Where do Calamari spawn in Northern Tasmania and how will this information aid the management of the Calamari fishery in Northern Tasmania?

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Contents

Tables

Figures

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Executive Summary

The Southern Calamari fishery on the north coast of Tasmania has experienced a rapid increase in effort since 2010 and volatility in catches since 2015. The present study was initiated by the Institute for Marine and Antarctic Studies in response to the need for an evidence-base to inform a management response to these changes in the fishery. This study surveyed the distribution and intensity of Southern Calamari spawning activity, in connection with trends in commercial and recreational fisheries targeting Southern Calamari across the north coast of Tasmania.

The surveys included underwater video transect methods to census the density and distribution of calamari egg masses across the breadth of the Tasmanian north coast, over four consecutive spawning seasons (2016 – 2020). The observed spatial and temporal patterns of spawning activity informed the application and refinement of annual spawning season closures, and offer a methodology for assessing the efficacy of current and future management responses.

Objectives

1. Determine spatial and temporal variation in calamari spawning aggregations and egg masses on the north coast of Tasmania.
2. Analyse the recent development of both the commercial and recreational calamari fisheries on the north coast.
3. Using the information gathered in objective 1 and 2, investigate the likely impact of the fishery on calamari populations and, if necessary, potential management options to ensure sustainable development.

Methodology

In the 2016/17, 2017/18, 2018/19 and 2019/20 Southern Calamari spawning seasons (September to January), egg mass surveys were conducted approximately monthly at sample sites considered to be representative of core spawning habitats across the north coast of Tasmania.

Each survey involved counting and staging egg masses on diver transects to determine temporal and spatial trends in spawning intensity. Diver tagging trials of egg masses were also conducted in three spawning seasons, to establish the rate of progression of eggs through each developmental stage from spawning to hatching.

During each spawning season, biological samples of Southern Calamari were collected approximately monthly across the extent of the Tasmanian north coast, to identify spatial and temporal variation in spawning status. Samples were processed to determine size, weight and reproductive status.

Southern Calamari commercial catch and effort data were extracted from the logbook returns database for fishing events from the 1995/96 fishing year (July–June) to the end of February 2020 (i.e. partial 2019/20 fishing year). Recreational catch and effort data were sourced from multiple IMAS recreational fishing surveys (2000, 2007, 2012 and 2017). Fishery data was used to examine spatial and temporal trends in catch and effort, and was compared with egg mass densities to investigate potential links between inshore spawning activity and fishery dynamics.

Spatial and temporal trends in spawning intensity were compared with trends in environmental parameters, including localised rainfall and sea surface temperature, to examine potential environmental influences on fisheries production.

Key findings

The egg mass surveys indicated that egg masses are deposited on inshore *Amphibolis antarctica* seagrass spawning habitats from mid-August to December. Consistent with fishers' advice, the eastern and western extremities of Bass Strait were found to be hot spots for spawning aggregations. Egg mass tagging trials estimated that the time from spawning to hatching was around 60 days and was consistent across the Tasmanian north coast and across the seasons sampled. Tallies of egg masses were corrected for potential repeat counting biases, and were back-calculated to represent spawning activity by subtracting the time taken to reach their observed developmental stage from their sample date.

Trends in egg mass densities showed clear spatial and temporal variation in the pattern and modality of spawning activity, both within and between seasons. For example, in the 2016/17 season, spawning activity was relatively intense and peaked in late October, whereas very low levels of spawning activity were observed in 2017/18 across the entire north coast. In 2018/19, spawning activity was moderate and peaked in September, and in 2019/20 moderate spawning activity occurred in the North West, with peaks in early September and in November, but spawning activity was low elsewhere on the north coast.

Spatial and temporal trends in commercial catch and effort on the north coast were significantly aligned with distributions and intensity of spawning activity, both within and between seasons. For example, catch, effort and fisher participation also follow the pattern of high levels in 2016/17, very low levels in 2017/18, a return to high levels in 2018/19, and low levels in the North East combined with high levels in the North West in 2019/20.

High winter rainfall preceding the commencement of the spawning season correlated strongly with subsequently high catches and spawning intensity, while low pre-season sea surface temperatures combined with a subsequent steep increase in temperature was linked to low catches. Within-season trends in environmental parameters were inconclusive as predictors of inshore Southern Calamari spawning intensity and subsequent trends in the fishery.

Implications for relevant stakeholders

The survey methodology applied in this project provided the evidence-base for implementing the first north coast Southern Calamari spawning season closure in 2017/18, and informed spatial and temporal extensions of closures in subsequent seasons. Since management controls are intended to directly influence effort and catch, fishery-dependent data sources will not provide a direct indication of the efficacy of management changes on inshore spawning activity. However, the approach of using egg production estimates can provide a fishery-independent estimate of inshore spawning dynamics. For example, this methodology can gauge the appropriateness of the timing, duration and spatial extent of future spawning season closures, by directly measuring inshore spawning activity, particularly during season closures in the absence of fishing.

Recommendations

Considering that Southern Calamari are a short-lived (~ one year) species spawning within one year, it is imperative to sustainability that populations have ample opportunity to spawn prior to capture. The recent rapid rise in catch and effort in both the commercial and recreational fisheries on the north coast, and particularly the volatility of the last five seasons, justify a precautionary approach to managing the fishery.

Spawning season closures need to be sufficiently long and broad to encompass the high variability in peak spawning activity observed both within and between seasons. Ongoing egg mass surveys are recommended to provide a fishery-independent means to assess the efficacy of current and future management, and to amass an ongoing dataset that may allow more responsive season closures in the future.

Keywords

Southern Calamari, spawning, egg mass, Tasmania, habitat, fishery, Sepioteuthis australis

Introduction

Southern Calamari occur in shallow inshore waters and are endemic to southern Australia and northern New Zealand coasts (Gomon et al., 2008). They are an important species in Tasmania, to both commercial and recreational fishers (Lyle et al., 2014, Moore et al., 2019). Southern Calamari seasonally aggregate on shallow *Amphibolis antarctica* seagrass beds to spawn and deposit egg masses onto *A. Antarctica* stalks beneath its leafy canopy (Pecl 2001, Triantafillos and Adams 2001, Triantafillos 2004, Pecl et al., 2006, Smith et al., 2015). However, it is also recognised that they adopt different spawning behaviour in different locations and seasons to spread the risk of mortality (Moltschaniwskyj and Steer 2004). For example, Southern Calamari spawning is sporadic beyond the southern limit of *A. antarctica* at Maria Island (Edgar 1997), resulting in more isolated, low density egg patches (Moltschaniwskyj and Steer 2004). While spawning undoubtedly occurs in other areas such as rocky reefs and potentially on deeper reef habitats, inshore *A. antarctica* seagrass meadows are a favoured habitat for Southern Calamari spawning (Moltschaniwskyj and Pecl 2003, Pecl 2004).

On the north and east coasts of Tasmania, fishers target spawning aggregations primarily on or adjacent to *A. antarctica* seagrass meadows, where the species' aggregative behaviour facilitates good catch rates. Since Southern Calamari have a short life span of approximately one year (Pecl and Moltschaniwskyj 2006), stock viability heavily depends on the spawning success of the preceding generation, highlighting the importance of ensuring that fished populations have ample opportunity to spawn prior to capture.

An ecological risk assessment of the Tasmanian Scalefish Fishery considered there was negligible risk to bycatch and threatened, endangered and protected species and habitats, from fishing for Southern Calamari using squid jigs (Bell et al., 2016). However, changes to the ecosystem and community structure from this method of fishing was considered a low risk rather than negligible, as they are an important predator and their removal could lead to negative effects on the ecosystem and community structure. Jig fishing of spawning aggregations is also sex-selective for males (Hibberd and Pecl 2007). As catches of Southern Calamari have continued to rise since 2012/13, it is likely that the overall risk has increased in the northern areas of the State.

Concerns regarding overfishing of Southern Calamari stocks have been raised previously in Tasmania (Moltschaniwskyj et al., 2003), including the issue of latent effort activating in both the commercial and recreational sectors when 'good' catches are reported in an area. Historically, areas on the east coast of Tasmania, in particular Great Oyster Bay and Maria Island, have produced the greatest catches of Southern Calamari. After concerns were raised about overfishing in the region, extensive research was undertaken to describe the timing and spatial dynamics of spawning, as well as connectivity of Southern Calamari using the seagrass beds both within and between Great Oyster Bay and Maria Island (Moltschaniwskyj et al., 2003).

The results of this research led to management intervention, including the introduction of a limited entry Southern Calamari licence and trip limits for other commercial fishers operating in South East waters. Spatio-temporal spawning closures were also introduced to allow Southern Calamari sufficient opportunity to spawn, with acoustic telemetry confirming that squid generally stayed within the management-closed areas (Pecl et al., 2006). Prior to implementing these measures, commercial scalefish licence-holders were able to target Southern Calamari in waters open to fishing without catch limits. A consequence of these management changes has been to incentivise industry to search for Southern Calamari stocks in other areas of the State, including off the north coast.

The state-wide maximum sustainable yield (MSY) estimate of 75 tonnes (t) was exceeded by more than 40% in the 2015/16, 2016/17, and 2018/19 seasons. This is of particular concern for the north coast region which has experienced a significant increase in catches that have exceeded the estimated regional MSY of 33 t by more than 100% (Krueck et al., 2020). While uncertainty remains about the status of stocks, recent fishing mortality has been high and is likely to cause the stock to become recruitment impaired. On this basis, Southern Calamari in Tasmania is classified as a depleting stock (Krueck et al., 2020).

In preparation for potential changes to the management of the Tasmanian Southern Calamari fishery, the Tasmanian State Government issued an investment warning on 23 August 2018 (DPIPWE 2018), and released a review of the Tasmanian Southern Calamari fishery (DPIPWE 2018). This review included a cost-benefit analysis of potential management tools for the fishery, including seasonal spawning closures, commercial trip limits, recreational bag and boat limits, regional catch capping, size limits, area closures, access by permit, limits to commercial effort, and total allowable catch or effort.

Objectives

No.	Details
1	Determine spatial and temporal variation in calamari spawning aggregations and egg masses on the north coast of Tasmania
2	Analyse the recent development of both the commercial and recreational calamari fisheries on the north coast
3	Using the information gathered in objectives 1 and 2, investigate the likely impact of the fishery on calamari populations and, if necessary, potential management options to ensure sustainable development

Methods

The project addressed the objectives through a combination of biological sampling of Southern Calamari, *in situ* egg density surveys on spawning grounds, analysis of existing data sets including commercial and recreational catch and effort data and environmental data, and a synthesis of the information gathered to inform management options to promote sustainable development of this emerging fishery.

Objective 1: Determine spatial and temporal variation in Southern Calamari spawning aggregations and egg masses on the north coast of Tasmania

This objective was addressed through analysis of data from field sampling during peak spawning seasons (spring/summer period), including the 2016/17, 2017/18, 2018/19 and 2019/20 seasons. Sampling encompassed the breadth of the Tasmanian north coast and involved dive surveys to assess locations, timing and density of egg deposition, and biological sampling of Southern Calamari to assess spawning condition of the animals.

Sampling was conducted in three regions on the Tasmanian north coast: North West (Figure 1), Central (Figure 2) and North East (Figure 3). Within each region, two sub-regions were chosen that best represented *Amphibolis antarctica* Southern Calamari spawning habitats (Figure 1, 2 and 3). Between five and 10 sample sites were assigned within each sub-region (Table 1), on the basis of advice from local commercial fishers regarding the general locations of spawning aggregations, observations of high densities of egg masses, commercial catch hotspots, and habitat characteristics (Appendix 3). Sites were fixed for the duration of the project and were defined by a central position (marked with a GPS) and were bounded by the extent of *A. antarctica* adjacent to the central position.

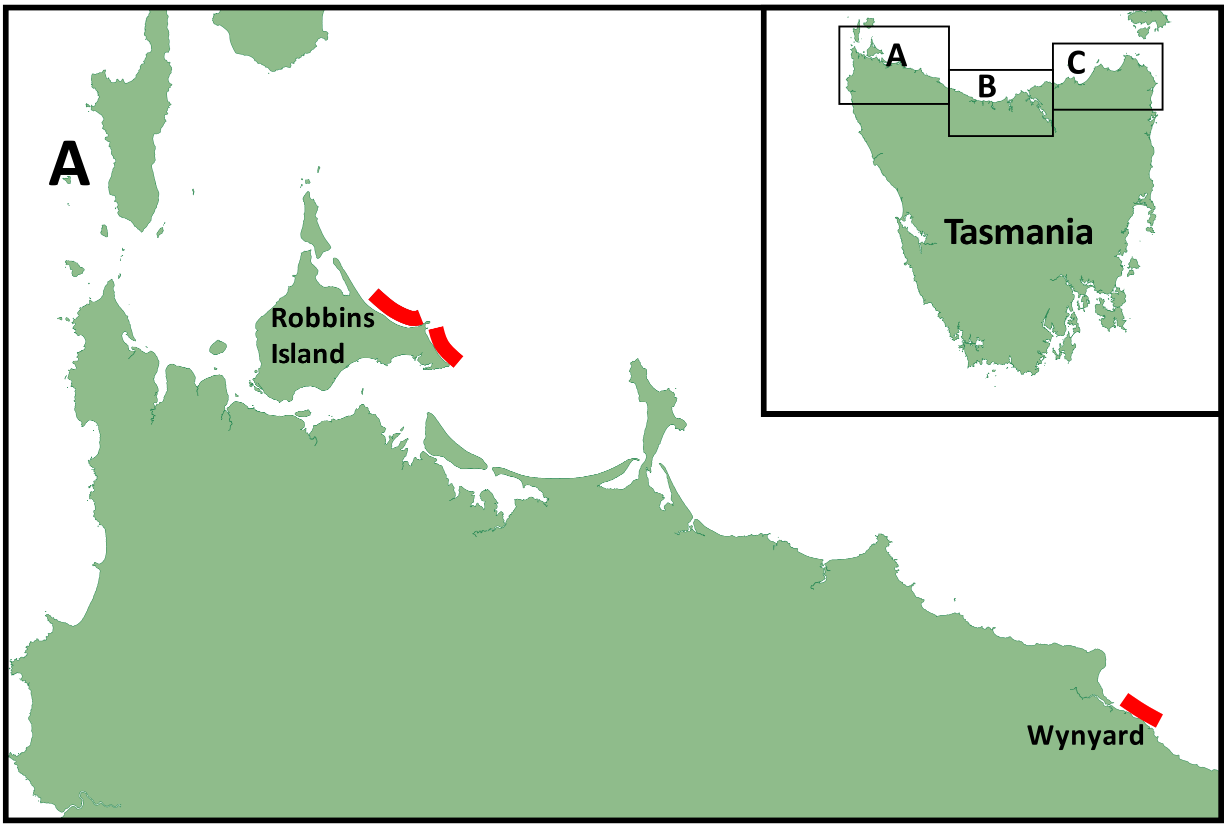


Figure 1. Robbins Island and Wynyard sub-regions in the North West region of the Tasmanian north coast. Inset map shows sample regions (A = North West, B = Central, C = North East) on the north coast of Tasmania.

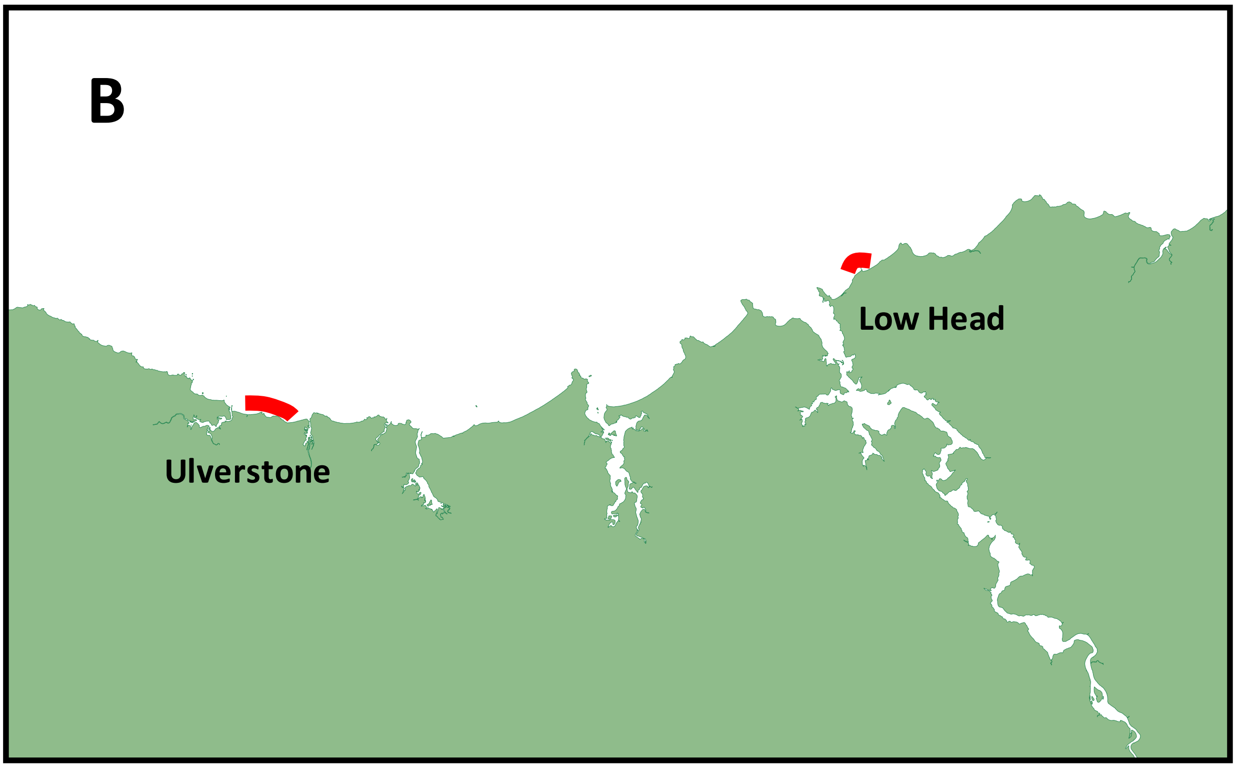


Figure 2. Map showing Ulverstone and Tamar sub-regions in the Central region of the Tasmanian north coast.

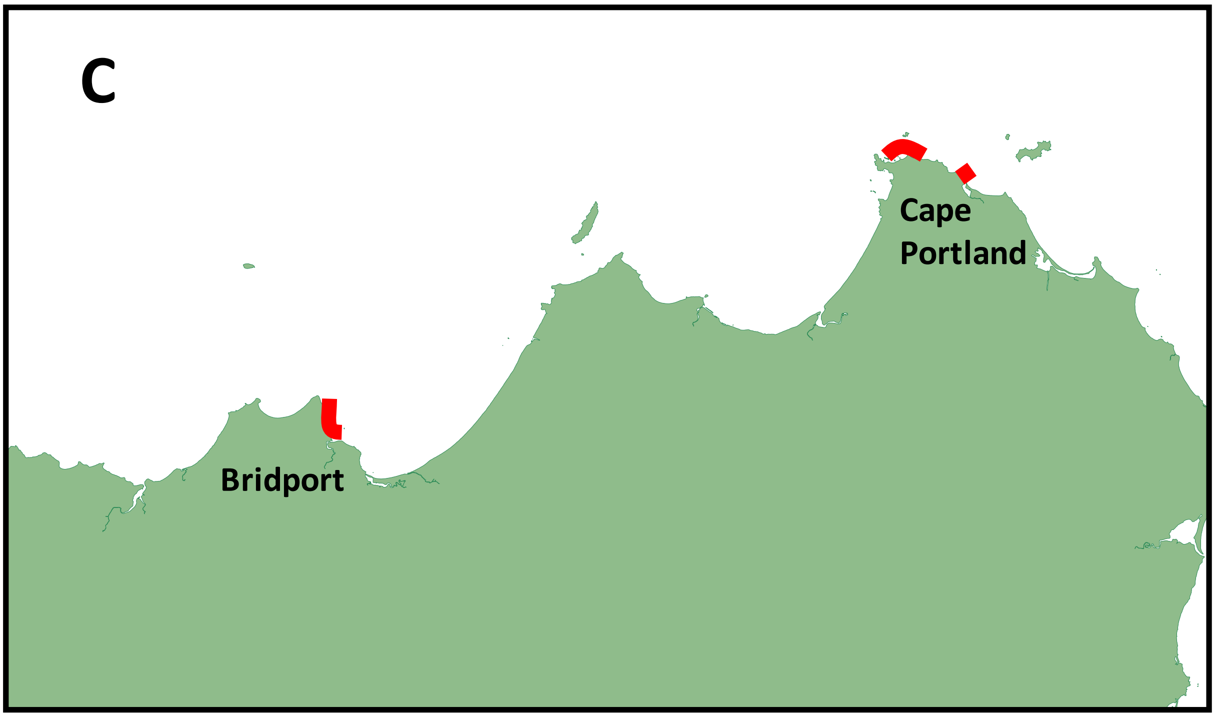


Figure 3. Map showing Bridport and Cape Portland sub-regions in North East region of Tasmanian north coast.

Table 1. Number of sites sampled (sample trips in brackets) and area of spawning habitat surveyed by region, sub-region and Southern Calamari spawning season.

Region	Sub-region	Number of sites sampled by season			
		2016/17	2017/18	2018/19	2019/20
North West	Robbins Island	10 (4)	10 (4)	10 (5)	10 (5)
	Wynyard	-	5 (4)	5 (5)	-
Central	Ulverstone	-	5 (4)	5 (5)	-

	Tamar	-	5 (4)	6 (5)	5 (5)
North East	Bridport	-	5 (4)	5 (5)	-
	Cape Portland	4 (3)	10 (4)	10 (5)	10 (5)
	Area surveyed:	10,400 m^2	24,000 m^2	31,000 m^2	25,000 m^2

Egg mass surveys

To investigate the spatial and temporal dynamics of Southern Calamari spawning, underwater visual censuses of the density and development stage of Southern Calamari egg masses were conducted at approximately monthly intervals over the presumptive peak spawning period at each of the sites (Table 1). At each site, 10 randomly defined 20m^2 belt transects (i.e. 200m^2 per site per sample session) were conducted on each trip. For each sample session, at each site, the starting point of the first transect was deployed in a haphazard direction from the central position of the site. The subsequent nine transects at each site started at least 5m from the end of its preceding transect and proceeded in a haphazard direction. If a site boundary was reached (i.e. an end to the extent of *A. antarctica* seagrass habitat) when positioning a transect, the transect direction was adjusted to stay within the site boundary.

The developmental stage and size of each egg mass encountered on a transect was recorded on an underwater slate (Table 2 as per Moltschaniwskyj et al., 2003). At times, egg masses were completely obscured from view by a dense *A. antarctica* canopy. Under these circumstances, transect divers carefully parted the canopy to ensure all egg masses on a transect were counted. The presence of 'flags' (isolated egg strands deposited high on the seagrass canopy) were also recorded, as they are considered an indication of current or imminent spawning activity.

In addition, to allow back-calculation of spawning dates from encountered egg masses, *in situ* egg mass tagging trials were conducted in the 2017/18, 2018/19 and 2019/20 seasons to establish the rate of egg development. Freshly deposited Stage I egg masses were marked by attaching a prominent plastic cattle tag with a unique identifier to an adjacent seagrass stalk. The developmental stage and size of tagged egg masses was recorded at the time of tagging, and at subsequent inspections. To assist finding tagged egg masses for subsequent observations, a steel picket was deployed 1m from each tagged mass, and a GPS mark was recorded. These trials were conducted at the Cape Portland and Robbins Island sub-regions, to provide an indication of spatial variation of egg mass development across the breadth of the Tasmanian north coast.

Table 2. Stage of egg masses – from Moltschaniwskyj et al., 2003.

Stage	Description
Flag	One or two stage one strands laid high in the seagrass canopy to attract male calamari for mating
I	Newly laid strands, pearly white, no fouling by algae, individual eggs not obvious
II	Strands no longer shiny, some fouling evident, the eggs are starting to become obvious
III	Eggs within the strand are clearly obvious, extensive fouling is present on the egg mass. The embryos have eye and body pigmentation and can be seen.
IV	Most of the embryos in the egg mass have hatched or are hatching and the egg mass is starting to fall apart

Biological sampling

A sample of up to 20 Southern Calamari were collected approximately monthly during the spawning season, from each region, in each survey year, to identify spatial and temporal variation in spawning status. Southern Calamari were caught using squid lures on rod and line from spawning sites, by IMAS staff or commercial fishers. Each individual Southern Calamari was processed to determine the dorsal mantle length (mm), total body weight (g), sex, and weight (g) of reproductive organs.

Individuals were assigned a maturity stage according to the relative size and colour of their reproductive organs, following the six-stage maturity scale of Lipinski (1979), as per Pecl (2001) and Moltschaniwskyj et al. (2003). Under this scheme, individuals assessed as stages IV and V are mature, so considered part of the spawning stock. Statoliths, which can be used to assess the age of individuals (Pecl 2004), were removed and stored to provide the opportunity for future extension of this research.

Objective 2: Analyse the recent development of the commercial and recreational Southern Calamari fisheries on the north coast

Commercial catch and effort data are recorded by Tasmanian Scalefish fishers in the *Commercial Catch, Effort and Disposal Record* logbook (see Appendix 5). Date, fishing block (see Appendix 6), method (e.g. squid jig), effort (amount of gear and hours fished), catch by species (weight in kilograms) are recorded for each day fished. Data for Southern Calamari catches was extracted from the logbook returns database for fishing events from the 1995/96 fishing year (July-June) to the end of February 2020 (i.e. partial 2019/20 fishing year).

Southern Calamari commercial catch data was summed by fishing year across all methods. However, only data for 'handline' and 'squid jig' were used to examine trends in fishing effort and catch rate. Fishers reporting the handline method for Southern Calamari are, in practice, using squid jigs to catch the species and thus these two 'methods' are effectively the same thing. Handline and squid jig methods have accounted for 94% of the total commercial Southern Calamari catch over last 10 fishing years. Standardised effort was the sum of the product of effort units and effort days, relative to the effort expended in the reference year used for management assessments of the north coast Southern Calamari fishery (2001/02).

Recreational fishing data was sourced from multiple recreational fishing surveys. Australian fisheries agencies implemented the National Recreational Fishing Survey as a series of state-wide surveys using a common methodology in 2000 (Henry and Lyle 2003). In the absence of plans to repeat a national survey, the Tasmania government committed to undertake regular state-wide recreational fishing surveys, the first of which was undertaken in 2007/08 (Lyle et al., 2009), followed by surveys in 2012/13 (Lyle et al., 2014) and 2017/18 (Lyle et al., 2019). Recreational catch data for Southern Calamari was recorded in the surveys as number caught, and converted to whole weight on the basis of average weight data available at the time. Recreational effort and catch rate data were reported as number of fisher days (Tasmanian residents aged five years or older).

Objective 3: Using the information gathered in objective 1 and 2, investigate the likely impact of the fishery on Southern Calamari populations and, if necessary, potential management options to ensure sustainable development

Seasonal and spatial variation in fishery-dependant data (Objective 2) was interpreted with respect to fishery-independent data (Objective 1), to infer the likely causes of fluctuations in the fishery and implications of recent increases in participation and effort.

Commercial catches were compared with egg mass densities to investigate potential links between inshore spawning activity and fishery dynamics. For this analysis, monthly time series of Southern Calamari catches were compared with back-calculated egg mass densities using cross-correlation analysis (Holmes et al., 2020).

Trends in environmental parameters including localised rainfall and sea surface temperature were compared qualitatively with the observed variability in spawning intensity. From these comparisons, the relative merits of potential management options are assessed in the discussion.

Results and discussion

Objective 1: Determine spatial and temporal variation in Southern Calamari spawning aggregations and egg masses on the north coast of Tasmania

The dynamics of Southern Calamari spawning aggregations on the north coast of Tasmania were investigated, with a focus on assessing the spatial and temporal variations in the density of egg masses on key inshore seagrass habitats.

Spatial and temporal variations in the density of egg masses on key inshore seagrass habitats

Dramatic variations in the density of egg masses were observed between both seasons and regions, consistent with previous studies in other geographical areas (e.g. Pecl et al., 2004). The 2016/17 and 2018/19 spawning seasons yielded substantially higher densities of egg masses than the 2017/18 season in each of the sub-regions, except for Ulverstone where densities were low in each of the surveyed seasons.

In contrast, in 2019/20, high egg densities were only recorded at Robbins Island, with low densities more typical of 2017/18 recorded at the other regions surveyed (Figure 4). Within season, the density of egg masses varied considerably at each spatial scale (i.e. between replicate transects, sites, sub-regions and regions). However, egg masses were generally encountered in highest densities at the eastern and western extremities of the north coast of Tasmania (i.e. Cape Portland and Robbins Island sub-regions).

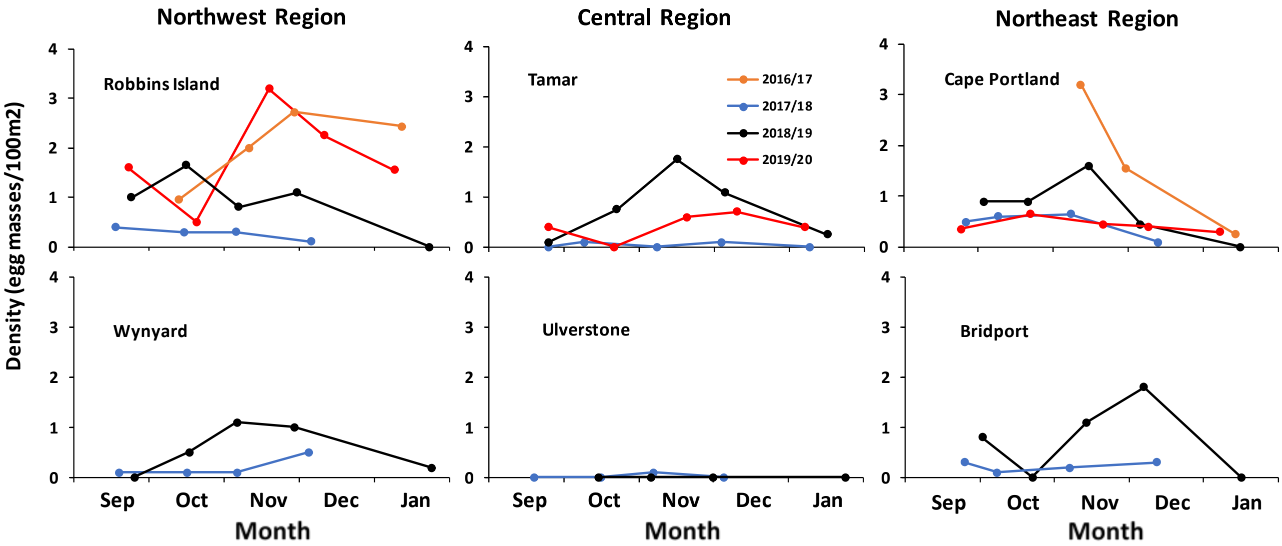


Figure 4. Density (masses/100 m^2) of egg masses by sub-region and for each calamari spawning season sampled (i.e. September to January in each of 2016/17, 2017/18, 2018/19 and 2019/20).

Spatial and temporal variation in timing of spawning activity derived from trends in egg mass stages and back-calculation of spawning timing from in-situ measurements of rate of egg mass development

Observed egg mass trends

Monthly trends in the distribution of egg masses by developmental stage showed a predominance of early stages from September to November and their absence in January, with a prevalence of Stage IV egg masses in December and January, but a near absence of this older stage in September and October (Figure 5). This progression suggests that spawning activity commenced as early as late August and had ceased before January, the timing of which is similar to that for Tasmanian east coast Southern Calamari populations (Moltschaniwskyj and Pecl 2006).

Trends in the density of Stage I egg masses across the north coast and within the seasons sampled suggested that spawning activity had commenced just prior to the start of sampling in September and had concluded by late December (Figure 6). Stage I egg masses generally peaked and terminated earlier at Cape Portland, particularly in the 2019/20 season, and were deposited later into the season at the Tamar and Robbins Island sub-regions.

A bimodal pattern of Stage I egg mass densities was evident at the Cape Portland sub-region in the 2018/19 season, and at the Robbins Island sub-region in the 2019/20 season, suggesting two peaks in spawning. On both occasions the dip between the peaks occurred in October.

An alternative explanation is that an initially strong start to spawning activity in September was suppressed by removal of Southern Calamari by the fishery, leading to low spawning activity in early October and subsequent low egg mass densities detected in October surveys. On these occasions, the protection of the closure may have allowed squid to aggregate back onto the spawning grounds, providing a second peak in spawning activity and subsequent pulse in egg mass densities (Figure 6).

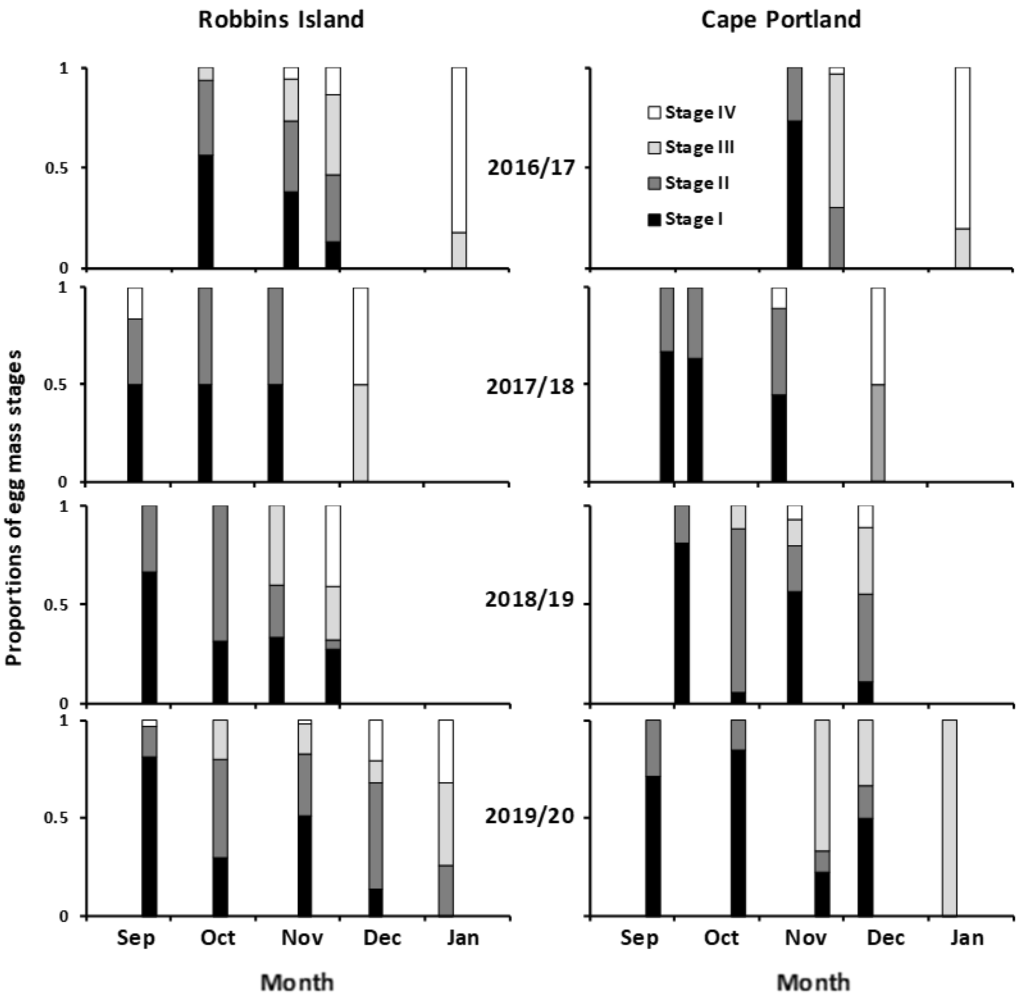


Figure 5. Proportions of egg masses in each developmental stage, sub-region and sample season.

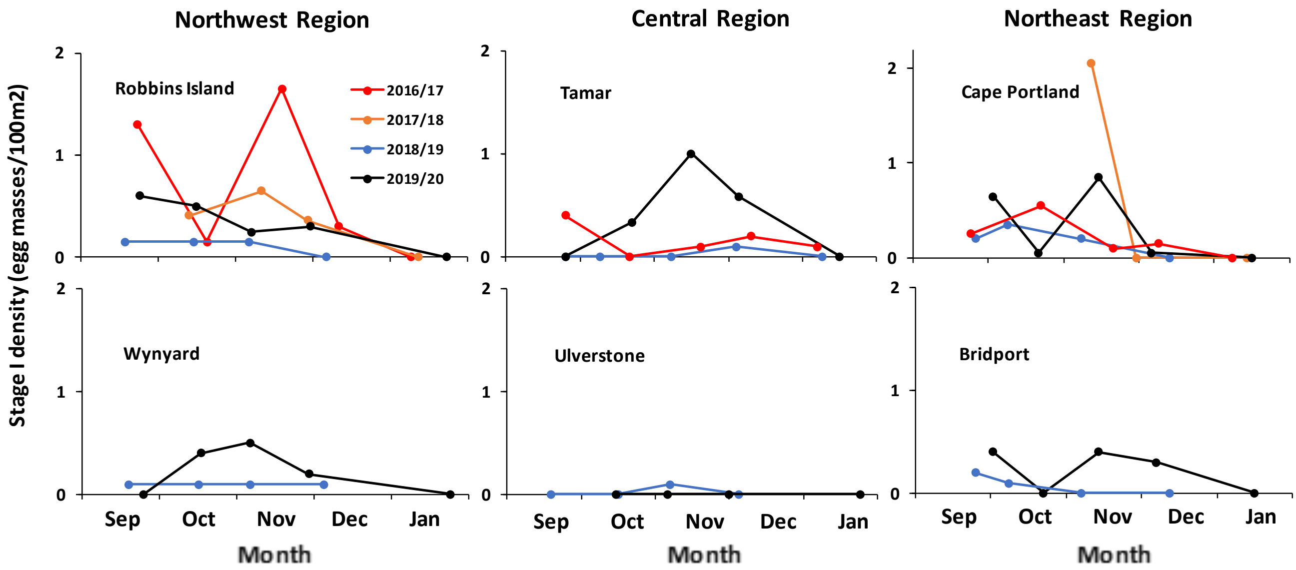


Figure 6. Density (egg masses/100 m^2) of Stage I egg masses by sub-region and sample season.

Egg mass tagging trials to determine the rate of egg stage progression

In situ egg mass stage progression trials entailed 170 stage determinations of 57 tagged egg masses in the Robbins Island and Cape Portland sub-regions (Table 3). The mean time elapsed from Stage I to Stage II was 26 days, from Stage I to III was 38 days and from Stage I to IV was 59 days (Figure 7). This rate of stage progression was generally supported by average times between advanced stages (23 days for Stage II to III, 24 days for Stage III to IV, 37 days for Stage I to III, and 40 days for Stage II to IV).

Consequently, the progression from spawning to hatching is estimated to be 59 days (Figure 7). This rate of progression is similar to that encountered in Southern Calamari egg masses in a previous study on the east coast of Tasmania (Steer et al., 2002). While progression rates are considered constant for the purposes of this study, it is likely they are influenced by environmental factors, and are probably variable across seasons. This may have implications for survival to hatching and subsequent growth rates (Pecl 2004, Pecl et al., 2004).

Table 3. Number of Stage I egg masses tagged for determination of timing of stage progression by month and Southern Calamari spawning season. Numbers in brackets are the number of previously tagged egg masses inspected and re-staged by month and season.

SUB-REGION	SEASON												
	2017/18			2018/19					2019/20				
	Oct	Nov	Dec	Sep	Oct	Nov	Dec	Jan	Sep	Oct	Nov	Dec	Jan
Robbins Island	–	–	–	5	6 (5)	(11)	–	–	5	2 (5)	5 (6)	1 (12)	(9)
Cape Portland	4	1 (1)	(5)	–	10 (7)	5 (10)	(15)	(4)	1	4 (1)	1 (4)	7 (7)	(11)

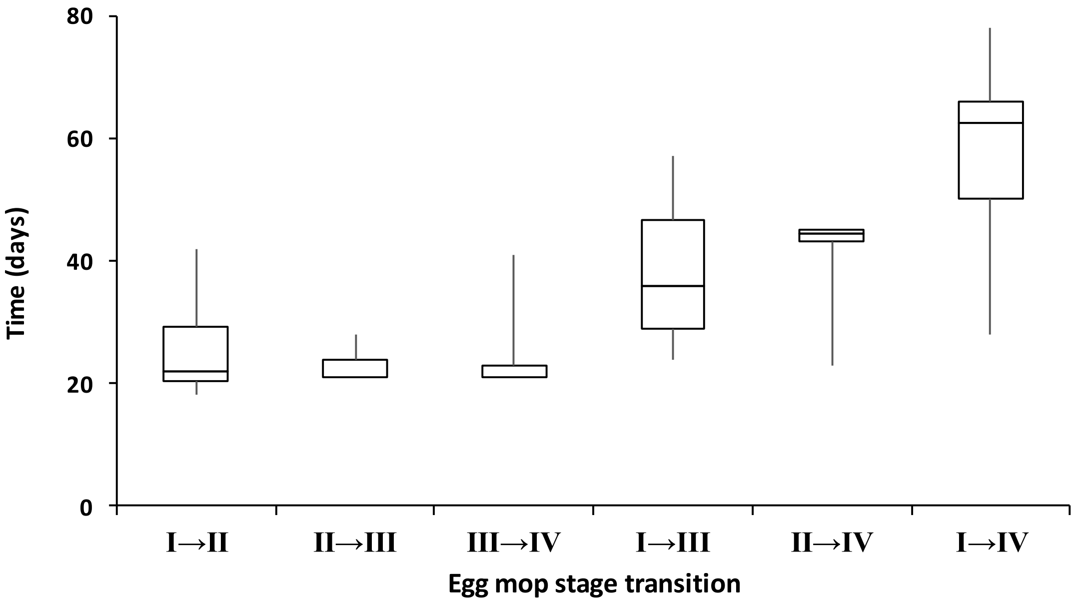


Figure 7. Time taken for egg mop stage transitions. Whiskers = minimum and maximum values, boxes = first to third quartiles, horizontal line = median value.

An understanding of trends in the intensity of spawning activity are required to assess the efficacy of the timing of spawning season closures. Trends in egg mass density can provide estimates of spawning activity, but care must be taken in interpreting egg mass density for this purpose.

As sampling was conducted at approximately monthly intervals, and eggs progress to hatching in around 59 days, egg masses deposited at a sample site were very likely to be present for at least two sampling events. Moreover, there is a time-lag associated with inferring spawning activity from egg masses, as they indicate the product of successful spawning activity in the past – the higher the development stage, the greater the lag. These biases promote inferring spawning activity from trends in Stage I egg mass densities alone, to eliminate repeat-counting and minimise the time-lag.

However, as it takes around 26 days for an egg mass to progress from Stage I to Stage II, monthly sampling will underestimate spawning activity, because egg masses deposited soon after a sampling event are likely to have progressed to Stage II prior to the next survey and would be excluded in documenting trends in Stage I egg mass numbers. Inferring spawning activity from trends of combined Stage I and II egg masses addresses the problem of under-estimation biases from monthly sampling, but still incorporates a time-lag of around 26 days for Stage II eggs.

To correct for repeat-counting biases, egg masses were excluded if they were present for preceding sample sessions, as per Moltschaniwskyj and Pecl (2003). This was achieved by comparing stage progression times against the time elapsed between sample sessions by site.

Back-calculation of advanced stage eggs to estimate intensity of spawning activity

Densities of staged egg masses were then converted to densities of egg production by subtracting (from the sample date) the number days to reach the observed stage at the date of sampling. This treatment avoided the underestimation bias from examining Stage I egg masses alone, and corrected for the time-lag associated with Stage II, III and IV egg masses.

It was considered this would provide a more accurate estimate of the timing and relative intensity of spawning activity (Figure 8) and provide the additional advantage of an indication of spawning activity occurring before seasonal sampling commenced. Back-calculated egg production is not presented as an estimate of spawning activity for Ulverstone, Wynyard and Bridport sub-regions due to very low egg mass densities.

Spawning activity showed clear spatial and temporal variation in pattern, modality and intensity, both within and between seasons. In the 2016/17 season, there was a marked peak in spawning activity in late October, whereas during 2018/19 activity peaked a month or so earlier (during September) at both the Cape Portland and Robbins Island sub-regions, followed by a slight increase in activity again during November at the Cape Portland sub-region (Figure 8). The spawning peak in the Tamar sub-region occurred later in the 2018/19 season, during October and November, and was the highest intensity experienced at that sub-region. There was very limited spawning activity in all sub-regions during 2017/18. The 2019/20 season yielded very low activity in the Tamar sub-region, moderately low activity in the Cape Portland sub-region, and high levels of activity in September and November in the Robbins Island sub-region.

The bimodal pattern evident in Stage I egg mass densities (Figure 6) at the Cape Portland sub-region in the 2018/19 season and at the Robbins Island sub-region in the 2019/20 season, was also evident in the back-calculated egg mass densities. This suggests that these dips in spawning activity are not an artefact of the biases associated with analysis of trends in Stage I egg masses alone. However, it is not possible to conclude whether this bimodality in spawning activity is due to the effects of fishing mortality and/or the subsequent closed season.

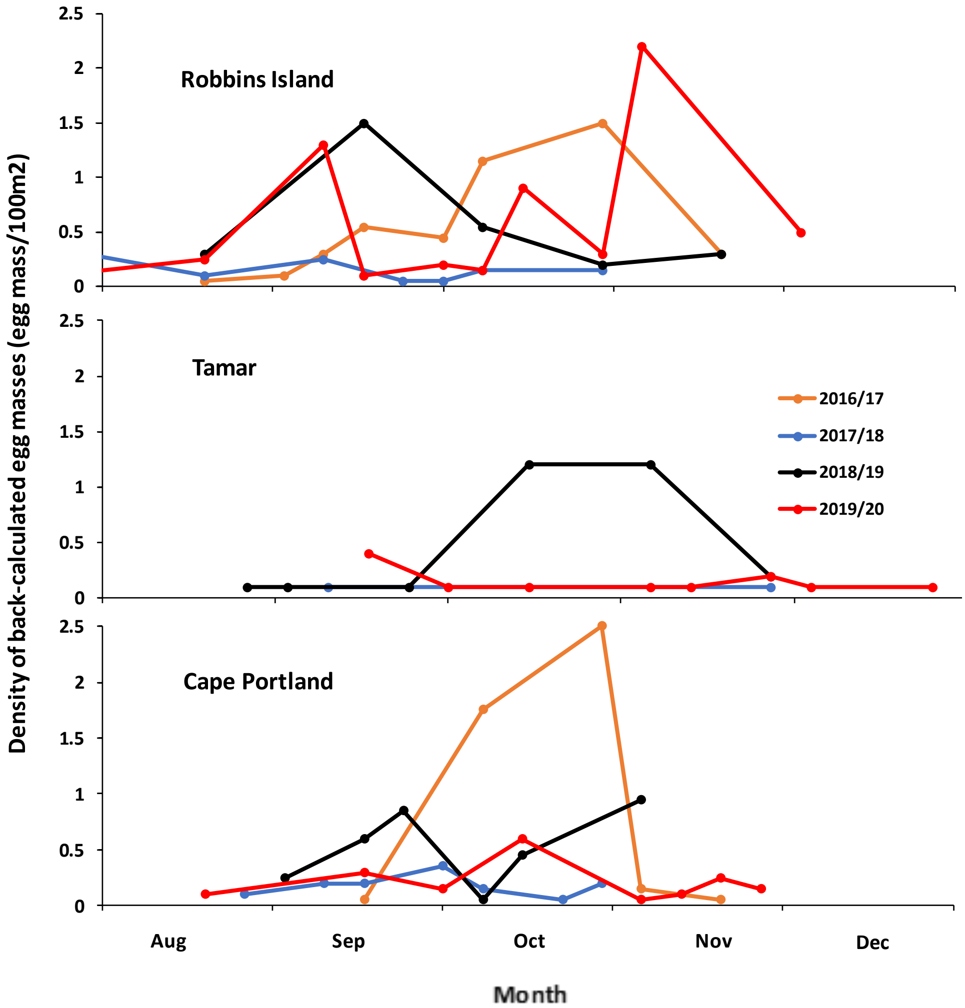


Figure 8. Back-calculated egg production from staged egg masses by sub-region and sample season.

Spatial and temporal variation in size, sex ratio and reproductive status of Southern Calamari caught at key commercial inshore spawning sites

A total of 650 Southern Calamari, captured on key spawning seagrass habitats, were retained for biological examination (

Table 4). Maxima in size and weight occurred around September, October and November, and size (Figure 9) and weight (
Figure 10) minima generally occurred in January. Males dominated catches, but the ratio of females present on spawning habitats increased during September, October and November (
Figure 11), with juveniles encountered consistently in December and January.

The timing of maxima in size and increased proportions of females in catches supports the timing of back-calculated peak spawning events. The absence of females and presence of juveniles in January supports the timing of spawning activity inferred from egg mass data. In addition, the early detection of juvenile Southern Calamari on seagrass beds in the 2018/19 season is consistent with the early peak in spawning inferred from egg mass data. Consequently, temporal and spatial trends in sex ratios and the occurrence of juveniles at key spawning sea grass habitats support the timing and variability of spawning activity observed in distributions of back-calculated spawning densities.

Table 4. Number of Southern Calamari processed from biological sampling by region and sample season.

REGION	MONTH	SEASON			
		2016/17	2017/18	2018/19	2019/20
North West	Sep	10	20	14	20
	Oct	56	21	–	20
	Nov	41	20	33	5
	Dec	20	9	–	20
	Jan	–	–	–	5
Central	Sep	–	–	–	1
	Oct	–	–	–	20
	Nov	–	18	11	1
	Dec	–	4	21	20
	Jan	–	–	7	5
North East	Sep	–	–	–	3
	Oct	–	22	53	20
	Nov	43	16	9	7
	Dec	–	4	21	20
	Jan	–	-	4	6

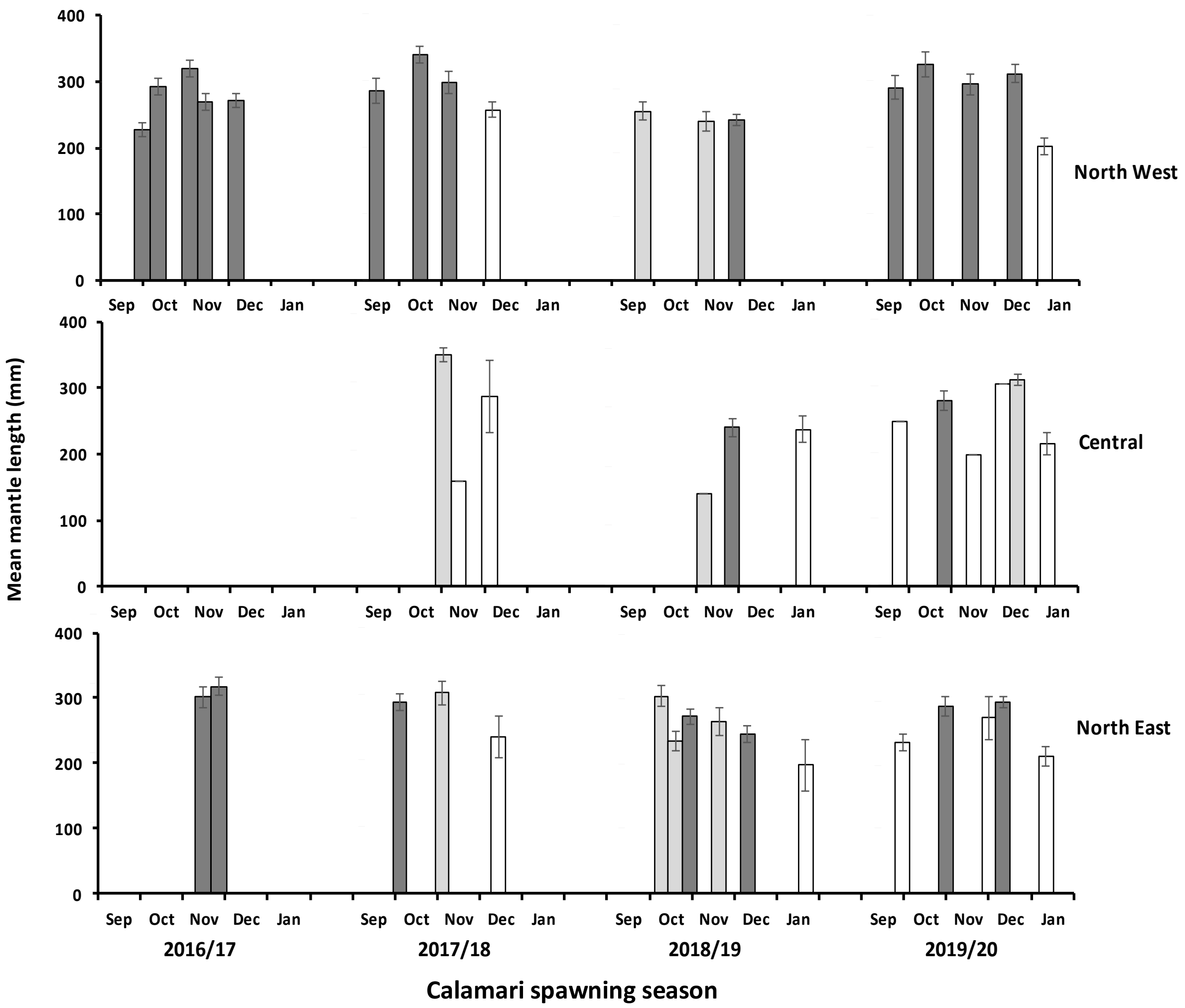


Figure 9. Mean mantle length by region and season. Grey-scale indicates sample size where white is <10, light grey is 10-20, and dark grey is 20 and above.

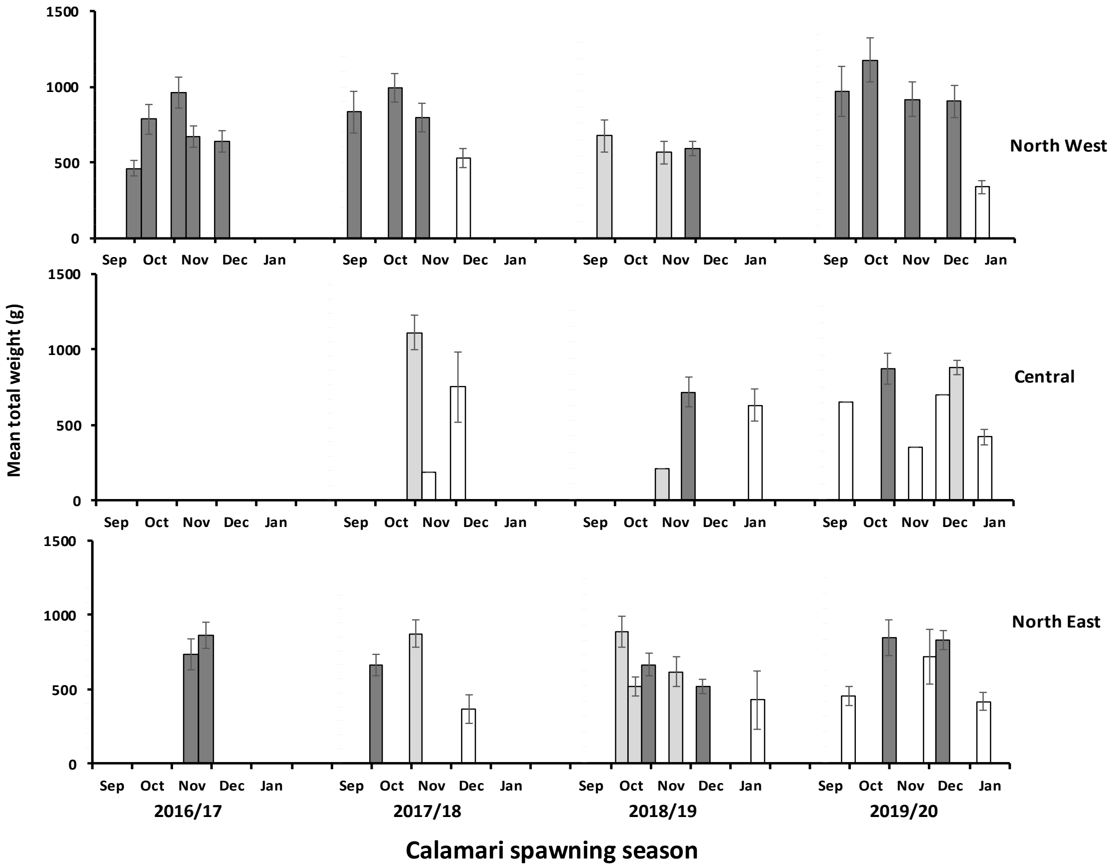


Figure 10. Mean total weight by region and season.

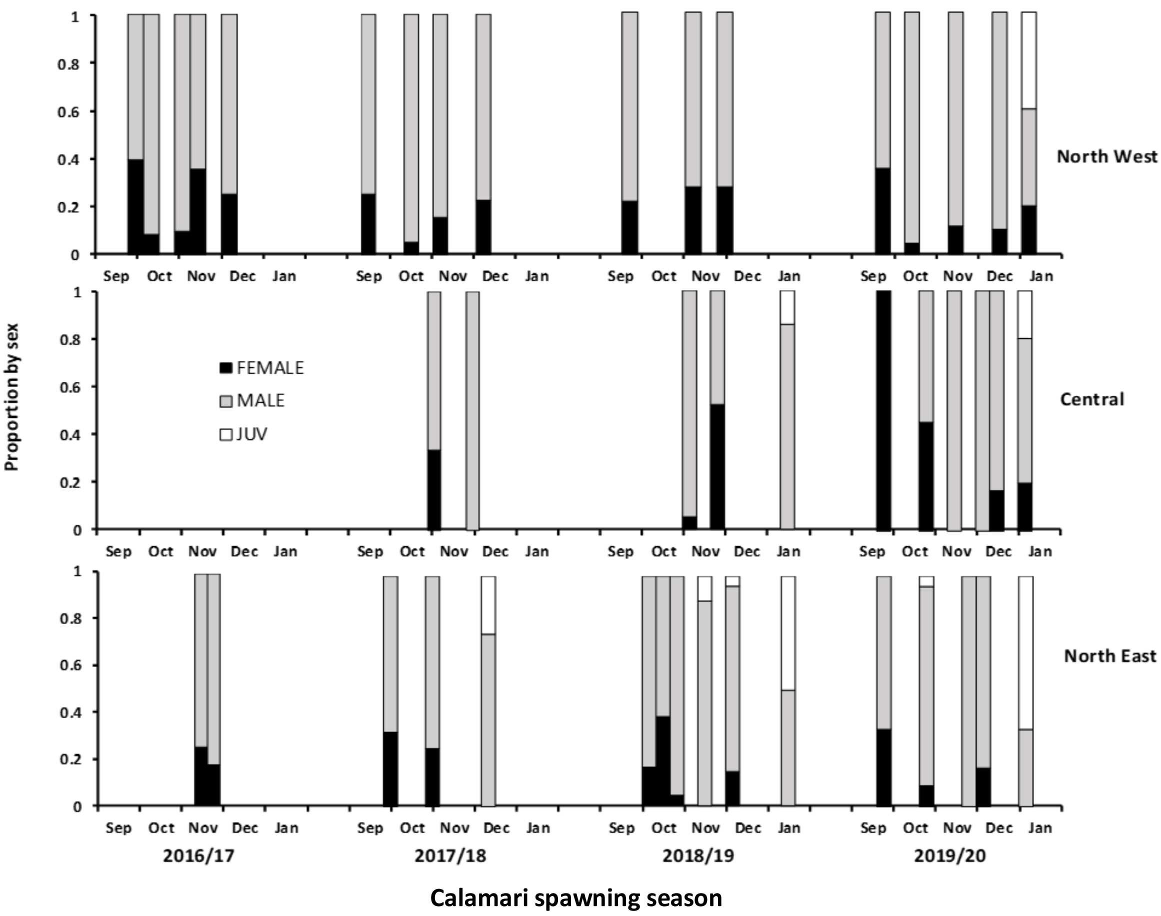


Figure 11. Sex ratios by region and season.

Objective 2: Analyse recent development of both commercial and recreational Southern Calamari fisheries on north coast

Commercial fishery

Commercial Southern Calamari catches on the north coast of Tasmania increased from less than 5 tonne (t) in seasons prior to 2000/01, to around 40 t in the 2013/14 fishing season (Figure 12). Catches subsequently increased dramatically to over 80 t in the 2016/17 season. While effort and the number of participating unique vessels have increased over the same period, catch rates have been relatively stable, with an overall slight decline (Figure 13). This may be due to the inexperience of new participants in the fishery, but it also suggests the increase in catches was due to increased effort rather than increased abundance of Southern Calamari.

Following the rapid increase to over 80 t in the 2016/17 season, catches declined to less than 30 t in the following season (2017/18). Catch, effort and catch rates on the north coast of Tasmania rebounded in the 2018/19 season to over 60 t, and dropped again in the 2019/20 season due mainly to low catches in the North East region.

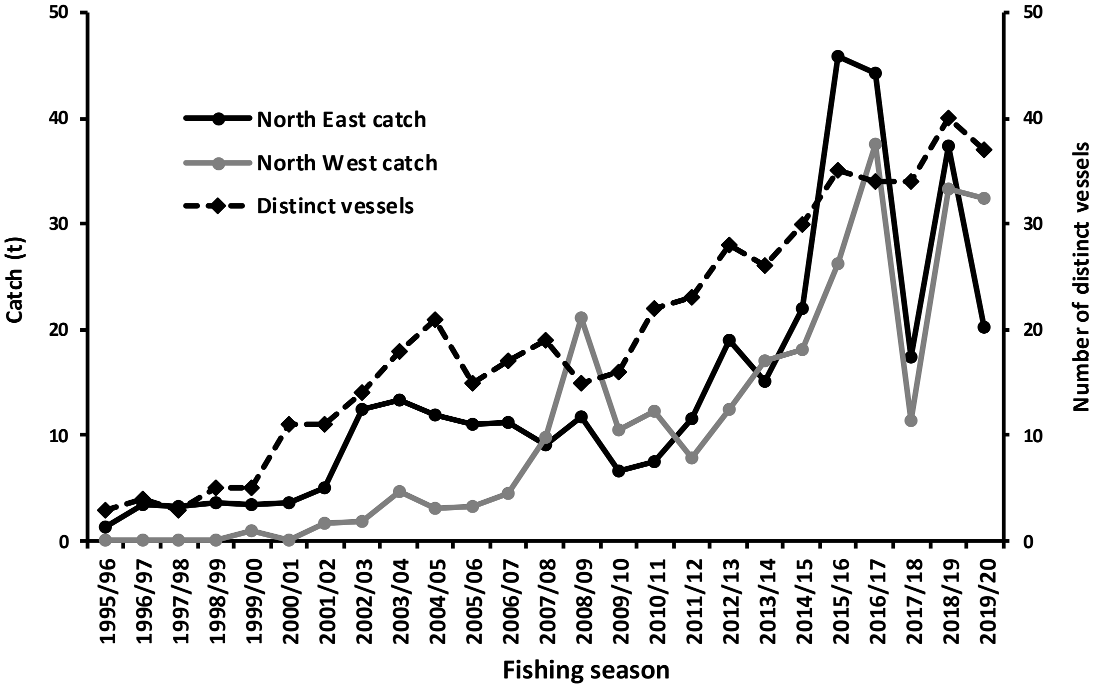


Figure 12. Participation and catch of Southern Calamari taken by jig on north coast of Tasmania plotted by fishing season.

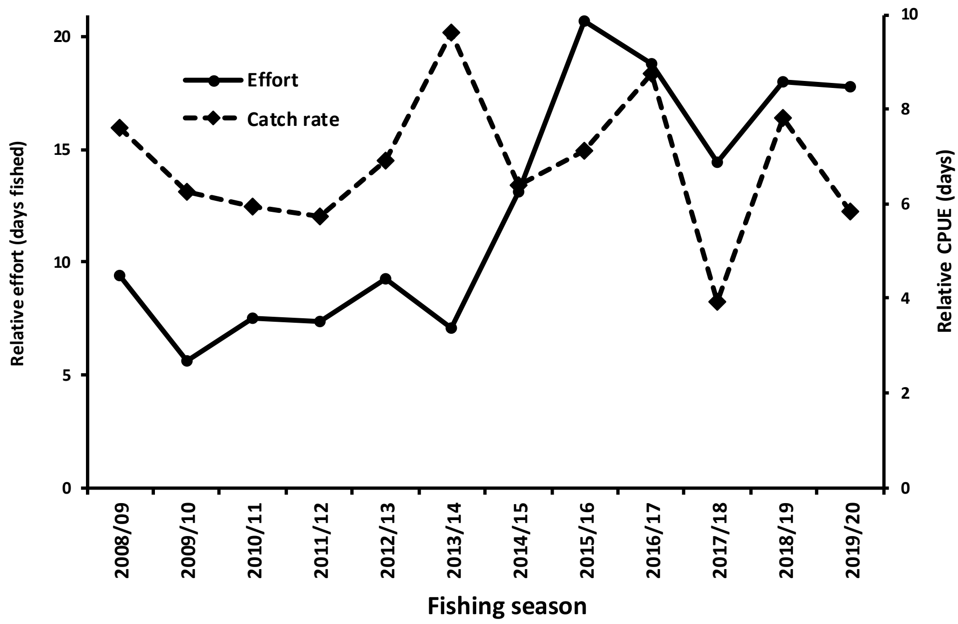


Figure 13. Relative effort (days fished) and relative catch per unit of effort (CPUE) by fishing season since 2008/09. Effort and catch rate are days fished relative to the reference year 2001/02

The recent rapid rise in catch and effort, the steady increase in participation, and the relative stability of catch rates suggest that the recent sharp increase in catches was not due to increased inshore abundance of Southern Calamari, but rather increased interest from fishers and knowledge of the species behaviour and distribution fuelled by a strong (interstate) market for the species. Further, the subsequent steep fall in catch, effort and catch rate in 2017/18 was most likely due to decreased inshore abundance of Southern Calamari.

The rapid expansion of the fishery and recent volatility sends a strong signal for a precautionary approach to the management of this fishery, as is recommended for short-lived cephalopods in general (Arkhipkin et al., 2020). Close monitoring of the status of inshore stocks is essential to gauge the efficacy of current and future management instruments, to allow adaption of management to responses in inshore spawning activity.

Relationship between commercial catches and observed inshore spawning activity

The north coast commercial Southern Calamari fishery primarily targets seasonal inshore spawning aggregations using trailered vessels, and Southern Calamari are landed individually with a rod and line using a single jig/lure. Consequently, catches are strongly associated with the inshore abundance of Southern Calamari encountered during the spawning season. While spawning undoubtably occurs in other areas, such as rocky reefs and potentially in deeper reef habitats, inshore *Amphibolis* seagrass meadows are a favoured habitat for Southern Calamari spawning, so provide high catch rates and easy access for fishers (Moltschaniwskyj and Pecl 2003, Pecl 2004).

Variability in inshore spawning activity determined from back-calculated egg mass densities corresponded with catches in the commercial fishery on the north coast both between seasons (Figure 14) and within seasons (Figure 15). Cross-correlation analysis of trends in monthly commercial catches against egg mass counts yielded a significant correlation (0.81) at zero lag time; Pearson's product-moment correlation ($t = 4.96$, $df = 13$, $p < 0.001$) (Figure 16).

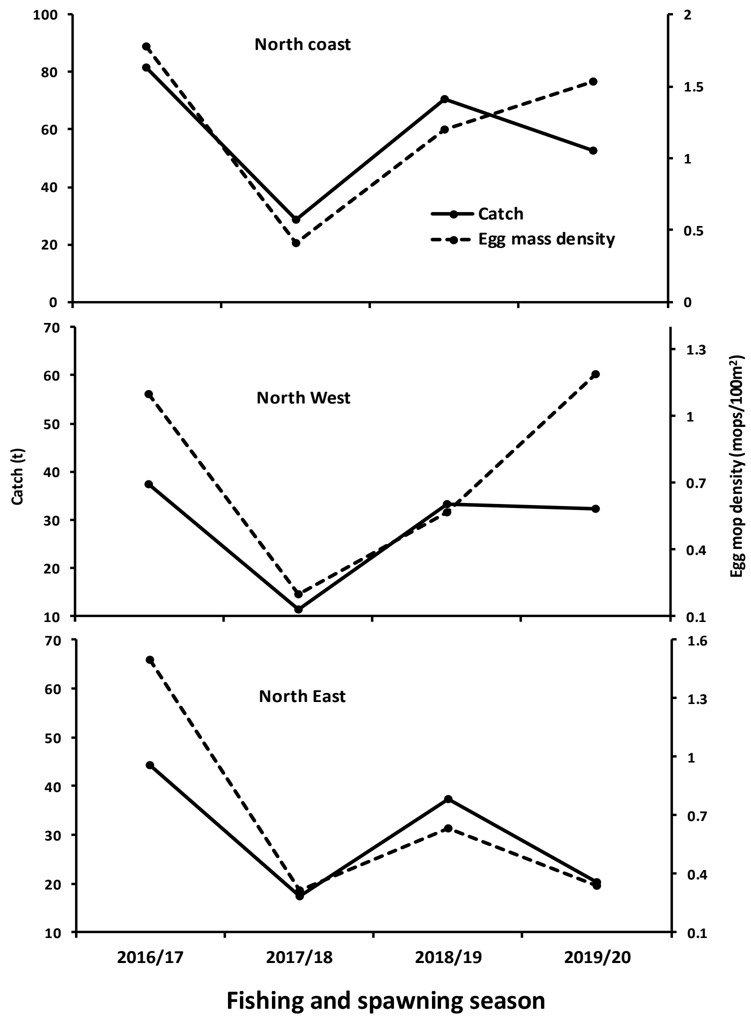


Figure 14. Annual commercial catches of Southern Calamari and back-calculated egg mass density on north coast of Tasmania (top), North West region (middle) and North East region (bottom) plotted by season.

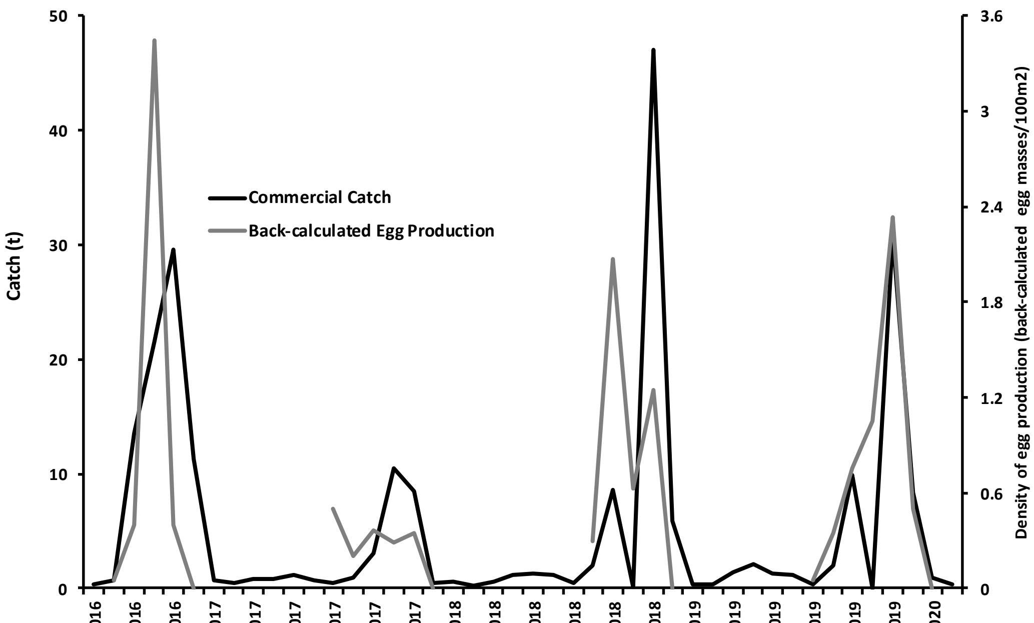


Figure 15: Plot of monthly back-calculated egg production and commercial Southern Calamari catches on north coast of Tasmania.

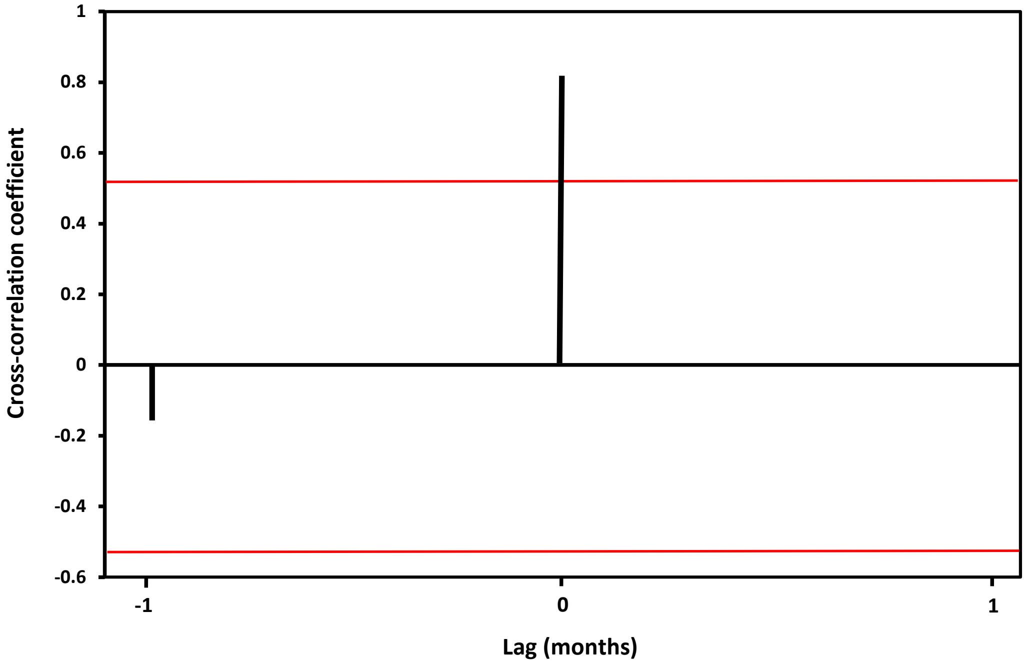


Figure 16: Cross-correlation of monthly commercial calamari catches against monthly egg mass counts on the north coast of Tasmania. Vertical line at zero months exceeds the upper red line indicating a significant positive correlation.

Recreational fishery

One of the more conspicuous developments in the recreational fishery over the past two decades has been the growth in fishery for Southern Calamari (Lyle et al., 2019). Much of this growth has been around increased awareness of the species by recreational fishers and, consistent with commercial catches, Tasmanian north coast recreational Southern Calamari catches increased steadily up to the 2017/18 season, which reported a dramatic fall in the catches on the north coast (Lyle et al., 2009, Lyle et al., 2014, Lyle et al., 2019). In previous surveys, the north coast recreational catches accounted for around 28% of recreational landings, but this fell to 16% in the 2017/18 season survey. Within the north coast, the distribution of north coast catches shifted from being dominated by the Tamar and North East at 23% of state-wide catches in 2007/08, to the North West at 18% of state catches in 2012/13 (Table 5). It should be noted that recreational catches on the north coast were of a similar magnitude to commercial catches in the fishing seasons when surveys were conducted (2007/08 and 2012/13), but fell to less than 15% of the commercial catch in the 2017/18 survey.

The north coast recreational Southern Calamari fishery displays a similar profile to the commercial fishery with steadily increasing catches and volatility in the most recent seasons. The magnitude of the recreational fishery, and its expansionary trajectory, underscores the necessity for precautionary management, management instruments that capture both commercial and recreational fishers, and the need for fishery-independent methods of assessing the status of inshore spawning activity.

Table 5. Recreational catch estimates from IMAS state-wide recreational fishing surveys for the state (TAS), North East (NEC) and North West (NWC) regions. The North East region includes the Tamar sub-region. Values in parentheses represent percentage of the state-wide recreational catch.

Region	2000/01		2007/08		2012/13		2017/18	
	Num.	Wt. (t)	Num.	Wt. (t)	Num.	Wt. (t)	Num.	Wt. (t)
NWC	-	-	2,722 (7%)	2.99	10,003 (18%)	11.0	3,082 (7%)	2.05
NEC	-	-	9,451 (23%)	10.4	4,750 (8%)	5.23	3,707 (9%)	2.46
TAS	29,473	32.4	40,525	44.6	57,728	63.5	41,498	27.58

Objective 3: Using information gathered in objectives 1 and 2, investigate likely impact of fishery on Southern Calamari populations and, if necessary, potential management options to ensure sustainable development

This project has provided insights into the timing and intensity of Southern Calamari spawning activity on key inshore seagrass habitats across the north coast of Tasmania. These habitats were chosen through consultation with key north coast commercial Southern Calamari fishers, so are likely to be closely linked to the dynamics of the fishery.

The recent sharp increases in participants, effort and catch on the north coast highlights the responsiveness of the commercial sector and the level of latent effort. Recent increases in catches are unlikely to be due to an increase in the abundance of Southern Calamari because catch rates have not increased dramatically. Rather it appears that 'word got out' that north coast fishers were making good financial returns from high catch rates in the spawning season, and good beach prices for fresh product. Since the rapid increase in catches, there has been strong inter-annual variability in catches across the north coast and also in the intensity of spawning on the seagrass beds that were surveyed.

This project has determined that the sharp decline in catches in the 2017/18 season coincided with very low densities of egg masses in key inshore seagrass beds. That is, unlike previous seasons, Southern Calamari were either in much reduced abundance or were not participating in aggregated spawning activity on inshore seagrass beds. It has also been determined that egg mass densities in inshore seagrass beds rebounded in the 2018/19 spawning season, but exhibited significant spatial variability in the following season, with strong spawning activity evident in the North West and reduced activity in the North East in 2019/20 (down to levels comparable to 2017/18). Catches in the commercial (and recreational) fisheries have been observed to fluctuate in line with observed variability in inshore egg masses densities.

The marked reduction in the north coast spawning intensity and catches evident in 2017/18 followed a period of rapid expansion of the fishery and could have been due to one or a combination of factors, such as:

- Reduced spawning activity was primarily a consequence of low spawning stock abundance, a result of the heavy fishing pressure in the preceding seasons, but the strength of the rebound in catches and egg production in 2018/19 imply a recovery in spawning biomass that was unexpectedly rapid, given the poor spawning season experienced the year before.
- It has been suggested by some industry members that increased predation pressure from the relocation of seals from the South East to the North West may have been a factor – this is unlikely to be a dominant factor as the decrease in catches and egg densities was uniform across the entire north coast rather than localised just to the North West.
- Reduced spawning activity on the inshore grounds may have been a behavioural response to unfavorable environmental conditions, as environmental conditions such as temperature and salinity are known to influence squid spawning behaviour. During the 2017/18 spawning season the north coast of Tasmania was influenced by two significant water temperature anomalies, an initial period of prolonged cold winter water temperatures which was followed by a rapid transition to warm summer temperatures (refer below). In response to these unusual conditions it is possible that inshore spawning may have been more dispersed and/or Southern Calamari may have spawned in deeper and more stable habitats (Pecl 2008) less influenced by coastal dynamics, including freshwater ingress from rivers and streams.

It is possible that the variability of Southern Calamari abundances on inshore seagrass beds during recent spawning seasons is due to a combination of factors including those listed above. Even if the fall in inshore abundance was due to Southern Calamari spawning elsewhere, other locations may not provide optimal spawning conditions and may lead to lower productivity in those spawning seasons.

Environmental influences on inshore Southern Calamari spawning activity

Cephalopods are environmentally hypersensitive and respond to environmental variation both actively, by migrating to areas more favourable for feeding or spawning, and passively (growth and survival vary according to conditions experienced) (Melzner et al., 2007, Pierce et al., 2008). Changes in environmental conditions at any life stage may cause changes in natural mortality resulting in variability in population abundance.

Temperature has a crucial impact on growth, larval survival and age of juvenile benthic settlement. Higher temperatures can also cause earlier maturation and subsequent extension of the spawning season, often dramatically increasing fecundity (Rodhouse and Hatfield 1990, Arkhipkin and Laptikhovsky 1994, Forsythe et al., 2001, Forsythe 2004). The effect of salinity on embryonic development is generally similar to that of temperature, with embryonic development and hatching survival strongly affected when salinity falls outside a species optimal range (Paulij et al., 1990). Oxygen tension is also important for egg development and survival, particularly in large egg clusters such as those deposited by Southern Calamari (Gowland et al., 2002, Steer and Moltschaniwskyj 2007), and the extent of biofouling on egg masses has been shown to influence egg survival (Gowland et al., 2002).

Migrations to inshore spawning grounds take advantage of favorable environmental conditions for egg development and hatching survival (Boletzky 1974, Ortiz et al., 2011). Eggs deposited at different times or locations will experience a variety of environmental conditions including temperature, light intensity, oxygen saturation, pollution, salinity, photoperiod and predation. As Southern Calamari egg masses are affixed to stable structures at spawning sites, successful embryonic development and egg survival are dictated almost entirely by environmental and physical conditions encountered at the spawning site.

Clearly, the environmental conditions at a chosen spawning habitat will have consequences for embryonic development and survival, subsequent growth, and the timing of the onset of maturity. The north coast fishery targets Southern Calamari on inshore spawning habitats which are likely to be strongly influenced by variations in water temperature and salinity (related to rainfall and river flow) (Pierce et al., 2008). Interannual variability in inshore spawning activity was compared with winter and spring rainfall, and sea surface temperature trends, to provide insight into the observed volatility.

Rainfall

Daily rainfall data for the Robbins Island region was sourced from the Australian Bureau of Meteorology (BOM) Smithton Aerodrome Weather Station (#091292), and from the Swan Island Weather Station (#092011) for the Cape Portland region. Rainfall summed over the 10-week period (mid-June to late August) preceding the beginning of the spawning season was compared with catches and back-calculated egg mass densities by year (Figure 17) and region (Figure 18). Comparisons of other time periods prior to and/or during the spawning season had no relationship to spawning activity or catches.

Rainfall in the period preceding the spawning season showed a similar trend to catches and egg mass densities, with the seasons yielding low catches and egg mass densities corresponding with episodes of low rainfall. This trend also appears to describe within-season spatial differences in catches and egg mass densities, with relatively low North East winter rainfall in 2019 corresponding with low catches and egg mass densities in contrast to the North West.

As low salinity has been shown to negatively influence cephalopod growth and increase mortality (Paulij et al., 1990), the positive relationship between high winter rainfall and inshore spawning activity may reflect more favorable conditions for high growth and low mortality of juvenile Southern Calamari over the winter period. This would provide a higher abundance of spawning squid at the onset of the spawning season.

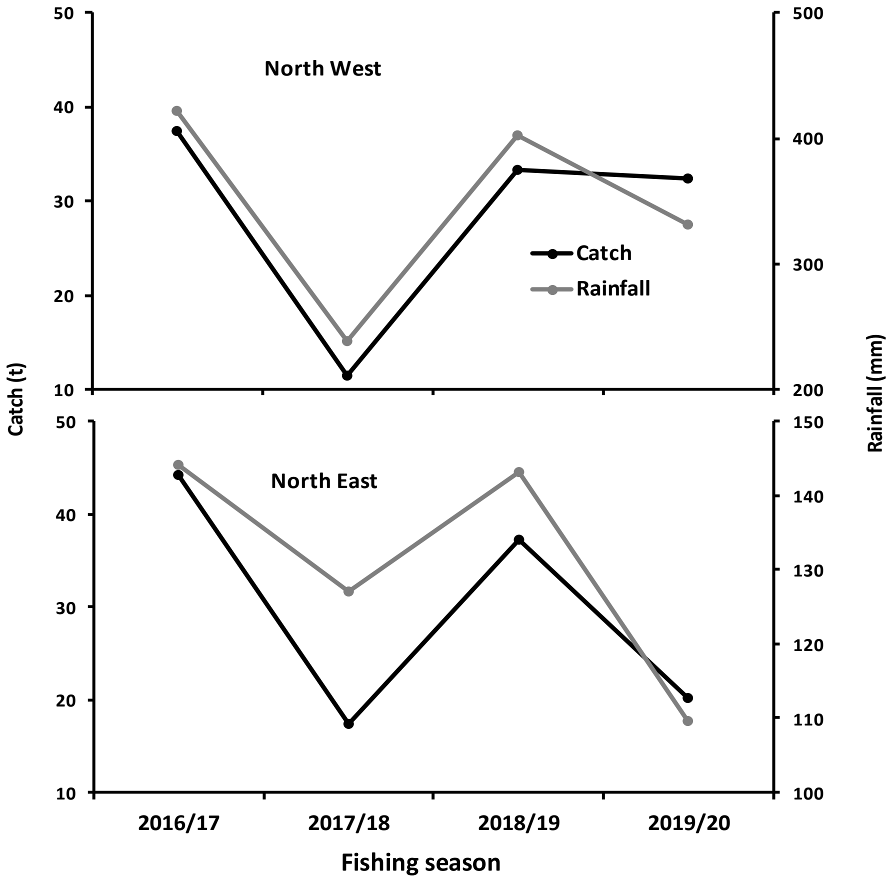


Figure 17. Comparison of commercial catches and total rainfall in 10 weeks preceding spawning season by fishing season and region.

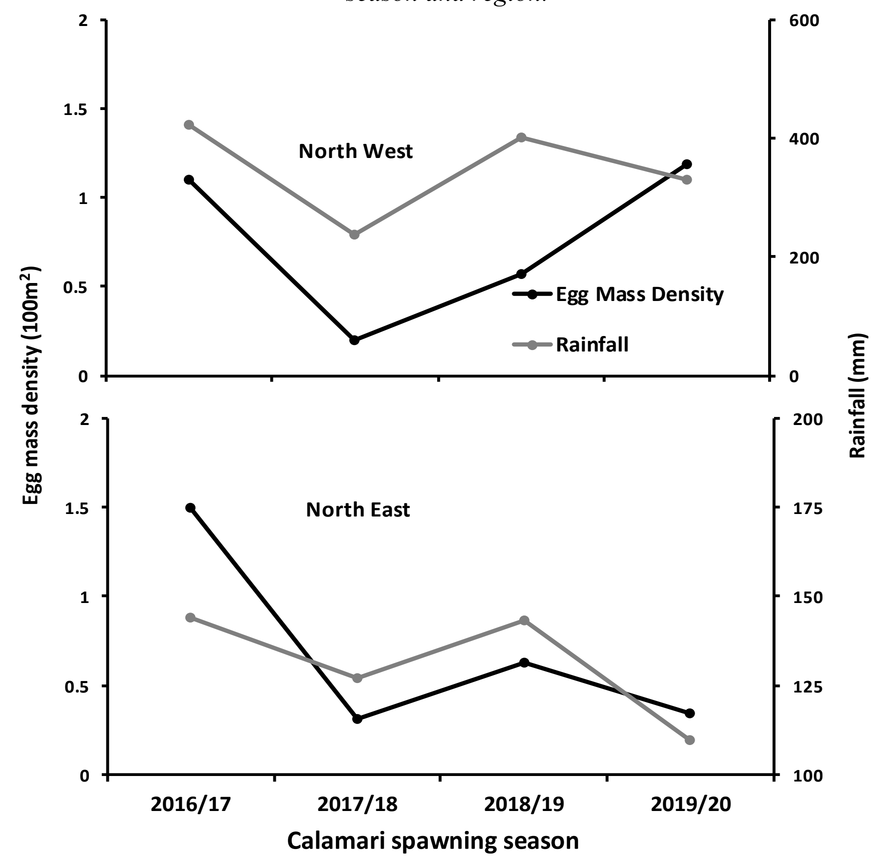


Figure 18. Comparison of back-calculated egg mass density and total rainfall in 10 weeks preceding spawning season by fishing season and region.

Sea surface temperature
High resolution sea surface temperature (SST) data was sourced using the Australian Ocean Data Network (AODN) Open Access to Ocean Data portal to the Regional Australian Multi-Sensor SST Analysis (RAMSSA) data collection, which blends multiple sources to interpolate SST on a 1/12-degree grid over the Australian region. Temperature data was downloaded for the North West region from an inshore cell, approximately two nautical miles (nm) to the east of the eastern shore of Robbins Island (40.6°S, 145°E), and for the North East region from a cell approximately 5 nm to the northwest of Cape Portland (40.6°S, 147.9°E) (Figure 19).

In the North West at the beginning of the 2017/18 season (mid-August to mid-September), the SST was almost one degree lower than the other seasons over the period of this project (Figure 20). The slope of the increase in temperature (from mid-September to mid-December) in the North West was higher in the 2017/18 season, delivering both the lowest and highest SST across the seasons sampled (Figure 21 & Figure 22). These temperature anomalies in the 2017/18 season coincide with very low commercial catches and inshore spawning activity relative to other seasons.

Low temperatures persisting into the spawning season coupled with a steep gradient of temperature change appears to correlate with low inshore spawning activity in the North West but this effect, while present, was not as strong in the North East (Figure 21 & Figure 22). Further, these conditions were not present in the 2019/20 season when low catch rates and low inshore spawning activity were encountered in the North East region.

While SST profiles show some relationship with spawning season activity, within-season comparisons of SST trends against fluctuations in peak spawning activity did not reveal clear signals (Figure 22). Peak spawning activity occurred at different temperatures in different seasons, and shifts in temperature trends did not consistently align with spawning events.

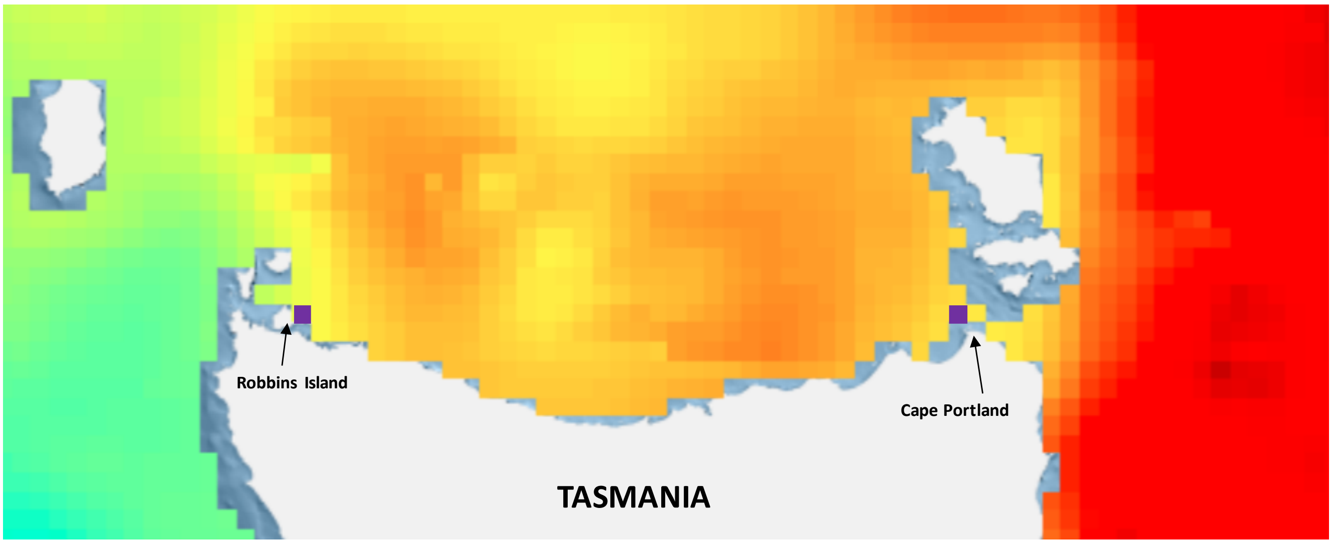


Figure 19. Sea surface temperature graphic for 20/04/2020 sourced from AODN. Purple squares indicate cells selected to represent inshore SST series for the North East and North West Southern Calamari regions.

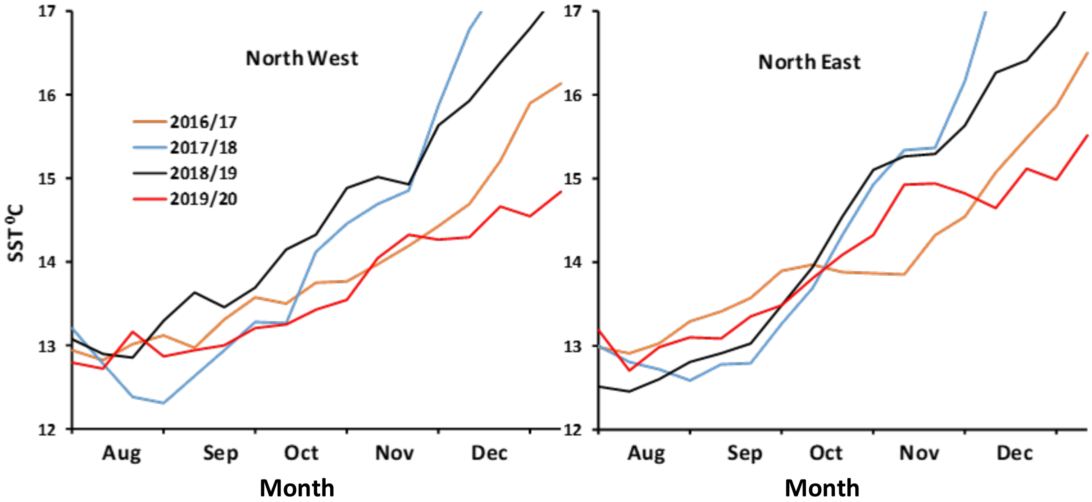


Figure 20. Weekly mean SST by spawning season and Region.

While SST and rainfall appear to influence inshore spawning activity, they are not likely to be the only environmental influences on inshore spawning activity. Water quality and clarity are strongly driven by local weather systems at the shallow inshore spawning habitats on the north coast of Tasmania. Research on the east coast of Tasmania found that spawning activity on inshore spawning habitats was composed of a series of microcohorts over the season (Moltschaniwskyj and Pecl 2006), and that there was a limited range of movement between favorable spawning habitats within a spawning season (Pecl et al., 2006).

This complexity makes the timing and duration of the spawning highly variable and difficult to predict. For example, the low spawning activity in the 2017/18 season may reflect poor inshore spawning conditions at the beginning of the season (unusually low SST), in combination with lower abundance in later microcohorts as a result of environmental factors influencing winter growth and mortality.

Empirical relationships between the distribution or abundance of cephalopod species and environmental conditions are widely documented (Pierce et al., 2008), and in some cases appear to be sufficiently predictable to be used for responsive fishery management (Waluda et al., 2001, Sobrino et al., 2002, Otero et al., 2008).

However, the inshore Southern Calamari spawning habitats on the north coast of Tasmania are likely to be highly responsive to a combination of oceanographic and local weather patterns, such as changes in salinity and temperature due to catchment rainfall events, which will in turn influence inshore Southern Calamari spawning activity at varying spatial and temporal scales. Clearly, this limits the potential for the use of environmental indicators in responsive management, and particularly with the additional uncertainty from environmental change due to climate change.

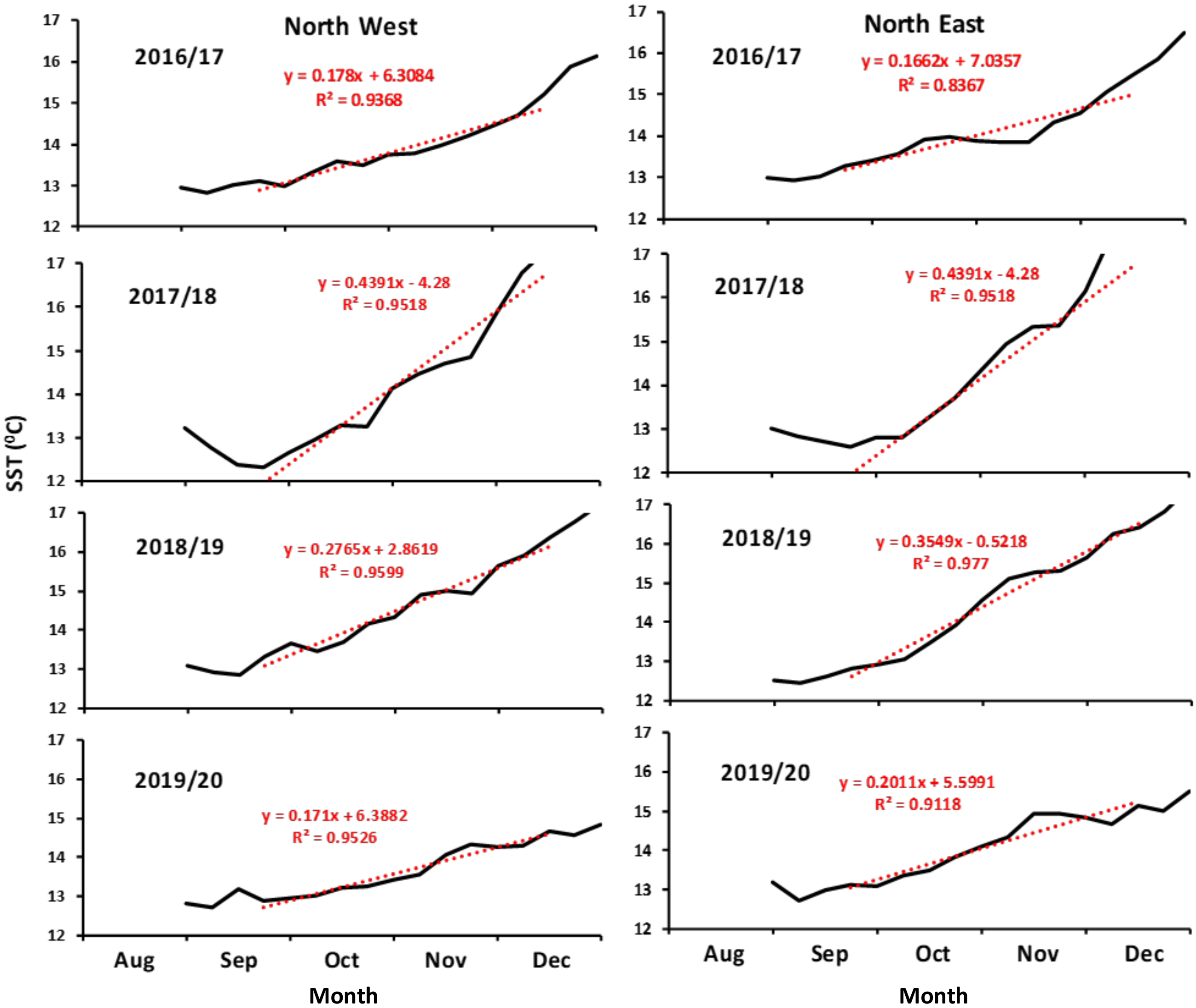


Figure 21. Weekly mean SST in North West (left) and North East (right) regions and linear model of temperature change from mid-September to mid-December.

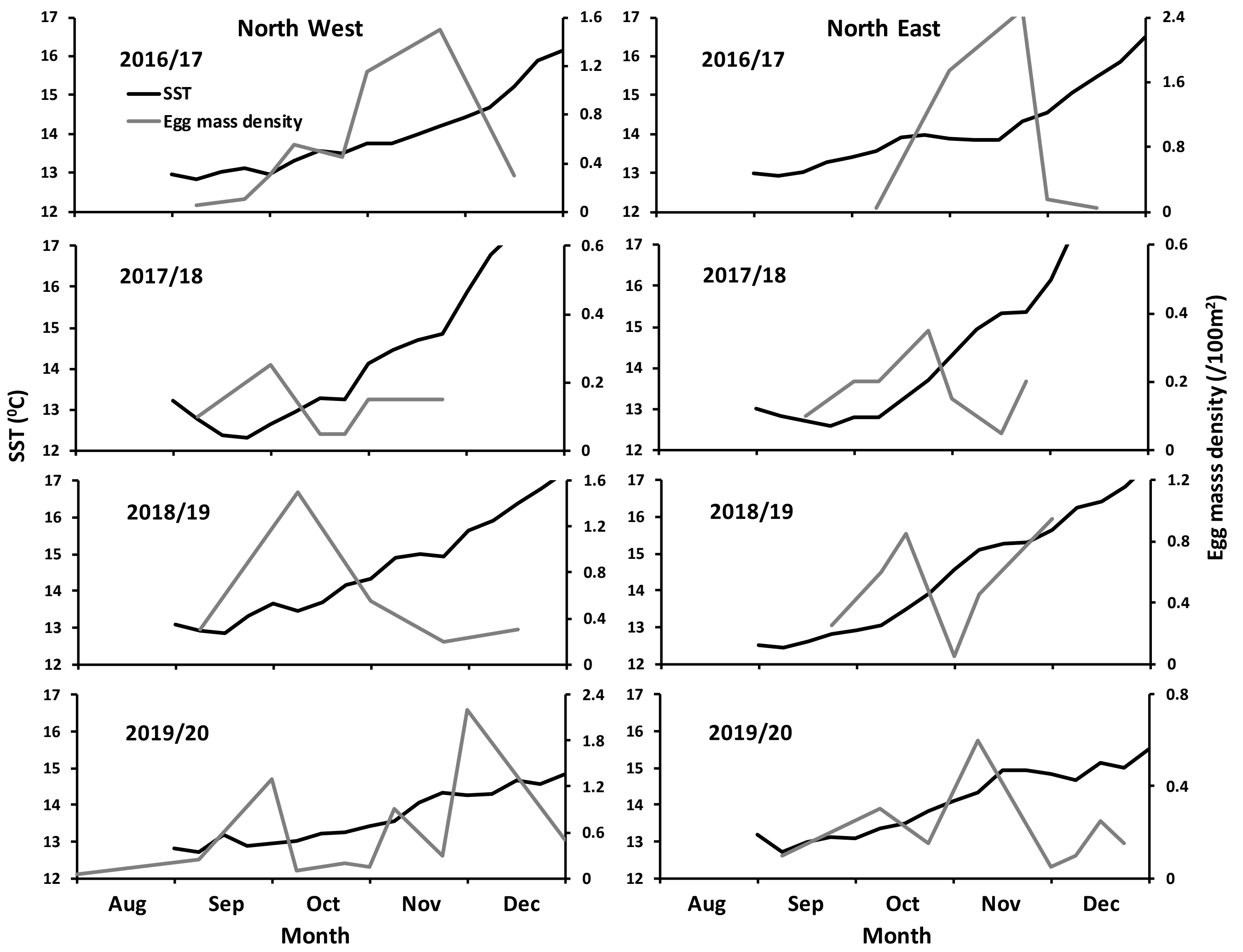


Figure 22. Weekly mean SST (primary y axis) and back-calculated egg mass density (secondary y axis), in North West (L) and North East (R) regions.

Conclusions

The volatility of catches and spawning activity in the last five seasons has underscored the need for a precautionary approach to management of the fishery, and has prompted consideration of further management changes. The evidence-base from this project will contribute to assessing the management tools currently applied and those under review by the Tasmanian Government. These include:

- **North coast seasonal spawning closures** which have already been implemented and are a control well-suited to Southern Calamari, due to their short lifespan (<12 months) and their participation in a single spawning season.

  While spawning season closures alone are unlikely to provide sufficient protection from the dramatic increase in catch and effort in the north coast fishery, they are an important instrument to protect spawning stocks. The effectiveness of the protection afforded by spawning closures should be considered in regard to the trade-off between a closure of sufficient length and breadth, to encompass the spatio-temporal variability in spawning activity while maintaining a period for fishers to exploit the spawning aggregations prior to senescence.

  Four-week closures are likely to provide a varying degree of protection contingent on the timing of seasonal peaks in spawning activity. The egg mass survey methodology applied in this project provides a fishery-independent means of directly assessing the efficacy of the current closure regime.

- **Recreational bag and boat limits** will, to some degree, control the rapid expansion of recreational Southern Calamari fishing on the north coast of Tasmania. However, ongoing monitoring of recreational catch and effort will be required to assess the effect of these measures on fisher behavior and catch.

- **Limiting commercial access** by introducing a new license issued based on catch history is a control that has precedent given it was applied to the east coast Southern Calamari fishery. Since spawning season closures of four weeks offer only moderate levels of protection, given the variability in spawning season, additional controls may need to be considered due to the potential for further activation of latent effort of commercial scalefish licence holders towards the fishery. This is particularly relevant for seasons with early and/or late peaks in spawning activity, where a far lower degree of protection would be afforded by the current spawning closure regime. While this control method is administratively complicated, as previously mentioned it is not unprecedented as a similar measure applies to the east coast Southern Calamari fishery.

- **Applying area closures** is a control that will likely drive spatial expansion of the Southern Calamari fishery into adjacent unfished areas, which currently offer refuge for spawning stocks. The inshore spawning aggregations currently targeted by the north coast Southern Calamari fishery may be resilient to current and/or future levels of exploitation due to egg production from other spawning habitats, such as the offshore islands at the eastern and western extremities of the Tasmanian north coast. To date, accessibility has determined the spatial extent of the north coast Southern Calamari fishery, as the commercial Southern Calamari fleet is primarily small dinghies. A shift to larger vessels to exploit less accessible spawning aggregations may influence the sustainability of the current fishery.

Implications

This project has responded directly to management and industry concerns over a rapid increase in catch and effort on the Tasmanian north coast Southern Calamari fishery. Calamari are increasingly becoming a valuable species and, if this resource is managed in a sustainable fashion, it will continue to increase in value. However, overexpansion in this fishery is likely to have negative economic ramifications for the fishery, due to both overcapacity and decreased productivity. Findings from this project will assist industry to maximise profitability by preventing overexpansion and maintaining productivity. DPIPWE managers have utilised the information obtained in this project to improve management of this fishery.

The survey methodology applied in this project provided the evidence-base for implementing the first north coast Southern Calamari spawning closure in the 2017/18 season. Extension of the spatial and temporal extent of subsequent closures in the 2018/19 and 2019/20 spawning seasons was also based on information generated by this project and was well accepted by stakeholders. Monitoring conducted has confirmed the close association of the fishery with inshore spawning aggregations, and has measured high spatial and temporal variability in the intensity and pattern of inshore spawning activity both within and between spawning seasons. The egg mass survey methodology implemented in this project has a demonstrated application in investigating the dynamics of inshore spawning aggregations of Southern Calamari on the north coast of Tasmania.

Recommendations

The results from this project highlight the need for a precautionary approach to management, and the need for consideration of additional controls for the Tasmanian north coast Southern Calamari fishery, due to the:

need to protect vulnerable spawning stock, due to the life history of Southern Calamari

rapid increase in catch, effort and participation by both commercial and recreational sectors

inter-annual variability in catch, effort and inshore spawning activity in recent seasons

responsiveness of inshore spawning activity to environmental changes.

Key recommendations from this project are:
consideration of ongoing fishery-independent monitoring of the efficacy of necessary changes during the current dynamic period of management intervention

potential ongoing research into environmental correlations with inshore spawning aggregation, to provide some predictive capacity for the timing of closures and seasonal-planning for the commercial sector (e.g. prediction of ‘good’ and ‘bad’ years to aid decisions on targeting or diversifying in the multi-species scalefish fishery)

further research to determine proximity and viability of other inshore spawning habitat, currently a natural refuge due to its remoteness from the small dinghy fleet (e.g. island groups along north coast), and consideration of protecting nearby unfished areas that may contribute to stock re-building if necessary.

Extension and Adoption

Information arising from this study has been well received by stake-holders and was applied directly by management. This project has also contributed to the information under-pinning a Tasmanian State Government review of the Tasmanian Southern Calamari Fishery (DPIPWE 2018) and the cost-benefit analysis of management options. A summary of consultation, extension and adoption associated with the development and delivery of this FRDC project is presented in Table 6.

Project stakeholders have been kept updated on the outcomes of the project primarily through presentations to the Tasmanian Scalefish Fishery Advisory Committee (SFAC) and the Recreational Fisheries Advisory Committee (RecFAC). The results each year have been used to provide an evidence base for spawning season closures in the 2017/18, 2018/19 and 2019/20 fishing seasons.

Table 6. A summary of consultation, extension and adoption associated with the development and delivery of this FRDC project

Year	**Event - outcome**
2016	Review/consultation of original FRDC application
	The project was discussed at length at the July 2016 meeting of the SFAC. Input was provided from multiple commercial fishers who had a history of catching calamari on the north coast. This assisted in refining the project objectives focusing on assessing the seasonal and spatial variation in the spawning of calamari to inform on a spawning season closure. The input also helped refine the spatial scope and survey regions and sites on the North Coast.
2018	A project update was presented to the RecFAC in April 2018 and to the SFAC in April 2018. The presentations were used as a basis of discussion that led to a proposal put to the Minister for a spawning season closure for calamari on the North Coast for the 2019 spawning season. The closure was subsequently implemented.
2019	A project update was presented to the RecFAC in March 2019 and the SFAC in July 2019. The presentation was used as a basis of discussion that led to two options put to the Minister for a spawning season closure for calamari on the North Coast for the 2019 spawning season. A closure was subsequently implemented.
2020	Tasmanian Seafood Industry News (TSIN) article – Revealing calamari spawning habits on Tasmania's north coast.

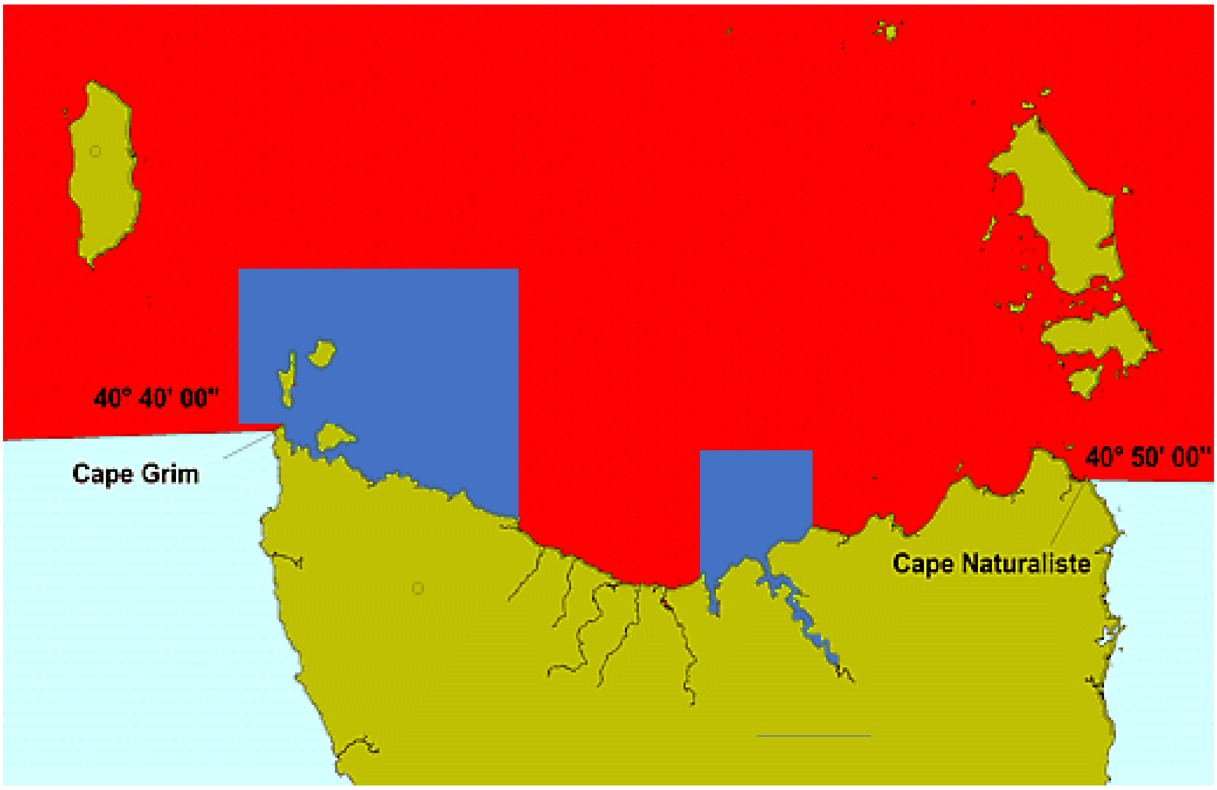


Figure 23. Areas closed to fishing during Tasmanian north coast spawning season closures in 2017/18 (blue zones), and subsequent seasons (blue and red zones).

Appendix 1: Staff

Name	Organisation	Funding
Tracey, Sean	IMAS	FRDC and in-kind
Lyle, Jeremy	IMAS	FRDC and in-kind
Pecl, Gretta	IMAS	FRDC and in-kind
Krueck, Nils	IMAS	in-kind
Ewing, Graeme	IMAS	FRDC and in-kind
Forbes, Edward	IMAS	FRDC and in-kind

Appendix 2: Intellectual Property

This research is for the public domain. This report and any resulting manuscripts are intended for wide dissemination and promotion.

Appendix 3: Ethics and permits

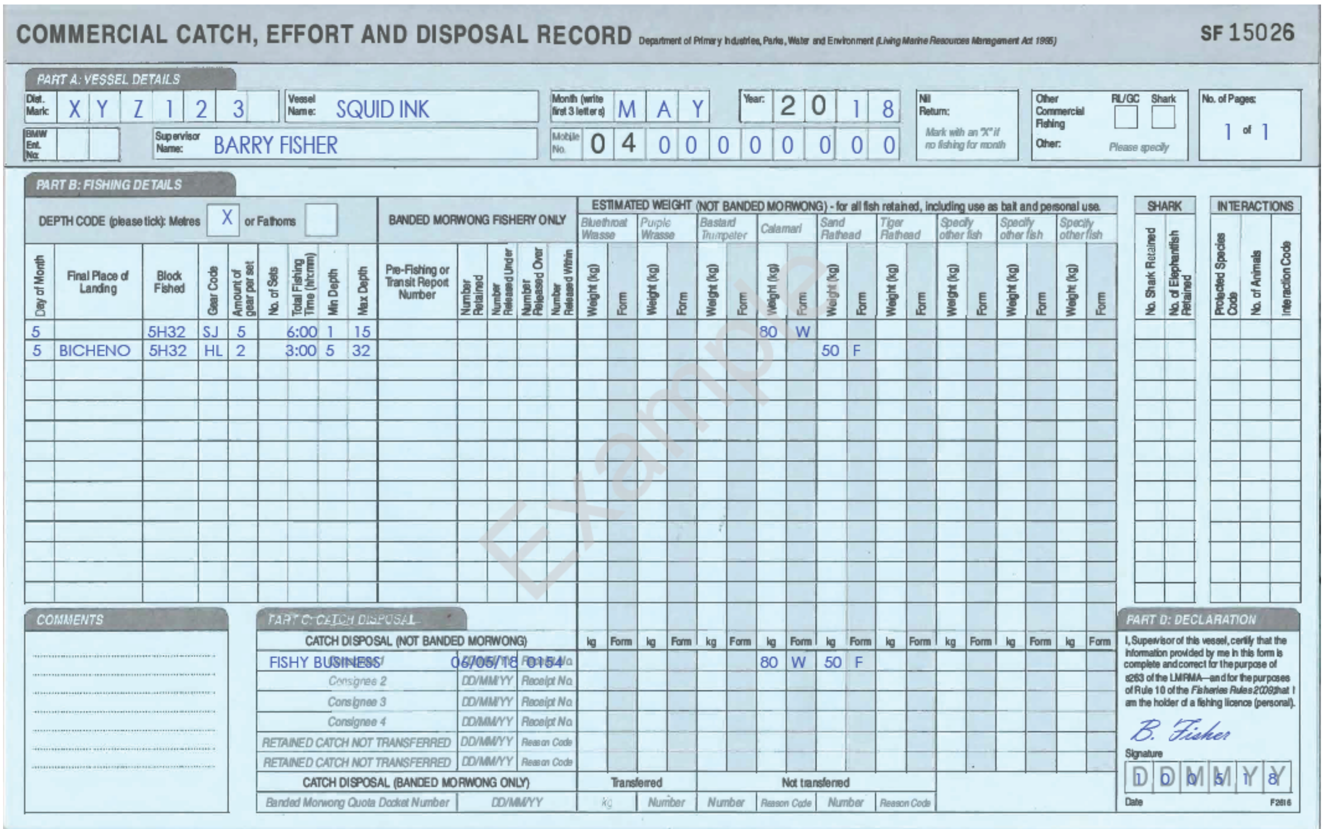
All procedures were undertaken with University of Tasmania Animal Ethics Committee approval (permits A15934 and A18370) and scientific permits 16132, 17134, 18125 and 19120 issued under Section 14 of the Living Marine Resources Management Act 1995.

Appendix 4: Location and habitat characteristics of sample sites

Region	Location	Site	Substrate	Plant Cover*	Sea Grass code	Depth (m)	Season 16/17	17/18	18/19	19/20
North West	Robbins Island	02	Sand	95% Amph 5% Sand	5	2.0	x	x	x	x
	Robbins Island	03	Cobble	95% Amph 5% Reef	4	4.0	x	x	x	x
	Robbins Island	04	Sand/Cobble	95% Amph 5% Reef	5	2.0	x	x	x	x
	Robbins Island	05	Sand	100% Amph	5	1.0	x	x	x	x
	Robbins Island	06	Cobble	80% Amph 20% Reef	4	4.5	x	x	x	x
	Robbins Island	07	Sand	100% Amph	5	1.1	x	x	x	x
	Robbins Island	08	Cobble	80% Amph 20% Reef	4	4.0	x	x	x	x
	Robbins Island	09	Cobble	80% Amph 20% Reef	4	4.0	x	x	x	x
	Robbins Island	10	Sand/Cobble	70% Amph 30% Reef	3	4.6	x	x	x	x
	Robbins Island	11	Sand/Cobble	70% Amph 30% Reef	4	3.5	x	x	x	x
	Wynyard	02	Sand	95% Amph 5% Sand	5	2.0	x	x	x	x
	Wynyard	03	Cobble	95% Amph 5% Reef	4	4.0	x	x	x	x
	Wynyard	04	Sand/Cobble	95% Amph 5% Reef	5	2.0	x	x	x	x
	Wynyard	05	Sand	100% Amph	5	1.0	x	x	x	x
	Wynyard	06	Cobble	80% Amph 20% Reef	4	4.5	x	x	x	x
Central	Tamar River	01	Gravel/Cobble	70% Amph 30% Reef	4	5.0		x	x	x
	Tamar River	02	reef	80% Amph 20% Reef	4	4.0		x	x	x
	Tamar River	03	reef	60% Amph 40% Reef	4	2.0		x	x	x
	Tamar River	04	reef	50% Amph 50% Reef	3	5.0		x	x	x
	Tamar River	05	cobble/gravel	100% Amph	5	3.0		x	x	x
	Tamar River	06	Cobble/Reef	90% Amph 10% Reef	4	5.0			x	
	Ulverstone	01	Coarse Cobble	Amph 90% Cobble 10%	4	2.0		x	x	
	Ulverstone	02	Coarse Cobble	Amph 90% Cobble 10%	4	1.5		x	x	
	Ulverstone	03	Large Cobble	Amph 50% Cobble 50%	3	1.5		x	x	
	Ulverstone	04	Cobble	Amph 70% Cobble 30%	4	1.5		x	x	
	Ulverstone	05	Cobble	Amph 80% Cobble 20%	4	2.5		x	x	
North East	Bridport	01	Sand	70% Amph 30% Reef	4	1.0		x	x	
	Bridport	02	Sand	60% Amph 40% Sand	4	1.5		x	x	
	Bridport	03	Sand	90% Amph 10% Pos	5	1.5		x	x	
	Bridport	04	Fine Sand	100% Amph	5	3.0		x	x	
	Bridport	05	Fine Sand	100% Amph	5	4.0		x	x	
	Cape Portland	01	Sand	100% Amph	5	2.0	x	x	x	x
	Cape Portland	02	Sand	70% Amph 30% Pos	5	3.5	x	x	x	x
	Cape Portland	03	Sand	100% Pos	0	6.0	x			
	Cape Portland	04	Sand	100% Amph	5	3.0	x			
	Cape Portland	05	Fine Sand	100% Amph	5	3.0		x	x	x
	Cape Portland	06	Fine Sand	100% Amph	5	2.5		x	x	x
	Cape Portland	07	Fine Sand	95% Amph 5% Reef	3	4.5		x	x	x
	Cape Portland	08	Sand Reef	70% Amph 30% Reef	3	4.0		x	x	x
	Cape Portland	09	Sand	80% Amph 20% Sand	4	4.0		x	x	x
	Cape Portland	10	Fine Sand	100% Amph	4	2.0		x	x	x
	Cape Portland	11	Sand Cobble	100% Amph	5	1.5		x	x	x
	Cape Portland	12	Sand	100% Amph	5	3.5		x	x	x
	Weymouth	01	Sand	100% Amph	5	5.0		x		
	Weymouth	02	Sand	100% Amph	5	2.5		x		
	Weymouth	03	Sand	100% Amph	5	3.0		x		
	Weymouth	04	Sand	100% Amph	5	3.5		x		

* *Plant Cover: Amph refers to the seagrass Amphibolis antarctica, reef refers to emergent rock hosting algae and/or seaweed, and Pos refers to the seagrass Posidonia australis.*

Appendix 5: Example Southern Calamari entry in the Tasmanian Commercial Catch, Effort and Disposal Record



COMMERCIAL CATCH, EFFORT AND DISPOSAL RECORD Department of Primary Industries, Parks, Water and Environment (*Living Marine Resources Management Act 1995*) SF 15026

PART A: VESSEL DETAILS

Dist. Mark: X Y Z 1 2 3 | Vessel Name: SQUID INK | Month (write first 3 letters): M A Y | Year: 2 0 1 8 | Nil Return: Mark with an "X" if no fishing for month | Other Commercial Fishing: RL/GC Shark; Other: Please specify | No. of Pages: 1 of 1

BMW Ent. No: | Supervisor Name: BARRY FISHER | Mobile No. 0 4 0 0 0 0 0 0 0 0

PART B: FISHING DETAILS

DEPTH CODE (please tick): Metres X or Fathoms

Day of Month	Final Place of Landing	Block Fished	Gear Code	Amount of gear per set	No. of Sets	Total Fishing Time (hh:mm)	Min Depth	Max Depth	Banded Morwong Fishery Only: Pre-Fishing or Transit Report Number	Number Retained	Number Released Under	Number Released Over	Number Released Within	Bluethroat Wrasse Weight (kg)	Form	Purple Wrasse Weight (kg)	Form	Bastard Trumpeter Weight (kg)	Form	Calamari Weight (kg)	Form	Sand Flathead Weight (kg)	Form	Tiger Flathead Weight (kg)	Form	Specify other fish Weight (kg)	Form	Specify other fish Weight (kg)	Form	Specify other fish Weight (kg)	Form	Shark: No. Shark Retained	No. of Elephantfish Retained	Interactions: Protected Species Code	No. of Animals	Interaction Code
5		5H32	SJ	5		6:00	1	15												80	W															
5	BICHENO	5H32	HL	2		3:00	5	32														50	F													

COMMENTS

PART C: CATCH DISPOSAL

CATCH DISPOSAL (NOT BANDED MORWONG)	DD/MM/YY	Receipt No.	Calamari kg	Form	Sand Flathead kg	Form
FISHY BUSINESS	06/05/18	0154	80	W	50	F
Consignee 2	DD/MM/YY	Receipt No.				
Consignee 3	DD/MM/YY	Receipt No.				
Consignee 4	DD/MM/YY	Receipt No.				
RETAINED CATCH NOT TRANSFERRED	DD/MM/YY	Reason Code				
RETAINED CATCH NOT TRANSFERRED	DD/MM/YY	Reason Code				

CATCH DISPOSAL (BANDED MORWONG ONLY): Banded Morwong Quota Docket Number | DD/MM/YY | Transferred: kg, Number | Not transferred: Number, Reason Code, Number, Reason Code

PART D: DECLARATION

I, Supervisor of this vessel, certify that the information provided by me in this form is complete and correct for the purpose of s263 of the LMRMA—and for the purposes of Rule 10 of the *Fisheries Rules 2009* that I am the holder of a fishing licence (personal).

B. Fisher

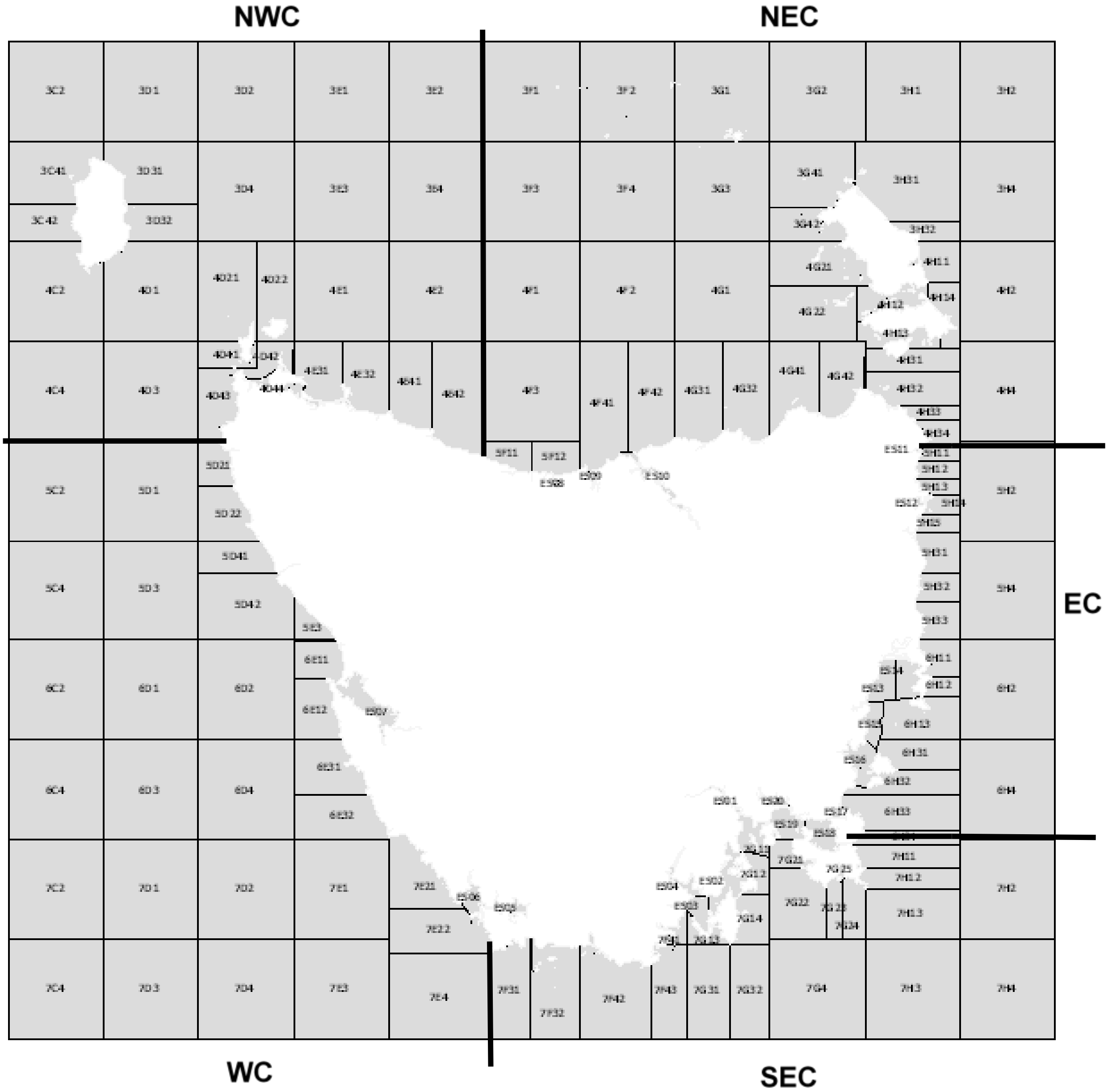
Signature

Date: 1 0 0 5 1 8

F2816

Appendix 6: Fishing blocks used to assign a location to fishing activity recorded in the Tasmanian Commercial Catch, Effort and Disposal Record

This map also shows the assessment regions used to aggregate catch and effort data in this report. NEC = northeast coast, NWC = northwest coast, SEC = southeast coast, EC = east coast, and WC = west coast. Catch and effort data referred to as “North Coast” in this report refers to data pooled from NEC and NWC regions.



Appendix 7: References

Arkhipkin, A. and V. Laptikhovsky (1994). "Seasonal and interannual variability in growth and maturation of winter-spawning *Illex argentinus* (Cephalopoda, Ommastrephidae) in the Southwest Atlantic." Aquatic Living Resources **7**: 221-232.

Arkhipkin, A. I., L. C. Hendrickson, I. Paya, G. J. Pierce, R. H. Roa-Ureta, J. Robin and A. Winter (2020). "Stock assessment and management of cephalopods: advances and challenges for short-lived fishery resources " ICES Journal of Marine Science, Contribution to the Symposium: 'Johan Hjort Symposium 2019'.

Bell, J. D., J. Lyle, J. Andre and K. Hartmann (2016). Tasmanian scalefish fishery: ecological risk assessment. Institute for Marine and Antarctic Studies, Hobart, Australia.

Boletzky, S. V. (1974). "The larvae of Cephalopoda: A review." Thalassia Jugoslavica **10**(1/2): 45-76.

DPIPWE (2018). Managing our Calamari Fishery. Hobart, Tasmanian Government (https://dpipwe.tas.gov.au/Documents/Managing%20our%20Calamari%20Fishery.pdf).

DPIPWE (2018). Review of the southern calamari fishery; Analysis of management tools. Hobart, Tasmanian Government (https://dpipwe.tas.gov.au/Documents/Calamari-2018-Analysis-of-Management-Tools.pdf).

Edgar, G. J. (1997). Australian Marine Life: the Plants and Animals of Temperate Waters. Melbourne, Reed Books.

Forsythe, J. (2004). "Does the Californian market squid (*Loligo opalescens*) spawn naturally during the day or at night? A note on the successful use of ROVs to obtain basic fisheries biology data." Fisheries Bulletin **102**: 389-392.

Forsythe, J. W., L. S. Walsh, P. E. Turk and P. G. Lee (2001). "Impact of temperature on juvenile growth and age at first egg-laying of the Pacific reef squid *Sepioteuthis lessoniana* reared in captivity." Marine Biology **138**: 103-112.

Gomon, M., D. Bray and R. Kuiter (2008). Fishes of Australia's southern coast, Reed New Holland.

Gowland, F. C., N. A. Moltschaniwskyj and M. A. Steer (2002). "Description and quantification of developmental abnormalities in a natural *Sepioteuthis australis* spawning population (Mollusca: Cephalopoda)." Marine Ecology Progress Series **243**: 133-141.

Henry, G. W. and J. Lyle (2003). The national recreational and indigenous fishing survey. Final Report to the Fisheries Research and Development Corporation, Project 99/158, NSW Fisheries Final Report Series 40**:** 188.

Hibberd, T. and G. T. Pecl (2007). "Effects of commercial fishing on the population structure of spawning southern calamary (*Sepioteuthis australis*)." Reviews in Fish Biology and Fisheries **17**(2-3): 207-221.

Holmes, E. E., M. D. Scheuerell and E. J. Ward (2020). Applied time series analysis for fisheries and environmental data. 2725 Montlake Blvd E., Seattle, NOAA Fisheries, Northwest Fisheries Science Center.

Krueck, N., J. M. Lyle and K. J. Hartman (2020). Tasmanian Scalefish Fishery Assessment 2018/19. Hobart, Institute for Marine and Antarctic Studies, University of Tasmania.

Lipinski, M. R. (1979). Universal maturity scale for the commercially important squids. The results of maturity classification of the *Illex illecebrosus* population for the years 1973-77. ICNAF Res. Doc. 79/2/38, serial 5364**:** 1-40.

Lyle, J., K. E. Stark and S. R. Tracey (2014). 2012-13 Survey of recreational fishing in Tasmania. Hobart, Institute for Marine and Antactic Studies, University of Tasmania.

Lyle, J. M., K. E. Stark, G. P. Ewing and S. R. Tracey (2019). 2017-18 Survey of Recreational Fishing in Tasmania. Hobart, Institute for Marine and Antarctic Studies, University of Tasmania 123.

Lyle, J. M., S. R. Tracey, K. E. Stark and S. Wotherspoon (2009). 2007-08 Survey of Recreational Fishing in Tasmania. Hobart, Tasmanian Aquaculture and Fisheries Institute, University of Tasmania 97.

Melzner, F., C. Bock and H. O. Portner (2007). "Allometry of thermal limitation in the cephalopod *Sepia officinalis*." Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology **146**(2): 149-154.

Moltschaniwskyj, N. A. and G. T. Pecl (2003). "Small-scale spatial and temporal patterns of egg production by the temperate loliginid squid *Sepioteuthis australis*." Marine Biology **142**: 509-516.

Moltschaniwskyj, N. A. and G. T. Pecl (2006). "Spawning aggregations of squid (*Sepioteuthis australis*) populations: a continuum of 'microcohorts'." Reviews in Fish Biology and Fisheries **17**(2): 183.

Moltschaniwskyj, N. A., G. T. Pecl, J. Lyle, M. Haddon and M. A. Steer (2003). Population dynamics and reproductive ecology of the southern calamari (*Sepioteuthis australis*) in Tasmania. Final Report to the Fisheries Research and Development Corporation, Project 2000/121, Tasmanian Aquaculture and Fisheries Institute, University of Tasmania**:** 159.

Moltschaniwskyj, N. A. and M. A. Steer (2004). "Spatial and seasonal variation in reproductive characteristics and spawning of southern calamary (*Sepioteuthis australis*): spreading the mortality risk." ICES Journal of Marine Science **61**: 921-927.

Moore, B., J. Lyle and K. Hartmann (2019). Tasmanian scalefish fishery assessment 2017/18. Hobart, Institute for Marine and Antarctic Studies, University of Tasmania.

Ortiz, N., M. E. Re, F. Marquez and N. G. Glembocki (2011). "The reproductive cycle of the red octopus *Enteroctopus megalocyathus* in fishing areas of Northern Patagonian coast." Fisheries Research **110**(1): 217-223.

Otero, J., X. A. Alvarez-Salgado, A. F. Gonzalez, A. Miranda, S. B. Groom, J. M. Cabanas, G. Casas, B. Wheatley and A. Guerra (2008). "Bottom-up control of common octopus *Octopus vulgaris* in the Galician upwelling system, northeast Atlantic Ocean." Marine Ecology Progress Series **362**: 181-192.

Paulij, W. P., R. H. Bogaards and J. M. Denuce (1990). "Influence of salinity on embryonic development and the distribution of *Sepia officinalis* in the Delta Area (South Western part of The Netherlands)." Marine Biology **107**(1): 17-23.

Pecl, G. (2001). "Flexible reproductive strategies in tropical and temperate *Sepioteuthis* squids." Marine Biology **138**: 93-101.

Pecl, G., S. R. Tracey, J. M. Semmens and G. Jackson (2006). "Use of acoustic telemetry for spatial management of southern calamary *Sepioteuthis australis*, a highly mobile inshore squid species " Marine Ecology Progress Series **328**: 1-15.

Pecl, G. T. (2004). "The in situ relationships between season of hatching, growth and condition in the southern calamary, *Sepioteuthis australis*." Marine and Freshwater Research **55**: 429-438.

Pecl, G. T. (2008). "Batch or trickle: understanding the multiple spawning strategy of southern calamary, *Sepioteuthis australis* (Mollusca : Cephalopoda)." Marine and Freshwater Research **59**: 987-997.

Pecl, G. T. and N. A. Moltschaniwskyj (2006). "Life-history strategies of tropical and temperate squids: differences in growth, reproduction and energy allocation." ICES Journal of Marine Science **63**: 995-1004.

Pecl, G. T., N. A. Moltschaniwskyj, S. R. Tracey and A. Jordan (2004). "Inter-annual plasticity of squid life history and population structure: ecological and management implications." Oecologia **139**: 515-524.

Pecl, G. T., M. A. Steer and K. E. Hodgson (2004). "The role of hatchling size in generating the intrinsic size-at-age variability of cephalopods: extending the Forsythe hypothesis." Marine and Freshwater Research **55**(4): 387-394.

Pecl, G. T., S. R. Tracey, J. M. Semmens and G. Jackson (2006). "Use of acoustic telemetry for spatial management of *Sepioteuthis australis*, a highly mobile inshore squid species." Marine Ecology Progress Series **328**: 1-15.

Pierce, G. J., V. D. Valavanis, A. Guerra, P. Jereb, L. Orsi-Relini, J. M. Bellido, I. Katara, U. Piatkowski, J. Pereira, E. Balguerias, I. Sobrino, E. Lefkaditou, J. Wang, M. Santurtun, P. R. Boyle, L. C. Hastie, C. D. MacLeod, J. M. Smith, M. Viana, A. F. González and A. F. Zuur (2008). "A review of cephalopod-environment interactions in European Seas." Hydrobiologia **612**(1): 49-70.

Rodhouse, P. G. and E. M. C. Hatfield (1990). "Dynamics of growth and maturation in the cephalopod *Illex argentinus* de Castellanos, 1960 (Teuthoidea: Ommastrephidae)." Philosophical Transactions of the Royal Society of London B **329**: 229-241.

Smith, T. M., C. P. Green and C. D. H. Sherman (2015). "Patterns of connectivity and population structure of the southern calamary *Sepioteuthis australis* in southern Australia." Marine and Freshwater Research **66**: 942-947.

Sobrino, I., L. Silva, J. M. Bellido and F. C. Ramos (2002). "Rainfall, river discharges and sea temperature as factors affecting abundance of two coastal benthic cephalopod species in the Gulf of Cádiz (SW Spain)." Bulletin of Marine Science **71**(2): 851-865.

Steer, M. A. and N. A. Moltschaniwskyj (2007). "The effects of egg position, egg mass size, substrate and biofouling on embryo mortality in the squid *Sepioteuthis australis*." Reviews in Fish Biology and Fisheries **17**(2): 173-182.

Steer, M. A., N. A. Moltschaniwskyj and F. C. Gowland (2002). "Temporal variability in embryonic development and mortality in the southern calamary *Sepioteuthis australis*: a field assessment." Marine Ecology Progress Series **243**: 143-150.

Triantafillos, L. (2004). "Effects of genetic and environmental factors on growth of southern calamary, *Sepioteuthis australis,* from southern Australia and northern New Zealand." Marine and Freshwater Research **55**: 439-446.

Triantafillos, L. and M. Adams (2001). "Allozyme analysis reveals a complex population structure in the southern calamary, *Sepioteuthis australis*, from Australia and New Zealand." Marine Ecology Progress Series **212**: 193-209.

Waluda, C. M., P. G. Rodhouse, G. P. Podesta, P. N. Trathan and G. J. Pierce (2001). "Surface oceanography of the inferred hatching grounds of *Illex argentinus* (Cephalopoda: Ommastrephidae) and influences on recruitment variability." Marine Biology **139**: 671-679.