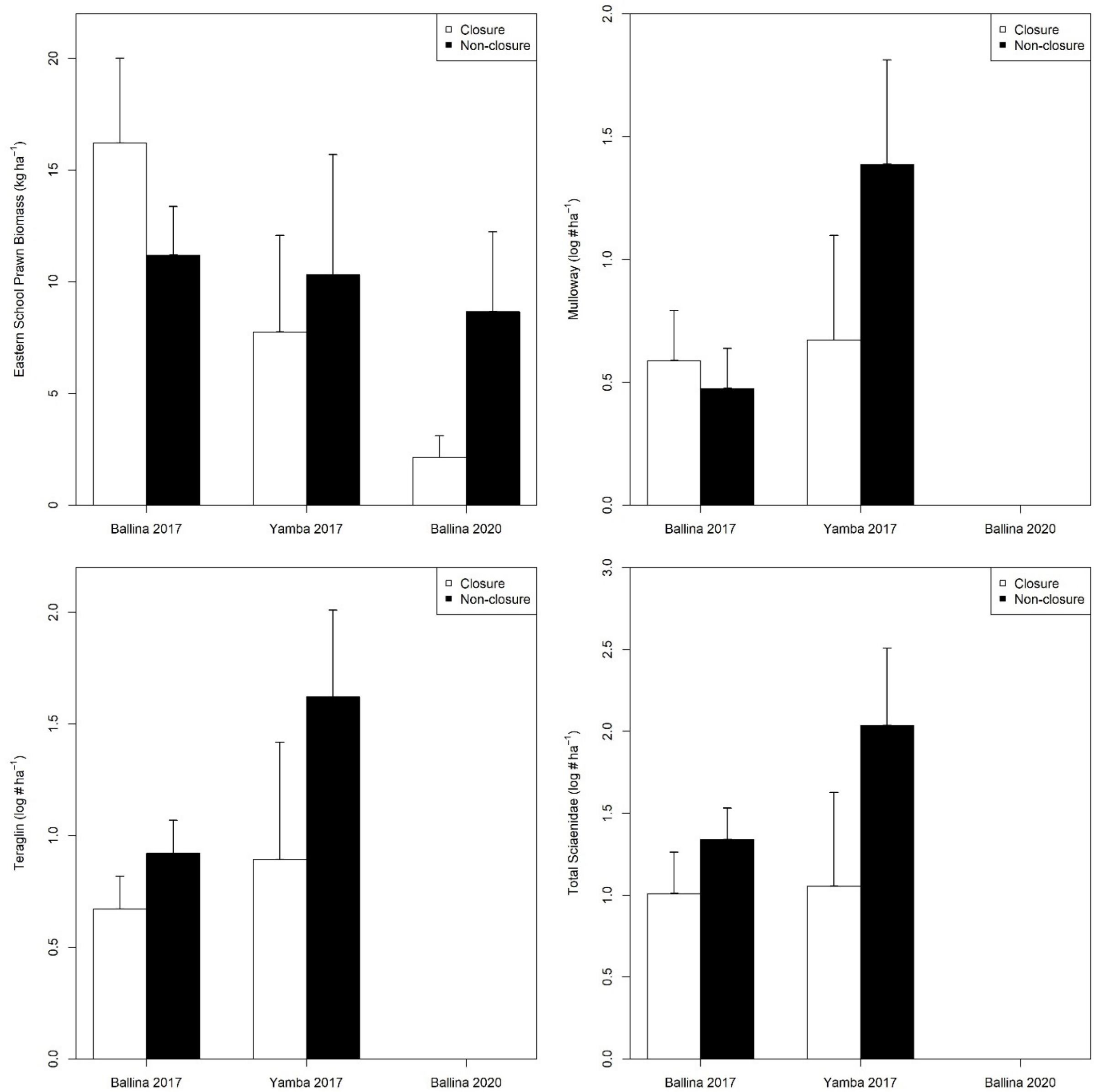


Figure 38 Categorical representation of Eastern School Prawn biomass, and Mulloway, Teraglin, and Total Sciaenidae abundance, collected from north coast inshore areas following flood conditions in adjacent estuaries.

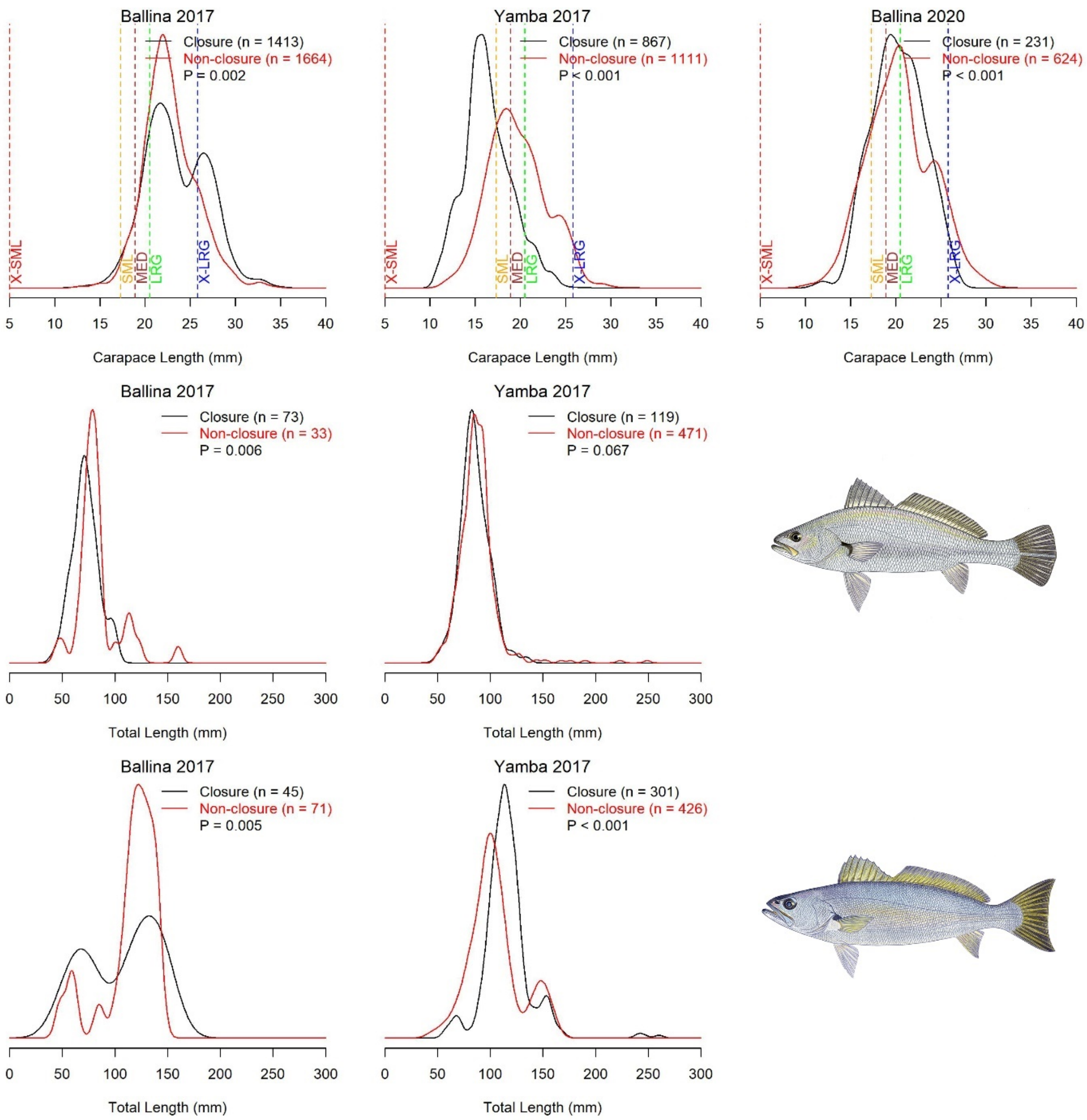


Figure 39 Relative size-structure of Eastern School Prawn (top row), Mulloway (middle row), and Teraglin (bottom row), encountered within north coast inshore areas following flood conditions in adjacent estuaries, presented as kernel density distributions for closure (black line) and non-closure (red 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 K-S test between the length distributions. Note that there were no Mulloway or Teraglin captured during the Ballina 2020 event. Also indicated is 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”).

Application of otolith chemistry to evaluate the contribution of putative nursery estuaries to post-recruited Mulloway

Classification of nursery estuaries for post-recruit Mulloway

Point-in polygon analysis indicated some overlap between the known-origin juvenile edge signatures and the sub-yearling signatures for post-recruited Mulloway (**Figure 40**), however a reasonable proportion of the samples lay outside the 90 % probability simulated mixing region, which led to the exclusion of 42 % of the post-recruit Mulloway samples from the subsequent classification analysis. The remaining samples (n = 217, captured between 2016 – 2018) were classified among six of the eight NSW putative nursery estuaries using the MLR (**Table 8** and **Table 9**, **Figure 41**). Based on similarity in otolith chemistry, a majority of the post-recruit fish analysed were classified to either the Hawkesbury River or the Hunter River (27.6% and 56.7% respectively), with Port Stephens contributing a further 10% (**Figure 41**).

Cluster analysis of post-recruit Mulloway based on otolith edge and sub-yearling region signatures

Multivariate analyses were used to further explore patterns of variation in otolith chemistry of post-recruit fish. There were significant differences in otolith edge chemistry among some capture locations (pseudo-F = 4.567, P = 0.001), with capture location explaining 20% of the variation in edge signatures. Pairwise comparison revealed that differences in otolith chemistry among estuary and ocean locations were uncommon (**Table 10**), with significant differences dominated by Clarence River and Ocean Zone 3 fish. K-means clustering showed that capture locations best split into two clusters based on edge chemistry of post-recruit Mulloway (**Figure 42**). The ocean zones tended to be more strongly associated with Cluster 1, along with Port Stephens, the Hunter River and Georges River. Estuaries north of Wallis Lake tended to group slightly more strongly toward cluster 2, although differentiation from the null model was comparatively small, ranging from 50-64% (**Figure 42**).

There were no significant differences among capture location when core signatures of post-recruit fish were compared (pseudo-F = 1.4754, P = 0.111), suggesting that each location contained a mixed group of animals. K-means clustering of sub-yearling signatures suggested the presence of three clusters, but there was no evidence for a consistent classification of capture locations among these (**Figure 43**).

Summary of historic tag-recapture data

Historic tag-recapture data included 2,503 tags deployed on Mulloway across four estuaries in northern (Clarence River and Richmond River, during 1988-1990) and southern (Shoalhaven River and Lake Conjola, during 1994) NSW. Overall, two-thirds or more fish were recaptured within the same estuary in which they were tagged (**Table 11**), but these proportions appeared to be higher in the southern estuaries. For the northern estuaries, tagged Mulloway were recaptured as far as 2.5° of latitude to the north, and 3° to the south, but most recaptures occurred to the north of the estuary-of-tagging. Conversely, the few recaptures obtained for the southern estuaries outside of their estuary of tagging occurred within 1.5° of latitude, however one of the fish from the Shoalhaven River was recaptured as far north as the Richmond River. Up to 10% of total recaptures occurred in ocean waters, and up to 5% were recaptured in an adjacent jurisdiction (**Table 11**).

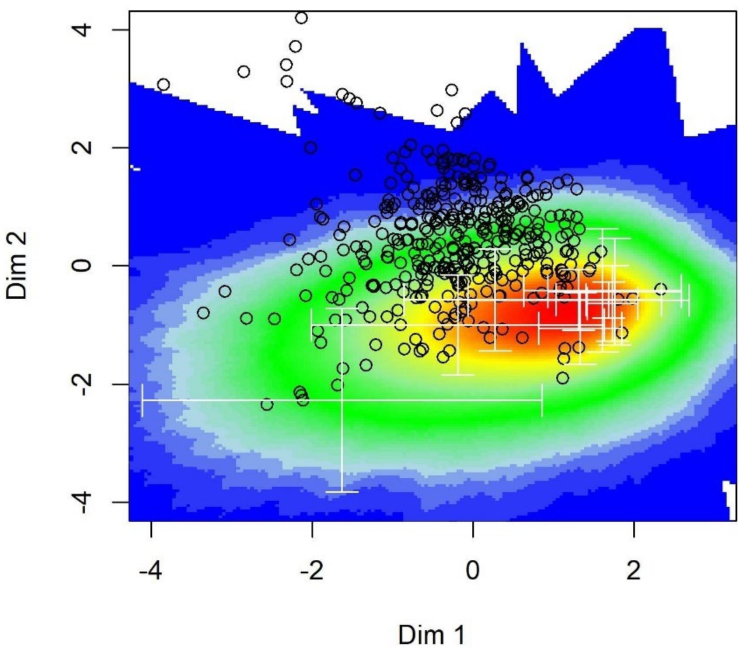


Figure 40 Point-in-polygon simulation (using primary and secondary principal coordinates) plotted in canonical space, with putative juvenile nursery signatures (white bars indicating mean and standard deviation) and sub-yearling signatures of post recruit fish (black circles). The heat map indicates the simulated probabilities, with dark blue representing the 90% threshold used to exclude samples from classification analysis.

Table 8 Summary of the proportion of commercially captured post-recruit Mulloway, allocated to putative estuaries of origin, using a Multinomial Classifier.

Capture location	Stepwise model selection (n = 5)	Predicted natal origin	Proportion allocated (%)
All Locations (*n* = 217)*	Sr, Ba, Li, Mg, Mn	Richmond River	0.5
		Clarence River	2.8
		Macleay River	0.0
		Manning River	0.0
		Hawkesbury River	27.6
		Port Stephens	10.1
		Hunter River	56.7
		Georges River	2.3

*After data reduction

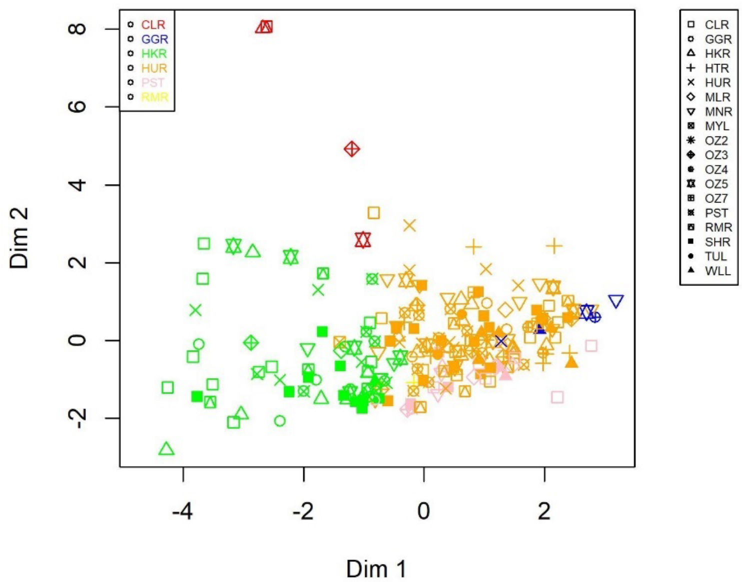


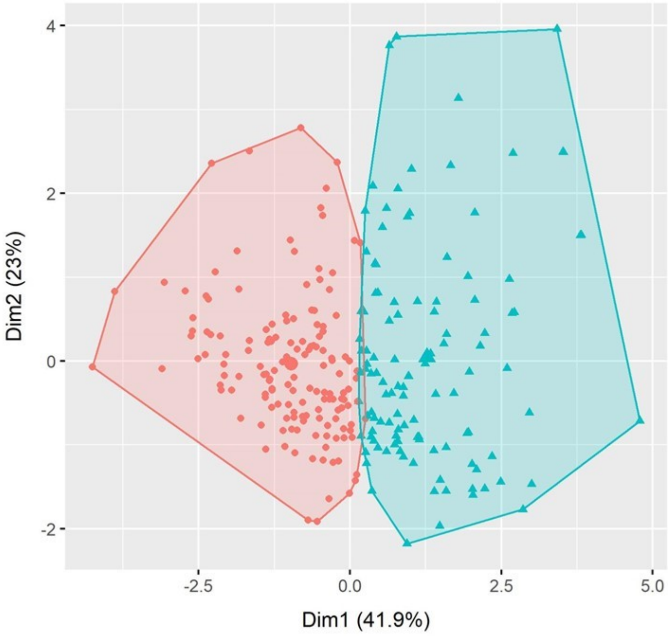
Figure 41 Non-parametric Canonical Variates Analysis (CVA) ordination of the heterogeneous distribution of post-recruit Mulloway to their capture locations, from their predicted natal origins. The capture locations for each individual is indicated by geometrical shapes (see right legend) and the nursery estuary to which they were classified is indicated as colours (see left legend).

Table 9 Classification of post-recruit Mulloway from the NSW stock back to their estuary of origin. Results are based on the otolith edge signatures of juvenile Mulloway of known origins (NSW putative nurseries) and the near-core signatures of post-recruit Mulloway of unknown origins, using a Multinomial Classifier. Ocean Zone is abbreviated to OZ.

NSW Putative Nursery Estuaries	**Capture Locations of post-recruit Mulloway from the NSW Stock**																					
	Richmond River	Clarence River	Macleay River	Hastings River	Camden Haven River	Manning River	Wallis Lake	Port Stephens	Hunter River	Tuggerah Lakes	Lake Illawarra	Hawkesbury River	Myall Lakes	Georges River	Shoalhaven River	OZ 1	OZ 2	OZ 3	OZ 4	OZ 5	OZ 6	OZ 7
Richmond River	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Clarence River	1	-	-	-	-	-	1	-	-	1	-	3	-	-	1	-	-	1	1	1	-	-
Macleay River	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Manning River	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Port Stephens	-	8	4	1	-	3	2	2	1	-	-	2	-	2	3	-	-	1	-	1	1	-
Hunter River	11	38	11	12	1	22	11	25	18	4	1	23	1	5	31	3	3	13	7	12	-	2
Hawkesbury River	7	21	2	2	-	4	2	12	10	1	-	10	-	15	14	-	1	2	-	7	1	-
Georges River	-	2	-	-	-	1	2	1	1	-	-	-	-	-	2	-	1	-	1	1	-	-

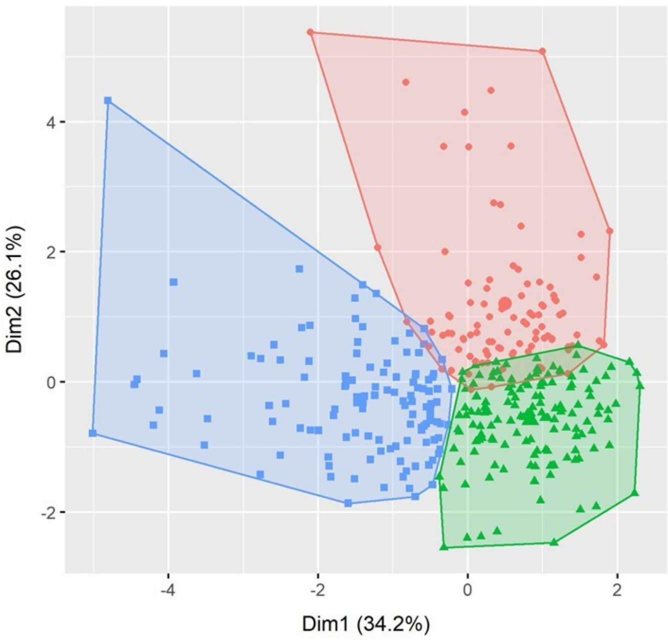
Table 10 Pairwise comparisons of variation in elemental fingerprints of post-recruit Mulloway among locations. Significance codes: - not significant, * P < 0.05 significant following Bonferroni correction for multiple comparisons.

Locations	Clarence River	Macleay River	Hastings River	Manning River	Wallis Lake	Port Stephens	Hunter River	Hawkesbury River	Georges River	Shoalhaven River	OZ 2	OZ 3	OZ 4	OZ 5
Richmond River	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Clarence River		-	-	-	-	*	*	-	-	-	-	*	*	*
Macleay River			-	-	-	-	-	-	-	-	-	*	-	-
Hastings River				-	-	-	-	-	-	-	-	-	-	-
Manning River					-	-	-	-	-	-	-	-	-	-
Wallis Lake						-	-	-	-	-	-	*	-	-
Port Stephens							-	-	-	-	-	-	-	-
Hunter River								-	-	*	-	-	-	-
Hawkesbury River									-	-	-	*	-	-
Georges River										-	-	*	-	-
Shoalhaven River											-	-	-	-
Ocean Zone 2												-	-	-
Ocean Zone 3													-	-
Ocean Zone 4														-



Location	Cluster 1 (%)	Cluster 2 (%)
Richmond River	44	56
Clarence River	41	59
Macleay River	36	64
Hastings River	42	58
Manning River	50	50
Wallis Lake	40	60
Port Stephens	71	29
Hunter River	76	24
Hawkesbury River	50	50
Georges River	84	16
Shoalhaven River	40	60
Ocean Zone 3	100	0
Ocean Zone 4	88	12
Ocean Zone 5	79	21

Figure 42 Cluster identities derived from *K*-means cluster analysis of otolith edge chemistry (i.e. the part of the otolith representing the capture location) for post-recruit Mulloway. The percent allocation of post-recruit fish captured in each location is indicated in the accompanying table, for which columns are coloured to match the clusters on the figure panel.



Location	Cluster 1 (%)	Cluster 2 (%)	Cluster 3 (%)
Richmond River	32	32	37
Clarence River	43	30	27
Macleay River	33	60	7
Hastings River	31	46	23
Manning River	25	39	36
Wallis Lake	20	60	20
Port Stephens	25	42	33
Hunter River	14	55	31
Hawkesbury River	12	27	61
Georges River	32	36	32
Shoalhaven River	20	47	33
Ocean Zone 3	21	36	43
Ocean Zone 4	50	33	17
Ocean Zone 5	24	43	33

Figure 43 Cluster identities derived from *K*-means cluster analysis of otolith sub-yearling chemistry (i.e. the part of the otolith representing the juvenile location) for post-recruit Mulloway. The percent allocation of post-recruit fish captured in each location is indicated in the accompanying table, for which columns are coloured to match the clusters on the figure panel.

Table 11 Summary of the historic tag-recapture data for Mulloway in NSW estuaries (previously reported in West 1993; and later summarised in Silberschneider and Gray 2008), showing the number of fish tagged, the time-at-large (mean, with range in brackets), the proportion of tagged fish that were recaptured, and the proportion of recaptures that occurred within the same estuary, within a different location (proportion in ocean is indicated in brackets), and in the adjacent jurisdiction (Queensland). Tagging locations are as shown in **Figure 3**.

Tagging Location	Latitude	# tagged	Time-at-large (d)	Proportion recaptured (%)	Proportion in same estuary (%)	Proportion in different location (%)	Proportion in Queensland (%)
Richmond River	-29.0°	1132	258 (0 – 1954)	13.4	65.8	34 (9.2)	4.6
Clarence River	-29.4°	518	231 (7 - 1873)	11.6	66.7	32 (10.0)	5.0
Shoalhaven River	-34.9°	783	184 (0 – 934)	34.2	95.9	2 (0.7)	0.0
Lake Conjola	-35.3°	70	83 (1 – 528)	31.4	86.4	9 (4.5)	0.0

Modelling the consequences of adaptive closure management for Eastern King Prawn

Parameterisation and operationalisation

The model well-described the current observations and understanding of the EKP population and fishery. Most parameters used (e.g., growth, natural mortality, recruitment at unfished conditions, current habitat available for recruitment, dispersal, movement of sub-adults and adults, etc.) were informed by previously published data or work. Based on work by Braccini *et al.* (2012), we considered the most likely sub-adult and adult movement to be generated by assuming the probability of remaining within inshore zones (p^i, **Table 2**) being equal to 0.6, and the probability of remaining within offshore zones (p^o, **Table 2**) being equal to 0.8. These probabilities were modified by the age-specific vulnerabilities, and were operationalised at a monthly time-step—thus they represent moderate proportions of movement on a per-month basis. The catchability parameters estimated under this assumption are provided in **Table 12**. These estimates produced a predicted EKP harvest that was very similar to the observed harvest (**Figure 45**)

Impact of closure removal and effects of effort allocation

The overall effect of closure removal on total NSW EKP harvest was estimated to be comparatively minor, regardless of assumptions of how effort changed—meaning that regardless of whether effort was redistributed, overall harvest would neither increase nor decrease much (in all cases <1% change per zone). However, alternative assumptions of effort redistribution had a substantial relative effect (**Figure 46**). Assuming that removing the closures generated wholly "new" effort (i.e., the additional effort in the inshore zones was comprised of no redistributed effort) resulted in the greatest increases in harvest, as would be expected (**Figure 47** and **Figure 48**). These increases were greatest in the zones where the closures were lifted and effort increased (NSW Zones 1 and 2), and they corresponded to almost certainly negligible decreases in offshore and northward zones (resulting from more EKP captured prior to their arrival at these locations). Still, the overall change in the magnitude of harvest in NSW was positive.

Conversely, if effort plying the newly opened inshore trawl grounds in NSW Zones 1 and 2 was wholly redistributed from the adjacent offshore zones, harvest decreased—both in the adjacent offshore zones as well as for NSW overall (**Figure 47** and **Figure 48**). We assume these alternative scenarios (all new, all redistributed) mark the boundaries of likely effort changes, and thus that the most likely outcome would be somewhere in between. However, making the assumption that new effort was comprised of 50% additional effort and 50% redistributed effort resulted in a net positive harvest for NSW as a region (**Figure 46**, **Figure 47** and **Figure 48**).

Uncertainty associated with EKP movement

Alternative assumptions about the movement of EKP, realized via alternative p^i and p^o values (**Table 2**) made small differences in the predictions of how the allowing fishing within closures would alter the harvest (**Table 12**). Assumptions of greater movement rates corresponded to a greater magnitude of change—in both directions. The proportional increase (relative to closures remaining unfished) with all new (and thus no redistributed) effort was slightly greater, whereas the proportional decrease when assuming all effort was redistributed from offshore zones was also greater. As would be expected, the inverse was true for lesser movement—the proportional increases assuming no redistributed effort and the proportional decreases in harvest assuming all redistributed effort were less, relative to the baseline scenario.

Uncertainty in future effort

The results of the uncertainty analyses considering substantially greater fishing effort in NSW zones, similar to the levels in the early 2000s, showed largely comparative patterns to the base model (**Figure 49**). Under these greater (nearly four-fold) effort scenarios, the "all new effort, no redistribution" scenarios still provided the greatest net increase in harvest for NSW, though the levels of harvest did result in slightly more noticeable decreases in harvest in the offshore NSW zones. This occurred because the inshore effort, and effort overall, was great enough that the harvest at the inshore zones is effectively detracting to some small extent from the harvest that might occur in offshore zones. If the effort is assumed to be partially (50%) or wholly redistributed, the gains at inshore zones are partially or almost completely offset by losses in offshore zones. As would be expected, the magnitude of harvest was greater under all assumptions of effort redistribution (**Figure 49**).

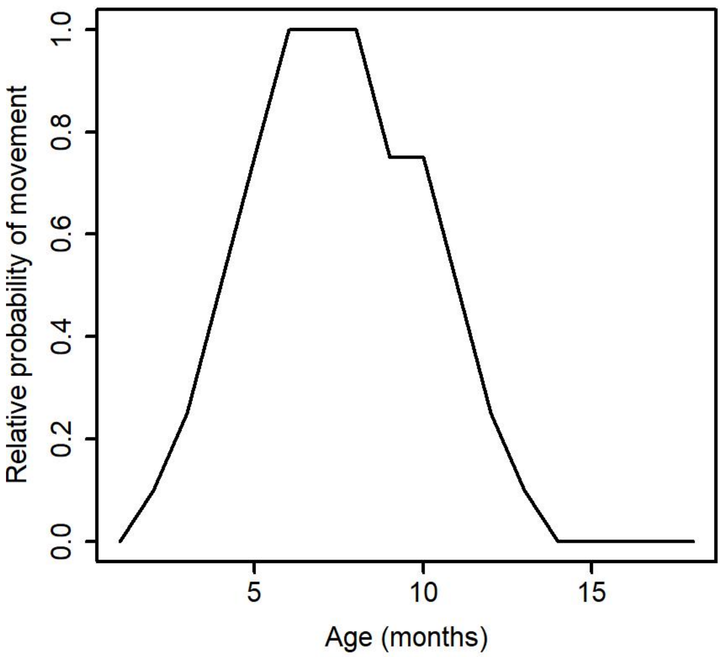


Figure 44 Age-specific vulnerability of EKP to movement

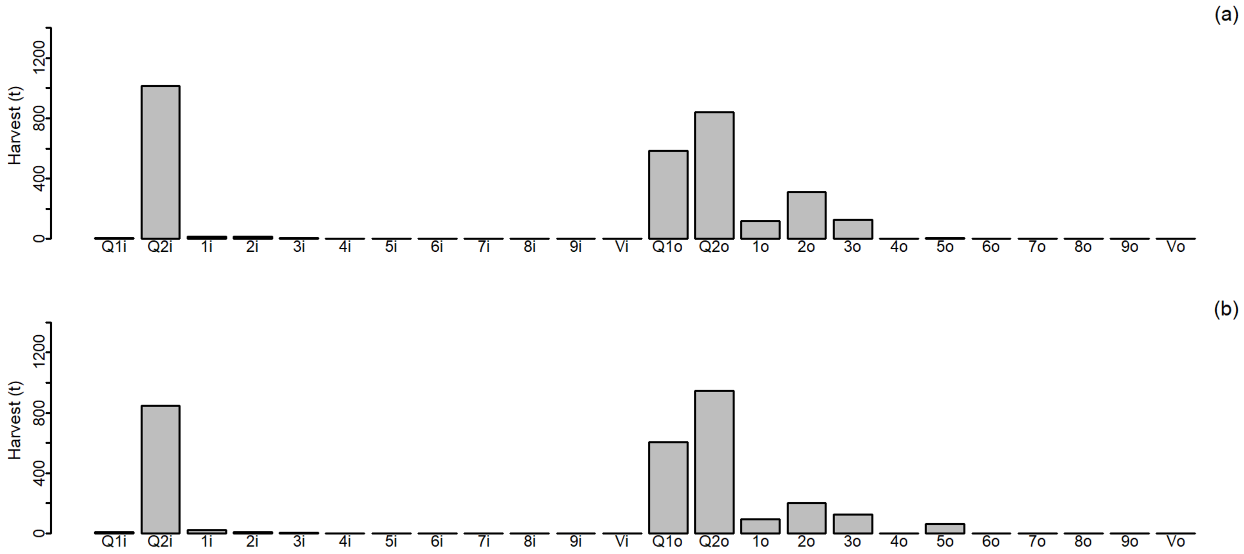


Figure 45 Comparison of predicted harvest (a) by zone to observed harvest by zone (b), under baseline movement assumptions. Prefix "Q" refers to Queensland model zones, no prefix indicates NSW model zones, and "V" indicates the Victoria model zone. Suffix "i" refers to inshore and "o" refers to offshore

Table 12 Estimated catchability parameter values under alternative assumptions of Eastern King Prawn movement, and proportional increase in New South Wales regional harvest under alternative assumptions of effort redistribution (columns) and under baseline and alternative assumptions of movement (rows).

Movement assumption	Movement parameters	q_N^o parameter estimate	q_N^i parameter estimate	q_Q^o parameter estimate	q_Q^i parameter estimate	All new effort (0% redist.)	Part new effort (50% redist.)	No new effort (100% redist.)
Baseline	p^i=0.6; p^o=0.8	0.5962	0.9415	0.5436	0.3816	1.24%	0.37%	-0.50%
Alternative	p^i=0.65; p^o=0.75	0.6329	0.7969	0.4914	2.7151	1.22%	0.34%	-0.54%
Moderately more movement	p^i=0.5; p^o=0.7	0.6953	1.2695	0.3750	0.5079	1.28%	0.36%	-0.56%
Much more movement	p^i=0.4; p^o=0.6	0.9012	1.7136	0.3242	0.7261	1.30%	0.34%	-0.62%
Less movement	p^i=0.7; p^o=0.7	0.6019	0.7236	1.6127	7.2622	1.15%	0.35%	-0.43%

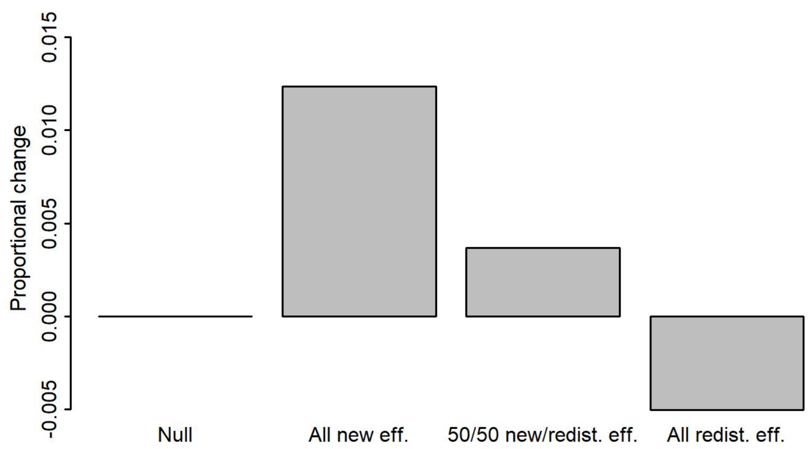


Figure 46 Proportional change in overall harvest for all scenarios evaluated

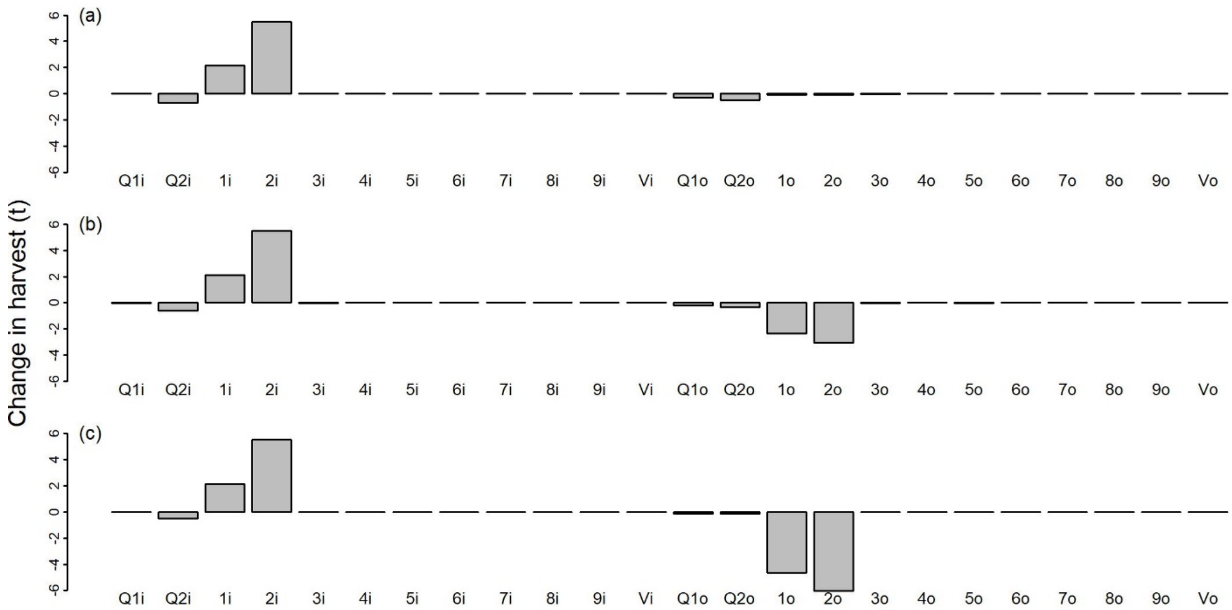


Figure 47 Zone-specific changes in harvest following opening of closures in NSW Ocean Zones 1 and 2 (1i, 2i), estimated under the baseline assumption scenarios (a) all new effort, (b) part new effort, and (c) no new effort (see **Table 12**). Prefixes are as described for **Figure 45**.

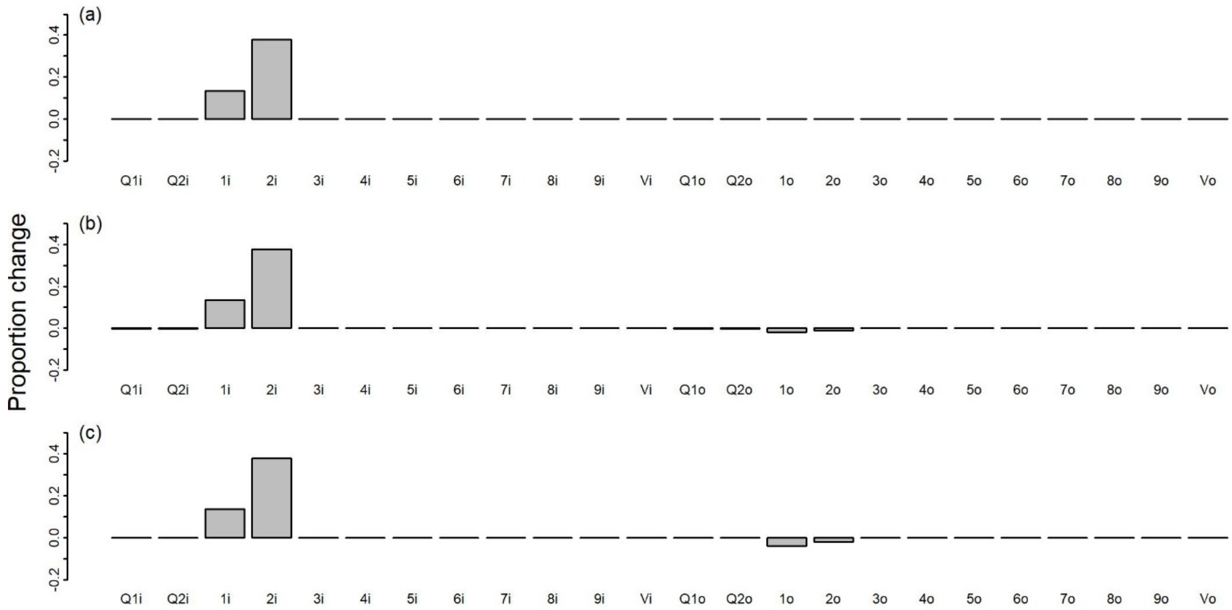


Figure 48 Zone-specific changes in harvest expressed as a proportion of total harvest, following opening of closures in NSW Ocean Zones 1 and 2 (1i, 2i), estimated under the baseline assumption scenarios (a) all new effort, (b) part new effort, and (c) no new effort (see **Table 12**). Prefixes are as described for **Figure 45**.

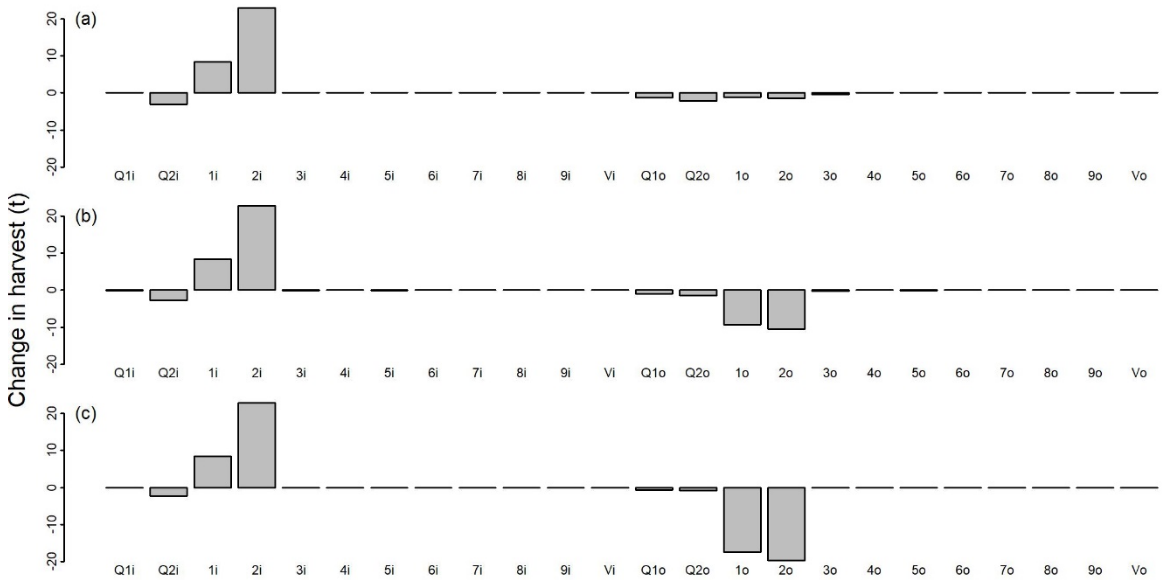


Figure 49 Zone-specific changes in total harvest, following opening of closures in NSW Ocean Zones 1 and 2 (1i, 2i), estimated under the alternative assumption of a reversion to former high fishing effort, for each effort scenario (a) all new effort, (b) part new effort, and (c) no new effort. Prefixes are as described for **Figure 45**.

Discussion

Biological evaluation of Juvenile Eastern King Prawn closures

Abundance of Eastern King Prawn

The comprehensive field-based evaluation of JEKP closures reported here provides significant insight into these historic industry-led changes to achieve spatiotemporal avoidance of less-desirable size classes of prawns. While there is a significant body of research already completed on EKP, previous survey work has largely ignored the important inshore areas that support EKP following emigration from the estuarine nursery, prior to migration to the main offshore trawling grounds. Earlier research by Racek (1959) identifies peaks in inshore EKP biomass during February and March, with a sharp fall in April. These findings concur with the temporal trends in our study, but there was some spatial variation in biomass observed across the inshore zones, and heterogeneity among locations. Within both Ballina and Yamba inshore areas, during some periods EKP biomass appeared to increase rapidly with distance from the adjacent estuary (to ~6-6.5 km), and then plateau out. But modelling indicated that depth had the biggest influence on biomass, at least within the depth ranges surveyed (although it is likely that biomass may decline in deeper waters further out to sea). Kriging showed some evidence for greater biomass toward the areas south of the estuary mouth during January and February, whereas greater biomass was found closer to the estuary mouth in March and April. Similar patterns to these were also found in an earlier survey conducted in the Ballina area (Taylor and Johnson 2020). Racek (1959) suggests there is some preference of EKP for sandy substratum within these inshore areas, as opposed to muddier substrates that may occur from deposition of fluvial sediments directly adjacent to estuaries. The spatial patterns in biomass may reflect this; and similar patterns were observed for Western King Prawn (Potter *et al.* 1991), which also prefer sandy substratum and tend to move away from the estuary following emigration from the estuarine nursery.

For both Ballina and Yamba, closure zones supported higher average densities of EKP than adjacent non-closure zones. However, Yamba generally supported higher densities than Ballina, which is likely to be due to the much larger size of the adjacent nursery (the Clarence River estuary). The Clarence River estuary is one of the largest estuarine systems within New South Wales, and the lower reaches of the estuary represents an important nursery for EKP (Taylor *et al.* 2018). The magnitude of available habitat within the estuary likely correlates with a larger number of recruits supported by the nursery (Camp *et al.* 2020), which in turn directly relates to the number of recruits that are available to emigrate to the adjacent inshore area. Although still significant, there was a smaller difference in total biomass between zones for Ballina. Part of the non-closure zone within the Ballina survey area was subject to a temporary closure until the end of February each year; this additional level of protection outside of the permanent closure may have influenced this, particularly in the southern temporary closure zone where prawns were somewhat abundant during February. The comparatively low biomass of EKP found in the Newcastle survey area was surprising, given that adjacent nurseries in the Hunter River (Taylor *et al.* 2017a) and Lake Macquarie (Taylor *et al.* 2017b) are known to periodically support high densities of juveniles. This section of coast is fed by recruits from south of the main spawning grounds (i.e. Coffs Harbour, Everett *et al.* 2017); lower reproductive potential of these areas may contribute to an unsaturated nursery, which in turn provides comparatively fewer recruits to colonise inshore habitats following emigration from the nursery.

For the majority of the sampling period, the size distribution of prawns moving through the inshore area was dominated by a single cohort at a time (particularly in the Ballina survey area), but there was some evidence for multiple cohorts being present. This reflects the previous hypothesis that EKP are only resident inshore for a comparatively short period of time (Racek 1959), with a cyclic emigration to offshore areas and replenishment from estuarine nurseries roughly occurring within each monthly cycle. The influence of temperature on size (and growth) was also evident, with monthly cohorts appearing to increase in carapace length from January to March, as growing conditions (i.e. temperature) within the adjacent estuarine nursery likely improved. Similar patterns were observed in the somatic condition of prawns, although the factors contributing to the comparatively higher condition of prawns in Ballina is uncertain, given that temperature and habitats were similar between these two survey areas.

Spatiotemporal avoidance of non-optimal size-classes

Comparison of trends in prawn biomass, and size relative to L_{YPR}, support some recommendations on the spatial management arrangements for EKP, although these should be considered in the context of the broader impact of the JEKP closure network on the EKP fishery, as outlined below. Structurally, the three spatial management units evaluated in this study are similar in design, as they encompass inshore areas of similar depths, directly adjacent to important estuarine nurseries for EKP. However, spatial and temporal nuances suggest there may be some room for more adaptive management of closure zones should this be desired by fisheries managers or sought by industry. It is important to point out that the L_{YPR} estimate used in this study was calculated from recent yield per recruit analyses for EKP (Courtney *et al.* 2014), which reported an optimal age at first capture of ~0.55 years (average of male and female). This estimate was converted to a corresponding carapace length for Ballina/Yamba region using the temperature and latitude-based growth function of Lloyd-Jones *et al.* (2012). This new estimate (31.5 mm CL) was only marginally different from the mid-range growth and mortality scenario reported in Montgomery (2000, 33 mm CL), and provided an updated benchmark against which to evaluate the closure zones. Comparison against this benchmark, when expressed spatially through interpolations across the survey areas, showed the current spatial extent of the Ballina and Yamba closure zones was largely appropriate for protecting prawns below this threshold (evident in **Figure 13** and **Figure 14**), but there may be some scope for improvements if alterations to closure boundaries were desired by industry. Higher proportions of pre-L_{YPR} prawns were present within the southern non-closure zone in the Ballina survey area during the early months of each year's survey. This area is periodically subjected to a temporary closure to prawn trawling until the end of February (for a similar reason that prawn trawling is prevented within JEKP closures). The patterns resolved here suggest this may be a useful strategy, although this should be considered in the context of simulation modelling (discussed further below).

Connectivity between Juvenile Eastern King Prawn closures and the broader fishery

The broad-scale temporal and spatial (across jurisdictions) patterns in EKP movement that are revealed in this unique data set are relevant to long-term spatial management arrangements for the species. The results showed a high degree of temporal and spatial variability in prawn recapture patterns, that is likely driven by both variability in prawn movement, and patterns in fishing effort. This variability impacts the jurisdictional context of any putative benefits derived from closures.

Eastern King Prawn migrations have been the subject of various studies since the early 1970s, across NSW, Queensland and Victoria. Lucas (1974) and Potter (1975) presented the first published studies describing large-scale movements of EKP within Queensland, and showed inshore to offshore movements as well northward migration by the species. Ruello (1975) first resolved large northward migrations of EKP from estuaries in southern NSW, to spawning grounds in northern NSW and Queensland. This was followed by the work of Glaister *et al.* (1987) which tagged prawns in the inshore waters of northern NSW, and later applied this in early yield-per-recruit analyses for EKP (Glaister *et al.* 1990). Montgomery (1990) tagged EKP in estuaries from northern NSW to Gippsland Lakes (Victoria), and showed migrations exceeding 1000 km. Gordon *et al.* (1995) presented modelling work that utilised the historical tagging data included in the present study, to estimate the potential impacts of removing prawn trawling from estuarine nurseries for EKP. Most recently, Braccini *et al.* (2012) conducted a meta-analysis including some of the historic data outlined above to estimate movement transition matrices for the species, in support of stock assessment. Despite this large body of work, none of these studies have explicitly dealt with evaluation of connectivity between the spatial management network in NSW, and the broader exploited stock.

Not surprisingly, broad trends in our data largely mirror the northward movement patterns that have been well established by these historical studies. However, an important finding of Braccini *et al.* (2012) was that there may be negligible longitudinal movement of prawns within NSW waters, restricted by the narrow continental shelf in NSW waters. In contrast, our data suggest that once prawns leave the trawl closure zone, they are most likely to be captured in the same ocean zone but in the deeper waters directly east of the inshore area. This point indicates that the probability of easterly movement could have been under-estimated in Braccini *et al.* (2012), however it is equally possible that this could be due to differences in the spatial resolution employed between the two studies.

The variation in recapture location between tagging events suggests that there may be a seasonal influence on recapture probabilities. Generally, cohorts tagged earlier in the growth season tended to have lower recapture rates, and this was consistent across tagging locations. Prawns also had generally longer times-at-liberty, were present in NSW waters for longer, were larger upon recapture, and had a higher proportion of recaptures within NSW waters. Conversely, prawns tagged later in the growth season appeared in Queensland waters sooner after tagging. These patterns were also consistent between the current study, and the historical South West Rocks tagging program. It is likely that an interactive combination of factors influence these patterns, including seasonal growth patterns (Lloyd-Jones *et al.* 2012; Taylor 2017), the influence of animal size on its tendency to undertake long migrations, seasonal patterns in fishing effort, and natural mortality (discussed below). In addition, seasonality in the coastal oceanography of eastern Australia may also influence the seasonality in migration patterns observed in our study.

The East Australian Current (EAC) drives much of the oceanography off the eastern Australian coastline (Tilburg *et al.* 2001), but the northward migration of EKP occurs in the opposite direction to this southward-moving current. The EAC is highly seasonal and interannually variable in the strength and southward penetration of its core flow (Ridgway 2007), with the southward flow being greatest during the Austral summer (Ridgway and Godfrey 1997). Some of the strongest seasonal variability in the EAC occurs off the northern NSW coast, in the area between South West Rocks and Ballina (Ridgway and Godfrey 1997), and modelling suggests southward water movement in this area declines substantially in late autumn (Ridgway and Godfrey 1997). In addition, the region between SWR and Ballina encompasses the northern section of a strong field of cyclonic eddies (Everett *et al.* 2012), which can create northward moving currents near the inshore area (Cresswell 1985). The observed lag in northward movement of EKP tagged early in the growth season may be a strategy aimed at exploiting these features (lower southward water movement and greater probability of northward currents), to reduce the energetic cost of migration. Northward moving counter-currents are thought to be a consistent feature of eddies in the EAC, especially when eddies occur near to the shelf break (Tranter *et al.* 1986). Although speculative, Montgomery (1990) also mentions anecdotal reports from trawl fishers who have observed migrating prawns on the ocean surface exploiting northward moving surface currents. Coastal cyclonic eddies also have higher chlorophyll content than other features in the EAC (Everett *et al.* 2012), which may fuel the trophic productivity required for large migrations by a small organism.

The potential lag in the time between tagging and recapture in “early” cohorts may indicate a seasonal influence on migration, whereby prawns that arrive in the closure earlier in the season tend to reside within inshore waters for longer. This could explain the presence of multiple cohorts observed within some closure zones in January and February during the trawl survey. This has implications for natural mortality, as mortality in penaeids is a function of size (Ye *et al.* 2005), and longer inshore residency leads to integration of mortality over a longer period before migration commences. This additional mortality could contribute to the generally lower recapture rates observed for early cohorts tagged in Yamba and South West Rocks. A greater number of days-at-liberty further suggests that prawns tagged earlier in the growth season at these locations may be resident within the inshore trawl closure for longer. The lower survival arising from these factors could have reduced the pool of tagged individuals available for recapture once migration commenced and progressed. These “early” cohorts also displayed greater movement distances, which may seem counterintuitive. However, this lag period would also provide a greater opportunity for growth before migration, which is evident in the larger average recapture size in “early” cohorts. Thus, when oceanographic conditions became conducive to migration, the pool of surviving tagged prawns were likely to be larger in size for these cohorts, which may have meant they were more inclined (or more able) to migrate further.

Connectivity between jurisdictions and implications for spatial management

Between 13 and 78% of prawns from each cohort were recaptured in Queensland waters, with the highest proportion of recaptures in Queensland zones occurring from the sole cohort tagged in 2016. Taylor and Johnson (2020), when evaluating the temporary trawl closure adjacent to Ballina during this time period, noted the potential contribution of a seasonal effect to the observed recapture patterns. The additional tagging work presented here confirms this effect (as discussed above), but the additional data also shows that proportional recaptures were generally greater in NSW than Queensland waters, including other cohorts tagged at Ballina.

The proportion of total recaptures within NSW ocean zones also tended to be greater for the more southern trawl closure. As our analysis indicates, this is likely a function of greater exposure to fishing mortality within NSW ocean zones. Relative fishing mortality on northward migrating prawns is higher for prawns emigrating from trawl closures at more southern latitudes, as the proportional area within the NSW jurisdiction through which prawns migrate (before leaving the jurisdiction) is greater. However, due to the longer time periods required to transition this area, prawns migrating from further south may also be subject to comparatively higher cumulative natural mortality (Gordon *et al.* 1995). Considering the spatial patterns in fishing effort among NSW ocean zones, and cumulative natural mortality with increasing latitude, it is probable that inshore closures in NSW Ocean Zone 2 and 3 will provide most benefit to the NSW fishery. This aligns with the modelling in Camp *et al.* (2020), which suggests that targeted repair of estuarine nursery habitats within these zones will also achieve the best outcomes for the NSW EKP fishery. While inshore trawl closures in NSW Ocean Zone 1 will certainly still provide benefits for the NSW fishery, there is greater leakage of “protected prawns” to the Queensland fishery. This area of south-east Queensland encompasses the major spawning area for EKP that recruit to northern NSW estuarine nurseries (Everett *et al.* 2017), and thus may have important benefits for recruitment back into northern NSW (and subsequently, catch).

Comparison of length-frequency distributions against L_{YPR} suggested that trawl closures in the areas examined were effective at ensuring prawns had exceeded YPR thresholds by the time they appeared in the fishery. For cohorts tagged early in the growth season, most prawns recaptured within NSW also exceeded L_{YPR}, but proportions exceeding this threshold were slightly lower for cohorts tagged late in the growth season (although still a majority of prawns exceed the threshold). Overall, the recapture patterns show good connectivity between all inshore trawl closure zones and the NSW fishery, and that this connection remains despite large decreases in fishing effort relative to previous tagging studies. There is also some “leakage” of prawns originating from inshore trawl closure zones in NSW, into the Queensland fishery, particularly the Queensland Inshore South and Offshore South areas, and particularly for the Ballina 2016 cohort. Accounting for the needs of fishers in the NSW jurisdiction (who ultimately forgo capture of prawns in these inshore trawl closure zones), the distribution of recaptures might be considered to be an optimal scenario for two reasons: 1) the prawns protected in the closure zones *primarily* contribute to the fishery within NSW waters; and 2) a portion of the protected prawns survive to reach the southern Queensland spawning grounds, which is the primary source of recruits for estuarine nurseries in NSW Ocean Zones 1, 2 and 3 (Everett *et al.* 2017). These patterns, however, need to be considered in the context of the simulation model, which is discussed below.

Impact of Juvenile Eastern King Prawn closures on the Eastern King Prawn fishery

The detailed simulation model presented here evaluated the expected impact of the JEKP closure network, by simulating the putative outcomes for harvest of the exploited stock if fishing was allowed within these closures. Given the parameter estimates provided to the model, and the observation and process error occurring within the system, our simulations suggest that it is unlikely that the JEKP closures are making a detectable difference to the overall harvest of EKP across either NSW or Queensland, under current effort regimes. There are numerous factors, however, which would affect this outcome, such as whether additional effort was to emerge in the fishery, and the movement metrics that have been estimated for EKP from previous tagging work. Further, the data from the trawl and tagging survey indicates that JEKP closures may alter and improve the size distribution of the harvest, so while harvest magnitude shows only small variations, some harvest is shifted into larger and more valuable size classes as a result of the closures (although this depends on the propensity of the current fleet to fish for EKP within inshore waters). These points are discussed in more detail below, and the findings are placed within the context of adaptive management within the NSW Ocean Trawl Fishery later in the Discussion.

Impact of closures and the influence of effort on simulation outcomes

The base model scenario suggested only marginal changes in the harvest of EKP, and these largely reflected a shift in harvest from offshore to inshore areas. This is likely due to the fact that the stock is comparatively lightly exploited under current effort levels, with spawning biomass >60% of virgin biomass and well above the spawning biomass at maximum sustainable yield of 42% (Helidoniotis *et al.* 2020), and current harvest levels in the fishery are well below those where recruitment overfishing would occur. Our findings are similar to those reported for EKP in Queensland by Die *et al.* (1999), which showed that juvenile EKP closures had a minimal impact on overall yield; however this study also suggested that ex-vessel values were enhanced by the closures (this is discussed in more detail below).

Simulations did however indicate that the redistribution of some existing fishing effort from offshore to inshore zones (with no new effort added) would lead to a drop in offshore EKP harvest, that was not completely offset by increases in inshore EKP harvest. For scenarios where new effort was introduced, there were concomitant increases in harvest, with greater increases in inshore harvest but lesser decreases in offshore harvest compared to other scenarios. While the magnitude of the predicted effects are unlikely to meaningfully impact the fishers or the markets into which they sell product, it is also interesting to note that there was virtually no effect evident on any locations within NSW and Queensland beyond the zones where the closures occur. This suggests that the impacts of closures are fairly localised, and concurs with recapture patterns of prawns tagged within NSW zone 1 and 2 closures, outlined above.

These different scenarios were selected to account for the range of different decisions that fishers may make in the absence of the closures (which, conversely, also accounts for the potential influence of trawl closures on their decision making). Since 2019, prawn trawl effort is managed using unitised effort quota within the NSW Ocean Trawl Fishery, with nights linked to units according to each vessels size. At present, effort levels for EKP (~5-6,000 nights per year) are substantially lower than available quota, which approximates to ~14,000 nights per year—i.e. the fishery appears as if it may be more limited by bioeconomic equilibrium, than regulation *per se*. Thus, there is currently considerable scope for increases in trawl effort within NSW, but given the current number of active vessels in the fleet, and current market characteristics, it would be surprising if effort approached the available quota. Nonetheless, we presented a scenario to highlight the potential influence of the closures under conditions similar to the peak effort levels that have been observed in the fishery, which were more reflective of the fishery when the closures were implemented. The comparative patterns of change in the distribution of harvest across the three scenarios were similar, although the magnitude of change was much greater with increases and decreases among zones as high as ~20 tonnes. It is important to point out that the fleet has also experienced an increase in average vessel size over time, which means that accessing inshore grounds may be less desirable to the contemporary fleet, than it was to the “historic” fleet.

Sensitivity analysis

As identified above, the estimates show some sensitivity to fishing effort, and large increases in the total fishing effort would alter the results somewhat, particularly at levels where harvest at inshore zones began to detract from offshore zone harvest. The other variable that influenced harvest was prawn movement rates, which indicated that movement patterns had the largest influence on the variables being considered. However, realistic variation on movement assumptions yielded only small changes in absolute outcomes, and they were relatively consistent in overall pattern, and the general patterns with respect to the effects of redistribution and inter-state harvest (Queensland versus NSW) were largely consistent.

One important caveat on the results presented above, is that our analysis was not intended to be used as a stock assessment. Thus, we did not re-estimate productivity parameters of the stock under any of alternative effort scenarios. This means that the results here assume, following the current assessment, that the current EKP fishery is lightly exploited under the current effort regime (Helidoniotis *et al.* 2020). If the EKP stock was being harvested at or above its biological limit, which may occur under the alternative effort scenario, opening the closed areas, especially under assumptions of all new effort, would almost certainly produce less positive effects on yield.

The specific habitat of the closed areas would also affect the implications of their opening. Here we implicitly assume the closed areas represent a similar quality of habitat to EKP and fishers alike as the open areas. Thus, this assumption meant that our simulations did not explicitly capture any potential aggregation of EKP within the closed areas, nor any particular avoidance of the closed areas by fishers (as might occur were the closures placed in areas fishers already avoid). Many marine closures are enacted to protect habitat or fish aggregations associated with spawning behaviors (Armstrong *et al.* 2013; Grüss *et al.* 2014). Opening such closures could conceivably result in much more fishing effort than would be indicated by their proportional size. Conversely, there can be occasions where policy specifies a certain area or proportion of area be closed, but to avoid economic hardships on fishers these closures are spatially located in areas unsuitable or unattractive for fishing (Walters *et al.* 2007). In such cases there would be little expected change in effort (redistribution or new). One of the primary limitations of this study is that it does not directly account for the mechanisms driving fisher behaviour (with respect to site choice and trips taken), and these dynamics are important for predicting the effects of spatial closures (Abbott and Haynie 2012). Future work could explore these behaviours with stated preference choice experiments.

Other species within closure zones

Non-target species

While there was some evidence for difference in biomass and richness between zones, these relationships were largely inconsistent. In Newcastle, the large total biomass within the trawl closure zone was driven by Ocean Jacket, a schooling monocanthid species, common to the temperate habitats of NSW and supports substantial commercial and recreational fisheries (Miller and Stewart 2013). In inshore trawl fisheries, individuals encountered are typically small and below marketable size (Graham 2008), and previous studies investigating bycatch of prawn trawling in northern NSW (Macbeth *et al.* 2012) have reported relatively low levels of interaction with Ocean Jacket. However, in depths less than ~55 m, discarded catches of commercially important species from fish trawling in south-eastern Australia comprised mainly Ocean Jacket (Graham 2008). Other monocanthids have shown high rates of mortality following capture, such as up to 88% immediate mortality of the Fanbelly Leatherjacket *Monacanthus chinensis* following capture in penaeid seine gear (Uhlmann and Broadhurst 2007). If such high rates of mortality are translatable to discarded monocanthids from penaeid trawl fisheries, this could explain the high numbers of this species observed in the Newcastle trawl closure zone.

In terms of species richness, Yamba was the only location where significantly higher richness was present within the trawl closure zone (with ~20% more species). Yamba is the largest port in NSW for prawn trawlers, and the adjacent coastal and ocean waters represent the largest concentration of trawl fishing effort in the NSW OTF (Pitcher *et al.* 2019). It is possible that this concentration of fishing effort (and associated concentration of discarding) could have contributed to an observable differential level of diversity at this location. It is important to point out that catches in our study had to be subsampled for sorting, so there may be a component of the species assemblage (rarer species, for example) that is not properly accounted for in our data (Silburn *et al.* 2020).

In addition to Ocean Jackets, other species of fish were clearly more abundant within JEKP closures, including *Lepidotrigla* spp. (gurnards) and *Platycephalus longispinis* (Longspine Flathead). Despite similar differences in abundance across areas, these species display divergent age and growth characteristics, with maximum observed age of 16 and 7 years for *P. longispinis* (Barnes *et al.* 2011) and *Lepidotrigla argus* (Longfined Gurnard, van der Meulen *et al.* 2013), respectively. Similarly to Ocean Jacket, these species likely experience high discard mortality (see Tsagarakis *et al.* 2010 for *Lepidotrigla* spp.). In contrast, other taxa such as Family Cynoglossidae showed much greater abundances in non-closure zones. Previous work has suggested that flatfish may benefit from trawling on sandy seabeds (Collie *et al.* 2017), due to scavenging on suspended benthic invertebrates (Kaiser and Spencer 1994). Similar behaviour could explain the patterns observed for this species.

For decapods, there was no real difference in the non-target assemblage between zones for Ballina, but Yamba and Newcastle did show significant differences. However, similarly for fish, contrasting patterns were observed in the main species driving these differences. The sand crab species *Portunus sanguinolentus* and *Ovalipes australiensis* were generally present in greater abundances in fished areas (although the latter species was only detected at extremely low densities). Again, scavenging of discarded fish or suspended sedimentary invertebrates could provide a level of trophic subsidy for species such as sand crabs in fished areas, which could contribute to greater abundance of these species. There is evidence for this occurring for other sand crab species elsewhere (McShane *et al.* 1999), but this is purely speculative and requires more research. Unidentified brachyuran crabs and stomatopods were more abundant within JEKP closures, but again, densities of these species were extremely low (i.e. 1 – 10 g per kilometre trawled). While a lack of available literature for these species makes interpretation of these patterns difficult, ecosystem level effects remain a possibility. Finally, non-target penaeid species were primarily detected only in low abundances, and there were no significant differences in the assemblage between areas, which suggests that JEKP closures have little influence on this group of species.

While neither gurnards nor Longspine Flathead are commonly commercially exploited in NSW waters, the data presented here provides a good example of the potential role that trawl closures can play for discarded species that are likely to experience mortality following capture. For both these species, there was some evidence for length-class truncation of post-recruited length classes (recruitment to trawl gear occurs at a size of around 100 mm for Cocky Gurnard, and around 150 mm for Longspine Flathead). Post-recruited length classes were almost non-existent for these species in non-closure zones, which suggests that despite being a non-retained species, trawling effort may well be having an impact on the populations of these species. It follows that JEKP closures may have a positive impact on populations of these species. Populations within the closure zones displayed what might be considered to be a more natural size-structure, and importantly fish >17.5 cm – the estimated length at maturity for Longspine Flathead (www.fishbase.org, accessed 28/08/2019) – were well represented within these zones. The fact that different length structures were present in adjacent closure and non-closure zones suggests that the impact of trawl closures was probably localised, but representation of size classes greater than the length of maturity suggests that trawl closure zones may also provide a source of progeny to the broader population that is affected by trawling. It is important to point out that comparisons of size ranges in our study were largely restricted to waters generally <20 fathom deep. Larger individuals of both species may occur at depths greater than sampled in the current study – for example, Macbeth *et al.* (2008) reported a greater number of Longspine Flathead >17.5 cm in northern NSW than observed within the current study. Inshore trawl closures may provide partial refuge to a smaller number of larger individuals in the inshore area, but may offer little protection if larger individuals typically migrate offshore.

Trawl Whiting

Juvenile Eastern King Prawn closures in northern NSW are clearly providing some protection from fishing mortality for Eastern School Whiting and Stout Whiting, although the degree of protection varies spatially and also appears to be influenced by the varying depth distributions of the two species. Differences in size-structure between closure and non-closure zones, particularly for the two northern JEKP closures, may be the result of protection from fishing mortality, but this cannot be confirmed from this study.

Stout Whiting were encountered at greater abundances in more northern survey areas, which is consistent with previous knowledge on species distribution. While there was little difference in Stout Whiting biomass between zones within the Ballina survey area, size-structure did differ between zones and was skewed toward both larger sizes, and a greater proportional representation of mature size classes within the closure zone. Stout Whiting biomass appeared higher in the closure zone than the non-closure zone within the Yamba survey area, but this difference was not significant, but similar differences in size-structure to the Ballina survey area were observed. The size-structure of Stout Whiting in our study was noticeably larger than previous surveys conducted off NSW (Gray *et al.* 2014b). Some of the differences between zones detected in our study may be attributable to minor differences in the depth strata that was sampled between zones, with on average more deeper tows in the closure zones. While the depth-stratified sampling reported in Gray *et al.* (2014b) did not show any major influence of depth on Stout Whiting size-structure, this study only included a single strata within the inshore area where most Stout Whiting are known to occur. In the current study, the finer scale spatial sampling that was concentrated in these inshore waters potentially had greater power to detect depth stratification in Stout Whiting size.

Eastern School Whiting were comparatively rare in the two northern survey areas, and present at only low abundances within the Newcastle survey area. This pattern could be attributable to a few factors. The Ballina and Yamba survey areas are toward the northern part of the species range, and while Eastern School Whiting can be seasonally abundant, biomass has been shown to be consistently lower here than in Newcastle (Gray *et al.* 2014b). In addition, the Ballina and Yamba survey areas did not encompass waters that were as deep as the Newcastle survey area (the Newcastle JEKP closure extends out to 60 m, deeper than the Ballina [~40 m] and Yamba [~50 m] survey areas; **Figure 2**). Unlike Stout Whiting, Eastern School Whiting show strong depth stratification in both abundance and size-structure, with fewer fish, and smaller fish present at depths <30 m (Gray *et al.* 2014b). While it may be tempting to attribute the greater biomass within the Newcastle JEKP closure to a lower level of fishing effort (i.e. fish trawling only, but no prawn trawling), the spatial patterns in biomass clearly point to a depth gradient, with the greatest biomass of fish evident in the deeper south-western corner of the closure (these depths were not represented in the non-closure reference zone). In terms of size-structure, while some length distributions were significantly different between zones, there were no real differences observed in the representation of mature size classes.

While our data suggests that there are few differences in mean biomass of trawl whiting between closure and non-closure zones, it does show that a larger proportion of Stout Whiting within JEKP closures are mature. It is possible that this is a result of fishing pressure, where the lower representation of mature individuals in non-closure reference zones arises due to the fishing mortality on these size classes within those areas. Alternatively, this may simply be an artefact of some closure zones covering deeper inshore waters where larger, mature Stout Whiting are more common. The lack of any difference in representation of mature size classes for Eastern School Whiting in the Newcastle survey area may also arise from fishing mortality, as fish trawling is allowed within the JEKP closure, and it thus provides a diminished refuge from fishing mortality.

Notwithstanding the potential factors that could lead to this difference, the greater representation of mature size classes of Stout Whiting within the northern closure zones may provide a spawning subsidy from these areas to the surrounding population. Given the considerable biomass of Stout Whiting that persist, unfished, within these closure zones, this could represent a substantial contribution to recruitment in areas adjacent to JEKP closures. The magnitude and spatial scale of these putative benefits ultimately depends on the metapopulation characteristics of the population, such as dispersal (e.g. Little *et al.* 2007), and unfortunately for Stout Whiting, these attributes are largely unknown. Although few differences between zones were detected for Eastern School Whiting in our study, our data do suggest that such spatial management arrangements still support mature individuals, despite the depth range of JEKP closures being typically constrained to <50 m. Eastern School Whiting juveniles are known to use very shallow inshore habitats, and it has previously been suggested that spatial management may reduce fishing-associated impacts on juveniles (Gray *et al.* 2014a). Certainly, restricting fishing in habitats where small juvenile fish occur will decrease unnecessary discard mortality. While the Newcastle JEKP closure is still subject to fish trawling, JEKP closures north of ~31°S are not, and thus may afford such protection for juveniles and adults alike, when they are abundant in the north of the species range. Given the southward dispersal of larvae along the EAC (Roughan *et al.* 2011), it is possible that progeny from these northern closures may also benefit more southern areas.

Influence of broader spatial management arrangements

While our data deals explicitly with three specific inshore JEKP closures, the overall JEKP closure network protects over 100,000 ha of inshore habitats from prawn trawling. Of this area, almost 40% is also protected from fish trawling as well, in the north of the state. In addition to this, there is almost 140,000 ha covered by inshore habitat protection zones and sanctuary zones within Marine Protected Areas (MPAs) along NSW, which have been implemented to conserve overall biodiversity. Regardless of the objective, this represents additional waters closed to all forms of trawling, of which a large proportion is sand/soft sediment habitat which are inhabited by Eastern King Prawn, Trawl Whiting, and the broader benthic community that is generally encountered by trawl nets on soft sediments in fished areas. Taken together, this represents a considerable area over which these species are “protected” from fishing mortality.

The lack of spatial variation in Stout Whiting biomass observed in northern regions suggests that our data may be representative of Stout Whiting populations within inshore habitats more broadly across these regions. Thus, for Stout Whiting at least, these extensive spatial management arrangements may well be protecting a considerable proportion of the population from fishing mortality, and contributing a spawning/recruitment subsidy to other fished areas. Applying the global average biomass-per-hectare obtained in our study (3.34 kg ha^{-1}) to the inshore waters that are closed to trawling in ocean zones 1-4 (38,178 ha of JEKP closures plus 44,065 ha of MPA habitat protection and sanctuary zones), this could equate to a biomass of ~275 tonnes of Stout Whiting that are protected from fishing mortality, the majority of which are mature and may be considered spawning biomass. If we apply an efficiency correction of 75% (expert opinion), then this estimate increases to ~367 tonnes. Applying similar estimates to the global EKP average (~1 kg ha^{-1}) suggests that 44 tonnes are periodically protected from fishing mortality (88 tonnes if our estimates are corrected for 50% capture efficiency for penaeid prawn trawls, Broadhurst 2020). Fundamentally, despite protection of specific taxa (other than EKP) not being an objective of JEKP closures or MPAs, they are likely to be supporting the sustainability of Trawl Whiting and other exploited species. In Queensland, all waters that are <20 fathoms in depth are closed to harvest of inshore Stout Whiting (Thwaites and Andersen 2008); these spatial management arrangements have undoubtedly contributed to the long-term sustainability of the Queensland Stout Whiting fishery (e.g. Zeller *et al.* 2012; Roelofs and Hall 2018).

Maintaining parts of exploited or impacted populations that are protected from fishing mortality reduces the scale of environmental impacts of fishing. Where such arrangements are spearheaded and supported by the fishing industry (such as JEKP closures), they contribute to the social license under which a fishery operates, and may also enhance the sustainability credentials of a fishery. This in turn may aid third party accreditation processes (such as Marine Stewardship Council). While detailed studies of reproductive characteristics are available for some of the species investigated here, quantifying the impact of these spatial management arrangements requires further description of connectivity patterns for eggs and larvae and adult movement patterns in and out of closure zones. Furthermore, bioeconomic modelling is needed to ascertain the influence of such recruitment subsidies on the fishery. Addressing these knowledge gaps will aid the inclusion of the patterns reported here in deliberations regarding recommended biological catches for quota species, and will support informed debate on the broader sustainability of trawl fishing.

Connectivity and source-sink dynamics within the Mulloway stock

Overall, otolith chemistry in post-recruit Mulloway suggested widespread mixing within the geographical area evaluated. Point-in-polygon analysis suggested that a reasonable proportion of post-recruit Mulloway had sub-yearling signatures that did not align well with edge signatures collected from the putative nursery estuaries. Furthermore, classification of post-recruit Mulloway among putative nursery estuaries was biased toward two estuaries, which does not concur with the degree of among-estuary connectivity observed in previous tag-recapture studies (West 1992). It is possible that these estuaries represent important nurseries for the species, however there is a substantial degree of uncertainty in the analysis which must also be considered when evaluating this, and these factors are discussed in more detail below.

Classification of nursery estuaries for post-recruit Mulloway, and contributing sources of variation

The lack of overlap observed between otolith chemistry indicative of putative nurseries and sub-yearling otolith chemistry for the exploited fish was surprising, as these putative nurseries were carefully selected based on our current understanding of the biology and ecology of Mulloway, and observations by the report authors of early-juvenile abundance across estuaries in NSW over many years. We remain confident that the most important juvenile nurseries within NSW were included in the analyses, which points to several alternate hypotheses on what might be driving these patterns. The first and most simple hypothesis is that a large proportion of the post-recruit Mulloway captured in our study grew up in nurseries outside of NSW. While possible, we believe this is unlikely considering the patterns evident in the tag-recapture data. The tag-recapture data show that inter-jurisdictional migrations were comparatively rare in this species, but we note that they have been observed between other jurisdictions in more recent studies (Barnes *et al.* 2019; Lieschke 2019). Given the northward bias in migration observed in tag-recapture data, if inter-jurisdictional migration was occurring it would create some bias towards the estuarine nurseries in Victoria (in the south).

The second, and probably more likely hypothesis, is that inter-annual environmental variability in these systems drove the differences between the edge otolith chemistry of known-origin juveniles, and the sub-yearling otolith chemistry for post-recruit Mulloway, and thus confounded our ability to confidently assign a nursery of origin. This is plausible when extrinsic effects (namely temperature and salinity) on otolith Ba, Sr and Mg (which have been reported for hatchery-reared Mulloway fingerlings, Barnes and Gillanders 2013) are considered alongside broader evidence for the influence of temporal environmental variation on otolith chemistry (e.g. Gillanders 2002; Elsdon and Gillanders 2003b; Gillanders 2005; Elsdon and Gillanders 2006). Nursery – fishery classification studies using otolith chemistry are most robust when they employ an experimental design that captures known-source juveniles initially and follows this cohort through time to collect them as they grow and recruit to the fishery. While ideal, this experimental design is not always feasible, due to both the logistical constraints imposed by sampling a somewhat elusive species over such a broad geographic scale and large number of estuaries, and due to the extended time scale required to effectively execute such a design for a long-lived species such as Mulloway. These reasons led to the design employed in this study but necessitated the assumption that there would be little influence of environmental variability among years, such that similar chemical profiles were expected in juveniles that grew up within a particular estuary, but in different years. Considering the variation in our data between the two groups (known-source juveniles and post-recruit fish), there is a reasonable chance that this assumption may have been violated. This is supported by the analyses of Russell *et al.* (2021), which showed that there was a significant effect of "year-of-collection" on the otolith chemistry of Mulloway. In particular, the NSW coast had several intense low-pressure systems during the period 2015-2017 (during which many of the fish sampled in our study would have initially recruited to estuarine nurseries), which led to extensive flooding on the central-NSW coast (in 2015 and 2016) and on the northern-NSW coast (in 2017). These events may have contributed considerable extrinsic variation into the data set and ultimately contributed to the observations outlined above.

Closer inspection of the chemical signatures of fish excluded from the MLR analysis (due to lack of overlap), points to another potential hypothesis—the potential for considerable numbers of east-coast Mulloway completing their early life history within inshore oceanic waters. The group of "excluded" fish tended to have higher Sr and lower Ba; and were more similar to juveniles sampled from inshore oceanic areas following estuarine floods that were reported in Russell *et al.* (2021). In fact, when these ocean-caught juveniles were included as another potential "ocean" source in our analysis, overlap between putative nurseries and sub-yearling otolith chemistry of exploited fish (and associated point-in-polygon evaluation) improved, such that only 5.2 % of fish were excluded (analysis not shown). Juvenile Mulloway primarily use estuaries in eastern Australia, however western Australian juvenile Mulloway primarily use estuaries (Farmer 2008). In eastern Australia, outside of periods where estuarine floods drive emigration of juvenile Mulloway from estuaries, juveniles are rarely encountered in inshore waters (the almost 700 trawls in inshore habitats undertaken during this project did not encounter any juvenile Mulloway, outside of post-flood periods). This suggests that the species is not normally present in any abundance in inshore waters of eastern Australia. It is worth noting, however, that trawling over reef structures is not always feasible. As such, trawl survey data may not encapsulate the potential that inshore reefs pose as nursery habitat for Mulloway. Further investigation may be needed to fully understand the range of habitat utilised by this species, particularly during the juvenile phase. Another alternative is that the "excluded" fish otoliths may have had higher Sr and lower Ba levels due to exposure to estuarine conditions more representative of nearshore ocean trace elemental concentrations, during the formation of otolith material at the juvenile phase.

Notwithstanding the sources of uncertainty highlighted above, there was little evidence to *directly* suggest that the classifications made using the MLR were inaccurate. In fact, there are several factors which suggest that the Hawkesbury River and Hunter River *could be* comparatively important nurseries for the species, relative to the other putative estuarine nurseries sampled. First, previous work has suggested that juvenile Mulloway are present in reasonable abundance within the Hawkesbury River at least (Gray and McDonall 1993; Broadhurst and Kennelly 1995). Second, several authors report that freshwater inflow is important for spawning and recruitment of Mulloway to estuaries (Griffiths 1996; Silberschneider and Gray 2008; Taylor *et al.* 2014; Stewart *et al.* 2020), and directly impacts year-class strength (Ferguson *et al.* 2008; Stewart *et al.* 2020). Both estuaries receive reasonable freshwater inflow, and this was particularly so during the years that immediately preceded this study, which suggests that strong recruitment might be expected during the period that many of the post-recruit Mulloway that we sampled were early juveniles. In addition, Stewart *et al.* (2020) showed strong correlation between Mulloway year-class strength and Eastern School Prawn biomass, suggesting that the relationship between rainfall and recruitment in Mulloway also reflects the positive influence of freshwater on School Prawn biomass. Both the Hunter River and Hawkesbury River support strong populations of Eastern School Prawn, but there is comparatively lower fishing effort for the species, as well as a ~6-month annual closure on prawn fishing (in the Hunter River), which means that this important Mulloway prey (Taylor *et al.* 2006a) may be particularly abundant within these nurseries. Finally, the Hawkesbury River contains abundant deep-hole structured habitats (Taylor *et al.* 2006b), which is also important for juvenile Mulloway. All these factors suggest that both the Hunter River and Hawkesbury River share a suite of attributes that are ideal for juvenile Mulloway.

The lack of contribution of the putative nursery estuaries in the north of the study area was surprising, particularly the Clarence River, which shares some of the attributes described above for the Hunter River and Hawkesbury River. There are some factors which could explain this. First, many of the coastal floodplain estuaries in northern NSW suffer from chronic and episodic water quality issues (Walsh *et al.* 2004), which may inhibit nursery function for Mulloway. Second, the northward bias in migration observed in the tag-recapture data suggests that juveniles from these rivers may well have migrated into Queensland waters; Mulloway were not collected from this jurisdiction in our study. However, this latter point further supports the classification results, which suggest that estuarine nurseries in central NSW are supplying recruits to fished populations in the north. Barnes *et al.* (2019) detected large directional movements by Mulloway of up to 550 km in South Australia. It is thus plausible that central NSW estuaries could contribute to more distant estuaries in northern NSW.

When edge otolith chemistry (indicative of recent habitats) was compared among post-recruit Mulloway, only two clusters were resolved, which suggests a general lack of separation of individual capture locations due to variability among the otolith edge signatures. This may be indicative of a highly mixed stock but may also be indicating potential age- and length-based variation in elemental chemistry, across the sampled population of post-recruit Mulloway (which included a range of ages and lengths, **Table 1**). Interestingly, based on percent allocation to clusters for each estuary, the two clusters tended to split by latitude, with estuaries south of Port Stephens more associated with cluster 1, and north of Port Stephens with cluster 2. Also, ocean zones had the highest allocation percentages (to cluster 1). These patterns in recent otolith chemistry suggest some delineation in groups may be driven by oceanographic factors; the EAC separates from the coast off Port Stephens, creating distinct oceanographic features to the north and south (Suthers *et al.* 2011), which may be having some influence on estuary chemistry. Furthermore, Port Stephens is at roughly the latitude that delineates coastal sub-tropical and temperate bioregions, and associated differences in environmental forcing may also influence the broader patterns that we observed. In contrast to the analysis for edge chemistry, there were no obvious patterns in sub-yearling chemistry among clusters, which means that the nursery origin may be well mixed among estuaries of capture, with little long-term residency. Inter-estuarine Mulloway movements have been reported in South Africa (Cowley *et al.* 2008; Childs *et al.* 2015), and broad coastal movements in Mulloway have been reported in South Australia (Barnes *et al.* 2019). This suggests that the degree of inter-location connectivity may be somewhat greater than has been previously resolved in tag-recapture studies.

Recommendations for future work

Our study highlights some important considerations for future research, both for improving knowledge of source-sink relationships in members of the family Sciaenidae and enhancing future studies that examine these dynamics in other species. Despite the long investigation time required, we strongly recommend future studies on long-lived sciaenids like Mulloway seek to match the timing of collection for the juveniles used to define estuarine nursery fingerprints, with the time that the post-recruit fish collected later are actually present in those nurseries, such that juvenile edge (for defining source nurseries) and sub-yearling (for classifying post-recruit fish) signatures better align in time and space (Gillanders 2002). This will involve following multiple cohorts from nursery to fishery, likely over extended periods. Obviously, this would not be possible for much older fish, but using an age range that includes the bulk of the exploited stock would provide some suitable goal posts for sampling (this would be ~3-5 years for Mulloway). Any future investigation using otolith chemistry would also benefit from targeted research on factors affecting chemical uptake and incorporation into Mulloway otoliths (e.g. Barnes and Gillanders 2013).

Implications of findings for the bycatch issue

The factors creating uncertainty in the source-sink patterns resolved for Mulloway (outlined above) preclude making strong conclusions on the importance of particular estuaries, or strong recommendations for the management of the species or their nursery habitats. The Hawkesbury River and Hunter River may well represent disproportionately important estuaries for Mulloway, and certainly possess the suite of attributes that would define a good estuarine nursery for the species, so any future work on Mulloway might consider examining the populations within these two systems. However, the work leaves some questions unanswered regarding natal origins and source-sink dynamics in Mulloway, including the health of coastal floodplain estuaries in northern NSW and their importance for the broader Mulloway stock, any cross-jurisdictional recruitment subsidies that might occur, and the extent to which inshore coastal habitats are used as nurseries. Consequently, it is not possible to contextualise the impact of Mulloway bycatch in inshore waters adjacent to northern NSW coastal floodplain estuaries with the current data set.

Adaptive use of Juvenile Eastern King Prawn closures to support post-flood harvest of Eastern School Prawn

Abundance and distribution of Mulloway and Eastern School Prawn within Juvenile Eastern King Prawn closures

While the number of post-flood sampling opportunities in this study were limited by drought, the data that was collected revealed some patterns for the species in question. Firstly, Mulloway and Teraglin were encountered at similar abundances, regardless of location or closure strata. This suggests that juvenile Mulloway largely 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 Mulloway nor Teraglin were encountered in any frequency during the regular trawl survey. Teraglin may well be moving into these habitats following floods to exploit the pulse of food sources that have washed out of the estuary. We suggested in the Introduction that the co-occurrence of Mulloway and Eastern School Prawn may well be due to the fact that prawns are an important prey of juvenile Mulloway. Our data revealed that the rather well-defined size-classes of Mulloway encountered within inshore habitats following floods were primarily 50-100 mm in size; at this size prawns are of minimal dietary importance for Mulloway (Taylor *et al.* 2006a).

Previous trawl surveys within the Yamba survey area using similar prawn trawl gear also encountered juvenile Mulloway following floods. The FRV Kapala, while conducting inshore trawl surveys in 1990/91, caught juvenile Mulloway at a mean abundance of 34 individuals per tow (Graham *et al.* 1993). However, the Mulloway captured in this earlier survey were much larger than in our irregular trawl survey, with most fish 100-200 mm TL.

The low number of flood events sampled, mean that the survey work completed is not sufficient to definitively evaluate the co-occurrence or otherwise of Eastern School Prawn and sciaenid bycatch across the strata surveyed. There is, however, important outcomes which may aid future decision making on accessing these grounds during the periods following floods, if bycatch issues are occurring on nominal Eastern School Prawn grounds. Firstly, the relationship between Eastern School Prawn and sciaenid bycatch was “shallower” within closure zones. This indicates that the number of sciaenids encountered per kilogram of prawns harvested was lower within closure zones. Secondly, although not statistically significant, there was some evidence for sciaenid bycatch being less abundant within closure zones compared to non-closure zones, which suggests that further exploration of JEKP closures as post-flood Eastern School Prawn grounds may be warranted.

Finally, the 2020 event was somewhat unique in that reasonable quantities of Eastern School Prawn were encountered, but juvenile Mulloway were completely absent from these catches. This suggests that floods occurring following protracted droughts (such as the 2020 floods) may be less likely to lead to large volumes of juvenile Mulloway being present on inshore prawn trawl grounds, due to the potential for recruitment limitation to arise during the preceding dry years. Such conditions should nominally affect Eastern School Prawn as well, whose life-history is similarly dependent on freshwater inflow to estuaries, however this was not evident in our data

Conclusions and recommendations

The JEKP closure network was implemented at a time when the NSW OTF fleet was much larger, expending up to 20,000 nights effort per year in the fishery (compared to the current ~5-6,000 nights), and when the stock was growth overfished. Today, the number of vessels in the fishery and overall effort levels are much lower, and tend to be concentrated in deeper waters targeting larger, more valuable prawns. As a result of this, recent catch rates are much higher, but the size-structure within the commercial harvest in also larger than it was historically (Helidoniotis *et al.* 2020). These changes in the fishery may mean that the scope and nature of benefits derived from the spatial management network for EKP are likely to have altered since their implementation, and JEKP closures do not currently appear to have a major impact on the overall productivity of the fishery for EKP (at least under recent effort regimes). The impact of JEKP closures is likely to have been further impacted by changing markets for prawns in Australia – anecdotally, EKP appear to be more commonly harvested and marketed as a higher grade product, that does not directly compete with imported aquaculture product on the Australian market. However, while not specifically intended in their implementation, the JEKP closure network provides considerable protection from fishing mortality for the broader assemblage of species which are impacted by the activities of the NSW OTF. Coupled with the fact that the closures were spearheaded by industry, this adds to the sustainability credentials for the fishery, and the social license which supports its operation.

With respect to the adaptive management scenario being considered to deal with Mulloway bycatch while targeting Eastern School Prawn, there were two main questions that were addressed in this study: 1) would temporarily allowing trawling within JEKP closures adversely impact yield of EKP in other areas; and 2) would fishing within the JEKP closures following floods in adjacent estuaries allow access to Eastern School Prawn without significant levels of Mulloway (and Teraglin) bycatch? Conclusions regarding these two questions are dealt with below.

Our evaluation suggests that under current effort scenarios, allowing trawling within JEKP closures would have a minimal impact on EKP yields in NSW and Queensland, even after accounting for different fisher decisions surrounding access to currently closed grounds (to target EKP). While there is unlikely to be significant changes in overall yield, the spatial trends in size-structure mean that there may be minor impacts on the ex-vessel value derived from expected yields if trawling within JEKP closures impacts EKP. Based on the commercial grade prices in Courtney *et al.* (2014), the size distribution of prawns within JEKP closures and the NSW ocean zone 1 and 2 commercial catch, the increase in size grade between inshore closures and the current commercial fishery (considering median sizes) probably equates to an increase in value per kilogram of around ~17%. Thus, harvest of EKP at smaller sizes within closures may impact their value, however, catching smaller prawns in inshore areas closer to port likely leads to reduced input costs as well. More detailed economic data on fishers in NSW is required to further elucidate these patterns.

The model simulations are supported by the irregular trawl survey that was undertaken during this study. While only a few post-flood events were sampled, EKP were hardly encountered at all during the daytime trawling during the irregular trawl survey, despite being abundant on these inshore grounds at the time (evidenced by catches from nocturnal trawling during the regular trawl survey). Our modelling was meant to represent the worst-case scenario; and given the lack of EKP encountered during the daytime trawling undertaken during the irregular trawl survey, it is unlikely that even the most minor of these impacts will come to pass if daytime trawling is temporarily allowed in JEKP closures.

The lack of flood events and associated sampling during this study does not really support strong conclusions regarding the comparative abundance Eastern School Prawn and Mulloway (and

Sciaenidae more broadly). The data that was collected suggested that Eastern School Prawn were present in “economic” quantities within JEKP closure zones, and there was some evidence for comparatively lower numbers of sciaenids being encountered within closure zones, but overall variability in the data and general patchiness meant that no significant differences were detected.

Considering the information above, the temporary and partial opening of JEKP closures could be considered as an ameliorative management strategy where other Eastern School Prawn grounds are closed due to Mulloway bycatch. Such a strategy would best be applied cautiously, with implementation accompanied by “trial” shots to evaluate whether Eastern School Prawn are present, and that Mulloway are encountered in comparatively low abundances (or not present), before trawling is allowed. If areas of abundant Eastern School Prawn are encountered, vessels could be permitted to temporarily operate within these closures, but some specific conditions should be considered to ensure the activity is well managed and temporary arrangements are not abused. This might include the use of Vessel Monitoring Systems to ensure 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. Finally, while the impacts 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 on adaptive spatial management.

Implications

Implications of this research are as follows:

1. This study provides data and analyses which will support the consideration of alternative management arrangements within the NSW OTF, which will subsequently support economic outcomes from the fishery (through facilitating harvest of Eastern School Prawn)
2. New information will broadly support the study of fisheries ecology and incorporation of this knowledge into fisheries management decisions within NSW, and elsewhere
3. New information will contribute to the sustainability goals for the NSW OTF, and could assist in 3rd-party certification if this is pursued in the future
4. The data collected will support future stock assessments for EKP.

Extension and Adoption

As the project was primarily designed to provide data and analyses to support decisions surrounding specific management questions, direct extension and communication has been occurring with fisheries managers within NSW DPI throughout the project. This has primarily occurred through conversations and presentation of project findings as they have become available.

Findings have been extended to other scientists (involved in work on EKP, and other species impacted by the JEKP closure network) through direct engagement, publication of scientific manuscripts (outlined in Project materials developed), and presentation at scientific conferences including the international Estuarine Coastal and Shelf Association Conference in Perth, in September 2018, and in the coming World Fisheries Congress in Adelaide in September 2021.

Printed materials distributed to Industry throughout the project included:

1. Several letters to NSW OTF endorsement holders, alerting them to the project and inviting them to submit an EoI if they were interested in participating in the survey work
2. Liaising with fishers one-on-one throughout the tender process, through the preparation of the tagging program and subsequent recaptures, and through the prawn trawl observer program that occurred at the same time as the regular survey program
3. Mail out of flyers to trawl license holders in NSW and Qld (**Figure 50** and **Figure 51**)
4. Tag recapture feedback cards provided to trawl fishers who returned tags (**Figure 52**); 350 of these were distributed through the project.

These printed materials were supplemented by informal conversations between project investigators/staff, and industry participants regarding the project, including observations following flooding in the northern rivers.

Project outcomes and recommendations are likely to be implemented and adopted following future flood events on the northern NSW coast.

Project coverage

A full-page article on the prawn tagging research was published in the *Sunday Telegraph* on October 11, 2020.

A Facebook post was issued by Queensland Department of Primary Industries on the tagging program.

Scientific Surveys of Juvenile Eastern King Prawn Closures

Several scientific trawl surveys were undertaken during February 2016, to examine the size and distribution of Eastern King Prawn across the permanent (JEKP), temporary and adjacent non-closure areas off Ballina, NSW.

What is inside the closure areas?

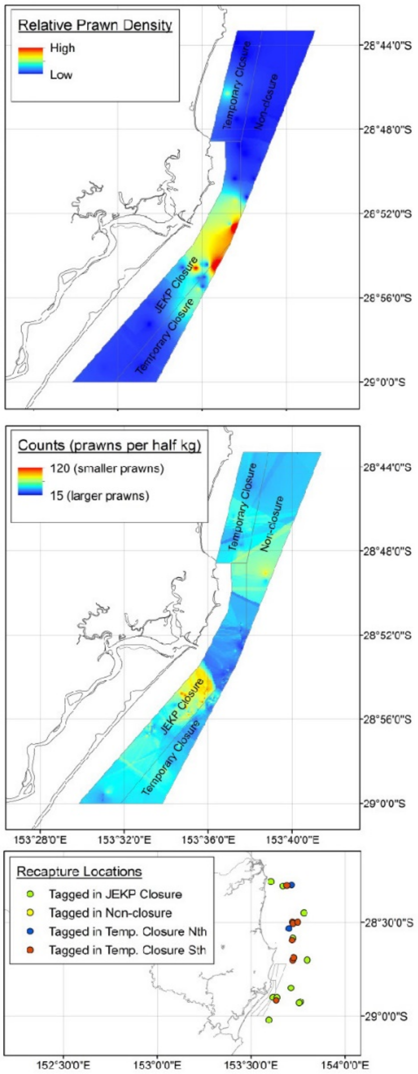
The greatest densities of Eastern King Prawn were concentrated in the permanent closure and southern temporary closure, with negligible densities in the non-closure areas.

Prawn sizes were lowest (higher counts) in the JEKP closure, the southern temporary closure, and the southern part of the northern temporary closure. Prawn sizes were greatest (lower counts) at the eastern edge of the survey area.

Where do prawns go once they leave the closure areas?

Thirteen-hundred prawns were tagged during the trawl surveys, with the majority of tagging occurring in the JEKP closure and southern temporary closure. The majority of prawn recaptures occurred at depths between 35 and 70 fathoms. Recaptures in NSW waters occurred just to the east of the closure areas, and then primarily along the 40 fathom depth contour north of the closures. Prawns moved as fast as 4 km per day, and grew at up to 7 mm per week in length. Tagged prawns were at large in NSW for an average of 52 days before recapture, and were recaptured in NSW waters between 11 days and 4 months following tagging.

More surveys will be undertaken over the next three years.



For more information contact fiona.mckinnon@dpi.nsw.gov.au

Figure 50 Research flyer #1

Juvenile Eastern King Prawn Tagging in Closure Areas

Scientific trawl surveys were undertaken off Ballina, NSW to examine Eastern King Prawn movement patterns in relation to permanent (JEKP) closure areas, temporary closure areas implemented in 2016, and adjacent non-closure areas. Over 1300 Eastern King Prawn were tagged during the trawl surveys, with the majority of tagging occurring in the JEKP closure and southern temporary closure areas. Tags were collected with the cooperation of trawl fishers in both NSW and Queensland.

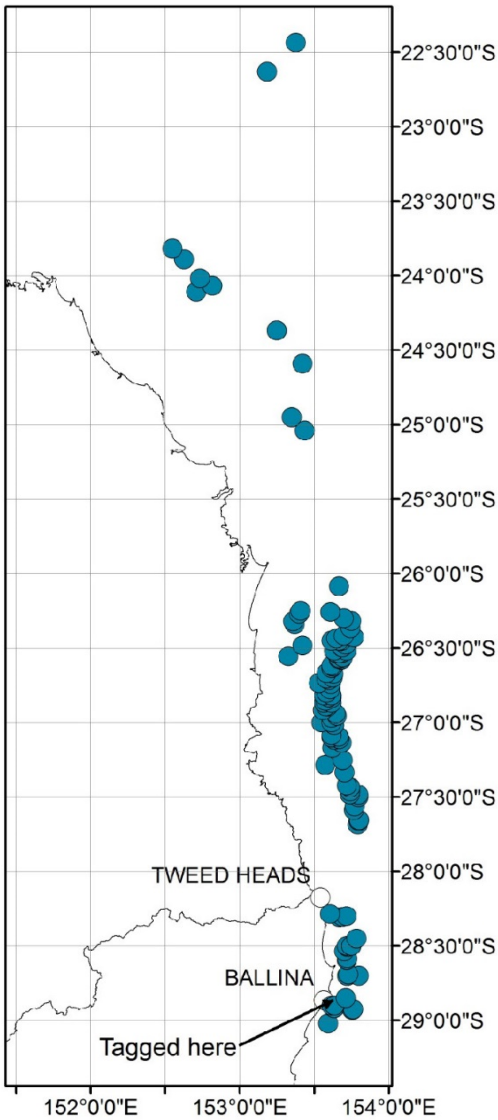
What did we find?

With the support of industry we achieved a recapture rate of 15%. The majority of prawn recaptures occurred at depths between 30 and 100 fathoms. Recaptures off NSW (34%) occurred just to the east of the closure areas, and then primarily along the 40 fathom depth contour north of the closures. Recaptures off Queensland (66%) occurred primarily between the Gold Coast and Noosa, but recaptures occurred as far north as Yeppoon. Tagged prawns were at large for 11-221 days following tagging, and the longest distance moved was ~700 km.

What is happening next?

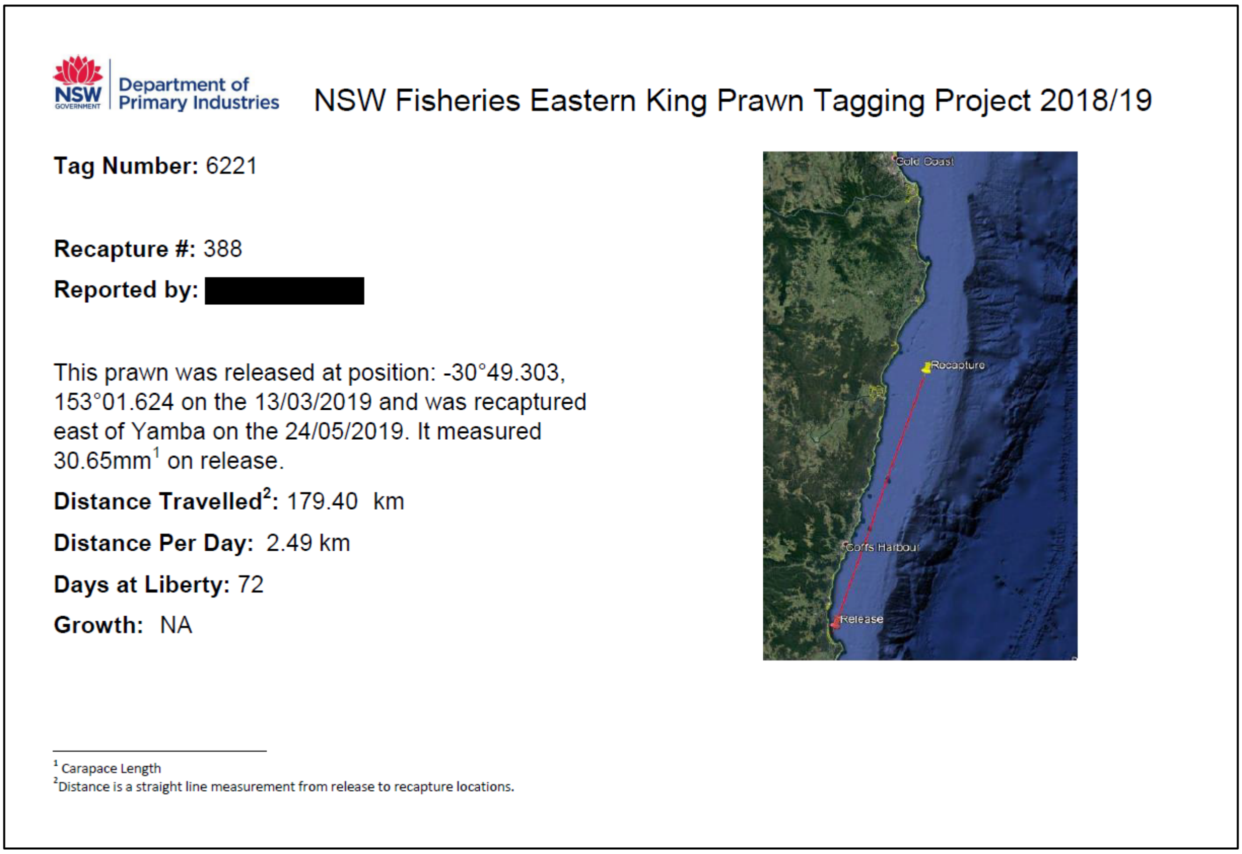
NSW DPI-Fisheries is currently undertaking a large trawl survey examining how these closure areas function for prawns and other species, supported by the Fisheries Research and Development Corporation on behalf of the Australian Government (project 2016/020).

Another tagging survey will occur in conjunction with this project in Nov. 2018 and Feb. 2019, off Ballina, Yamba, and South West Rocks.



For more information contact matt.taylor@dpi.nsw.gov.au

Figure 51 Research flyer #2



NSW Department of Primary Industries

NSW Fisheries Eastern King Prawn Tagging Project 2018/19

Tag Number: 6221

Recapture #: 388

Reported by: [redacted]

This prawn was released at position: -30°49.303, 153°01.624 on the 13/03/2019 and was recaptured east of Yamba on the 24/05/2019. It measured 30.65mm[1] on release.

Distance Travelled[2]: 179.40 km

Distance Per Day: 2.49 km

Days at Liberty: 72

Growth: NA

[1] Carapace Length
[2] Distance is a straight line measurement from release to recapture locations.

Figure 52 Recapture feedback card provided to trawl fishers who returned tags

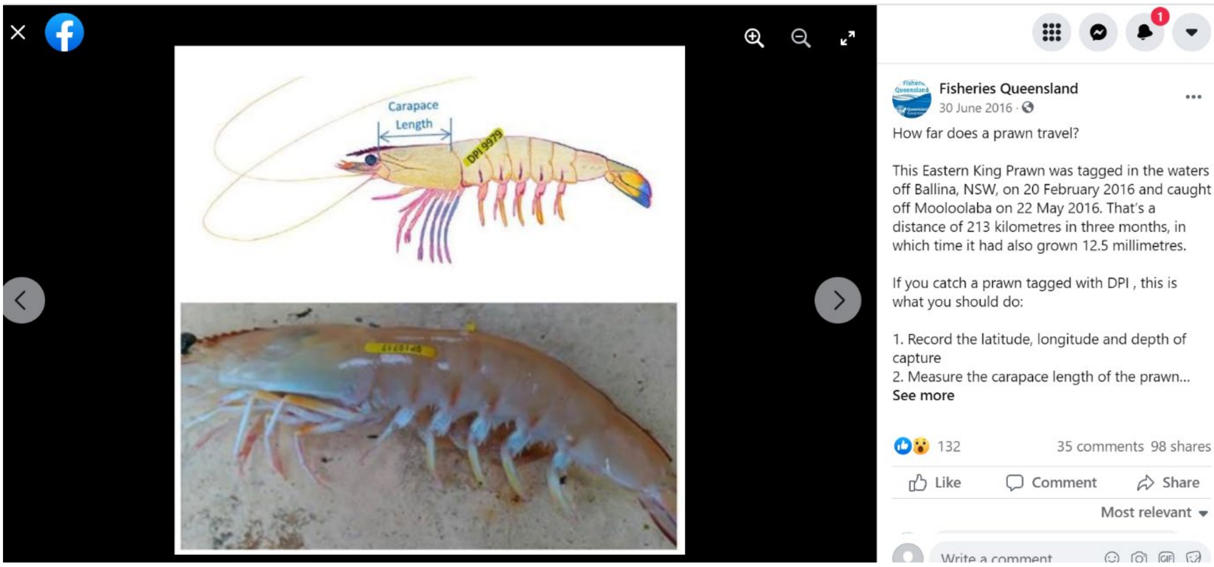


Figure 53 Facebook post by Queensland Department of Primary Industries on the tagging program, from an early tagging event

Project materials developed

Camp, E.V., D.D. Johnson, and M.D. Taylor. Biological evaluation of a spatial management network targeted at avoidance of non-optimal size classes of a high-value penaeid species. *Aquaculture and Fisheries*. Manuscript has been submitted to the journal and was awaiting a final decision follow review at the time this report was finalised.

Russell, A., B.M. Gillanders, T.C. Barnes, D.D. Johnson, and M.D. Taylor. 2021. Inter-estuarine variation in otolith chemistry in a large coastal predator: A viable tool for identifying coastal nurseries? *Estuaries and Coasts*, doi.org/10.1007/s12237-12020-00825-x.

Russell, A., Taylor, M.D., Barnes, T.C., Johnson, D.D., and B.M. Gillanders. 2021. Potential linkages between juvenile nurseries and exploited populations of Mulloway (*Argyrosomus japonicus*), explored using otolith chemistry. *Fisheries Research* **243**, 106063, https://doi.org/10.1016/j.fishres.2021.106063.

Sarakinis, K.G., M.D. Taylor, D.D. Johnson, J. McGilvray, and B.G. Gillanders. Under Review. Determining population structure and connectivity through otolith chemistry of stout whiting, *Sillago robusta*. *Fisheries Management and Ecology*. This manuscript conducted additional analysis of samples collected under the sampling program outlined in this report. The associated manuscript has been submitted to the journal and was still undergoing revision at the time this report was finalised.

Silburn, J., D.J. Johnson, D.J. Booth, and M.D. Taylor. 2020. The effect of subsampling when monitoring bycatch in a penaeid trawl fishery. *Fisheries Research*, 224, 105459, doi.org/10.1016/j.fishres.2019.105459

Silburn, J. 2017. Bycatch of trawl fisheries in SE Australia: Optimising methods and assessing spatial and closure effects. Honours Thesis, University of Technology Sydney, 79 p.

Taylor, M.D., D. Hale, and D.D. Johnson. 2021. Biological evaluation of a spatial management network targeted at avoidance of non-optimal size classes of a high-value penaeid species. *Regional Studies in Marine Science*, 101924, https://doi.org/10.1016/j.rsma.2021.101924

Taylor, M.D., K. Hall, and D.D. Johnson. Additional benefits of spatial management in a penaeid fishery for other quota species: A case study of trawl whiting. *Fisheries Management and Ecology*. Manuscript has been submitted to the journal and was still undergoing peer review at the time this report was finalised.

Taylor, M.D., and D.D. Johnson. 2021. Connectivity between a spatial management network and a multi-jurisdictional ocean trawl fishery. *Ocean and Coastal Management*, 105691, https://doi.org/10.1016/j.ocecoaman.2021.105691.

Taylor, M.D., and D.D. Johnson. 2020. Evaluation of adaptive spatial management in a multi-jurisdictional trawl fishery. *Regional Studies in Marine Science*, 35, 101206, https://doi.org/10.1016/j.rsma.2020.101206

Taylor, M.D., and D.D. Johnson Adaptive spatial management to deal with post-flood inshore bycatch in a penaeid trawl fishery. *North American Journal of Fisheries Management*. Manuscript has been submitted to the journal and was still undergoing peer review at the time this report was finalised.

Taylor, M.D., J. Silburn, D.D. Johnson, and D.J. Booth. 2020. Impact of spatial management on non-target species in an oceanic penaeid trawl fishery. *North American Journal of Fisheries Management*, https://doi.org/10.1002/nafm.10427.

References

Abbott, J.K., and Haynie, A.C. (2012) What are we protecting? Fisher behavior and the unintended consequences of spatial closures as a fishery management tool. *Ecological Applications* **22**(3), 762–777.

Abdi, H., and Williams, L.J. (2010) Principal component analysis. *Wiley interdisciplinary reviews: computational statistics* **2**(4), 433-459.

Anderson, M.J., and Robinson, J. (2003) Generalized discriminant analysis based on distances. *Australian & New Zealand Journal of Statistics* **45**(3), 301-318.

Anderson, M.J., and Willis, T.J. (2003) Canonical analysis of principal coordinates: a useful method of constrained ordination for ecology. *Ecology* **84**(2), 511-525.

Armstrong, M.P., Dean, M.J., Hoffman, W.S., Zemeckis, D.R., Nies, T.A., Pierce, D.E., Diodati, P.J., and McKiernan, D.J. (2013) The application of small scale fishery closures to protect Atlantic cod spawning aggregations in the inshore Gulf of Maine. *Fisheries Research* **141**, 62-69.

Barnes, L.M., Gray, C.A., and Williamson, J.E. (2011) Divergence of the growth characteristics and longevity of coexisting Platycephalidae (Pisces). *Marine and Freshwater Research* **62**(11), 1308-1317.

Barnes, T.C., and Gillanders, B.M. (2013) Combined effects of extrinsic and intrinsic factors on otolith chemistry: implications for environmental reconstructions. *Canadian Journal of Fisheries and Aquatic Sciences* **70**(8), 1159-1166.

Barnes, T.C., Rogers, P.J., Wolf, Y., Madonna, A., Holman, D., Ferguson, G.J., Hutchinson, W., Loisier, A., Sortino, D., Sumner, M., and Gillanders, B.M. (2019) Dispersal of an exploited demersal fish species (*Argyrosomus japonicus*, Sciaenidae) inferred from satellite telemetry. *Marine Biology* **166**(10), 125.

Braccini, M., O'Neill, M.F., Courtney, A.J., Leigh, G.M., Campbell, A.B., Montgomery, S.S., and Prosser, A. (2012) Quantifying northward movement rates of eastern king prawns along eastern Australia. *Marine Biology* **159**(10), 2127-2136.

Broadhurst, M.K., and Kennelly, S.J. (1995) A trouser-trawl experiment to assess codends that exclude juvenile mulloway (*Argyrosomus hololepidotus*) in the Hawkesbury River prawn-trawl fishery. *Marine and Freshwater Research* **46**(6), 953-958.

Broadhurst, M.K. (2020) Improving penaeid-trawl efficiencies via ground gear with tickler chains. *Aquaculture and Fisheries*.

Camp, E.V., Lorenzen, K., and Taylor, M.D. (2020) Impacts of habitat repair on a spatially complex fishery. *Estuarine, Coastal and Shelf Science* **244**, 106102.

Campana, S.E. (1999) Chemistry and composition of fish otoliths: pathways, mechanisms and applications. *Marine Ecology Progress Series* **188**, 263-297.

Childs, A.R., Cowley, P.D., Næsje, T.F., and Bennett, R.H. (2015) Habitat connectivity and intra-population structure of an estuary-dependent fishery species. *Marine Ecology Progress Series* **537**, 233-245.

Collie, J., Hiddink, J.G., van Kooten, T., Rijnsdorp, A.D., Kaiser, M.J., Jennings, S., and Hilborn, R. (2017) Indirect effects of bottom fishing on the productivity of marine fish. *Fish and Fisheries* **18**(4), 619-637.

Courtney, A.J., O'Neill, M.F., Braccini, M., Leigh, G.M., Kienzle, M., Pascoe, S., Prosser, A.J., Wang, Y.-G., Lloyd-Jones, L., Campbell, A.B., Ives, M., Montgomery, S.S., and Gorring, J. (2014) Biological and economic management strategy evaluations of the eastern king prawn fishery. Department of Agriculture, Fisheries and Forestry, Brisbane, Queensland.

Cowley, P.D., Kerwath, S.E., Childs, A.R., Thorstad, E.B., Okland, F., and Naesje, T.F. (2008) Estuarine habitat use by juvenile dusky kob Argyrosomus japonicus (Sciaenidae), with implications for management. *African Journal of Marine Science* **30**(2), 247-253. [In English]

Cresswell, G.R. (1985) East Australian Current on the northern NSW Continental Shelf. CSIRO Marine Laboratories Research Reports, 153-154.

Dall, W., Hill, B., Rothlisberg, P., and Sharples, D. (1990) Life Histories. In The Biology of the Penaeidae. Vol. 27. pp. 283-313. (Academic Press: London)

Die, D., Courtney, A.J., and Cosgrove, M.G. (1999) Effects of trawl fishing closures on yield and ex-vessel value on the Wide Bay Bar Eastern King Prawn fishery. Queensland Department of Primary Industries, Information Series QI99059.

Earl, J., Fairclough, D.V., Stauton-Smith, J., and Hughes, J.M. (2021) Mulloway (*Argyrosomus japonicus*). In Status of Key Australian Fish Stocks 2020. pp. https://www.fish.gov.au/report/368-Mulloway-2020 accessed 26 July 2021. (Fisheries Research and Development Corporation: Canberra)

Elsdon, T.S., and Gillanders, B.M. (2003a) Reconstructing migratory patterns of fish based on environmental influences on otolith chemistry. *Reviews in Fish Biology and Fisheries* **13**(3), 219-235.

Elsdon, T.S., and Gillanders, B.M. (2003b) Reconstructing migratory patterns of fish based on environmental influences on otolith chemistry. *Reviews in Fish Biology and Fisheries* **13**(3), 217-235.

Elsdon, T.S., and Gillanders, B.M. (2006) Identifying migratory contingents of fish by combining otolith Sr:Ca with temporal collections of ambient Sr:Ca concentrations. *Journal of Fish Biology* **69**(3), 643-657.

Everett, J.D., Baird, M.E., Oke, P.R., and Suthers, I.M. (2012) An Avenue of Eddies: Quantifying the biophysical properties of mesoscale eddies in the Tasman Sea. *Geophysical Research Letters* **39**, L16608 doi:10.1029/2012GL053091

Everett, J.D., van Sebille, E., Taylor, M.D., Suthers, I.M., Setio, C., Cetina-Heredia, P., and Smith, J.A. (2017) Dispersal of Eastern King Prawn larvae in a western boundary current: New insights from particle tracking. *Fisheries Oceanography* **26**(5), 513–525.

Farmer, B. (2008) Comparisons of the biological and genetic characteristics of the Mulloway *Argyrosomus japonicus* (Sciaenidae) in different regions of Western Australia. Murdoch University,

Ferguson, G.J., Ward, T.M., and Geddes, M.C. (2008) Do recent age structures and historical catches of mulloway, Argyrosomus japonicus (Sciaenidae), reflect freshwater inflows in the remnant estuary of the Murray River, South Australia? *Aquatic Living Resources* **21**(2), 145-152.

Gillanders, B.M. (2002) Temporal and spatial variability in elemental composition of otoliths: implications for determining stock identity and connectivity of populations. *Canadian Journal of Fisheries and Aquatic Sciences* **59**(4), 669-679.

Gillanders, B.M. (2005) Using elemental chemistry of fish otoliths to determine connectivity between estuarine and coastal habitats. *Estuarine, Coastal and Shelf Science* **64**(1), 47-57.

Glaister, J.P. (1978a) Impact of river discharge on distribution and production of School Prawn *Metapenaeus macleayi* (Haswell) (Crustacea-Penaeidae) in Clarence River region, northern New South Wales. *Australian Journal of Marine and Freshwater Research* **29**(3), 311-323.

Glaister, J.P. (1978b) Movement and growth of tagged school prawns, *Metapenaeus macleayi* (Haswell) (Crustacea-Penaeidae), in Clarence River region of northern New South Wales. *Australian Journal of Marine and Freshwater Research* **29**(5), 645-657.

Glaister, J.P. (1983) Dynamics of the Eastern Australian King Prawn Population. PhD Thesis, University of New South Wales, Sydney

Glaister, J.P., Lau, T., and McDonall, V.C. (1987) Growth and migration of tagged eastern Australian king prawns, *Penaeus plebejus* Hess. *Australian Journal of Marine and Freshwater Research* **38**(2), 225-241.

Glaister, J.P., Montgomery, S.S., and McDonall, V.C. (1990) Yield-per-recruit analysis of eastern king prawns *Penaeus plebejus* Hess, in eastern Australia. *Australian Journal of Marine and Freshwater Research* **41**(1), 175-197.

Gordon, G.N.G., Andrew, N.L., and Montgomery, S.S. (1995) Deterministic compartmental model for the eastern king prawn (*Penaeus plebejus*) fishery in New South Wales. *Marine and Freshwater Research* **46**(5), 793-807.

Graham, K.J., Liggins, G.W., Wildforster, J., and Kennelly, S.J. (1993) Kapala Cruise Report No. 110. Fisheries Research Institute, Cronulla.

Graham, K.J. (2008) The Sydney inshore trawl-whiting fishery: Codend selectivity and fishery characteristics. NSW Department of Industries - Fisheries Final Report Series, Cronulla.

Gray, C.A., and McDonall, V.C. (1993) Distribution and growth of juvenile mulloway, *Argyrosomus hololepidotus* (Pisces, Sciaenidae), in the Hawkesbury River, South-Eastern Australia. *Australian Journal of Marine and Freshwater Research* **44**(3), 401-409.

Gray, C.A., Barnes, L.M., Ochwada-Doyle, F.A., van der Meulen, D.E., Kendall, B.W., and Robbins, W.D. (2014a) Age, growth and demographic characteristics of *Sillago flindersi* exploited in a multi-species trawl fishery. *Fisheries Science* **80**(5), 915-924.

Gray, C.A., Barnes, L.M., van der Meulen, D.E., Kendall, B.W., Ochwada-Doyle, F.A., and Robbins, W.D. (2014b) Depth interactions and reproductive ecology of sympatric Sillaginidae: *Sillago robusta* and *S. flindersi*. *Aquatic Biology* **21**(2), 127-142.

Griffiths, M.H. (1996) Life history of the dusky kob *Argyrosomus japonicus* (Sciaenidae) off the east coast of South Africa. *South African Journal of Marine Science* **17**, 135-154.

Grüss, A., Robinson, J., Heppell, S.S., Heppell, S.A., and Semmens, B.X. (2014) Conservation and fisheries effects of spawning aggregation marine protected areas: What we know, where we should go, and what we need to get there. *ICES Journal of Marine Science* **71**(7), 1515-1534.

Helidoniotis, F., O'Neill, M.F., and Taylor, M.D. (2020) Stock assessment of eastern king prawn (*Melicertus plebejus*). Queensland Department of Agriculture and Fisheries, Brisbane.

Helsel, D.R. (2006) Fabricating data: How substituting values for nondetects can ruin results, and what can be done about it. *Chemosphere* **65**(11), 2434-2439.

Hiemstra, P.H., Pebesma, E.J., Twenhöfel, C.J.W., and Heuvelink, G.B.M. (2009) Real-time automatic interpolation of ambient gamma dose rates from the Dutch radioactivity monitoring network. *Computers & Geosciences* **35**(8), 1711-1721.

Kaiser, M., and Spencer, B. (1994) Fish scavenging behaviour in recently trawled areas. *Marine Ecology Progress Series* **112**(1), 41-49.

Kaufman, L., and Rousseeuw, P.J. (2009) 'Finding groups in data: an introduction to cluster analysis.' (John Wiley & Sons)

Kennelly, S.J., Graham, K.J., Montgomery, S.S., Andrew, N.L., and Brett, P.A. (1993) Variance and cost-benefit analyses to determine optimal duration of tows and levels of replication for sampling relative abundances of species using demersal trawling. *Fisheries Research* **16**(1), 51-67.

Lazartigues, A.V., Plourde, S., Dodson, J.J., Morissette, O., Ouellet, P., and Sirois, P. (2016) Determining natal sources of capelin in a boreal marine park using otolith microchemistry. *ICES Journal of Marine Science* **73**(10), 2644-2652.

Lieschke, J. (2019) Angling pressure impedes a three-year telemetry study on mulloway (Argyrosomus japonicas) in a western Victorian estuary, Southern Australia. *Cogent Environmental Science* **5**(1), 1602101.

Little, L.R., Punt, A.E., Mapstone, B.D., Pantus, F., Smith, A.D.M., Davies, C.R., and McDonald, A.D. (2007) ELFSim—A model for evaluating management options for spatially structured reef fish populations: An illustration of the "larval subsidy" effect. *Ecological Modelling* **205**(3), 381-396.

Lloyd-Jones, L.R., Wang, Y.-G., Courtney, A.J., Prosser, A.J., Montgomery, S.S., and Chen, Y. (2012) Latitudinal and seasonal effects on growth of the Australian eastern king prawn (*Melicertus plebejus*). *Canadian Journal of Fisheries and Aquatic Sciences* **69**(9), 1525-1538.

Lucas, C. (1974) Preliminary estimates of stocks of king prawn, *Penaeus plebejus*, in south-east Queensland. *Australian Journal of Marine and Freshwater Research* **25**(1), 35-47.

Ludden, J.N., Rui, F., Gauthier, G., Stix, J., Lang, S., Francis, D., Machado, N., and Wu, G. (1995) Applications of LAM-ICP-MS analysis to minerals. *The Canadian Mineralogist* **33**(2), 419-434.

Macbeth, W.G., Gray, C.A., and Johnson, D.D. (2008) Assessment of a 35-mm square-mesh codend and composite square-mesh panel configuration in the ocean prawn-trawl fishery of northern New South Wales. NSW Department of Industries - Fisheries Final Report Series, Cronulla.

Macbeth, W.G., Millar, R.B., Johnson, D.D., Gray, C.A., Keech, R.S., and Collins, D. (2012) Assessment of relative performance of a square-mesh codend design across multiple vessels in a demersal trawl fishery. *Fisheries Research* **134-136**, 29-41.

McShane, P.E., Hall, S.J., and Carrick, N.A. (1999) Trophic consequences of prawn trawling: Linking bycatch to benthos. In Establishing Meaningful Targets for Bycatch Reduction in Australian Fisheries. (Eds. CD Buxton and S Eayrs) pp. 106-112. (Australian Society for Fish Biology, Sydney)

Miller, M.E., and Stewart, J. (2013) Reproductive characteristics of the ocean leatherjacket, *Nelusetta ayraudi*. *Reviews in Fish Biology and Fisheries* **23**(1), 87-101.

Montgomery, S.S. (1990) Movements of juvenile eastern king prawns, *Penaeus plebejus*, and identification of stock along the east-coast of Australia. *Fisheries Research* **9**(3), 189-208.

Montgomery, S.S., and Gray, C.A. (1991) Effects of sizes of streamer tags on mortality and growth of juvenile eastern king prawns *Penaeus plebejus*. *Marine Ecology Progress Series* **76**(1), 33-40.

Montgomery, S.S., Brett, P.A., Blount, C., Stewart, J., Gordon, G.N.G., and Kennelly, S.J. (1995) Loss of tags, double-tagging and release methods for eastern king prawns, *Penaeus plebejus* (Hess): Laboratory and field experiments. *Journal of Experimental Marine Biology and Ecology* **188**(1), 115-131.

Montgomery, S.S. (2000) Status of Eastern King and School Prawn stocks. In Juvenile Prawn Summit: Summary of Proceedings. pp. 25-47. (NSW Fisheries, Cronulla)

Montgomery, S.S., Courtney, A.J., Blount, C., Stewart, J., Die, D.J., Cosgrove, M., and O'Neill, M.F. (2007) Patterns in the distribution and abundance of female eastern king prawns, *Melicertus plebejus* (Hess, 1865), capable of spawning and reproductive potential in waters off eastern Australia. *Fisheries Research* **88**(1-3), 80-87.

NSW State Emergency Service (2018) Provision of and Requirements for Flood Warning (Supplementary Document to the State Flood Plan). NSW State Emergency Service, Wollongong.

O'Neill, M.F., Leigh, G.M., Wang, Y.-G., Braccini, J.M., and Ives, M.C. (2014) Linking spatial stock dynamics and economics: evaluation of indicators and fishery management for the travelling eastern king prawn (*Melicertus plebejus*). *ICES Journal of Marine Science* **71**(7), 1818–1834.

Oksanen, J., Blanchet, G.F., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., and Wagner, H. (2017) vegan: Community Ecology Package. R package version 2.4-3. https://CRAN.R-project.org/package=vegan.

Parnell, P.E., Dayton, P.K., Fisher, R.A., Loarie, C.C., and Darrow, R.D. (2010) Spatial patterns of fishing effort off San Diego: implications for zonal management and ecosystem function. *Ecological Applications* **20**(8), 2203-2222.

Paton, C., Hellstrom, J., Paul, B., Woodhead, J., and Hergt, J. (2011) Iolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry* **26**(12), 2508-2518.

Pitcher, R., Rochester, W.A., Dunning, M., Broadhurst, M.K., Noell, C.J., Tanner, J.E., Kangas, M., Newman, S.H., Semmens, J., and Rigby, C. (2019) Putting potential environmental risk of Australia's trawl fisheries in landscape perspective: Exposure of seabed assemblages to trawling, and inclusion in closures and reserves. . Final Report to the Fisheries Research and Development Corporation on project FRDC2016/039.

Potter, I.C., Manning, R.J.G., and Loneragan, N.R. (1991) Size, movements, distribution and gonadal stage of the western king prawn (*Penaeus latisulcatus*) in a temperate estuary and local marine waters. *Journal of Zoology* **223**, 419-445.

Potter, M.A. Movements of the eastern king prawn, *Penaeus plebejus* in southern Queensland waters. In 'Proceedings of the First National Prawn Seminar, 1973', 1975, Maroochydore. (Ed. PC Young),

Prosser, A.J., and Taylor, M.D. (2016) Eastern King Prawn (*Penaeus plebejus*). In Status of Key Australian Fish Stocks 2015. pp. http://fish.gov.au/report/24-Eastern-King-Prawn-2016, accessed 10 Feb 2017. (Fisheries Research and Development Corporation: Canberra)

Prosser, A.J., and Taylor, M.D. (2019) Eastern King Prawn (*Penaeus plebejus*). In Status of Key Australian Fish Stocks 2018. pp. http://fish.gov.au/report/172-Eastern-King-Prawn-2018 accessed 13 June 2019. (Fisheries Research and Development Corporation: Canberra)

Queen, J.P., Quinn, G.P., and Keough, M.J. (2002) 'Experimental design and data analysis for biologists.' (Cambridge University Press)

R Core Team (2020) R: A language and environment for statistical computing. (R Foundation for Statistical Computing: Vienna, Austria)

Racek, A.A. (1959) Prawn investigations in eastern Australia. *State Fisheries Research Bulletin* **6**, 1-57.

Ridgway, K.R., and Godfrey, J.S. (1997) Seasonal cycle of the East Australian Current. *Journal of Geophysical Research: Oceans* **102**(C10), 22921-22936.

Ridgway, K.R. (2007) Long-term trend and decadal variability of the southward penetration of the East Australian Current. *Geophysical Research Letters* **34**, 1-5.

Roelofs, A., and Hall, K. (2018) Stout Whiting (*Sillago robusta*). In Status of Australian Fish Stocks 2018. (http://fish.gov.au/report/211-Stout-Whiting-2018# accessed 29 January 2021: Canberra)

Rothlisberg, P.C., Church, J.A., and Fandry, C.B. (1995) A mechanism for near-shore concentration and estuarine recruitment of postlarval *Penaeus plebejus* Hess (Decapoda, Penaeidae). *Estuarine, Coastal and Shelf Science* **40**(2), 115-138.

Roughan, M., Macdonald, H.S., Baird, M.E., and Glasby, T.M. (2011) Modelling coastal connectivity in a Western Boundary Current: Seasonal and inter-annual variability. *Deep Sea Research Part II: Topical Studies in Oceanography* **58**(5), 628-644.

Rousseeuw, P.J. (1987) Silhouettes: a graphical aid to the interpretation and validation of cluster analysis. *Journal of computational and applied mathematics* **20**, 53-65.

Ruello, N.V. (1973) Influence of rainfall on distribution and abundance of school prawn *Metapenaeus macleayi* in Hunter River Region (Australia). *Marine Biology* **23**(3), 221-228.

Ruello, N.V. (1975) Geographical distribution, growth and breeding migration of eastern Australian King Prawn *Penaeus plebejus* Hess. *Australian Journal of Marine and Freshwater Research* **26**(3), 343-354.

Ruello, N.V. (1977) Migration and stock studies on Australian school prawn *Metapenaeus macleayi*. *Marine Biology* **41**(2), 185-190.

Russell, A., Gillanders, B.M., Barnes, T.C., Johnson, D.D., and Taylor, M.D. (2021) Inter-estuarine variation in otolith chemistry in a large coastal predator: A viable tool for identifying coastal nurseries? *Estuaries and Coasts* **44**, 1132–1146.

Schaffler, J., Miller, T., and Jones, C. (2014) 'Spatial and Temporal Variation in Otolith Chemistry of Juvenile Atlantic Menhaden in the Chesapeake Bay.'

Silberschneider, V., and Gray, C.A. (2008) Synopsis of biological, fisheries and aquaculture-related information on mulloway *Argyrosomus japonicus* (Pisces : Sciaenidae), with particular reference to Australia. *Journal of Applied Ichthyology* **24**(1), 7-17.

Silburn, J., Johnson, D.J., Booth, D.J., and Taylor, M.D. (2020) The effect of subsampling when monitoring bycatch in a penaeid trawl fishery. *Fisheries Research* **224**, 105459.

Smith, J.A., Mazumder, D., Suthers, I.M., and Taylor, M.D. (2013) To fit or not to fit: evaluating stable isotope mixing models using simulated mixing polygons. *Methods in Ecology and Evolution* **4**, 612–618.

Stewart, J., Hughes, J.M., Stanley, C., and Fowler, A.M. (2020) The influence of rainfall on recruitment success and commercial catch for the large sciaenid, *Argyrosomus japonicus*, in eastern Australia. *Marine Environmental Research* **157**, 104924.

Suthers, I.M., Young, J.W., Baird, M.E., Roughan, M., Everett, J.D., Brassington, G.B., Byrne, M., Condie, S.A., Hartog, J.R., Hassler, C.S., Hobday, A.J., Holbrook, N.J., Malcolm, H.A., Oke, P.R., Thompson, P.A., and Ridgway, K. (2011) The strengthening East Australian Current, its eddies and biological effects — an introduction and overview. *Deep Sea Research Part II: Topical Studies in Oceanography* **58**(5), 538-546.

Taylor, M.D., Fielder, D.S., and Suthers, I.M. (2006a) Spatial and ontogenetic variation in the diet of wild and stocked mulloway (*Argyrosomus japonicus*, Sciaenidae) in Australian estuaries. *Estuaries and Coasts* **29**(5A), 785-793.

Taylor, M.D., Laffan, S.D., Fielder, D.S., and Suthers, I.M. (2006b) Key habitat and home range of mulloway (*Argyrosomus japonicus*) in a south-east Australian estuary: Finding the estuarine niche to optimise stocking. *Marine Ecology Progress Series* **328**, 237-247.

Taylor, M.D., van der Meulen, D.E., Ives, M.C., Walsh, C.T., Reinfelds, I.V., and Gray, C.A. (2014) Shock, stress or signal? Implications of freshwater flows for a top-level estuarine predator. *PLoS ONE* **9**(4), e95680.

Taylor, M.D., Smith, J.A., Boys, C.A., and Whitney, H. (2016) A rapid approach to evaluate putative nursery sites for penaeid prawns. *Journal of Sea Research* **114**, 26-31.

Taylor, M.D. (2017) A preliminary evaluation of the costs and benefits of recreational prawn stocking in recruitment limited nurseries. *Fisheries Research* **186**, 478-487.

Taylor, M.D., Fry, B., Becker, A., and Moltschaniwskyj, N.A. (2017a) The role of connectivity and physicochemical conditions in effective habitat of two exploited penaeid species. *Ecological Indicators* **80**, 1–11.

Taylor, M.D., Fry, B., Becker, A., and Moltschaniwskyj, N.A. (2017b) Recruitment and connectivity influence the role of seagrass as a penaeid nursery habitat in a wave dominated estuary. *Science of The Total Environment* **584–585**, 622–630.

Taylor, M.D., Becker, A., Moltschaniwskyj, N.A., and Gaston, T. (2018) Direct and indirect interactions between lower estuarine mangrove and saltmarsh habitats and a commercially important penaeid shrimp. *Estuaries and Coasts* **41**, 815-826.

Taylor, M.D., and Creighton, C. (2018) Estimating the potential fishery benefits from targeted habitat repair: A case study of School Prawn (Metapenaeus macleayi) in the lower Clarence River estuary. *Wetlands* **38**, 1199-1209.

Taylor, M.D., and Johnson, D.D. (2020) Evaluation of adaptive spatial management in a multi-jurisdictional trawl fishery. *Regional Studies in Marine Science* **35**, 101206.

Thwaites, A., and Andersen, C. (2008) Cooperative management in the Queensland Finfish (*Stout Whiting*) Trawl Fishery. In Case Studies in Fisheries Self-Governance. Vol. 504. (Eds. R Townsend, R Shotton and H Uchida) pp. 259-268. (FAO Fisheries Technical Paper 504, Rome)

Tilburg, C.E., Hurlburt, H.E., O'Brien, J.J., and Shriver, J.F. (2001) The dynamics of the East Australian Current system: The Tasman Front, the East Auckland Current, and the East Cape Current. *Journal of Physical Oceanography* **31**(10), 2917-2943.

Tranter, D.J., Carpenter, D.J., and Leech, G.S. (1986) The coastal enrichment effect of the East Australian Current eddy field. *Deep Sea Research Part A. Oceanographic Research Papers* **33**(11), 1705-1728.

Tsagarakis, K., Coll, M., Giannoulaki, M., Somarakis, S., Papaconstantinou, C., and Machias, A. (2010) Food-web traits of the North Aegean Sea ecosystem (Eastern Mediterranean) and comparison with other Mediterranean ecosystems. *Estuarine, Coastal and Shelf Science* **88**, 233-248.

Uhlmann, S.S., and Broadhurst, M.K. (2007) Damage and partitioned mortality of teleosts discarded from two Australian penaeid fishing gears. *Diseases of Aquatic Organisms* **76**(3), 173-186.

van der Meulen, D.E., West, R.J., and Gray, C.A. (2013) An assessment of otoliths, dorsal spines and scales to age the long-finned gurnard, *Lepidotrigla argus*, Ogilby, 1910 (Family: Triglidae). *Journal of Applied Ichthyology* **29**(4), 815-824.

Venables, W.N., and Ripley, B.D. (2002) 'Modern Applied Statistics with S.' Fourth Edition edn. (Springer: New York) 495

Walsh, S., Copeland, C., and Westlake, M. (2004) Major fish kills in the northern rivers of NSW in 2001: causes, impacts and responses. *NSW Department of Primary Industries. Fisheries final report series*(68), 55.

Walters, C.J., Hilborn, R., and Parrish, R. (2007) An equilibrium model for predicting the efficacy of marine protected areas in coastal environments. *Canadian Journal of Fisheries and Aquatic Sciences* **64**(7), 1009-1018.

West, R.J. (1992) Mulloway. In The Australian Anglers Fishing World. Vol. August 1992. pp. 84-85.

West, R.J. (1993) Estuarine Fisheries Resources of Two South Eastern Australian Rivers. University of NSW, Sydney

Ye, Y., Loneragan, N., Die, D., Watson, R., and Harch, B. (2005) Bioeconomic modelling and risk assessment of tiger prawn (*Penaeus esculentus*) stock enhancement in Exmouth Gulf, Australia. *Fisheries Research* **73**, 231-249.

Yoshinaga, J., Nakama, A., Morita, M., and Edmonds, J.S. (2000) Fish otolith reference material for quality assurance of chemical analyses. *Marine Chemistry* **69**(1-2), 91-97.

Young, P.C. (1978) Moreton Bay, Queensland - Nursery area for juvenile penaeid prawns. *Australian Journal of Marine and Freshwater Research* **29**(1), 55-75.

Zeller, B., Rowling, K., Jebreen, E., O'Neilla, M., and Winning, M. (2012) Stout Whiting (*Sillago robusta*). In Status of Australian Fish Stocks 2012. (http://fish.gov.au/report/211-Stout-Whiting-2018# accessed 29 January 2021: Canberra)

Zuur, A.F., Ieno, E.N., and Elphick, C.S. (2010) A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution* **1**(1), 3-14. [In English]