Knowledge to improve the assessment and management of Giant Mud Crabs (*Scylla serrata*) in Queensland

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Abbreviations

CW	Carapace width (legal size measurement in Queensland) is the distance between the tips of the largest opercular spines on each side of the dorsal carapace.
$CW_{50\%Male}$	Carapace width at which 50% of male crabs were functionally mature.
$CW_{50\%Female}$	Carapace width at which 50% of female crabs were mature, based on abdominal flap morphology.
CW_{mean_mature}	Carapace width
CW_{opt}	Carapace width size-class at maximum biomass of an unexploited cohort, i.e., 1st maturity instar and is, on average, 2/3rd of $L_{infinity}$ (Miethe et al. 2016).
CL	Carapace Length (legal size measurement in New South Wales) is the distance from the base of the notch between the frontal medial spines to the posterior dorsal margin of the dorsal carapace.
$C_{law}H$	Crusher claw Height is the width at the widest point of the crusher claw i.e., the claw with 'molar'-like teeth as opposed to the cutter claw which has 'incisor'-like teeth.
CPUE	Catch rate (number or weight) per unit of effort (pots or days fished)
EC1	East Coast management unit of mud crab component of Queensland Crab Fishery
FQ	Fisheries Queensland
GC1	Gulf of Carpentaria management unit of mud crab component of Queensland Crab Fishery
GLMM	Generalised Linear Mixed Model
GoC	Gulf of Carpentaria
GtG	Growth type group modelling
ITQ	Individual transferable quota
$L_{infinity}$	Average maximum size
MLS	Minimum legal size
NW	Notch width (NW, standard research/monitoring measurement) – the distance (to the nearest mm) between the notches anterior to the last opercular spines of the dorsal carapace.
NSW	New South Wales
NT	Northern Territory
SNPs	Single nucleotide polymorphisms
TACC	Total allowable commercial catch

Executive Summary

The current project researched Giant Mud Crabs to meet information needs and research priorities of the harvest strategy for the mud crab component of the Queensland Crab Fishery. It was conducted in collaboration with commercial crabbers, and between scientists from the Queensland Department of Primary Industries, CQUniversity and New South Wales Department of Primary Industries and Regional Development. Research aims were to investigate spatial stock structure, indices of abundance to monitor populations and assist in setting or predicting the Total Allowable Catch and biological information on regional populations. Whilst ubiquitous and relatively simple to catch, the complex behaviour, size-sex spatial habitat use, and variable catchability posed challenges to researching these topics. Abundance indices of pre-recruits were developed but were insufficient to robustly predict exploitable biomass and/or harvest. We suggest that whilst theoretically attractive, forecasting exploitable biomass of Giant Mud Crabs based on a pre-recruit index is unobtainable in the real world at the scale of the East Coast (EC1) and Gulf of Carpentaria (GC1) management units. The research generated new knowledge about Giant Mud Crabs, including confirmation of their genetic connectivity along the eastern Australian continental shelf (i.e., Queensland and New South Wales), estimates of regional size-at-maturity for males and females in Queensland (east coast and Gulf of Carpentaria), evidence of high insemination rates of females not supporting speculation of sperm limitation as a consequence of Queensland's single sex harvest policy, new insights into the spawning migration of females through the successful application of archival pop-up satellite tags, and a review of biological aspects of potential female harvest – given the new knowledge acquired in the current project. An intangible outcome of the project was the extensive interaction and knowledge exchange between project staff and industry stakeholders.

Background

The Giant Mud Crab (*Scylla serrata*) is an iconic and major target species of commercial, recreational and Indigenous fisheries in northern Australia. Between 2020 and 2022, the commercial harvest of Giant Mud Crabs in Australia averaged 1,000 tonnes, with approximately 64% of this taken in Queensland waters and an estimated GVP of $25-$30M annually. Popular recreationally, approximately 160 tonnes is estimated to be harvested annually by recreational fishers in Queensland (https://www.daf.qld.gov.au/business-priorities/fisheries/monitor/rec/statewide-survey).

Key aspects of the harvest strategy for mud crabs in Queensland are a financial year Total Allowable Commercial Catch (TACC), with Individual Transferable Quota (ITQ) within each of the two management units – the East Coast (EC1) and the Gulf of Carpentaria (GC1). The harvest strategy has a 'breakout' rule whereby if reported quota-usage does not achieve 70% of the TACC, then the TACC is reduced to the reported quota-usage plus 10%, assessed on the calendar year in which the financial year commences. The mud crab component of the Queensland Crab Fishery is assumed to be at low risk of non-sustainability, because of its conservative management arrangements. These include no female harvest, a male minimum legal size (MLS in Queensland of 150 mm carapace width, CW) considered to be above the size at 50% male maturity, and since September 2021, a TACC output control.

Aims and objectives

1. Assess the utility of next generation genetic analysis to inform the spatial stock structure of the Giant Mud Crab, using south east Queensland and northern New South Wales as a case study.
2. Develop and assess the feasibility of survey pots suitable for long-term implementation as a means of monitoring Giant Mud Crabs.
3. Gather key quantitative biological information on Giant Mud Crabs relevant to assessment and management, including the use of tagging studies and a pilot evaluation of means to understand the spawning migration of female Giant Mud Crabs.

Methods and results

Genetic samples were analysed using Single Nucleotide Polymorphisms (SNPs) from ten locations - Queensland east coast (n = 4), New South Wales (n = 5) and the south-eastern Gulf of Carpentaria (n = 1). Results confirm that the east coast stock is genetically different to the Gulf of Carpentaria stock. Genetic structuring was not detected from different locations along the east coast, despite sampling across 2,300 km of coastline (i.e., Hinchinbrook Island ~18.5°S to Port Stephens ~23.7°S). This result is consistent with the paradigm of offshore spawning and broadscale distribution of larvae. However, further analysis is recommended, as equal transfer of larvae and/or crabs between locations is somewhat at odds with published larval simulations which suggest some level of structuring by distance.

Populations of Giant Mud Crabs in south-east and central Queensland were sampled on a regular basis by fishery-independent means (i.e., scientists setting commercially equivalent pots, n = 90 days). Populations of Giant Mud Crabs in regional Queensland (south-east and northern Gulf of Carpentaria, and north Queensland) were sampled on an intermittent basis by fishery-dependent means (i.e., scientists onboard commercial crabbing operations, n = 85 days) due to cost-efficiencies, intense effort in some regions, to engage stakeholders and include data that reflected industry's experience. These two data sources were the basis for analysing biological parameters of regional populations and monitoring possibilities. This spatially and temporally extensive dataset provided the following insights into the biology of Giant Mud Crabs in Queensland waters.

For males (n = 14,004), the overall size-at-50%-maturity ($CW_{50\%Male}$) was 143 mm CW with regional variation in $CW_{50\%Male}$ ranging from 124 mm CW for the Townsville/Burdekin region to 156 mm CW for the Stanage/Broadsound region. Overall, 59% of male Giant Mud Crabs were estimated to be functionally mature by 150 mm CW (i.e., MLS) and capable of contributing to reproduction (once their shells have hardened). Temporal patterns in relative size-frequencies of males in the data rich south-east Queensland region were explored to identify seasonal growth of wild cohorts, but no clear patterns could be identified for quantitative analysis of growth by modal progression.

For females (n = 6,094), the overall size-at-50%-maturity ($CW_{50\%Female}$) was 136 mm CW, with regional variation in $CW_{50\%Female}$ ranging from 127 mm CW for the Weipa region to 150 mm CW for the Stanage/Broadsound region. The modal size of mature females in south-east Queensland was 155-165 mm CW. Analysis of relative frequency distributions indicated that most mature females were in their first mature intermoult, with few in their 2nd or 3rd mature intermoult. Results from the current research concurs with published speculation that spawning incurs high natural mortality, with few female Giant Mud Crabs surviving to moult to the larger sizes (i.e., >185 mm CW) associated with the 2nd or 3rd maturity intermoults.

Ovarian development occurred throughout the year in all regions where females were sampled and reproductively staged (n = 994). Multiple lines of evidence indicated spawning in south-east Queensland occurs mostly between late spring and autumn, whilst in north Queensland spawning occurs mostly winter to autumn, although a pulse was noted in winter to spring – potentially indicating year-round spawning in north Queensland. Year-round reports of early benthic stage crablets (i.e., ≤ 30 mm CW) in crab pots of north Queensland also provide evidence of year-round spawning.

Post-spawn females were extremely rare. This concurs with other lines of evidence that female Giant Mud Crabs likely incur high natural mortality during spawning migration (i.e., >90%).

The pilot study on understanding the spawning migration deployed miniature satellite tags attached to female Giant Mud Crabs showing advanced ovarian development (n = 12), including one egg-bearing individual. Data was retrieved for eight individuals, providing new information on where and how the females moved to spawn, incubate and hatch their eggs. Offshore migration is likely variable, depending on local conditions, which has consequences for larval distribution and genetic connectivity of Giant Mud Crab stocks on the east Australian continental shelf and the north Australian shelf associated with the Gulf of Carpentaria.

Juvenile survey pots (steel wire with restricted entry funnels) were trialled as a means to obtain an index of pre-recruit abundance but were not more effective at catching sub-legal crabs (i.e., 100 to 149 mm CW) than standard trawl-mesh pots. In terms of monitoring Giant Mud Crab populations, fishery-independent sampling had greater control over the location of sampling effort, and metrics measured, but was cost and time intensive. Fishery-dependent sampling had less control on location (and sometimes timing) of effort, but provided reasonable metrics on Giant Mud Crab populations, and was less cost and time intensive. As identified by others, the relative size-frequency distribution of males can be a qualitative proxy of fishing mortality, as male crabs of 150 mm CW and greater have decreased abundance. Metrics based on sex ratios can provide a more quantitative proxy of fishing mortality, although variation in the size-sex spatial habitat use needs to be accounted for, with adequate sampling across habitats and replicate temporal sampling. Theoretically, the Total Allowable Commercial Catch is a forecast of the likely male biomass at 150 mm CW or greater for a 12-month period from July to June. The abundance of pre-recruits (i.e., 100 to 140 mm CW) was explored in relation to commercial catch to determine if these 1+ year-old males could predict the likely scale and timing of catch of legal marketable crabs over the ensuring 12 months. Despite temporally regular and spatially extensive sampling, the abundance of pre-recruits (likely one and two moults before legal size) was poorly predictive of the abundance of legal males. Whilst theoretically an attractive concept, we suggest that multiple factors indicate that a cost-effective and robust pre-recruit index of Giant Mud Crab abundance is not pragmatically possible at the scale of the management units (i.e., EC1 and GC1).

On request, the biology of female Giant Mud Crabs in the Gulf of Carpentaria was reviewed in terms of a regional trial harvest. We recommend that the mean size of the 1st maturity intermoult inform any decision on the minimum legal size (MLS). This was estimated to be approximately 156 mm CW for females in Queensland waters of the Gulf of Carpentaria. Therefore, we recommend any MLS for females be larger than 156 mm CW. A range of potential biomass extractions were considered, ranging from 20% (a 1:4 ratio of female-to-male harvest) to 9% (a ratio of 1:10 female-to-male harvest). We concur with previous recommendations that any trial of female harvest should be set at a precautionary level. Further, we consider that effectively constraining and accurately recording harvest is the most critical aspect of any trial of female harvest in Queensland, so as to understand reduction in the spawning biomass and any consequences. There are multiple issues associated with a trial of female harvest that require further consideration and careful decision making, including access rights, given none currently exist for commercial or recreational fishers. We neither advocate for or against the harvest of females but have generated new quantitative knowledge in the current research that should support managers and stakeholders to duly consider the issue of female harvest.

Implications

The genetic analysis provides strong evidence that stocks of Giant Mud Crab along the Australian east coast are highly connected, probably mostly through larval dispersal. We concur with Hewitt *et al.* (2023b), that female Giant Mud Crab that mature in Queensland estuaries (and are not subject to major fishing mortality) are likely to support larval recruitment into estuaries of New South Wales, particularly in the north of that jurisdiction. Genetic analysis reaffirmed that stocks of Giant Mud Crab in the Gulf of Carpentaria are genetically distinct from the Australian east coast, supporting separate management arrangements for the EC1 and GC1 management units.

Results from the assessment of regional biology indicate that the current male minimum legal size combined with a no female harvest policy produces a very low risk of recruitment overfishing to Giant Mud Crab populations in Queensland waters. There was no evidence of sperm limitation in females as a consequence of a male-only harvest policy, despite evidence of high fishing mortality in many of the regions sampled for length frequency. However, there was evidence that physiologically mature small-clawed males (referred to in previous literature as adolescents) may be participating to a greater degree in mating and reproduction than previously thought, potentially because of high fishing mortality on males of 150 mm CW or greater. Multiple lines of evidence suggest that mature females suffer high mortality during the spawning migration. Differential natural mortality between males and females should be accounted for in any stock assessment.

Currently, the most representative means of ‘monitoring’ male Giant Mud Crab populations in Queensland at the scale of the management units (i.e., East Coast and Gulf of Carpentaria) is the reported commercial harvest. There are potential opportunities to develop within quota-year assessments of exploitable biomass trajectories for regions within the management units based on the prior reports of quota usage. Assessment of the quota usage trajectory could provide a within-quota year signal to whether exploitable biomass (as indexed by reported catch) is tracking as expected or has deviated from 'average' and thus trigger a review as to the conditions in a region (e.g., environmental, effort or market driven), to better assist management and understanding of catch fluctuations.

Recommendations

The current research gathered key quantitative biological information on Giant Mud Crabs in regions of Queensland and significantly improved our understanding of their population biology. The research achieved broadscale spatial sampling, but not all areas were sampled equally, and the far north Queensland east coast was not sampled (except for genetics, reported on separately). Further data collection on biological parameters of Giant Mud Crabs in regional Queensland is recommended if there are further concerns about these populations – although multiple lines of evidence suggest there is no immediate threat to the sustainability of Giant Mud Crab populations in Queensland.

T-bar tagging of Giant Mud Crabs could undergo further testing to verify the tag-associated mortality during moulting observed during the current study. We recommend t-bar tagging studies on wild Giant Mud Crabs should consider the effects of cryptic mortality.

There is clear evidence of high fishing mortality on legal males in some areas, but there is no strong evidence that this is a threat to the sustainability of Giant Mud Crab populations in Queensland. We recommend that a watching brief is kept on the fishery harvests. A cost-effective means of doing so is the development of regional summaries of quota usage, so that deviations from the 'normal' trajectory of cumulative harvest within a quota year can be identified promptly and a review of causes instigated.

There exists the opportunity to conduct further research on the Orange Mud Crab (*Scylla olivacea*) in Queensland waters, particularly the far northern regions, with the aim of determining the size-at-maturity, and informing an appropriate and separate minimum legal size to enable a greater harvest of this species, which can readily be distinguished from the Giant Mud Crab (*Scylla serrata*).

We recommend caution in the further deployment of resources towards a pre-recruit index to forecast exploitable biomass for TACC setting. Whilst theoretically attractive, such an index would require spatially extensive sampling – potentially only possible through fishery-dependent sampling (noting associated costs) and using crab pots capable of retaining pre-recruits (i.e., 100-149 mm CW or smaller).

We recommend the application of micro pop-up archival satellite tags to females with advanced ovary development to understand spawning migration. Broadscale deployment of this technology across the species' range would provide insight into this previously elusive aspect of their life history. However, this is not critical to the sustainability of the fishery, unless there is a change to the no-female harvest policy.

Whilst this report contains a review of female biology in regard to a trial harvest, we do not recommend for or against progression of a such a trial, leaving such matters to management.

Keywords

Giant Mud Crab, *Scylla serrata*, *Scylla olivacea*, Queensland Crab Fishery, single nucleotide polymorphisms, spawning migration

Introduction

Background

The Giant Mud Crab (*Scylla serrata*) is an iconic and major target species of commercial, recreational and Indigenous fisheries in northern Australia. The Orange Mud Crab (*S. olivacea*) is also caught, but only in low numbers (i.e., <1% of harvest). Between 2020 and 2022, the commercial harvest of Giant Mud Crabs in Australia averaged 1,000 tonnes per annum, of which approximately 64% was taken in Queensland waters (Kirke *et al.* 2023). Based on an average beach price of $37 per kg (Sydney Fish Market) and a Queensland commercial harvest of 664 tonnes (in 2023), the Mud Crab Component of the Queensland Crab Fishery has an estimated Gross Value Production in the order of $25-$30M annually. Popular recreationally, approximately 165 tonnes is estimated to be harvested annually by recreational fishers in Queensland (Kirke *et al.* 2023). Specifics of Indigenous harvest is unknown, with some potentially included in the recreational estimates.

In Queensland, the harvest of Giant Mud Crabs is managed as a component of the Queensland Crab Fishery. It's formal harvest strategy 2021-2026 (DAF 2021) outlines the overall fishery objectives, key indicators, reference points, and decision rules that trigger pre-agreed management actions. The biological sustainability of Giant Mud Crab stocks in Queensland is considered to be at low risk because of conservative management arrangements i.e., prohibited female harvest (since around 1900), and a male minimum legal size of 150 mm carapace width, which is thought to be above the size of 50% male maturity (Heasman 1980). The primary objective of the harvest strategy for Giant Mud Crabs is to "maintain the mud crab resource at, or return it to, a target exploitable biomass level that aims to maximise economic yield (MEY) for the fishery". Giant Mud Crab stocks in most Queensland estuaries incur very heavy fishing mortality on males greater than or equal to legal size (i.e., 150 mm carapace width), particularly in locations adjacent to large human population centres (Jebreen *et al.* 2008; Flint *et al.* 2017; Flint *et al.* 2021). Ease of capture, live storage and market demand contribute to the ongoing illegal harvest of females and males of unknown scale, but likely considerable (e.g., https://archive.dpi.nsw.gov.au/content/media-releases/2012/fisher-fined-$35,000, https://www.detsi.qld.gov.au/our-department/news-media/mediareleases/2022/covert-investigation-leads-to-hefty-fine-for-illegal-crabbers, https://statements.qld.gov.au/statements/90649, https://bnbfishing.com.au/bundaberg-fishers-fined-7180-crabs/). Giant Mud Crabs are designated as a priority species under the Queensland Fisheries Act 1994 (https://www.legislation.qld.gov.au/view/pdf/2024-09-01/act-1994-037), and thus a priority species for enforcement activities by the Queensland Boating and Fisheries Patrol.

Need

The harvest strategy for the Mud Crab component of the Queensland Crab Fishery has processes for monitoring and assessing fishery performance. A key part of the harvest strategy is a Total Allowable Commercial Catch (TACC), which was introduced in September 2021 as a control on fishing mortality. The TACCs for the Queensland east coast (EC1) and Gulf of Carpentaria (GC1) were informed by a modified catch-MSY analysis, which is an assessment widely applied in Australia to data-limited fishery species (Haddon *et al.* 2019). Catch-MSY uses the time-series of catch and assumed parameter ranges for carrying capacity, resilience and initial depletion, to estimate current depletion levels (see Northrop *et al.* 2019). The analysis was performed at large spatial scales (East Coast and Gulf), knowing that it does not capture regional variability in biological processes that impact on harvestable biomass (e.g., larval dispersal, seasonal growth, size-at maturity), as well as environmental influences (e.g. rainfall, flow, temperature), but of which there is limited quantification.

FQ Fisheries Management and stakeholders expressed the desire to improve the assessment of Giant Mud Crab stocks (if possible) to better reflect spatial and temporal variation in harvestable stock size. A potentially suitable method is the data-moderate delay-difference model applied in the Northern Territory (Grubert *et al.* 2019). This method requires an index of annual abundance (e.g., catch rate), a growth-natural survival parameter, and a temporal catchability parameter.

Objectives

(i) Assess the utility of next generation genetic analysis to inform spatial stock structure of the Giant Mud Crab (*Scylla serrata*), using south east Queensland and northern New South Wales as a case study.

(ii) Develop and assess the feasibility of 'survey' pots suitable for long-term implementation as a means of monitoring Giant Mud Crabs.

(iii) Gather key quantitative biological information on Giant Mud Crabs relevant to assessment and management, including the use of tagging studies and a pilot evaluation of means to understand the spawning migration of female Giant Mud Crabs.

Chapter 1. Giant Mud Crabs in Queensland: regional life history and fishery characteristics

J.B. Robins and N. Flint

This chapter summaries the life history information available for Giant Mud Crabs, as relevant to regional populations along the Queensland east coast and Gulf of Carpentaria. The characteristics of the fishery and its management are also reviewed.

Stock structure

Gopurenko and Hughes (2002) used mitochondrial DNA (mtDNA) to evaluate the spatial stock structure of Giant Mud Crabs sampled from three coastal-shelf regions in northern Australia (i.e., western, northern and eastern, Figure 1). A single haplotype (A1) was present in all shelf regions, being most abundant on the eastern shelf (Table 1). The frequency of the A1 haplotype was much reduced at locations north of Hinchinbrook (~18°S), with crabs from Cape Grenville (~12°S) considered to be genetically distinct from crabs sampled from Hinchinbrook and further south of 18°S. Clade-1 haplotypes indicated low genetic differentiation among locations on the eastern coastal shelf, while Clade-2 haplotypes indicated considerable genetic differentiation among locations on the western and northern shelfs (Table 1).

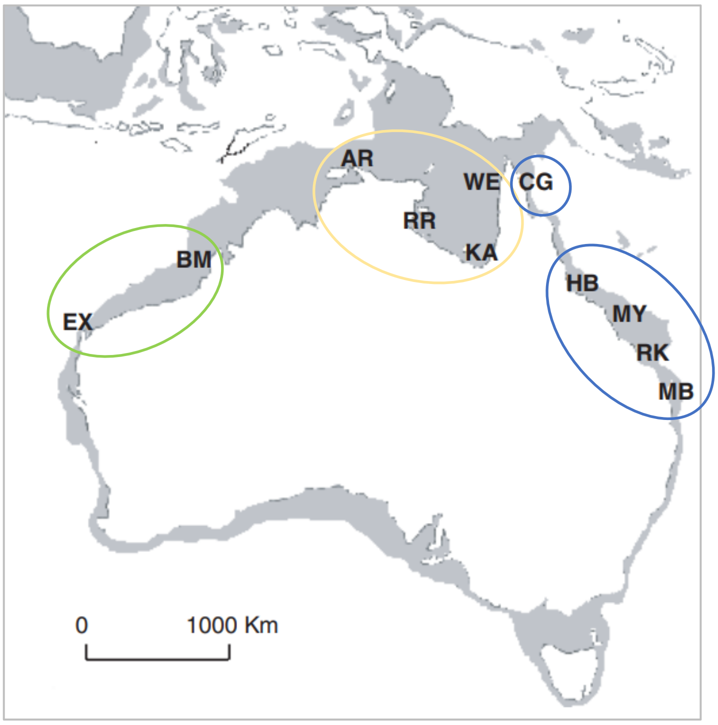

Figure 1. Stock structure and sampling locations of Giant Mud Crabs. western shelf: EX = Exmouth, BM = Broome, northern shelf: AR = Adelaide River, RR = Roper River, KA = Karumba, WE = Weipa, eastern shelf: CG = Cape Grenville, HB = Hinchinbrook, MY = Mackay, RK = Rockhampton, MB = Moreton Bay. Grey shading is 200 m sea level contour. (adapted from Gopurenko and Hughes 2002). Circles indicate genetic subdivision, see Table 1.

Giant Mud Crabs occur and are commercially fished in New South Wales (NSW i.e., south of 28°S) but samples were not included in Gopurenko and Hughes (2002). Recent larval particle simulations (Hewitt *et al.* 2022b; Charles *et al.* 2024) suggested a high likelihood of genetic connectivity along the length of the eastern shelf but this requires confirmation.

Gopurenko and Hughes (2002) noted significant genetic subdivision of samples from the northern shelf, with haplotype composition in the Adelaide and Roper rivers (Northern Territory), being significantly different from Karumba and Weipa (Table 1). Preliminary larval particle simulation suggested that western Gulf of Carpentaria locations were likely reliant on self-recruitment, whereas eastern Gulf of Carpentaria locations were likely to share larval recruits between locations (Patterson 2020). Further work using nuclear markers to provide a rigorous means of delineating genetically independent stocks of Giant Mud Crabs was recommended, as nuclear markers operate on a faster evolutionary (and thus shorter) time scales than mtDNA.

Table 1. Giant Mud Crab haplotypes among Australian locations (reproduced from Gopurenko and Hughes 2002). Colours indicate shelf location of sample sites cross referenced to Figure 1.

Shelf	Location	Haplotype																					
		1A	1B	1C	1D	1E	1F	1G	1H	1I	1J	2A	2B	2C	2D	2E	2F	2G	2H	2I	2J	2K	2L
eastern	Moreton Bay	65	2	3	4	1	4																
	Rockhampton	19						2	1														
	Mackay	27		1	4			2	1														
	Hinchinbrook	19		1			1																
	Cape Grenville	1									21												
northern	Weipa	1										9					18	3	3	1			
	Karumba											4					9						
	Roper River	3										20	5	1	1	1							
	Adelaide River	1										10	2				3						
western	Broome	1																			5	2	
	Exmouth	3																			18	2	1

Life history

Connectivity of stocks of Giant Mud Crabs is facilitated by the life history of this species. The juvenile and adult stages are associated with mangrove habitats of estuaries and inshore coastal areas, while spawning individuals and pelagic larval stages are associated with offshore locations (Hill 1994). We note that there is no clear definition of 'offshore' in regard to the spawning of *Scylla serrata*, but rather it is some undefined distance from "inshore, especially estuaries" (Hill 1994).

Offshore spawning

Offshore spawning is the current paradigm for Giant Mud Crabs (Hill 1994; Hewitt *et al.* 2022a). The infrequency of encountering egg-bearing females in inshore waters has been interpreted as mature females disengaging from feeding activities to migrate offshore to spawn (Hewitt *et al.* 2022a). Offshore sightings (Hill 1994) and laboratory studies (Baylon 2010), suggest that spawning females seek stable, warm, high salinity water conditions that optimises egg and larval development (Hill 1974; Quinn and Kojis 1987; Hill 1994; Alberts-Hubatsch *et al.* 2016). Offshore hatching of larvae allows maximal dispersal in ocean currents (Hill 1994), with end-point drift reliant on regional currents during the approximately three-week pelagic larval phase. Broadscale larval dispersal is consistent with oceanographic particle simulations along the Australian eastern shelf (Hewitt *et al.* 2022b; Charles *et al.* 2024). Regional currents, such as the coastal boundary layer in the Gulf of Carpentaria (Wolanski 1993), potentially limit the mixing of nearshore and offshore waters. Therefore, larval dispersal (i.e., distance from maternal estuary) may also depend on the location where egg hatch occurs. In northern Australia, there is a distinct difference in wind directions during the monsoon (wet) and trade-wind (dry) seasons, which effects surface currents along the northern east coast of Queensland (Figure 2) and Gulf of Carpentaria (Figure 3). Thus, the timing of spawning migrations will also determine larval dispersal along Australian coastlines and genetic connectivity between shelf regions.

Along the eastern shelf, spawning migration is thought to begin in early spring (September) and end by early autumn (April) at sub-tropical latitudes (approximately 27.5°S), being associated with water temperatures above 22°C (Heasman *et al*. 1985). In locations further south along the eastern shelf (i.e., approximately 30°S) downstream movement to offshore waters is triggered by a rapid decrease in estuarine salinity (Hewitt *et al.* 2022a).

Along the northern shelf (i.e., Gulf of Carpentaria and Northern Territory Top End), the absence of mature females from the inshore pot fishery and the timing of peak female gonad condition was considered as evidence for the offshore spawning migration to occur between December and March (Knuckey 1999). However, some spawning probably occurs throughout the year on the northern shelf, as females with ripe ovaries occurred in most months (Knuckey 1999). The incidental capture of female Giant Mud Crabs in offshore trawling operations in the Gulf of Carpentaria indicated that spawning occurred between September and November (Hill 1994). Combined, these observations suggest an extended spawning season for Giant Mud Crabs on the northern shelf, potentially occurring between September and March (i.e., Austral spring and summer). There may be temporal and spatial influences of the monsoon season, and the sometimes extensive estuarine and inshore flooding associated with large wet seasons in northern Australia. Spawning migrations are thought to follow the lunar cycle (last quarter until three days after the new moon) and that offshore migrations are stimulated by major decreases in estuarine salinity (Hewitt *et al.* 2022a). Variability in the offshore migration of Giant Mud Crabs has been previously noted, such that egg-bearing females may occur within a few kilometres of mangrove habitats or up to 50 km from shore (Heasman *et al.* 1985).

Spawning and larval production of mud crabs (*Scylla* species) is well studied in aquaculture conditions, as they are commonly farmed in Asia. In laboratory conditions, female Giant Mud Crabs spawn their eggs whilst sitting or swimming above the bottom, with a preference for coarse sediment i.e., sand or coral grit; (Davis *et al.* 2004; Fazhan *et al.* 2022). Eggs dropped from an egg mass were commonly infected with fungi, polycheate or nematode worms.

Fecundity is, on average, related to size, ranging from 2-11 million eggs per batch (Figure 4), with mean fecundity of 4.5 million eggs (Mann *et al.* 1999). Females can produce at least three egg-masses whilst in the same inter-moult, with 34-59 days between spawning events (Quinitio and Parado-Estepa 2003). The duration of egg incubation is temperature dependent (Heasman and Fielder 1983; Quinitio and Parado-Estepa 2003), with hatching into planktonic zoea larvae occurring after approximately 15 days at 28°C.

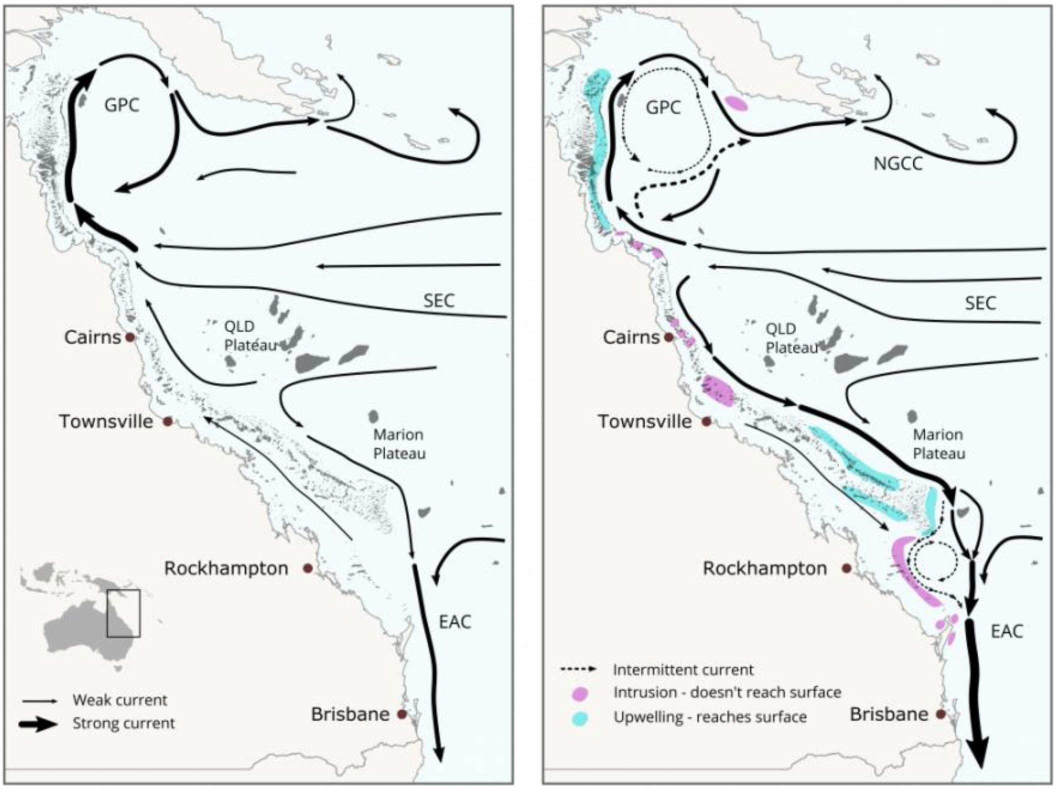

Figure 2. Prevailing surface currents of the north-east Australia for trade winds (left) and monsoon (right) seasons. Reproduced from Steinberg and Lawrey (2018). Variations due to weather and eddies are not depicted. GPC = Gulf of Papua Current, NGCC = New Guinea Coastal Current, SEC = South Equatorial Current, EAC = East Australian Current. The Gulf of Papua Current includes the North Queensland Current and the Hiri Gyre.

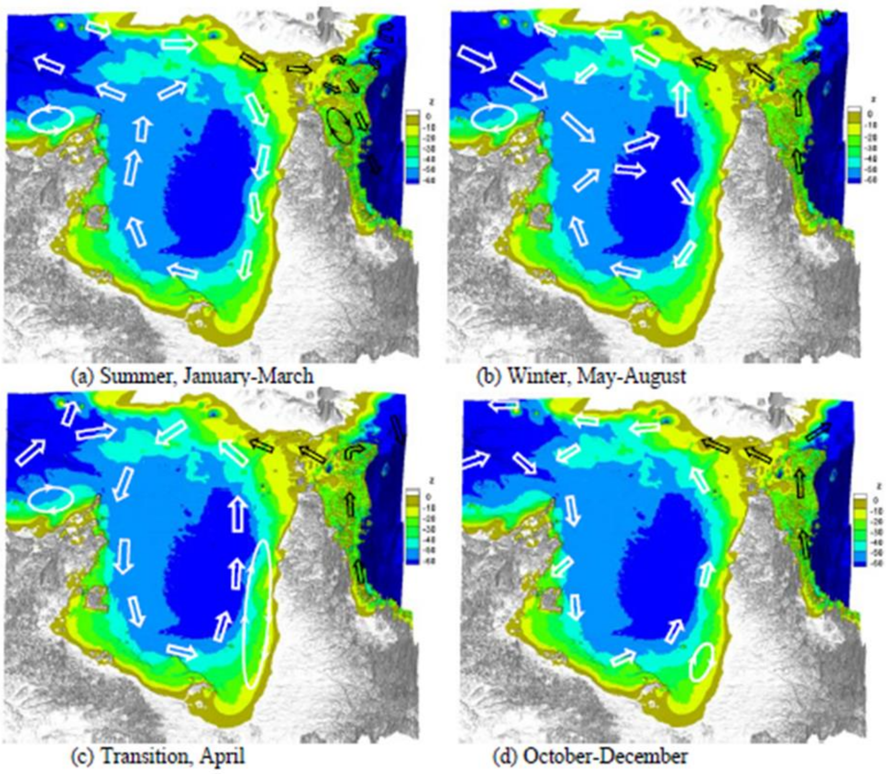

Figure 3. Seasonal generalised, wind-driven circulation patterns in the Gulf of Carpentaria. Depth contours (m) are depicted by colour as per the legend. Reproduced from Li et al. (2006).

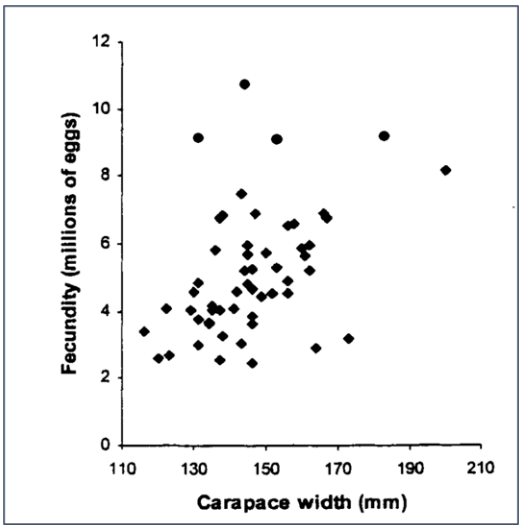

Figure 4. Fecundity-at-size (carapace width) for wild-caught Giant Mud Crabs that spawned in aquaculture conditions (n = 60). Reproduced from Davis et al. (2004).

Larval phases

There are five moult stages of zoea larvae, with intermoult period and survival dependent on physical conditions i.e., food availability (rotifers and artemia), water temperature, and salinity (Hill 1974; Hamasaki 2003; Nurdiani and Zeng 2007). Critical thresholds for zoea-I larvae were 20°C (Baylon 2010) and salinity of 15 ppt (Hill 1974; Sara *et al.* 2006; Baylon 2010). Zoea-5 larvae metamorphose into demersal megalopae and remain in that stage for one to two weeks (Holme *et al.* 2007), with the duration being temperature and nutrition dependent.

Zoea and megalopa stages have poor swimming ability, with selective tidal stream transport (STST) a likely movement mechanism (Forward and Tankersley 2001; Sara *et al*. 2006). Selective tidal stream transport would enable Giant Mud Crab larvae to move from offshore hatch locations to coastal and estuarine habitats using onshore currents associated with tidal cycles. Megalopa occur in swarms (Lucas and Southgate 2012) but are difficult to sample on a regular basis (Knuckey 1999; Sumpton *et al.* 2003; although see Forbes and Hay 1988). Larval duration to the first crab instar (C1) is significantly related to temperature, being 16 days at 32°C, 21 days at 26°C and 50 days at 20°C (Baylon 2010). The successful recruitment of larval Giant Mud Crabs to any given region will be heavily influenced by the physical conditions offshore, as well as oceanographic conditions that enable inshore return.

Benthic phases

Megalopa have a settlement preference for complex habitats (Webley and Connolly 2007), where they metamorphose into the first crab body form (C1 instar). The crab stage has four phases (Heasman 1980; Alberts-Hubatsch 2015):

(i) crablets (C1 to C5 - early benthic stage EBS), 3 to 30 mm CW,
(ii) juveniles, 30 to 80 mm CW,
(iii) adolescents, 70 to about 130 mm CW, and
(iv) mature adults, greater than 130 mm CW.

Early benthic stage (EBS) crablets have broad salinity tolerance (3 to 45 ppt). They occur in a wide variety of soft-bottom estuarine habitats i.e., sub-tidal mud flats and saltmarsh behind mangroves (Alberts-Hubatsch 2015). A binocular microscope is required to identify the forked pleopods on the abdomen of the female and the oviduct depressions on cephalothorax, as the abdomen shape has not yet differentiated between males and females crablets less than about 30 mm CW. During the current research, project staff and commercial fishers observed EBS crablets intermittently during sampling with crab pots – something not previously reported in the literature. Of particular note, was the frequent occurrences of EBS crablets in most months by commercial crabbers in north-east Queensland, which is suggestive of year-round spawning in this tropical region.

Evidence from research studies and anecdotal reports from commercial fishers indicate that there is degree of spatial separation of habitat use by juvenile, adolescents and adult Giant Mud Crabs, as well as between mature males and mature females (Hill *et al.* 1982; Hyland *et al.* 1984; Jebreen *et al.* 2008). Commercial fishers in many regions of Queensland comment that female Giant Mud Crabs are abundant at times on estuarine flats and are thus not a preferred fishing location for commercial fishers targeting legal males. Spatial separation of Giant Mud Crab populations across habitats will have consequences for the interpretation of male:female ratios sampled dependent or independently of the fishery, in addition to the effects of sex and size harvesting policies in a jurisdiction. The spatial distribution of Giant Mud Crabs, including sex-based differences, is currently being investigated through a PhD research project by W. Charles at CQUniversity.

Maturity and reproduction

Maturity is defined as the ability to contribute to reproduction. The time to maturity is speculated to vary regionally as a function of water temperature, taking about 18 months in the tropics and about 36 months in the sub-tropics (Fielder and Heasman 1978). Reproduction in Giant Mud Crabs is a two-step process. The first step is mating, where mature males inseminate females during moulting, with the female often moulting from immature to mature carapace form (Figure 5). The second step is the spawning migration, where mature females migrate offshore to (extrude and) incubate eggs prior to larval hatch. Portunid crabs have internal fertilisation, where eggs are fertilised as they pass down the oviduct past the spermatheca, where sperm is stored from the mating process.

Maturity in male crabs can be separated into three phases (Knuckey 1996):

(i) immature – undeveloped gonads, no spermatophores,

(ii) adolescent – developed gonads, spermatophores present in the vas deferens, claws proportionally small and of limited use in cradling females, considered physiologically mature, but (on average) functionally immature/ineffective, and

(iii) adult – well developed gonads, spermatophores present in the vas deferens, claws proportionally large and important in defending moulting females during cradling, considered physiologically mature and functionally mature.

Functionally mature males that have contributed to the breeding population are considered to be identifiably by the presence of mating scars on the thoracic sternum and on the anterior surface of the merus of the first walking legs (Figure 5). Mating scars are the consequence of abrasion to the male carapace during the pre-copulatory embrace with the female (Knuckey 1999). Abrasion of the exoskeleton allows chitinoclastic bacteria to proliferate in the inner layers of the shell, causing brown colouration of the mating scars, which are present until the male next moults. Physiological maturity (i.e., adolescence) for males was reported as 110 mm CW for Giant Mud Crabs in the Northern Territory (n = 104), with functional maturity at 125 mm CW (Knuckey 1999).

Knuckey (1999) found that mating scars were non-existent on recent post-moult males, occurring on about 2% of new inter-moult males, and about 36% of late inter-moult males. Crabs with mating scars were significantly heavier-at-size than those without, likely as consequence of muscle development that would confer a mating advantage. Male crabs regain breeding condition (i.e., sperm levels) within two weeks of a previous mating (Knuckey 1999).

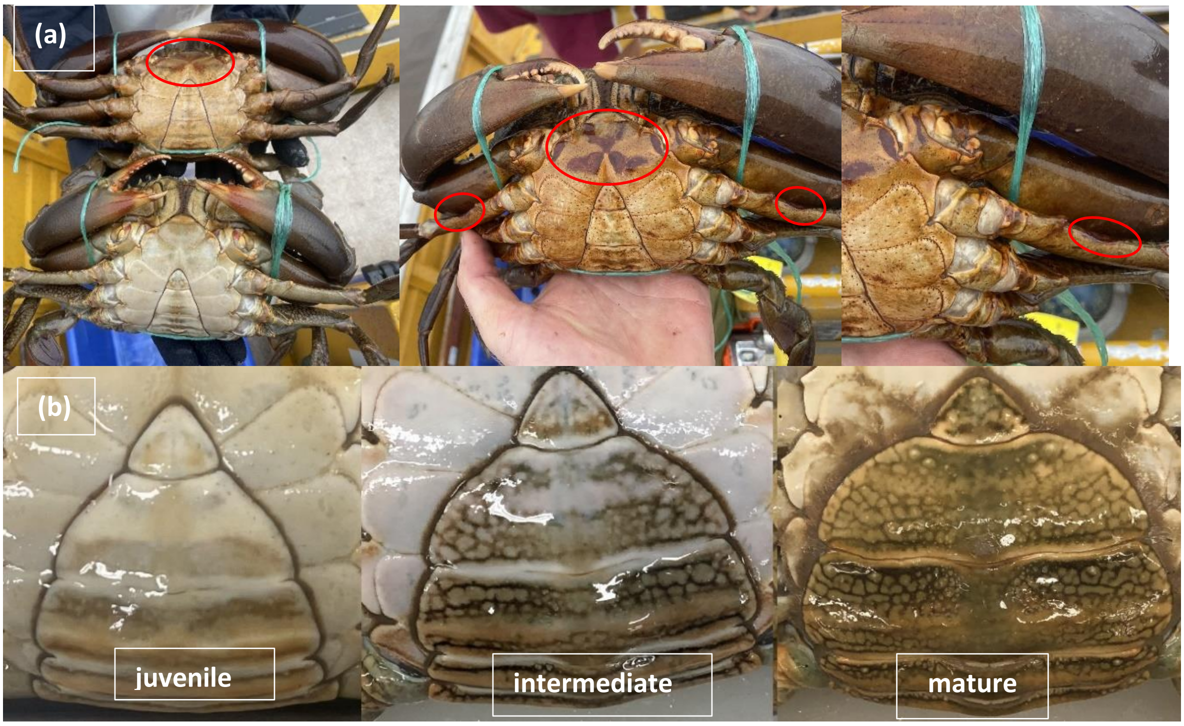

Figure 5. Gender and maturity indicators on Giant Mud Crabs. (a) male abdominal V-shaped abdominal flap and mating scars (red circles) on the cephalothorax and/or first walking legs. (b) female abdominal shapes, indicating juvenile (V-shape uncoloured), intermediate (U-ish shaped, but not as rounded on the 2nd last segment as the mature individuals, setae on edge not well developed and limited colouring), and mature (U-shape, developed setae on edges and dark/mottled). Photo credit: Queensland DPI.

Knuckey (1996) used the ratio of claw height to carapace width (CH:CW), analysed using Bhattacharya's method, to infer the distribution of adolescent males from mature males. Critical values of claw height to carapace width were 0.375 for Van Diemen Gulf and 0.365 for the Gulf of Carpentaria, with the results being verified by internal examination of the extent of spermatophore development (Knuckey 1996).

Maturity in female crabs is identified by the relative size, shape and pigmentation of their abdomen (Figure 5) and the presence of long filamentous setae (i.e., the 'feathers') on the four bilateral pairs of abdominal pleopods (i.e., endopodites), which support the egg-mass during its incubation. V-shape and intermediate abdominal flaps are indicative of immaturity for *Scylla paramomosian* (Islam *et al.* 2010). Immature female Giant Mud Crabs also have the abdomen physically locked to the cephalothorax by small, calcified hooks on the 6th thoracic segment (Knuckey 1999, Waiho *et al.* 2016). In the Adelaide River, Northern Territory, 86% of 140 mm CW females were reported as mature, with 100% of 150 mm CW females being mature (Haddon *et al.* 2005).

Mating occurs when females moult, and the carapace is soft. Males guard females prior to, during and immediately after the moulting process. When soft, the male turns the female upside down, so their thoracic surfaces meet with abdomens extended. Males inseminate the females with spermatophores (i.e., packets of sperm) via paired ejaculatory ducts that pass the spermatophores into paired vulva of the female. The spermatophores are stored in the paired spermatheca of the female, each being a small 'pouch' attached to the oviduct of the female, located approximately 10 mm internally from the vulva. Eggs are fertilised as they pass the spermatheca during spawning.

Giant Mud Crabs, like other portunids, have a sperm plug deposited in the female spermatheca during the insemination. The sperm plug is a ball of glycoprotein (approximately 10 mm in diameter, white, translucent, and wax-like in texture) in freshly inseminated females. Sperm plugs are thought to have a variety of purposes (e.g. sperm nutrition, prevent other males mating, or to separate spermatophores of different males) and persist for varying amounts of time. In Blue Crabs (*Callinectes sapidus*), sperm plugs dissolve within three weeks of mating and in some species, dissolution of the sperm plug is synchronised with ovarian development (Zara *et al*. 2014). The sperm plug is derived from the rosette glands and secretions from the vas deferens of males. Female Giant Mud Crabs can store viable sperm for more than six months, and reportedly spermatophores can be retained through the moulting (Brick 1974).

The single sex harvest policy in Queensland causes speculation amongst commercial and recreational crabbers as to whether large female Giant Mud Crabs still reproduce. Many speculate that the low abundance of sufficiently large male crabs to mate with large female crabs' causes sperm limitation and precludes the ability of large females to produce a viable egg mass. The detailed description of mating provided above has been included to underpin the observations, data collected and inferences about insemination rates of female Giant Mud Crabs in Queensland (see Chapter 6).

Longevity, mortality and growth

Giant Mud Crabs are thought to have a maximum life span of around four years (Heasman and Fielder 1977; Knuckey 1999), with methods to reliably age them yet to be found (Crook *et al.* 2018). A life span of this duration implies their natural mortality rate (*M*) is high, with an estimated mean value of 1.21 per annum (Knuckey 1999).

Despite the inability to estimate absolute or relative age, time to full vulnerability to fishery harvest (i.e., minimum legal size), is an important parameter for fishing mortality, harvest variability and potentially allowable catch. To estimate time to legal size, growth (i.e., moult increment) and intermoult duration-at-size are required. Growth in most decapods is indeterminant i.e., indefinite continuation of moulting and enlargement of the body throughout life, with intermoult period increasing with size and age (Vogt 2012). Indeterminate growth is usually associated with negligible decline in reproductive capability or physical senescence, although 'feeble' and presumably 'old' male Giant Mud Crabs are reported by fishers.

Growth (i.e., increase in carapace width) of Giant Mud Crabs has been estimated using tank experiments, tag-recapture studies and length-frequency analyses. To better understand likely growth increments of males (and assist modal analysis in Chapter 6), data (i.e., sex, pre-moult size referred to hereafter as $CW_{initial}$ and post-moult size, referred to hereafter as CW_{final}) published in previous studies was collated and analysed by simple linear regression. For males, moult increments less than 5 mm are likely to be measurement errors (Knuckey 1999), whilst those greater than 30 mm are likely to represent two moults (Hill 1975). Results of the regression indicated that for males, carapace width, on average, proportionally increased in size by 1.18 times (± 0.007, n = 32) the $CW_{initial}$ (Figure 6a). This was similar to that reported for Northern Territory crabs (Knuckey 1999), in which the regression was reported but the underlying data on $CW_{initial}$ and CW_{final} were not. Growth of Giant Mud Crabs is linear to about 120 mm CW, estimated to take approximately 6 months to reach this size (Haddon *et al.* 2005).

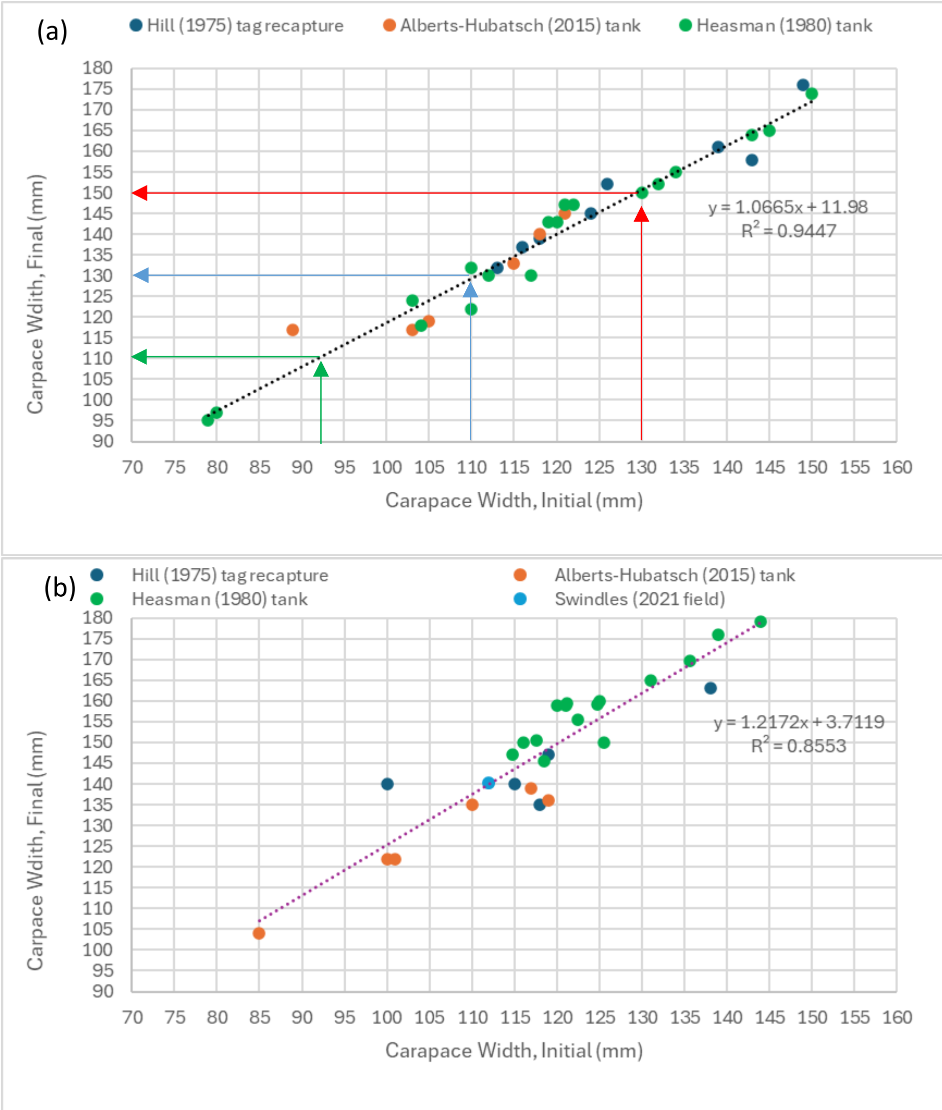

Figure 6. Initial and final carapace width of Giant Mud Crabs indicative of 'growth' compiled from data available in previous studies (Hill 1975; Alberts-Hubatsch 2015; Heasman 1980, plus 1 wild-caught and released female reported by a fisher), with simple linear regression fitted to all data combined for (a) males and (b) females. Red line indicative of $CW_{initial}$ that would theoretically result in a CW_{final} of 150 mm for males. Blue line indicative of a $CW_{initial}$ that would results in a CW_{final} of 130 mm for males. Green line indicative of a $CW_{initial}$ that would results in a CW_{final} of 110 mm for males.

Similarly for females, reported $CW_{initial}$ and CW_{final} data published in previous studies was collated and analysed by simple linear regression, plus a wild-caught moulting female whose $CW_{initial}$ and CW_{final} was measured during the current research project (Figure 6b). For females, moult increments less than 5 mm are also likely to be measurement errors (Knuckey 1999). Results of the regression indicated that for females, the proportional increase in carapace width averaged 1.25 (± 0.011, n = 26, Figure 6), again similar to the results for NT crabs (Knuckey 1999).

Knuckey (1999) estimated von Bertalanffy growth curves derived from tag-recapture data (males and females combined), with the estimated time to 150 mm CW being 16 months using NT data or 12 months using Qld data. This contrasts with the analyses by Heasman (1980), who used length-converted catch curves to estimate time to 150 mm CW for Giant Mud Crabs in Moreton Bay was between 18 and 26 months, with crabs 12 months old being approximately 100 to 110 mm CW. Differences in time to 150 mm CW are likely caused by the regional effects of seasonal water temperatures on feeding rates and thus feeding efficiency, as well as timing spawning (i.e., early or late in relation to water temperatures). Heasman (1980) inferred that the shortest intermoult duration in post-larval stages of Giant Mud Crab occurred at around 27°C (± 1°C) and that 'nett growth' (i.e., feeding and deposition of energy reserves in excess of basal metabolic rate) was restricted (at best) to between September to May in south-east Queensland, on the basis of feeding rate and that maximum growth rates only occur between December and March.

At sub-tropical latitudes (e.g., approximately 27°S), high feeding rates (>85% of maximal feeding rate) was predicted to occur between late November to end of March but was restricted in all other months (Heasman 1980). Feeding activity of Giant Mud Crabs is greatly reduced at water temperatures below 20°C (Hill 1980; Hill 1984) with temperatures <18°C impacting on moult frequency (Heasman 1980). Their lower thermal limit is 10°C (Hill 1980), but their upper thermal limit is uncertain, although Giant Mud Crabs can survive sequential short-term exposure to extreme temperatures (Islam and Bhuiyan 1981). More recent studies (Moksnes *et al.* 2014), have used stepwise growth to model estimated time to size for east African populations of Giant Mud Crabs.

Fishery characteristics

Development and expansion of the Mud Crab Component of the Queensland Crab Fishery has been documented previously (Hill 1982; Brown 2010). The fishery, whilst always occurring, has greatly expanded since approximately the year 2000 because of increasing market demand and value. Average price for Giant Mud Crabs increased from $8 per kilogram in the early 2000's (Ryan 2003), to $30 per kilogram in 2022/2023 (SFM 2023). Brown (2010) includes a summary of the economics of the Fishery, with recent economic and social indicators survey information available in BDO EconSearch (2023).

The intra-annual harvest of Giant Mud Crabs in many areas is a 'short-term' fish-down of available legal-size male crab as a consequence of this species stepwise growth and mangrove/estuarine-habitat association. Spikes in harvest or catch rate likely represent the abundance of sub-legal crabs moulting to legal size and becoming 'available' to the fishery (Haddon *et al.* 2005). The temporal and spatial intensity of fishing mortality from commercial and recreational sectors combined determines how rapidly this fish-down occurs. Competition for pot placement and prior harvest are factors that affect catch rates, with competition varying in time and space (Jebreen *et al.* 2008).

Management arrangements

The minimum legal size (MLS) of mud crabs varies with jurisdiction (Table 2). In Queensland, Giant Mud Crabs must be ≥ 150 mm CW and male to be legally harvested.

Table 2. Minimum legal size (MLS) and size-at-50% mature ($CW_{50\%Mature}$) of Giant Mud Crabs (Scylla serrata) in Australian jurisdictions.

Jurisdiction	Male		Female		Source
	MLS (mm CW)	**$CW_{50\%Mature}$ (mm)**	**MLS (mm CW)**	**$CW_{50\%Matue}$ (mm)**	
Queensland	150	164.5 GPIV 141.8 GPIIIB	No take	147	Heasman (1980)
Northern Territory	130 recreational 140 commercial	149 VDG 146 GoC	140 recreational 150 commercial	136	Knuckey (1999) Grubert *et al.* (2008)
New South Wales	~125*		~125*		Butcher *et al.* (2012)
Western Australia	150 120 *S. olivacea*		150 120 *S. olivacea*		Butcher *et al.* (2012)

CW (carapace width) is the distance between the antero-lateral spines, specifically the 9th spine in NT and WA, but not specified in Qld. VDG =- Van Dieman Gulf, GoC = Gulf of Carpentaria; * = 85 mm carapace length converted using CL = 0.68*CW-1.51 (Hewitt *et al.* 2022a). GP = growth phase, see Heasman (1980).

The Queensland Harvest Strategy aims to manage fishing mortality on Giant Mud Crabs via a Total Allowable Catch (TAC), with a total quota entitlement (TQE) for the commercial sector and recreational possession limits to achieve a specified exploitable biomass target. The financial year TQE is actioned by individual transferable quota (ITQ), with assessment of harvest in comparison to the TAC occurring for a calendar year. The Harvest Strategy includes several decision rules for the commercial and recreational sector and social and economic performance indicators (Appendix 3).

The primary objective of the Harvest Strategy is to maintain Queensland Giant Mud Crab resources at a level that achieves maximum economic yield (MEY). An assumed proxy for MEY is an exploitable biomass of 60%, where exploitable biomass refers to legal-size male Giant Mud Crabs. The Harvest Strategy also aims to:

- Minimise and mitigate any unacceptable ecological risks arising from fishing-related activities.
- Maintain sectoral allocations.
- Maximise the economic performance of the commercial sector.
- Manage excess capacity to improve social and economic benefits.
- Monitor the broader social and economic benefits of the fishery to the community.

Key performance indicators are:

- Exploitable biomass - 60% target, 20% limit reference point[1]
- Estimated recreational harvest – reference level 2013 recreational survey (338 tonnes).

The Fishery has two spatially separate management units – Queensland east coast (EC1) and Gulf of Carpentaria (GC1). Although the Giant Mud Crab is the predominate target species caught by the same gear type (i.e., crab pots – predominately collapsible trawl mesh pots), there are fundamental differences in the seasonality of fishing effort and harvest in EC1 and GC1 driven by: (i) climate patterns and (ii) catchability. The other difference between EC1 and GC1 is the level of competition for fishing locations between participants within the commercial sector, and between participants from the commercial and recreational sector. Overall, there is more intra- and inter-sector competition in the EC1 management unit than the GC1 management unit.

Reported daily catch and effort between 1988 and 2023 inclusive were requested from Fisheries Queensland (Data Request 2796) for the Queensland Crab Fishery. Catch and effort fluctuated in the fishery, with the maximum catch reported being 1,235 tonnes in 2011 for the east coast and 199 tonnes in 2012 for the Gulf of Carpentaria (Appendix 4).

Prior to the introduction of quota (01/09/2021), commercial catch and effort data is non-validated. Whilst many operators accurately reported their harvest and effort, anecdotal reports (past and present) indicate that some reported data is unlikely to be accurate. Additionally, there is the strong likelihood that an uncertain proportion of operators used, and still do so, in excess of 50 pots per C1 symbol, sometimes referred to as 'over-potting' (Brown 2010). The effects of over-potting (i.e., cryptic fishing effort or 'apparent efficiency') on stock density trends were examined by Brown (2010). However, there was limited value in adjusting catch for misreporting or adjusting effort for over-potting, as any adjustments are broad-scale (i.e., generally applied equally across regions or boat marks) and require additional non-validated assumptions. A further complexity in short-term patterns of catch and catch rates is variable soak time i.e., the duration between when a pot is baited, when it is checked and legal crabs removed for harvest. Most operators check pots on a daily basis (i.e., soak time in the order of 24 hours), but longer soak times do occur i.e., 48 hours up to 7 days. These issues add complexity to analyses of commercial logbook data, particularly catch rate.

[1] Limit reference point (B_{lim}) is the level at which the risk to the stock is unacceptably high and the stock is defined as 'overfished'

East Coast (EC1)

The EC1 management unit covers commercial fishing and harvest of Mud Crabs along the east coast of Queensland from Cape York to the New South Wales border; a distance of approximately 2,600 km. Commercial effort and associated catch is concentrated in areas with sheltered, mangrove-lined estuaries and embayments. Reported commercial catch of Giant Mud Crabs expanded from 389 tonnes in 1990 to a peak of 1,235 tonnes in 2011. Of note are the investment warnings for the fishery in 1997 (Gulf of Carpentaria), September 2003 (east coast) and 2014 (all Queensland commercial fisheries) information stakeholders that no subsequent catch history will be taken into account in any further management changes. There have also been a series of re-zoning of areas as part of marine park management that has impacts on the distribution of effort and thus catch. Since the peak in 2011, harvest has decreased to 566 tonnes in 2023 (Appendix 4, Figure 8). Effort prior to the introduction of Vessel Monitoring Systems (VMS) in 2019 is non-validated and potentially includes inaccurate catch and effort data (see Brown 2010, Northrop *et al.* 2019 for further details). Catch prior to the introduction of ITQ in September 2021 is also non-validated.

To better understand regional patterns in catch (as an insight to abundance) and effort, the EC1 management unit was sub-divided in the current project into seven regions based on geography, climate patterns and the fishery (Table 3). Regions are sufficiently large to ensure anonymity in catch and effort but sufficiently small to capture temporal patterns in climate. The regions are similar to that analysed by Haddon *et al.* (2005) and Jebreen *et al.* (2008), with slight adjustment to reflect project staff's knowledge of the fishery.

Table 3. Nominal regions within the east coast (EC) management unit of the Queensland Crab Fishery.

Region name	Latitude (°S)	Key landmarks	Commercial logbook grids
EC far north	10.5 to 15.0	Cape York to Starke River, including Princess Charlotte Bay	B4, B5, B6, C6, C7, C8, D8, C9, D9, D10, D11, E11, F11, D12, E12, F12, G12
EC north	15.0 to 19.0	Cooktown to Ingham including Hinchinbrook Channel	G13, G14, G15 G16, H16, H17, I17, I18, H19, I19, I20
EC north central	19.0 to 20.0	Townsville to Bowen, including the Bowling Green Bay, Burdekin, Edgecombe Bay	I21, J21, K21, L21, K22, L22, M22, M23
EC central	20.0 to 22.5	Arlie Beach to Yeppoon, including Broadsound and Stanage Bay	N23, N24, O24, N25, O25, O26, P26, O27, P27, Q27, R27, P28, Q28, R28
EC south central	23.0 to 24.5	Fitzroy River to 1770, including The Narrows, Gladstone and Eurimbula Creek	Q29, R29, S29, R30, S30, S31, T30, T31, U31
EC south	24.5 to 26.5	Bundaberg to Sunshine coast, including Great Sandy Strait	T32, U32, V32, W32, U33, V33, W33, U34, V34, W34, U35, V35, W35
EC south-east	26.5 to 28.5	Sunshine Coast to NSW border, including the Logan River and Moreton Bay	V36, W36, W37, W38, W39, X39

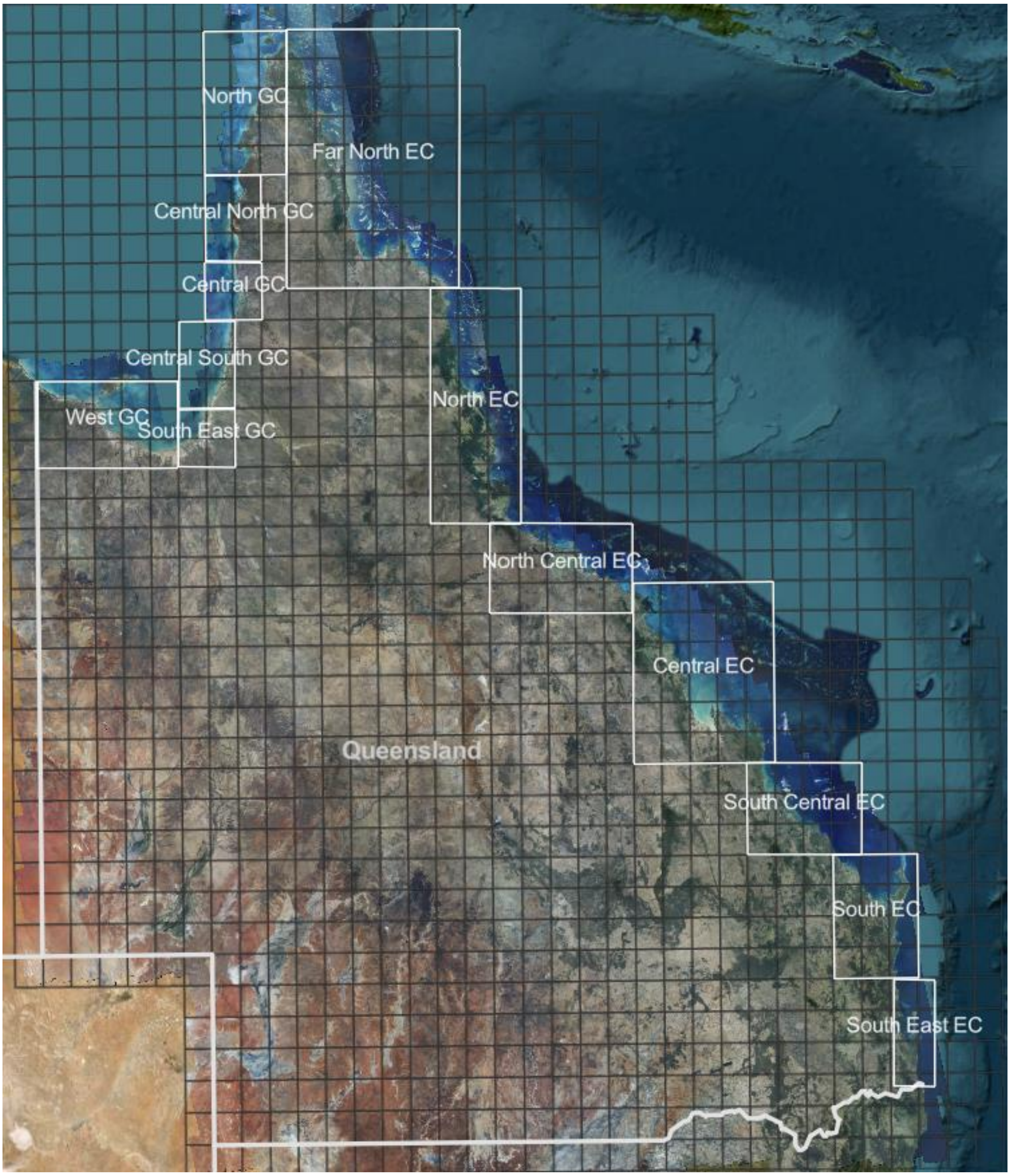

Figure 7. Spatial extent of the Queensland Mud Crab Fishery - management units East Coast (EC) and Gulf of Carpentaria (GC), with the regions considered in the current research project to better understand patterns of catch and effort. See Table 3 for details. Commercial logbook grids (30 nm^2) indicated in black. Figure produced in Queensland Globe.

All regions within the EC1 management unit showed seasonal patterns in the mean monthly catch rate (kg/days fished), with the lowest mean catch rate in September, October, or November (Figure 9). The seasonal pattern is similar across years for each region, although there are isolated temporal spikes or troughs in the monthly catch rate time series (Figure 10).

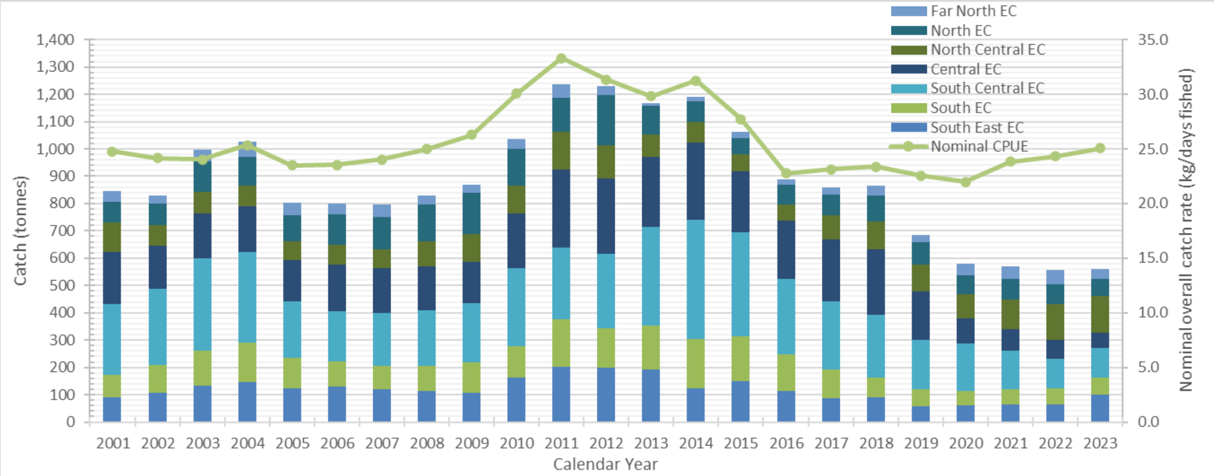

Figure 8. Reported harvest (tonnes) and nominal catch rate (kg/day fished) of Giant Mud Crabs for regions of the EC1 management unit, Queensland Crab Fishery, 2001 to 2023 calendar years. Financial year data presented in Appendix 4.

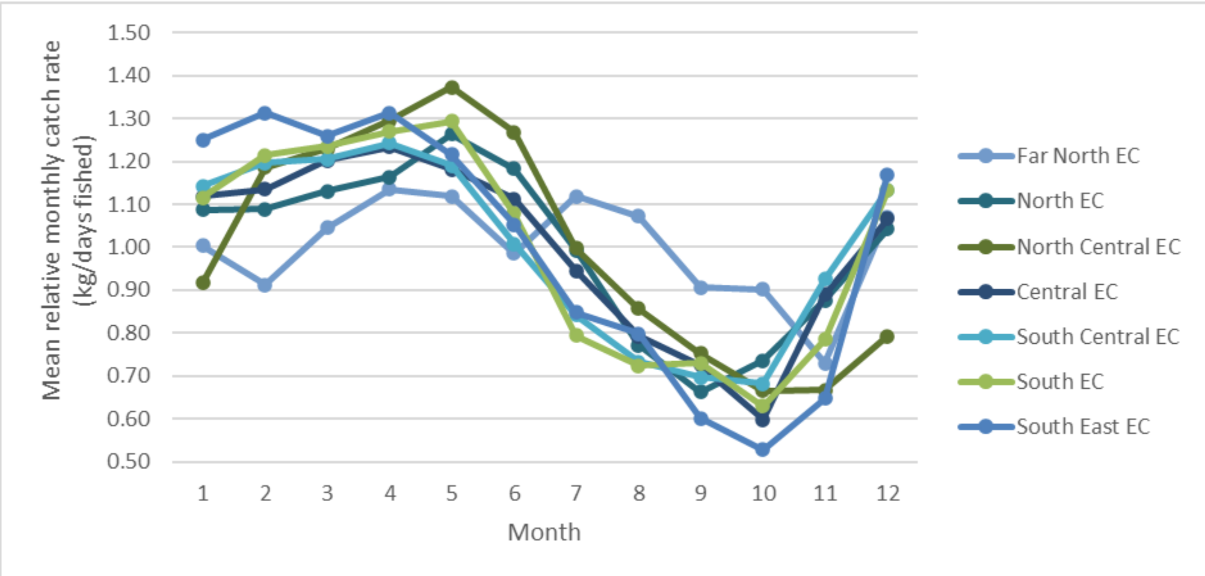

Figure 9. Mean monthly catch rate (kg/days fished) of Giant Mud Crab for regions of the EC1 management unit, Queensland Crab Fishery, standardised to the regional mean annual catch rate for boat marks reporting at least 15 days of fishing per month per region.

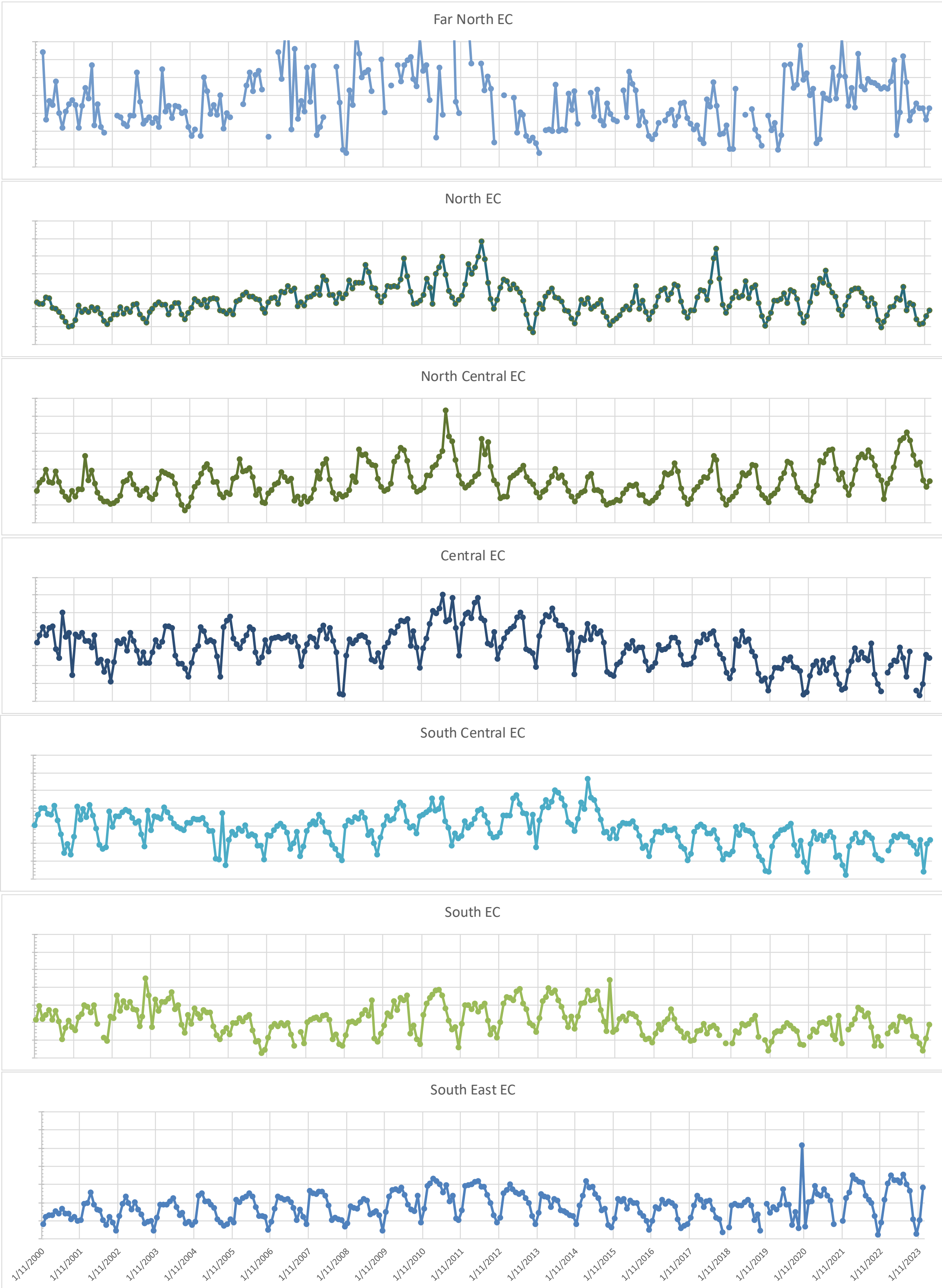

Figure 10. Mean monthly catch rate (unitless kg/day fished for logbook confidentiality) of Giant Mud Crabs for region for the EC1 management unit, Queensland Crab Fishery, November 2000 to December 2023, based on boat marks reporting at least 15 days of fishing per month per region.

Effort-to-yield plots were complied to explore the potential of a dome-shaped relationship that may indicate maximum yield (Brown 2010). These plots require a fishery to be heavily exploited to determine when yield declines, despite increasing effort. They also assume constant recruitment.

Nothwithstanding changes to management arrangements, and reliability of logbook data, there are patterns in the yield plots.

For the northern regions (i.e., far north, north, north central), the yield plots are predominately circular, with peak yield in 2004, 2022 for far north, 2012 for north, and 2011, 2022 and 2023 for north central (Figure 11). For the central and southern regions, yield increases from 2001, peaking in 2011 or 2014, then declines, with 2023 having low or the lowest yield. Most notable in these plots is the drop in yield from 2018 or 2019 onwards, potentially an indication of the consequences of the introduction of VMS and ITQ on catch and effort reported in the commercial logbooks.

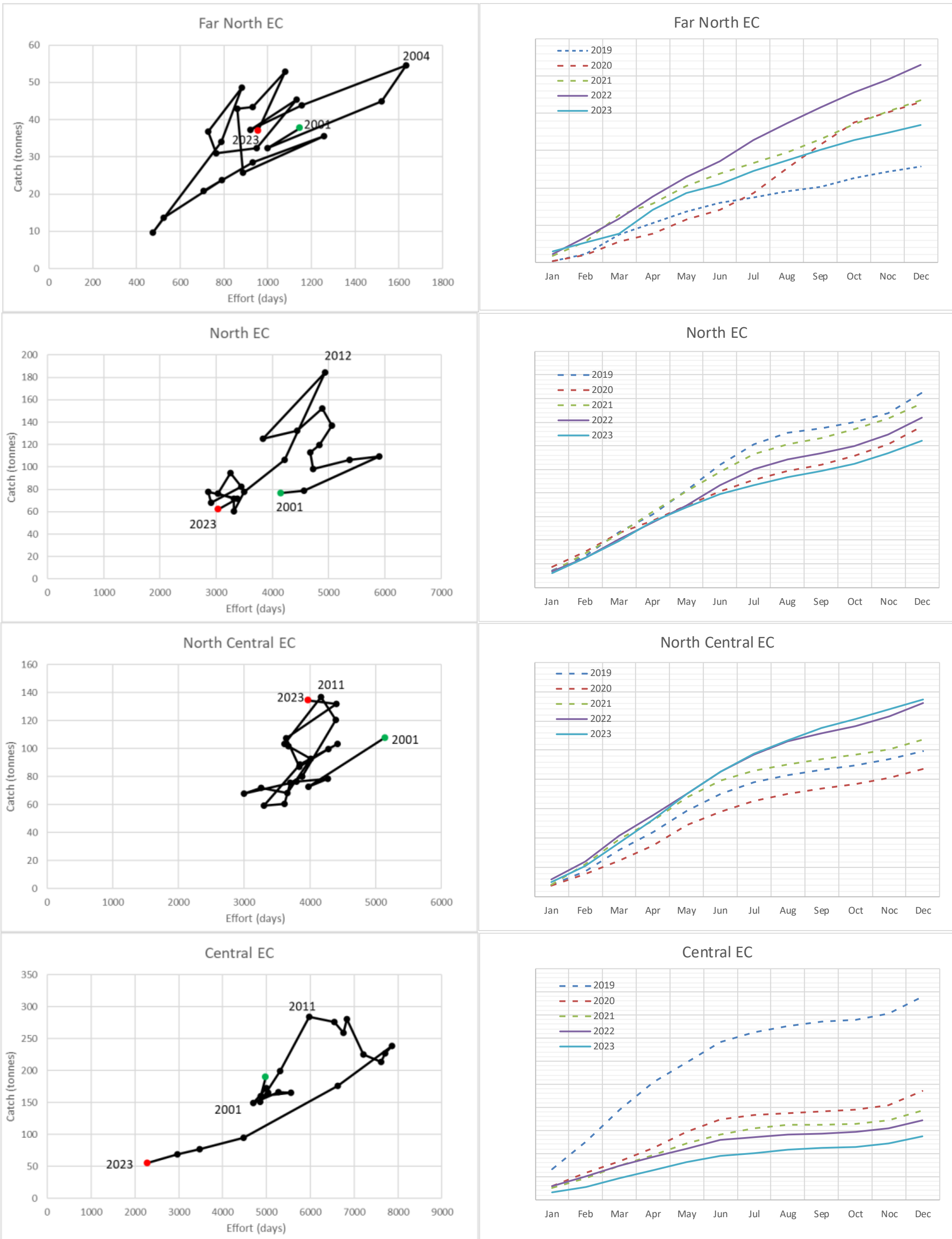

Figure 11. Harvest plots (calendar year) of Giant Mud Crabs for regions within the EC1 management unit, Queensland Crab Fishery, based on logbook data. Plots on the left are yield plots (annual catch against effort, 2001 to 2023). Plots on the right are cumulative monthly catch (unitless for logbook confidentiality, dashed lines are pre-ITQ, solid lines are post-ITQ, 2019 to 2023).

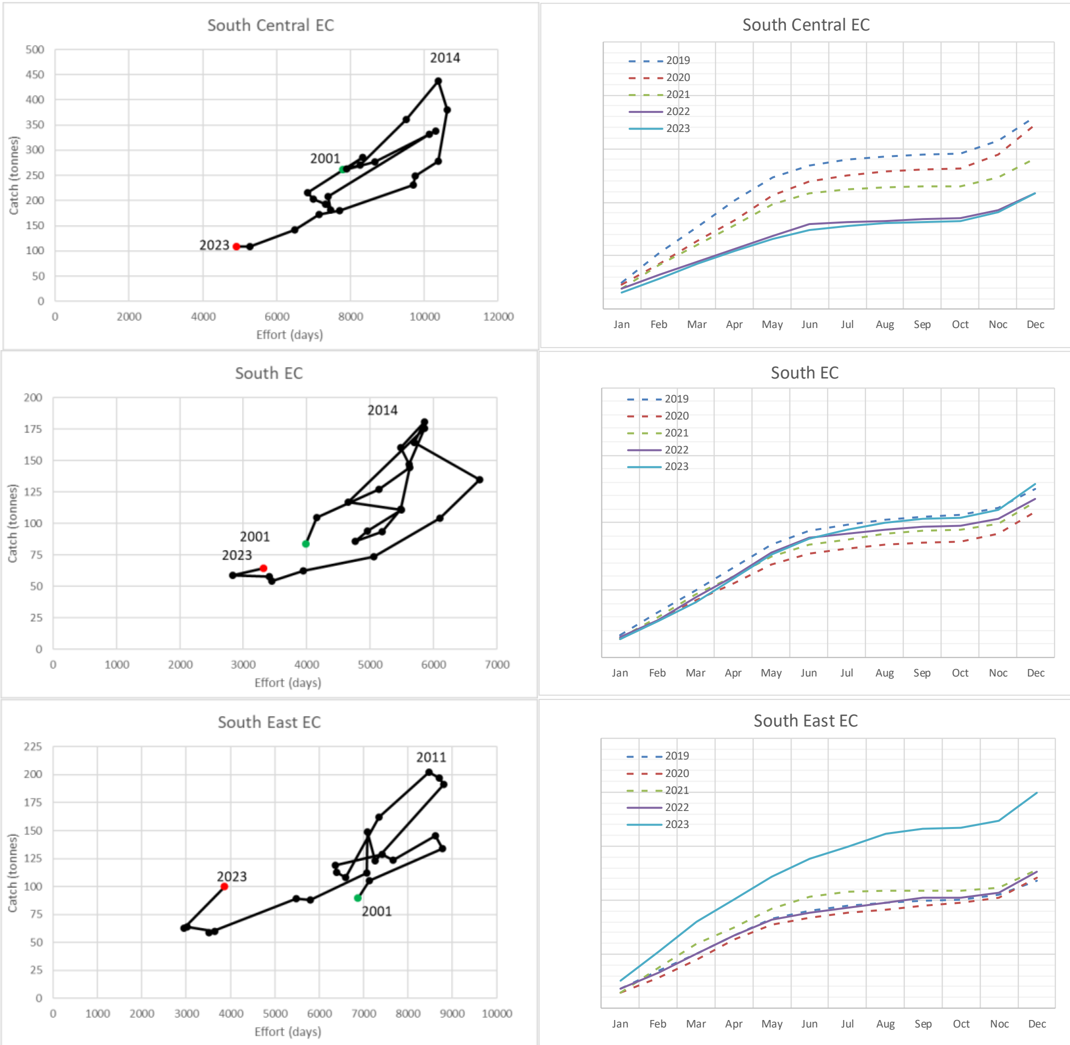

Figure 11 cont. Harvest plots (calendar year) of Giant Mud Crabs for regions within the EC1 management unit, Queensland Crab Fishery, based on logbook data. Plots on the left are yield plots (annual catch against effort, 2001 to 2023). Plots on the right are cumulative catch (unitless for logbook confidentiality) dashed lines are pre-ITQ, solid lines are post-ITQ, 2019 to 2023).

Background information on EC1 regions that affect catch, including climate

Regional climate information is provided below to assist in understanding seasonal fluctuations in the catch related to water temperature, growth patterns, and moulting of 'cohorts' to legal size (Heasman 1980; Hill 1982; Williams and Hill 1982). Inter-annual variation in the catch of Giant Mud Crabs is understood to be a function of recruitment more so than productivity (Heasman 1980; Grubert *et al.* 2008). Meynecke *et al.* (2011) reported that the maximum Southern Oscillation Index (SOI) and mean annual rainfall explained up to 50% of the variation in catch rate for three of the ten EC1 catchments analysed. Seasonal rainfall patterns along the EC1 regions is either classed by the Australian Bureau of Meteorology as either summer dominant (i.e., marked wet summer and dry winter) or summer (i.e., wet summer and low winter rainfall), with variable amounts of median annual rainfall (see Climate classification maps, Bureau of Meteorology).

Far north: Easten side of Cape York to approximately Cape Flattery. Catch and effort is somewhat variable between years. Logistical challenges for this remote fishing region include the transport in of bait and fuel, and the transport out of a live product to markets (i.e., Carins and then onwards to southern markets e.g., Brisbane, Sydney, Melbourne). This region is classed as having summer dominant seaonal rainfall, with 650-1200 mm median annual rainfall. Wet season flooding adds to the complexity to understanding catch and catch rate fluctuations in this region. No recreational harvest estimate is available.

North: Cape Flattery to approximately Rollingstone, with multiple small-scale bays, coastal creeks and several major wet-tropics rivers. The region is dominated by catch and effort from the estuarine mangrove habitats associated between Hinchinbrook Island, Channel and mainland. This region is classed as summer dominant seasonal rainfall, with more than 1200 mm median annual rainfall. Wet season rain and associated flooding plays a major role in catch variability, in especially in the Hinchinbrook area which is affected by flooding from the Herbert and Seymour Rivers. The region was heavily affected by cyclone Yasi (2011) which was highly destructive of mangrove habitat. No recreational harvest estimate is available.

North central: Approximately Rollingstone to Cape Gloucester. It includes several large bays (Cleveland, Bowling Green, Upstart, Abbot, and Edgecumbe) and associated rivers and mangrove lined estuaries). This region is classed as summer dominant seasonal rainfall, with 650-1200 mm median annual rainfall. Including the dry tropics, wet season rain and associated flooding plays a major role in catch variability, especially in the bays associated with the Ross, Haughton, Barratus, Burdekin, Don, and Gregory Rivers/Creeks. Estimated annual recreational harvest is approximately 9,000 crabs.

Central: Cape Gloucester to approximately Yeppoon, with numerous small bays, the Proserpine and Pioneer Rivers, Rocky Dam Creek, as well the Styx River and Herbet Creek of the Broadsound/Stanage Bay area. The northern part of this regions is classed as summer dominant seasonal rainfall, with 650-1200 mm of median annual rainfall, while the southern part (i.e., Broadsound) is classed as summer, with more than 1200 mm median annual rain. No recreational harvest estimate is available.

South central: Approximately Yeppoon to Round Hill Head, with major features being the mangrove lined estuarine habitats of the Fitzroy River, The Narrows, Gladstone Harbour, Rodds Harbour and Turkey Beach. This region is classed as summer seasonal rainfall with greater than 1200 mm median annual rainfall. Being south of the summer monsoon trough that occurs seasonally over tropical Australia, the region has high inter-annual variation in wet-season rain and associated flooding in the key river systems of the Fitzroy, Calliope and Boyne Rivers. Most rainfall and flooding occurs November to May (Halliday and Robins). Estimated annual recreational harvest is approximately 10,000 crabs.

South: Round Hill Head to the Sunshine Coast (approximately Coolum), with the major features being the mangrove lined habitats of the Burnett River, Mary River and Great Sandy Strait. This region is classed a summer seasonal rainfall with 650-1200 mm median annual rainfall. Estimated annual recreational harvest is approximately 11,000 crabs.

South-east: Sunshine Coast to the Queensland-NSW border, with the major features being the mangrove lined habitats of greater Moreton Bay. This region is classed a summer seasonal rainfall with greater than 1200 mm median annual rainfall. Major rain and flooding can occur in most months of the years, although is rare in spring. Major river influences are the Logan and Coomera rivers, which influence the southern Bay, as well as the Brisbane, Pine and Caboolture Rivers, which influence the northern Bay. In extreme events (e.g., 2011), all of Moreton Bay can be influenced by floodwater. High human population (approximately four million) and ease of access, results in a high participation in recreational crabbing in this region, with Giant Mud and Blue Swimmer Crabs being targeted. Total harvest (and discard mortality) of Giant Mud Crabs by the recreational sector in this region is likely to be significant (estimated annual harvest is approximately 14,000 crabs).

Gulf of Carpentaria (GC1)

The GC1 management unit covers the Queensland Gulf of Carpentaria coastline from western Cape York to the border with the Northern Territory - approximately 1,150 km of coastline. Commercial catch and associated effort are concentrated in the Gulf's mangrove lined estuaries, as well as along sections of the coastal foreshore. Reported commercial catch expanded from 29 tonnes in 1990 to 156 tonnes in 2001, peaking at 199 tonnes in 2012 (Appendix 4, Figure 12). In 2023, reported catch was 96 tonnes. Effort prior to 2019 (and the introduction of VMS) is non-validated. Catch prior to September 2021 (and the introduction of ITQ and prior catch reporting) is non-validated.

To better understand regional patterns in Giant Mud Crab catch (as an index of abundance) and effort over time, the GC1 management unit was sub-divided within the current project into six regions based on geography and climate patterns (Table 4), similar to that used in Robins *et al.* (2020) but adjusted to better reflect climatology and spatial fishing patterns. All regions show seasonal patterns in the mean monthly catch rate (Figure 13). The seasonal pattern is similar across years for each region, although there are isolated temporal peaks and troughs in the monthly catch rate time series (Figure 14). Further background information on GC1 regions that affect catch, including climate is detailed in Robins *et al.* (2020).

Table 4. Nominal regions within the Gulf of Carpentaria (GoC) management unit of the Queensland Crab fishery.

Region name	Latitude (°S) & Longitude (°E)	Key landmarks	CFISH grids
GoC far north	10.5 to 13.0	Weipa & Mapoon	A5, A6, A7, AB6, AB7, AB8
GoC north	13.0 to 14.5	Archer, Kirke, Holroyd Rivers	AB9, AB10, AB11, AC9, AC10, AC11
GoC central	14.5 to 15.5	Pormpuraaw incl. Edward River, Mitchell River	AB12, AC12, AB13, AC13
GoC central south	15.5 to 17.0	Nassau River to approx. Gilbert River	AB14, AC14, AB15, AC15, AC16, AD16
GoC south-east	17.0 to 18.0 140.5 to 141.5	Smithburne River to approx. Morning Inlet incl. Norman and Flinders Rivers	AC17, AD17, AC18, AD18, AE18
GoC west	16.5 to 18.0 138.0 to 140.5	Morning Inlet to the NT border	AF17,AF18, AG16, AG17, AG18, AH16, AI16

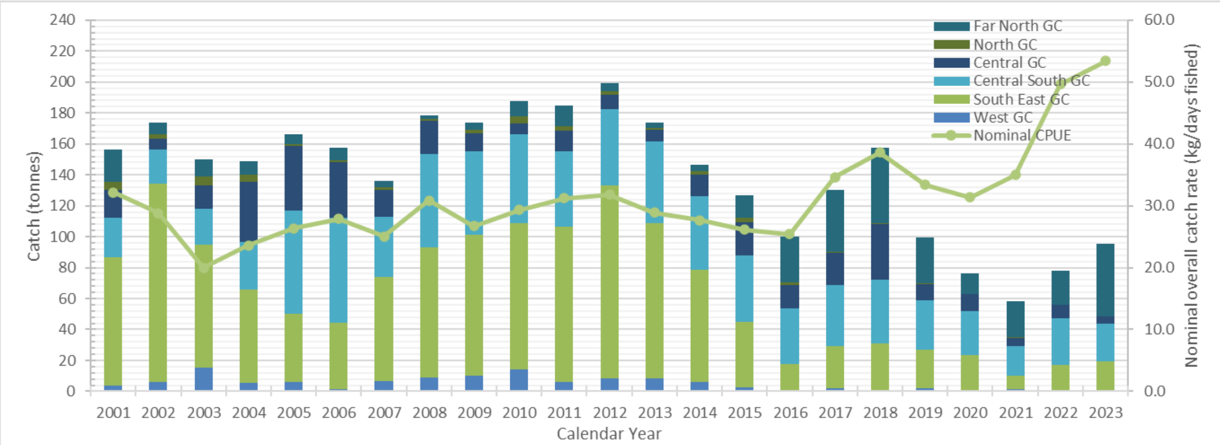

Figure 12. Reported catch (tonnes) and nominal catch rate (kg/day fished) of Giant Mud Crabs for regions in the GC1 management unit of the Queensland Crab Fishery 2001 to 2023 calendar years. Financial year data presented in Appendix 4.

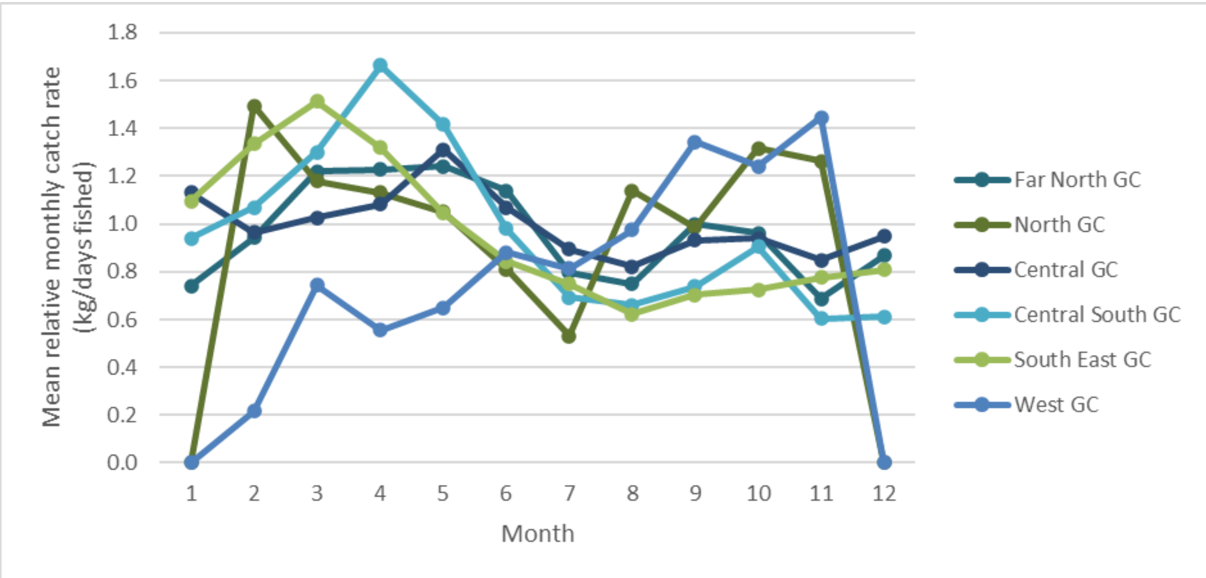

Figure 13. Mean monthly catch rate (kg/days fished) of Giant Mud Crabs for regions of the GC1 management unit of the Queensland Crab Fishery, standardised to the regional mean annual catch rate for boat marks reporting at least 15 days of fishing per month per region.

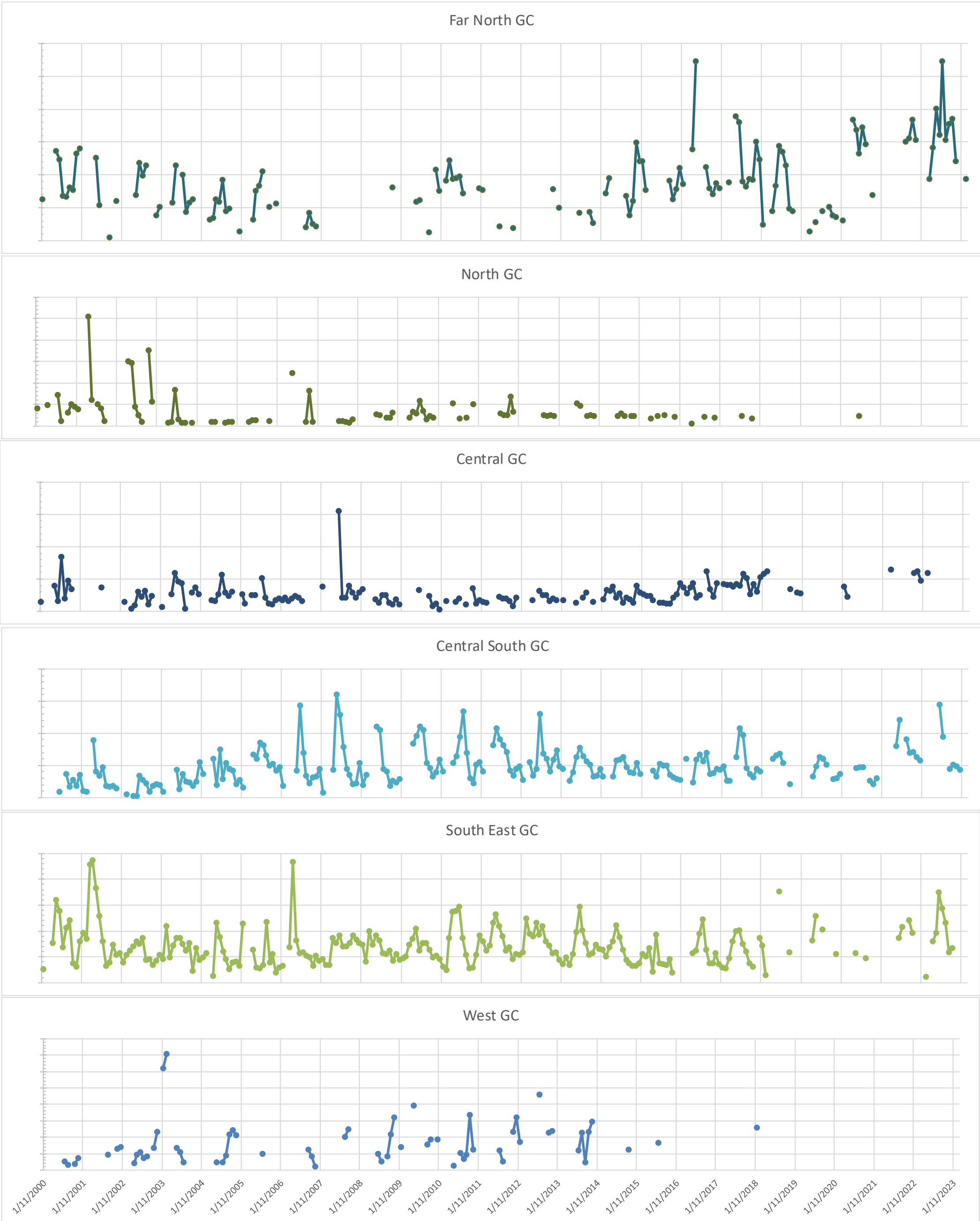

Figure 14. Mean monthly catch rate (unitless kg/day for logbook confidentiality) of Giant Mud Crabs for regions of the GC1 management unit of the Queensland Crab Fishery, November 2000 to December 2023 for boat marks reporting at least 15 days of fishing per month per region.

For the far north GoC region, yield has been high (and circular) over the last eight years (Figure 15). For all other regions within the GC1 management unit, effort-to-yield plots show a decline in yield from 2018 onwards, likley as a consequence of VMS and ITQ and associated effects on reported catch and effort in the commercial logbooks.

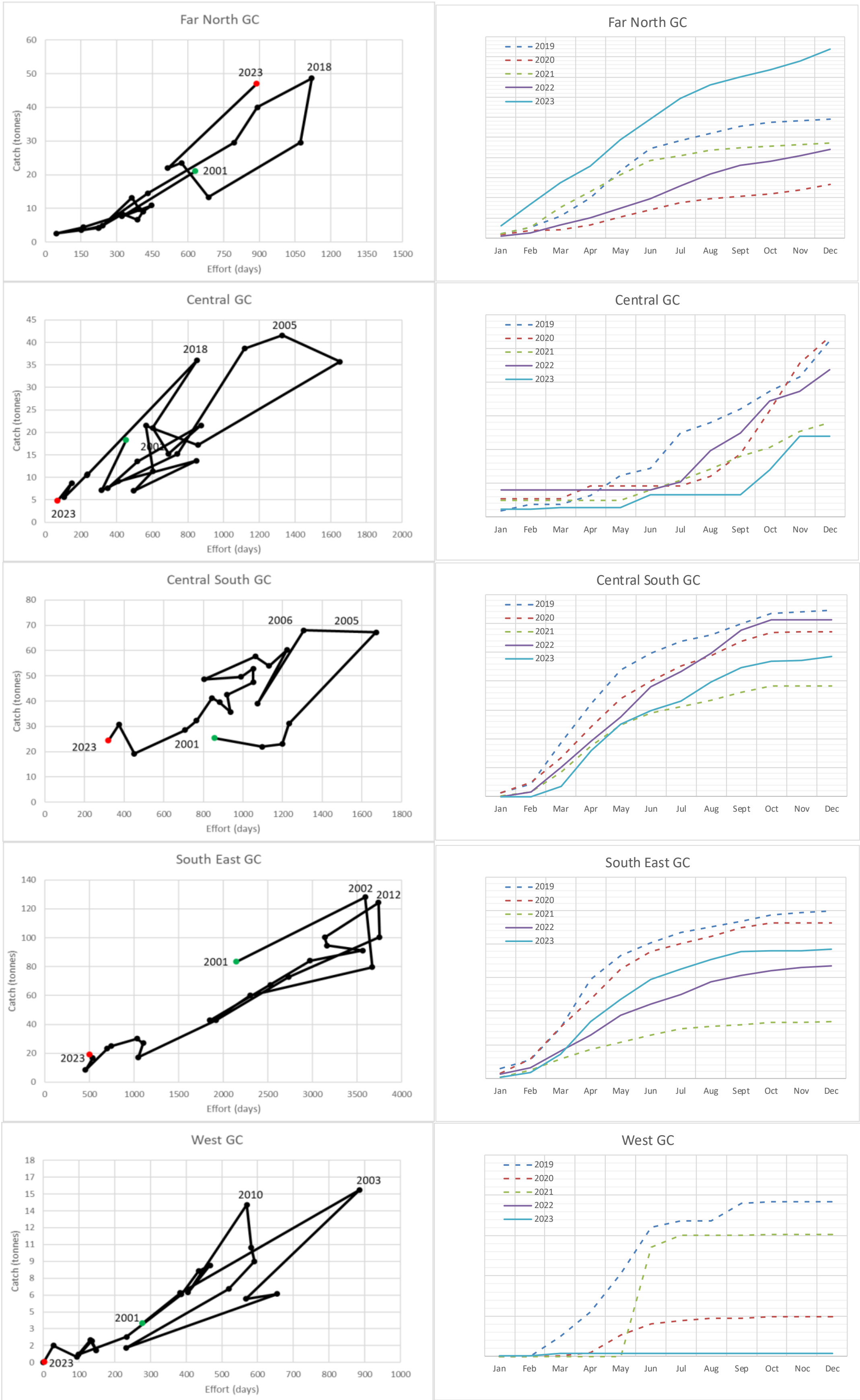

Figure 15. Harvest plots (calendar year) of Mud Crabs for regions of the GC1 management unit, Queensland Crab Fishery, based on logbook data. Plots on the left are yield plots (annual catch against effort, 2001 to 2023). Plots on the right are cumulative catch (unitless for logbook confidentiality, dashed lines are pre-ITQ, solid lines are post-ITQ, 2019 to 2023).

Monitoring and assessment

The Fisheries Queensland Fishery Monitoring Program included Giant Mud Crabs between 2000 and 2009 and monitoring four regions in the Gulf of Carpentaria and thirteen regions along the East Coast. The objectives were to obtain fishery-independent catch rate data as an index of annual relative abundance and size-frequency and sex ratios for long-term comparison of population structure and sustainability indicators. The main findings were that there were significant differences in mean carapace width of males and females between regions and between locations within regions (i.e., foreshore, mouth, mid- and upper-estuarine, Jebreen *et al.* (2008)). Smaller crabs tended to be caught further upstream, and larger crabs tended to be caught downstream. The relative abundance of males declined sharply above 150 mm CW, while females show a bimodal size-frequency distribution, indicative of fishing pressure and Queensland regulations (i.e., no female harvest policy). Standardised catch rates suggested that lower catch rates and lower proportion of female crabs occurred in the Gulf of Carpentaria than on the east coast (Jebreen *et al.* 2008). While spatial representation within the long-term study was high, temporal replication was cost-limited, with each region monitored once per year using 20 pots per location within region (i.e., 80 pots per region).

Numerous models have been used to assess the status of Giant Mud Crab populations, most of which are fundamentally based on time series analysis of catch and/or catch rates. In the Northern Territory, the delay-difference model of Walters (2016) and Grubert *et al.* (2019) uses simple biomass dynamics based on a carryover-recruitment equation (i.e., biomass is recruitment plus [the remaining biomass from the preceding year minus harvest, adjusted for growth and natural survival]). It includes an explicit spawning-stock relationship (the number of females determine recruits two years in the future) and an estimated growth-survival function based on empirical data that is assumed to be representative of the population over time. Application of this model in Queensland would require an estimate of the unfished female biomass, likely assumed as some proportion to the legal male harvest.

In Queensland, the Mud Crab component of the Queensland Crab Fishery was assessed using a Catch-MSY approach (Northrop *et al*. 2019), to assist in setting initial Total Quota Entitlement harvests. It's considered a model-assisted data-poor assessment method for species where catch data is available, but there is limited information about other values needed for a more sophisticated approach (i.e., life-history or effort parameters). Catch-MSY models population biomass, with biomass in subsequent years being the post-catch exploitable biomass (i.e., residual crab biomass left after harvest) plus the non-exploitable biomass (i.e., sub-legal crab biomass) response to natural mortality (i.e., survival), growth and recruitment. Thus, it is like the delay-difference model used in the NT, but the spawning-stock relationship is implicit in the Catch-MSY model (via the response of the non-exploitable biomass). In addition to the time series of catch data, an estimate (range) of the intrinsic rate of population growth is needed (referred to as 'resilience'), as is an estimate (range) of the carrying capacity (*K* – analogous to the unfished exploitable biomass). Johnson (2020) noted that Catch-MSY assumes average recruitment across all stock sizes, including those below half of B_{MSY}. If recruitment is lower at reduced stock sizes, then biomass recovery will be overestimated and thus the exploitation rates underestimated. This is unlikely to be an issue in the Queensland assessment, given the no female take policy, unless high exploitation rates of mature males in a management unit (or regions) impedes recruitment because of sperm limitation.

Mud Crabs are managed in the New South Wales as part of the Estuary General Fishery. Harvest method is by pots/traps and the current total allowable commercial catch (TACC) for Giant Mud Crabs is 185 tonne, reduced from the previous TACC of 206 tonne (NSW Total Allowable Fishing Committee 2024). In recent years, the catch of Giant Mud Crabs in NSW has been around 90 tonnes (Kirke *et al.* 2023). The NSW TACC is the combined total across seven regions, although most catch occurs in the four northern regions and is approximately 49% female and 51% male. The minimum legal size in NSW is 85 mm carapace length (CL = approximately 125 mm CW). Standardised annual commercial catch rates (kg/day – adjusted for year, month, management region, fisher and transformed fishing effort) is suggested to provide the most reliable index of relative abundance for Giant Mud Crabs in the NSW Estuary General Fishery, assuming factors (e.g., market or quota) do not unduly influence the catch (Johnson 2020). No formal limit or target reference levels of status indicators are specified in the Harvest Strategy for Giant Mud Crabs in NSW. The trajectory of the annual standardised catch rate has declined in most NSW regions. Application of a Schaefer surplus production model with a Bayesian state-space implementation, indicated a stock size (based on exploitable biomass) greater than a B_{Limit} of 20% unfished. The assessment noted that Queensland spawning females may provide recruits to NSW estuaries (Hewitt *et al*. 2022b), and flooding, particularly major to extreme floods in 2018 and 2022, likely reduced recruitment and thus contributed to declines in catch rate over time.

Potential stock indicators

The current project had objectives regarding monitoring inter-year trends in stock abundance, at an appropriate spatial scale (e.g. regions within management units), and quantification of key biological parameters relevant to assessment and management. The following have been previously suggested as stock indicators for Giant Mud Crab (Grubert *et al.* 2008):

- Proportion of female crabs in the first and second mature instars, with the latter indicating the percentage of females that had successfully completed at least one spawning migration.
- Mean size of crabs harvested – indicating stock exploitation relative to the minimum legal size.
- Mating success (mating scars on males or presence of spermatophores in females) – indicate whether size or sex-harvest arrangement are detrimental to spawning success.
- Catch rate – as an index of abundance at appropriate spatial/temporal scales, and whether cryptic effort (over-potting, variable soak time) should/can be considered.
- Adult/pre-recruit abundance – a pre-recruit index that could be gauged at least six months before the main season would assist business planning (and potentially TACC setting).

Market forces

Market forces (supply, demand and price) play a role in the intra-year patterns of Giant Mud Crab harvest. Since the 2000's the price paid for Giant Mud Crabs has significantly increased, and this has played a role in increasing the number of full-time commercial crabbing operations in Queensland. The catch-to-plate supply chain is not fully understood for Giant Mud Crabs harvested in northern Australia. A significant proportion (likely >50%) of harvest is shipped (often by air) to southern markets (e.g., Sydney and Melbourne). The remainder is consumed in regional cities and towns near the harvest location, excepting the Gulf of Carpentaria.

There is seasonal complexity in the market value of Giant Mud Crabs (Figure 16), which is predominately linked to social celebrations (e.g. Christmas, New Year, Easter, Chinese New Year, Chinese Mid-Autumn Festival, University graduations). Although a known effect, and indices of market forces are available, there is complexity in adjusting for the effects of market forces in the catch data. Additionally, shipment costs vary between operators depending on catch location and market location.

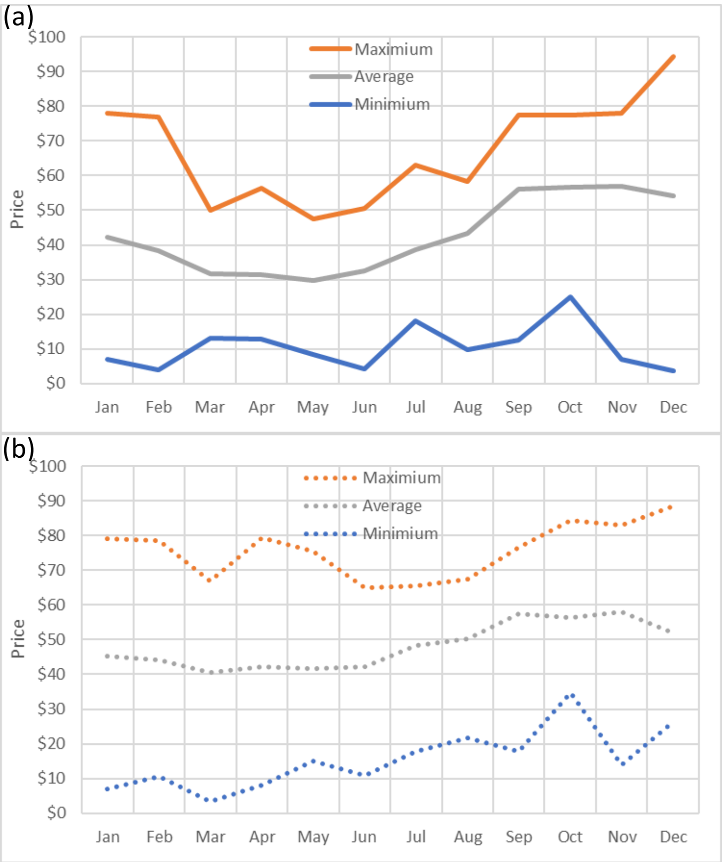

Figure 16. Monthly average of daily values of Giant Mud Crabs (maximum, average, minimum price per kg) illustrating seasonal fluctuations in market value. (a) A-grade males. (b) A-grade females. Source Sydney Fish Market daily reports 04/01/21 to 30/06/24).

Conclusion

This literature review has provided background information and context for the current research to assist in interpretation of results. Despite some gaps in knowledge such as age and moulting frequency, the general life cycle of Giant Mud Crabs is reasonably well understood, with likely differences between regions in the growth, maturity and reproduction of Giant Mud Crabs. These were key research objectives when the current research was initiated as limited monitoring and research has been conducted on population biology in regional areas of Queensland.

Chapter 2. Sampling methods

N.J. Stratford, W.D. Charles, N. Flint and J.B. Robins

Sampling within the project aimed to collect data about Giant Mud Crabs in regions throughout Queensland sufficient to address project Objectives 2 and 3 (i.e., 'survey' pots as a means of monitoring Giant Mud Crabs, regional biological information, tagging studies and spawning female migration). The project was conceptualised during 2019/2020, with genetic sampling occurring in 2020/2021 and more extensive field sampling from September 2021 onwards. During the experimental design phase (~2021), industry participants were recovering from the consequences of COVID (e.g., lockdowns, reduced market demand, difficult transport logistics, etc), as well fishery reforms (i.e., TACC, ITQ, prior reporting requirements, 7-day rule). It became apparent, that fishery-independent sampling would likely not be effective in all regions because of pot saturation in key harvest regions. For cost-efficiencies and to engage stakeholders with the project, the sampling strategy adopted a mix of regular fishery-independent sampling in two key harvest regions (south-east and central Queensland east coast) and intermittent fishery-dependent sampling in all other key harvest regions. This aligned with the request during proposal development that the project involve industry and use local fisher knowledge. At the same time as the current research, FRDC 2021-119 was conducting research on the performance of escape vents (with fishery-independent and fishery-dependent sampling), with data shared between projects (Robins et al . 2024). Further opportunity to enhance information on crab populations of the northern Gulf of Carpentaria occurred through collaboration with TMSFB000012 (Reducing bycatch of speartooth sharks in a commercial crab fishery, led by Dr R Pillans, CSIRO, in collaboration with DPI, Queensland and the Gulf of Carpentaria Commercial Fishermen Association) with data sharing arrangements negotiated.

Morphometric definitions and field measurements

The following metrics were defined and measured during field sampling as indicated:

- Notch width (NW, standard measure) - the distance (to the nearest mm) between the notches anterior to the last opercular spines of the dorsal carapace.
- Carapace width (CW, secondary measure, used for legal-size in Queensland) - the distance (to the nearest mm) between the tips of the largest opercular spines on each side of the dorsal carapace.
- Crusher claw height ($C_{law}H$, standard measure) and side (left or right) - the distance (to the nearest mm) of the crusher claw (i.e., the claw with 'molar'-like teeth as opposed to the cutter claw which has 'incisor'-like teeth) at its widest dimension. Not measured if the crusher claw was missing.
- Sex – males distinguished by a narrow V-shaped abdomen, with functional maturity indicated by the presence or absence of mating scars; females distinguished by abdominal shape (following Islam *et al.* 2010), with immatures having a narrow, triangular V-shaped abdominal flap, mature individuals having a wide, rounded and mottled in colour U-shaped abdomen flap, and intermediates have a somewhat broadened in shape abdominal flap but lacking the darkened colour (Figure 5). Heasman (1980) and Knuckey (1999) did not distinguish between V-shape and intermediate-shape immature females in their studies, partly due to the sizes of crabs they sampled.
- Intermoult stage (≅ commercial grading i.e., A, B or C-grade crab Guide to Using the Australian Industry).
- For some crabs, the following additional data were also recorded: weight (where field conditions permitted), carapace length, carapace height and tag number (if applied).
- Bycatch data (species, number, fate-at-release were recorded as part of animal ethics permit condition.

- Environmental data (in situ measurements of water quality parameters) were also collected during some sampling events.

The opercular spines on the dorsal carapace of Giant Mud Crabs change in length over time, being longest in a newly moulted crabs, and shorter in 'older' intermoult crabs due to wearing or chipping. As such, CW is somewhat an inconsistent metric, as for any given individual, it will reduce over time or if the shell is damaged. Therefore, for a more consistent morphometric measurement and speed in field work measurements, NW was adopted as the standard size measurement for all Giant Mud Crabs sampled, consistent with Jebreen *et al.* (2008) and Flint *et al.* (2021). A sub-set of crabs in every region were also measured for CW to provide a conversion from NW. Linear regressions were fitted using the "stats" package in R (v 4.2.2) to enable conversion from NW to CW so results can be compared to legal-size. Retention of regression terms was assessed using a backwards stepwise approach, informed by the Akaike information criterion (AIC). Sex specific conversion equations between notch width and carapace width were $CW_{Male} = 1.030106*NW + 2.971876$ (n = 1,136) and $CW_{Female} = 1.030106*NW + 4.016038$ (n = 429) see Robins *et al.* (2024).

Fishery-independent sampling

Fishery-independent sampling to collect juvenile, adolescent and mature Giant Mud Crabs occurred in south-east and central regions of the Queensland, enabling control of pot type, placement, bait type, soak time and the use of pots not fitted with escape vents. Multiple pot types were trailed, including the following.

Juvenile research pots were supplied by Northern Territory Department of Agriculture and Fisheries. They are rigid, rectangular pots, constructed of 25 mm steel mesh, 700 mm long by 600 mm wide by 200 mm high (Figure 17a), have two plastic 20 mm mesh funnels, 72 mm x 180 mm. A second version was covered in shade cloth and had the entry funnel restricted midpoint by a vertical bar.

Munyama pots, as used by Fisheries Queensland in their Giant Mud Crab monitoring program 2000 to 2009, were available to the current project (Figure 17b). These pots are collapsible, circular mesh pots, 800 mm in diameter, 6 mm top and bottom rings, two plastic 20 mm mesh funnels, 72 mm x 180 mm (Jebreen *et al.* 2008).

Commercially equivalent pots were sourced from several manufacturers to encompass the range of pots used by EC1 and GC1 fishers (Figure 17c). CrabNGear™ 900 mm (diameter) collapsible circular pots, with a 12 mm bottom and 10 mm top rings, covered in 30 ply 55 mm mesh, four entry funnels (230 mm stretched width at tensioning strings, 50 mm high mid centre at tensioning strings, with four posts 320 mm in length. CrabNGear™ 800 mm (diameter) collapsible circular pots, with a 10 mm bottom and 10 mm top ring, covered in 30 ply 55 mm mesh, three-entry funnels (270 mm stretched width at tensioning strings, 50 mm high mid-centre at tensioning strings, with four posts 320 mm in length.

Figure 17. Crab pots used during fishery-independent sampling targeting Giant Mud Crabs. (a) NT juvenile research pot. (b) Munyama pot. (c) commercially equivalent collapsible trawl-mesh pot.

South-east region Queensland east coast

The Logan River and southern Moreton Bay was selected for fishery-independent sampling because of logistical constraints (proximity, access), it's history as a high catch area, as well as the occurrence of a protected zone (MNP28), where fishing mortality was likely to be low. Sampling occurred on a regular basis (Table 5), with on average 30 pots set across a broad suite of habitats i.e., upper estuarine, mid-estuarine, mouth and foreshore (Figure 18). Flexibility in pot placement on any given sampling occasion was necessary to accommodate pots already set in effective locations by commercial or recreational fishers. Pots were baited with either fish frames or chicken frames and allowed to soak for approximately 24 hours before checking.

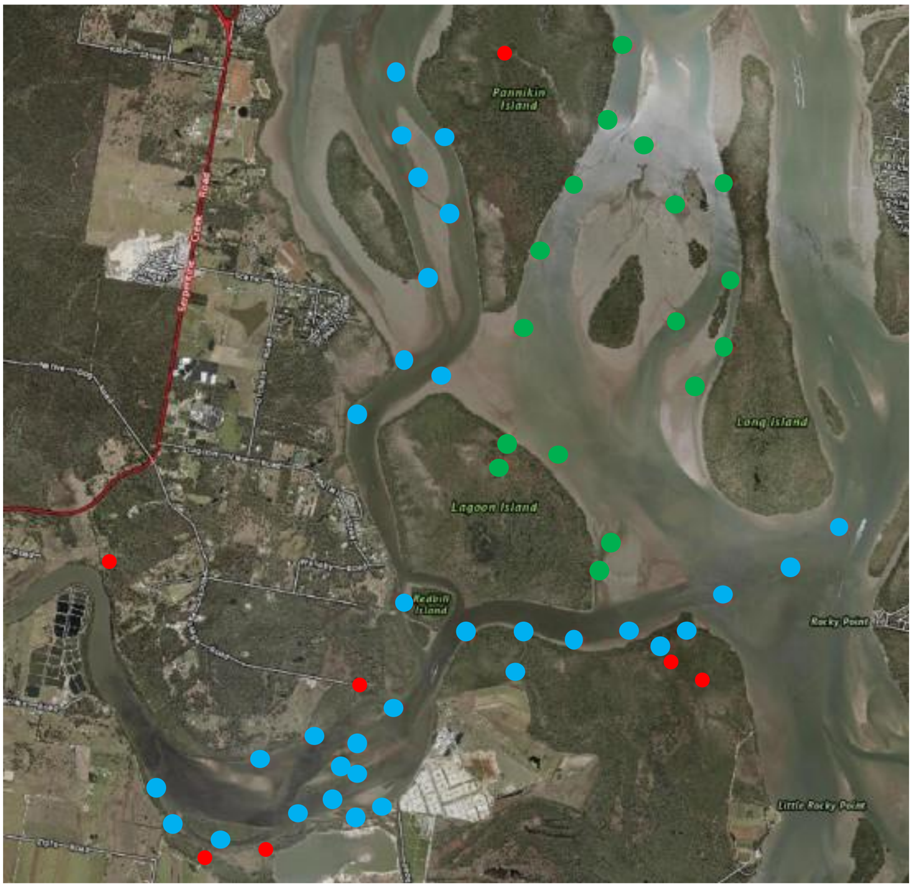

Figure 18. Site placement of crab pots during fishery-independent sampling in south-east Queensland. Blue dots are areas open to fishing, green dots areas closed to fishing (i.e., within Marine National Park 28). Red dots are sites where juvenile research pots were set, these pots being rigid, rectangular wire pots, Figure 17a).

Central region Queensland east coast

Two areas were selected in central Queensland for fishery-independent sampling because of logistical constraints (proximity, access), it's history as a high catch area, as well as the occurrence of a protected zone (Eurimbula Creek), where fishing mortality was likely to be low. Sampling in Gladstone Harbour occurred on a regular basis (Table 5), with 40 commercially equivalent pots set each month across a broad suite of habitats i.e., upper estuarine, mid-estuarine, mouth and foreshore in four estuaries (Figure 19). Twenty pots were set at Eurimbula Creek every second month. Pots were baited with a mullet head and allowed to soak for approximately 24 hours before checking.

Figure 19. Site placement of crab pots during fishery-independent sampling targeting Giant Mud Crabs in Gladstone Harbour (Black Swan Creek, Graham Creek, Boat Creek and Enfield Creek). Pots were also set at Eurimbula Creek in the Baffle River catchment.

Table 5. Sampling dates of fishery-independent surveys for Giant Mud Crabs. Regular sampling used commercially equivalent crab pots without escape vents. DPI intensive sampling used commercially equivalent crab pots, 20% no escape vents, 14% with 120 x 50 mm escape vent, 13% with 105 mm round escape vent, and 13% with 75 x 60 mm escape vent. See Robins et al. (2024).

	Locations	Dates	Locations	Dates
central region, Queensland east coast	CQUniversity regular Boat Creek Enfield Creek	*26/07/2022 06/09/2022 16/11/2022 12/01/2023 14/03/2023 16/05/2023 26/07/2023 13/09/2023 17/11/2023	CQUniversity regular Graham Creek The Narrows (Black Swan Creek)	17/08/2022 27/10/2022 08/12/2022 02/02/2023 20/04/2023 08/06/2023 22/08/2023 11/10/2023 08/12/2023
central region, Queensland east coast	CQUniversity regular Eurimbula Creek	28/02/2023 28/04/2023 21/06/2023 08/08/2023 19/10/2023 05/12/2023	DPI intensive[#] Eurimbula Creek	23-26/05/2022 17-20/04/2023
south-east region, Queensland east coast	DPI regular preliminary Logan River	**19/11/2021 **07/12/2021 **21/12/2021 **20/01/2022 17/02/2022 10/03/2022 13/04/2022 29/04/2022	DPI intensive[#] Logan River	10-12/05/2022
south-east region, Queensland east coast	DPI regular*** Logan River southern Moreton Bay Marine National Park 28 (MNP28)	01/07/2022 28-29/07/2022 12/08/2022 24/08/2022 30/09/2022 19/10/2022 21-22/12/2022 24-25/01/2023 **16-17/02/2023 05/04/2023 12-13/04/2023 10-11/05/2023 6-7/06/2023 20/06/2023 4-5/07/2023 11-12/08/2023 5-6/09/2023 10-11/10/2023 14-15/11/2023 19-20/12/2023 10-11/01/2024 8-9/02/2024 12-13/03/2024	DPI intensive[#] Logan River southern Moreton Bay MNP28	22-25/11/2022 21-24/03/2023

* only Boat Creek sampled; ** dates during preliminary sampling when juvenile research pots (Figure 17a) were trialled; ***broadscale sampling in the south-east region of the Queensland east coast did not occur until July 2022 because of substantial processing delays in the Marine National Park permit application to conduct research using crab pots.

Fishery-dependent sampling

Active C1 symbol holders were approached to allow project staff onboard during commercial operations to assist with regional sampling of Giant Mud crabs for the current project and FRDC 2021-119. Target regions included Moreton Bay/south-east Queensland, Great Sandy Strait, Mackay and Sarina, Gladstone and Rockhampton, Stanage and Broadsound, Townsville and the Burdekin, Hinchinbrook, Karumba, Weipa and Mapoon. Fishery-dependent sampling was dependent upon the willingness of commercial operators to have DPI staff onboard, safety considerations (i.e., certificate of operation) and logistical constraints in getting staff to regional areas at times suitable for commercial operators.

Field measurements during fishery-dependent sampling included the pot type, NW, sex, maturity indicators (i.e., mating scars in males and abdominal flap in females) and, depending on the number of crabs and distance between pot checks, crusher claw height and CW. Broadscale coverage of regional Giant Mud Crab populations across Queensland (Gulf of Carpentaria and east coast, Table 6) was achieved because of the generous cooperation of selected commercial fishers, who allowed DPI staff onboard and accommodated the handling and measuring of legal and non-legal crabs, often under tidally-driven time constraints and varying weather conditions.

Table 6. Summary of fishery-dependent sampling of Giant Mud Crabs in regional Queensland.

Region	Locations	Days observed	Pot lifts	Crabs measured
north Gulf of Carpentaria	Mapoon Weipa	31	3,396	3,443
south-east Gulf of Carpentaria	Karumba	13	650	663
north Qld east coast	Hinchinbrook	20	1,000	1,871
north central Qld east coast	Townsville Burdekin Mackay	5	225	631
central Qld east coast	Stanage/Broadsound Gladstone	11	750	1,262
south-east Qld east coast	Great Sandy Strait Moreton Bay	5	300	355
Total		85	6,321	8,225

Chapter 3. Spatial stock structure of the Giant Mud Crab along the Australian east coast.

S.M. Williams, G. Scata, N. Stratford, M.D. Taylor, D.D. Johnson, N. Flint and J.B. Robins

Introduction

Previous genetic studies of Giant Mud Crabs in northern Australia used allozymes and mitochondrial DNA to evaluate the spatial stock structure (Gopurenko and Hughes 2002). Results indicated considerable genetic differentiation among seven locations across northern Australia, spanning from Exmouth (Western Australia) to Cape Grenville on eastern Cape York (Queensland). In contrast, there was a lack of genetic population structuring throughout locations along the Queensland east coast from Hinchinbrook Island (approximately 18°S) to Moreton Bay (approximately 27.5°S), which are separated by greater than 1,000 km of coastline. No samples were included from locations south of 28°S (i.e., New South Wales). To better understand contemporary population structure and consequences for differing jurisdictional management, Gopurenko and Hughes (2002) recommended the need for further work using nuclear markers. In the current research, we used a genomic-wide single nucleotide polymorphism (SNP) panel to evaluate the contemporary stock structure of Giant Mud Crabs throughout eastern Australia.

The initial objective for this aspect of the project was to use south-east Queensland and northern New South Wates as a genetic case study, as requested by the FRDC Queensland Research Advisory Committee during project development. Opportunities arose during the project to expand the spatial extent of the study. We report herein on the results from the Australian east coast (~18°S to ~33°S) compared to an outgroup from the Gulf of Carpentaria. Larval particle simulations published after the commencement of this project suggest a high theoretical likelihood of genetic connection (Hewitt *et al.* 2022b; Charles *et al*. 2024). Further opportunistic samples acquired from far northern Queensland east coast, northern and western Gulf of Carpentaria will be reported upon in an upcoming scientific publication (Williams *et al.* 2025 in prep).

Methods

Muscle tissue samples (n = 192) were obtained from Giant Mud Crabs from Queensland and New South Wales between November 2020 and March 2021 (Table 7). Collection locations were selected to test for differentiation among management jurisdictions, their importance as a key harvest region or to provide insight into possible biogeographic barriers to geneflow. Tissue samples were obtained through dedicated research sampling in Queensland and through landed commercial product in New South Wales. The carapace width or length, weight and sex were recorded for each individual. Samples were stored in 90% ethanol at -20°C until extraction.

DNA extraction along with quality assurance checking was performed by Diversity Arrays Technology (DArT) and SNP loci were discovered and genotyped following the DArTseq™ protocol (Kilian *et al.* 2012) for 188 individuals across the ten collection locations (Table 7). Quality control, read assembly and SNP calling were undertaken using proprietary DArTseq™ analytical pipelines (DArTsoft14) described in detail by Georges *et al.* (2018). Genetic markers returned from DArT were further filtered using R (R-Core-Team, 2018) package Dart R (Gruber *et al.* 2018). The filters removed samples with greater than or equal to 20% missing data, removed loci where the minor allele count (MAC) was less than three and missing data was greater than 10%, selected for coverage between five and

100 where read depth of individual genotypes was averaged across markers, removed loci in short linkage-disequilibrium and removed intentional duplicate samples. To ensure that sex ratios among collection locations did not influence population structure analysis, radiator filtering was also undertaken to detect and remove sex-linked markers using the ‘sexy markers’ function.

Table 7. Summary information of Giant Mud Crabs collected to provide tissue samples for genetic single nucleotide polymorphism analysis.

Latitude (°S)	Jurisdiction	Coastline	Location	n	Weight mean (g)	Carapace width mean (mm)	Sex
17.48	Qld	Gulf of Carpentaria	Karumba (Kar)	18	623[a]	156	F
18.33	Qld	east coast	Hinchinbrook (HI)	19	NA	155	F
21.14	Qld	east coast	Mackay (Mac)	19	793	171	F
23.84	Qld	east coast	Gladstone (GH)	19	643	148	F
27.25	Qld	east coast	Moreton Bay (MB)	19	667	161	F
28.18	NSW	east coast	Tweed River (TR)	19	643	101	F, M
29.42	NSW	east coast	Clarence River (CR)	19	652	96	F, M
30.86	NSW	east coast	Macleay River (MR)	19	281	77	F, M
32.18	NSW	east coast	Wallis Lake (WL)	18	653	149[b]	F, M
32.71	NSW	east coast	Port Stephens (PS)	19	767	155[b]	F, M

[a] based on unpublished data for Karumba weight = 0.0002 x $CW^{2.9609}$ (R^2= 0.9329, n = 61); [b] based on 0.68*CW-1.51 (Hewet *et al.* 2022a)

The level of genetic differentiation among collection locations (i.e., F_{ST}) was calculated using the *diveRsity* R package (Keenan *et al.* 2013), with significant pairwise comparisons tested by 20,000 permutations via bootstrapping (R-Core Team 2018). We explored the SNP dataset across all collection locations using a model-based clustering method; sparse non-negative matrix factorization (SNMF) (Frichot and François 2015), which is comparable to STRUCTURE (Pritchard *et al.* 2000) but produces a least-squares estimate of ancestral (source) populations given *K* ancestral populations. These methods estimate the number of ancestral populations (K) that were proposed to have existed at some point in the past and assume that modern individuals were produced by recent mixing and interbreeding of these ancestral populations. We estimated ancestry coefficients over K = 1 to K = 10 using ten repetitions per *K*, and default parameters. To explore the appropriate number of ancestral populations, we plotted the minimum entropy criterion and against K, searching for the inflection point in the plot where additional cross-entropy loss was minimal (Forester *et al.* 2018).

Genetic population analyses were performed to determine the relationships among individuals from each location through principal components analysis (PCA) with the package ADEGENET 2.1.1 (Jombart and Ahmed 2011). Group membership for PCA was defined by location and Bayesian Information Criterion (BIC) scores were used to assess the optimal number of genetic clusters across a range of K values. Models with the lowest BIC scores were identified as representing the optimal number of K for use in PCA.

Results

A total of 38,693 SNPs were scored and filtered using the DartR package. A total of 23,598 SNPs were unsuitable for downstream analyses as features such as call rate, monomorphism, coverage, minor allele frequency (MAF), linkage-disequilibrium (LD), observed and expected heterozygosity, and Hardy-Weinberg Equilibrium (HWE) values diverged outside of the thresholds. From the filtering steps applied, the filters on MAF (8,387 SNPs excluded) and coverage (6,873 SNPs excluded) had the strongest influence when detecting non-conforming markers. The final dataset after filtering included 15,095 SNPs which were used for further evaluation of genetic population structure.

Pairwise comparison between collection locations showed three different outputs which included:
(1) significant comparison with a moderate pairwise difference value ($p < 0.001$; F_{ST} 0.020-0.022),
(2) significant comparison with a very low pairwise difference value ($p < 0.001$; F_{ST} 0.001-0.002), or
(3) non-significant comparison with a very low pairwise difference value ($p < 0.001$; $F_{ST} < 0.001$),
where F_{ST} is the fixation index, a measure of population differentiation due to genetic structure (Hudson *et al.* 1992).

The mean pairwise F_{ST} estimate between the outgroup location (Karumba, Gulf of Carpentaria) with east coast locations was 0.021, while the mean pairwise F_{ST} estimate amongst east coast locations was 0.001. Pairwise comparisons with moderate vales of F_{ST} occurred between the outgroup location and all other locations. Comparisons which showed very low, but significant F_{ST} values included Moreton Bay with New South Wales, except Port Stephens, and several other comparisons among New South Wales locations and between Queensland and New South Wales locations. Similarly, all non-significant comparisons occurred among east coast locations from both Queensland and New South Wales, and among New South Wales.

The Discriminant Analysis of Principal Components (DAPC) revealed similar patterns of variation as identified through F_{ST} comparisons. The DAPC analysis indicated the greatest confidence around the K=2 clustering scenario. When observing K=2 clustering, separate clustering occurred between of the outgroup (Karumba) and all other locations. The clustering of individuals from the east coast showed strong overlap among all locations (Figure 20).

Ancestry analysis using SNMF with the SNP loci allowed the exploration of alternate drivers to genetic population structure in Giant Mud Crabs. Using a genetic clustering approach and the SNP dataset, the inflection point of the minimum cross entropy plot was K=2. However, acknowledging the K=2 conundrum (Janes *et al.* 2017), the assignment of individual Giant Mud Crabs to 2, 3, 5, and 10 hypothesized ancestral populations is presented in Figure 21. The K=2 assignment plot showed strong differentiation in the ancestral entity of the outgroup (Karumba) and east coast locations (which all remained relatively uninformative). An overall similar trend was found for the K=3 assignment plots, however, there was some subtle variability among individuals from east coast. Individuals from the Macleay River, and to a lesser extent Gladstone Harbour and Tweed River assignment was directed towards a specific ancestral entity. Directional ancestral patterns (to a different entity) were also seen for Wallis Lake and to a lesser extent Moreton Bay and Clarence River under the K=3 assignment. However, the strong assignment patterns for K=5 and K=10 were much less evident among individuals from east coast locations, but remained strong for divergence of samples from Karumba, providing support for homogeneity throughout the east coast.

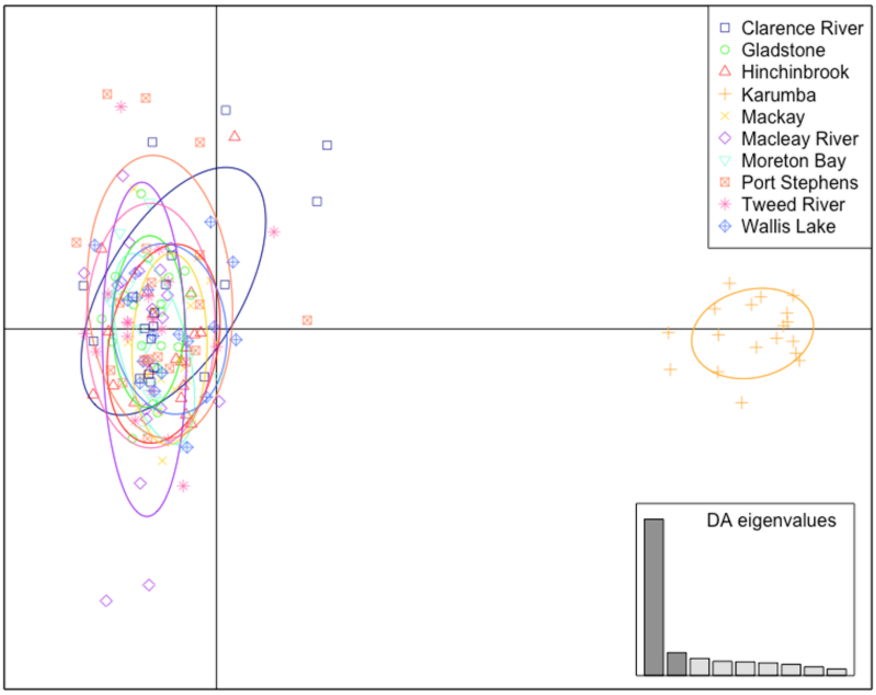

Figure 20. Discriminate analysis of principal components (DAPC) of Giant Mud Crabs from locations across northern Australia (for details see Table 7).

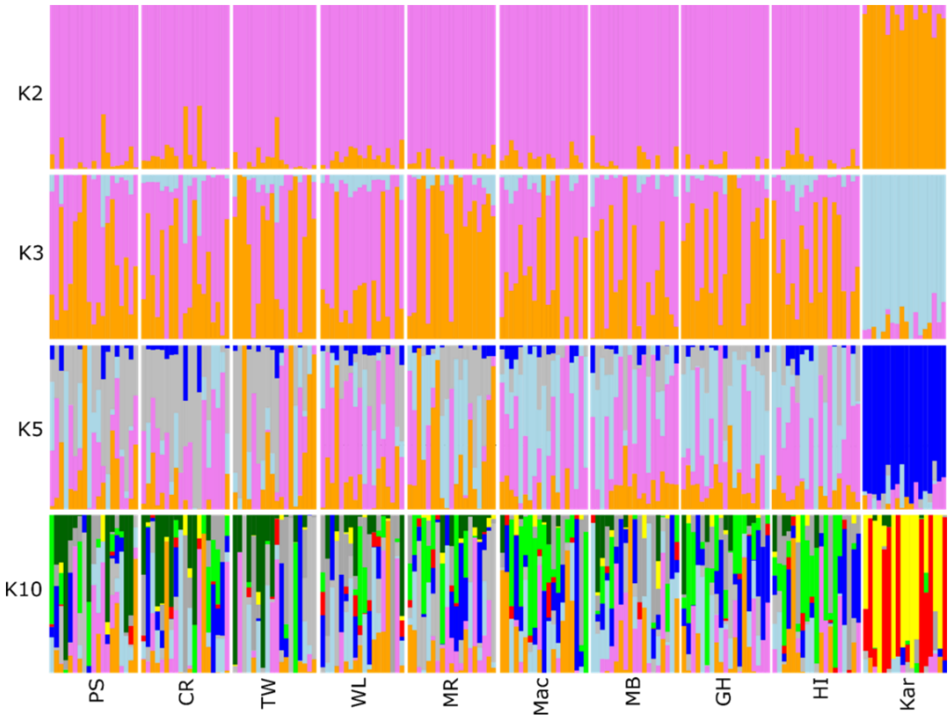

Figure 21. Assignment plots Giant Mud Crabs from locations across northern Australia based on SNMF analysis showing individual ancestry coefficients to the ancestral genetic cluster (K) for K=2, K=3, K=5, and K=10 using SNP loci. PS = Port Stephens, CR = Clarence River, WL = Wallis Lake, MR = Macleay River, Mac = Mackay, MB = Moreton Bay, GH = Gladstone Harbour, HI = Hinchinbrook Island, Kar = Karumba.

Discussion

Our study was unable to detect genetic differentiation between Giant Mud Crabs from locations along the Australia east coast (i.e., Hinchinbrook Island to Port Stephens). The presence of low fixation indices and homogeneous clustering among east coast locations indicate the presence of genetic connectivity. There was strong genetic differentiation of individuals from the southern Gulf of Carpentaria to that of the Australian east coast. The lack of genetic population structure for Giant Mud Crab along the Australian east coast is inconsistent with highly structured populations found elsewhere throughout the range of Giant Mud Crabs (Gopurenko and Hughes 2002; Fratini *et al.* 2010; Saher *et al.* 2019). However, offshore spawning of Giant Mud Crabs (Hill 1994) and likely broadscale dispersal of larvae across a large latitudinal range, via the East Australian Current, is consistent with genetic homogeneity over several thousand kilometres (Gopurenko *et al.* 1999; Hewitt *et al.* 2022b; Charles *et al.* 2024).

The presence of a single panmictic population of Giant Mud Crab throughout the Queensland waters was previously reported based on mitochondrial markers (Gopurenko and Hughes 2022). Their sampling did not extend into New South Wales and lacking nuclear markers, the potential for widespread homogeneity across the east coast remained uncertain, although postulated (Hewitt *et al.* 2022b).

Our findings are consistent with the reproductive biology of Giant Mud Crabs*.* Egg bearing females of Giant Mud Crab have been regularly reported in offshore waters (Hill 1994; Alberts-Hubatsch *et al.* 2016) and has been assumed as the default spawning migration for most mature females. The capacity to disperse eggs into offshore currents such as the East Australia Current, provides for broad scale distribution of larvae and a mechanism for maintain geneflow. Given this, we suggest that the lack of genetic structure identified herein most likely indicates the presence of genetic mixing and provides evidence to support the assumption of a single Giant Mud Crab population from Hinchinbrook Island in north Queensland to the southern extent of their distribution in New South Wales. Previous evaluation using mitochondrial DNA indicated some level of population structuring between Hinchinbrook Island and Cape Grenville, suggesting some form of barrier that restricts or reduces geneflow to far north Queensland from the remainder of the Australian East Coast. If connectivity is driven by larval dispersal, this population divergence would likely occur around the bifurcation point of the East Australian Current (Church 1987). Further sampling and genetic analysis to clarify this genetic structuring has been undertaken and will be reported on separately in a journal publication (Williams *et al.* 2025 in prep).

In summary, we have confirmed that Giant Mud Crabs are genetically connected along the Australian East Coast, across the jurisdictions of Queensland and New South Wales. Clarification of mechanisms that allow geneflow between regions would benefit from empirical validation – such as the preferred destination of spawning females (see Chapter 5), and larval dispersal, which has been simulated by Hewitt *et al.* (2022b) and Charles *et al.* (2024).

The current management arrangements for Giant Mud Crabs in Queensland (i.e., 150 mm CW minimum legal size, no legal female harvest) are conservative, theoretically providing a near unfished spawning biomass of female crabs. Thus, we suggest that there is limited need for cross-jurisdictional management of Giant Mud Crabs unless offshore currents and larval distribution change significantly or Queensland changes its no-female harvest policy. The lack of spatial genetic differentiation within the Queensland jurisdiction of the Australian east coast supports the maintenance of a single management unit for Giant Mud Crabs within the EC1 fishery, notwithstanding regional climatic influences that may impact the survival of larval recruits to legal size.

Chapter 4. Tagging Giant Mud Crabs to inform population biology – trials (and tribulations)

N. Flint, J.B. Robins, N.J. Stratford and W. Charles

Introduction

Tagging techniques have been used for many decades to generate biological estimates of growth, movement, mortality and sometimes exploitation rates or estimates of population size of marine animals. Tagging to identify individual crustaceans, including brachyurans (crabs) is less straightforward than for animals such as fish or mammals, as crustacean growth is controlled by ecdysis (moulting). During ecdysis, the inelastic exoskeleton is shed, including some internal structures such as the gills, stomach and hind-gut lining (McLay 2015). External markings or tags remain attached to the old exoskeleton, which is replaced by a new, larger integument. If crustaceans are to be tagged through moult cycles for later identification, tags need to be secured to internal musculature to reduce tag loss during ecdysis (Thorsteinsson 2002).

A range of externally and internal tagging methods have been utilised for brachyurans with varying success. Some externally visible tagging methods include carapace marking or branding, plastic plate tags wired to the carapace and t-bar tags. Advanced internal methods often require either scanning to detect a tag, or lethal collection and dissection of crabs to obtain identification or data. Some tag types provide only for the individual identification of crabs, while others gather information on animal movements (e.g., for determining migration or habitat use), environmental and water quality data.

Internally secured tags have been used for mark-recapture studies over short periods to estimate population size (Hay *et al.* 2005), or over longer time periods to develop growth models, for example as used for *S. olivacea* in Thailand (Moser *et al.* 2002) and Giant Mud Crabs in East Africa (Mosknes *et al.* 2015). Improvements in experimental design and analysis mean that population size estimates can be achieved, for example using models and software that take account of temporal, behavioural and individual variations in recapture (Hay *et al.* 2005).

For this project, we aimed to identify and trial suitable tagging methods for Giant Mud Crabs, and to assess the utility of various tag types to gather data on their population biology. This involved conducting a detailed review of the scientific literature and research reports to identify potential tags (see Appendix 5), then trialling the selected tags in the laboratory and field.

Review of tagging methods

The review searched the available published literature (available as at February 2021, and then updated in April 2024), with each publication read, and data harvested for the following categories: location, species, life history stage, tag type used, stated aims, and tag results. We considered all publications written in English that included the following search terms: crab, tag*, movement, decapoda, brachyura, crustacea, *Scylla, Portunus*.

A total of 119 publications were found to be relevant and were retained for inclusion in the review, 12 of which were about Giant Mud Crabs. Seven publications were about other *Scylla* species i.e., *S. paramamosain, S. tranquebarica* and *S. olivacea*. There were 20 studies from Australia, including eight on Giant Mud Crabs, four on *Portunus pelagicus* (now reclassified as *P. armatus*), one on *Ranina*

ranina and one on *Pseudocarcinus gigas*. In comparison, 47 publications reported research from the USA. Grey literature about *S. serrata*, including FRDC reports, Fisheries Queensland reports and theses, were added separately and some are cited in this review

Tags for identification of individual crabs included t-bar and anchor tags, plastic plate tags and strap tags, coloured beads and string as tags, visible implant elastomer tags and coded microwire tags. Tagging methods for location and environmental data collection included passive integrated transponder tags, acoustic tags, satellite tags and a novel Marine skin tagging system.

Preferred tagging options

Mark-recapture tags for biological information (growth, longevity, movement)

T-bar tags and other anchor tags have been used on several species of mud crab including *S. serrata*, in Australia and elsewhere. Refinements in the tag and the insertion method reported improved survival rates and higher retention of tags by mud crabs through ecdysis (Meynecke *et al.* 2015). While other mark-recapture tag options are available, these are either not effective when used on adult mud crabs (e.g., Visible Implant Elastomer), present risk to consumers of edible crustaceans (e.g., coded microwire tags), or are shed during ecdysis (e.g., spaghetti tags, plastic plate tags or disc tags, wired or glued to the carapace). The benefit of obvious external tags such as spaghetti tags or plastic plate tags over t-bar tags, is that they are easily seen by fishers who capture the crab, potentially increasing the likelihood of tag reports. The successful use of such tags in Blue Crab (*C. sapidus*) fisheries in the USA, demonstrates they can be effective in some circumstances. As such, a combination of tags may be the most effective strategy for maximising tag reports and data. Sticker tags glued to the carapace provide an obvious alert to assist with recapture reporting, acknowledging they are shed during moulting.

The review reinforced the original proposed use of standard t-bar tags for mark-recapture to gather quantitative biological information required to inform assessment and management of Giant Mud Crabs in Queensland. Hence, t-bar tags and sticker tags were trialled, with results reported below.

Tags for tracking movements of spawning female crabs

The project also aimed to improve understanding of the spawning migration of female Giant Mud Crabs, with options considered being acoustic and satellite tags. Acoustic tags have been successful used in a range of applications researching crab movement (Appendix 5, Appendix 6), but rely on the presence of acoustic receivers in the targeted tag deployment regions as well the likely movement field. Central Queensland was one of several regions identified as potentially suitable for a pilot migration study using acoustic receivers, and this study has been incorporated into the CQUniversity PhD research project that is currently underway (W.D. Charles). Satellite tags transmit data on movement and environmental conditions via satellite, when the tag is on the surface of the water. Animals that don't surface regularly can be tagged with pop-up archival satellite transmitters (PAT tags). Satellite tags were identified as an option for this project and trialled (see Chapter 5).

Methods and results

Following the literature review, a series of tag-mortality laboratory trials and a field tagging program were designed to collect key biological data for Giant Mud Crabs, such as growth (requiring retention of the tags during and following ecdysis), movement and longevity.

The aim of the tag-mortality laboratory trials was to develop a protocol for t-bar tag application, assess the effects of t-bar tags on crab moulting and any associated mortality, and trial the durability of both t-bar tags and sticker tags glued to the carapace. A series of three laboratory experiments was proposed, the results of which would be applied to field trials (Experiment 4).

Tag-mortality trials of t-bar tags

Three sequential tank experiments were used to assess the effects of tags on crab mortality and moulting and develop a protocol for t-bar tag application. Subsequent field deployment was dependent on the outcomes of the tank experiments (Figure 22).

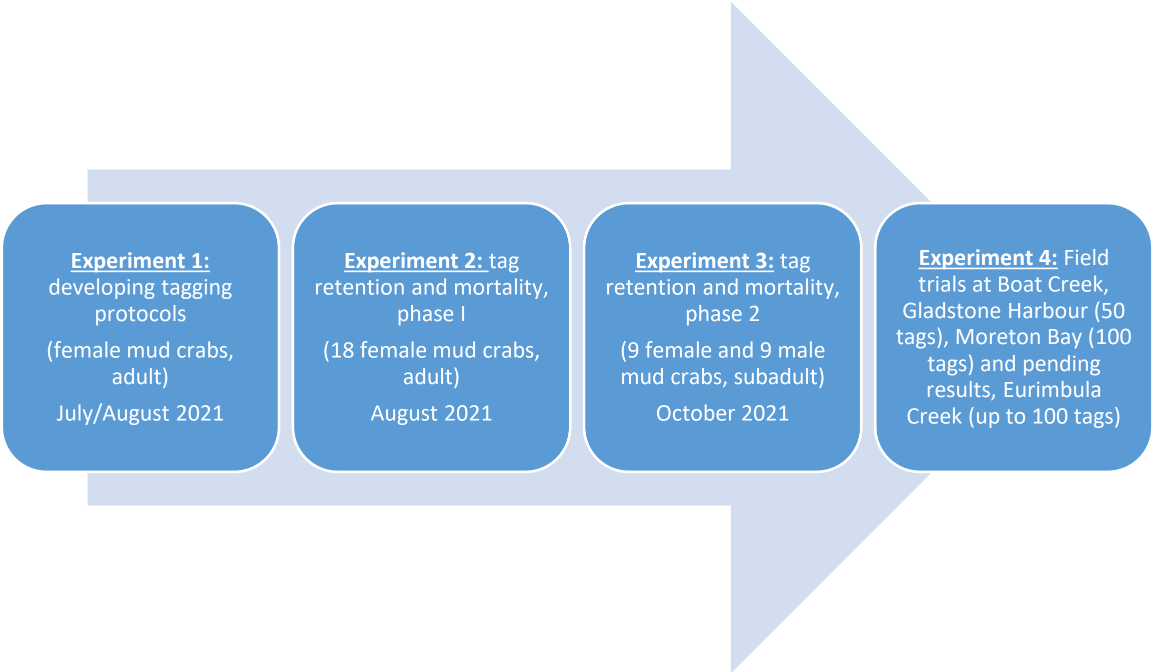

Figure 22. Sequence of experiments to develop tagging protocols, test mortality rates and tag retention, and conduct field trials.

Tagging Experiment 1: developing protocols

Dead female Giant Mud Crabs were available (stored frozen) at CQUniversity from genetic sampling (see Chapter 3). Those crabs were retained frozen and were able to be defrosted and used as models for achieving the correct tag insertion angle and depth, avoiding contact with internal septa, major organs and the developing membrane that lines the dorsal carapace. The crabs were dissected post-tagging to observe the location of the t-bar tag in relation to internal structures.

Once researchers were well-practiced at accurately tagging dead crabs, planning for the introduction of live Giant Mud Crabs into the experiment began. A delivery of female crabs, provided by a local commercial crabber (under GFP 210183) arrived in good condition on 8th September 2021. To ensure tag placement was accurate, five of the live crabs were tagged using the same methods as practiced with dead crabs, then euthanised and dissected to ensure correct placement of the t-bar in the right swimmer muscle. During dissection, the t-bar tags were found to be correctly placed in all five crabs (Figure 23). As a result, experiment 2 commenced immediately.

Tagging Experiment 2: mortality and moult-retention (individuals in 50-L tanks)

The aims of this tank-based experiment were to quantify tag-induced mortality and record any inhibition of moulting caused by insertion of t-bar tags. T-bar tags were inserted using the above methods.

On 8th September 2021, five crabs were tagged with small t-bar tags (Hallprint, TBF fine anchor t-bar tag with 17 mm fine monofilament and 7 mm T-anchor) before the needle of the small tagging gun broke. A larger tagging gun was delivered to CQUniversity from DPI, along with some larger sized t-bar tags (TBA standard anchor t-bar tag with 30 mm standard monofilament with 12 mm T-anchor). On 12th September 2021, five additional crabs were tagged with the larger t-bar tags. Before tagging, each crab was weighed and measured (NW and CW) and checked for abnormalities such as missing limbs or rust shell lesions. Five further crabs were assigned as controls (not t-bar tagged). Each of the 15 crabs were also fitted with a flexible plastic sticker tag (Hallprint FPN 60 x7 mm), glued on to the dorsal carapace with Loctite 424 adhesive (recommended by Hallprint, Figure 23, Table 8). This enabled individual identification and tested the durability of the applied sticker tags. A series of individual tanks in a recirculating seawater system were used to house the crabs (Figure 24).

Figure 23. Placement of t-bar tag (in the right swimmer muscle) and sticker tags on a female Giant Mud Crab which was tagged while alive, euthanised, and then dissected to ensure correct t-bar tag placement.

The crabs were housed in individual tanks (Figure 24) and fed chopped fish each morning. Excess food and waste was removed each afternoon. Water temperature was maintained between 25 and 27°C and day-length was set to summer conditions (i.e., 14 hours light, 10 hours dark). Physicochemical parameters (i.e., temperature and salinity) were logged daily. Nitrate, nitrite and ammonia were tested every two to three days, and larger water changes were undertaken as necessary to maintain suitable nutrient levels. Mortality or signs of ill health were recorded and photographed. Tagging experiment 2 continued until 15th December 2021, when Tagging Experiment 3 commenced.

Figure 24. Recirculating seawater system housing Giant Mud Crabs in individual tanks for Tagging Experiment 2: mortality and moult retention (individuals in 50-L tanks).

Tagging Experiment 3: mortality and moult-retention (groups in 1,150-L troughs)

Experiment 3 was conducted in a custom-built recirculating seawater system designed for Giant Mud Crabs, at CQUniversity's Coastal Marine Ecosystem Research Centre in Gladstone. The system included six approximately 1,000-L troughs on a recirculating system containing a sump and biofilter (Figure 25). Three Giant Mud Crabs (one male and two females) were placed into each trough. Six sub-legal males were sourced from Gladstone Harbour on 15th December 2021 to add to the experiment, along with 12 females remaining from Tagging Experiment 2.

Feeding, water temperature and collection of physicochemical parameters was as per Tagging Experiment 2. Water quality in the recirculating system was maintained by the biofilter but was refreshed with filtered seawater approximately weekly.

The larger t-bar tags appeared to have caused mortality of some females during moulting in Tagging Experiment 2 (see results section, below), so the smaller tag size (Hallprint, TBF fine anchor t-bar tag with 17 mm, fine monofilament and 7 mm T-anchor) was used on the sub-legal males. After two male crabs moulted successfully but were attacked by females in the same tank, dividers were added to the troughs to make three separate sections housing individual crabs.

Figure 25. Purpose-built recirculating seawater system at CQUniversity's Gladstone campus, housing crabs in groups of three. Lids were added to the tanks one week after crabs were introduced, and then the water level in troughs was increased to approximately 40 cm.

Tagging Experiment 4: Field tag deployment trials

As described in the results section (below), tag-related mortality across experiments 2 and 3 was higher than anticipated based on reported t-bar tagging in the published literature. The project team considered the mortality risk associated with deploying thousands of t-bar tags on crabs in localised areas. The risk to males, which need to successfully moult up to legal size for fishery harvest was considered too high, as the project did not want to negatively impact fishable biomass. Therefore, field experiments used only sticker tags.

Giant Mud Crabs of a range of sizes were opportunistically fitted with sticker tags and released during regular monthly monitoring at field sites in south-east Queensland (DPI) and Gladstone Harbour (CQUniversity), and irregular trips to Eurimbula Creek (DPI and CQUniversity, Table 5), north Queensland and the Gulf of Carpentaria (DPI, Table 6). Crab capture and processing methods were as described in Chapter 2. Sticker tags were attached to the dorsal carapace of Giant Mud Crabs using Loctite 424 (Figure 26). Crabs were held on the boat for several minutes until the glue dried, before they were returned to the capture location for release.

Figure 26. CQUniversity research team deploying sticker tags on Giant Mud Crabs in Gladstone Harbour. L-R: Jacob Bulow, Nicole Flint, Mohammad Amzad Hossain (PhD student), William Dantas Charles (PhD student). Photo: Matt Pfeiffer.

Results

Tagging Experiment 1 (protocols)

Researchers used dead crabs to practice tagging with t-bar tags, aiming to insert the tagging needle through the ecdysial line and into the right swimmer muscle as recommended by previous research (Meynecke *et al.* 2015), while avoiding internal structures (Figure 27). Once the technique was perfected on approximately 20 dead and five live crabs, the project proceeded to Tagging Experiment 2.

Figure 27. Giant Mud Crab tagged with a t-bar tag in the right swimmer muscle, dissected to check tag position. Note the presence of an internal structure that is an extension of the abdominal flap. This structure runs along the full length of the ecdysial line and is unable to be avoided when tagging through this line.

During post-tagging dissections of dead crabs, it was noted that the tag would always penetrate an internal shell structure (i.e., septum) when inserted anywhere along the ecdysial line as this line does not correspond with a gap in the shell itself. It is impossible to avoid this structure when tagging along this line as it is an internal extension of the crab's external tail/abdominal flap (Figure 27).

Tagging Experiment 2 (individuals in 50-L tanks)

During Experiment 2, one of the 15 crabs died because of water quality issues when a pump failed overnight. The results for the remaining 14 crabs are provided in Table 8. Of the five crabs tagged with the small t-bar tags, none moulted or died during the experiment, but one tag fell out. Of the five crabs tagged with the large t-bar tags, four crabs moulted. One of these survived and the t-bar tag was successfully retained in the new shell. One survived but the t-bar tag was lost in the old shell. Two died during moulting as a result of the t-bar tag, as the crabs were unable to free themselves from their old shell (Figure 28). In both cases, the right swimmer muscle was the t-bar anchor point, and the right swimmer leg did not moult properly.

By the conclusion of Tagging Experiment 2 on the 15th December 2021, nine of the surviving female crabs had not moulted. These individuals were retained and moved into the troughs for Tagging Experiment 3, to supplement additional numbers of wild caught crabs. We note that sticker tags were attached to the cleaned and dried dorsal carapace of crabs using the recommended adhesive but after 90 days in Experiment 2, half of the remaining crabs had lost their sticker tags.

Table 8. Details and outcomes of Giant Mud Crabs in Tagging Experiment 2, commenced 8th September 2021, finished 15th December 2021.

Crab number (sticker/t-bar tag numbers)	Details, NW = notch width (mm)	Comments	Tagging result
101/300	Female, 171 mm NW, small t-bar tag	Did not moult.	
102/299	Female, 161 mm NW, small t-bar tag	Tag fell out, noticed on 4/10/21. Did not moult.	T-bar tag fell out.
103/298	Female, 158 mm NW, small t-bar tag	Did not moult.	
Untagged	Female, 158 mm NW, control	Did not moult.	
104/297	Female, 142 mm NW, small t-bar tag	Did not moult.	
105/295	Female, 158 mm NW, small t-bar tag	Spawned on 8/11/21. Did not moult.	
106/na	Female, 157 mm NW, control	Did not moult.	
107/na	Female, 152 mm NW, control	Did not moult.	
108/4209	Female, 137 mm NW, large t-bar tag	Moulted 23/11/21. Successful but gills protruding on right side.	Survived moulting and tag retained in new carapace.
109/4206	Female, 138 mm NW, large t-bar tag	Moulted 8/11/21. Moult stuck on tag, died 10/11/21.	Died during moulting as a result of the t-bar tag.
Untagged	Female, 149 mm NW, control	Died 31/10/21, water quality issue.	
116/4205	Female, 135 mm NW, large t-bar tag	Moulted 15/11/21, survived. $CW_{initial}$ = 142 mm, CW_{final} = 166 mm.	Survived moult but t-bar tag remained in old carapace.
Untagged	Female, 154 mm NW, control	Did not moult.	
114/4208	Female, 135 mm NW, large t-bar tag	Did not moult.	
115/4207	Female, 135 mm NW, large t-bar tag	Moulted 10/11/21. Moult stuck on tag, died.	Died during moulting as a result of the t-bar tag.

Figure 28. Giant Mud Crabs t-bar tagged that moulted during Tagging Experiment 2, both dying because the tag was stuck in the original carapace. (a) Original carapace (with the sticker tag attached) is still attached to the crab via the right swimmer. (b) abdomen/tail of old carapace still attached to the crab in its new carapace.

Tagging Experiment 3 (groups of three crabs in 1,150-L troughs)

Twelve of the 17 Giant Mud Crabs that were t-bar tagged and included in Experiments 2 and 3 moulted during the experiments – six of seven males and six of ten females. Three of the 12 crabs died during moulting apparently as a direct result of being tagged and unable to complete the moulting process. Nine survived the moulting process, though two survivors had tag-related injuries and five lost the t-bar tag with the moulted shell (Table 8, Table 9). The experiments also provided moult increments (i.e., growth data points), potentially useful for growth aspects of the project.

In summary, of the 12 crabs that moulted:

- 17% (n = 2) survived moulting, tag retained in carapace, crab healthy,
- 42% (n = 5) survived moulting, but tag was lost,
- 17% (n = 2) survived moulting, tag retained in new carapace, but crab damaged,
- 25% (n = 3) died during moulting.

Both of the two crabs that successfully moulted with the t-bar tag successfully retained in new carapace were tagged with small t-bar tags.

On the 15th February 2022, one female crab dropped both claws, and on close inspection was found to have lesions on the dropped claws and the dorsal carapace. Likely causes of the lesions were a bacterial build-up, a problem common in *Scylla* broodstock held captive in tanks for longer than several months (Lavilla-Pitogo *et al.* 2001). The issue was discussed with David Mann at DPI's Bribie Island Research Centre, who agreed the lesions were likely caused by populations of bacteria common in marine water building up on the shell. The reasons bacterial build-up occurs are not clear, but do not appear to be related to water quality or animal husbandry. A thorough health check of all crabs was conducted on 17th February 2022, and six crabs with severe lesions were removed from the experiment and euthanised (Table 9). Crabs were subsequently removed from the tanks on a weekly basis, to be checked for lesions.

Table 9. Details and outcomes of Giant Mud Crabs in Tagging Experiment 3, commenced 15th December 2021, finished 27th April 2022.

Crab id. sticker/t-bar tags	**Details**				**Comments**	**Tagging result obtained during experiment 3**
	Date of entry to experiments	**Sex**	**Notch Width (mm)**	**t-bar tag size**		
101[a], 119[b] /300	08/09/21[a] 15/12/21[b]	F	171	small	Did not moult. Lost two claws. Euthanised 17/2/22 due to shell lesions.	
102/299	08/09/21[a] 15/12/21[b]	F	161	small	t-bar tag fell out ~ 4/10/21. When dissected, end of t-bar was still lodged in swimmer muscle. Moulted 09/03/22.	Died during moulting as a result of tag
103[a], 120[b] /298	08/09/21[a] 15/12/21[b]	F	158	small	Spawned 24/1/22. Euthanised 17/2/22 due to shell lesions.	
Untagged	08/09/21[a] 15/12/21[b]	F	158	-	Died 28/1/22, cause not known but had lost limbs the day before.	
104[a], 121[b] /297	08/09/21[a] 15/12/21[b]	F	142	small	Moulted 09/03/22. $CW_{initial}$ = 152 mm, CW_{final} = 162 mm.	Survived moult. tag remained in old carapace.
105[a], 122[b] /295	08/09/21[a] 15/12/21[b]	F	158	small	Spawned 8/11/21 and 22/1/22. Euthanised 17/2/22 due to shell lesions.	
106 (sticker tag only)	08/09/21[a] 15/12/21[b]	F	157	na	Euthanised 17/2/22 due to shell lesions.	
107 (sticker tag only)	08/09/21[a] 15/12/21[b]	F	152	na	Euthanised 17/2/22 due to shell lesions.	
108/4209	08/09/21[a] 15/12/21[b]	F	137	large	Moulted 23/11/21. $CW_{initial}$ = 143 mm, CW_{final} = 175 mm. Died on 31/01/22, after losing several legs in previous days. Not a fight injury as was separated.	Survived moulting. Tag retained in new carapace, but right swimmer and gills were protruding.
untagged[a], 117[b] (sticker tag only)	08/09/21	F	154	na	Euthanised 17/2/22 due to shell lesions.	
114/4208	08/09/21	F	135	large	22/12/21 Appeared to be in a mating hold with a male crab. 27/12/21 deceased in tank, with dorsal carapace removed. Male not cradling.	
123/238	15/12/21	M	122	small	Moulted 4/4/22. Tag retained in new carapace and positioned correctly. $CW_{initial}$ = 127 mm, CW_{final} = 143 mm. Euthanised at experiment end.	Survived moulting. Tag retained in new carapace.
124/237	15/12/21	M	129	small	Moulted 22/4/22. Tag remained in old carapace. $CW_{initial}$ = 135 mm, CW_{final} = 148 mm. New carapace damaged where tag pulled through.	Survived moulting but t-bar tag remained in old carapace.
125/236	15/12/21	M	134	small	Moulted 16/01/22. Newly moulted crab was killed 5 days after moulting. Too damaged for post-moult measurement.	Survived moulting. Tag remained in old carapace.
126/234	15/12/21	M	134	small	Euthanised 18/3/22 due to shell lesions.	
127/233	15/12/21	M	113	small	Moulted 27/02/22. Died during moult. Half left side fully separated from carapace and right claw, back right legs remained in old carapace. Tag attached to old carapace. Unable to measure new shell as it hadn't fully emerged.	Died during moult as a result of the tag.
128/232	15/12/21	M	126	small	Moulted 18/01/22. Tag retained in new carapace. $CW_{initial}$ = 131 mm, CW_{final} = 139 mm (measured as new soft carapace) as crab had died, possibly attacked by another crab.	Survived moulting. Tag retained in new carapace.
129/231	15/12/21	M	111	small	Moulted 13/4/22. Tag retained in new carapace, but was not positioned correctly, had moved down the tail. $CW_{initial}$ = 117 mm, CW_{final} = 125 mm.	Survived moulting. Tag retained in new carapace. Right swimmer lost and gills protruding on R side.

[a] Tagging Experiment 2, [b] Tagging Experiment 3

Field deployment of sticker tags

Results from Tagging Experiments 2 and 3 indicated that t-bar tagging can impede normal moulting, often resulting in injuries and crab death. These results precluded initiating a large-scale t-bar tagging program for wild Giant Mud Crabs in regions like Gladstone or Moreton Bay that are important to the commercial fishery. Instead, a sticker tagging program was deployed to gather mark-recapture data. From November 2021 to March 2024 (approximately 28 months), a total of 21,108 captures of tagged Giant Mud Crab were recorded from 35 monitoring sites in Queensland, plus seven captures of the Orange Mud Cab (at Mapoon).

In this field study, sticker tags have no impact on crab health or moulting and can be more liberally deployed without affecting stocks but will be lost during moulting or possibly sooner. There are no studies on whether sticker tags increase predator vulnerability or have social impacts. Sticker tags were trialed on adult and sub-adult crabs as a means of collecting short-term observational movement data out of, or residency within individual estuaries.

Of the 3,292 Giant Mud Crabs tagged and released, 528 were recaptured at least once (16%), 89 were recaptured twice, 18 were recaptured three times and two were recaptured four times. Recapture rates are of a similar order of magnitude to other mud crab tagging studies e.g., 6% Hill (1975), 19% Hyland *et al.* (1984), 15% Knuckey (1999), 15% Hay and Calogeras (2000) and 12% Pillans *et al.* (2005). Sixty-three percent of all recaptures occurred within three days of tag-release and 69% within seven days of tag-release; effectively being recaptured within the same sampling event to which they were tagged (Figure 29). The highest proportion of recaptures occurred in south-east Queensland where the most tags were deployed, frequent fishery-dependent sampling occurred and there was significant effort by commercial and recreational fishers who reported recaptures via the telephone number on the sticker tag. In this regard, 66% of recaptures were during fishery-dependent sampling, with 21% of recaptures by commercial crabbers and 13% by members of the public. There were also considerable recaptures in Eurimbula Creek where there was repeated fishery-independent sampling, noting this location is a mud crab sanctuary (i.e., harvest prohibited).

Recaptures included individual crabs caught multiple times over consecutive days, with the maximum number of recaptures of an individual being four. Recapture rates declined sharply after seven days post-tagging (Figure 29), with 19% captured within eight to 14 days of tag-release, 13% within 15-21 days of tag-release and 8% within 22-28 days of tag-release.

Seventeen males were recaptured after more than 28 days post tagging (range 30 to 329 days). Notable individuals were:

- a 153 mm CW C-grade male tagged in Eurimbula Creek in May 2022, that was recaptured in April 2023, as an A-grade male with mating scars (i.e., 329 days-at-liberty).
- a 139 mm CW male, tagged in Missionary Bay, Hinchinbrook Island in May 2023, that was recaptured in July and September 2023 (i.e., 69 and 119 days-at-liberty).

Thirty-six females were recaptured after more than 28 days post tagging (range 30 to 118 days). Notable individuals were:

- a 154 mm CW female tagged near Pannikan Island (MNP28, Moreton Bay) in April 2023, that was recaptured in September 2023 (i.e., 118 days-at-liberty), which developed externally visible ovary (see Figure 30) whilst at liberty.
- a 175 mm CW female tagged in the Logan River in May 2023, that was recaptured in August 2023 by a member of the public (i.e., 98 days-at-liberty) and which had moved down river and then approximately 6 NM northwards into southern Moreton Bay.

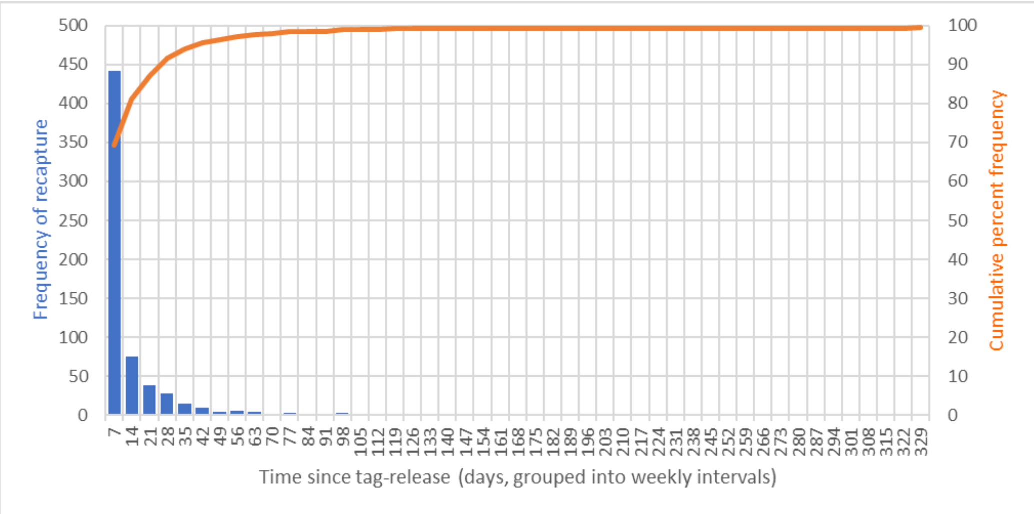

Figure 29. Pareto chart showing frequency of recapture (y-axis$_1$) and cumulative percent frequency of recapture (y-axis$_2$) for time since tag-release for tagged Giant Mud Crabs.

Estimating population size based on tagging

We explored the value of tag-recapture data as a means of indexing population size (potentially addressing Objective 2 of the project i.e., means of monitoring Giant Mud Crabs populations).

Eurimbula Creek is a mud crab conservation zone and provides an unfished population in a relatively small estuary, so was suitable as an example for using mark-recapture to estimate population size. Sticker tags were attached to Giant Mud Crabs in Eurimbula Creek during two intensive sampling events (23rd to 26th May 2022 and 17th to 20th April 2023, DPI) and during a series of bimonthly crab surveys in February, April, June, August, October and December 2023 (CQUniversity). The two intensive sampling events were used to generate population estimates of Giant Mud Crabs in this semi-enclosed estuary.

Sampling in May 2022 (as part of FRDC 2021-119) followed substantial rainfall in the Eurimbula Creek catchment[2]. Crabs of all sizes were tagged and released each day. Population estimates were based on the recapture rates on days two, three or four of each trial and were calculated using the Lincoln-Peterson model (Pollock *et al.* 1990; Robertson and Piper 1991). Based on the recapture of 134 crabs (size range 121-195 mm CW), the estimated number of individuals in the Eurimbula Creek during May 2022 ranged from 667 to 775 crabs (Table 10).

Relatively drier conditions were experienced at Eurimbula Creek in April 2023 prior to the sampling (as part of FRDC 2021-119)[3]. Crabs were tagged and released each day. Based on the recapture of 75 crabs (size range 136-195 mm CW), the estimated number of individuals in Eurimbula Creek in April 2023 ranged from 348 to 407 crabs (Table 10).

Thus, we derived two population estimates for Eurimbula Creek: 667-775 crabs in 2022 and 348-407 crabs in 2023. It is unlikely that the population of pre-recruit and adult Giant Mud Crabs in Eurimbula Creek halved in the 13 months between the two intensive sampling events. Sampling was undertaken in similar months (i.e., May 2022, April 2023). Emigration of females out of the estuary as part of the spawning migration is unlikely to be the cause the reduced population estimate. We postulate that

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http://www.bom.gov.au/climate/maps/rainfall/?variable=rainfall&map=totals&period=week&region=qd&year=2022&month=05&day=19
http://www.bom.gov.au/climate/maps/rainfall/?variable=rainfall&map=totals&period=week&region=qd&year=2023&month=04&day=16

the scale of the difference in population estimates between 2022 and 2023 likely reflects a change in catchability, rather than in absolute abundance. High rainfall prior to May 2022 (Event 1) likely moved more crabs out of lower-salinity mangrove habitats or downstream to the estuary where sampling occurred, increasing their chance of capture in baited crab pots (as per Hewitt *et al.* 2022a).

Table 10. Population estimates of adult and sub adult Giant Mud Crabs, based on the Lincoln-Peterson Index (Pollock et al. *1990), which uses tag-recapture data collected during intensive sampling events in May 2022 (Event 1) and April 2023 (Event 2).*

Event 1 (527 crabs, 134 recaptures)	**23/05/2022**	**24/05/2022**	**25/05/2022**	**26/05/2022**
Proportion marked crabs in sample	0	0.16	0.25	0.37
Number of tagged crabs at large	0	109	190	283
Population estimate	**na**	**667**	**760**	**775**

Event 2 (470 crabs, 75 recaptures)	**17/04/2023**	**18/04/2023**	**19/04/2023**	**20/04/2023**
Proportion marked crabs in sample	0	0.07	0.19	0.24
Number of tagged crabs at large	0	25	72	99
Population estimate	**na**	**348**	**377**	**407**

Discussion

We reviewed the growing literature reporting crab tagging studies. Two publications reviewed the use of telemetry methods for decapod research, two decades apart (Freire and Gonzalez-Gurriaran 1998; Florko *et al.* 2022). The key gap in the literature is an assessment of the effectiveness of conventional tags used for mark-recapture studies such as t-bar, sticker and strap tags.

Our review and subsequent experiments suggest that there remain significant challenges with mark-recapture studies for Giant Mud Crabs, given their anatomy and growth necessitates moulting. These include:

- t-bar tag mortality and loss may be higher than was previously documented or assumed,
- sticker tags have a limited life, likely between several weeks to three months,
- as expected, recapture rates are low, except in the days immediately following the initial tag application, and
- reporting of recaptures captures is dependent on repeat fishery-independent sampling or strong links with commercial crabbers and/or interested members of the public. In the current study, 33% of recaptures were by commercial fishers and members of the public.

Use of t-bar tags on Giant Mud Crabs

The tank experiments suggest that the incidence of t-bar tag mortality, injury and tag-loss during moulting may be relatively high. This appears to be due to the carapace catching on the t-bar tag, related to the placement of the tag through the internal structure above the ecdysial line. Further tank trials to test the repeatability of our results are recommended. If applied to wild populations of Giant Mud Crabs, results from t-bar tagging should consider cryptic mortality effects.

Smaller t-bar tags may be a lower risk option, in terms of risk of tag-induced mortality. These smaller tags still caused mortality in the experiments, but at a lower rate than standard t-bar tags. It is worth noting that all the crabs that moulted in tanks were smaller than Queensland's MLS of 150 mm CW. Larger tags may be more effective for tagging larger crabs and particularly for gathering data on individuals likely to be in their terminal moult. The tagging process itself does not appear to have any adverse health impacts on Giant Mud Crabs.

Husbandry of Giant Mud Crabs

Observations on housing and handling are useful for the development of future experiments. In Tagging Experiment 3, groups of one male and two female crabs were kept together in large troughs. The two male crabs that moulted during the experiment were quickly attacked by the females in the same trough, so separators were then placed into the troughs to prevent interactions. Before the separators were installed, a pair of crabs had adopted the copulatory position. The pair stayed in this pose for several days before the female was found dead.

After several months of holding in tanks, shell lesions developed on many of the captive crabs because of bacterial load. There is currently no known method of avoiding this issue, so it needs to be accounted for in tank experiments on mud crabs and makes long-term experiments problematic. We postulate that the provision of sediment for burying, or another surface on which crabs could manually clean their own carapace may be beneficial in reducing bacterial build-up. Several female crabs spawned during the experiment and interestingly, one individual spawned twice within three months.

Conclusions

The project identified a greater than expected mortality of t-bar tags on Giant Mud Crabs during moulting, which requires further investigation. Of the several published studies on t-bar tagging, only Butcher (2004) mentions tag interference with moulting. As expected, sticker tags are most suited to short-term studies. Future mark-recapture studies on *Scylla* spp. using t-bar tags should thoroughly examine effects of such tags on the success of moulting and tag retention, particularly if a long time-at-large period is required to meet the study objectives such as for growth.

CQUniversity is planning to test the repeatability of results by re-running experiments applying t-bar tags to Giant Mud Crabs.

Chapter 5. Spawning migration of Giant Mud Crabs - inferences from satellite tracking and reported sightings of egg bearing females

N.J. Stratford, J.B. Robins, S. Seghers and N. Flint

Introduction

Broadscale genetic connectivity of Giant Mud Crabs throughout the Indo-West Pacific (Gopurenko *et al.* 1999) and in northern Australia (Gopurenko and Hughes 2002) is likely a consequence of offshore spawning (Hill 1994) and is congruent with oceanographic particle simulations of effective larval advection patterns (Hewitt *et al.* 2022b; Charles *et al.* 2024). There is genetic subdivision of populations in some areas (Gopurenko and Hughes 2002), where coastal currents limit the mixing of nearshore and offshore waters (e.g., coastal boundary current, Gulf of Carpentaria, Wolanski 1993). In some locations, local currents may transport the larvae close to their natal area, resulting in greater self-recruitment than broadscale dispersal (Patterson 2020; Charles *et al.* 2024).

Details of the spawning migration of female Giant Mud Crabs are limited, although regional variation in the migration is thought to be related to hydrological conditions and/or geographic features (Heasman *et al.* 1985). Changes in temperature and salinity are thought to be triggers for migration from estuarine habitats in some locations (Hewitt *et al.* 2022a). However, it is currently unclear whether migration occurs to the same extent in all parts of this species' distribution, what determines the migration pathway, why the distance travelled offshore varies and whether or how females return to the coastline after spawning. There is contradictory evidence as to what proportion of mature females survive the offshore spawning migration and return in inshore coastal/estuarine areas. Heasman *et al.* (1985) reported that approximately 15% of mature intermoult females (n = 96) in a sub-tropical embayment on the Australian east coast as having post-spawn ovaries, but no other study reports observing spent females (Robertson and Kruger 1994; Knuckey 1999).

Hill (1994) reported Giant Mud Crabs in offshore waters of the Gulf of Carpentaria, northern Australia, incidentally caught during bottom trawling for penaeid prawns; many of which were female and egg-bearing. Mean distance offshore was 10 NM (range 1.6 to 51.3 NM). Mean depth-of-capture was 28.5 m, (range 10 to 60 m). These incidental captures suggested a spawning migration between September and November, although catch rates and female gonadosomatic index in the adjacent inshore pot fishery suggested a spawning season of December to February (Knuckey 1999). As part of the spawning migration occurred before the main monsoon season, at least in the Gulf of Carpentaria, the spawning migration was not triggered only by low estuarine salinity.

Along the east coast towards the southern limit of their distribution in Australia, Hewitt *et al.* (2022a) reported acoustic sightings of 14 females at oceanic receivers, from 89 acoustically tagged Giant Mud Crabs released in two estuaries of New South Wales (latitude 29.5 to 30.5°S). All were detected offshore, between 12 and 38 NM north of their original estuary, two to 35 days after their last estuarine detection. The northwards movement is (on average) counter to the southerly flow of the main offshore current in this region - the East Australian Current. Hewitt *et al.* (2022a) suggested that the northward offshore migration in oceanic waters of New South Wales may be facilitated by transient, sub-mesoscale currents. Movement downstream to the estuary mouth in this region was strongly associated with low temperatures (i.e., <22°C) and large declines in salinity due to heavy rainfall.

In contrast to offshore sightings, egg-bearing female Giant Mud Crabs have been infrequently observed in inshore or estuarine waters in South Africa (Hill 1975), Australian east coast (Hyland *et al.* 1984) and the Gulf of Carpentaria (Hill 1994). It is uncertain whether inshore egg-bearing females represent individuals at the start of their offshore migration (but who have spawned prior to offshore movement), or whether under certain circumstances (e.g. appropriate temperature and salinity), successful inshore incubation is possible.

We used the collation of reported sightings of offshore and/or egg-bearing females, and the novel application of pop-up archival satellite tags (PATs) to better understand the spawning migration of female Giant Mud Crabs.

Methods

Study locations

Coastal waters of Queensland were included in the study. The Queensland east coast is open to the Pacific Ocean, whilst the Gulf of Carpentaria is a western or northern facing coastline to a semi-enclosed sea. Both coastlines have extensive areas of mangrove-lined estuarine habitats and support valuable fisheries for Giant Mud Crab but differ in their hydrological and geographical complexity.

Queensland east coast

The Queensland east coast extends for over 2,600 km from Cape York at approximately 10° 41'S to the New South Wales border at approximately 28° 10'S. Offshore from many estuaries of Queensland's east coast is the Great Barrier Reef (GBR), which occurs from Cape York to approximately 25°S. The GBR provides a complex continental shelf that includes coral reefs (both eastern outer boundary reefs, and inner individual reefs), continental islands, and coral sand cays dispersed beside and amongst a deeper 'lagoon' area that occurs between the mainland (where most mangrove-lined estuaries are located) and the outer barrier reef. Shallow water (<20 m) occurs in a narrow area generally within 3 km of the coast (Wolanski and Ridd 1990), seaward of which depth increases across the continental shelf, until the 100 m depth contour (considered the GBR eastern boundary), east of which is the drop-off to the continental slope. The width of the continental shelf from the mainland to the outer reef is on average about 100 km, but ranges from 23 km (at 14°S) to 260 km wide (at 22.5°S).

Within the GBR, currents are a function of semi-diurnal tides and prevailing seasonal winds, which are northwesterly during the monsoon season (on average October to April), and southeasterly during the tradewind season (on average May to September). Seaward of the outer barrier reefs, the westward flowing South Equatorial Current (and jets) splits when it hits the outer GBR, creating complex currents that flow either generally northward (i.e., North Queensland Current and Hiri Gyre) or generally southward (i.e., East Australian Current https://research.csiro.au/cem/projects/current-projects/ereefs/overview/hydrodynamics/).

Below the GBR, parts of the south-eastern Queensland coast are sheltered from the Pacific Ocean by large, sandy barrier islands (K'gari, Bribie Island, Mulgumpin, North and South Minjerribah). The offshore waters south of Sandy Cape (K'gari, approximately 24° 41'S) are greatly simplified in comparison to the offshore waters of the GBR, generally characterised by fine sandy sediments, a narrow continental shelf, with an eastward continental slope that rapidly increases in depth. Offshore waters south of Sandy Cape are exposed to the dynamics of the East Australian Current and associated eddies (e.g., temperature, velocity, direction). Inshore water temperatures of this region may be potentially close to the lower thermal limit of Giant Mud Crabs, including their eggs and larvae. However, during winter, oceanic waters can be warmer than inshore estuarine waters.

Gulf of Carpentaria

The Gulf of Carpentaria (GoC) is a semi-enclosed sea with a coastline extending for approximately 1800 km from Cape York (~11°S, 142°E) to Cape Wessel (11°S, 136°45'E), of which approximately 1100 km occurs within the state of Queensland. The coastline of the GoC is relatively smooth and there are extensive (20 km wide), shallow (<20 m) coastal flats that are turbid and well-mixed (Wolanksi and Ridd 1990). Offshore, water depths increase to a maximum of 65 m, and are oceanic in quality, being separated from inshore coastal waters by a coastal boundary layer (Wolanksi 1993). GoC currents are a function of diurnal tides and the prevailing seasonal winds, which are northwesterly during the monsoon season and southeasterly during the trade wind season (Forbes and Church 1983; Ashbridge *et al.* 2016). Although occurring well within tropical latitudes (i.e., approximately 10°30'S to 18°S), inshore coastal waters of the GoC are more prone to greater seasonal variation in temperature than inshore coastal waters of equivalent latitude on the Queensland east coast and GBR. The diurnal tides, and adjacent land features, amplify the seasonal range of water temperatures inshore coastal flats and adjacent estuaries (Robins *et al.* 2020).

Sightings of offshore and/or egg-bearing females

Sightings of female mud crabs 'offshore' and egg-bearing females were collated from social media posts (Instagram, Facebook), and directly from commercial and recreational fishers following a media release requesting the reporting of such sightings. Collated information included the source of information, date of sighting, location (latitude and longitude, or bearing and distance from a landmark), water depth, photographic evidence to confirm species and egg mass development, colour of egg mass (where possible, to infer development stage), plus other relevant comments (e.g. sighted at surface, type of fishing activity – pot or trawl caught).

Sightings confirmed as Giant Mud Crabs and containing precise location information were plotted in Queensland Globe (https://qldglobe.information.qld.gov.au/). Photographs of the egg-mass were visually assessed (colour, larval development) to roughly estimate development (i.e., days post extrusion). Assessment occurred with the guidance of David Mann (DPI), an expert in portunid crab aquaculture (Mann *et al.* 1999; Mann *et al.* 2001; Mann *et al.* 2007). Where possible, perpendicular distance to the nearest shoreline was calculated. Seasonality of spawning migration for each region was investigated by assessing the month of sightings.

Satellite tagging

Satellite tags

A variety of tagging options were considered based on previous research - acoustic as per Alberts-Hubatsch (2015) and Hewett *et al.* (2022a), or satellite as per Davidson and Hussey (2019) and Green et al. (2021) (Appendix 6). We selected pop-up archival satellite tags (PATs) because the active acoustic receiver network in Queensland waters, whilst considerable (Barnett *et al.* 2024), was spatially insufficient in the preferred study regions, and the novel application of PATs had provided insights into the migration of porcupine crabs *Neolithodes grimaldii* in Davis Strait, Canada (Davidson and Hussey 2019), and giant spider crabs *Leptomithrax gaimardii* in Port Phillip Bay, Australia (Green *et al.* 2021).

Wildlife Computers microPAT (https://wildlifecomputers.com/qr/micropat/) was considered the most appropriate to generate novel data on spawning migration behaviour of Giant Mud Crabs, as they were the smallest archival satellite tag available, being 95 mm x 33 mm, plus antennae (Figure

31). We considered that migrating female Giant Mud Crabs were unlikely to spend sufficient time at the surface to allow the use of real-time Argos satellite tags such as SPLASH or SPOT tags. Upon deployment, microPATs record depth, temperature and light information, with their programmed release from the animal occurring by a burn-pin which detaches the tag from its tether to the animal. Once released, the microPAT, which is only just positively buoyant, floats to the surface and a wet-dry sensor notifies the tag that it has surfaced, after which the tag transmits data to the Argos satellite network. The microPATs provide a pop-up location as well as depth, temperature and light level readings which can be used to generate broadscale, light-based estimates of geolocation (Wildlife Computers 2024). If the tags are physically recovered, the complete archived data series can be downloaded, otherwise 'packaged' data consisting of daily minimum and maximum depths, temperatures and light levels over 6-hourly intervals are transmitted to the Argos satellite network whilst the microPAT has capacity (i.e., battery life and clear transmission pathway to satellites).

The microPATs were set to record depth (0.5 m resolution), temperature and light data every 30 seconds, with the release-pin set to burn at 30, 45, or 60 days depending on the time of year and condition of the crab (Table 11). Tags attached to egg-bearing females had tag-release set at 30 days, whilst on females with less developed ovaries, tag-release was set to 60 or 45 days to enable further ovary development prior to them migrating to spawn.

Site selection

Sites for microPAT application to female Giant Mud Crabs were based on the logistics of collecting females with advanced ovary development (i.e., likelihood of capture), estuarine habitat complexity (to minimise the risk of tag entanglement) and relevance to high catch fishery areas. Analysis of egg-bearing female sighting data and larval modelling papers led to the deployment of 12 microPATs across three locations (Table 11): five tags in the Norman River estuary, Karumba, south-east region of the GoC, five tags at Missionary Bay, Hinchinbrook Island, north region of the Queensland east coast and two tags at Deception Creek, The Narrows, south central region of the Queensland east coast.

The microPATs were deployed in the Austral spring and autumn when female Giant Mud Crabs are thought to have peak spawning (Heasman *et al.* 1985; Hill 1994). Females to be tagged were collected with the assistance of local commercial fishers, from baited trawl-mesh crab pots which had been set overnight in the intertidal zone where there is limited structure (e.g., mangrove prop roots) and limited additional fishing pressure (i.e., other crab pots).

Capture of specimens for tagging

Female Giant Mud Crabs >150 mm CW, limbs intact and showing advanced ovary development were selected for tagging. Females in advanced stage-V ovary development (i.e., tertiary vitellogenesis, Islam *et al.* 2010) can be externally assessed by visual examination of the transparent membrane between the junction of the first abdominal segment and the ventral carapace (thoracic sternites). The ovary of advanced stage-V females fills the body cavity to such a degree that the ovary (usually orange in colour) extends into the abdominal segment of the crabs (i.e., tail flap), resulting in one or two orange crescents being visible to the naked eye (Figure 30). Observation of orange ovary material in the abdominal flap of female mud crabs is used in aquaculture operations to identify when spawning is imminent i.e., expected to occur within two to three weeks (Quinitio and Parado-Estepa 2003). Previous dissection of over 1,000 female Giant Mud Crabs to examine ovary development identified that females with externally visible orange crescent(s) on one or both sides of the abdominal flap had fully mature ovaries considered to be late stage-V, whereby the ovary occupied >95% of the body cavity and individual eggs were noticeable (see Chapter 6).

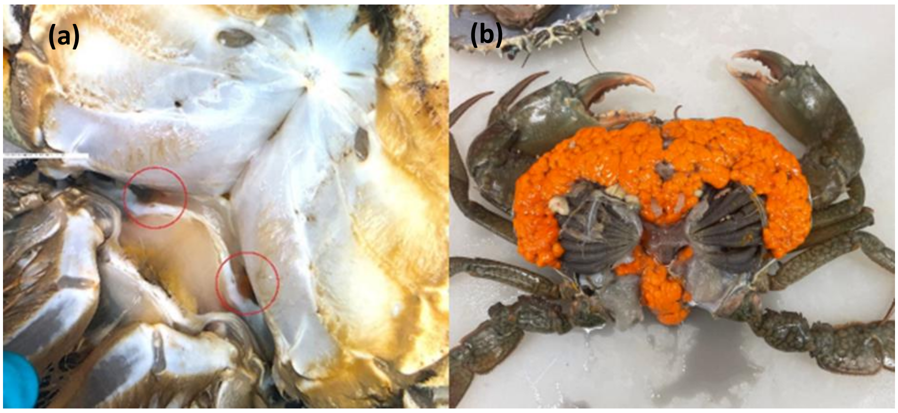

Figure 30. Indicators of late stage-V (i.e., fully mature) ovary development in female Giant Mud Crabs. (a) orange crescents (inside red circles) visible externally through the transparent membrane between the junction of the first abdominal segment and the ventral carapace. (b) dissected late-stage-V female Giant Mud Crab showing full mature ovary (orange tissue). Photo credit: DPI.

Tag attachment

Tags were coated with antifouling paint (International Interprotect High Performance Epoxy Primer as an undercoat and International Ultra 2 High Strength Antifouling as a topcoat; as per Wildlife Computers recommendation). Harness attachment methods utilised in previous brachyuran PAT studies were inappropriate as obstruction to opening of the abdominal flap of female Giant Mud Crabs would prevent egg extrusion and subsequent collection and attachment of the eggs to the abdominal pleopods. We developed a bridle system whereby adhesive attached a stainless-steel saddle to the dorsal carapace of the crab from which the microPAT was tethered using a short length of crimped, flexible 7x7 strand 0.81 mm stainless steel wire (Figure 31). The carapace was wiped clean then abraded to enhance bond strength and a patch of Iccons Pure Epoxy applied to bond the stainless-steel saddle to the carapace. The larger the epoxy footprint the greater the overall bond strength, so we choose an epoxy footprint approximately 5 cm by 2 cm to provide strong adhesion without interfering with the animals' natural behaviours. Following tag application, individuals were released as close as feasible to their capture location.

Figure 31. Method developed to attach a Wildlife Computers microPAT to female Giant Mud Crabs that would not impede extrusion of an egg mass. Example shown is crab-253088, an egg-bearing female deployed with a microPAT in Missionary Bay, Hinchinbrook Island, north region of the Queensland east coast. Photo credit: DPI.

Prior to deployment on wild individuals, we conducted tank trials on tagged female crabs to explore response to attachment options, adhesive types, address any microPAT buoyancy effects and observe the behaviour of tagged crabs. We tested several quick set adhesives (i.e., Gorilla glue, Araldite, Loctite easy fix, Loctite 406, Loctite super glue, Ecotec Coral Glue, Gorilla epoxy putty, Selley's power grip, Iccons Pure epoxy). Iccons Pure epoxy was selected as it created the strongest bond, did not produce significant heat when curing and did not soften or weaken after seven days submerged in sea water.

Table 11. Details of female Giant Mud Crabs tagged with Wildlife Computers microPAT satellite tags.

Deployment Location	Deployment Date	PTT ID	Size CW mm	Tag Set Duration (days)	Release Lat/Long	Early Release	Pop up Lat/Long[b]	Pop up Location	Inferred Tag Release Depth (M)	Days at liberty	Distance (direct line) between Release and Pop up location (NM)
Norman River, Karumba, Gulf of Carpentaria south-east region	4/10/2023	253092	166	60	17° 27.911' S 140° 49.694' E	No Data Received[a]	N/A	N/A	N/A	N/A	N/A
	5/10/2023	253090	160	60	17° 27.911' S 140° 49.694' E	No	16° 36.820' S 140° 25.476' E	Offshore north of Karumba	19	60	55.7
	5/10/2023	253091	169	60	17° 27.911' S 140° 49.694' E	No	16° 34.442' S 140° 30.592' E	Offshore north of Karumba	21	60	57.1
	5/10/2023	253093	178	60	17° 28.022' S 140° 49.235' E	Yes	17° 00.194' S 140° 57.506' E	Van Dieman's Inlet	19	41	29.1
	5/10/2023	253096	167	60	17° 28.022' S 140° 49.235'E	No	16° 57.281' S 140° 23.273' E	Offshore north of Karumba	19	60	39.5
Missionary Bay, Hinchinbrook Island, Queensland northeast coast	17/10/2023	253088	150	30	18° 09.449' S 146° 17.480' E	No	18° 09.443' S 146⁰ 17.480' E	Brook Island, Inner GBR	18	30	5.9
	17/10/2023	253089	157	60	18° 15.958' S 146° 13.914' E	Yes – Depredation	17° 53.550' S 146° 5.954' E	Washed ashore Wongaling Beach	15	18	20.8
	17/10/2023	253094	147	60	18° 12.453' S 146° 13.295' E	No Data Received	N/A	N/A	N/A	N/A	N/A
	17/10/2023	253095	168	60	18° 12.454' S 146° 13.295' E	No	19° 10.770' S 149° 30.896' E	Hydrographers Passage, Outer GBR	320	60	196.2
	17/10/2023	253097	156	60	18° 16.377' S 146° 11.823' E	No Data Received	N/A	N/A	N/A	N/A	N/A
Deception Creek, The Narrows, Queensland central south east coast	11/04/2024	262950	163	45	23° 33.552' S 150° 57.503' E	Yes –WetDry function triggered release	20° 12.536' S 150° 02.603' E	Henderson Reef, Whitsundays, Outer GBR	69	23	209.1
	11/04/2024	262949	166	45	23° 33.552' S 150° 57.503' E	Yes – Depth function triggered release	23° 30.930' S 150° 48.715' E	Egg Island, Fitzroy River delta	0	6	11.6

[a] no data received = never heard from, tag not recovered; b based on Argos Location Quality Class-3 = four message or more per satellite pass, estimated error on location <250 m

Results

Sightings of spawning females

Between October 2020 and June 2024, we collated 101 reported sightings of female Giant Mud Crabs in offshore locations (i.e., well beyond estuarine habitats), as well as egg-bearing females in inshore locations (i.e., within estuarine habitats). The egg-mass of most egg-bearing females reported was bright orange, suggesting extrusion was within the past few days, although several brown to dark-brown egg-masses, signalling late-stage egg development, were also observed (Figure 32).

The spatial distribution of spawning female Giant Mud Crabs collated in the current study (Figure 33) reflects opportunistic sightings, rather than an explicitly designed survey. However, given the almost complete lack of knowledge about the spawning migration of female Giant Mud Crabs in Queensland east coast waters, these sightings provide useful insight into the regional seasonality, migration pathways and potential end points of the spawning migration. The extensive distribution of Giant Mud Crabs in Queensland, occurring in all estuaries, and the intensity of commercial and recreational fishing effort, would imply that migrating females should be sighted (even if at low frequencies) in all regions, with the chance of sightings increasing in proportion to the level of human activity in a region.

Most reports of female Giant Mud Crabs came from the southern and northern Queensland east coast regions, with 38 and 36 reports respectively (Table 12). In the south-east region, the sightings were most frequent in October and November, with three or fewer sightings in all other months. Whilst reports included trawl-caught and recreational fisher sightings, most reports were of female Giant Mud Crabs incidentally caught by commercial fishers using crab pots targeting Blue Swimmer Crabs (*Portunus armatus*) in nearshore oceanic waters adjacent to a barrier sand island. In the northern region, the highest number of sightings occurred in September, October and November, with four or fewer sightings in all other months. Like the south-east region, most reports were of egg-bearing females caught in commercial crab pots targeting legal males in inshore estuarine areas.

For the other regions, limited inference can be made on the seasonality of the spawning migration of female Giant Mud Crabs due to six or fewer reports (Table 12). However, for the GoC north region, four female giant mud crabs were reported in offshore waters in October, which concurs with the seasonality reported for trawl-caught females off Weipa by Hill (1994).

Figure 32. Examples of reported egg-bearing female Giant Mud Crabs, showing range of egg-mass development. All reported caught from inshore estuarine habitats. Photo credit: C. Perkins, P. Hyland, and B. Bright with thanks.

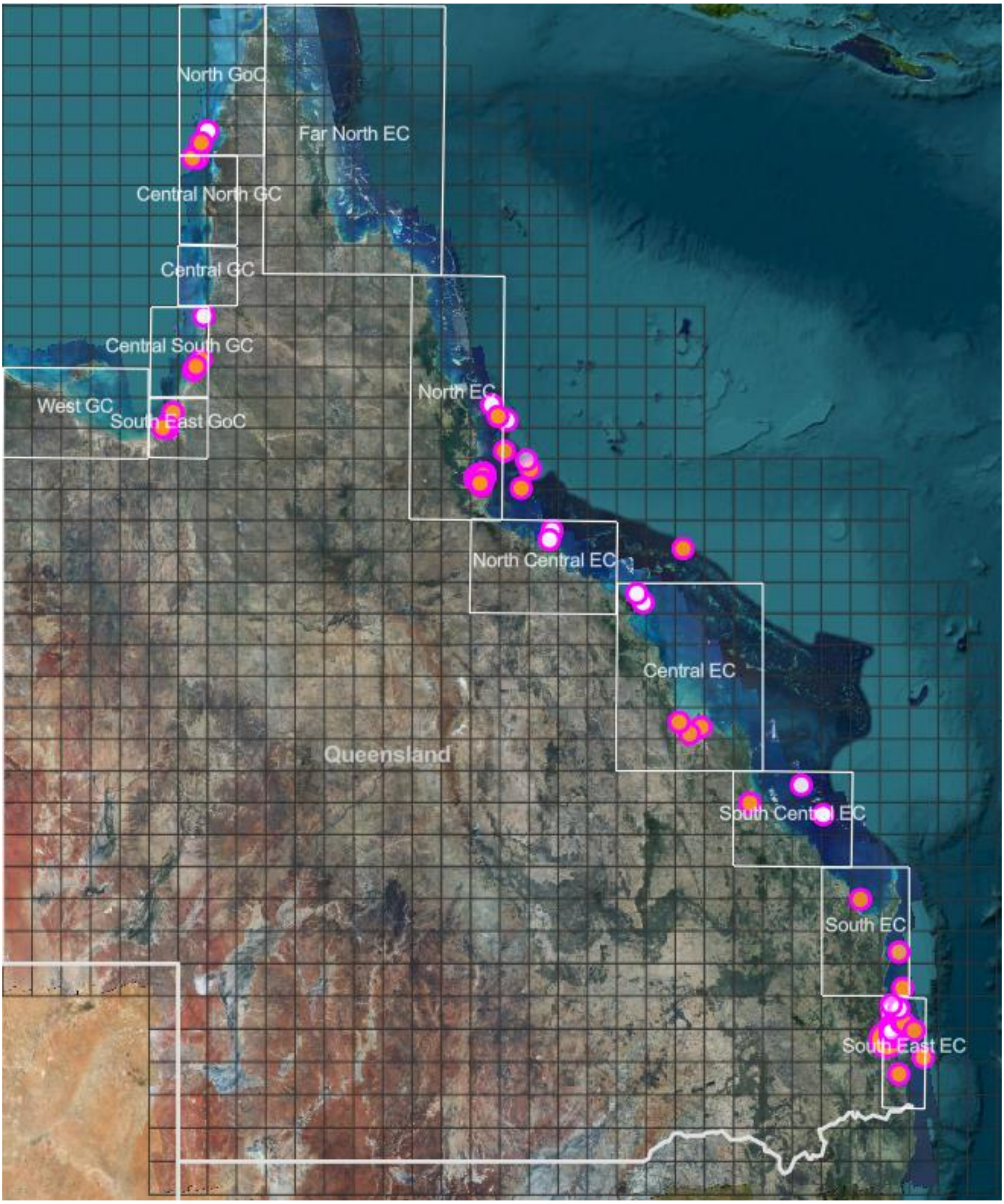

Figure 33. Spatial distribution of female Giant Mud Crabs considered to be undertaking spawning migration in Queensland waters[3]. Pink circles indicate females, orange fill indicates confirmed by photo as egg-bearing, white fill indicates non-egg bearing or unknown. White boxes illustrate fishery regions, black square illustrate 30 NM commercial logbook grids (image is a product of Queensland Globe[4]).

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[3] Includes the inshore report of egg-bearing females by Hyland *et al.* (1984) and Hill (1994).

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Table 12. Seasonality of reported sightings of female Giant Mud Crabs in offshore (egg-bearing and non-egg bearing) and inshore locations (egg-bearing) by fishery region for the Queensland east coast and Gulf of Carpentaria between October 2020 and June 2024.

Fishery region	**Month**											
	9	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Qld east coast												
north	8	6	7	1	3		1	3	1		4	2
north central	2											
central		1	1	2	1		1					
south central		1	1									
south		1			1							
south-east	2	16	8	2	1		1	2	1	1	2	2
Gulf of Carpentaria												
north[a]		4				1	1					
central		1						1	2			
south-east		2		1				3				

[a] one egg-bearing Orange Mud Crab (*Scylla olivacea*) was also reported in March from the north GoC region, but is not included in the above numbers

Table 13. Water depth (m) where reported female Giant Mud Crabs were sighted in offshore (egg-bearing and non-egg bearing) and inshore locations (egg-bearing) by fishery region for the Queensland east coast (EC) and Gulf of Carpentaria (GoC) between October 2020 and June 2024.

Fishery region	**Depth class (m)**					
	0-5	**5-10**	**10-20**	**20-50**	**50-100**	**>100**
Qld east coast					2	
north	28	2	1	3		
north central		2				
central	3		1	1		1
south central	1			1		
south		1		1		
south-east	1	15	14	7		1
Gulf of Carpentaria						
north			2	4		
central	4					
south-east	6					

Satellite tagging

Of the 12 microPATs deployed, nine (75%) successfully uploaded data to the Argos satellite network, while three (25%) did not return any data. Five of the successful tags (55%) remained attached for the programmed duration, while four (45%) released early due to depredation or other causes. Two microPATs were retrieved post-deployment providing archived data (temperature, depth and light) at 30 second intervals. All tags that provided data indicated that the female Giant Mud Crabs moved from the shallow estuarine waters in which they were tagged to deeper waters, of varying distance 'offshore' (Figure 34).

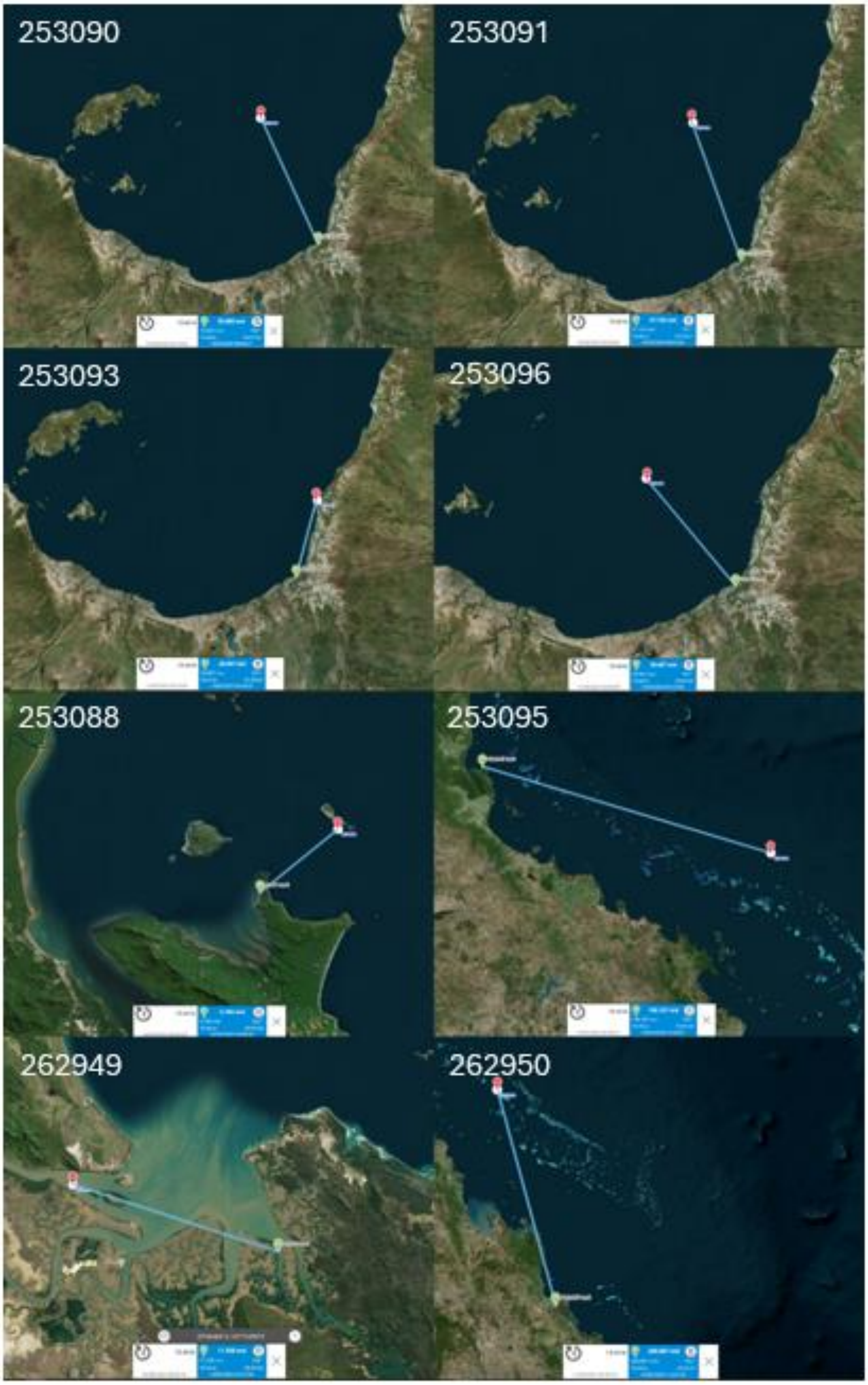

Figure 34. Deployment (green marker) location of microPAT-tagged female Giant Mud Crabs and pop-up location (red marker) of the tag after release from the crabs, for those tags that uploaded data to Argos. The blue line is the path of least distance between deployment and pop-up location. See Table 11 for details. No data for microPAT 253089 was uploaded to Argos, and therefore deployment and pop-up location is not displayed.

Gulf of Carpentaria south-east region – Norman River, Karumba, deployed October 2023

In the south-east region of the Gulf of Carpentaria, the females were tagged in early October 2023, which is towards the end of the dry season. At this time, water temperature increases, and build-up conditions of the monsoon season start, but rain is unlikely (BOM 2019). October coincides with the decline in commercial catch rates of legal males and when fishers note mature female Giant Mud Crabs moving offshore, away from estuaries and the coastal flats (Knuckey 1999). None of the five GoC microPATs were retrieved, so all results for this region are based on summary data transmitted to Argos satellite network from the floating tags.

PTT ID 253090, 160 mm CW

After the programmed duration of 60 days, microPAT 253090 released at a depth of 19 m (Table 11), approximately 100 km north-northwest of its deployment location (Figure 34). Depth summary data (min/max) suggests that crab-253090 remained within the Norman River estuary (at ~10 m depth) until about day 15 post-deployment, then moved to deeper offshore water (Figure 35). Crab-253090 was active for next 19 days, moving between depths of 0 m (i.e., animal at surface), to a maximum of 43 m, then decreasing to 20 m depth. On day 36 post-deployment, crab-253090 remained consistently at around 20 m depth (± 2 m i.e., tidal range, see Figure 35), suggestive of sedentary behaviour. Temperature-at-depth (from the LightLoc file) indicates initial water temperature of approximately 27.5°C, which increases over the 60-days to approximately 30°C.

We infer that crab-253090 continued to move, possibly searching for appropriate conditions to incubate eggs. Following discussions with local fishers and examination of navigation charts (noting the GoC is poorly surveyed), we suspect this crab may have moved offshore possibly via an old river channel, eventually reaching a maximum depth of 43 m. After day 35 post-release, the temperature remained stable (at approximately 30°C). That the depth data follows the diurnal tide cycle suggests the crab was sedentary (Figure 35). At 29-30°C, incubation of Giant Mud Crab eggs is estimated to take 11-10 days (Heasman and Fielder 1983). If so, crab-253090 was sedentary at-depth, either recovering from egg-incubation or had extruded and was incubating another batch of eggs. Giant Mud Crabs are able to produce up to three batches of egg per inter-moult (Quintello and Parado-Estepa 2003). Sediment type at the pop-off location is unconfirmed, but anecdotal reports suggest it is likely course, clean sand. Given the pop-off location (Figure 34), and lack of movement for the final 25 days of the tag duration, there is no evidence that crab-250390 returned to shallow inshore or estuarine waters.

PTT ID 253091, 169 mm CW

After the programmed duration of 60 days, microPAT 253091 released at a depth of 21 m approximately 105 km north-northwest of its deployment location (Figure 34). Depth summary data suggests that crab-253091 remained in the estuary for nine days post-deployment before moving to deeper offshore waters (Figure 35). Large changes in the min/max depth indicates crab-253091 was constantly moving, likely offshore as water depth gets deeper, before stabilising at about 22 m depth on day 17 post-deployment. Crab-253091 remains consistently at this depth for the remainder of the tag deployment. The recorded depth data closely follows the diurnal tide cycle. Temperature-at-depth indicates initial temperature of approximately 26°C, which increases to approximately 30°C at 58 days post-deployment. Given the pop-off location and lack of movement for the final 43 days of the tag duration, there is no evidence that crab-250391 returned to shallow inshore or estuarine waters. Whether crab-253091 spawned once or more, is unknown.

PTT ID 253092, 166 mm CW

This tag failed to connect to the Argos network and no data were recovered.

PTT ID 253093, 178 mm CW

After 41 days, microPAT 253093 prematurely released at a depth of 19 m before washing ashore approximately 55 km north of the Norman River (Figure 34). Depth summary data suggests that crab-253093 remained in the estuary or inshore waters for 28 days post-deployment before moving to deeper offshore waters. Crab-253093 was somewhat settled at a water depth of 20 m for five days before the tag disconnected from the crab. Temperature-at-depth indicates initial temperature of approximately 27°C, which increased to approximately 29°C at ~ 29 days post-deployment (Figure 36).

Although data collection occurred for only 41 days, crab-253093 showed similar patterns in its depth profile (Figure 36), moving to similar depths and water temperatures as the other crabs. Visual analysis of tag drift patterns and GoC currents suggest that microPAT 253093 is likely to have detached from the crab near where the other tags popped up (Figure 34). The microPATs that popped-up at 60 days post-deployment tended to drift south-east post-release, which given enough time would have seen them wash ashore in a similar area to tag 253093. The summary light data is inadequate to confirm the cause of tag loss (e.g., predation). Whether crab-253093 spawned and had settled on the bottom to incubate an egg-mass is unknown.

PTT ID 253096, 167 mm CW

After the programmed duration of 60 days, microPAT 253096 released at a depth of 19 m approximately 74 km north-northwest of its deployment location (Figure 34). Depth summary data suggests that crab-253096 remained in the estuary for 14 days post-deployment before moving to deeper offshore waters (Figure 36). Depth summary data suggest crab-253096 moved for a further 14 days, with maximum depth gradually increasing to and stabilising at 20 m. The depth summary data indicate minor activity at day 41 post-deployment. The recorded depth data closely follows the diurnal tide cycle. The first temperature-at-depth data was 28°C on day 17 post-deployment. Temperature-at-depth fluctuated slightly (27.8 to 29.4°C), eventually reaching approximately 30°C at 59 days post-deployment.

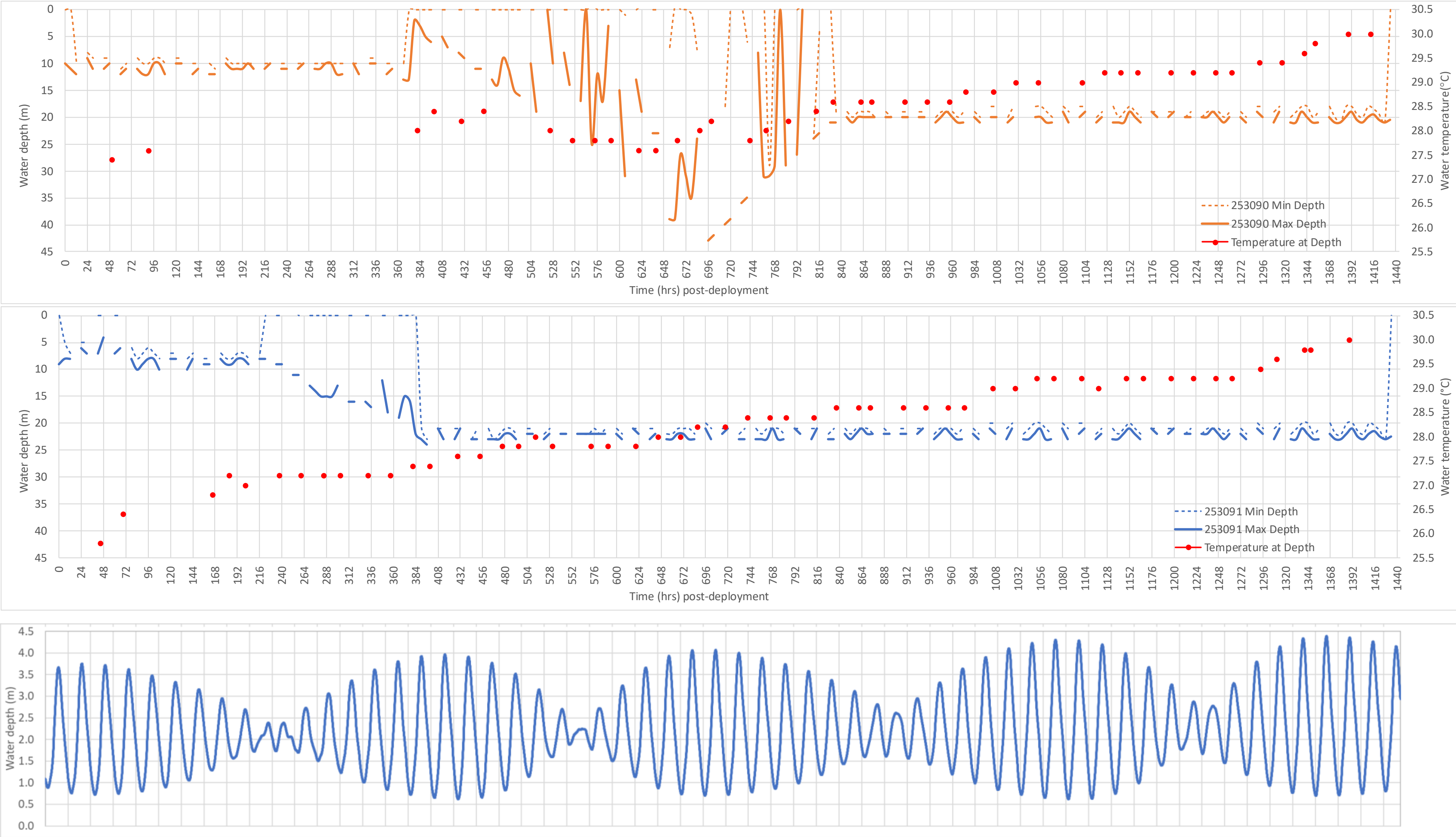

Figure 35. Depth and temperature profiles of summary data transmitted to Argos from microPATs attached to spawning female Giant Mud Crabs in the Gulf of Carpentaria south-east region. See Table 11 for details. Lower panel shows observed tide Karumba (station number 071004A).

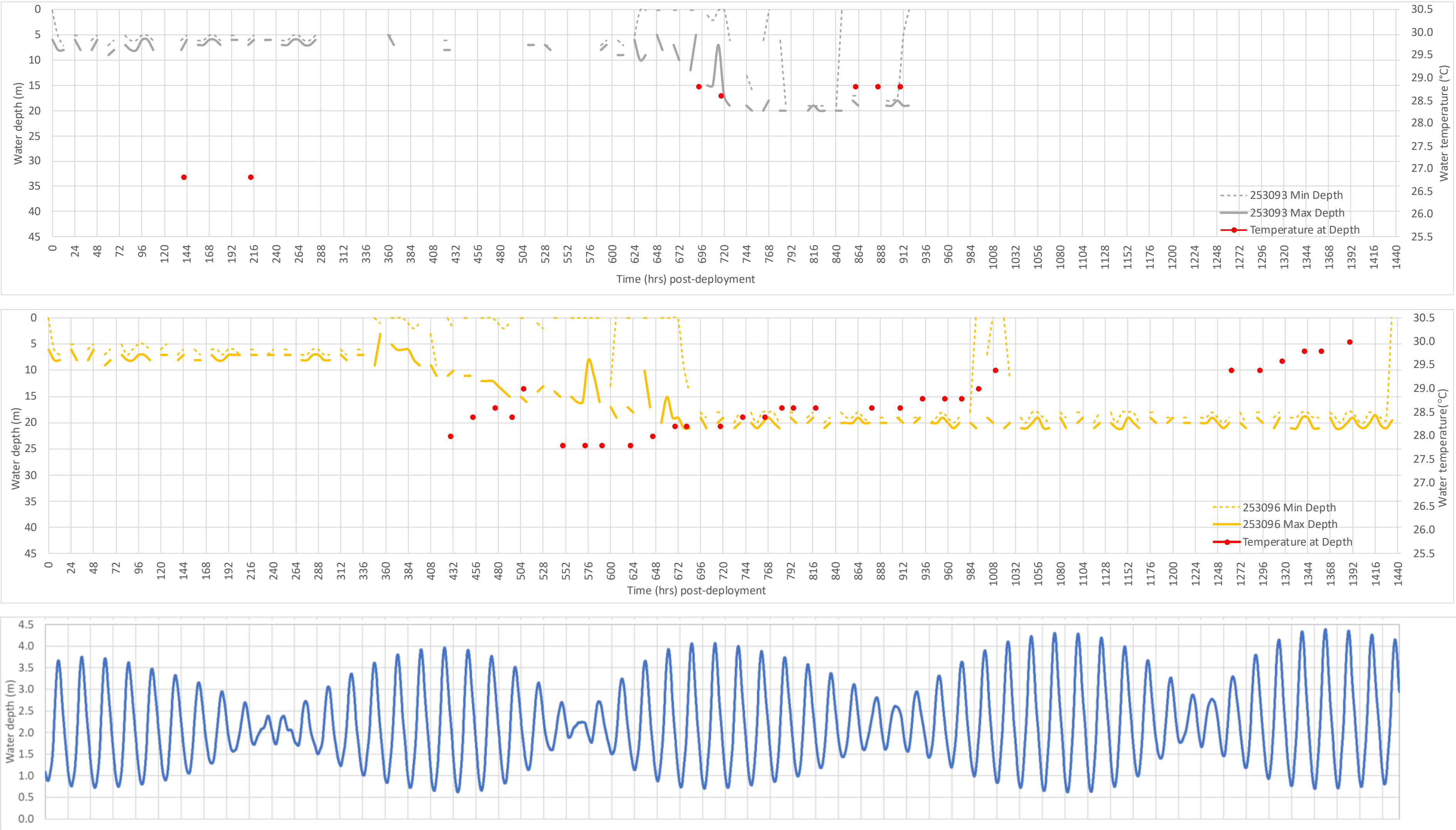

Figure 36. Depth and temperature profiles of summary data transmitted to Argos from microPATs attached to spawning female Giant Mud Crabs in the Gulf of Carpentaria south-east region. See Table 11 for details. Lower panel shows observed tide Karumba (station number 071004A).

Queensland east coast north region – Missionary Bay, Hinchinbrook Island, deployed October 2023

Female Giant Mud Crabs were tagged at Missionary Bay, Hinchinbrook Island, in mid-October 2023 when water temperatures were increasing, and increased sightings of egg-bearing females were reported by commercial fishers in the region. October is prior to the onset of the monsoon season, and main months of rainfall and flooding (i.e., January to April, BOM 2019). Anecdotally, commercial fishers report mature females are in higher densities on the coastal flats adjacent to mangrove-lined estuaries. Two of the Queensland east coast north region microPATs were retrieved and allowed comparison of the summary data transmitted to Argos satellite network and the archived data recorded at 30 second intervals.

PTT ID 253088, 150 mm CW – egg-bearing

After the programmed duration of 30 days, microPAT 253088 released from a depth of 20 m, about 11 km from its deployment location (Figure 34). This microPAT was recovered from the beach of North East Bay, Palm Island, 74 NM southeast of its pop-up location. Based on depth summary data, this egg-bearing female moved to deeper water within four days post-deployment (Figure 37), and remained at this depth, suggestive of sedentary behaviour, until the tag released. There is no evidence in the summary depth or temperature data that crab-253088 returned to shallow or estuarine waters. At water temperatures between 25 and 30°C, egg-incubation is estimated to take 10-15 days (Heasman and Fielder 1983; Quintello and Parado-Estepa 2003). The egg mass of crab-253088 was about three days post-spawn when deployed, based on visible characteristics i.e., bright orange colour, lack of black pigmentation associated with more advanced egg development, and should have hatched at around 12 days post-deployment.

Temperature-at-depth indicates initial water temperature was approximately 26°C, which gradually increased to approximately 27°C (Figure 37). These values concur with 30-second archive data, indicating that the summary data transmitted to Argos captures key changes in the depth and temperature encountered by the tagged crabs.

Based on the 30-second archive data (Figure 38), we infer that crab-253088 immediately left the shallow coastal flat where it was caught and released, and moved into deeper, cooler water. We aligned the depth data with the nearest observed 10-minute tide records (Cardwell, station number 035012A) to examine evidence of location in the water column (i.e., at surface or on the sea floor), and tidal water movement (i.e., selective tidal stream transport). On the flood tide, crab-253088 moved up and down within the water column, being more near the surface during the flood tide and more near the sea floor during the ebb tide. After about three days, crab-253088 had a stable depth profile, which continued until the microPAT released as programmed at 30 days post-deployment. The constant depth profile (approximately 20 m) suggests crab-253088 did not move back into shallow estuarine waters. There was no indication as to whether this crab spawned another egg mass, remained offshore to feed and gain resources to spawn another egg-mass[5], or died at the site.

[5] Post-spawn female Giant Mud Crabs are resource depleted and actively feed in aquaculture conditions, presumably to acquire resources that would enable further spawning (D. Mann pers. comm 2024).

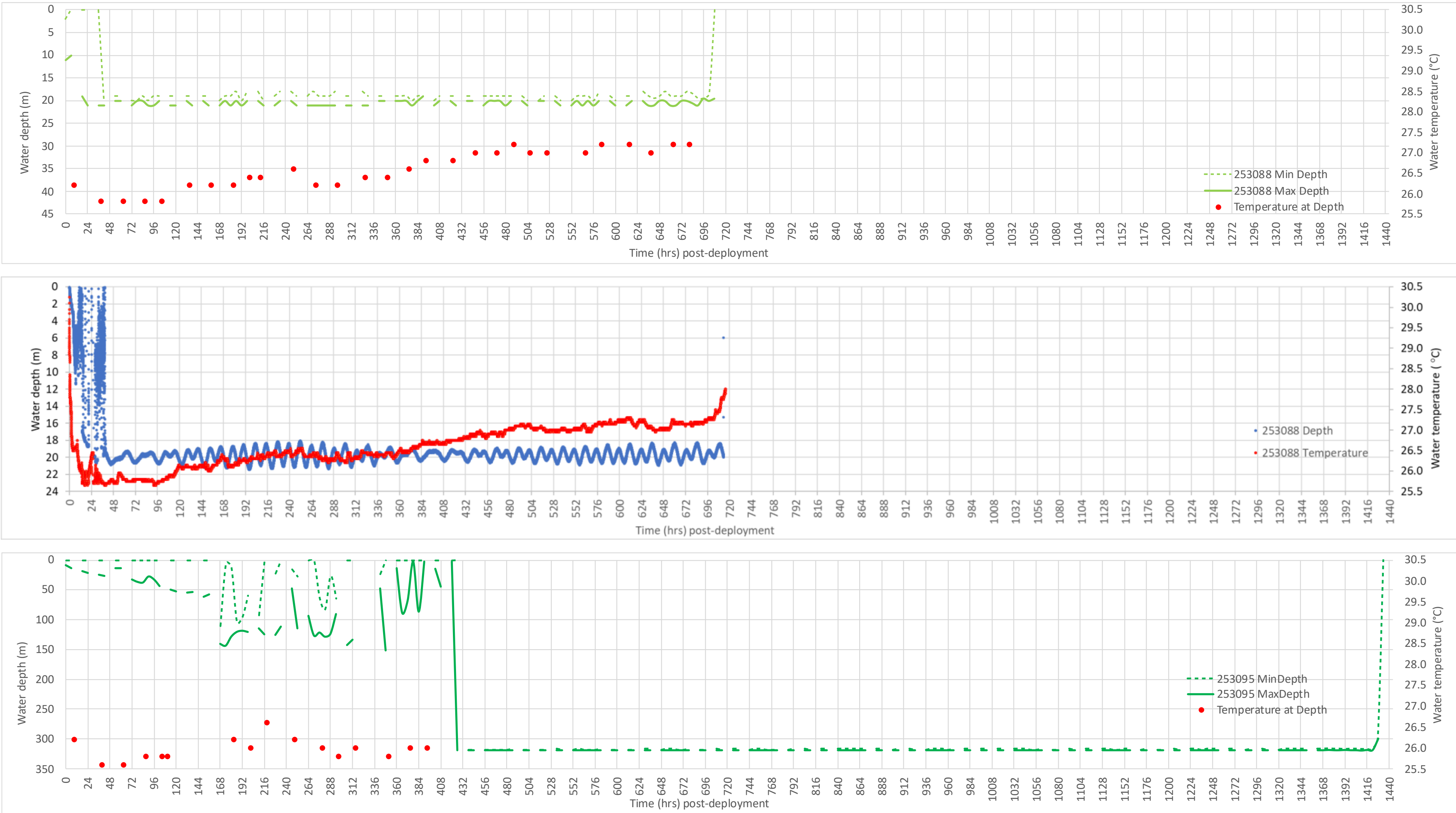

Figure 37. Depth and temperature profiles (top and bottom panels) of summary data transmitted to Argos from microPATs attached to spawning female Giant Mud Crabs along the Queensland east coast north region. See Table 11 for details. Mid panel is depth and temperature data from tag 253088, which was physically recovered and archived 30 second data downloaded.

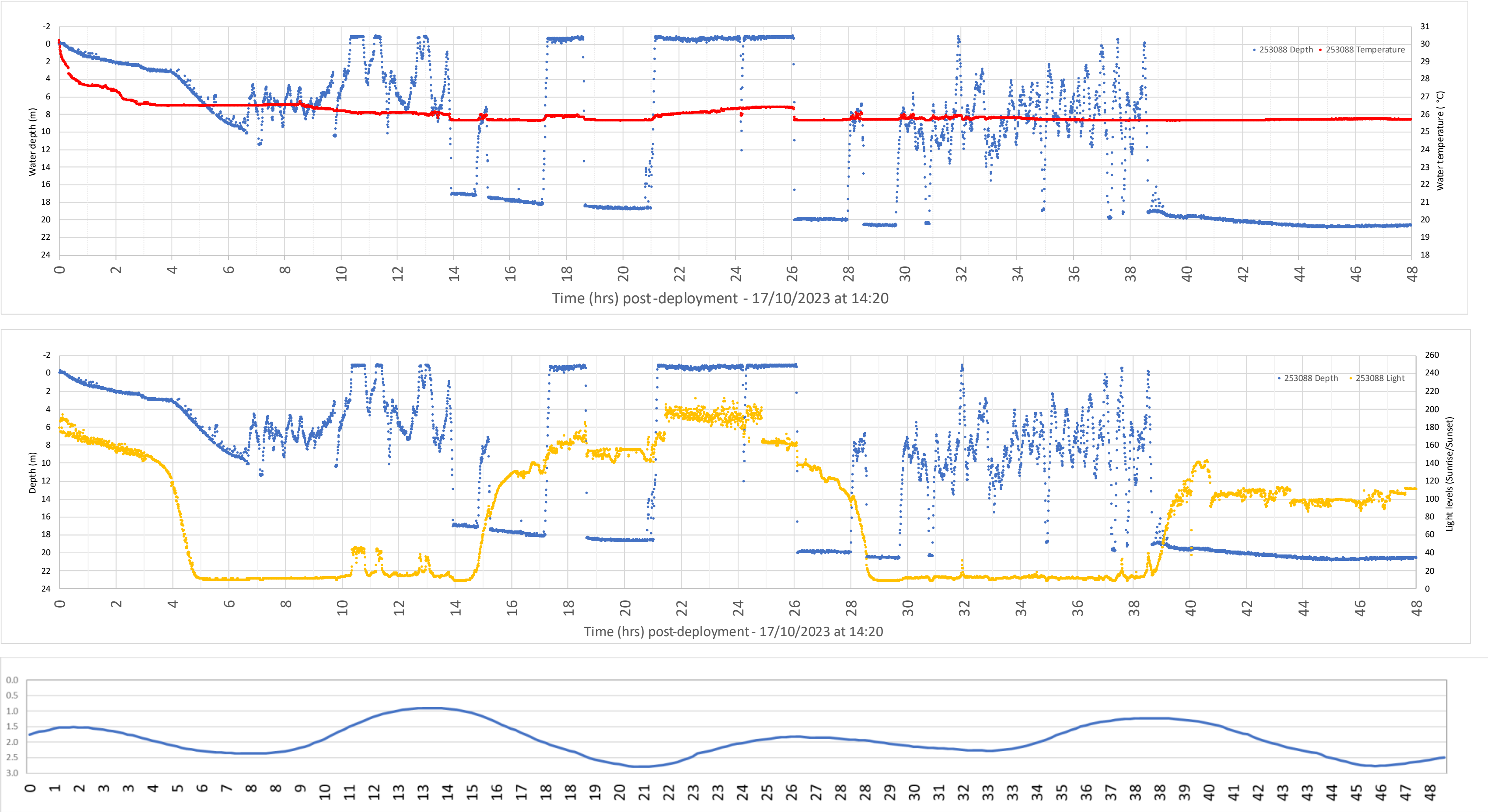

Figure 38. Archived 30 second interval data for crab-253088, a 150 mm carapace width egg-bearing female Giant Mud Crab for the first 48 hours post-deployment. Top panel is depth and temperature), middle panel is depth and light, lower panel is observed tide at Cardwell (station number 035012A).

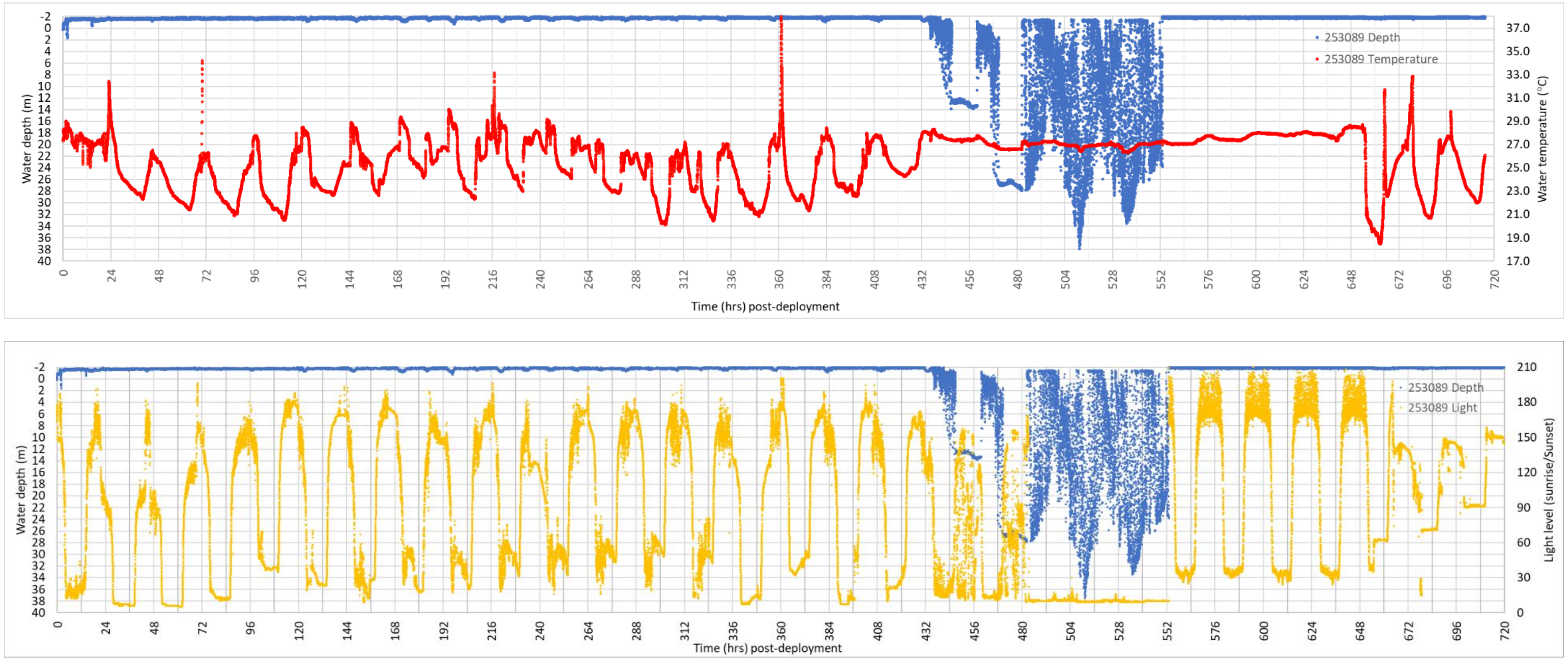

Figure 39. Archived 30 second interval data for crab-253089, a 157 mm carapace width female Giant Mud Crab. Top panel is depth and temperature. Bottom panel is depth and light level. Likely period of predation indicated by no day/night cycle in the light profile (yellow line) between ~480 and 522 hours post-deployment.

PTT ID 253089, 157 mm CW

MicroPAT 253089 was recovered before its programmed 60-day release date, so no data were transmitted to Argos. However, this tag was recovered from a beach 39 km northwest of its deployment location (Table 11). Archived 30 second interval data was downloaded from the recovered tag (Figure 39), from which the following inferences have been made. The depth, temperature and light data suggest that crab-253089 remained in shallow water, likely the coastal flats where it was initially tagged, for about 18 days post-deployment. The temperature and light data suggest that crab-253089 then moved into deeper water (approximately 26 to 28 m deep). The light data, which had previously tracked the sunrise/sunset cycle until 20 days post release, showed a 72-hour period of darkness (i.e., light level below 20), during which it is likely the tag had been ingested (Figure 39). Temperature readings stabilise during this 72 hrs, while the depth data is extremely variable. After 23 days post-deployment, the light data returned to a cycling light/dark pattern, indicative that the microPAT having likely passed through the predator. Recovered microPAT 253089 was missing its antenna and was covered in teeth marks, supporting the inference of predation.

PTT ID 253094, 147 mm CW

This tag failed to connect to the Argos network and no data were recovered.

PTT ID 253095, 168 mm CW

After the programmed duration of 60 days, microPAT 253095 released from a depth of 320 m, approximately 362 km south-east from its deployment location (Figure 34). The tag first surfaced outside the Great Barrier Reef in deep waters (i.e., ~320 m) north-northeast of Whitsunday Island. Similar to crab-253088, this female had moved to deeper, offshore waters within one day of deployment.

Depth summary data suggests that crab-253095 had reached the edge of the continental shelf in the GBR region (i.e., deep water, greater than 100 m) by day seven post-deployment (Figure 37). The shortest route from Missionary Bay the edge of the GBR is approximately 111 km. Significant daily differences between minimum and maximum depth (between approximately 0 to 150 m) suggests continuous activity by crab-253095. The main current direction at the time would support a likely southward movement (https://oceancurrent.aodn.org.au/product.php?product=daily&region=CGBR&date=20231017120000&rtype=DR). By day 18 post-deployment, the depth data indicate crab-253095 was in water about 320 m deep, where it remained until the tag released at 60 days post-deployment. Recorded water temperature at 320 m was ~13°C (from the Series Range file). Incubation is unlikely to have been successful at this temperature (Heasman and Fielder 1983) and we assume that this crab had died. If crab-253095 was alive, the prevailing currents and the distance from shore (approximately 130 km) suggest it would be implausible for crab-253095 to return to shore. Temperature-at-depth data indicates initial water temperature of around ~26°C (Figure 37).

PTT ID 253097, 156 mm CW

This tag failed to connect to the Argos satellite network and no data were recovered.

Queensland east coast south-central region – The Narrows, deployed April 2024

Two female Giant Mud Crabs collected from Deception Creek, at the northern end of 'The Narrows' (north of Gladstone, central Queensland) were tagged in mid-April 2024, when water temperatures were decreasing, and sightings of mature females were increasing. Release settings on these two microPATs were different to tags deployed in October 2023. These microPATs were programmed such that the tag would commence the release sequence when the tag was more than 25% dry or shallower than 1 m, or the tag was at a constant depth ±4 m for longer than 120 hours. These settings were trialled to overcome the loss of data from microPATs that released early, but that never successfully transmitted to the Argos satellite network (Table 11). Tags that release early, and do not transmit until the programmed release date, can become entangled in mangrove habitat which interferes with transmission. The two microPATs deployed in The Narrows were programmed for the release-pin to burn at 45-days post-deployment.

PTT ID 262949, 166 mm CW

MicroPAT 262949 released after six days post-deployment. Crab-262949 had moved 11 NM northwest from Deception Creek to a mangrove island at the mouth of the Fitzroy River (Figure 34). Crab-262949 remained there for several days in amongst mangroves in water less than 0.5 m deep, which resulted in programmed 'mortality' conditions being met and a premature tag release. A few signals were received by Argos satellite network (mostly location), but no useful data were received.

PTT ID 262950, 163 mm CW

MicroPAT 262950 transmitted data to the Argos satellite network at 21 days post-deployment (i.e., early release). Depth summary data suggests that the tag had detached three days prior from a depth of 69 m near Henderson Reef, east of Whitsunday Island - approximately 388 km north-northwest of its release location (Figure 34). Crab-262950 remained inshore (i.e., less than 10 m depth) for five days post-deployment, then moved into deeper water (40 to 50 m, Figure 40). The summary data indicated crab-262950 was constantly moving, with depth fluctuating between the surface and deeper water (possibly near the seafloor) but never settled at steady depth like some of the other tagged crabs. There was no indication in the light data that this crab was predated. Satellite SST imagery which includes current vectors during this tags' deployment shows a current flowing from south to north up the Capricorn Channel, potentially aiding the movement of crab-262950 (https://oceancurrent.aodn.org.au/product.php). Once microPAT 262950 was transmitting data to the Argos satellite network, it remained drifting close to the pop-up location for seven days. The lack of substantial movement of the tag (due to tide, current or wind drift) suggests that active swimming and depth choice by crab-262950 was primarily responsible for its large-scale movement (i.e., 388 km in less than 21 days). The tag was indicated as releasing because of the WetDry function. As crab-262950 didn't appear to stop moving and settle at a depth, it is possible that spawning did not occur.

Figure 40. Depth and temperature profile of summary data transmitted to Argos from microPAT 262950 attached to a spawning female Giant Mud Crab along the Queensland east coast central region.

Discussion

A combination of egg-bearing female sightings and the application of pop-up archival satellite tags has provided new and unique quantitative information on the spawning migration of female Giant Mud Crabs. The sightings provided information on migration pathways and seasonality, while the satellite tags 'tracked' females to provide insight into offshore movement behaviour, locations where egg incubation may occur and allow inference about whether females survive and return to estuaries after spawning.

Satellite tagging of brachyuran crabs - comments on methods

The results suggest that the judicious application of satellite tags can successfully provide data on the spawning movement of brachyuran crabs. We considered that the following key logistical aspects that supported the successful deployment of satellite tags. Firstly, females with signs of advanced ovary development (i.e., externally visible orange crescents in the abdominal flap) were targeted for tag deployment. Secondly, the microPAT was securely attached to the carapace in a novel manner unlikely to impede spawning (i.e., harness attached to the dorsal carapace by specialised glue). And thirdly, the microPATs were deployed where and when there was the least risk of entanglement in mangrove prop roots or in other crab pots. Collaboration and support from Queensland commercial crab fishers was very important to the success of the research, and for which we are very grateful.

In the first two deployments of satellite tags (Gulf of Carpentaria and Queensland east coast north region), we decided to not activate the premature release capabilities of the microPAT; instead choosing to have automated pin-burn and the tag pop-up at 60 days post-deployment for most females. This was because female Giant Mud Crabs live in estuarine intertidal areas, where during parts of tidal cycle they may move into very shallow water, which would cause premature release of the tag. We chose a shorter automated pin-burn and tag pop-up for the egg-bearing female (30 days) because she had already spawned. During these first two tag deployments, two tags released and popped-up earlier than programmed and three tags did not successfully upload any data to the Argos satellite network. If premature release capabilities had been activated, some of these five tags might have successfully transmitted data to Argos.

In the third deployment of satellite tags (Queensland east coast central region), we activated the premature release capabilities of the microPAT, with the following conditions – the tag is more than 25% dry or is shallower than one metre, or the tag is at a constant depth of ±4 m for longer than 120 hours. This was beneficial as microPAT-262950 transmitted data as soon as it released from the crab. However, it also resulted in premature release of a microPAT-262949 from a female crab that stayed in shallow estuarine habitat for longer than 120 hours. In hindsight, we think this latter premature release could have been avoided by setting the 'first dive below' condition to a greater depth (e.g., 50 m).

Insights into the spawning migration of female Giant Mud Crabs

There are few empirical studies on the spawning migration of female Giant Mud Crabs (e.g. Hill 1994; Hewitt *et al.* 2022b). In general, it is assumed that the spawning migration is towards an offshore destination, dependent on hydrological and geographical features (Heasman *et al.* 1985, Hewitt *et al.* 2022b; Charles *et al.* 2024). It has been assumed that the spawning migration is driven by females seeking suitable and/or stable water quality conditions (e.g., temperature and salinity) to maximise larval survival (Alberts-Hubatsch *et al.* 2016). Previous reports of spawning female Giant Mud Crabs have focused on the distance offshore and depth of capture (Hill 1994). Using satellite tagging technology, the current research provides valuable new insight into some of the abiotic characteristics of the migration pathway (e.g., depth and temperature), and given the diversity of locations within the current research, allows further speculation on aspects of the migration.

Region specific comments – Gulf of Carpentaria

In the south-east region of the Gulf of Carpentaria, the satellite tagged female Giant Mud Crabs migrated to offshore locations that ranged from 54 to 105 km from their deployment location and averaged about 20 m in depth. The south-eastern Gulf of Carpentaria had limited sampling by Hill (1994), so the recorded movement in the current research fills a knowledge gap. When reports of egg-bearing females were collated, six egg-bearing females were sighted in the south-eastern Gulf of Carpentaria, all of which were caught in crab pots either in an estuary or on coastal flats. Five female Giant Mud Crabs were reported offshore in the northern Gulf of Carpentaria, all of which were 27 to 37 km from the coast and free-swimming at the surface in water depths of 20 to 30 m. These results are congruent with those reported by Hill (1994).

In the Gulf of Carpentaria, it appears that female Giant Mud Crabs migrate predominately to offshore waters between 20 and 40 m in depth that provide salinity and temperature water quality characteristics appropriate for egg-incubation and pelagic larvae (Rothlisberg *et al.* 1989). We speculate that the migration is also to locations that are beyond inshore turbid waters, where fine sediment is frequently resuspended by wind or tide (Rothlisberg and Burford 2016). This may have implications for larval distribution and genetic connectivity of Giant Mud Crab stocks in this region which has a coastal boundary layer (Wolanski 1993). Indeed, further genetic sampling and analysis has found a degree of genetic structuring between the western and eastern Gulf of Carpentaria (Williams in prep).

Region specific comments – Queensland east coast

Along the Queensland east coast, the satellite tagged female Giant Mud Crabs migrated to offshore locations that ranged from 11 to 389 km from their deployment locations and ranged from shallow waters (i.e., <5 m) to depths beyond the continental shelf (>100 m). Combined with the reported sightings, this is the first quantitative evidence of the movements, likely pathways and behaviours that female spawning Giant Mud Crabs undertake along the Queensland east coast. Compared to other locations, the Queensland east coast has a highly complex ‘offshore’ continental shelf with a diversity of sea floor sediments (e.g., mud, sand, shell grit), and current regimes. Water temperature and salinity tends to be more stable in offshore continental waters than inshore waters (Wolanksi and Ridd 1990). Most reports of egg-bearing females along the Queensland east coast were from either the south-east or north regions. In the south-east region, sightings were most common in October and November by commercial crabbers targeting Blue Swimmer Crabs (*Portunus armatus*) in oceanic areas slightly offshore of the Moreton Bay barrier islands. In the north region, sightings were most common between September and November, being reported by commercial crabbers targeting Giant Mud Crabs in estuarine areas adjacent to Hinchinbrook Island. This provides some evidence that the timing of spawning may differ between latitudes (Heasman 1980), occurring later in more southern latitudes and slightly earlier at more northern latitudes (noting the work occurred in the Southern Hemisphere). Many of the reported sightings of egg-bearing females from the Queensland east coast were from offshore waters where turbidity was low. However, the non-rare occurrence of egg-bearing females in baited crab pots in estuarine locations is somewhat perplexing. It could be a consequence of the entrapment of mature, stage-V females in pots, but this is unlikely as this should then be a fishery-wide phenomena. It could be the consequence of appropriate water quality conditions in some locations.

Spawning offshore – benefits versus risk

Mud crab reproduction, including spawning and egg incubation is well studied under aquaculture conditions. Spawning involves the extrusion of eggs via the paired oviduct and gonopores, with the eggs being fertilised by sperm that has been stored in the spermatheca. Extruded eggs are initially loose, then gathered up into an egg-mass attached to the female with the support of the long silky setae of the four bilateral pairs of the abdominal pleopods. Females maintain the egg-mass, with dropped eggs commonly infected by fungi, polycheate or nematode worms (Davis *et al.* 2004). Clean water quality is noted as a key requirement for successful mud crab hatcheries (Quinitio and Parado-Estepa 2003) and more recently Fazhan *et al.* (2022) reported that female *Scylla* species preferentially select fine sand substrates during spawning.

On the basis of this aquaculture research, combined with our field results, we speculate that wild spawning female Giant Mud Crabs seek out locations with features that support successful egg survival during extrusion and incubation, so as to maximise the successful hatch of the pelagic larvae. In addition to previously identified optimum temperature and salinity, we suggest that females seek locations with low turbidity and sandy or coral-grit substrates, thereby minimising the chance and rate of eggs becoming infected. In many regions where Giant Mud Crabs inhabit, this may necessitate an offshore migration. Offshore continental shelf waters generally have more stable temperature than inshore waters. The temperatures recorded by the microPAT satellite tags (26 to 28°C from east coast sites, and 30°C in the Gulf of Carpentaria) are near the embryonic development range recommended for aquaculture hatcheries (Quinitio and Parado-Estepa 2003). As suggested by Hewitt *et al.* (2022a), while the spawning migration may involve movement against prevailing currents in some locations, results from the satellite tagging herein provide evidence neither for nor against this theory.

High fecundity (i.e., millions of eggs per batch), with maximal larval production is part of the broadscale larval dispersal strategy of Giant Mud Crabs*.* It is likely that offshore spawning results in high larval loss, with only those larvae that successfully recruit back to inshore estuaries surviving and potentially contributing to the next generation in any given estuary.

Previous studies have inferred that egg-bearing female Giant Mud Crabs feed at lower levels than non-egg-bearing individuals and so would not be attracted to and caught in baited crab pots. (Heasman *et al.* 1985). Egg-bearing females were repeatedly caught in baited pots in certain locations. Speculation that female Giant Mud Crabs have a capital breeding strategy, whereby females rely on stored energy reserves during ovarian development (Hewitt *et al.* 2022a) is inconsistent with our field results and the laboratory dissection observations (Chapter 6). The satellite tagging did provide some evidence that spawning females utilise selective tidal stream transport, potentially to conserve energy, as has speculated by Patterson (2020) and Hewitt *et al.* (2022a).

Hewitt *et al.* (2022a) suggested that the spawning migration of female Giant Mud Crabs was terminal, despite the species' ability to spawn multiple times after a single mating event. This is contrary to the report of recently spent females in an estuary by Heasman *et al.* (1985) and the assertion by Hill (1994) that many females return to the coast after offshore spawning, which was based on the modal size of females in coastal waters being larger than those caught offshore (Hill 1994). Our satellite tagging results lead us to concur with Hewitt *et al.* (2022a); that most female Giant Mud Crabs likely die during or immediately after their spawning migration, particularly those that migrate offshore.

Our satellite tag data, along with anecdotal reports and the historical literature, provide evidence of offshore spawning by female Giant Mud Crabs. However, there were reliable reports of egg-bearing females captured inshore and in estuarine environments in some regions of Queensland. This raises the question of whether each female crab's 'decision' to migrate or not is random, or based on local water quality conditions, or whether there might be a mixed reproductive strategy in which some individuals migrate offshore, while others remain inshore. One possibility would be that smaller/younger individuals preferentially spawn closer to shore (thereby improving their chance of survival and multiple spawning events) and larger/older individuals preferentially spawn further offshore, with increased chance of mortality but greater likelihood of broadscale larval dispersal. However, there is limited evidence to determine whether this possibility is real.

The pilot study presented in the current chapter has developed the protocol for tracking the spawning migration of female crabs using microPAT satellite tags. Judicious application of more satellite tags to female Giant Mud Crabs in Queensland waters would enable further understanding of this elusive stage of the mud crab life cycle. Such information may be useful if female Giant Mud Crabs are ever legally harvested in Queensland.

Implication for fisheries

In Queensland, female Giant Mud Crabs are prohibited from harvest. Therefore, their population dynamics and mortality are relatively natural. As such, supply of post-larvae to estuarine habitats of Queensland waters, and adjacent jurisdictions (i.e., Northern Territory and New South Wales), is a function of prevailing hydrological conditions, mostly without human effects. As noted by Hyland *et al.* (1984), there is limited movement between regions once Giant Mud Crabs have the body form of a crab (i.e., C1 crablet). As suggested by Hyland *et al.* (1984), discrete regions within the Queensland east coast (EC1) or Gulf of Carpentaria (GC1) could be treated as separate units for fisheries management, notwithstanding the high genetic connectivity between these regions (see Chapter 3).

In jurisdictions where females are harvested, management should consider the impacts of fishing mortality on female spawning biomass, given the likelihood that most females do not survive spawning. For example, the minimum size limit for females should ensure that a significant proportion of the female population is mature and below legal size (for further discussion of this topic see Chapter 6 and Chapter 7). Alternatively, the spawning biomass of females prior to the onset of the spawning season, should be estimated, and if need be, fishing mortality reduced to ensure sufficient spawners remain, such as occurs in the Northern Territory Mud Crab Fishery Harvest Strategy.

Giant Mud Crabs are highly fecund, with egg-masses producing between about a one and eight million eggs (Mann *et al.* 1999). This implies high natural mortality, likely of particular life history stages e.g., high larval mortality/loss.

Stock assessments of Giant Mud Crabs assume that females have the same natural mortality rates (*M*) as males i.e., that there is no increase in natural mortality associated with the spawning migration (Grubert *et al.* 2019). Grubert *et al.* (2008) suggested that evidence in support of post-spawn survival could be taken directly from the occurrences of females with post-spawn ovaries. As detailed in Chapter 7, we dissected and internally examined the ovarian development of approximately 1,000 female Giant Mud Crabs from multiple Queensland locations yet found only a handful of females that displayed ovary characteristics consistent with the description of post-spawn. Size-at-female-maturity, examined and reported upon in Chapter 7, indicated that most mature females were in their first mature intermoult, with few in their 2nd or 3rd mature intermoult. These multiple lines of evidence led us to concur with others (e.g., Hewitt *et al.* 2022b) that spawning incurs high natural mortality rates for mature females (90% or greater), and should be accounted for in stock assessment, with application of higher natural mortality rates for mature females than mature males.

Chapter 6. Population biology of Giant Mud Crabs in Queensland

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Introduction

Key sources of empirically-based, wild-capture research on the regional population biology of Giant Mud Crabs in Queensland are Heasman (1980), Hyland *et al.* (1984), the previous monitoring programs by Fisheries Queensland (Jebreen *et al.* 2008) and the current annual monitoring by the Gladstone Healthy Harbour Partnership (Flint *et al.* 2017; 2021).

Analysis of Fisheries Queensland monitoring data suggested there were differences in the size structure of Giant Mud Crab populations between regions within Queensland (Grubert and Lee 2013). This is consistent with anecdotal reports from fishers. However, while the size of Giant Mud Crabs may differ between regions, Robins *et al.* (2024) found limited differences in their morphometrics i.e., carapace width to carapace height to carapace length. The size-sex spatial habitat use, and variable catchability suggests that Giant Mud Crab populations operate at a much greater spatial scale than that at which most catch programs operate, either research sampling or individual commercial fishery operations.

Previously, the most spatially extensive sampling program in Queensland had been the Fisheries Queensland Giant Mud Crab monitoring program. A review of this program recommended within-year replicated sampling to better understand the seasonal catch patterns in within and between regions (Webley 2005). Other jurisdictions have noted sinusoidal patterns in the mean monthly size of commercially harvested Giant Mud Crabs (Grubert *et al.* 2013). Whilst relatively easy to sample individuals, Giant Mud Crabs are challenging to sample sufficiently in order to robustly quantify their population biology (Heasman 1980; Knuckey 1999; Hay *et al.* 2005).

Notwithstanding this challenge, the current research aimed to quantify key biological parameters and population dynamics of Giant Mud Crabs in regions of Queensland – east coast and Gulf of Carpentaria - using the available project resources (i.e., staff resources and budget). As detailed in Chapter 2 (Sampling methods), to sample across such large areas, we used a combination of fishery-independent and fishery-dependent sampling to acquire data and gain insight as to whether there was strong evidence to indicate significant regional differences in the biology of Giant Mud Crabs that should be accounted for in the assessment and management of this species. The acquired data has been analysed to provide insight into the following areas, which are of relevance to either stock assessment, management or issues consistently raised by stakeholders:

- Regional reproductive parameters - size-at-maturity, seasonality of reproduction (including mating if possible), insemination rates of mature females (confirmed by laboratory examination).
- Regional growth - size distributions, asymptotic maximum size ($L_{infinity}$) for male and females, length frequencies over time to assess their usefulness in analysis by modal progression to estimate growth rates of cohorts in the absence of an effective tag-recapture program (see Chapter 4).
- Sex ratios - below and above the minimum legal size.

Qualitative assessment of insemination rates was conducted to address the perception by some stakeholders that large, mature female Giant Mud Crabs could not be mated by the available males. The reasoning behind this perception is that there are insufficient large males to be able to cradle, mate and inseminate large females. While there is evidence of size-assortative mating in other species of *Scylla* (Fazhan *et al.* 2017), no assessment has been made of whether Queensland's male only harvest policy has led to sperm limitation.

Methods

Sample acquisition

Samples were drawn from the fishery-independent and fishery-dependent sampling (see Chapter 2) and were included depending on whether pot selectivity (unvented or vented and the size of escape vent) was likely to significantly affect the metric of interest. Analyses were also conducted for all regions pooled and at regional levels where sample sizes were sufficient.

Laboratory processing

A sub-set of crabs were retained for detailed examination in the laboratory. In females, this was to qualitatively assess ovarian development and insemination. Ovarian development was assessed into one of six stages based on macroscopic features (Table 14). Insemination was macroscopically assessed based on the presence of spermatophores in either of the paired spermatheca. When present, the occurrence of sperm plugs was noted.

Table 14. Ovarian development stages of Giant Mud Crabs adapted from Quinitio et al. (2007) and Islam et al. (2010).

Stage	Descriptor	Macroscopic characteristics
A	immature	ovary translucent (beige), thin (<3 mm in width), ribbon-like in structure
B	mature, but undeveloped	ovary white to cream, still thin and ribbon-like in structure
C	mature, & developing	ovary shades of yellow to orange, wider than 3 mm, occupies less than 20% of the body cavity
D	mature, developed	ovary yellow to orange, wider than 10 mm, occupies between 20 and 80% of the body cavity
E	mature	ovary yellow to orange, wider than 10 mm, occupies greater than 80% of the body cavity, individual eggs visible when ovary is smeared
	mature with advanced development	as above and the ovary extends into the abdominal flap, visible externally through the transparent membrane at the junction of the first abdominal segment and the ventral carapace
Post spawn	mature, previously spawned	ovary similar to stage C, coloured (yellow to orange), with flecks or speckled appearance, flaccid

The following data were also recorded: source, location, date of capture, weight (only crabs with all limbs intact), carapace width, notch width, carapace length, carapace height, female abdominal flap shape, female abdominal flap width, maximum width of sixth ventral thoracic segment in females, pleopod length and width, crusher claw length, crusher claw height and side, and moult stage (Table 15).

Up to 20 females were retained from sampling events in south-east Queensland that occurred between October 2021 and March 2023. This region had the greatest temporal coverage of samples retained for ovarian development. In other locations, ovarian development and insemination assessment were ad hoc, except for the south-east Gulf of Carpentaria, where up to 20 females were retained by a local commercial operator from commercial crabbing activities around each new and full moon (under delegation of GFP 210183) and shipped to Ecosciences Precinct for laboratory processing and assessment.

Initially, V-shaped, intermediate and U-shaped abdominal flap females (Figure 5, Chapter 1) were retained and dissected to check for insemination. It became apparent that V-flap females were immature, as were intermediate females, with none of these females having developed gonads or containing spermatophores (i.e., inseminated). This is consistent with reports for *Scylla paramamosain* (Islam *et al.* 2010). To minimise unnecessary mortality, after June 2022, only U-shaped abdominal flap female Giant Mud Crabs were retained for laboratory processing.

Table 15. Moult stage criteria of juvenile, adolescent and mature Giant Mud Crabs (adapted from Heasman 1980).

Stage	Name	Drach's 1959 Scheme	Diagnostic features general
I	ecdysis (moult)	E	active and passive phases of exuviation, initiation marked by cleavage of the ecdysial suture, termination marked by total extraction from exuvia
II & III	soft shelled	A_1, A_2	A_1 – taut unwrinkled integument (end of rapid water uptake) [1]. A_2 – hardening of the carpus and propodus of the chelae [1]
IV	paper shelled	B_1 & B_2	peripods (limbs) still very flexible [1].
V, VI	hard shelled to	C_1, C_2, C_3	C_1 – Abdominal thoracic sternites translucent, with bluish tinge [1] C_2 – Thoracic sternites partially translucent, with pale bluish tinge [1] C_3 - Thoracic sternites not fully opaque, very faint bluish tinge [1]
VII, VIII	early peeler	C_4 – D_1	sternites fully opaque, teeth of chelae usually display some erosion little, if any, development of limb buds where limbs absent [1]
IX	advanced peeler	D_2 – D_3	teeth of chelae usually highly eroded, limb buds, when present moderately to highly developed, separation of new pigmented epicuticle from old integument, demineralization of ecdysial line evident in advanced stage
X	buster	D_4	open ecdysial sutures

[1] principle diagnostic feature of Heasman (1980)

Analyses

Reproduction

Size-at-maturity

For males, size-at-maturity was based on the claw height to carapace width ratios (CH:CW) in order to determine the size-frequency of adolescent males (i.e., small-clawed indicative of physiologically mature but functionally immature) from the fully mature males (i.e., large-clawed indicative of physiologically and functionally mature, see Chapter 1). Analysis was conducted in RStudio, using the Bhattacharya function in the package TropFishR. This analysis uses the frequency distribution of cohorts in the observed size-frequency distribution to resolve its Gaussian components (https://rdrr.io/cran/TropFishR/man/Bhattacharya.html), with the intersection of the distributions determining the critical CH:CW ratio above which (relatively) large-clawed individuals are classified as adult and those below as adolescent (Knuckey 1996).

The distributions of size-at-maturity (adolescent from functional adults) were assessed using a binomial general linear model (GLM) to estimate the size at which 50% of males were functionally mature. Logistic curves fitted to percent mature per size class (e.g., Knuckey 1996; Haddon *et al.* 2005; Islam and Kurokura 2013) and probit analysis (e.g., Roberston and Kruger 1994; Overton and Macintosh 2002; Ali *et al.* 2020) were considered but deemed to not make full use of the available data given uneven sample numbers per size-class and between locations. A model using only main effects (i.e., carapace width and location) was compared against a model with an interaction. Results were compared against the size-frequency distribution of males that were known to be functionally mature (i.e., presence of mating scars).

For females, abdominal-flap shape was used as the basis for size-at maturity. Similar to the analyses for males, the size at which 50% of females were mature was assessed using binomial GLM.

Growth

$L_{infinity}$

Asymptotic maximum size ($L_{infinity}$) is a parameter used in modelling growth. We used the average size of the largest 1% of male and female Giant Mud Crabs from a location as an initial estimate of regional average maximum size ($L_{infinity}$) as per Knuckey (1999).

Size distributions

Size distributions were collated for males and females for all locations pooled across Queensland and locations within each region, where sample sizes were sufficient. Previously, Giant Mud Crabs have been reported to have a slight bimodal distribution for females, and a normal distribution for males that peaked at 130-140 mm CW, with a sharp decline above 150 mm (Jebreen *et al.* 2008). We expected similar results, except when sampling from protected areas, where a greater frequency of males larger than 150 mm CW was expected (Pillans *et al.* 2005).

Size frequencies over time

The project initially proposed to quantitatively estimate growth from tag-recapture information from the application of t-bar tags to wild Giant Mud Crabs, as previous studies had done (Hill 1975; Hyland *et al.* 1984; Robertson and Piper 1991; Knuckey 1999; Hay and Calogeras 2000; Moser *et al.* 2002; Butcher 2004; Pillans *et al.* 2005; Meynecke *et al.* 2015). However, the potentially high mortality rates from t-bar tags during moulting (see Chapter 4) and the decision to not t-bar tag wild crabs meant growth rates had to be inferred by other means. Analysis of relative size-frequencies for modal progression to estimate growth was explored using the available catch data. Size-frequencies of male and female Giant Mud Crabs were extracted from the project's database, with consideration of the inclusion/exclusion of spatial/temporal factors, or pots with or without escape vents, depending on the parameter of interest, whilst aiming to maximise the retention of data in analyses.

Males

Where sample sizes were sufficient, relative size-frequency distributions were generated for all males in locations open to fishing, and for locations closed to fishing. Estimates were also made for GC1 and EC1 locations open to fishing, grouped by mating scars and unscarred.

Growth in crustaceans can be estimated by modal progression analysis, which requires identification of modes in the size-frequency distributions over time (i.e., cohorts through subjective visual identification), so that ' cohorts' can be linked over sequential sampling events. The differences in modal size of 'cohorts' provides an estimate of growth over time. Bhattacharya's method is then used to resolve the observed size-frequency distribution into its Gaussian components, and thus provide estimates of 'cohort' growth (Haywood and Staples 1993). Previous research suggested male Giant Mud Crab have multi-modal size-frequencies with modes at 121 mm, 142 mm and 165 mm CW based on growth phase allocations (Heasman 1980), with the moult increment between these modes approximately aligning with the average proportional increase in carapace width for males (Figure 6, Chapter 1). Therefore, in theory, size-frequency data collected with sufficient spatial coverage and temporal replication should support the analysis of growth in Giant Mud Crabs by modal progression.

The south-east region of the Queensland east coast (i.e., Logan River, southern Moreton Bay, Marine National Park 28) had the most temporal replicate sampling: 34 events between November 2021 and March 2024 (Table 5, Chapter 2) offering the best opportunity to detect modal progression. Fifty-nine days of sampling occurred in this region, 11 of which were trialling escape vents. Size-frequencies recorded from non-vented pots (as controls) and pots fitted with small escape vents (75 x 60 mm - which are effective for crabs less than 90 mm CW, Robins *et al.* 2024) were included in the size-frequency data. A variety of size-class aggregations (i.e., 1 mm, 2 mm, 5 mm, 10 mm, 20 mm) and temporal aggregations (i.e., sample event, monthly, growth season) were trialled with the aim of identifying modes in the relative size-frequency distributions.

Females

As a preliminary analysis, relative size-frequency per 5 mm CW size-class were generated for all females, grouped by abdominal flap shape (i.e., V-shape, intermediate or U-shape) from the south-east region of the Queensland east coast, all sampling dates, all locations (i.e., open or closed) and pot types (non-vented and small vents). As noted in the size-at-maturity analysis (see results below), there were clear differences in the relative size-distributions of female Giant Mud Crabs with different abdominal flap shapes, something which was not widely published in previous studies, potentially because of small sample sizes of the immature flap types. Relative size-frequency distributions within each abdominal flap type were generated and analysed by non-linear regression (curve type Gaussian, separate curves) fitted in Genstat (2024) with the aim to identify cohort modes and gain insight growth by modal progression.

Sex ratios

Heasman (1980) noted that sex ratio of small juvenile crabs was approximately 1:1 (male:female), suggesting initial parity in sex ratio. Gender proportions have been suggested as an indicator of fishing pressure (Heasman 1980; Williams and Hill 1982; Alberts-Hubatsch *et al.* 2016), but once maturity is reached, require the assumption that there is no sex bias in natural mortality. There is strong evidence to suggest that this is unlikely to be true, with several authors suggesting high natural mortality of mature females associated with spawning migrations (Heasman *et al.* 1985; Hewitt *et al.* 2022b), which results from the current research provide further supporting evidence (Chapter 5).

Removal of males above legal size through fishing will reduce the abundance of males of ≥150 mm CW, with observed sharp declines in relative abundance of males >150 mm CW considered to be indicative high fishing mortality (e.g., Jebreen *et al.* 2008). However, we have little understanding of the consequence of this reduced abundance of large males for either population dynamics or the ecosystem in which Giant Mud Crabs play a role (Alberts-Hubatsch *et al.* 2016; Flint *et al.* 2021).

Sex ratios were considered using a size-sex ratio (Equation 1) and sex ratio (Equation 2). The size-sex ratio standardises the sex ratio for crabs above minimum legal size by the sex ratio of crabs below minimum legal size (and thus not exposed to fishing mortality), on the assumption that a similar ratio should prevail in an unfished population (Flint *et al.* 2017).

$$\text{Size-sex ratio} = \frac{males_{\geq 150\ mm}/females_{\geq 150\ mm}}{males_{<150\ mm}/females_{<150\ mm}} \qquad \text{Equation 1}$$

$$\text{Sex ratio} = \frac{males_{\geq 150\ mm}}{females_{\geq 150\ mm}} \qquad \text{Equation 2}$$

We also considered sex ratios in relation to size-at-maturity of males and females. As noted, size-at-maturity is more complex to estimate in males (where fishing removes large males and there is physiological and functional maturity) than in females where abdominal flap morphology is a simple external indicator of maturity.

A sex ratio indicator that includes maturity status (e.g., functional males, intermediate or U-shaped abdominal flap females) may be more informative of relative abundance before and after females reach maturity given it considers size-at-maturity, and thus changes in natural mortality associated with the spawning migration rather than the size at which fishing mortality affects male abundance. Like other metrics the size-sex ratios assumes that sampled catch is indicative of the whole population (which is unlikely), similarity in sex-specific natural mortality rates throughout life (already discussed) and seasonality variability in growth (and thus abundance-at-size) is the same for males and females. As noted in Chapter 1 (growth section), moult increments of males and females are likely to diverge around the size-at-maturity. Males divert energy into allometric claw growth as well as carapace width, presumably as large claws potentially confer a mating advantage. Females divert energy primarily into an increase in carapace width, with no disproportionate increase in claw size, presumably as a larger body and associated larger ovarian tissue and egg-mass carrying capacity of the abdominal flap confers a reproductive advantage.

Assumptions and limitations

Results presented in the current chapter were based on the sampling achieved and the assumption that these samples were representative of the 'population' of Giant Mud Crabs at the spatial scale analysed. There is known spatial and temporal variation in the catch of male and female Giant Mud Crabs that is likely a consequence of their complex behavioural response to a multitude of factors. Almost all fishery-dependent data was collected from pots fitted with an escape vent – noting a vast diversity in escape vent size and placement of commercial crab pots (see Robins *et al.* 2024). Regional data analysis and interpretation is limited by this condition. However, the regional fishery-dependent data analyses and interpretation still provided insight into the regional population biology of Giant Mud Crabs, as escape vents are never 100% effective at excluding all crabs smaller than their dimension.

Results

Crabs infected with 'Loxy' aka 'hermaphrodites'

Loxothylacus ihlei, (aka Loxy), is a Rhizocephalan parasite that infects Giant Mud Crabs. Reported infection rates in Australia average approximately 2% but can be up to 7% (Knuckey 1995). During field sampling, 20,573 Giant Mud Crabs were caught, inspected, measured and mostly released. Loxy was observed on a total of 23 individuals sampled from Hinchinbrook Channel, Weipa, Mapoon and Stanage Bay/Broadsound. All 12 infected males (96-164 mm CW) had a feminised abdominal flap and male reproductive pleopods absent (Figure 41). All 11 infected females (87-138 mm CW) had a U-shaped abdominal flap despite several being of small size, and reproductive pleopods (i.e., 'feathers') on all these females were atrophied or absent. Infected males (i.e., having male-shaped carapace and claws, but with a female-shape abdominal flap) are often referred to colloquially as 'hermaphrodites'. However, these individuals are not true hermaphrodites (i.e., having male and female reproductive organs either simultaneously or sequentially) but rather individuals infected with Loxy and showing associated symptoms (atrophied reproductive organs, feminised abdominal flap in males). All individuals showing visible symptoms of Loxy were excluded from further analyses of biological parameters, as they are not capable of functionally contributing to the reproduction of the population.

Figure 41. Giant Mud Crab showing externally visible symptoms of infection with Loxothylacus ihlei - male with female shaped U-abdominal flap and reproductive body of the parasite. Note the absence of male reproductive appendages. The white sac on the abdominal flap is the reproductive 'mass' of the parasite and can range in colour from white to cream to pale brown.

Reproduction

Between October 2021 and March 2024, 994 females (and 41 males) were assessed for reproductive biology. Greatest sample size and temporal coverage occurred for south-east regions of the Queensland east coast and Gulf of Carpentaria (Table 16).

Table 16. Number of Giant Mud Crab assessed macroscopically for gonad development and insemination in females.

Region	Males	Females		
		V-shape flap	intermediate	U-shape flap
north Gulf of Carpentaria				40
south-east Gulf of Carpentaria			14	407
central Queensland east coast	4		5	82
south Queensland east coast				14
south-east Queensland east coast	38	5	29	398

Seasonality of reproduction

For the south-east region of the Queensland east coast, retained females with advanced ovarian development (i.e., occupying >80% of the body cavity, stage-E) were observed between September and May, with pulses in September and February (Figure 42). This compares with the results of Heasman (1980), who reported that spawning in this region began in spring, peaked in early summer and ended during autumn (n = 382 females sourced from commercial fishers).

For the south-east region of the Gulf of Carpentaria, females with advanced ovarian development were observed in all months with pulses in July, November and April – noting that no samples were acquired in February due to flooding (Figure 42). This compares with the results of Knuckey (1999) who reported a major peak in gonad condition (via microscopic assessment) of female Giant Mud Crabs in the western Gulf of Carpentaria between November and January, but with secondary peaks mid-year.

In the north region of the Gulf of Carpentaria, ovarian development was examined for 40 individuals in September and October 2023, with 53% having stage-D ovaries, and 5% having stage-E ovaries.

Notwithstanding the relatively small sample size, advanced ovarian development was observed in females sampled from the central region of the Queensland east coast (Eurimbula to Stanage Bay) in June, March, April and May.

Complementary to laboratory examination of ovarian development, was the noting of females caught and released during field sampling with ovary extending into the abdominal flap (see Figure 30) - noted from March 2022 onwards. Of the 5,232 mature females (i.e., U-shaped abdominal flap) examined in the field between March 2022 and March 2024, 8.8% were noted with ovary material visible externally in the ventral part of the abdominal flap, indicative of advanced stage-E. Seasonal patterning of these field observations were somewhat similar to the laboratory processed results (Figure 42).

In the north region (i.e., Hinchinbrook), females assessed in the field with advanced ovarian development occurred in 13-25% of individuals during opportunistic fishery-dependent sampling events in July, December and October, 6% in June (although small sample size, n = 47), with none were recorded in May. The prevalence of females with advanced ovarian development in late winter as well as in spring and summer in the north region of the Queensland east coast is suggestive of year-round spawning. Further evidence supporting 'year-round' reproduction in north Queensland is the seasonality of reported egg-bearing females (Table 12) as well as the year-around anecdotal reports of small crablets (i.e., 15-30 mm CW). Photographic evidence of these crablets was sent to the PI of the current research project in all months of the year by commercial crabbers in the north region, confirming species identification of these crablets as *Scylla serrata* and not other mangrove/estuarine associated brachyuran crabs (e.g., *Portunus* or *Graspis* etc).

Figure 42. Seasonality of ovarian development (stages-B to -E as defined in Table 14), assessed by laboratory dissection of mature female Giant Mud Crabs.(a) south-east region of the Queensland east coast(n = 389). (b) south-east region of the Gulf of Carpentaria (n = 407). (c) central region of the Queensland east coast (n = 82).

Figure 43. Photographic evidence of small juvenile Giant Mud Crabs (<30 mm CW) reported by commercial fishers showing the key features identifying these crablets as Scylla serrata i.e., colour and shape of the claws, shape of the dorsal carapace including spines not excessive for the carapace width. Photo credit: C. Perkins.

Post-spawn

Female Giant Mud Crabs with ovaries showing post-spawn characteristics were rare, despite this being a focus in laboratory processed individuals. Of the 941 females with U-shaped abdominal flaps that were macroscopically assessed for ovary condition, eight crabs (i.e., <1%) had ovaries with characteristics suggestive of post-spawn (Figure 44). This is a much lower rate than the 15% reported by Heasman *et al.* (1985), who sampled in the same general location, but with a sample size of 96 females. Knuckey (1999) did not report the frequency of post-spawn females, although his GSI results indicate that some were encountered in the 75 mature females examined from the Adelaide River, NT.

Figure 44. Dissected female Giant Mud Crab (206 mm CW, sampled from Great Sandy Strait, December 2021) with an ovary showing signs consistent with descriptions of post-spawn i.e., ovary yellow to orange, wider than 10 mm, and flecked or speckled in appearance. The opaque white tissue circled in red in the right image are spermatophores in the spermatheca.

Insemination

Five V-shaped abdominal flap female Giant Mud Crabs (79-105 mm CW) were dissected and macroscopically assessed for reproductive condition. All were 'clipped' (Knuckey 1999), had immature stage-A ovaries, no development of the spermatheca and no spermatophores present.

Forty-eight intermediate-shaped abdominal flap females (105-160 mm CW) were macroscopically assessed for reproductive condition. The larger individuals were caught in the south-east region of the Gulf of Carpentaria (i.e., Karumba) and Stanage Bay – areas renowned for large male Giant Mud Crabs. Thirty-eight of intermediate females were clipped (i.e., 79%), with most having immature (stage-A) ovaries. Three had ovaries classed as stage-B (i.e., mature but undeveloped), with these individuals being assessed as late inter-moult (i.e., moult cycle stage VII or VIII). The remaining ten intermediate females had unclipped abdominal flaps, with 50% having immature (stage-A) ovaries and 50% mature but undeveloped (stage-B). Development of the spermatheca ranged from non-existent (i.e., straplike and translucent) to quite developed (i.e., pouch-like and translucent pink) but none contained spermatophores (i.e., inseminated).

Nine-hundred and twenty-seven U-shaped abdominal flap females (128-213 mm CW) were macroscopically assessed for reproductive condition. All were unclipped. Six (128-152 mm CW) had immature (stage-A) ovaries (i.e., thin, straplike and translucent), 81 had stage-B ovaries, 279 had stage-C ovaries, 391 had stage-D ovaries and 170 had stage-E. Thirteen individuals could not be assessed due to decomposition during transport and storage.

Of the mature females examined, greater than 98% had spermatophores in their spermatheca, ranging from recently inseminated (evidenced by enlarged spermatheca and the presence of a sperm plug) to barely visible spermatophores, sometimes only present on one side. In the remaining individuals (i.e., <2%), no evidence of spermatophores could be determined from macroscopic inspection and occurred across a broad range of sizes (i.e., not biased towards larger individuals). All mature females above 185 mm CW that were dissected (n = 62) were inseminated. This included individuals greater than 200 mm CW from south-east Queensland, south-east Gulf of Carpentaria, Stanage Bay/Broadsound and Great Sandy Strait.

Insemination results for Queensland waters were consistent with those reported for the NT, where 92% of mature females were inseminated (Knuckey 1990). Results from the current research provide no evidence in support of the perception that 'large' female Giant Mud Crabs are unable to be mated by the available males and thus unable to contribute to reproduction and spawning. The mature females examined for insemination included approximately 800 individuals from two locations with high fishing mortality (Table 16) – the south-east region of the Queensland east coast (Logan River and southern Moreton Bay) and the south-east region of the Gulf of Carpentaria (Karumba). We found no evidence that the current size and sex-specific management arrangements in Queensland are detrimental to the mating or likelihood of successful spawning success of Giant Mud Crabs in Queensland.

Morphometrics indicative of growth phase

Flap width - females

Pooled across all regions, the relationship between abdominal flap width and carapace width was similar for female Giant Mud Crabs in the current study to that reported by Knuckey (1990).

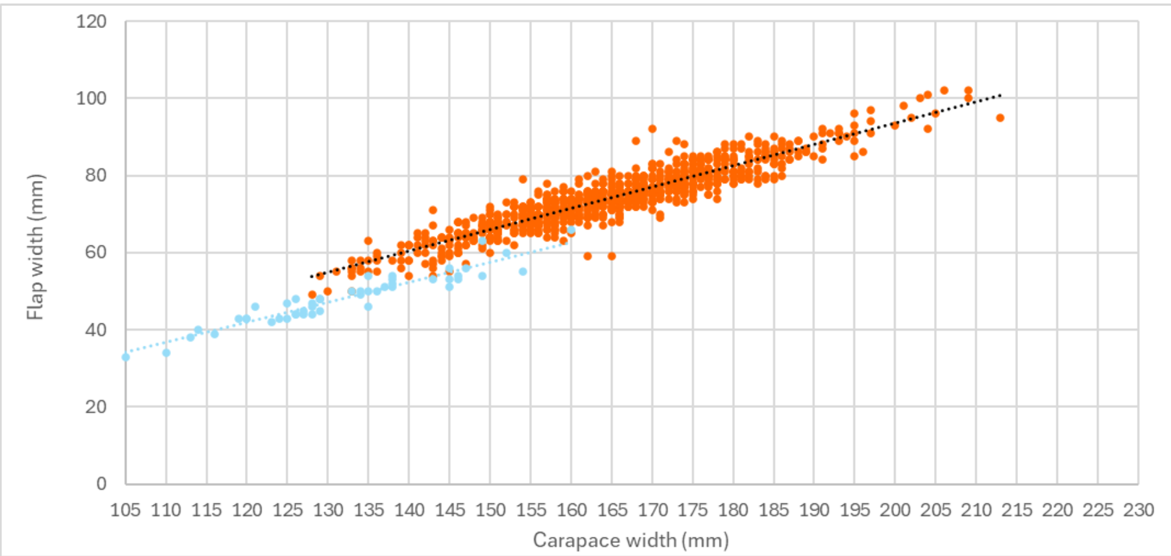

*Figure 45. Abdominal flap width against carapace width for female Giant Mud Crabs, all regions pooled for mature (orange markers, black regression line, flap width= 0.5524*CW – 16.985, R^2 = 0.85, n = 938) and immature stages (blue markers, blue regression line, flap width = 0.5203*CW – 20.471, R^2 = 0.90, n = 48).*

Pleopod dimension

Another morphometric dimension measured in laboratory processed crabs was the length and width of the swimmeret (i.e., 4^{th} pleopod). Pooled across all regions, the relationship between the area of the pleopod (length by width) increased with carapace width, although for females greater than 185 mm CW, there was a noticeable change in the relationship (circled in Figure 46). In previous research, changes in the relationship between carapace width and morphometric dimension has been used to infer 1st, 2nd or 3rd maturity intermoult. If so, this would suggest that females in the order of 190 mm CW or greater may be in their 2nd or 3rd maturity intermoult.

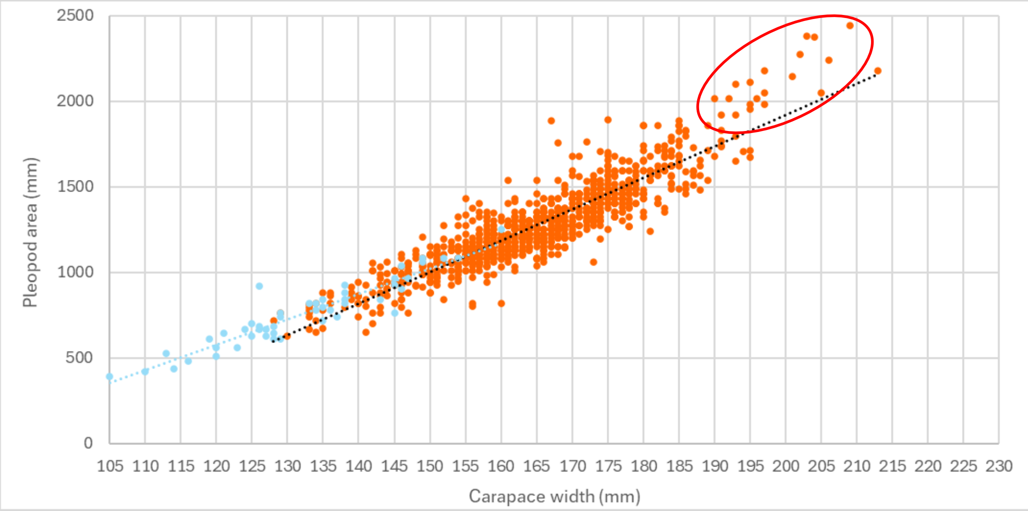

Figure 46. Swimmeret pleopod area (length by width) against carapace width for female Giant Mud Crabs, all regions pooled for mature (orange markers, black regression line) and immature stages (blue markers and blue regression line), noting deviation from linear relationship for females >185 mm CW, potentially indicative of 2nd or 3rd maturity intermoult (circled in red).

Size-at-maturity

Males

Pooled across regions (including locations closed to fishing), 14,004 male Giant Mud Crabs were measured between November 2021 and March 2024, based on fishery-dependent and fishery-independent samples combined. Males ranged in size from 61 to 200 mm CW, with 60% smaller and 40% greater than the Queensland minimum legal size of 150 mm CW (Figure 47).

Mating scars, indicative of functional maturity, were noted on 3,194 males. The smallest scarred male was 107 mm CW, the largest 200 mm CW, with the mean size of scarred males being 152.7 mm CW (± 0.21 mm s.e.). Of the scarred males, approximately 50% were below 150 mm CW (i.e., Queensland minimum legal size), and the peak modal size-class of scarred males being 145-149 mm CW (Figure 47).

Crusher claw height was measured for 11,709 males. Individuals missing a crusher claw, or when it was an obvious replacement claw (i.e., atypically smaller than the cutter claw) were not measured for claw height, or when time constraints limited field measurements. ClawHt:CW ratio was measured from 2,790 scarred males and ranged from 0.24 to 0.46, with the smallest value (i.e., 0.24) recorded on crabs ranging in size from 141 to 153 mm CW. The smallest scarred male observed was a 107 mm CW crabs, with a ClawHt:CW ratio of 0.36 captured in the Logan River, Moreton Bay. ClawHt:CW ratio was measured from 8,919 unscarred males and ranged from 0.17 to 0.56. Unscarred males include immature males, adolescent males (i.e., physiologically mature but not functionally mature) and recently moulted male adult that are physiologically mature and functionally mature but are yet to participate in mating for a number of reasons (e.g., hardness of shell, mating opportunity).

The ClawHt:CW frequency distribution was plotted to determine if there was evidence of a bimodality that would indicate a size-based separation of adolescents from adults, as found by Knuckey (1996). The overall distribution of ClawHt:CW ratio was bimodal with modes at 0.31-0.32 and 0.38-0.39 (Figure 47). The increase in the proportion of scarred males with a ClawHt:CW ratio of 0.35 or greater suggested further analysis may provide a useful proxy of functional maturity. Analysis of ClawHt:CW frequency data (Bhattacharya function in TropfishR) yielded two distributions (Figure 47). Cohort-1 (small-clawed adolescent males) with mean ClawHt:CW of 0.310 (± 0.0196 s.d.) and cohort-2 (large-clawed functionally mature adults) with mean ClawHt:CW of 0.386 (± 0.0214 s.d.). The distributions intersected at 0.3475 (i.e., mid-point of the 0.345-0.350 size class) and this was assumed indicative of the critical value separating small-clawed adolescents from large-clawed functionally mature adults, as per Knuckey (1996). This method of analysis incurs some level of misclassification, which theoretically was approximately 3%, based on the area common under the distributions - similar to that reported by Knuckey (1996). The assignment of adolescent or adult, based on a critical ClawHt:CW ratio of 0.345, was checked against the size-frequency distributions of males with and without mating scars, on the assumption that mating scars are indicative of functional maturity. Overall, mating scars were present on 20% of crabs classified as adolescent based on their ClawHt:CW being below 0.3475. Essentially, these individuals were functionally mature despite being small-clawed males. Correct assignment of functional maturity for scarred males decreased with decreasing carapace width, being greater than 90% correct for males greater than 145-149 mm CW, 79% correct for males 145-149 mm CW, 72% correct for males 140-145 mm CW, 53% correct for males 135-139 mm CW, and less than 30% correct for scarred males less than 135 mm CW.

Size-at-maturity was estimated using a binomial GLM based on application of the critical ClawHt:CW vale of 0.345 derived above. The fitted binomial GLMs of functional maturity with size (i.e., carapace width) are presented (Figure 47). Accumulated analysis of deviance indicated that the inclusion of an interaction term between carapace width and region significantly improved model fit (χ^2 <0.001). Therefore, parameter estimates (Table 17) and predicted mean size-at-maturity ($CW_{50\%Male}$) were based on the full model (i.e., carapace width + region + carapace width*region).

For all regions pooled, the size at 50% male maturity ($CW_{50\%Male}$) was 143.5 mm CW, but was significantly different between regions. In the Townsville/Burdekin and Weipa regions, $CW_{50\%Male}$ was 124 mm and 129 mm respectively, whilst in the Stanage/Broadsound and Great Sandy Strait regions, $CW_{50\%Male}$ was 156 mm and 152 mm respectively. The differences in $CW_{50\%Male}$ between regions will be partly due to true differences between regional populations and partly due to sampling artifacts. The critical value of ClawHt:CW and $CW_{50\%Male}$ results were dependent on the number and size diversity of Giant Mud Crabs sampled across and within regions. During field sampling, project staff noted the size differences in regional Giant Mud Crab populations that is often commented upon by commercial crabbers and the size-sex spatial habitat use suggested by Jebreen *et al.* (2008). For example, the Stanage Bay area in Queensland is renowned for its catch of large male Giant Mud Crabs. It is possible that in areas like Stanage Bay, only part of the crab population is available for capture in the locations where crab pots can be fished, with the remainder of the population unavailable to capture (i.e., remains inside the extensive mangrove habitat).

In most regions, the smallest males with mating scars (considered indicative of functional maturity) were 130 mm CW or greater (Table 18), except for south-east Queensland and Mapoon, which had sampled extensively, both spatially and temporally during the current research project, as well as FRDC 2021-119 and TMSFB000012. There are no published reports of mating scars on male Giant Mud Crabs in Queensland with which we can compare the above results. The smallest male Giant Mud Crab in the Northern Territory with mating scars was about 125 mm CW, which Knuckey (1996) considered as an adolescent rather than a functional adult. Both Knuckey (1996) and Heasman (1980) considered that while adolescent males could mate, they likely only contributed to a small proportion of mating and reproductive outcomes.

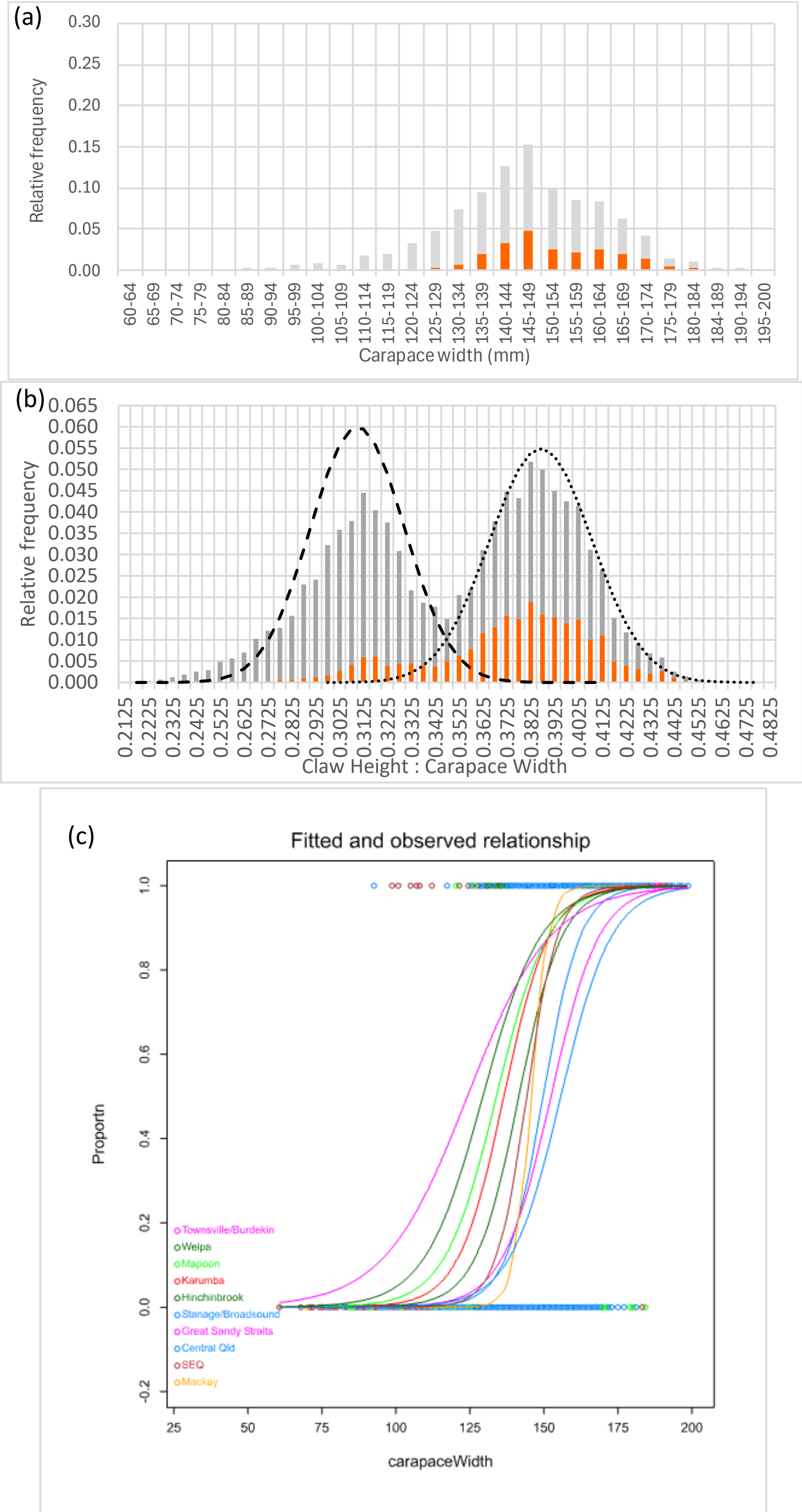

Figure 47. Maturity in male Giant Mud Crabs. Scarred males indicated by orange bars. Unscarred males indicated by grey bars. (a) relative frequency at size (CW) all regions pooled. (b) relative frequency crusher Claw Height:Carapace Width ratio (n = 11,709). Dotted lines are the normal distributions fitted in TropFishR using Bhattacharya function. Intersection of the distributions indicates the critical value for assessing functional maturity for all regions pooled. (c) fitted binomial General Linear Model showing predicted proportion functionally mature based on carapace width and region as main effects and an interaction effect.

Table 17. Parameter outputs from the binomial General Linear Model (main effects and interaction of carapace width and region) estimating size-at-maturity for male Giant Mud Crabs in Queensland. Significant effects bolded.

	Estimate	Std. Error.	t(*)	t pr.	antilog of estimate
Constant	**-24.50**	**1.380**	**-17.71**	**<0.001**	**2.282E-11**
Carapace Width	**0.16**	**0.009**	**18.00**	**<0.001**	**1.178**
Karumba	4.84	4.940	0.98	0.328	126.0
Weipa	**11.32**	**3.260**	**3.47**	**<0.001**	**82564**
Mapoon	**9.21**	**1.860**	**4.94**	**<0.001**	**9949**
Hinchinbrook	**5.18**	**2.230**	**2.32**	**0.020**	**177.2**
Townsville/Burdekin	**11.33**	**4.590**	**2.47**	**0.014**	**83019**
Mackay	-27.1	21.6	-1.25	0.211	*
Stanage/Broadsound	**6.38**	**2.980**	**2.14**	**0.033**	**589.1**
Great Sandy Strait	5.85	4.050	1.45	0.148	346.6
south-east Queensland	**-4.24**	**1.570**	**-2.70**	**0.007**	**0.014**
CW*Karumba	-0.02	0.033	-0.61	0.539	0.980
CW*Weipa	**-0.06**	**0.022**	**-2.78**	**0.005**	**0.940**
CW*Mapoon	**-0.05**	**0.012**	**-3.97**	**<0.001**	**0.952**
CW*Hinchinbrook	-0.03	0.015	-1.80	0.073	0.973
CW*Townsville/Burdekin	-0.06	0.032	-1.95	0.051	0.940
CW*Mackay	0.19	0.145	1.31	0.189	1.210
CW*Stanage/Broadsound	**-0.05**	**0.019**	**-2.46**	**0.014**	**0.954**
CW*Great Sandy Strait	-0.04	0.026	-1.58	0.114	0.960
CW*south-east Qld	**0.04**	**0.010**	**3.43**	**<0.001**	**1.036**

Table 18. Estimates of size-at-maturity for male Giant Mud Crabs in Queensland.

	Size range All males CW (mm)	Size range scarred males CW (mm)	ClawHt:CW range scarred males	Estimated $CW_{50\%Male}$ (mm)	Estimated % mature @150 mm CW (± s.e.)
All regions pooled	61 - 200 (n = 13,992)	107 - 200 (n = 3,194)	0.24 - 0.46 (n = 2,790)	143.5	59 (± 0.6)
Karumba	107 - 200 (n = 475)	138 - 200 (n = 123)	0.32 - 0.42 (n = 74)	137.2	86 (± 4)
Weipa	135 -184 (n = 220)	135 - 176 (n = 178)	0.28 - 0.45 (n = 192)	129.4	89 (± 2)
Mapoon	77 - 190 (n = 2,152)	120 - 181 (n = 576)	0.24 - 0.44 (n = 467)	134.0	86 (± 1)
Hinchinbrook	105 - 185 (n = 937)	130 - 181 (n = 331)	0.24 - 0.46 (n = 313)	141.6	76 (± 2)
Townsville/Burdekin	101 - 173 (n = 306)	132 - 173 (n = 95)	0.30 - 0.40 (n = 74)	124.4	86 (± 3)
Mackay	70 - 190 (n = 57)	144 - 184 (n = 9)	0.36 - 0.40 (n = 9)	145.7	82 (± 13)
Stanage/Broadsound	109 - 199 (n = 169)	139 - 190 (n = 2)	0.39 - 0.41 (n = 2)	155.8	34 (± 6)
Central Qld	72 - 200 (n = 1,932)	130 - 194 (n = 538)	0.24 - 0.52 (n = 1,380)	149.8	51 (± 2)
Great Sandy Strait	135 - 190 (n = 111)	139 - 179 (n = 16)	0.29 - 0.41 (n = 15)	152.4	43 (± 7)
south-east Qld	61 - 189 (n = 7,622)	107 - 189 (n = 1,310)	0.24 - 0.45 (n = 1,213)	144.3	75 (± 1)

The above analysis has provided the first estimates of regional variability in size-at-maturity for male Giant Mud Crabs in Queensland. Our estimate of $CW_{50\%Male}$ for south-east Queensland (i.e., 144.3 mm) is lower than the previous estimate by Heasman *et al.* (1985). Their estimate, 163 mm CW (± 12 mm) was based on 27 functionally mature males captured during courtship. The current analysis had a much larger sample size (i.e., 1,310 scarred males) acquired over a larger and more diverse area. Our estimated $CW_{50\%Male}$ for all regions pooled (i.e., 143.5 mm CW) is similar to estimates for the Northern Territory (i.e., 146 to 149 mm CW, Knuckey 1996).

Robustly estimating size-at-maturity for male Giant Mud Crabs is challenging because high fishing mortality in many areas removes functionally mature males before mating scars can develop. Thus, analyses in the current research were based on inference using Claw Height to Carapace width ratios (as per Knuckey 1996). Extensive field work (fishery-independent and fishery-dependent) identified to project staff that most sampling only covers a portion of the Giant Mud Crab population that is available to the capture in the sampling equipment, which in the current research was crab pots. Therefore, it is difficult to obtain population scale estimates of parameters such as size-at-maturity, unless sampling is extensive.

An alternate way of viewing the size-at-maturity results is to consider the percent of males estimated to be functionally mature at the Queensland minimum legal size of 150 mm CW. Across all regions pooled, an estimated 58% (± 1% s.e.) of male Giant Mud Crabs were functionally mature by 150 mm CW (Table 18). Overall, this result supports the current minimum legal size for males of 150 mm, as it is greater than the $CW_{50\%Male}$. However, in some regions (e.g. Stanage/Broadsound or Great Sandy Strait), the estimated a regional $CW_{50\%Male}$ was above 150 mm CW. This is most likely a sampling bias rather than a true difference in regional $CW_{50\%Male}$. If of concern, further sampling to confirm the $CW_{50\%Male}$ should occur in these regions.

Females

Pooled across regions, 6,094 female Giant Mud Crabs were measured between November 2021 and March 2024, based on fishery-dependent and fishery-independent samples combined. Determining the size-at-maturity for female Giant Mud Crabs was less challenging than for males, as female abdominal flap morphology (shape and colour) distinctively changes with the pubertal moult. This was reconfirmed in the laboratory dissections of the current research. Immature females with V-shaped abdominal flap ranged in size from 66 mm to 147 mm CW (mean 99.2 mm CW ± 0.88 s.e.). Immature females with an intermediate-shaped abdominal flap ranged in size from 94 mm to 156 mm CW (mean 126.8 mm CW ± 0.39 s.e.). Mature females with a U-shaped abdominal flap ranged in size from 116 mm to 230 mm CW (mean 160.3 mm CW ± 0.16 s.e.). Pooled across all regions, the data indicate a progression in modal size of females having different shaped abdominal flaps i.e., immature V-shaped, to immature intermediate-shaped to mature U-shaped flaps (Figure 48).

Size-at-maturity was estimated using a binomial GLM based on abdominal flap morphology, where V-shaped or intermediates were considered immature and U-shaped abdominal flaps were considered mature. Accumulated analysis of deviance indicated that the inclusion of an interaction term between carapace width and region significantly improved model fit (χ^2 = 0.010). Therefore, parameter estimates (Table 19) and predicted mean size-at-maturity (Table 20) were based on the full model (i.e., carapace width + region + carapace width*region), with the fitted binomial GLMs presented in Figure 48. For all regions pooled, the size at 50% female maturity ($CW_{50\%Female}$) was 136.3 mm CW, but did vary significantly between regions. Notwithstanding varying sample sizes between regions, the Townsville/Burdekin and Weipa regions had a $CW_{50\%Female}$ less than 130 mm CW, while Stanage/Broadsound and Great Sandy Strait had a $CW_{50\%Female}$ greater than 140 mm CW. Regional differences in $CW_{50\%Female}$ will be partly due to true differences between in regional populations and partly due to sampling artifacts. Like males, the $CW_{50\%Female}$ results were dependent on the number and diversity in size of females sampled across and within regions.

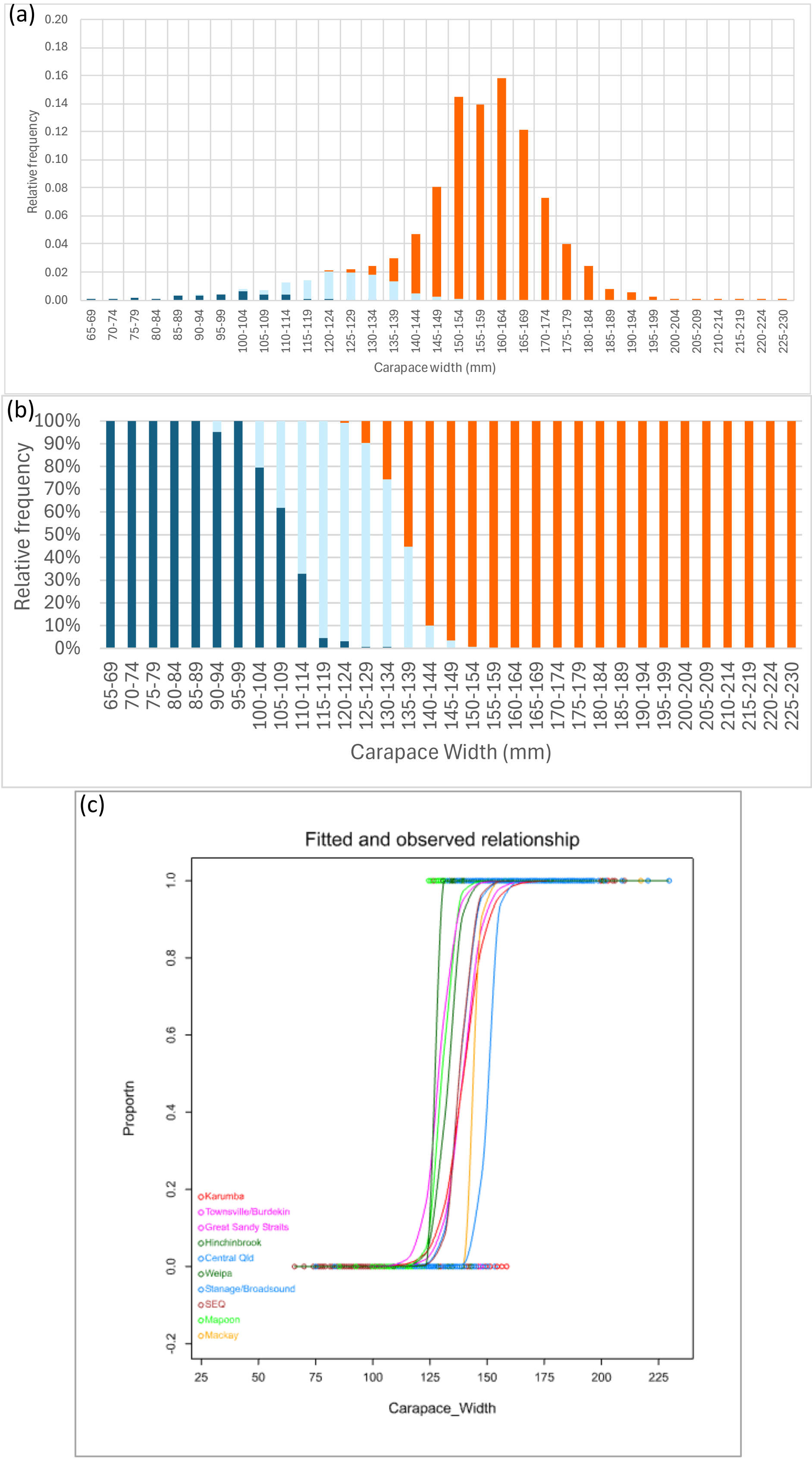

Figure 48. Maturity in female Giant Mud Crabs for all regions pooled (n = 6,487). Immature V-shaped abdominal flap females indicated by dark blue bars. Immature, intermediate abdominal flap females indicated by light blue bars. Mature U-shaped abdominal flap females indicated by orange bars. (a) relative frequency at size. (b) relative frequency per size class. (c) fitted binomial general linear model, showing predicted proportion mature (based on abdominal flap shape) as a function of carapace width and region as main effects and an interaction effect.

Table 19. Parameter outputs of the binomial General Linear Model (main effects and interaction of carapace width and region) estimating size-at-maturity for female Giant Mud Crabs in Queensland. Significant effects bolded.

	Estimate	Std. Error.	t(*)	t pr.	antilog of estimate
Constant	-45.55	7.740	-5.88	<.001	*
Carapace Width	0.33	0.055	5.99	<.001	1.390
Karumba	17.58	8.760	2.01	0.045	43306519
Weipa	-173.00	256.000	-0.68	0.499	*
Mapoon	-7.30	10.700	-0.68	0.495	0.001
Hinchinbrook	-1.20	12.500	-0.10	0.921	0.290
Townsville/Burdekin	9.20	16.000	0.58	0.565	9847
Mackay	-85.00	267.000	-0.32	0.750	*
Stanage/Broadsound	-25.90	30.500	-0.85	0.395	*
Great Sandy Strait	11.80	24.300	0.49	0.627	132272
south-east Queensland	-3.51	8.320	-0.42	0.673	0.030
CW*Karumba	-0.13	0.062	-2.10	0.036	0.879
CW*Weipa	1.40	2.020	0.69	0.488	4.042
CW*Mapoon	0.08	0.079	0.96	0.337	1.078
CW*Hinchinbrook	0.02	0.090	0.26	0.797	1.023
CW*Townsville/Burdekin	-0.05	0.114	-0.42	0.677	0.954
CW*Mackay	0.57	1.790	0.32	0.750	1.771
CW*Stanage/Broadsound	0.15	0.204	0.72	0.472	1.158
CW*Great Sandy Strait	-0.09	0.164	-0.53	0.594	0.916
CW*south-east Qld	0.03	0.059	0.43	0.668	1.026

Table 20. Estimates of size-at-maturity for female Giant Mud Crabs in Queensland.

	All females CW (mm)	Mature females CW (mm)	$CW_{50\%Female}$ (mm)	Percent mature @50 mm CW (± s.e.)
All regions pooled	66 - 230 (n = 6,487)	125 - 230 (n = 5,645)	136.3	98.5 (± 0.2)
Karumba	121 - 209 (n = 588)	133 - 209 (n = 559)	139.8	89 (± 2.7)
Weipa	105 - 177 (n = 75)	130 - 177 (n = 70)	126.7	100 (± 0.0)
Mapoon	85 -180 (n = 965)	125 -180 (n = 875)	130.7	99 (± 0.0)
Hinchinbrook	109 - 201 (n = 926)	131 - 201 (n = 913)	132.8	99 (± 0.0)
Townsville/Burdekin	116 - 177 (n = 201)	131 - 177 (n = 198)	129.1	99 (± 0.0)
Mackay	137 - 217 (n = 62)	153 - 217 (n = 61)	145.2	98 (± 18.0)
Stanage/Broadsound	99 - 230 (n = 62)	148 - 230 (n = 42)	150.2	48 (± 16.7)
Central Qld	75 - 220 (n = 740)	133 - 220 (n = 699)	138.3	98% (± 1.2)
Great Sandy Strait	141- 199 (n = 89)	141 - 199 (n = 88)	139.6	93 (± 7.8)
south-east Qld	66 - 210 (n = 2,780)	126 - 210 (n = 2,141)	138.3	98 (± 0.0)

The above analysis has provided the first estimates of regional variability in size-at-maturity for female Giant Mud Crabs in Queensland. The estimated $CW_{50\%Female}$ for south-east Queensland (i.e., 138.3 mm) is lower than previously estimated by Heasman (1980). His estimate of 147 mm was based on 339 mature females ranging in size from 137 mm to 204 mm CW. The current research had a much larger sample size (i.e., 2,141 mature females and 639 immature females) acquired over a greater and more diverse spatial area. The estimated of $CW_{50\%Female}$ for all regions pooled (i.e., 136.6 mm CW) is similar to that estimated by Knuckey (1999) for Giant Mud Crabs in the Northern Territory (i.e., 136.5 mm CW).

Neither Heasman (1980) nor Knuckey (1999) reported females with an intermediate-shaped abdominal flap, but which we observed in the current research as have others (e.g., Islam *et al.* 2010). Immature females with an intermediate-shaped abdominal flap appear to be the intermoult stage in between V-shaped and U-shaped abdominal flap females (Figure 48).

Growth

Average maximum size ($L_{infinity}$)

Average maximum size (i.e., $L_{infinity}$) was estimated for the regions, based on the largest one percent of individuals sampled in the current research and compared against that estimated based on the data collected by the Fisheries Queensland monitoring program for Giant Mud Crabs 2002 to 2009 (Table 21). Regional estimates of $L_{infinity}$ were largest in the Stanage Bay/Broadsound region for males and females (196 mm and 204 mm CW respectively) and smallest in the Townsville/Burdekin region (171 mm and 173 mm CW respectively); a pattern that was mostly consistent with the monitoring program data (Table 21).

Table 21. Estimated average maximum size ($L_{infinity}$) of Giant Mud Crabs in regions of Queensland, based on data collected during the current research (November 2021 to March 2024) as part of FRDC 2019-062, 2021-119 and TMSFB000012, compared to data collected during the Fishery Queensland monitoring program for Giant Mud Crabs (2000 to 2009).

Region	Males (CW mm)		Females (CW mm)	
	Current	Fishery Monitoring	Current	Fishery Monitoring
Karumba	191 (n = 478)	185 (n = 172)	187 (n = 599)	179 (n = 172)
Weipa	176 (n = 283)	184 (n = 277)	176 (n = 75)	177 (n = 121)
Mapoon	177 (n = 2,150)	na	173 (n= 1,085)	na
Hinchinbrook	179 (n = 913)	181 (n = 208)	185 (n = 926)	183 (n = 271)
Townsville/Burdekin	171 (n = 306)	169 (n = 1,546)	173 (n = 204)	170 (n = 537)
Mackay	189 (n = 57)	na	198 (n = 64)	na
Stanage/Broadsound	196 (n = 169)	186 (n = 114)	204 (n = 62)	184 (n = 112)
central Qld	184 (n = 1,928)	181 (n = 562)	196 (n = 831)	194 (n = 928)
Great Sandy Strait	188 (n = 111)	175 (n = 906)	197 (n = 89)	187 (n = 991)
south-east Queensland	174 (n = 7,599)	163 (n = 1,717)	186 (n = 2,840)	182 (n = 1,164)

The above analysis has provided the first estimates of regional variability in average maximum size (i.e., $L_{infinity}$) of male and female Giant Mud Crabs in Queensland. These estimates are biased by the removal of male crabs above legal size. However, they represent populations of Queensland Giant Mud Crab as they function in the presence of heavy fishing mortality, whereby the abundance of large male crabs is substantially reduced in many locations. Some of the regional estimates of $L_{infinity}$ were similar to that reported for NT regions (i.e., males 185-193 mm CW, females 186-191 mm CW, Knuckey 1999), although there were a few locations, where $L_{infinity}$ was considerable smaller (e.g. Townsville/Burdekin).

Size distributions

Size distributions were collated for males and females for all regions pooled and regionally where sample sizes were sufficient. Previously, Giant Mud Crabs have been reported to have a slight bimodal distribution for females, and a normal distribution for males that peaked at 130-140 mm CW, with a sharp decline above 150 mm CW (Jebreen *et al.* 2008). We expected similar results, except for protected areas, where we expected a greater frequency of males larger than 150 mm CW (Pillans *et al.* 2005). Where inferences were made about growth phases (e.g. Heasman 1980, Knuckey 1999), the size-frequency distribution of male Giant Mud Crabs was suggested to be multi-modal.

Males

Across fishery-independent and fishery-dependent sampling, a wide size distribution of male Giant Mud Crabs was sampled. Approximately 75% of males measured were from areas open to fishing and the remaining 25% of males were from areas closed to fishing (i.e., Marine National Park 28, southern Moreton Bay and Eurimbula Creek, a mud crab sanctuary in central Queensland). Data from these areas that are closed to fishing gave some insight into what an unfished/lightly fished male population might look like. Both closed areas are adjacent to fished areas, with an undetermined prevalence of illegal fishing and immigration/emigration of crabs. Previous research suggested that mature males are somewhat sedentary with limited migration (Pillans *et al.* 2005). Anecdotally multiple fishers in spatially disparate locations reported a seasonal 'movement' of male Giant Mud Crabs that are mature, hard-shelled and moving/aggregating in certain locations, although the prevalence of this is uncertain.

The size distribution of males from areas open to fishing (all regions pooled, n = 10,753) had an approximately normal distribution, that peaked at 145-149 mm CW (i.e., just below size MLS), while the size distribution of males from areas closed to fishing (all regions pooled, n = 3,251) had elements that suggested a bimodal distribution, with peaks at 145-149 mm and 160-164 mm CW (Figure 49). As expected, there was a greater frequency of males larger than 150 mm CW in areas closed to fishing, compared to areas open to fishing.

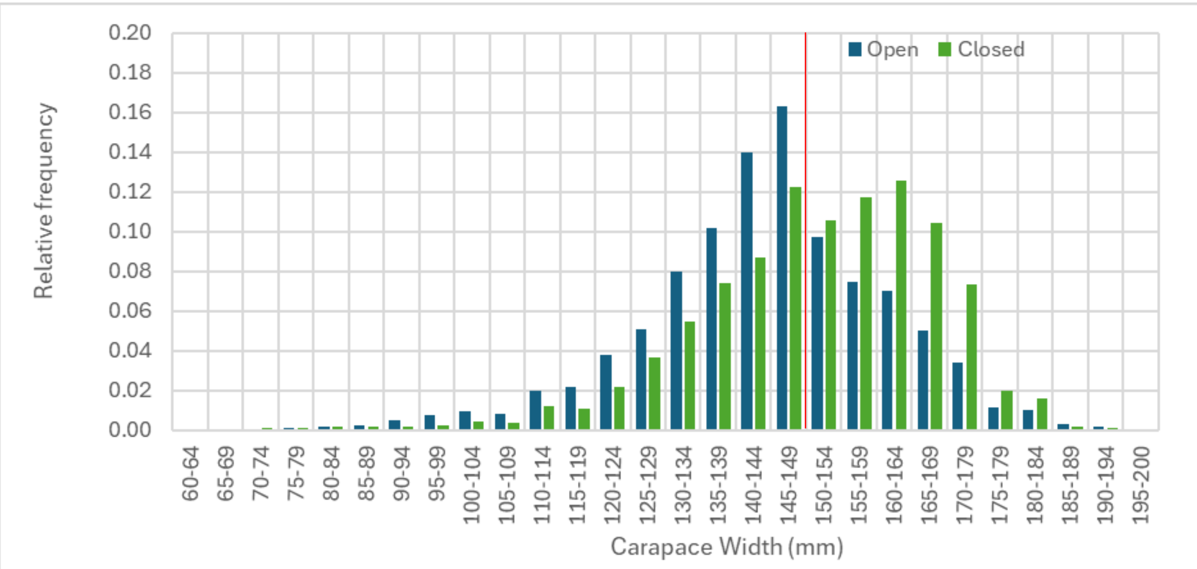

Figure 49. Size distribution of male Giant Mud Crabs measured across all regions pooled, but separated into areas open to fishing (blue bars, n = 10,753) and closed to fishing (green bars = 3,251). Red line indicates 150 mm CW (Qld MLS).

The relatively frequency size-distributions of male Giant Mud Crabs in areas open to fishing differed between regions of Queensland (Figure 50; Figure 51).

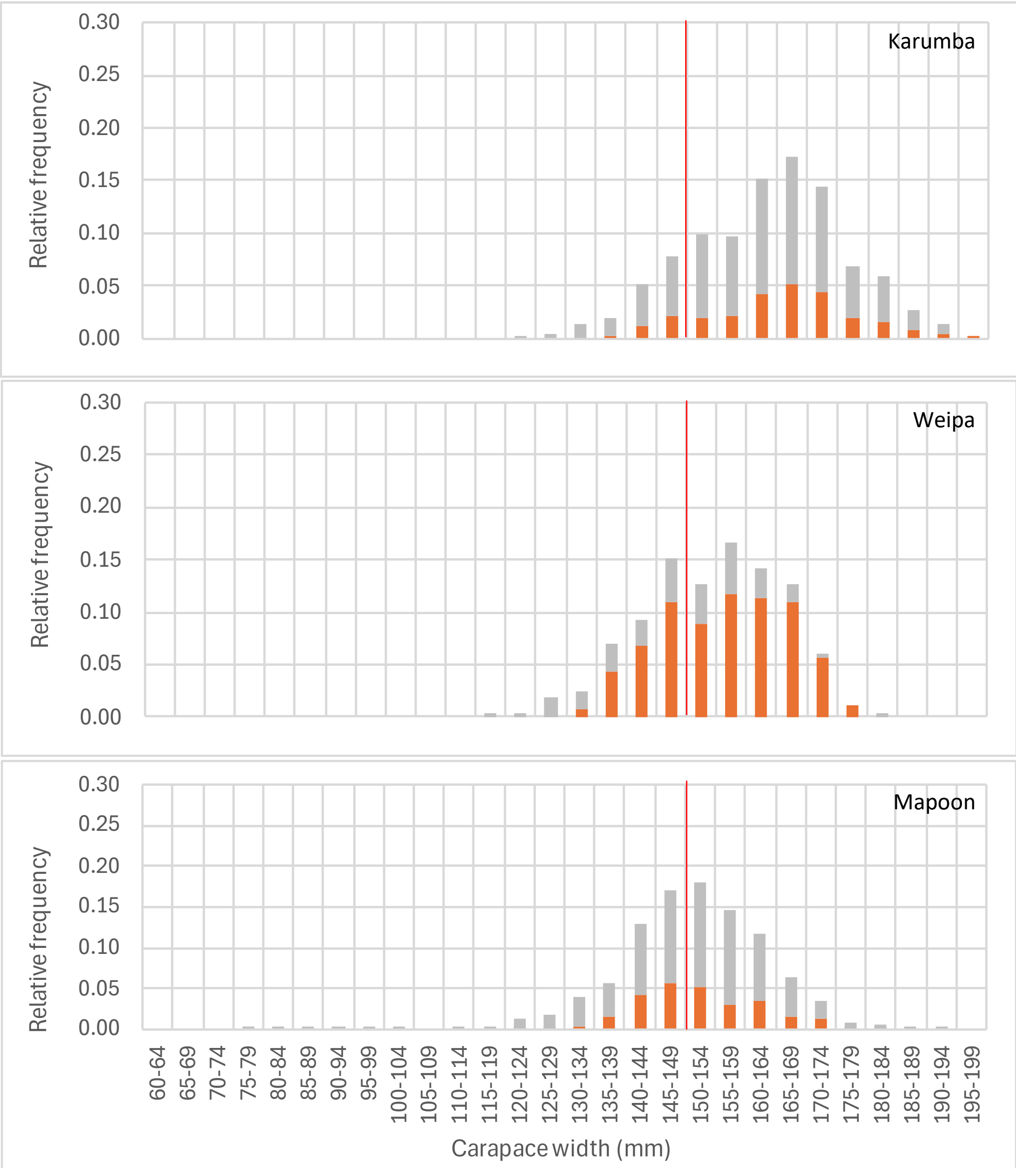

Figure 50. Relative size-frequency distributions of male Giant Mud Crabs from Gulf of Carpentaria regions of Queensland sampled from locations open to fishing. Scarred males indicated by orange bars. Unscarred males indicated by grey bars. Red line indicates 150 mm CW (Qld MLS).

In GC1 regions (where the data was based on fishery-dependent samples), there was little evidence of multiple modes (that could be used to infer growth by modal progression) although there was some evidence of bimodality for the Weipa samples (Figure 50). Of note for the GC1 regions was the lack of a steep decline in the frequency of males 150 mm CW or larger. This is likely a function of the habitats sampled and the intensity of fishing mortality in these regions.

In EC1 regions (where data was based on fishery-dependent and fishery-independent samples), there was little evidence of multiple modes in the size-frequency (Figure 51). A common feature of several EC1 regions was the noticeable reduction in the frequency of males 150 mm CW or larger. This is likely a function of the habitats sampled and the intensity of fishing mortality, which in some regions is very high.

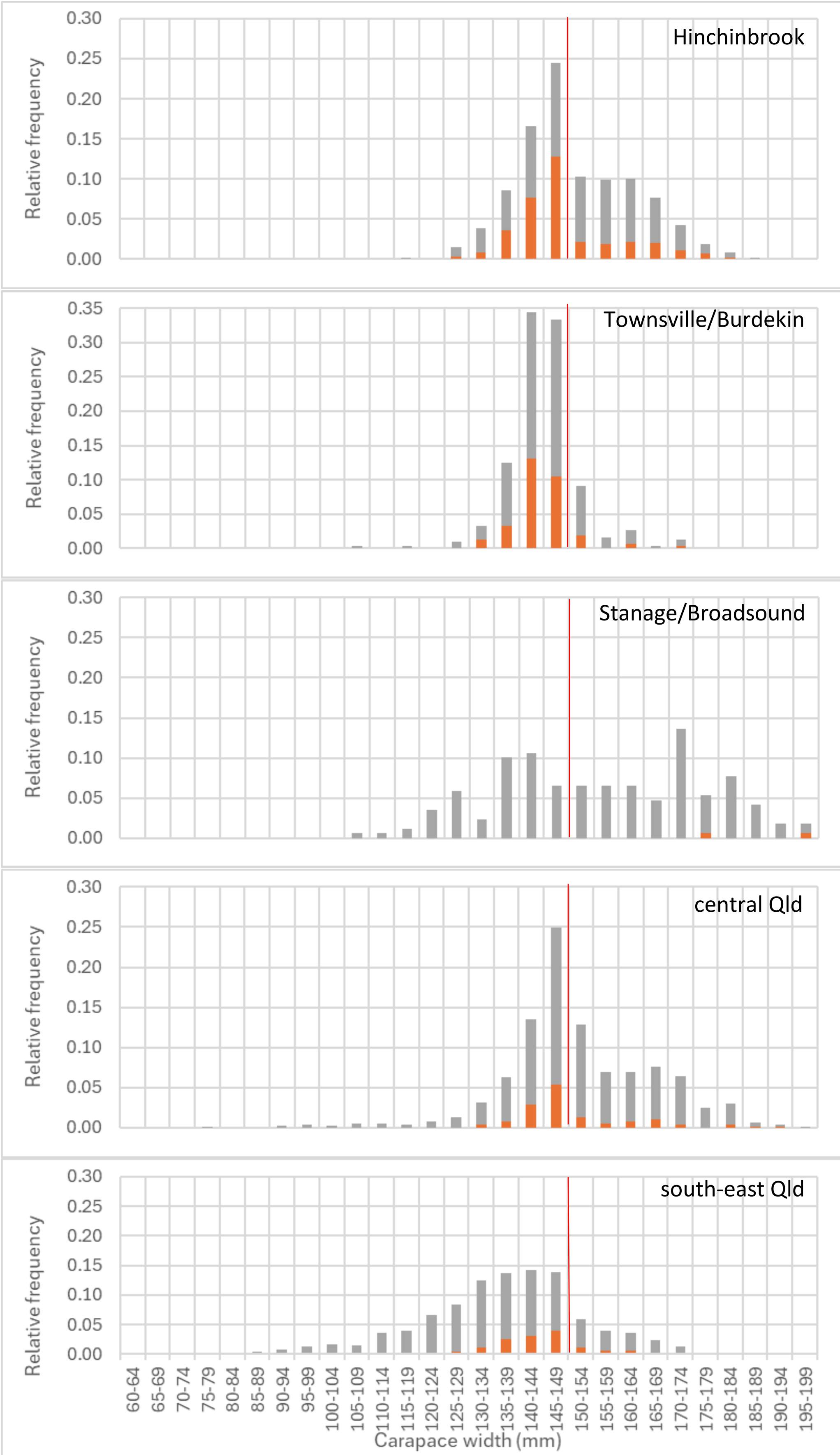

Figure 51. Relative size-frequency distributions of male Giant Mud Crabs sampled from EC1 regions of Queensland in locations open to fishing. Scarred males indicated by orange bars. Unscarred males indicated by grey bars. Red line indicates 150 mm CW (Qld MLS).

In EC1 regions closed to fishing, there was no strong evidence of bimodality in the relative size-frequency distributions (Figure 52). However, at Eurimbula Creek, the peak modal size was 160-164 mm CW, which was larger than areas open to fishing in central Queensland. For MNP28 (south-east Queensland), the peak modal size was 145-149 mm CW, similar to the adjacent areas that are open to fishing.

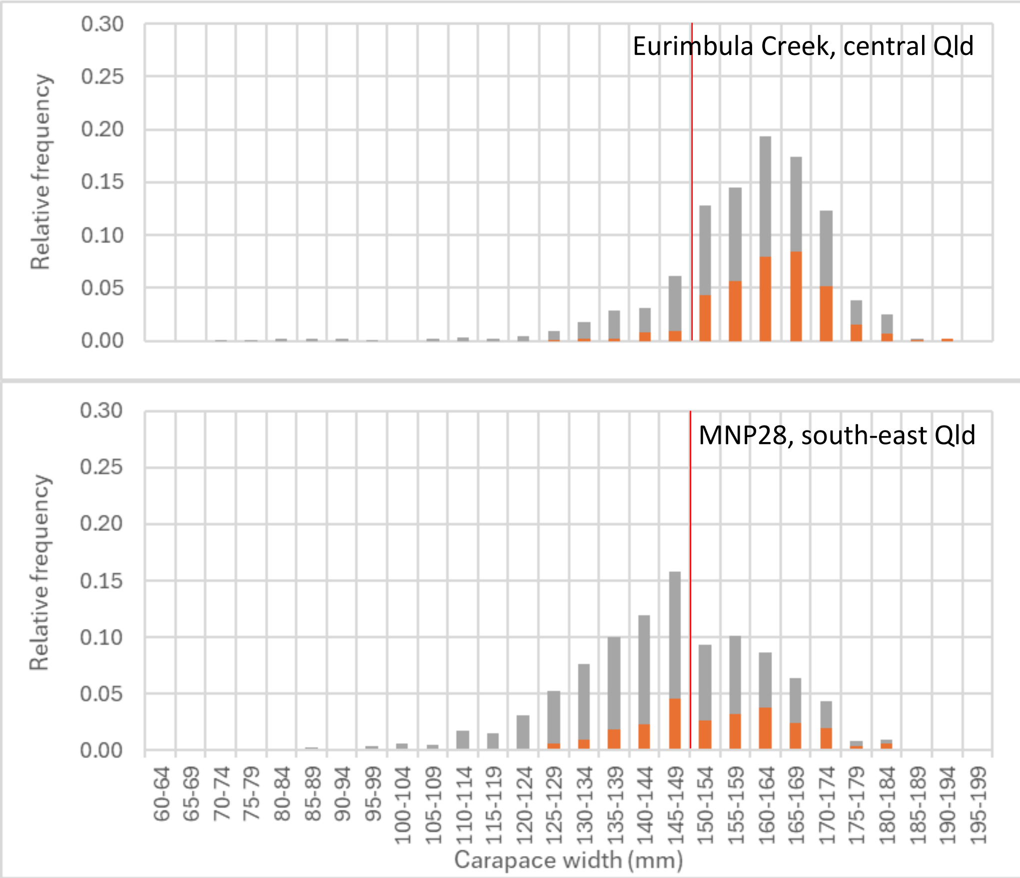

Figure 52. Relative size-frequency distributions of male Giant Mud Crabs sampled from EC1 regions of Queensland in locations closed to fishing. Scarred males indicated by orange bars. Unscarred males indicated by grey bars. Red line indicates 150 mm CW (Qld MLS).

Females

Across fishery-independent and fishery-dependent sampling, a wide size distribution of female Giant Mud Crabs were sampled. About 90% of females were from areas open to fishing and about 10% areas closed to fishing (i.e., Marine National Park 28, southern Moreton Bay and Eurimbula Creek – a mud crab sanctuary in central Queensland). Given Queensland's no female harvest policy, we expected a similar size-distribution for females between areas open and closed to fishing, with any differences attributable to sampling different habitats as there is only natural mortality affecting the size-distributions.

The relative size-frequency distribution of females from areas open to fishing (all regions pooled, n = 5,541) had an approximately normal distribution, with slight bimodality (at 150-154 mm CW and 160-164 mm CW). The size distribution of females from areas closed to fishing (all regions pooled, n = 835) had a single mode at 160-164 mm CW (Figure 53).

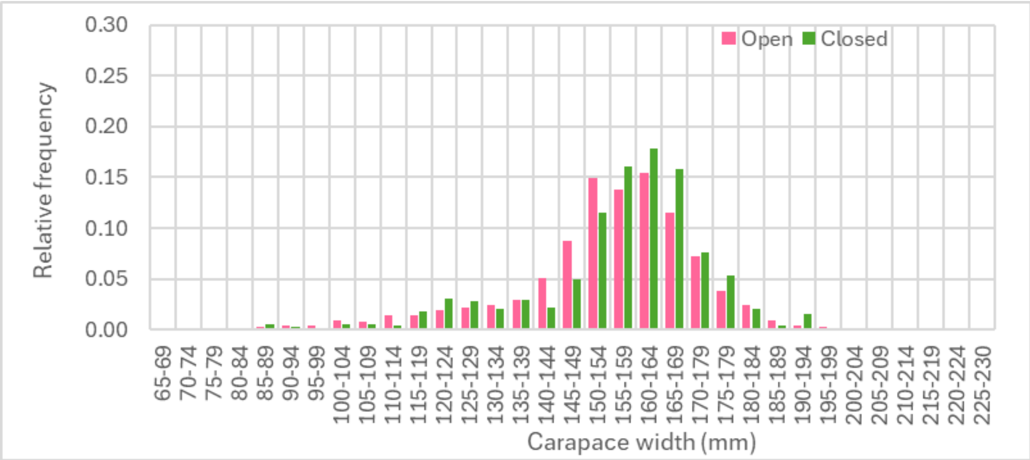

Figure 53. Relative size-frequency distribution of female Giant Mud Crabs measured across all regions pooled, but separated into areas open to fishing (pink bars, n = 5,541) and closed to fishing (green bars n = 835).

The relative frequency size-distributions of female Giant Mud Crabs in areas open to fishing differed between regions of Queensland (Figure 54, Figure 55,Figure 56), which we suspect was a function of sampling different habitats.

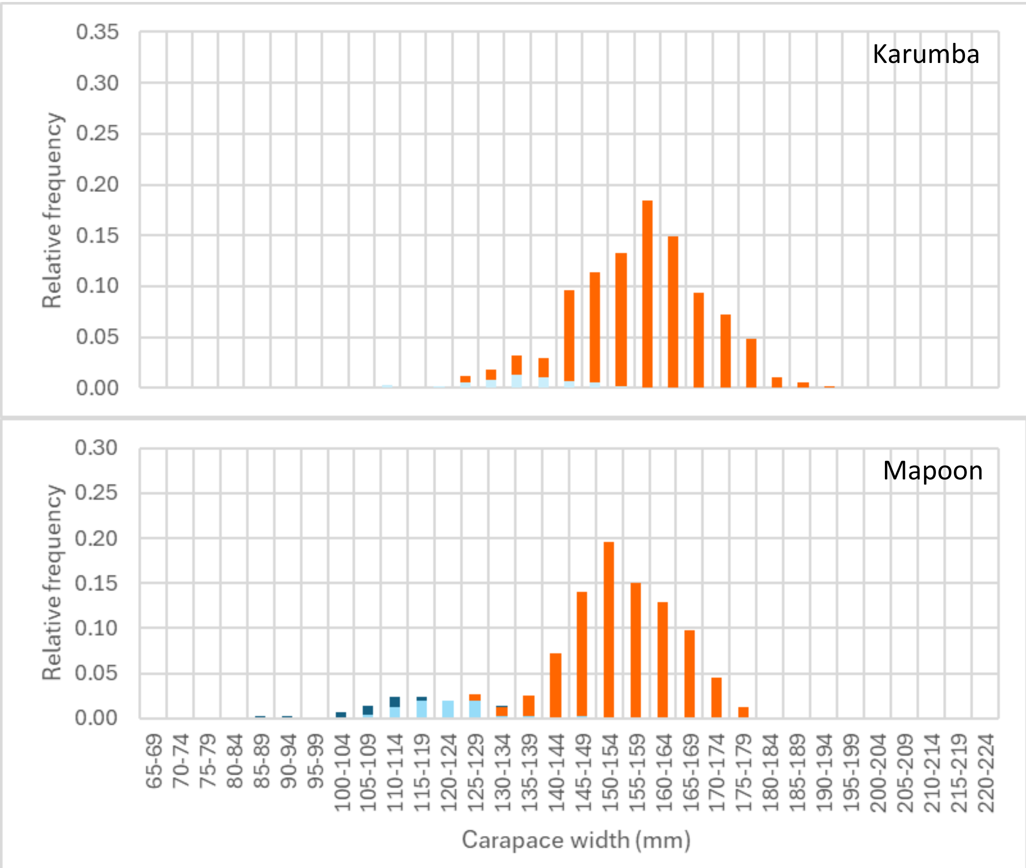

Figure 54. Relative size-frequency distributions of female Giant Mud Crabs sampled from Gulf of Carpentaria regions of Queensland in locations open to fishing. Immature V-shaped abdominal flap females indicated by dark blue bars. Immature, intermediate shaped abdominal flap females indicated by light blue bars. Mature U-shaped abdominal flap females indicated by orange bars.

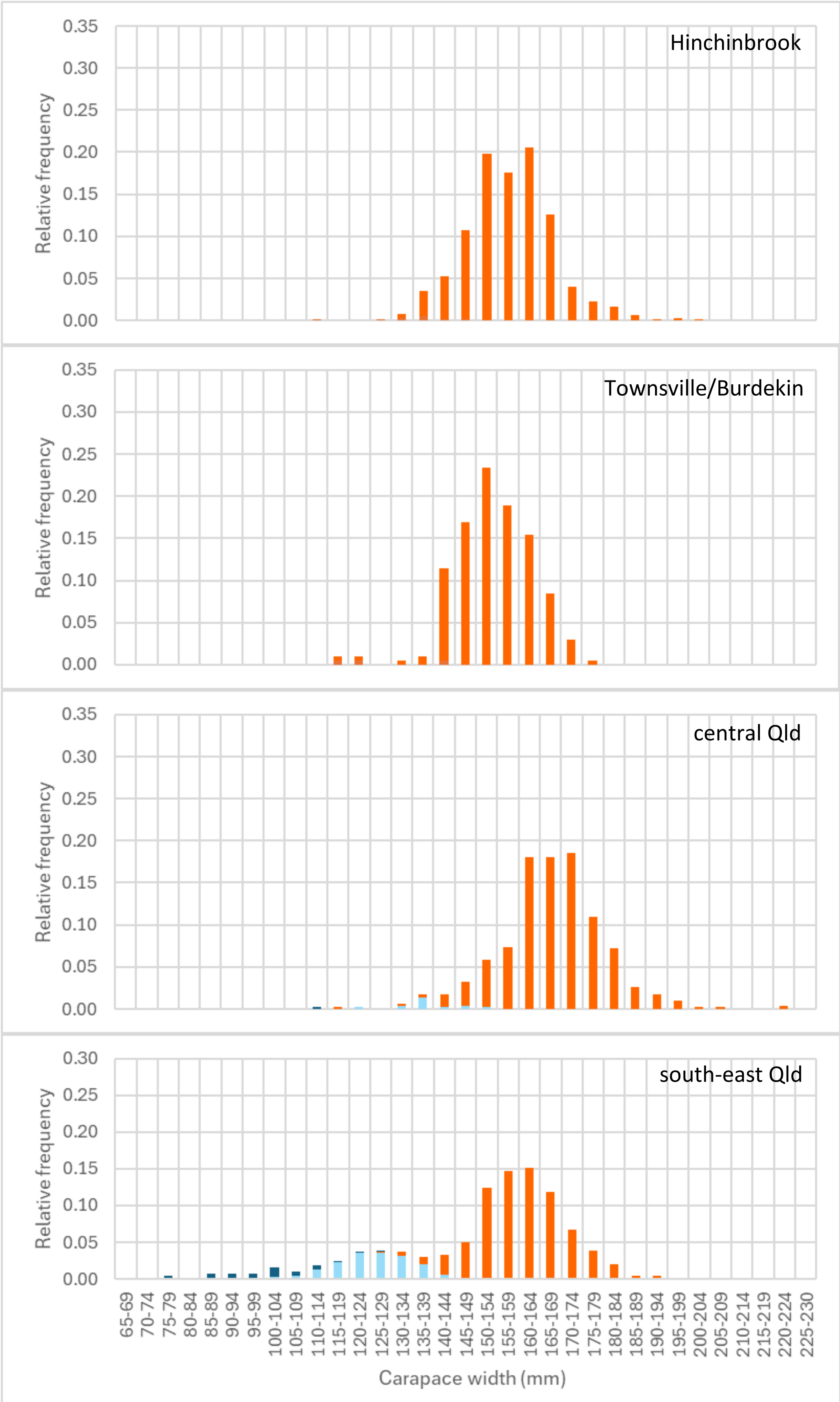

Figure 55. Relative size-frequency distributions of female Giant Mud Crabs sampled from east coast regions of Queensland in locations open to fishing. Immature V-shaped abdominal flap females indicated by dark blue bars. Intermediate abdominal flap females indicated by light blue bars. Mature U-shaped abdominal flap females indicated by orange bars.

Modal progression

Males

Estimating growth for male Giant Mud Crabs using modal progression was explored for the south-east region of the Queensland east coast, which had the most spatially and temporally extensive dataset. A variety of size-class aggregations (i.e., 1 mm, 2 mm, 5 mm, 10 mm, 20 mm) and temporal aggregations (i.e., sample event, monthly, growth season) were trialled with the aim of identifying modes in the relative size-frequency distributions. However, there were no clear modal patterns the relative size-frequency distributions of males over temporal sampling events that would support analysis by modal progression (Figure 56).

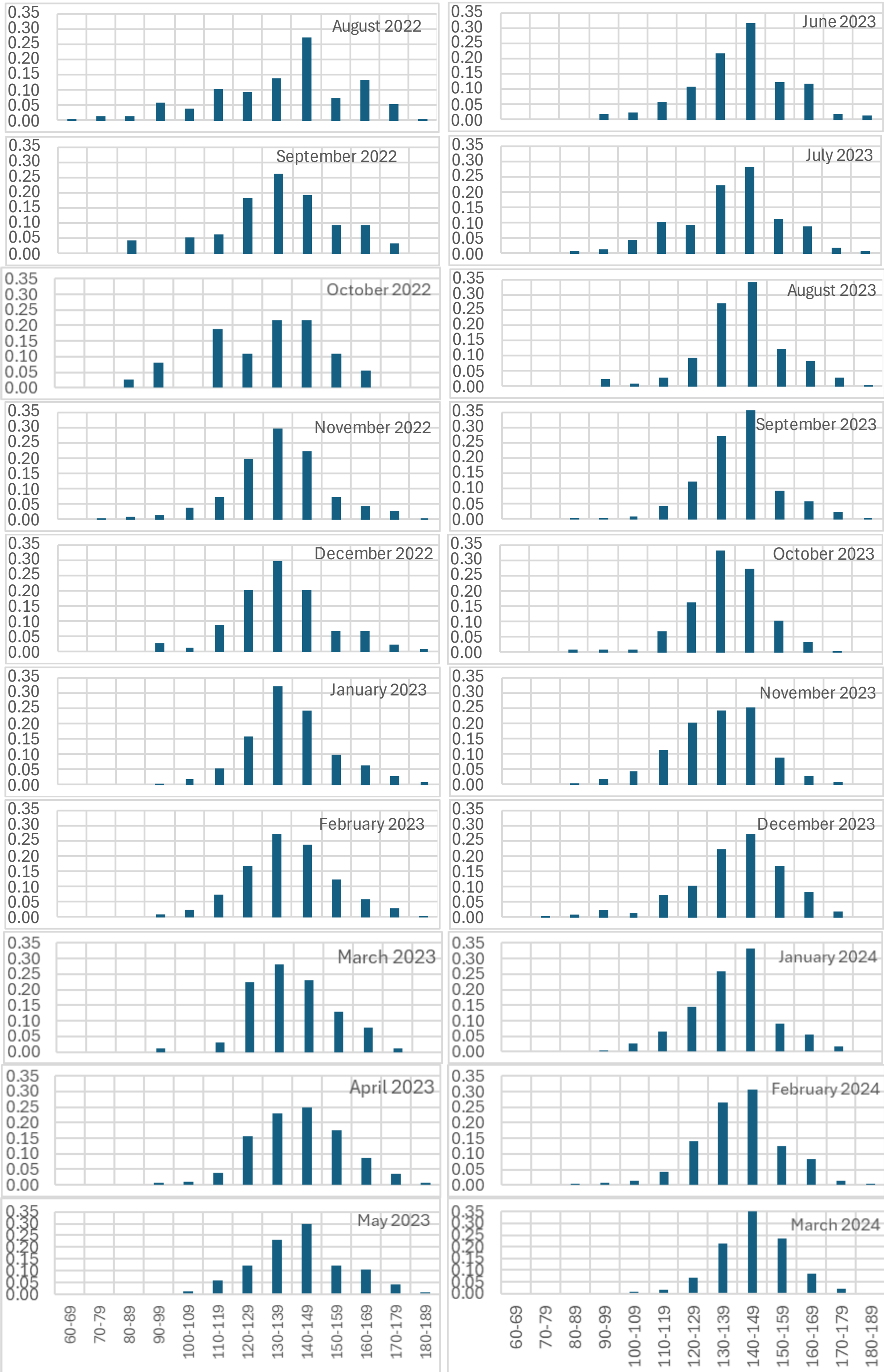

Figure 56. Monthly relative size-frequency distributions of male Giant Mud Crabs sampled from the south-east region of the Queensland east coast between August 2022 and March 2024.

As an alternate means of identifying modes in the size-frequency, the claw height: carapace width ratios were plotted for males from the south-east region to confirm that the critical value of 0.345 appropriately identified adolescents from functional adults (Figure 57). This supported the classification of males into small-clawed males-at size compared to large-clawed males-at=size. Whilst there were hints of modes (e.g., 130-139 mm CW for small-clawed males, and 140-149 mm CW for large-clawed males), the modes were insufficiently distinct to support modal progression analysis to estimate growth increments for males.

Interestingly, it appears that in the south-east region of the Queensland east coast, there is a relatively high frequency of small-clawed males that have been participating in reproduction, as evidenced by the frequency distribution of scarred males against claw height to carapace width ratio (Figure 57). This may be a function of the sampling in this region, which was predominately fishery-independent and including multiple locations including within the Logan River. It may also be a function of the region's heavy fishing mortality on large-clawed males enabling small-clawed males to successfully cradle and mate with females undergoing their pubertal moult.

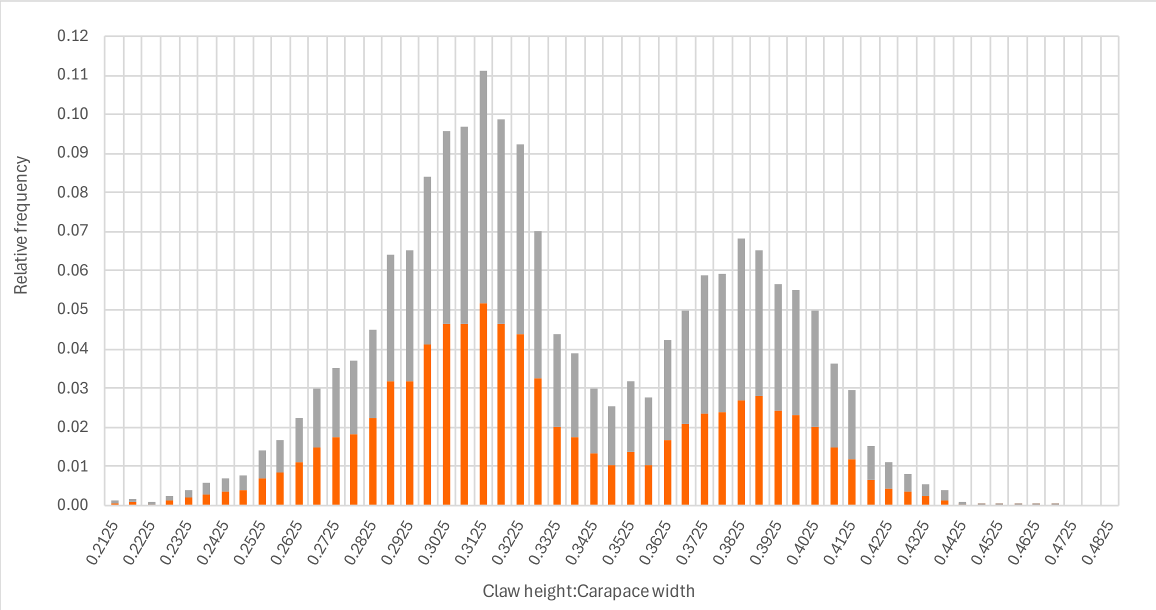

Figure 57. Relative frequency of crusher claw height to carapace width ratio for male Giant Mud Crabs sampled from the south-east region of the Queensland east coast (n = 6,897 with claw height measurements). Scarred males indicated by orange bars. Unscarred males indicated by grey bars.

Figure 58. Monthly relative size-frequency distribution for male Giant Mud Crabs sampled from the south-east region of the Queensland east coast between August 2022 and March 2024, separated into small-clawed adolescents (grey shading) and large-clawed functional adults (orange shading), based on a critical claw height:carapace width value of 0.345.

Females

Relative size-frequencies of females categorised by abdominal flap (V-shape, intermediate, U-shape) were calculated for the south-east region of the Queensland east coast (all sampling events, all locations, all pot types) to elucidate modes of cohorts, and infer field estimates of moult-increments (i.e., modal progression). The relative size-frequency distribution of intermediate females suggested a mode at approximately 120-129 mm CW (Figure 59). The relative size-frequency distribution of U-shaped abdominal flap females (mature) suggested a mode at approximately 155-165 mm CW. The relative size-frequency distribution of V-shaped abdominal flap females suggested modes at 100-104 mm CW, and possibly 75-79 mm CW, noting small sample sizes for females smaller than 100 mm CW (i.e., n < 20 per 5 mm size-class). Although requiring further analysis, these preliminary indications of modes at 75-79, 100-104, 125-139, and 155-165 approximately align with the expected increase in size (i.e., growth) due to moult increment (see Chapter 1, Figure 6b).

Non-linear regression fitting Gaussian curves to the relative size-frequency distributions by flap type produced reasonable fits: F_{pr} <0.001, R^2 = 97.3 for the separation of intermediates from U-shaped females and $F_{pr.}$ <0.001, R^2 = 87.4 for separation of small V-shaped from large V-shaped abdominal flap females. Parameter estimates for the fitted curves are provided in Table 22, with the means of the distributions (i.e., *M*) aligning with the preliminary estimates of modes.

Table 22. Parameter estimates (± s.e.) of Gaussian curves ($Y = a + b/(2\pi s^2)^{-½} e^{-(x-m)2}/2s^2$, see https://genstat.kb.vsni.co.uk/knowledge-base/gaussian-curves/) fitted to the relative size-frequency distributions of female Giant Mud Crabs based on carapace width and abdominal flap shape.

Gaussian curve parameters	Abdominal flap shape			
	V-shape small <90 mm CW	V-shape large >90 mm CW	Intermediate	U-shape
S	6.79 (± 1.47)	6.394 (± 0.675)	9.37 (± 0.411)	9.5 (± 0.437)
M	85.96 (± 1.29)	102.611 (± 0.597)	125.7 (± 0.321)	160.5 (± 0.395)
B	1.611 (± 0.367)	3.174 (± 0.347)	5.45 (± 0.214)	4.785 (± 0.223)
A	0.0004 (± 0.0071)	0.0025 (± 0.0069)	-0.0007 (± 0.0028)	0.0017 (± 0.0028)

The results from fitting Gaussian curves to the relative frequency distributions suggest that:

(i) most adult females in the south-east region of the Queensland east coast were in their first mature intermoult, which was supported by (a) the mean proportional increase in CW of 1.277 i.e., intermediates had a mean CW of 125.7 mm, with an estimated moult to U-shaped matures which had a mean CW of 160.5 mm, with the proportional increase in CW being in a similar order of magnitude as that reported in the literature (see chapter 1); and (b) the mean CW of mature females was similar to the projected size of the 1st maturity female intermoult estimated for southern Moreton Bay (i.e., 163.8 mm CW) by Heasman (1980);

(ii) the modes identified in the current analysis approximately aligned with that reported by Heasman (1980 cited by Grubert and Lee 2013), who suggested modes for females at 127 mm, 167 mm and 193 mm CW; and

(iii) females approximately 175 to 180 mm CW and greater in the south-east region of the Queensland east coast were likely in their 2nd mature intermoult and comprised approximately 4% of mature females sampled. This concurred with speculation that fewer than 10% of first mature intermoult females survive the spawning migration to moult up/grow to become 2nd mature intermoult females.

The large females sampled during the project (i.e., >200 mm CW, largest 230 mm CW from Stanage Bay) were likely to be in their 2nd or 3rd maturity intermoult. Assuming a proportional moult increment of 1.25 (Figure 6, Chapter 1), females 200-230 mm CW are likely to be derived (i.e., moulted up in size) from females approximately 160 to 185 mm CW (i.e., $CW_{initial}$). In several regions (e.g., Karumba, Stanage Bay/Broadsound, central Queensland east coast and south-east Queensland east coast), large females with an intermediate-shaped abdominal flap (i.e., immature at 150-156 mm CW) were observed, noting that greater than 99.5% of females 150-159 mm CW in size (all regions pooled) had a U-shaped abdominal flap and were mature. It is unknown as to whether large female Giant Mud Crabs (i.e., greater than 185 mm) have either survived spawning (by not migrating far) or have skipped spawning at smaller sizes for unknown reasons.

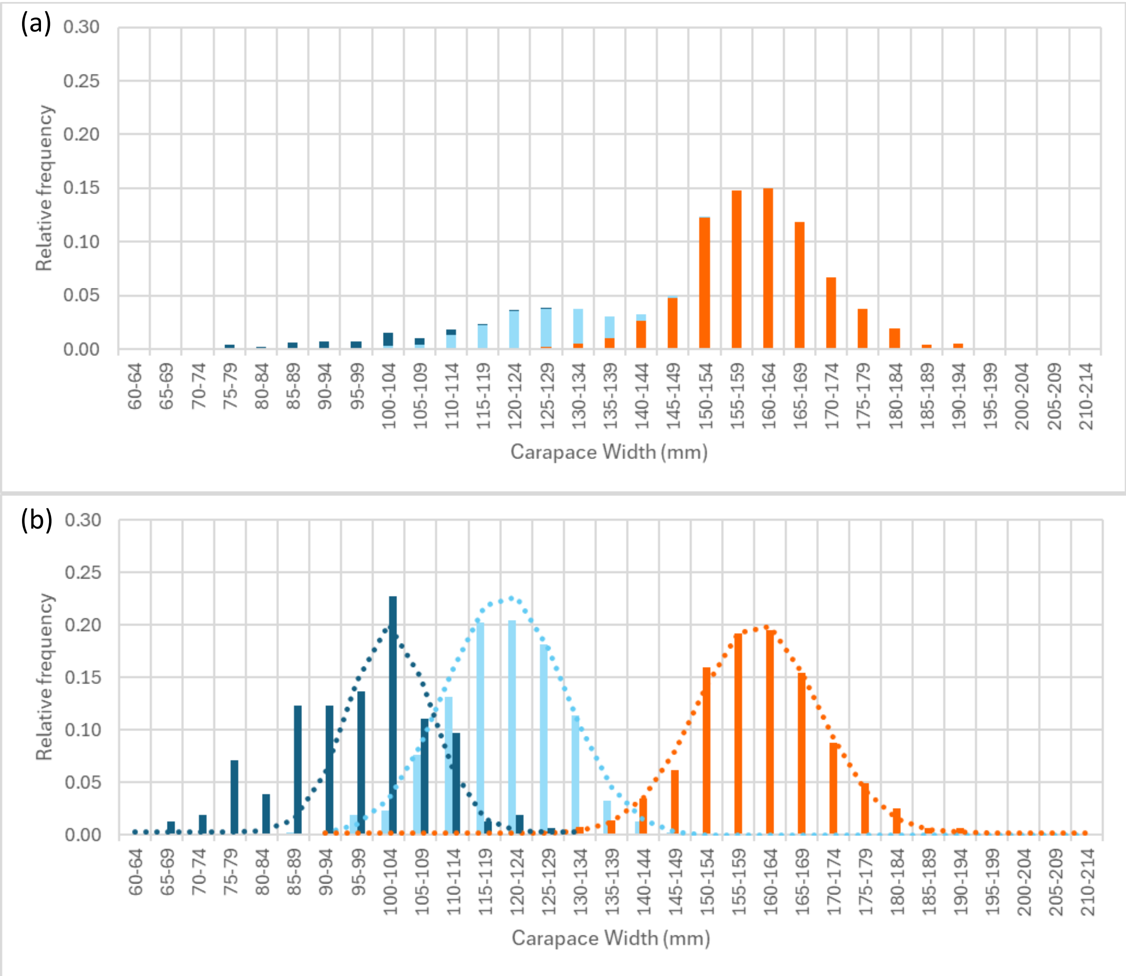

Figure 59. Relative size-frequency distribution for female Giant Mud Crabs sampled from the south-east region of the Queensland east coast. (a) relative size-frequency all females sampled (n = 2,780). (b) relative size-frequency per abdominal flap shape. Immature V-shaped abdominal flap females (n = 154) indicated by dark blue bars, intermediate females (n = 485) indicated by light blue bars, mature U-shaped abdominal flap females (n = 2,141) indicated by orange bars. Dotted lines are the Gaussian distributions fitted in Genstat using nonlinear regression analysis. Samples numbers for size-classes <90 mm CW were fewer than 20 females, and precluded robust fitting of distrubitions in the smallest size classes.

Sex ratios

Sex ratio and size-sex ratio were calculated the south-east region of the Queensland east coast for areas open to fishing (and locations within) and closed to fishing (Table 23), as well as sex ratio per size-class (Figure 60). Areas within the south-east region that were open to fishing had sex ratios below <1.0, whilst the area closed to fishing had a sex ratio of >2.0, noting that sex ratio only consider crabs ≥150 mm CW. This result aligns with the sex ratio of approximately 2.0 previously reported as the benchmark of sex ratio for unfished population of Giant Mud Crabs in Australian estuaries (Flint *et al.* 2017, 2021). Against this benchmark, a sex ratio below 2.0 is indicative of fishing mortality, with lower ratios indicative of higher fishing mortality on males above legal size. This may be true; however, if sampling is not carefully standardised, then sex ratios could be biased by size-sex spatial habitat use suggested to occur for Giant Mud Crabs by Jebreen *et al.* (2008). Further research into size-sex spatial habitat use is the subject of a current PhD project by W. Charles, CQUniversity. Sex ratios do not consider the consequences of mortality incurred by the spawning migration of mature females. In the current research, sex ratio varied considerably between size-classes and was different between areas that were open and closed to fishing. Sex ratio is potentially appropriate as a quantifiable metric of relative fishing mortality with a region, such as for annual ecosystem report cards where standardised monitoring provides an index of inter-annual trends. From a fisheries assessment and management perspective, sex ratio is relevant to population modelling and potentially estimates of mortality, both fishing (*F)* and natural (*M*), but by itself does not inform about sustainability of harvest.

Table 23. Metrics of sex ratio (male/female) for Giant Mud Crabs in the south-east region (open and closed to fishing) and central region (closed to fishing) of the Queensland east coast for all sampling events where crab pots had no vents or 75 x 60 mm escape vents.

Location	**Males**		**Females**		**Sex ratio[1]**	**Size-sex ratio[2]**
	n <150 mm CW	**n ≥150 mm CW**	**n <150 mm CW**	**n ≥150 mm CW**		
south-east region open to fishing	3,973	738	635	1,025	0.720	0.115
Logan River	1,307	242	252	299	0.809	0.156
southern Moreton Bay	2,666	496	383	726	0.683	0.171
south-east region closed to fishing (Marine National Park 28)	799	942	114	316	2.133	0.228
central region closed to fishing (Eurimbula)	133	480	25	64	7.500	1.140

[1] Sex ratio = $\frac{males_{\geq 150\ mm}}{females_{\geq 150\ mm}}$; [2] Size-sex ratio = $\frac{males_{\geq 150\ mm}/females_{\geq 150mm}}{males_{<150\ mm}/females_{<150mm}}$

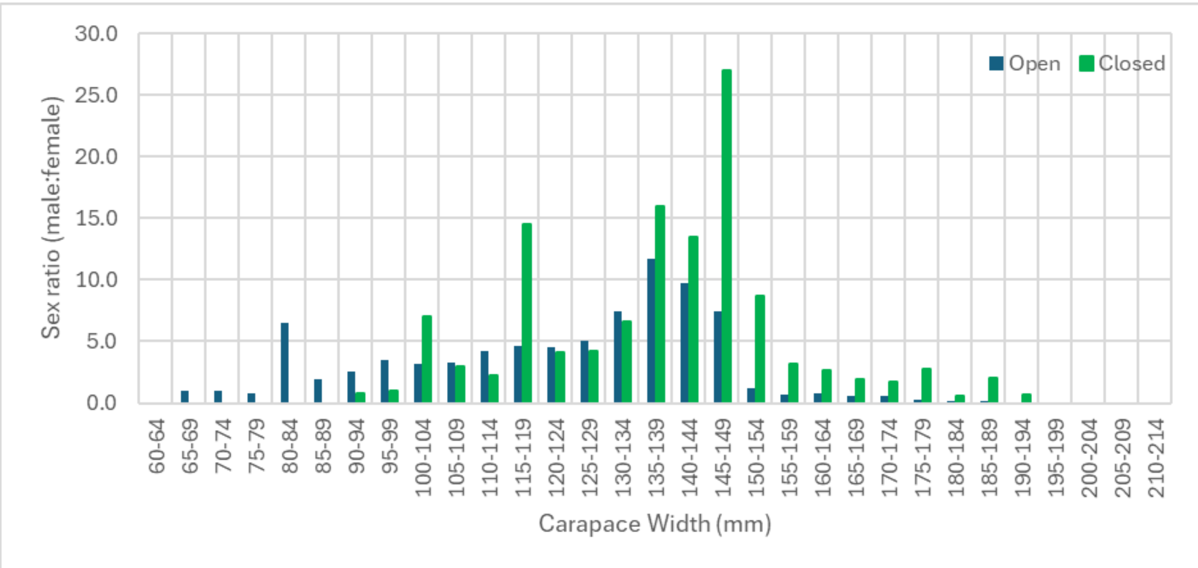

Figure 60. Sex ratio (male/female) per size-class for Giant Mud Crabs sampled from the south-east region of the Queensland east coast in locations open or closed to fishing, using crab pots with no escape vents or 75 x 60 mm escape vents.

Scylla olivacea, the Orange Mud Crab

Whilst undertaking sampling for Giant Mud Crabs, the project encountered 172 individuals of *Scylla olivacea*, the Orange Mud Crab (Figure 61). The features that distinguish this species from *S. serrata* are the lack of pronounced spines on the merus of the claw, the bulbish nature of the claws of males, and the often pronounced red-orange colouration of the claws.

Males ranged in size from 111-167 mm CW, with mating scars on crabs 115-154 mm CW. Females ranged in size from 84-156 mm CW, with mature U-shaped abdominal flaps for crabs 116-156 mm CW. Most males were below the Queensland MLS of 150 mm CW, with only 17% of the Orange Mud Crabs caught being of legal size. Sample sizes of Orange Mud Crabs encountered during the current research project were insufficient to robustly estimate size-at-maturity for this species.

Figure 61. The Orange Mud Crab, Scylla olivacea, encountered at low frequency (142 males, 30 females) in the Gulf of Carpentaria.

There are no quantitative published reports on the Orange Mud Crab from Queensland waters. Anecdotally, commercial fishers catch them most frequently, albeit with variable repeatability, in the northern Gulf of Carpentaria (i.e., Weipa and Mapoon), with validated reports of their capture as far south as the Gilbert River in the Gulf of Carpentaria (approximately 16.5°S) and Taylors Beach on the Queensland east coast (approximately 18.5°S).

Western Australia is the only Australian jurisdiction where there is a separate size limit for Orange Mud Crab (MLS = 120 mm CW), which is smaller the WA size limit for Giant Mud Crab (MLS = 150 mm CW, Table 2). There exists the opportunity to conduct further research on Orange Mud Crabs in Queensland waters, particularly in the far northern regions, to determine their size-at-maturity to inform a separate MLS and enable a greater harvest of this species.

Discussion

The current research collected, in collaboration with industry, an extensive quantum of data to assist in understanding Giant Mud Crab population biology in regions throughout Queensland – east coast and Gulf of Carpentaria. This considerably adds to the previous data and research that has been conducted on Giant Mud Crabs, especially for Queensland regions. It has provided the first estimates of regional reproductive parameters, such as size-at-maturity, seasonality of reproduction and insemination rates of mature females.

We have also generated information towards understanding regional growth, including relative size-frequency distributions, male and female average maximum size (i.e., $L_{infinity}$) and estimates of cohorts based on morphological features i.e., claw heights in males and abdominal flap shape in females. Robust estimates of maturity intermoult modes and growth have been inferred for females. Inference based on claw height to carapace width for males has provided some insight into their growth, but also insight into the consequence of high fishing mortality in some regions, with the evidence suggesting that small-clawed adolescent males maybe having a greater role in reproduction than previously thought (Knuckey 1996). Estimating growth is problematic in crustaceans because of the inability to reliable age individuals.

Several versions of sex ratio were calculated (below and above legal-size limit). Sex ratio per 5 mm size class was variable, and consistent with other studies. Sex ratios were lower in areas open to fishing compared to areas closed to fishing. Whilst being a quantitative metric of fishing mortality and relevant, the samples underpinning the calculation of sex ratios, i.e., what is sampled relative to the ‘population’ requires consideration.

The data collected, analysed and interpreted herein indicates that the current minimum legal size of 150 mm CW for males in Queensland enables a considerable proportion of males to participate in reproduction either as individuals not subject to fishing mortality (i.e., individuals <150 mm CW) or individuals ≥150 mm CW that have evaded fishing mortality for a sufficient length of time to harden their carapace (i.e., become A-grade), participate in reproduction and acquire mating scars. We found no strong evidence to suggest that the male size limit nor the no-take female harvest policy was a cause of sperm-limitation in females in Queensland waters.

Current sampling identified valuable information that can easily and cost-effectively be gathered by adding the following parameters to any Giant Mud Crab research or monitoring endeavour. In addition to the standard metrics of size (NW or CW) and sex, recording for males, the presence of mating scars and crusher claw height, and for females, abdominal flap shape and checking for externally visible ovarian material in the ventral section of the abdominal flap would assist in identifying size-at-maturity, and indexing seasonality of reproduction.

The data collected during the current research and presented herein (which included data collaboratively collected during FRDC 2021-119 and TMSFB000012), has provided new insights into the biology of Giant Mud Crabs in Queensland. This rich dataset is a valuable asset to DPI, which will be useful to the ongoing assessment and management of Giant Mud Crabs in Queensland.

Chapter 7. Monitoring Giant Mud Crabs in Queensland to inform management

N. Flint and J.B. Robins

Introduction

Monitoring has long been recognised as critical to sustainable fisheries management. Monitoring data can inform harvest strategies and ecosystem-based fisheries management, provides verifiable information on fishing activities, be used to set catch limits, and provide information on bycatch and interactions with threatened and endangered species (Zollett *et al.* 2015). Designing effective monitoring programs is challenging and a strong understanding of the fishery and fishing activities are required to determine the program scope, objectives and parameters. Monitoring methods for crustaceans are often similar to those for fish, but stepwise growth in crustaceans that requires shedding of the exoskeleton (and thus challenges to tagging individuals), inability to reliably age, complex life histories (e.g., offshore spawning), ontogenetic habitat utilisation and distinct population dynamics require careful consideration when developing appropriate monitoring approaches (Plagányi *et al.* 2024).

Giant Mud Crabs were monitored in Queensland by Fisheries Queensland between 2000 to 2009 (Jebreen *et al.* 2008). Analysis of the data identified a high level of variation between the 17 regions sampled, between sampling locations within each region, and between years (Jebreen *et al.* 2008). The spatial and temporal variability in Giant Mud Crab catch identified by Jebreen *et al.* (2008) is consistent with results of the current research (see Chapter 6) and more recent monitoring programs (e.g., Flint *et al.* 2021), which suggests regional biological differences in Giant Mud Crabs. Biological variability is likely driven or influenced by differing environmental conditions across the species' distribution throughout Queensland. In comparison to other jurisdictions where Giant Mud Crabs are harvested in significant quantities, Queensland has a long (i.e., ~7,000 km), complex and variable coastline, characterised by the Great Barrier Reef and the East Australian Current along the east coast, and the warm shallow coastline and coastal boundary current in the Gulf of Carpentaria (see Chapter 1). A monitoring program for Giant Mud Crabs in Queensland to provide data relevant to the management of the fishery would need to account for habitat complexity, temporal and spatial variability. The 2000-2009 Fisheries Queensland monitoring program accounted for habitat and spatial variability, but the cost of monitoring at the scale of the fishery (i.e., Queensland-wide) limited its ability to account for temporal variability.

The spatial variation in biological parameters also extends to catch and catch rate. The regions that contribute large tonnages to the total commercial catch on the east coast (EC1 management unit, see Chapter 1) are the Hinchinbrook Channel area (north EC), the Townsville/Burdekin area (north central EC), the Fitzroy River, The Narrows and Gladstone Harbour area (south central EC), and Moreton Bay (south-east EC, Figure 8). Catches are temporally variable. Higher catch and catch rates occur in the EC1 fishery between November to May (Figure 9), coinciding with warmer water temperatures. Higher catch and catch rates occur in the GC1 fishery between January and June (Figure 13). Seasonality in catch is also linked to fluctuations in market demand and price associated with social celebrations (e.g., Christmas, New Year, Easter, Chinese New Year, and Chinese Mid-Autumn Festival) (State of Queensland, 2019).

Following the introduction of Total Allowable Commercial Catch (TACC) and Individual Transferable Quotas (ITQs) as part of the fisheries' harvest strategy (DAF 2021), the discussion of options for cost-effective and representative monitoring program for Giant Mud Crabs has been reignited. In particular, data to inform biomass estimates for stock assessment and TACC setting are of interest to management and stakeholders. For both of these purposes, the target population is the exploitable biomass, that is, legal-sized male Giant Mud Crabs. Theoretically, the TACC is a forecast of the likely male biomass (by weight, not number) at 150 mm CW or greater, with the harvest thought to predominately comprise a single years' cohort in most locations. Pre-recruits are relevant as they are the sub-legal males that will moult and increase to legal size within the present or upcoming TACC year (i.e., within 12 months or within 15 to 28 months respectively). The timing of spawning suggests the recruitment of crablets less than 30 mm CW (see Chapter 1) between October and May (Figure 42), moulting to pre-recruit size (i.e., 100-130 mm CW) after approximately 12 months, then moulting to legal size or greater after a further six to 12 months. Heasman (1980) noted a distinct influx of 1+ year-old males into commercial catches in south-east Queensland east coast in spring and speculated that they would provide a theoretical basis for predicting the likely scale and timing of catches of legal marketable crabs over the ensuing 12 months.

In this chapter, we discuss the monitoring options trialed to meet the second Objective of the current project (investigate survey methodologies), including fishery-dependent data, within the broader aim of using multiple lines of evidence to move the species from a data-limited assessment, towards a better understanding of drivers of harvest and abundance.

Previously, the following have been suggested as potential stock indicators for Giant Mud Crabs (Grubert *et al.* 2008).

(i) Proportion of female crabs in the first and second mature intermoults, with the latter indicating the percentage of females that had successfully completed at least one spawning migration.
(ii) Mean size of crabs harvested – indicating stock exploitation relative to the minimum legal size.
(iii) Mating success (mating scars on males or presence of spermatophores in females) – indicating whether size or sex-harvest arrangement are detrimental to spawning success.
(iv) Catch rate – as an index of abundance at appropriate spatial/temporal scales, and whether cryptic effort (over-potting, variable soak time) can or should be considered.
(v) Adult/pre-recruit abundance – a pre-recruit index that could be gauged at least six months before the main season would assist business planning and potentially TACC setting.

These concepts are well considered and theoretically attractive, but after extensive sampling of Giant Mud Crabs throughout regional Queensland, we offer the following comments on each indicator. The first of the above is unlikely to provide insight into the stock status, as based on multiple lines of evidence (see Chapters 5 and 6), most females probably die during the spawning migration.

The second (mean size of crabs harvested for exploitation levels relative to the MLS) has some merit, but extensive sampling has demonstrated regional variation in the mean size (i.e., CW) of Giant Mud Crabs, likely a combination of the complex size-sex spatial habitat use speculated for Giant Mud Crabs and that pots often only sample part of the population – either because of the type of pot or their placement and/or spatial coverage. However, size-frequencies and sex ratios (see Chapter 6) were explored further for their suitability of monitoring Giant Mud Crab populations (i.e., stock indicators).

The third (indicators of mating success) also has merit, although we found no evidence of sperm limitation, but some evidence of a shift in male mating success to adolescent males (i.e., physiologically mature but with small claws) in a region with high fishing mortality (i.e., south-east Queensland, see Chapter 6, Figure 57). The consequence of this to spawning success and larval viability is unknown but we speculate that this is not limiting recruitment to the fishery.

The fourth (catch rate as an index of abundance) and fifth (adult/pre-recruit abundance) were considered in detail, given the data and information collected by the current project. Specifically, key questions addressed in this chapter include:

1. Can fishery-independent or fishery-dependent surveys provide estimates of exploitable biomass?
2. Can commercial catch data be utilised as an index of exploitable biomass?
3. What are the survey options for monitoring pre-recruits (i.e., males less than 150 mm CW)?
4. Can size-frequency distributions provide information on exploitation rates of legal crabs?
5. What are the relative benefits of fishery-independent surveys, fishery-dependent surveys, and reported commercial catch data?

Methods

Fishery-independent sampling

Fishery-independent sampling was conducted by the research teams from DPI and CQUniversity between November 2021 and March 2024 (Table 5, Chapter 2). Regular sampling focused on the central and south-east regions of the Queensland east coast. Both regions include no-take areas for Giant Mud Crabs. Intensive sampling was conducted periodically at Eurimbula Creek, a mud crab conservation zone in central Queensland, whilst Marine National Park 28 (MNP28, green zone) was sampled on a regular basis as part of sampling in south-east Queensland.

Fishery-dependent sampling

Fishery-dependent sampling occurred in regional Queensland (Table 6) and involved project staff sampling Giant Mud Crabs caught during commercial crabbing operations. Project staff achieved broadscale coverage of regional Queensland Giant Mud Crab populations because of the voluntary cooperation of commercial fishers who allowed staff onboard and accommodated the handling and measuring of legal and non-legal crabs, often under tidally-driven time constraints and varying weather conditions. Fishery-dependent sampling occurred in most regions of the EC1 fishery, excepting the far north region[6], and in two of the main GC1 fishery regions. Project staff aimed to collect the same information as that collected during fishery-independent sampling, but time and tidal constraints caused prioritisation of crab measurements with first priority to sex, notch width, flap shape, mating scars on males; and secondary priority to carapace width (tip-to-tip), crusher claw height, carapace length, carapace depth, and intermoult stage.

Commercial catch data

Commercial logbook data is not considered reliable for the years prior to the implementation of VMS, TACC and ITQ (Northrop *et al.* 2019). A review of logbook data identified spurious reporting of catch coincident with the 2003 fishery investment warning (Brown 2010). Metrics of effort (i.e., number of pots operated and lifted) are not always accurately or consistently recorded, creating uncertainty in catch rates (Northrop *et al.* 2019). For the fishery's initial TACC assessment, catch was universally reduced by 30% to adjust for these uncertainties when estimating biomass trends (Northrop *et al.* 2019). Since the introduction of the ITQ in September 2021, commercial logbook data is somewhat more reliable because of compulsory prior reporting of landings and catch disposal records (see

[6] Logistical challenges in accessing the far north region of the Queensland east coast prevented fishery-dependent sampling. However genetic samples were acquired from this region with the cooperation of a commercial fisher for extension of the genetic analysis to ~14°S. The results of which will be reported upon in a Williams *et al.* in prep (2025).

Chapter 1). On this basis, commercial data from 2021 onwards was used in the following analyses. Anonymised catch and effort data (Data Request 2796) were summarised to determine relationships between the fishery-independent sampling, fishery-dependent sampling and regional trends in catch – as an exploration of means to monitor Giant Mud Crab populations in Queensland.

Results and discussion

1. Can fishery-independent or fishery-dependent surveys provide estimates of exploitable biomass?

In Queensland, the exploitable stock biomass consists of male Giant Mud Crabs greater than or equal to 150 mm CW. For the TACC year, exploitable biomass includes male Giant Mud Crabs 150 mm CW or greater, plus sub-legal male crabs that will moult to or above 150 mm CW during July to the following June.

Working backwards from available growth information (i.e., proportional moult increment-at-size, Figure 6, Chapter 1), 150 mm CW males are derived from (on average) 130 mm CW males after they moult, and 130 mm CW males are derived from (on average) 110 mm CW males. Whilst simplistic, the theoretical proportional increase in size suggests that the exploitable biomass of males ≥ 150 mm CW between July and the following June is derived from males in the order of 110 mm CW, plus any remnant larger males that have avoided capture. Thus, males 100 to 149 mm CW may provide a pre-recruit index for the upcoming TACC year. Males smaller than 100 mm CW may also contribute to the exploitable biomass, but intermoult duration is likely to be seasonally variable as a function of feeding efficiency and regional temperatures and requires further consideration.

Catch and catch rates of legal-size male Giant Mud Crabs

The catch rates of males ≥ 150 mm CW in the Queensland east coast central region from locations open to fishing were compared between fishery-independent surveys (catch per unit effort, CPUE = number of crabs per pot), fishery-dependent sampling and regional commercial CPUE. Patterns in legal-size male Giant Mud Crab CPUE were not consistent between the fishery-independent surveys and the commercial logbook data (Figure 62), noting that the commercial data reflects a larger spatial area than the selected locations sampled in the fishery-independent surveys and includes a greater quantum of effort (operators, pots and pot days).

Seasonal patterns in the CPUE of female crabs in the fishery-independent surveys were mostly similar to the catch rates of legal males (Figure 62). This suggests that the lower catches of male crabs in the fishery-independent surveys were not a result of high commercial catches at the same time (i.e., caused by short-term population fish-down). The difference between fishery-independent and fishery-dependent catch rates likely reflects differences in the spatial distribution of 'sampling' effort. Commercial fishers are highly specialised at targeting legal male crabs, have knowledge of prior fishing effort at localised sites, where higher densities of legal males are likely to occur, move pots to optimise catch rates and are not subject to research sampling constraints of deploying pots in deep water (for animal ethics reasons).

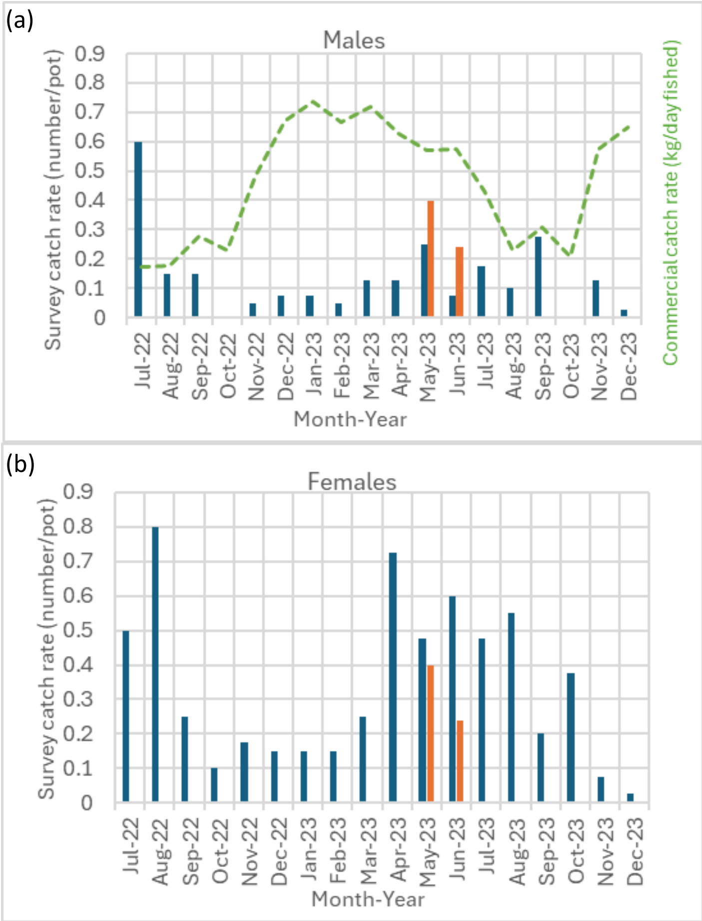

Figure 62. Comparisons of catch rate trends in surveyed central Queensland locations open to fishing using fishery-independent (blue bars) and fishery-dependent surveys (number of crabs per pot lift, orange bars), and commercial catch data (male only, green line, unitless kg/day for logbook confidentiality). (a) legal male Giant Mud Crabs. (b) female Giant Mud Crabs.

2. Can commercial catch data be utilized as an index of exploitable biomass?

TACC year patterns EC1 and GC1 management units

Reporting of ITQ usage prior to landing (i.e., at the end of a ‘trip’) is a compulsory part of the commercial crab fishery in Queensland. Daily updates of total ITQ usage for the EC1 and GC1 management units is available at (https://fishnet.fisheries.qld.gov.au/Content/Public/ViewReport.aspx?ReportID=2v), which was downloaded on a regular basis by project staff and is presented in Figure 63. The within-year trend in ITQ reporting approximates the seasonal patterns in mean monthly catch rates (Figure 9, Figure 13). For the limited number of years examined (subsequent to the introduction of ITQ in September 2021), quota usage (i.e., catch in kg) in the EC1 management unit accelerates in approximately mid-December, whilst in the GC1 management unit, it accelerates initially in September to October, and then again from approximately March. The plot of the EC1 management unit suggests it may be possible to forecast the trajectory of the catch, based on a pre-recruit index sampled prior to the mid December increase in catch of legal sized males. In other words, can the abundance of males <150 mm CW in October and November be used as an index of abundance of males ≥150 mm CW from December onwards. This concept was explored further below as a case study for two EC1 regions.

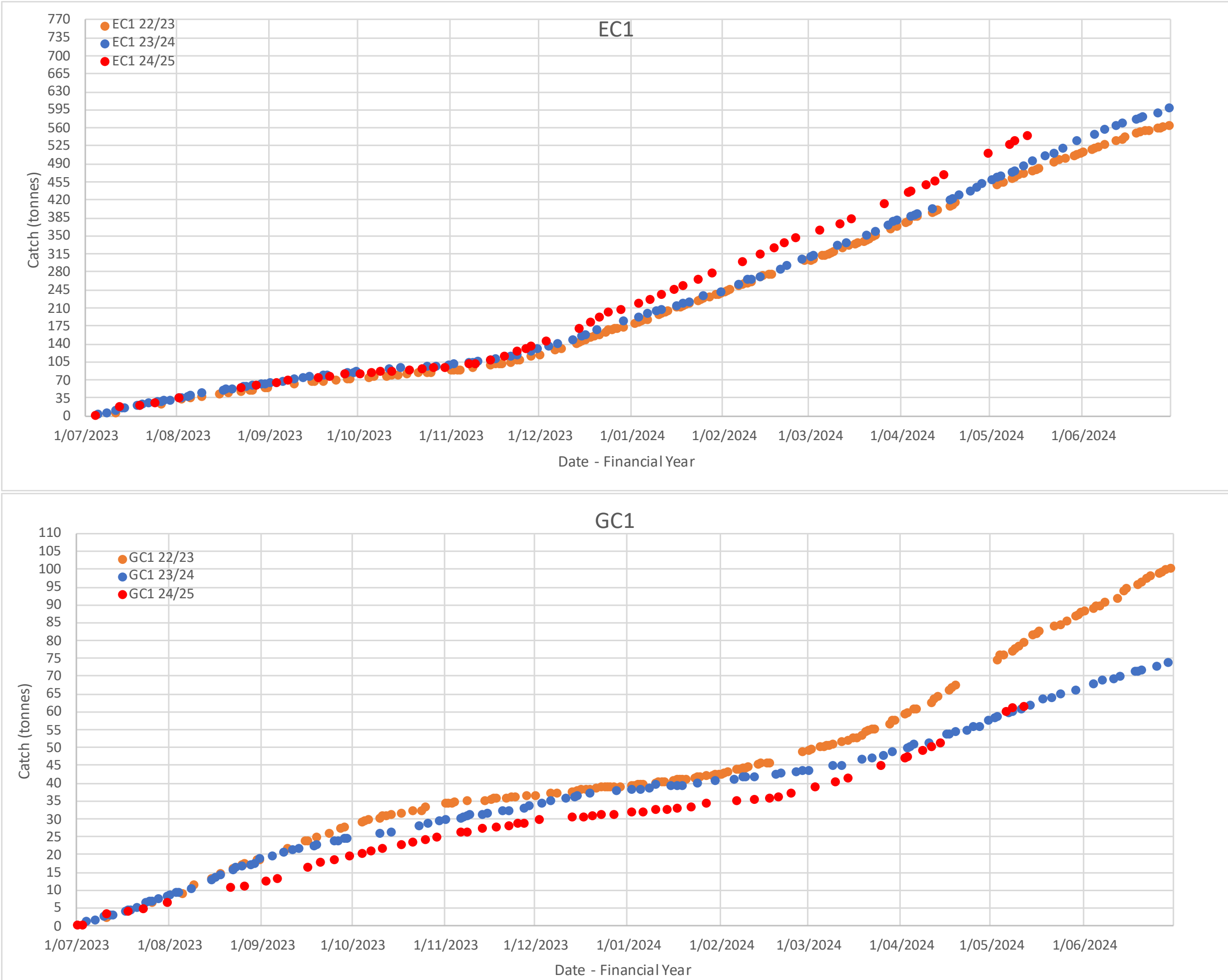

Figure 63. Cumulative quota usage East Coast (EC1) and Gulf of Carpentaria (GC1) for Giant Mud Crabs for the 22/23, 23/24, and 24/25 (to 27/01/25) quota years, noting Total Quota Entitlement (=TACC) of 770 tonnes and 108 tonnes for the EC1 and GC1 management units respectively.

Monthly patterns – a case study of two regions within the EC1 management unit

Monthly commercial catch and catch rates (kg/day) between January 2021 and December 2023 were plotted for two fishery regions within the EC1 management unit: (i) the south central and (ii) south-east regions (for definitions see Table 3, Chapter 1). Seasonal patterns in harvest (Figure 64) are likely a combination of: (i) the moult-up of pre-recruits to legal size, which then becomes biomass available to harvest, (ii) seasonal water temperatures that drive feeding regimes of Giant Mud Crab and thus influence their catchability, (iii) market forces (demand and price) increasing effort and retained catch, and (iv) by the end of the 'season' the fish-down of available legal males.

Within-year regional patterns in the logbook data (Figure 64) potentially offer greater insight into the within-year management unit patterns of quota usage (Figure 63). Further analytical development of the reported quota usage at broadscale regions, such as fishery regions considered in the current research project, could provide timely insight into the cumulative catch and catch rates of Giant Mud Crabs to keep management informed of harvest trajectories.

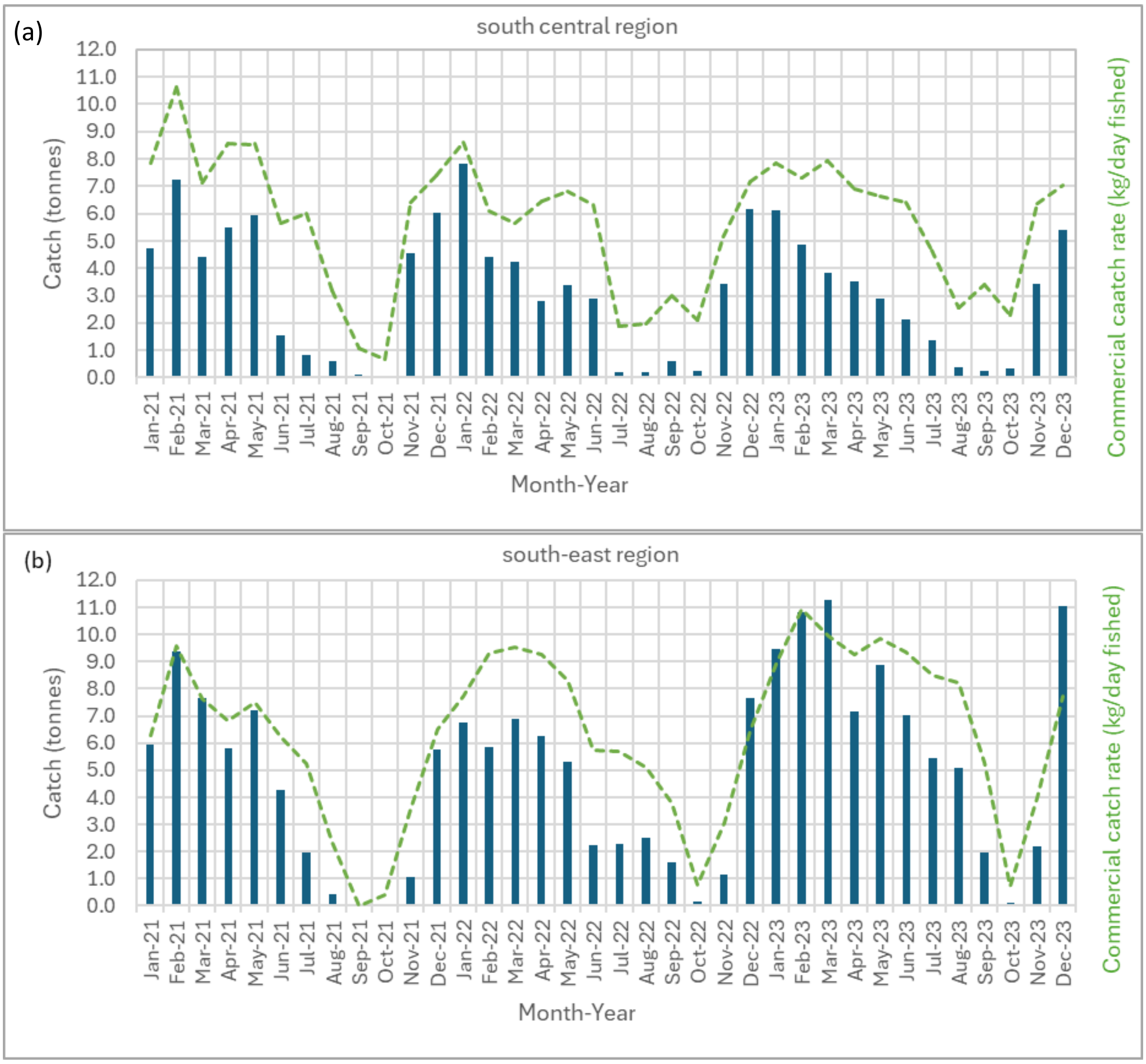

Figure 64. Monthly commercial catch (kg, blue bars,) and catch rate (male only, green line, unitless kg/day for logbook confidentiality) of Giant Mud Crabs. (a) south central and (b) south-east regions of the EC1 management unit of the Queensland Crab Fishery.

3. What are the survey options for monitoring pre-recruits (males 100-149 mm CW)?

A pre-recruit index of abundance, preferentially up to six-months prior to the main 'season' of the fishery would be useful to industry for business planning (Grubert *et al.* 2008) and could potentially inform the likely total harvest for the TACC year. Two survey types can potentially be utilised to monitor pre-recruits: fishery-independent surveys and fishery-dependent surveys. Fisheries independent sampling provides greater control over the metrics measured and the location and type of sampling effort but is cost and time intensive. Fishery-dependent sampling has less control on location (and sometimes timing) of effort but can provide some metrics about pre-recruits and is less costly or time intensive. An option for pre-recruits is to use specialised pots that larger crabs are unable to entry.

Juvenile research pots targeting pre-recruit Giant Mud Crabs (i.e., all size less than 150 mm CW) were trialled in the south-east region of the Queensland east coast during preliminary sampling (Table 5). These steel-wire pots have restricted entry funnels (Figure 17a). They were specifically set in shallow inter-tidal areas, amongst significant structure (e.g. mangroves) or other likely juvenile habitats such as brackish swamps (Figure 18). They were set and retrieved at the same time as the standard trawl mesh pots, using the same bait and with a soak time of approximately 24 hours, over the full semi-diurnal tidal cycle (i.e., two highs and two lows). As expected, these pots caught only small crabs, 77-142 mm CW but at a very low catch rate i.e., overall mean 0.82 (± 0.465 s.e.) crabs per pot lift. Standard, non-vented pots also caught small crabs, 74-149 mm CW, but at a much higher rate i.e., 1.67 (± 0.208 s.e.) crabs per pot lift on the same sampling dates (Figure 65).

Whilst only 12 juvenile research pots were set across four sampling occasions, their very low catch rates and the logistical challenges of working with large and rigid juvenile research pots on a relatively small research vessel, did not justify further use of these pots. Instead, pre-recruits were sampled through their catch in standard trawl mesh pots without escape vents (or the 75 x 60 mm escape vent which has limited effect on crab escapement (Robins *et al.* 2024).

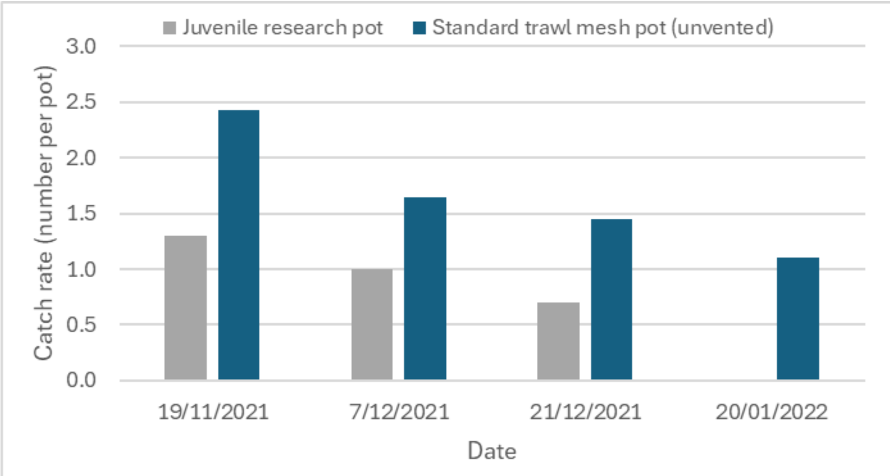

Figure 65. Mean daily catch rates (number per pot) of pre-recruit Giant Mud Crabs (<150 mm CW) in juvenile (wire) research pots and standard trawl mesh pots.

Theoretically, the TACC is a forecast of the likely male biomass (by weight not number) at 150 mm CW or greater. The abundance of pre-recruits 100-149 mm CW was explored in relation to commercial catch to determine if these 1+ year-old males could predict the likely scale and timing of catch of legal marketable crabs over the ensuring 12 months – as speculated by Heasman (1980) and Northrop *et al.* (2020), using the south-east region of the Queensland east coast as a case study.

To achieve this required bringing together the temporal patterns in abundance of pre-recruits from fishery-independent sampling with the monthly commercial catch and effort (Data Request 2796) in the area equivalent/adjacent to the fishery-independent sampling. Pre-recruits were separated into two size-class groups: 100-129 mm CW, representing males that were likely two-moults away from legal size and 130-149 mm CW representative males that were likely one moult away from legal size (see Figure 6). Pre-recruit catch data (numbers) were standardised by the number of pots set per sampling event to generate an index of abundance. Fishery-independent data from commercially equivalent pots with no escape vents or 75 x 60 mm escape vents and from locations open to fishing were included in the pre-recruit index. Data was aggregated by month of sampling and standardised by the number of pots to give a nominal catch rate (number of crabs per pot). Monthly commercial catch and effort data were used to calculate total catch, and nominal catch rate (kg/days fished) and were presented as unitless so as to preserve confidentiality of the catch data from the commercial fishing operations in areas equivalent/adjacent to the fishery-independent sampling.

Overall catch rates of legal males caught during fishery-independent sampling followed a similar pattern to that of the commercial fishery operating in the same/adjacent area (Figure 66), especially once research was permitted in the Moreton Bay Marine Park (July 2022 onwards).

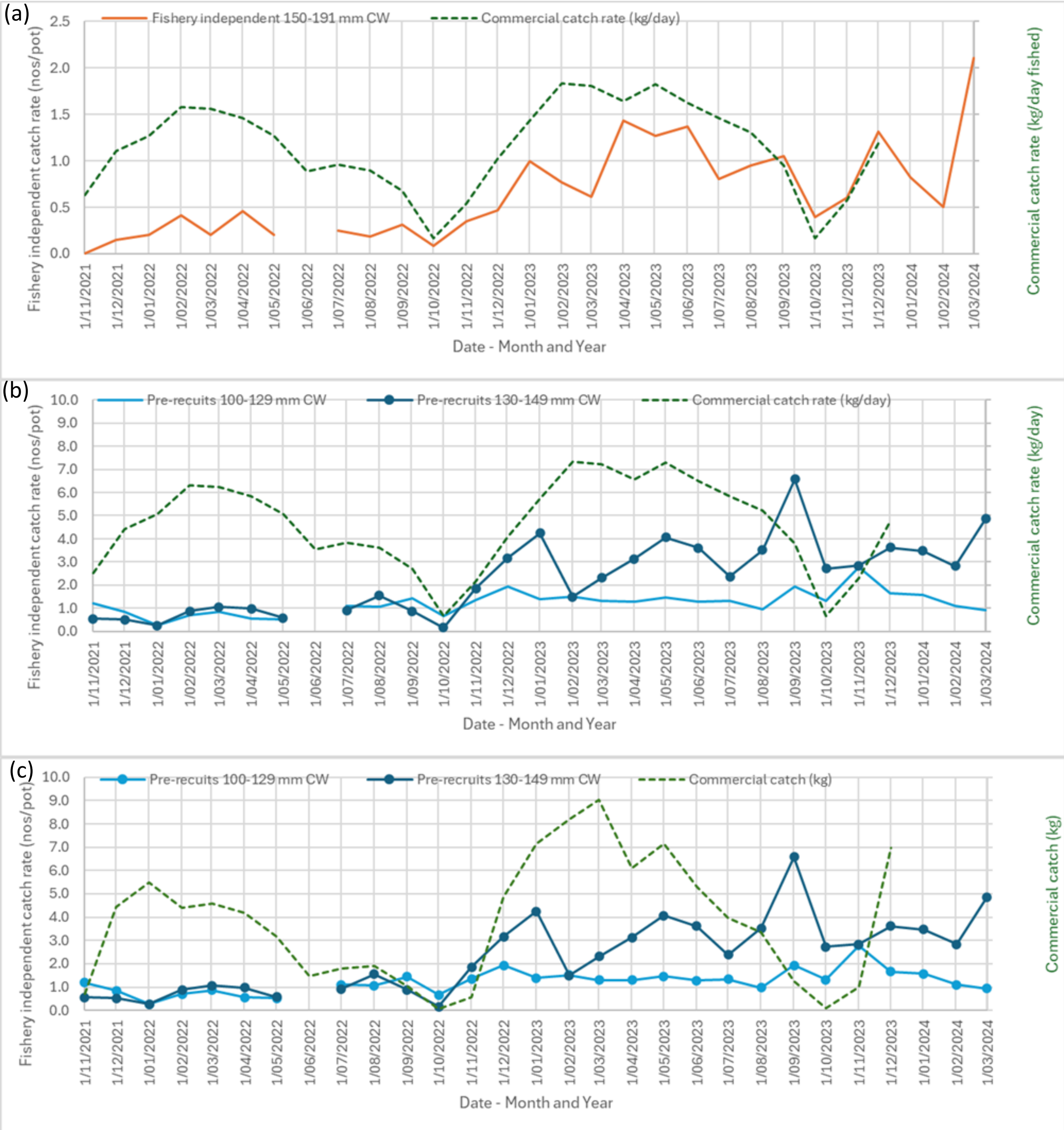

Figure 66. Monthly abundance indices of Giant Mud Crabs in the south-east region of the Queensland east coast. (a) fishery-independent catch rate of legal males and commercial catch rate (unitless for commercial in confidence reasons).(b) fishery-independent catch rate of pre-recruit males and commercial catch rate. (c) fishery-independent catch rates of pre-recruit males and commercial catch (unitless for logbook confidentiality). Prior to July 2022, fishery-independent sampling was restricted to the Logan River upstream of the border of the Moreton Bay Marine Park. From July 2022 onwards, fishery-independent sampling included areas that are commercially fished, see Figure 18.

Despite regular, spatially extensive fishing-independent sampling, the abundance of pre-recruits was not particularly predictive of the abundance of legal males. We speculate that this is primarily because the seasonal increases in water temperature effects crabs of all sizes equally in terms of increasing their feeding activities and thus attraction to baited crab pots. Whilst theoretically an attractive concept, we suggest that multiple factors indicate that a cost-effective and robust pre-recruit index of Giant Mud Crab abundance is not pragmatically possible at the scale of the EC1 Or GC1 management units.

4. Can size-frequency distributions provide information on exploitation rates?

Relative size-frequency distributions can provide additional information on crab populations, such as fishing mortality and trends in exploitable biomass (i.e., legal size male crabs, as previously suggested by (Webley 2005; Northrop *et al.* 2019).

Males central Queensland

Pooled over all sampling events, the relative size-frequency distributions of male Giant Mud Crabs were different between fishery-dependent and fishery-independent surveys in Gladstone Harbour (open to fishing, Figure 67). Males larger than the MLS were much less abundant than sub-legal males, indicative of fishing mortality. Pre-recruits (i.e., 100-149 mm CW) were less abundant in the fishery-dependent samples than from fishery-independent samples, especially those less than 130 mm – likely a consequence of escape vents. The relative size-frequency distribution of males from Eurimbula Creek (a no-take mud crab sanctuary), was different to that for areas open to fishing, with an approximately normal distribution, with a modal size-class of 160-164 mm (Figure 67).

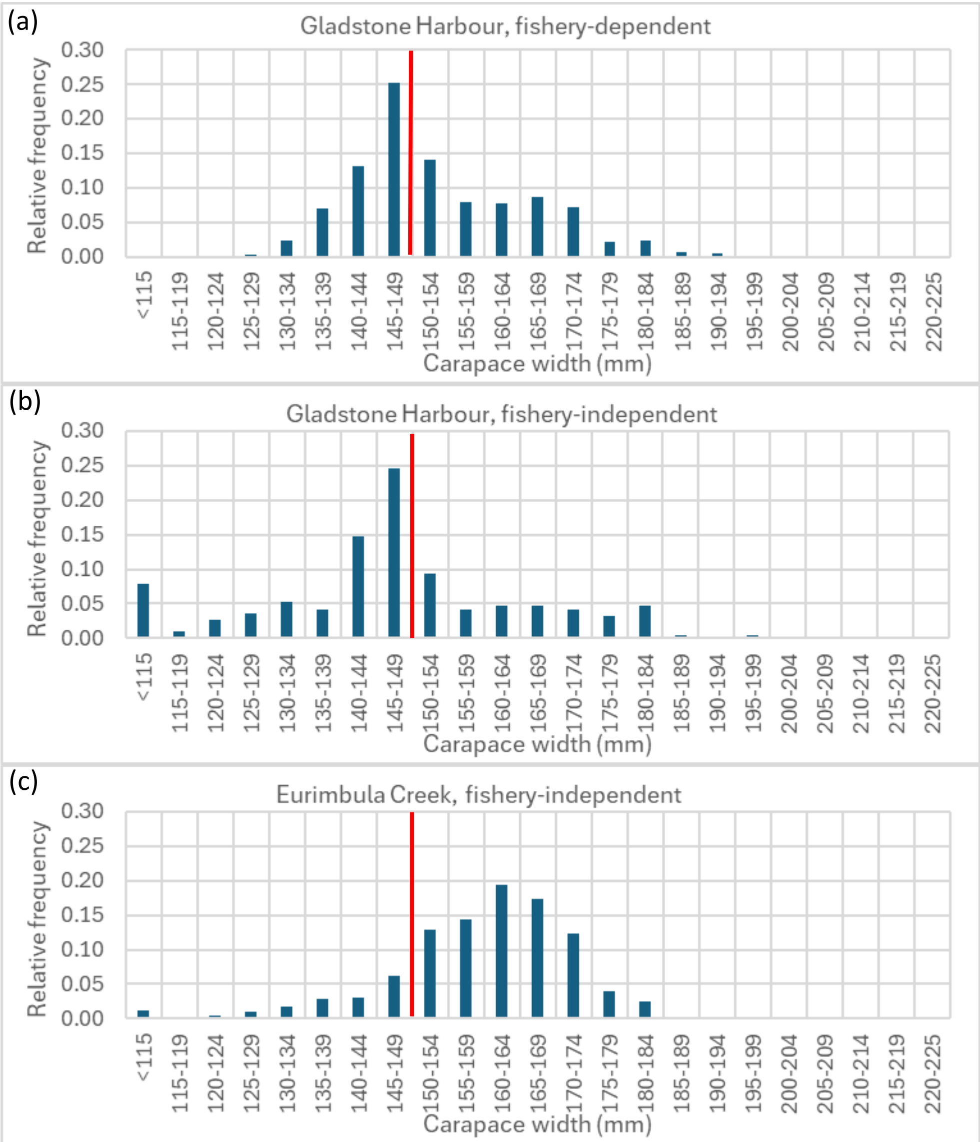

Figure 67. Relative size-frequency of male Giant Mud Crabs. (a) Gladstone Harbour, fishery-dependent surveys (n = 553). (b) Gladstone Harbour, fishery-independent surveys (n = 222). (c) Eurimbula Creek (non-take mud crab sanctuary), fishery-independent surveys (n = 1,211). Red line indicates 150 mm CW (Qld MLS).

Females, central Queensland

Pooled over all sampling events, the relative size-frequency distributions of female Giant Mud Crabs from locations open to fishing in central Queensland (i.e., Gladstone Harbour) were similar between fishery-dependent and fishery-independent surveys (Figure 68). The relative size-frequency distribution of female Giant Mud Crabs from all locations was approximately normally distributed, with a modal size class at 160-180 mm CW for Gladstone Harbour and 155-170 mm CW for Eurimbula Creek (Figure 68).

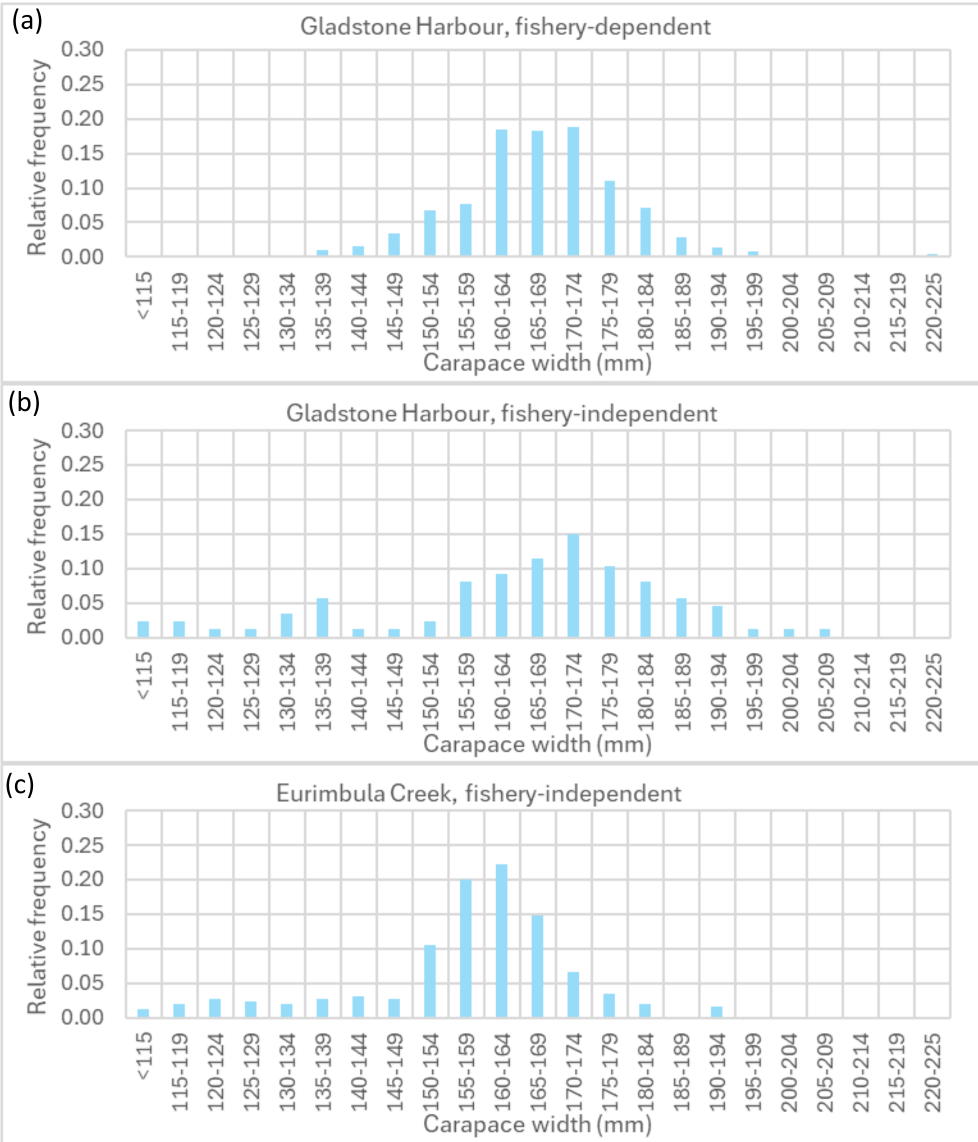

Figure 68. Relative size-frequency of female Giant Mud Crabs (all sampling events pooled). (a) Gladstone Harbour, fishery-dependent surveys (n = 493). (b) Gladstone Harbour, fishery-independent surveys (n = 231). (c) Eurimbula Creek, fishery-independent surveys (n = 256).

Male mud crabs, south-east region of Queensland east coast

The relative size-frequency distributions of male Giant Mud Crabs from locations open to fishing in in south-east Qld were slightly different between fishery-dependent and fishery-independent surveys Figure 69). Similar to central Queensland, males greater than the 150 mm CW were much less abundant in areas open to fishing, indicative of fishing mortality. The relative size-frequency distribution of male Giant Mud Crabs from Marine National Park 28 (MNP28 – an area closed to fishing) was similar to that of the areas open to fishing, with a modal size class of 145-150 mm CW. This was less than the modal size-class for Eurimbula Creek, which was 160-165 mm CW. In south-east Queensland, MNP28 is located adjacent to areas open to fishing, with some potential for males to move between closed and open areas. However, past research (e.g., Hyland et al .1984; Pillans *et al.* 2005) indicates that males have a limited home range and in general, do not move significant distances unless stimulated by changes in salinity.

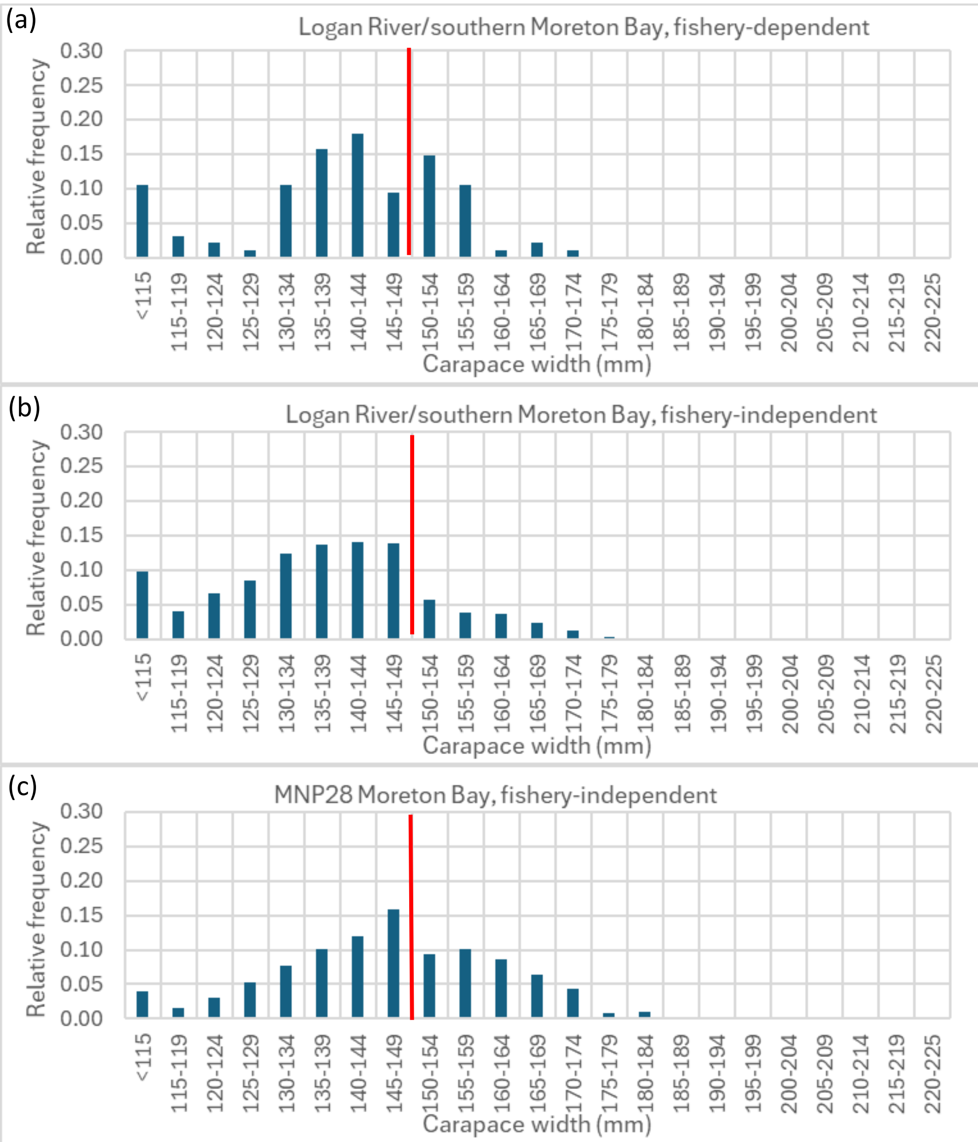

Figure 69. Relative size-frequency of male Giant Mud Crabs (all sampling events pooled) for south-east region of the Queensland east coast. (a) fishery-dependent surveys (n = 96). (b) fishery-independent surveys (n = 5,450). (c) areas closed to fishing (MNP28) (n = 1,963).

Female mud crabs, south-east region of the Queensland east coast

The relative size-frequency distributions of female Giant Mud Crabs from locations open to fishing in south-east Qld differed between the fishery-dependent and fishery-independent surveys (Figure 70). This likely represents differences in locations fished. There was some evidence of bimodality, with a small mode at 125-135 mm CW and a major mode at 160-170 mm CW in the fishery-independent sampling (Figure 70b), which had was spatially and temporally extensive, high sample numbers (>2,000 female crabs) and overall likely to have encompassed a broad range of habitats used by female Giant Mud Crabs. In the south-east region, the relative size-frequency distributions of females were similar between areas that were open and closed to fishing. In general, more smaller female crabs were caught in the south-east region than the south central region (i.e., Gladstone Harbour).

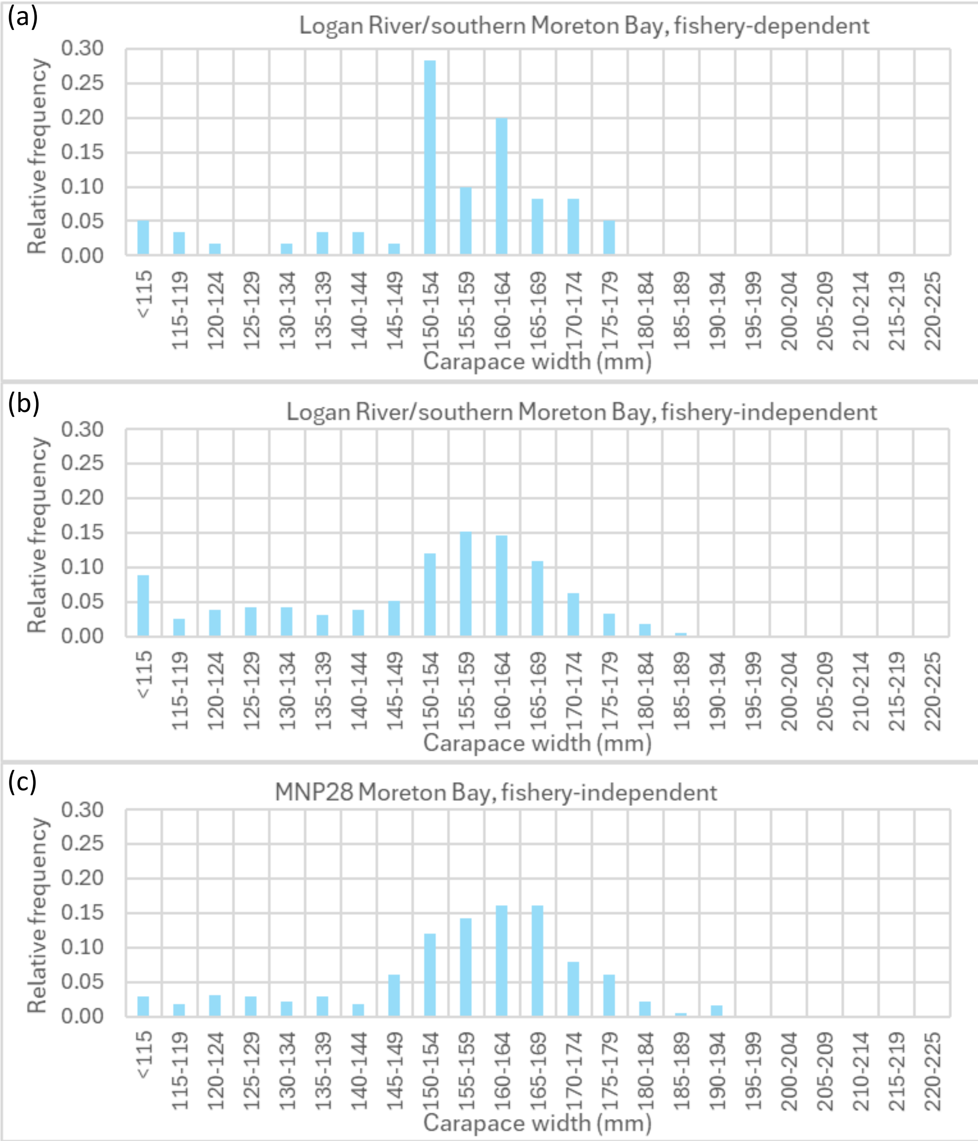

Figure 70. Relative size-frequency of female giant Mud crabs (all sampling events pooled) for south-east Queensland. (a) fishery-dependent surveys (n = 60). (b) fishery-independent surveys (n = 2,189). (c) areas closed to fishing (MNP28) (n = 556).

As identified by above, and by others (e.g. Jebreen *et al.* 2008; Flint *et al.* 2021), the relative size-frequency distribution of males of legal size can be a qualitative proxy of fishing mortality. Sex ratios metrics (see Chapter 6) can provide a more quantitative proxy of fishing mortality, although a range of factors including variation size-sex spatial habitat utilisation by Giant Mud Crabs needs to be accounted for in the sampling design of monitoring programs.

5. What are the relative benefits of fishery-independent surveys, fishery-dependent surveys, and commercial catch data?

In terms of monitoring Giant Mud Crab populations, fisheries-independent sampling provided greater control over the location of sampling effort and the metrics measured but was cost and time intensive.

Fishery-independent data (i.e., scientists using research vessels) was the highest cost method, having costs for travel, boat use and labour for two to four crew. Data acquisition was relatively lower per unit of funding available, but data were of high quality, standardised, and collected in a way that maximised statistical analysis, notwithstanding inherent variability in sampling Giant Mud Crabs. Fishery-independent surveys were constrained by animal ethics permit conditions, which include setting crab pots only in locations where they will remain submerged throughout the tidal cycle, to minimise bycatch mortality. This potentially excludes large parts of the preferred foraging habitats of large male crabs, in intertidal mangrove forests and mud flats. Limited placement of pots may have had some influence on the different catch rates recorded by fishery-independent surveys and commercial logbooks (see “Catch volume and catch rate” section, above). Fishery-independent surveys using pots permitted (under a General Fisheries Permit) provided the most data on pre-recruits and under Marine Park permits, provided data on crabs in conservation zones such as Eurimbula Creek and the MNP28.

Fishery-dependent data relies on cooperation with commercial operators, to allow a scientist aboard to take various measurements on retained crabs, as well as those returned to the water. This option has lower costs but still had costs for travel and labour. The data collected during fishery-dependent surveys were of high quality and in the current study in relatively higher volume than fishery-independent surveys. This is somewhat to be expected as is the probable bias towards the targeted catch of large males. Many commercial crabbing operations are constrained by tidal access and therefore operate at a rapid pace. This can pose challenges for the onboard scientist to be able to collect the same range of data as that gathered during fishery-independent surveys. A limitation of fishery-dependent data in Queensland waters is the effect of legally required escape vents on crabs sampled. The 120 x 50 mm and 105 mm round escape vents significantly reduce the catch of pre-recruits, whilst the 75 x 60 mm escape vent has limited effect (Robins *et al.* 2024). Therefore, if targeting pre-recruits and using fishery-dependent surveys, escape vents would need to be disabled (e.g., via cable tie and under a General Fisheries Permit). A major benefit of the fishery-dependent surveys was that it enabled the exchange of experience and knowledge between survey staff (in this instance DPI research scientists) and industry stakeholders.

In Queensland, commercial catch data has become somewhat more reliable since September 2021 with the introduction of ITQ and associated reporting requirements. Commercial catch data has two forms, but both are currently limited to information about the retained catch (i.e., harvest), with little information about the catch returned to the water (i.e., sub-legals, pre-recruits or females). Whilst it is possible for more data to be gathered by commercial operators on non-harvested Giant Mud Crabs, the detail required (i.e., measured size plus gender for all crabs from all pots checked, at least once per week) would be logistically challenging, given most operations are time-constrained by tide.

The first form of commercial data is the long-standing logbook data (1988 onwards), which is a large, ‘free’ dataset that includes fishing date, number of pots deployed (often reported as the maximum number per C1), number of C1 symbols in use, retained catch (number and/or whole weight in kg), and effort (count of fishing days). Effort is imprecisely recorded as it does not include soak time, lifts per day or a means of validating the number of pots checked. Effort metrics (beyond days fished) in recent years (i.e., 2021 onwards) could be improved through detailed, artificial intelligence assisted analysis of VMS tracks. Currently, only the total number and/or total weight of crabs is recorded in the logbook, providing limited insight into biological information (i.e., size-frequency, weight, grade, mating scars, crusher claw height, incidence of *Loxothylacus ihlei,* number and size-frequency of Giant Mud Crabs returned to the water).

Giant Mud Crab stocks in some high catch regions of Queensland experience high to very high fishing mortality from the commercial and recreational fishers. This is inferred from the distinctive decrease in the frequency of legal male crabs (i.e., ≥ 150 mm CW) compared to the frequency of sub-legal males crabs (i.e., <150 mm CW, Jebreen *et al.* 2008, see also Chapter 6). In such areas, this means once males are 150 mm CW or greater, the catch is likely a reasonable estimate of relative abundance. This was demonstrated by the size-frequency distribution of male crabs in high catch regions, as the relative frequency of legal males decreased markedly compared to unfished areas and to females. Size-frequency distributions gathered through fishery-dependent or fishery-independent surveys, could potentially provide a qualitative metric of fishing mortality, but should have sufficient replication to address temporal trends in catchability (seasonal and inter-annual, and pot attraction/avoidance behaviours) and spatial patterns in ontogenetic habitat use by different parts of population including density effects.

The second form of commercial catch data is quota usage in the EC1 and GC1 management units (i.e., FishNet Public, Reports, Quota Usage – Non-Coral, available at https://fishnet.fisheries.qld.gov.au/Content/Public/ViewReport.aspx?ReportID=2). This extensive commercial catch data resource is updated daily reflecting prior reports of landings for ITQ balances (by weight). Although this index is not forecasting exploitable biomass 12 to 18 months in the future, it may potentially provide an early indicator as to the likely trajectory of harvest within a TACC year, by acting as a proxy of available exploitable biomass. Currently, quota usage is the most up-to-date index of exploitable biomass harvest, as logbook data can be delayed for a number of reasons. We suggest that queries of quota usage for regions within the EC1 and GC1 (e.g. by the regions developed by the current research project to better understand the fishery, see Table 3 and Table 4, Chapter 1) may provide a quantitatively based, early-assessment of the likely exploitable biomass. For example, if the trajectories significantly deviate from previous years, this could trigger an immediate review of conditions in a region (environmental, effort or market driven) to assist in understanding catch fluctuations.

The current research project identified that valuable information can easily and cost-effectively be gathered by including the following additional 'measurements' to Giant Mud Crab research and monitoring programs. Besides the standard metrics of size (NW or CW) and sex (male or female), we recommend recording for males the presence of mating scars and crusher claw height, and for females abdominal flap shape in females and externally visible signs of ovarian development. These form the basis for understanding key population parameters, such as size-at-maturity, mean size of the mature or reproductively active parts of the population, and average maximum size, which can guide stock assessments and/or harvest strategies.

Conclusion

This chapter compared three types of data that could be used to monitor Giant Mud Crabs in Queensland: fishery-independent surveys, fishery-dependent surveys and commercial catch data. We found that no single data type could be used for all purposes, but that all three were useful for different aspects of monitoring Giant Mud Crab populations and their associated fisheries.

Whilst the commercial catch data (logbook or quota usage priors) provides information on between year and within-year patterns of catch (assumed as a proxy index of abundance where moderate to high levels of fishing mortality occurs), the abundance of pre-recruits and females requires either fishery-independent or fishery-depending monitoring. Further consideration needs to be given to the value of a pre-recruit index, and the acceptability of the costs associated with collecting the necessary data.

Chapter 8. Harvesting female Giant Mud Crabs in Queensland: a reconsideration and a case study

J.B. Robins

Introduction

Two species of mud crab occur in Queensland waters: the Giant Mud Crab (*Scylla serrata*) and the Orange Mud Crab (*Scylla olivacea*), with the harvest consisting of more than 99% Giant Mud Crab. Females of both *Scylla* species have been regulated as a no take fishery species in Queensland waters since approximately 1913 (Brown 2010). However, females are legally harvested in Western Australia, the Northern Territory and New South Wales, with jurisdictional size limits reflecting regional size-at-maturity (Table 2). In the western Gulf of Carpentaria, large harvest declines in 2016 (Grubert *et al.* 2019), created concerns that fishing mortality on females may have been a contributing factor, although it was more likely a response to a severe climate event (Robins *et al.* 2020), with increased catches in recent years (Kirke *et al.* 2023). However, the decrease led to a spawning indicator being included in the Northern Territory's mud crab harvest strategy, aimed at preventing recruitment overfishing (NTDPIR 2017).

The complete protection of females provides a large brood stock (equivalent to unfished) from which recruitment can occur. Giant Mud Crabs are highly fecund, having between two and ten million eggs per egg mass, with females able to multi-batch spawn up to three times during an intermoult period (Brick 1974, D. Mann pers. comm.). This level of fecundity suggests that there is significant reproductive redundancy, most probably to account for high larval loss/mortality. Fewer than 1% of offspring are estimated to survive to become adults (Vogt 2012). The harvest of mature female Giant Mud Crabs will lessen the number of larvae produced; therefore, any harvest needs to balance an increased risk of reduced reproduction (and less recruitment) with the benefits of the harvest of females. This is an ongoing concern in the Northern Territory and New South Wales (Haddon *et al.* 2005; Grubert *et al.* 2019; Johnson 2023).

The growth and survival of Giant Mud Crabs is speculated to have some density-dependency associated with habitat limitation (Hay *et al.* 2005). Harvest of large and aggressive crabs reduces the density of crabs across the available habitat, that is limited and likely of different 'quality' or 'optimality'. In theory, the removal of large crabs through harvest may result in greater access for smaller crabs to higher quality habitat and food resources, leading to faster growth, better survival and shortened time to maturity.

Taking of females in Queensland

The issue of female take in Queensland has been the subject of several reviews, with their key points summarised below.

Hill (1984) noted that "disproportionate sex ratios (due to single sex harvest) by themselves do not constitute a case for exploitation" but that the number of spawners necessary for maintenance of the population is not known and would be difficult to estimate. Earlier, Hill (1980) suggested that any harvesting of females should monitor for signs of "recruitment overfishing" and that a stepwise approach using tight catch controls on a single sector is more likely to detect recruitment overfishing.

In 1993, a National Mud Crab Workshop (Barleet *et al.* 1993) noted that there was 'no valid scientific reasons for protecting female mud crabs above a certain size and that Queensland should examine its current regulation'. The need to estimate size of maturity in females was noted, as was the suggestion that the minimum legal size (MLS) should be based on the size at which 50% of the females in the population are mature, referred to in the current research as $CW_{50\%Female}$ (see Chapter 6). Prior to the current research, the only data on size-at-maturity in Queensland waters was for Moreton Bay, based on the work by Heasman (1980), and estimated to be 147 mm CW.

In November 2009, a four-day workshop reviewed the risks and benefits of allowing the harvest of female Giant Mud Crabs in Queensland and developed a plan for implementing a policy change to enable female harvest (Brown 2010). The review included assessment of the reported commercial and estimated recreational harvest for the Queensland east coast and Gulf of Carpentaria. Brown (2010) noted that the ability to control and validate the number of pots in water (often referred to as 'over-potting') needed to be addressed before changes in the single sex harvest policy should occur. Brown (2010) also noted that an initial 'fish-down' would occur but should be a transient effect that would stabilise with potential for increase in yield over time. The perceived risks of permitting a female harvest were:

(i) decreased profitability from increased supply and thus decreased market value[7],
(ii) potential for recruitment overfishing, and
(iii) activation of latent commercial and recreational effort and associated conflict around sectoral allocation.

<u>These perceived risks remain a concern.</u>

During the 2009 review, desktop Growth-type-Group (GtG) simulation models, using parameters from Heasman (1980) informed management strategy evaluations. These indicated that theoretically "conservative levels of minimum legal size (i.e., 150 mm CW) would not impact adversely on the stocks sustainability". Four population metric indicators were considered as part of the GtG modelling:

(i) commercial catch – legal males and legal females,
(ii) egg production – spawning biomass of female crabs and recruitment via a non-linear stock recruitment relationship in the GtG model,
(iii) vulnerable male biomass, and
(iv) vulnerable female biomass.

A MLS for females of 160 mm CW was "considered appropriate, as any MLS greater than that would start impacting on the benefits of permitting female harvest". This MLS was estimated to reduce the vulnerable female biomass by 30-40% and up to 50% of egg production, but not necessarily 50% of recruitment. The modelling suggested that catches (i.e., tonnages) would initially spike as fishing impacted the (previously unfished) population (i.e., large females), then would stabilise at a lower level. In terms of catch rates (i.e., kg/day fished), high catch rates and 'easy fishing' were predicted in the first year or two of any female harvest experiment, with lower catch rates (and fishing less 'easy') in subsequent years. The same pattern in catch and catch rate has been explicitly stated herein, in order to raise awareness of the likely patterns in the tonnage of catch that potentially has market implications and catch rates that potentially has population size perception implications.

Brown (2010) reiterated that a female harvest MLS should 'ensure' that protection of the spawning biomass is achieved i.e., that each female crab has on average, the opportunity to spawn once or

[7] The beach price of mud crabs has doubled since 2009, from approximately $25 per kg to approximately $50/kg, noting variation with Grade and seasonal market demand.

twice. This statement needs re-consideration given the results of the current research, which concur with other studies, that most females probably do not survive the spawning migration (see Chapter 6).

In regard to female harvest, Brown (2010) recommended:

(i) minimise the "risk of recruitment overfishing",
(ii) MLS not be below 160 mm CW,
(iii) a reliable indicator of stock size would be "paramount",
(iv) impact on female biomass should be "very carefully (and accurately) controlled" – with an output control (i.e., allowable catch) more appropriate for managing risk than input control (i.e., MLS, number of pots),
(v) state-wide allocation of single-use crab tags to the commercial fishery be in proportion to 'recent history', say 20% of the average of the last two years' catch of male crabs, and
(vi) proceeds from female harvest should contribute to the administration and monitoring costs of the fishery.

Brown (2010) concluded that:

(i) "in principle, there is no justification for pursuing the single-sex harvest policy for mud crabs in Queensland (or elsewhere). However, until such time as a reliable indicator of stock abundance is developed, it would not be wise to allow the take of female crabs", and
(ii) an 'experiment' on the harvest of female mud crabs should be carried out a regional level.

Methods, results and discussion

The current consideration of female harvest drew upon size-at-maturity results produced by the current research (see Chapter 6), cross-referenced against estimates from other research on *Scylla serrata* (e.g., Heasman 1980; Knuckey 1999), as well as inferences about the proportion of females in their 1st and 2nd maturity intermoults (Chapter 6), and the likelihood of females surviving the offshore spawning migration.

The reconsideration presented in this chapter does not advocate for or against a trial of female harvest to occur, nor for such a trial to occur in the GC1 management unit. It simply uses the Gulf of Carpentaria as a case study to consider what an 'experimental' harvest of female Giant Mud crabs might look like if carried out at a regional scale. The reconsideration was initiated after a request from Fisheries Queensland management and industry stakeholders. We recommend that any trial harvest of female Giant Mud Crabs should aim to not increase effort in the fishery either through the activation of more C1 symbols or through the use of more pots in the water. From an empirical perspective, the GC1 management unit has the following advantages and disadvantages:

- genetically different to east coast stock (see Chapter 3, Williams in prep),
- a limited number of commercial operators spread across a broad geographic area, but which could change depending the activation of C1 symbols,
- relatively small recreational fishing pressure,
- relatively few landing points,
- remote and spatially extensive fishery, presenting enforcement challenges,
- somewhat genetically 'closed' population due to the circulation patterns in the GoC, and therefore higher 'risk' of the harvest impacting recruitment, and
- the stock potentially at a higher risk to severe climatic events than east coast stocks.

We considered the following key biological issues in regard to a trial female harvest:

(i) permittable size of females harvested (i.e., minimum legal size), and
(ii) biomass of females harvested (limited, unlimited).

Other issues that need consideration include who has access to female harvest, what entity 'owns' the biomass to be harvested as there is no precedent for the take of female *Scylla serrata*, is Crown-owned quota leased to interested individuals or existing operators a cost-effective means of enabling a trial without risks of transfer of novel property rights, what are effective means of constraining harvest to the permitted take/biomass extraction. These are beyond the biological focus of this case study but are as equally important as the biological issues discussed.

Size-to-harvest

Minimum legal size is often based on size-at-maturity, with the aim of allowing a certain proportion of individuals the opportunity to reproduce before being exposed to fishing mortality. As female Giant Mud Crabs moult to a mature body form there are two size-at-maturity metrics (Roberston and Kluger 1994). The first metric is size-at-50%-maturity ($CW_{50\%Female}$), which is based on the numbers of immature and mature individuals at size (i.e., CW) or per size-class and usually fitted with a logistic regression (Knuckey 1999) or a binomial regression (Mesquita *et al.* 2020, and as in Chapter 6). Estimated $CW_{50\%Female}$ for Gulf of Carpentaria regions varied from 126.7 to 139.8 mm CW (Table 20, Chapter 6). The second metric is the mean size of the 1st maturity intermoult (CW_{mean_mature}), which was estimated as 155.7 mm CW (± 0.32 mm s.e.) pooled across all regions sampled in the Gulf of Carpentaria. Regionally, CW_{mean_mature} was larger in the south-east region of the Gulf of Carpentaria (i.e., 166.6 mm CW ± 0.85 mm s.e.) and smaller in the north region (i.e., 153.6 mm CW ± 1.31 mm s.e. for Weipa and 153.9 mm CW ± 0.31 mm s.e. for Mapoon).

An alternate metric could be the optimal harvest size (CW_{opt}), which is the size-class at maximum biomass of an unexploited cohort and is, on average, 2/3rd of $L_{infinifty}$ (Miethe *et al.* 2016). In the case of female Giant Mud Crabs, CW_{opt} would be the 1st maturity intermoult, given high mortality associated with the spawning migration. For females from the Gulf of Carpentaria, CW_{opt} was estimated to be the 160-164 mm CW size class, based on the cumulative size-frequency of mature female sampled during the current research.

As noted previously, there are differences in the size-frequency of Giant Mud Crabs between regions for reasons that are unknown, but that likely reflect habitat differences and fishability. Estimated average maximum size ($L_{infinity}$), also varied between Gulf of Carpentaria regions (i.e., 187 mm in the south-east but 173 mm and 176 mm in the north, see Table 21, Chapter 6). Relative size-frequency size distributions of females are presented in Figure 71 to illustrate size-at-maturity, mean size of the mature intermoult and regional differences. Data for Giant Mud Crabs collected as part of the Fisheries Queensland monitoring program (Jebreen *et al.* 2008) were also plotted to gain further insight into the relative size-frequency of females in the locations not sampled by the current research project. Note that abdominal flap shape was not recorded in that program, and maturity metrics cannot be calculated from the FQ data.

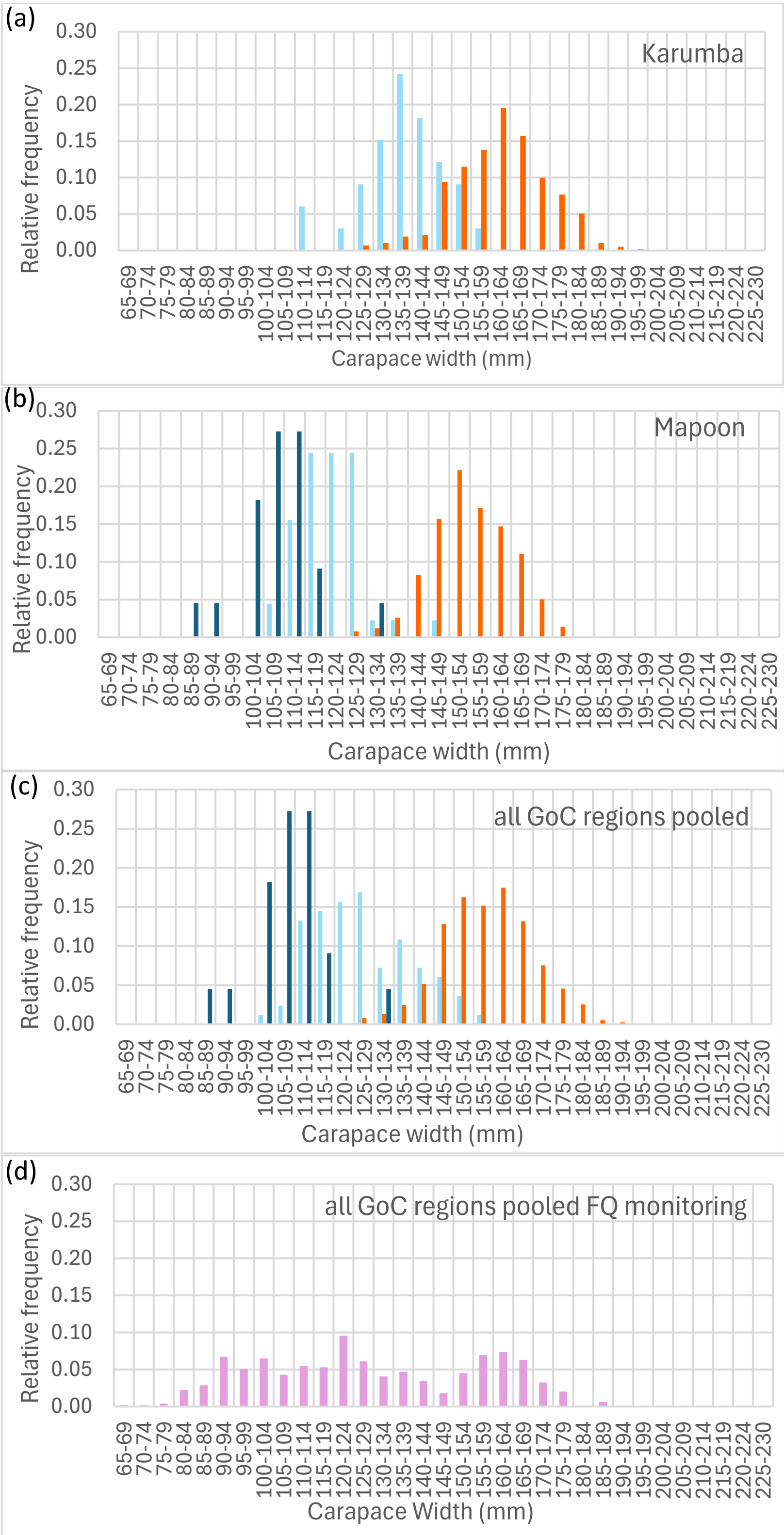

Figure 71. Relative size-frequency distribution of female Giant Mud Crabs (per flap type), sampled from the regions within the Gulf of Carpentaria. (a) Karumba (n = 606, current research). (b) Mapoon (n = 563, current research). (c) all GoC data pooled (n = 1,245 including Weipa, current research). Immature V-shaped abdominal flap indicated by dark blue bars, intermediate abdominal flap indicated by light blue bars, mature U-shaped abdominal flap indicated by orange bars. (d) Fisheries Queensland monitoring program (n = 491) all regions 2000-2008, abdominal flap shape not recorded.

More sampling of females (immature and mature) smaller than 140 mm CW and greater than 175 mm CW would make inferences about female harvest more robust, so that females that are immature, or in their 1st or 2nd mature intermoult are adequately represented in the maturity estimation process.

We suggest that CW_{mean_mature} or CW_{opt} are more robust metrics upon which to base any hypothetical MLS for female Giant Mud Crabs, as they theoretically protect 50% to 66% (or more) of the spawning stock; allowing these individuals to undertake a spawning migration, and even if 90% die during spawning, still provide a significant number of larvae and potentially recruits. It was beyond the resources of the current research to replicate the GtG modelling of Brown (2010), but the data and results from the current project provide a robust empirical base for further consideration.

Size-to-harvest is a trade-off of several factors i.e., size-at-maturity traded off against the availability of leg-sized crabs, such that frequency of catch is feasible and cost-effective. The cumulative frequency of mature females sampled from the Gulf of Carpentaria is based on fishery-dependent sampling, where the fishery is targeting the legal males and the areas they inhabit. Females of large size (i.e., ≥ 170 mm CW) were relatively rare, whilst those 160-170 mm CW were more common (Figure 72). Noting females 160-170 mm CW were more common in the south-eastern Gulf of Carpentaria, while females 150-160 mm CW were more common in the northern Gulf of Carpentaria).

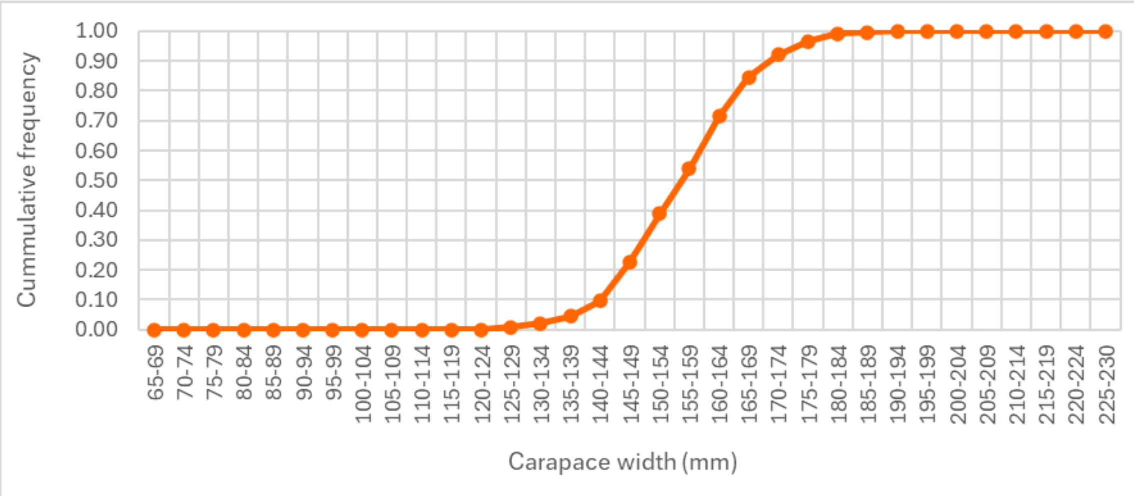

Figure 72. Cumulative frequency distribution-at-size of mature female Giant Mud Crabs from the Gulf of Carpentaria (all regions pooled, n = 1,140).

Amount to harvest

Output controls in Queensland are often a harvest amount e.g., TACC and are usually by weight (in tonnes) rather than the number of individuals. To assist consideration of the number of crabs in a given harvest amount, weight-at-size is presented in Table 24. This length-weight relationship was based on female Giant Mud Crabs from the Gulf of Carpentaria weighed during laboratory processing (see Chapter 6). The length-weight relationship for Queensland Gulf of Carpentaria female crabs is similar to that reported for the Northern Territory (1999). However, the exact weight will vary depending on the 'grade' of crab (i.e., intermoult duration) and thus 'fullness'. Females do not undergo significant enlargement of claws at maturity, and thus their weight-at-size is considerably less than for males. Weight-at-size is relevant for the conversion of a harvest tonnage at different minimum legal sizes to an estimated number of females removed from the population.

Table 24. Weight (g) at size (mm CW) for female Giant Mud Crabs in the Gulf of Carpentaria based on weight = 0.004 x $CW^{2.809}$ (n = 411, R^2=0.904)[8].

	Size (mm CW)					
	150	155	160	165	170	175
Weight (g)	518	568	621	677	736	800

There is no reference point upon which to base the setting of an initial sustainable harvest of female Giant Mud Crab in Queensland. Further consideration is required, noting that the current research project has provided quantitative estimates of some parameters that would be useful to further modelling of the harvest. Brown (2010) suggested an initial female harvest of 20% of the recent male harvest. In the GC1 management unit, recent reported harvest was 97 tonnes in 2022/2023 and 74 tonnes 2023/2024. Catch and catch rates of Giant Mud Crabs are known to fluctuate between years, with environmental factors playing a key role in crab abundance and catchability (Robins *et al.* 2020).

Potential harvest tonnages derived from ratios of females-to-males and based on recent harvests are presented in Table 25, including the initial 20% suggested by Brown (2010) as well as smaller ratios which would be more conservative in terms of risk to recruitment overfishing. Small tonnages of female harvest may not be commercially viable in terms of market supply or continuity, unless targeted at times of peak demand. However, the case study reported upon here is based on biology. A 20% female harvest (recommended by Brown 2010 – being part of the total harvest not in addition to the current harvest) is equivalent to a 1:4: ratio of female-to-males. Alternative more conservative harvests are 12.5% and 9% female harvest, equivalent to ratios of 1:7 and 1:10. Based on these ratios, the TACC and reported GC1 harvests in the last two quota's years, a trial female harvest could range between 21.6 tonnes to 6.75 tonnes, depending on the chosen values (Table 25). These values are not recommendations but initial values upon which further discussion could occur.

Table 25. Potential harvest allocations for female Giant Mud Crabs based on a ratio relative to male harvest and TACC or reported harvest.

Ratio female-to-male (% of harvest all genders)	**TACC**	**Reported harvest per quota year**	
	108 tonnes	**~100 tonnes 22/23**	**~75 tonnes 23/24**
1:4 = 20%, suggested by Brown (2010)	21.6 t	20.0 t	15.0 t
1:7 = 12.5%, hypothetical alternative	13.5 t	12.5 t	9.4 t
1:10 = 9%, hypothetical alternative	9.7 t	9.0 t	6.75 t

Combining potential harvest allocations (Table 25) with hypothetical MLS for females provides an estimate of the possible number of female crabs removed under various harvest scenarios (Table 26). If replicated for the reported GC1 harvest in 2022/2023 and 2023/2024, the numbers would be proportionally reduced to reflect 97 and 74 tonnes respectively. While hypothetical, Table 26 illustrates the interaction between allowable catch and MLS.

Biologically, any trial harvest of female Giant Mud Crabs in Queensland needs to minimise the risk of significantly effecting recruitment whilst allowing resource exploitation. Given the likely high mortality of females during their spawning migration and that larval dispersal and effective recruitment is the consequence of forces beyond human control (e.g. hydro-dynamic dispersal and climate conditions during immature stages), we suggest that any trial should aim to minimise the

[8] Knuckey (1999), female Giant Mud Crabs, Weight = 0.00028914 x $CW^{2.88207}$

number of individuals removed, whilst achieving the management-determined level of resource exploitation.

Table 26. Estimated maximum number of female crabs harvested given a hypothetical minimum legal size and various ratios of female-to-male harvest, based on the 108 tonne TACC, noting reported GC1 harvest was 97 and 74 tonnes in the last two quota years.

Ratio female-to-male (% of harvest all genders)	**Female harvest tonnes**	**Hypothetical minimum legal size (mm CW)**					
		150	**155**	**160**	**165**	**170**	**175**
		Estimated number of female crabs					
1:4 = 20% of 108 TACC	21.6	41,699	38,028	34,783	31,905	29,348	27,000
1:7 = 12.5% of 108 TACC	13.5	26,062	23,768	21,739	19,941	18,342	16,875
1:10 = 9% of 108 TACC	9.7	18,764	17,113	15,652	14,357	13,207	12,150

Brown (2010) argued that developing a reliable indicator of stock abundance was prudent before the take of female crabs should occur. The reasons behind this argument are unclear in terms of managing the risk of recruitment overfishing. Several of the research gaps identified by Brown (2010) have been addressed in the current research project i.e., regional size-at-maturity (minimum, $CW_{50\%Female}$ and mean size of mature females, see Chapter 6). Genetic connectivity has been revisited using single nucleotide polymorphisms (Chapter 3), with larval modelling by Patterson (2020), Hewitt *et al.* (2022b) and Charles *et al.* (2024). The current research also increased our understanding of the spawning migration by females (Chapter 5). Multiple lines of evidence (ovary dissection, modal progression in Chapter 6) and migration behaviour (Hewit et al 2022a, satellite tracking of spawning females in Chapter 5) strongly suggest that in the order of 90% of mature female Giant Mud Crabs are in their 1st mature intermoult and will likely die during or immediately after their spawning migration.

Given the improved knowledge since the review by Brown (2010), the remaining challenge of a trial female harvest is the removal of mature females without significant detrimental risk to larval production and effective recruitment which supports future harvest in the fishery.

Females are known to be in relatively high abundance in certain places (i.e., coastal flats, Hay *et al.* 2005) and at certain times (i.e., September to October in the GoC prior to spawning migrations, Knuckey 1999) and thus can be highly vulnerable to capture and fishing mortality.

We <u>strongly recommend</u> that any trial of female Giant Mud Crab harvest be very carefully (and accurately) controlled (i.e., no leakage) and that stringent output controls (i.e., allowable catch, all harvested females requiring post-harvest tags that are traceable and have limited life to reduce the risk of re-use) would more robustly manage the risk of recruitment overfishing than input controls (e.g. MLS), although a MLS is necessary to ensure a large proportion of mature females are able to participate in a spawning migration.

This is a re-iteration of Brown's (2010) conclusion, who also recommended that single-use crab tags would be important to accurately and accountably managing female harvest, regardless of which sector has access. We do not recommend access to female harvest where or when allowable catch cannot be effectively contained, and thus the reduction in spawning biomass cannot be effectively monitored. We concur with Hill (1984) and Brown (2010) the any trial of female harvest should be set at a precautionary level such that fishing mortality does not dramatically accentuate the fluctuations in recruitment that are primarily environmentally driven – which can occur in the Gulf of Carpentaria

Comments on monitoring and research in regard to female harvest

Three other jurisdictions in Australia sustainably harvest female Giant Mud Crabs without having an explicit "reliable indicator of stock abundance" (as recommended by Brown 2010). In order to manage the risk of recruitment overfishing, the Northern Territory estimates spawning stock biomass based on a delay-difference population model (Grubert et al 2019) and then regulates the date the fishing season is closed. As experienced in the current research into Giant Mud Crabs, and many other studies, reliable indicators of stock abundance at a population-scale are challenging to acquire, because of complexity in the spatial and temporal use of habitats by Giant Mud Crabs and limitations on the areas that can be sampled effectively.

Before or during any trial harvest of female Giant Mud Crab in Queensland waters, we recommend:

- confirmation of regional variation in size-at-maturity,
- confirmation of high natural mortality during the spawning migration,
- temporal modelling of larval dispersal so that depressed recruitment due to hydrological conditions could be identified and potentially separated from fishing mortality effects, and
- consideration be given to how the harvest could be spatially distributed across the trial area, so that localised overfishing of females and thus recruitment limitation does not occur.

Brown (2010) recommended quantifying changes in size-structure, sex ratio, reproductive activity and abundance resulting from trial female harvest. We suggest that this requires size and maturity information of harvested as well as non-harvested individuals.

The harvest of females is a passionate subject for many individuals with an interest in mud crabs. There are multiple management, economic and sectoral allocation issues relevant to any trial harvest of female Giant Mud Crabs in Queensland. These were not considered herein but represent significant challenges that need to be considered and addressed.

Chapter 9. Conclusions, implications and recommendations

Conclusions

Genetic samples were analysed using single nucleotide polymorphisms (SNPs) from ten locations (four from the east coast of Queensland, five from New South Wales, one from the south-eastern Gulf of Carpentaria). Results confirm that the east coast stock is genetically different to the Gulf of Carpentaria stock. Genetic structuring was not detected from different locations along the east coast, despite sampling across 2,300 km of coastline (i.e., Hinchinbrook Island ~18.5°S, north Queensland to Port Stephens ~23.7°S, New South Wales). This result is consistent with the current paradigm of offshore spawning and broadscale distribution of larvae. However, further analysis is recommended, as equal transfer of individuals (larvae and/or crabs) between locations (north to south, and south to north) is somewhat at odds with larval simulations which suggest there should be some level of structuring by distance.

Populations of Giant Mud Crabs in the south-east and central regions of the Queensland east coast were sampled on a regular basis by fishery-independent means (i.e., scientists setting commercially equivalent pots). Populations of Giant Mud Crabs in regional Queensland (south-east and north regions of the Gulf of Carpentaria, and north region Queensland east coast) were sampled on an intermittent basis by fishery-dependent means (i.e., scientists onboard commercial crabbing operations) due to a combination of cost-efficiency, intense effort in some regions, and to engage stakeholders and ensure that collected data appropriately reflected industry's experience of Giant Mud Crab populations. These two sources of data formed the basis for analysing biological parameters of regional Queensland crab populations, as well as informing monitoring possibilities. The data collected from this spatially and temporally extensive sampling program provided the following insights into the biology of Queensland Giant Mud Crabs.

For males, the overall size-at-50%-maturity ($CW_{50\%Male}$) was 143.5 mm CW with regional variation ranging from 124.4 mm CW for the Townsville/Burdekin region to 155.8 mm CW for the Stanage/Broadsound region. Overall, 59% of male Giant Mud Crabs were estimated to be functionally mature by 150 mm CW (i.e., MLS) and capable of contributing to reproduction (once their shells have hardened). Temporal patterns in relative size-frequencies of males in the data rich south-east region of the Queensland east coast were explored to identify seasonal growth of wild cohorts, but no clear patterns could be identified for quantitative analysis of growth by modal progression.

For females, the overall size-at-50%-maturity ($CW_{50\%Female}$) was 136.3 mm CW, with regional variation ranging from 126.7 mm CW for the Weipa region to 150.2 mm CW for the Stanage/Broadsound region. The modal size of mature females in the south-east region of the Queensland east coast was 155-165 mm CW, with analysis of the relative size-frequency distributions indicating that most mature females were in their first mature intermoult, with few in their 2nd or 3rd mature intermoult. This was consistent with published speculation and results from the current research, that indicate the spawning migration incurs high natural mortality, with few female Giant Mud Crabs surviving to moult to the large size (i.e., >185 mm CW) associated with 2nd or 3rd maturity intermoult.

Ovarian development occurred throughout the year in all regions where females were sampled and reproductively staged. Multiple lines of evidence indicated spawning in the south-east region of the Queensland east coast occurs mostly between late spring and autumn, whilst in the north region of the Queensland east coast spawning occurs mostly winter to autumn, although a pulse was noted in winter to spring. This potentially indicates year-round spawning in north Queensland. Year-round reports of early benthic stage crablets (i.e., ≤ 30 mm CW) in crab pots also provides evidence of year-round spawning in the north.

Post-spawn females were extremely rare. This concurs with other lines of evidence that female Giant Mud Crabs likely incur high natural mortality during the spawning migration.

The pilot study on understanding the spawning migration deployed 12 miniature satellite tags attached to female Giant Mud Crabs showing advanced ovarian development, including one egg-bearing individual. Data was retrieved for eight individuals, providing new information on where and how the females moved presumably to spawn, incubate and hatch their eggs. Offshore migration is likely variable, depending on local conditions, which has consequences for larval distribution and genetic connectivity of Giant Mud Crab stocks on the east Australian continental shelf and the north Australian shelf associated with the Gulf of Carpentaria.

Juvenile survey pots (steel wire with restricted entry funnels) were trialled as a means to obtain an index of pre-recruit abundance but were not more effective at catching sub-legal crabs (i.e., 100-149 mm CW) than standard, non-vented, trawl-mesh pots. In terms of monitoring Giant Mud Crab populations, fishery-independent sampling had greater control over the location of sampling effort, and metrics measured, but was cost and time intensive. Fishery-dependent sampling had less control on location (and sometimes timing) of effort, but provided reasonable metrics on Giant Mud Crab populations, and was less cost and time intensive. As identified by others, the relative size-frequency distribution of males can be a qualitative proxy of fishing mortality, as males 150 mm CW and greater have decreased abundance. Metrics based on sex ratios can provide a more quantitative proxy of fishing mortality, although variation caused by the size-sex spatial habitat use needs to be accounted for, with adequate sampling across habitats and replicate temporal sampling preferably over years. Theoretically, the TACC is a forecast of the likely male biomass (by weight not number) at 150 mm CW or greater for a 12-month period from July to June. The abundance of pre-recruits (i.e., 100-140 mm CW) was explored in relation to commercial catch to determine if the abundance of 1+ year-old males could predict the likely scale and timing of catch of legal marketable crabs over the ensuring 12-months. The south-east region of the Queensland east coast was used as a case study. Despite temporally regular and spatially extensive sampling, the abundance of pre-recruits (likely two and one intermoults before legal size) was poorly predictive of the abundance of legal males. Whilst theoretically an attractive concept, we suggest that multiple factors indicate that a cost-effective and robust pre-recruit index of Giant Mud Crab abundance is not pragmatically possible at the scale of the Queensland mud crab fishery management units (i.e., EC1 and GC1).

On request, the biology of female Giant Mud Crabs in the Gulf of Carpentaria was reviewed in terms of a regional trial harvest. We recommend that the mean size of the 1st maturity intermoult inform any decision on the minimum legal size (MLS). This was estimated to be approximately 156 mm CW for Queensland waters of the Gulf of Carpentaria. Therefore, we recommend any MLS for females be larger than 156 mm CW. A range of potential biomass extractions were considered, ranging from 20% – a 1:4 ratio of female-to-male harvest; to 9% – a ratio of 1:10 female-to-male harvest. We concur with previous recommendations that any trial of female harvest should be set at a very precautionary level. Further, we consider that effectively constraining and accurately recording harvest is the most critical aspect of any trial of female harvest in Queensland, so as to understand reduction in the spawning biomass and any consequences. There are multiple issues associated with a trial of female harvest that require further consideration and careful decision making, including access rights, given none currently exist for commercial or recreational fishers. We neither advocate for nor against the harvest of females but the new quantitative knowledge generated in the current research project should support mangers and stakeholders to duly and responsibly consider female harvest.

Implications

The genetic analysis provided strong evidence that stocks of Giant Mud Crab along the Australian east coast are highly connected, probably mostly through larval dispersal. We concur with Hewitt *et al.* (2022b), that female Giant Mud Crab that mature in Queensland estuaries (and are not subject to major fishing mortality) are likely to support larval recruitment into New South Wales estuaries, particularly in the north of that jurisdiction. Genetic analysis reaffirmed that stocks of Giant Mud Crab in the Gulf of Carpentaria are genetically distinct from the Australian east coast, supporting separate management arrangements for the EC1 and GC1 management units.

Results from the assessment of regional biology indicates that the current MLS of males combined with a no female harvest policy produces a very low risk of recruitment overfishing populations of Giant Mud Crab of Queensland waters, notwithstanding seasonal, localised depletion due to harvest. There was no evidence of sperm limitation in females as a consequence of a male-only harvest policy, despite evidence of high fishing mortality in many of the regions sampled based on length frequencies. However, there was evidence that physiologically mature small-clawed males (referred to as adolescents in previous literature) may be participating to a greater degree in mating and reproduction than previously thought potentially because of high fishing mortality on males of 150 mm CW or greater. The consequence of this is unknown. Multiple lines of evidence suggest that mature females suffer high mortality during the spawning migration. Differential natural mortality between males and females should be accounted for in any stock assessment.

Currently, the most feasible and representative means of ‘monitoring’ Giant Mud Crab populations in Queensland at the scale of the management units (i.e., East Coast and Gulf of Carpentaria) is the reported commercial harvest. There are potential opportunities to develop within-quota-year assessments of exploitable biomass trajectories for regions within the management units based on the prior reports of quota usage. Assessment of the quota usage trajectory could provide a within-quota-year signal as to whether exploitable biomass (as indexed by reported catch) is tracking as expected or has deviated from ‘average’ and thus trigger a review on the conditions in a region (e.g., environmental, effort or market driven). This would better assist management and assessment to understand catch fluctuations in a timely manner.

Monitoring

- Commercial logbooks can be used to monitor trends in catch of exploitable biomass during the TACC year, though the effort measures available are imprecise.
- Fishery-independent surveys likely underestimate the exploitable biomass available to the commercial fishery.
- Fishery-independent and fishery-dependent surveys can provide a wide range of catch, effort and biological data relevant to the management.
- Fishery-dependent surveys can be conducted at a lower cost than fishery-independent surveys. Fishery-dependent surveys can also provide the co-benefit of understanding the logistics and the dynamics of the fishery, at fine spatial and temporal scales.
- Only fishery-independent surveys can access areas closed to harvest/fishing (e.g., Eurimbula Creek and Moreton Bay Marine Park), which are useful reference sites.
- Size-frequency analysis from fishery-dependent and fishery-independent surveys could potentially provide information on the proportion of exploitable biomass that is harvested each year.

Recommendations

The research achieved broadscale spatial sampling, but not all areas were sampled equally, and the far north region of the Queensland east coast was not sampled (except for genetics, reported on separately in Williams *et al.* 2025 in prep). Further data collection on biological parameters of Giant Mud Crabs in regional Queensland is recommended if there are further concerns about mud crabs. However, multiple lines of evidence suggest there is no immediate threat to the sustainability of Giant Mud Crab populations in Queensland, other than illegal harvest, whose scale is unknown and thus impact on the population is unconsidered.

We recommend that t-bar tagging of Giant Mud Crabs undergoes further testing under controlled conditions to verify tag associated mortality that occurs during moulting. Studies using t-bar tags on wild populations of Giant Mud Crabs should consider the effects of cryptic mortality.

There is clear evidence of high fishing mortality on legal males in some areas of Queensland, but there is no strong evidence that this is a threat to the sustainability of Giant Mud Crab populations. We recommend that a watching brief is kept on the fishery harvests by management. A cost-effective means of doing so could be the development of regional summaries of quota usage, visible to management or other appropriate persons (e.g. members of the Crab Working Group) so that deviations from the average trajectory of cumulative harvest within a quota year can be identified promptly and a review of causes instigated.

We recommend caution in the further investment of resources towards a pre-recruit index to forecast exploitable biomass for TACC setting. Whilst theoretically attractive, such an index would require substantial, spatially extensive sampling – potentially only possible through fishery-dependent sampling and using crab pots capable of retaining pre-recruits. The exception to this would be where and when seasonal harvest trajectories (e.g., identified through regional analysis of quota usage) significantly (especially negatively) deviate away from the ‘average’ trajectory of quota usage. On-water fishery-dependent or fishery-independent surveys could sample pre-recruits (i.e., males <150 mm CW) but sufficient spatial and temporal coverage in the region/area in question would be needed.

We recommend the application of micro pop-up archival satellite tags to females with advanced ovary development to further understand the offshore spawning migration of *Scylla serrata* as a further research endeavour. Broadscale deployment of this technology would provide insight into this previously elusive aspect of their life history. However, this is not critical to the sustainability of the fishery, unless there is a change in the Queensland’s no-female harvest policy.

Whilst this report contains a review of female biology in regard to a trial harvest, we do not recommend for or against progression of a such a trial, leaving such matters to management.

Further development

Tagging of Giant Mud Crabs using t-bar tags could undergo further testing to verify tag associated mortality during moulting.

Further deployment of micro pop-up archival tags on female Giant Mud Crabs with advanced ovary development could provide insight into the offshore locations where females migrate to spawn and incubate their eggs, with consequences for the seed point of larval dispersal in model simulations.

There exists the opportunity to conduct further research on the Orange Mud Crab (*Scylla olivacea*) in Queensland waters, particularly the far northern regions, with the aim of determining species specific size-at-maturity and informing an appropriate and separate minimum legal size to enable a greater harvest of this species, which can readily be distinguished from the Giant Mud Crab (*Scylla serrata*).

Regional summaries of quota usage could be developed as a cost-effective means of monitoring regional harvest in almost real time, such that deviations from the 'normal' trajectory of cumulative harvest within a quota year can be identified promptly and a review of causes instigated.

A review of issues beyond biological considerations into the harvest of female Giant Mud Crabs in Queensland waters could occur, given the renewed interest but ongoing controversy on their harvest. These issues include management, economic and sectoral allocation matters such as trial location, duration and form, access, controls, monitoring, economics, and market impacts.

Chapter 10. Extension and adoption

Media release November 2020

QDPI Ag New Article December 2020

DPI Queensland Agriculture social media post March 2023 – tagging females

FRDC News June 2023 https://www.frdc.com.au/theres-crabs-and-theres-giant-mud-crabs?_cldee=oZ2e00LzZC4SfOeHPbfcY-67Q9yEhXhx75W4eyNjM_dl1RezbuX-BTqC00NNco48&recipientid=contact-fb98773c3aefeb119430000d3ae012a4-51179af9be364102b50f07cd30c257fa&esid=3ab94858-b114-ee11-b4b6-002248148e6c

Presentations of results to the Fisheries Queensland Crab Working Group

- May 2021 – collation and update on Giant Mud Crab research in Australia
    - FRDC 2019-062
    - FRDC 2017-006, including associated PhD by Daniel Hewitt, University of NSW
    - Gladstone Healthy Harbour Partnership: Mud Crab monitoring since 2017
    - FRDC 2017-047
    - FRDC 2015-012
    -
- December 2021 – progress report FRDC 2019-062
    - Genetic results
    - Tagging trials
- May 2022 – progress report FRDC 2019-062
- March 2023 – progress report FRDC 2019-062
- March 2024 – progress report FRDC 2019-062

Presentation to the FRDC Qld Research Advisory Committee

- March 2024

Australian Marine Sciences Association 2024 Conference (August, Hobart), Presentation N. Flint

Project materials developed – Project fact sheet

Department of Agriculture and Fisheries

Queensland mud crab research project: FRDC 2019/062

Researchers from the Department of Agriculture and Fisheries (DAF) Queensland, CQUniversity (CQU) and the Department of Primary Industries (DPI) NSW Fisheries are collaborating on a Fisheries Research and Development (FRDC) co-funded research project on mud crab populations in Queensland. The project aims to provide a better information base to assess and sustainably manage Queensland mud crab fisheries.

Recreational catch (K. McLennan)

Background

The management of mud crabs in Queensland (i.e., minimum legal size of 150 mm carapace width for males, and prohibited harvest of females) is generally assumed to ensure their sustainability. However, mud crabs are subject to heavy commercial and recreational fishing pressure in some regions, as well as black market harvesting. Recent evidence from the Western Gulf of Carpentaria suggests that mud crab populations can be vulnerable to environmental events – in this case, prolonged drought combined with high temperatures and a drop in sea level led to a major failure of catch in 2016 in Northern Territory waters. Additionally, for most areas in Queensland, there is no index of female abundance, nor male to female ratios which are needed in stock assessments. Currently in Queensland, the main data used to assess mud crab biomass (against target levels) is commercial catch rates, which may not represent changes in population abundance for a number of reasons.

Objectives

1. Examine the extent of genetic mixing of mud crabs between South East Queensland and New South Wales. This work will occur during 2020/2021 and is led by Dr Sam Williams (DAF), Professor Matt Taylor and Daniel Johnson (NSW DPI-Fisheries). Due to limited information about the spawning movements of female mud crabs, there remains uncertainty about the amount of larval connection between regions due to drifting in regional currents. A genetic approach using 'Single nucleotide polymorphisms' (SNPs) will be used to assess the genetic connectivity of mud crabs between regions in Queensland and New South Wales. This will inform regional stock structure and suggest options for a possible regional management approach in the future.

2. Tag and recapture mud crabs to provide regional estimates of growth, natural mortality and movement. This work will occur in late 2021 and 2022 and is led by Dr Julie Robins (DAF) and Dr Nicole Flint (CQU). Crabs between 80 and 100 mm carapace width will be tagged and released at their catch locations. Researchers will be seeking assistance from crab fishers to report the tag-recaptures, as this information can be used to estimate movement, natural mortality, and growth (if the crab has moulted). These values are important in stock assessments and are likely to vary regionally throughout Queensland. Focus regions will be south-east Queensland (greater Moreton Bay), central

Tagged mud crab (M. Grubert)

CQUniversity AUSTRALIA | NSW Department of Primary Industries | FRDC | Queensland Government

Queensland (Gladstone/ Rockhampton), north Queensland (Hinchinbrook), and the south-eastern Gulf of Carpentaria (Karumba).

3. Develop a cost-effective method to monitor key biological information of regional Qld mud crab populations. This work will collaborate with interested fishers and is led by Dr Julie Robins (DAF) and Dr Nicole Flint (CQU). It will examine what a pragmatic and cost-effective monitoring program might look like that can provide key ongoing biological information, such as the abundance of sub-legal sized crabs, male to female ratios and size-frequencies over time (to infer growth rates). Survey pots are one means by which data on sub-legal crabs could be collected, but the project will consider a range of ideas. One option is to photograph non-retained catch and use image recognition technology to estimate the number, size and sex of sub-legal crabs. Researchers will be consulting with interested crab fishers in each focus region (Moreton Bay, central Queensland, north Queensland and the south eastern Gulf) to identify and assess workable solutions to this objective.

4. Better understand the spawning migration of female mud crabs. This objective will examine whether tagging technologies (acoustic or satellite tags) can track the migration of egg-bearing female mud crabs, to identify where the eggs are released, and what proportion of these females return to estuaries after spawning.

Egg-bearing female mud crab (Port Alma fisher)

The project is asking recreational and commercial fishers in Queensland and New South Wales to assist by reporting current sightings of egg-bearing females.

Sighting information should include date, location (e.g., lat/long), whether the crab was at the surface or caught in gear (i.e., pot or trawl-caught). Photos of the egg-bearing crab are best (top and underneath, to confirm species identification). The colour of the egg mass will indicate how old the eggs are (i.e., when did the female lay the eggs), as well as how long before the eggs hatch (i.e., where will the eggs be released and using oceanographic information determine where the larvae might end up). Researchers will map the sightings to better quantify when and where mud crab spawning occurs. **Fishers are reminded that it is prohibited under the *Fisheries Act 1994* to possess female mud crabs in Queensland**.

An ongoing research and monitoring program on mud crabs brings this species into line with other target fishery species regularly monitored by the Queensland Government. Better data will support informed decision-making, such as the Total Allowable Catch, that is necessary for the Queensland Mud Crab Fishery Harvest Strategy: 2021 – 2026 (see https://www.daf.qld.gov.au/business-priorities/fisheries/sustainable/harvest-strategy for more information).

How can you help?

Report sightings of egg-bearing females via email to info@daf.qld.gov.au or by phoning 13 25 23.

For further information or if you are interested in providing information or assistance to the project contact Dr Julie Robins at Julie.Robins@daf.qld.gov.au.

Project materials developed – Egg-bearing female flyer

Department of Agriculture and Fisheries

Wanted. Sightings of egg-bearing female mud crabs.

Researchers are asking recreational and commercial fishers in Queensland and New South Wales to report sightings of egg-bearing female mud crabs. The information will be used to map and to better quantify when and where mud crab spawning occurs.

Report sightings of egg-bearing females via email to info@daf.qld.gov.au or by phoning 13 25 23. Reported information should include:

- date
- location (e.g., GPS lat/long or named position)
- approximate water depth
- whether the crab was at the surface or caught in gear (e.g. pot or trawl-caught)
- a photo of the crab (top and underneath, if possible) for species identification
- the colour of the egg mass, which indicates how old the eggs are (i.e., when did the female lay the eggs), as well as how long before the eggs hatch (i.e., where will the eggs be released and using oceanographic information determine where the larvae might end up)
- contact details (if willing), so researchers can follow up for any further information if need be.

Female mud crab sighted offshore - east of Swinbourne Shoal, North Qld (C. Bolton)

Fishers are reminded that it is prohibited under the *Fisheries Act 1994* to possess female mud crabs in Queensland. If you do handle a female mud crab, it must be immediately returned unharmed to the water.

Trawl-caught egg-bearing female mud crab (J. Lee). Based on egg colour - eggs are about 10 days into incubation with about 5 days until hatch.

Pot-caught egg-bearing female mud crab (Port Alma fisher). Based on egg colour – eggs are about 3 days into incubation.

Mapping sightings of egg-bearing female mud crabs is part of a Fisheries Research and Development Corporation co-funded research project with collaborators from Agriculture and Fisheries (DAF) Queensland, CQUniversity (CQU) and the Department of Primary Industries (DPI) NSW Fisheries. The research aims to provide a better information base to assess and sustainably manage Queensland mud crab fisheries.

For further information on the research project contact Dr Julie Robins at Julie.Robins@daf.qld.gov.au.

CQUniversity AUSTRALIA — NSW GOVERNMENT Department of Primary Industries — FRDC — Queensland Government

Appendix 1. Project staff

Department of Primary Industries, Queensland (in alphabetical order)

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Dr Gabrialla Scata, Fisheries Scientist, Fisheries & Aquaculture, Agri-Science Queensland

Mr Samuel Seghers, Fisheries Technician, Fisheries & Aquaculture, Agri-Science Queensland

Mr Nicholas Stratford, Fisheries Technician, Fisheries & Aquaculture, Agri-Science Queensland

Dr Samuel Williams, Senior Fisheries Scientist, Fisheries & Aquaculture, Agri-Science Queensland

CQUniversity

Associate Professor Nicole Flint, Principal Research Fellow, CQUniversity

Mr William Charles, PhD candidate, CQUniversity

Department of Primary Industries, New South Wales

Dr Matthew Taylor, Principal Research Scientist & Program Leader, Recreational Fisheries Research

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Appendix 3. Management arrangements for the Queensland mud crab fishery

Year	Management measure[a]	Instrument	Source
1891	Minimum legal weight • 3 lb (1.4 kg) males • 10 lb (4.5 kg) females		
1913	Minimum legal size (MLS) • 5” (12.74 cm) males Complete protection of females		
1926	6” (~15 cm) MLS		
1997	Investment warning Gulf of Carpentaria		Grubert 2008, page 150
September 2003	Investment warning crab fishery, east coast – no subsequent catch history will be taken into account in any further management changes		Brown 2010
2009	Rezoning of Moreton Bay Marine Park, with additional green zones		
2014	Investment warning all Queensland commercial fisheries		
	2 x C1 permitted per PCFL		
1st January 2019	Vessel Monitoring Systems compulsory on commercial vessels operating with C1 symbol		
1st September 2021	Harvest strategy implemented including • TACC and ITQ – financial year • TACC 80% in 2021/2022 • Compulsory Prior reporting of landings (by number) • Compulsory Catch Disposal Record (by weight) • 7-day pot service rule • 70% breakout rule to trigger a reduction in TACC • Escape vents in commercial pots	Harvest Strategy	

[a] updated from Brown (2010)

Table 27. Harvest Strategy decision rules for the Mud Crab component of the Queensland Crab Fishery.

1.0 Decision rules for the commercial harvest of east coast mud crab (EC1) and Gulf of Carpentaria mud crab (GC1)

The decision rules below provide guidance to set the TACC based on estimate of biomass being available. The decision rules use the outputs of a stock assessment and aim to achieve a target biomass (B*targ*) of 60% as a proxy for MEY. The decision rules also include breakout rules that are in place to ensure the TACC aligns with the commercial harvest level. See Appendix A.

1.1 If the biomass is at or above B*targ*, set the TACC at a level that maintains biomass at B*targ*.

1.2 If biomass is below B*targ* and above B*lim*, the TACC should be set at a level where fishing mortality is reduced to the rate that allows the biomass to increase effectively back to B*targ*.

1.3 If biomass is at or below B*lim*, there will be no targeted fishing permitted for that species, and a rebuilding strategy will be developed to increase the stock biomass to above B*lim* within a biologically reasonable timeframe and as informed by the *Queensland Harvest Strategy Policy*.

1.4 If any new information becomes available indicating that the assessment and TACC-setting arrangements are not consistent with the sustainable management of the fishery, decision rules must be reviewed and, if appropriate, the reference points or timeframes should be adjusted.

Notwithstanding that:

1.5 The rate of fishing mortality should not exceed that required to achieve B*targ*.
AND

1.6 The TAC should not exceed the level of fishing mortality required to maintain a stock at maximum sustainable yield (MSY) at equilibrium.

Breakout rule

1.7 If the annual commercial harvest is 30% or more below the TACC, then the TACC will be reduced to 10% above the most recent annual commercial harvest.

2.0 Decision rules for the recreational and charter sector harvest of mud crab

The below decision rules have been designed to maintain catch shares between sectors. If a new estimate of recreational or charter harvest indicate that either sector have increased their catch outside of their allocated catch share, then management action will be taken to constrain them within this share.

2.1 If a recreational harvest estimate is no more than 12% above the allocated recreational catch proportion, then no management action is required.

2.2 If an estimate of recreational harvest exceeds the catch share by greater than 12%, the recreational in-possession limit will be decreased.

2.3 If a stock assessment recommends an increase in the TACC to a level that would result in an increase or decrease to the commercial catch share by 25% or more, then the recreational in-possession limit will be adjusted to ensure catch shares match allocated proportions.

Notwithstanding that:

2.4 If a stock is below B*lim* and a stock assessment recommends a TAC of zero, no targeted fishing for the species will be permitted for all sectors.

2.5 The new recreational limit must not be increased or decreased by more than two crabs in any given year.

Table 28. Harvest Strategy social and economic indicators for the Mud Crab component of the Queensland Crab Fishery.

Objective	Performance indicators	Management options
Maximise economic performance of the commercial sector	Potential indicators to monitor include: • capacity utilisation • catch per unit effort (average per day) • costs, earnings and net financial and economic profit • net economic returns, gross state product, gross value of production • quota sale and lease price • profit decomposition (using profit or lease price) to determine impacts of prices, costs and stock/catch rates on changes in profits	Consider regulatory and non-regulatory options Adjust management as needed Options include minimum quota holding, latent effort review
Monitor the broader social and economic benefits of the fishery to the community	Potential indicators to monitor include: • fisher satisfaction (with their fishing experience – commercial and recreational) • Recreational fisher participation and economic information • percentage of quota/licences that are owned (rather than leased) • Gini coefficient of quota owner (measure of concentration) • percentage of total costs/inputs purchased from local businesses/residents • income generated (crew plus profit – gross value added) • proportion of catch sold locally • fish prices • number of platforms / number of active licences/ total capacity • community satisfaction (with their fisheries and the way in which they are managed)	Consider regulatory and non-regulatory options Adjust management as needed

Appendix 4. Calendar year catch and effort – EC1 and GC1

https://qfish.fisheries.qld.gov.au/query/451d4ee9-ef16-4c54-83a7-c965baf0dcc9/table?customise=True#

downloaded 30/01/2025

Calendar year	East Coast			Gulf of Carpentaria		
	Licences	Days	Tonnes	Licences	Days	Tonnes
1990	303	14,593	358.8	38	1,702	28.82
1991	328	14,522	339.2	33	1,357	26.4
1992	306	14,721	372.3	45	1,905	23.5
1993	352	18,572	433.6	53	2,234	22.2
1994	340	19,247	411.4	44	1,958	28.6
1995	330	19,981	382.4	58	2,958	61.8
1996	362	22,001	443.4	66	4,326	93.2
1997	384	24,742	459.4	84	5,117	131.0
1998	382	28,445	623.2	74	3,478	50.8
1999	396	32,683	722.7	67	4,424	114.6
2000	406	33,973	842.5	76	4,902	157.5
2001	428	33,905	845.2	77	4,867	156.5
2002	416	34,297	830.8	83	6,063	174.5
2003	432	41,414	997.5	85	7,529	150.1
2004	427	40,379	1,025.9	79	6,320	149.5
2005	360	34,098	801.9	72	6,321	166.8
2006	365	33,882	799.1	78	5,659	157.7
2007	361	33020	796.5	75	5,436	136.2
2008	377	33,162	830.2	71	5,744	178.4
2009	353	33,082	870.9	75	6,494	173.8
2010	333	34,365	1,035.3	62	6,305	187.6
2011	341	36,981	1,235.3	59	5,839	184.7
2012	332	39,195	1,230.4	66	6,267	199.8
2013	335	39,052	1,167.7	62	6,009	173.7
2014	324	37,959	1,188.9	56	5,290	146.6
2015	322	38,194	1,062.9	39	4,825	126.7
2016	300	38,988	889.8	36	3,931	100.1
2017	297	37,092	860.5	34	3,748	130.1
2018	293	36,994	865.5	32	4,049	157.5
2019	270	30,364	686.2	33	2963	99.3
2020	259	26,255	579.6	33	2412	76.2
2021	240	23,707	568.3	22	1,663	58.5
2022	206	22,584	557.5	18	1,564	78.0
2023	209	22,180	567.7	18	1,761	97.1
2024 incomplete	192	15,388	459.8	15	1,260	51.8

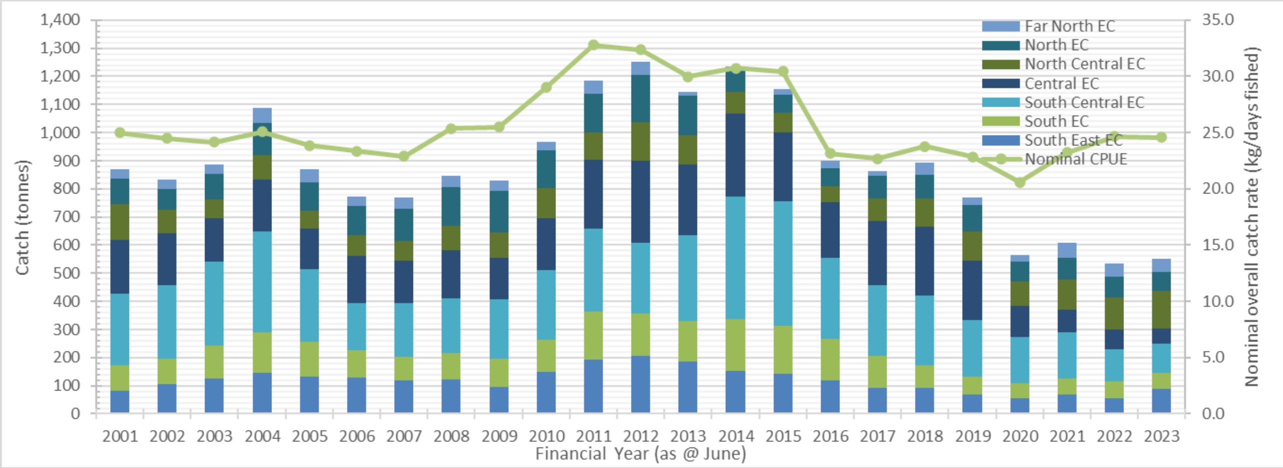


Figure 73. Reported harvest (tonnes) and nominal catch rate (kg/day fished) of Mud Crabs for regions of the EC1 management unit, Queensland Crab Fishery, 2001 to 2023 for financial year (i.e., quota year) aggregation.

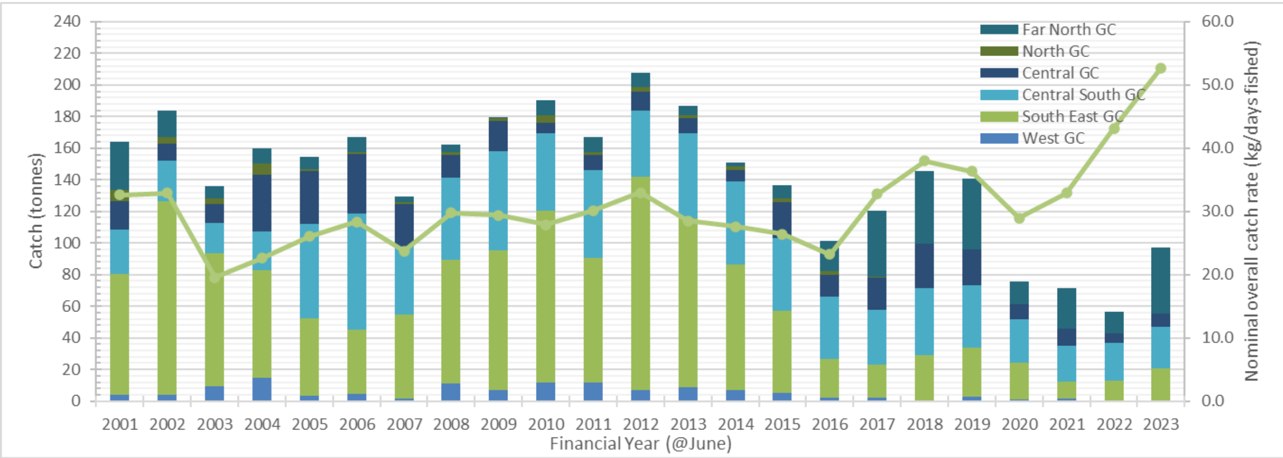


Figure 74. Reported catch (tonnes) and nominal catch rate (kg/day fished) of Mud Crabs for regions in the GC1 management unit of the Queensland Crab Fishery 2001 to 2023 for financial year (i.e., quota year aggregation).

Appendix 5. Literature review of tagging methods for Giant Mud Crabs

N. Flint

As the first step in investigating the utility of tagging for population biology (i.e., growth and longevity) of Giant Mud Crabs, the tag types that have previously been used on crustaceans, their applications, and potential for use in this project, were reviewed.

Methods

Published literature was searched through Scopus, using combinations of search terms including: crab, tag*, movement, decapoda, brachyura, crustacea, *Scylla, Portunus*. Only publications available in English were reviewed. The titles and abstracts of 791 publications were checked for relevance to the review, by February 2021. A total of 103 publications were found to be relevant and were retained for inclusion in the review. Citations and abstracts were exported into an Endnote library for cataloguing and cross referencing. Each paper was read, and data harvested for the following categories: location, species, life history stage, tag type used, stated aims, and tag results.

Grey literature about *S. serrata*, including FRDC reports, Fisheries Queensland reports and theses, were added to the library separately and some are cited in this review. The search was repeated in April 2024, to gather new papers published since the initial search was conducted in February 2021. An additional 79 journal articles were identified, 16 of which were relevant and included in the review.

Results

Of the 119 publications reviewed, 12 were about Giant Mud Crabs. An additional seven publications about other species within the genus *Scylla* were identified, including for *S. paramamosain, S. tranquebarica* and *S. olivacea*. There were 20 studies from Australia, including eight on Giant Mud Crabs, four on *Portunus pelagicus* (now reclassified as *P. armatus*), one on *Ranina ranina* and one on *Pseudocarcinus gigas*. In comparison, 47 publications reported research from the USA.

Tags for identification of individual crabs

T-bar and anchor tags

T-bar tags (sometimes called t-tags) and similar anchor tags, have been used in multiple studies of *S. serrata* over many years (Hill 1975; Williams and Hill 1982; Hyland *et al.* 1984; Tait *et al.* 1985; Butcher 2005; Pillans *et al.* 2005; Meynecke et al, 2015) and have been utilised with varying success for mark-recapture studies of a wide range of other brachyurans. When used to estimate population size, mark-recapture methods accept the following assumptions (Hay *et al.* 2005):

- The population is constant for the duration of the experiment (no births, deaths, immigration or emigration) – which in reality is difficult to achieve unless the study period is very short
- Tags are not lost (off animals) during the experiment
- Both marks and animals are correctly recorded on each occasion
- Each animal has a constant and equal probability of capture on each occasion
- Marked and unmarked animals mix and have equivalent recapture probabilities.

One of the most directly relevant previous studies identified during the literature review, was the FRDC research project on Giant Mud Crabs in northern Australia by Hay *et al.* (2005). The study experimented with mark-recapture as a method of population estimation using t-bar tags. Two experimental methods were used – a web layout and a linear depletion experiment. No substantial differences in the mark-recapture results were identified between the two methods. The simpler method was the linear depletion experiment, in which 60 baited crab pots were set at 25 m intervals from creek mouth, alternating along creek banks. Each pot was checked and rebaited every 24 hrs (on the daylight high tide) for 8 days. The creek was divided into three zones for the experiment – a 500 m depletion zone enclosed by 2 x 500 m mark-recapture buffer zones. Mud crabs caught within the buffer zones were sexed, assessed for moult stage, measured and tagged using numbered t-bar tags, then returned to the water at capture location. Crabs caught in depletion zone were measured, sexed, assessed for moult stage and removed from the study site, and later returned live to the site after the conclusion of the experiment. This experimental approach had better recapture rates of tagged crabs (36%) than those recorded in other studies of the same species. For example, a recreational fisher mark-recapture program (OZFISH) reported only 0.9% recapture (Hay *et al.* 2005).

Meynecke *et al.* (2015) trialled a t-bar tag combined with a passive integrated transponder (PIT) on *S. serrata* in both captive and field environments (Figure A.1). The study targeted crabs between 80 and 130 mm carapace width, as the authors noted that t-bar tagging could be lethal to smaller crabs and that larger crabs were unlikely to moult within the experimental time frame of 3 months. The aim was to both trial the combined tag approach and an alternative tag insertion method, in which the combined tag was injected into the right swimmer muscle tissue. Successful tagging at this site was indicated by a movement of the right swimmer leg. The tag was inserted midway along the right side at the join between the carapace and tail where moult separation occurs (the ecdysial line). The alternative tag insertion method used by Meynecke *et al.* (2015) resulted in a significantly higher tag retention rates after moulting; 85% of tags were retained using this insertion method, in comparison to 13% using the tag insertion method previously described for mud crabs (Hill, 1975). A mortality rate of 15% was observed.

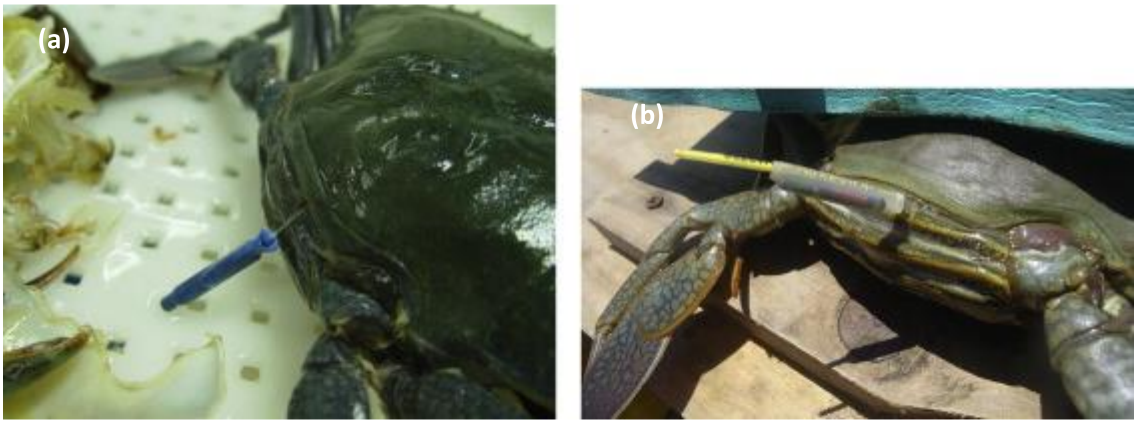


Figure A.1. Giant Mud Crabs tagged with a combined t-bar and passive integrated transponder tag (reproduced from Meynecke et al. 2015). (a) following moulting (exoskeleton on the far left of image, tag retained in moulted crab on the right. (b) tagged crab in the field study.

Plastic plate tags and strap tags

Blue crabs (*Callinectes sapidus*) are a valuable seafood product in the USA. Extensive and long-running tagging programs for this species have revealed biological and ecological information, including on movements, spawning, population size, the effectiveness of marine reserves and microhabitat use (Wolcott and Hines 1990; Carr *et al.* 2004; Aguilar *et al.* 2005; Lambert *et al.* 2006; Zohar *et al.* 2008; Goldstein and Carloni 2021; Semler *et al.* 2021; Bell and Eggleston 2022). A range of tag types are used in blue crab research programs, the simplest being a plastic plate wired to the spines of the carapace and printed with an identification number and return contact details (Figure A.2) and strap tags made of plastic-coated wire and printed with similar details (Figure A.3). Often, adult female blue crabs are studied as they do not moult (Lambert *et al*. 2006). Similar tags are buttoned with a plastic pin onto the dorsal carapace of horseshoe crabs (*Limulus polyphemus* – which are not true crabs, but belong to a different arthropod order, Xiphosura) and can last for long periods of time between moults (Swan 2005).

The benefit of these tags is that they are simple and obvious on the crab potentially increasing reporting rates by commercial and recreational fishers who recapture the tagged crabs. Because tags are cast off with the old carapace during ecdysis, some studies target recently moulted crabs to increase the likelihood of recapture before tags are lost. The loss of the tags during ecdysis means this method could not be used alone to study growth rates, however it could be useful for mortality estimates.

Figure A.2. Plastic tags wired to the carapace of Blue Crabs (Callinectes sapidus), ready for release, with a close up of the information on the tags (reproduced from SERC).

Figure A.3. Female Blue Crab (Callinectes sapidus) wearing a strap tag that includes identification and return details (reproduced from Lambert et al. 2006).

Coloured beads and string

Six glass beads of various colours were glued to the carapace of 333 adult Giant Mud Crabs in different patterns to individually identify crabs, in a study from Micronesia (Bonine *et al.* 2008). Eighty beaded crabs were recaptured during the study, and 12 had been at large for at least one month after being tagged and released.

In North Maluku, Indonesia, Coconut Crabs (*Birgus latro) were* tagged by tying coloured nylon strings to the walker legs in different patterns depending on the tagging date (Serosero *et al.* 2021). The recapture rate was very low, with only 3 of the 365 tagged crabs were later recaptured (0.82%).

Visible implant elastomer

When used on Mud Crabs, visible implant elastomer (VIE) tags are suitable for juveniles with a shell that is still sufficiently transparent to see the tag within. Liu *et al.* (2011) used VIE tags of different colours, injected into the pereiopods in single and double-mark patterns, to individually identify captive juvenile *S. paramamosain* (15-25 m CW). After eight weeks untagged, single-tagged and double-tagged treatments showed no differences in survival and growth and tags were still visible after three moult cycles. VIE tags have also been used for field identification of early benthic stage Giant Mud Crabs with a 7.8% recapture rate (Alberts-Hubatsch *et al.* 2014), other mud crabs (Fazhan *et al.* 2022) and for smaller crab species such as *Pachygrapsus crassipes* (Spilseth and Morgan 2006). Once Mud Crabs have grown into the adult stages, VIE tags can be difficult to see through the thick carapace.

Coded microwire tags

Internal coded microwire tags have been used in a variety of crustaceans, to study natural populations or to track the stocked juveniles after release into wild populations (Fitz and Wiegert 1991; Davis *et al.* 2004; Zohar *et al.* 2008). Coded microwire tags are injected into the basal muscle of the crab leg, a simple exercise which can be undertaken in the field. They can be extremely small (1.1 mm long and 0.25 mm in diameter) and are detected using a handheld scanner. The tags are reportedly tolerated well, with low mortality and no effect on growth reported in juvenile Blue Crabs (Fitz and Wiegert 1991). Another benefit is their high retention rate through moult cycles. Ut *et al.* (2007) demonstrated that the injection of microwire tags into juvenile *Scylla paramamosain* crabs (23-41 mm CW) did not affect growth or survival in aquaculture settings. The crabs experienced four to five moults during this period, with 100% tag retention. A study from East Africa used microwire tags when developing a natural growth function for Giant Mud Crabs (Mosknes *et al.* 2015). Coded microwire tags were injected into the base of the third walking leg, and recaptured crabs were identified using a handheld scanner, on regular scientific collections (Mosknes *et al.* 2015). Downfalls of this tagging system are that the tags are not visible externally so must be detected with a scanner, and the potential for consumer impacts in the case of edible species (Thorsteinsson 2002).

Tagging methods for location and environmental data collection

Passive integrated transponder tags

Passive integrated transponder (PIT) tags are typically inserted into the body of the tagged animal. However, internal tags requiring surgery are problematic for crustaceans as they have open blood systems meaning surgery is often fatal, resulting in extensive blood loss or necrosis (Thorsteinsson 2002). An external PIT tagging method for Giant Mud Crabs was trialled by Meynecke *et al.* (2015), in which PIT tags were combined with a t-bar tag injected into the right swimmer leg muscle at the ecdysial line (Figure 1). The benefit of using PIT tags externally is a reduction in injury to the crab (potentially improving post-tagging survival), and better consumer safety. The external tags are also more likely to be seen by the person who catches a tagged crab, increasing the likelihood of recapture reporting. PIT tags can be used to monitor movement and t-bar tags with external PIT tags moulded into them are now readily commercially available. Portable handheld wands can be used to identify and read the tags after the crabs have been recaptured.

PIT tags were successfully used to assess growth and mortality of the land crab *Cardisoma guanhumi* in Pernambuco State, Brazil (Schwamborn *et al.* 2021). Of the 291 crabs that were tagged, 95 were recaptured at least once and 130 useful growth increments were obtained through recaptures.

Acoustic tags

Passive acoustic tracking uses two components, a transmitter (tag) attached to the animal either externally or internally, and receivers which are permanently fixed in the marine environment. When the tagged animals are within range, the receiver detects and stores the data until it is manually retrieved by the researchers. Acoustic tracking is limited by the need for receivers in suitable locations, meaning that information on likely crab movements must be available prior to deployment. Active acoustic tracking differs from passive tracking as researchers 'listen' from a boat with a mobile receiver and follows the animal's movements (Green and Barnett 2021). Due to the high labour requirements, active acoustic tracking is only suitable for short-term deployment, but can be useful for deciding on placement of passive receivers (Green and Barnett 2021). Acoustic tags can also record depth, temperature and activity, and variations of these tags have been to track movements of Alaskan red king crabs *Paralithodes camtschaticus* (Figure A.4), Australian blue swimmer crabs *P. pelagicus* (Gribble and Thorne 1998), mangrove crabs (*Carcinoscorpius rotundicauda*) in Singapore (Cartwright-Taylor *et al.* 2012) and Atlantic rock crabs (*Cancer irroratus*) in Canada (Comeau *et al.* 2012). Alberts-Hubatsch (2015) successfully tracked female *S. serrata* in Moreton Bay, in a pilot study attempting to identify a spawning migration, as did Hewitt *et al.* (2022; 2023) in estuaries of northern New South Wales. A CQUniversity PhD student is currently tracking mud crab movements in, and departures from, a central Queensland estuary using acoustic tagging methods (W. D. Charles, in preparation).

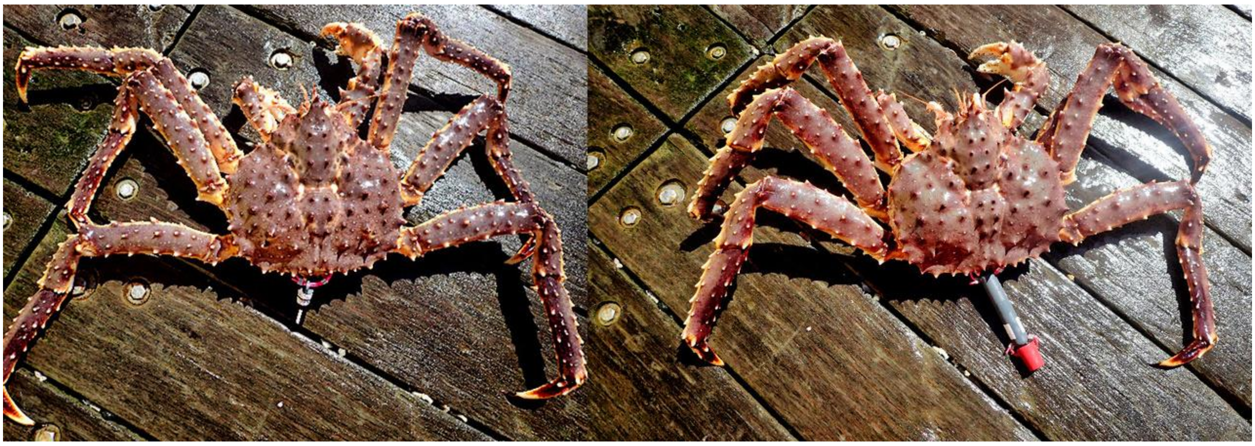


Figure A.4 Alaskan red king crabs (Paralithodes camtschaticus) tagged with a small (left) and large (right) acoustic tag. (Source NOAA).

Satellite tags

Satellite tags transmit collected location and environmental data via satellite back to a receiving station to be made available to researchers. In marine environments, fixed satellite tags only transmit data when the animal surfaces, as signal transmission cannot occur through water. This makes the tags most effective on air-breathing animals such as marine mammals and turtles, and on animals that occasionally surface for example, when feeding, e.g. some large sharks (Green and Barnett 2021).

Animals that don't surface can instead be tagged with pop-up archival satellite transmitters (PAT tags). These tags log and archive data on movement and environmental parameters (e.g., depth, temperature) and are automatically released from the animal at a pre-programmed time. PAT tags float to the surface and summarized data is then transmitted via satellites. If the tag can be relocated, the full logged dataset can be retrieved. Like most other telemetry tagging methods, satellite tags are expensive (thousands) and additional payments are made for satellite time and processing.

Marine skin tagging system

A 'marine skin' sensory tagging system, recently developed and trialled on *P. pelagicus* from the Red Sea, shows promise for combined environmental and population monitoring of crabs (Nassar *et al.* 2018). The system continuously logs parameters including temperature, pressure and salinity while tracking animal movement, transmitting real-time data when the animal resurfaces (Figure A.5). The tag is lightweight and flexible, reducing the likelihood of influencing animal behaviour, with a battery life of up to 1 year while logging every 2 seconds. This product is not yet commercially available.

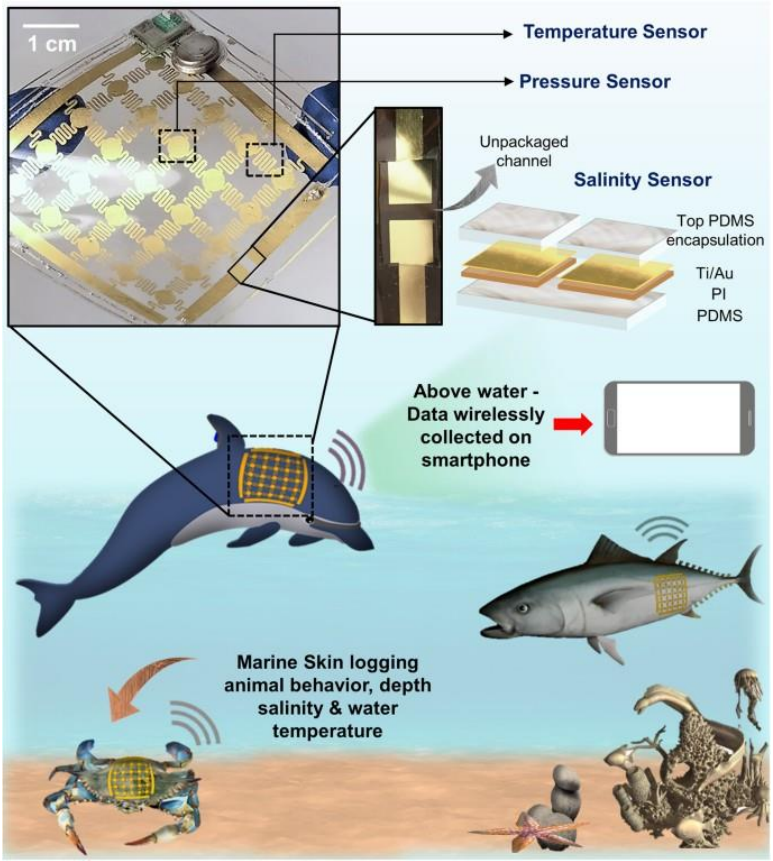


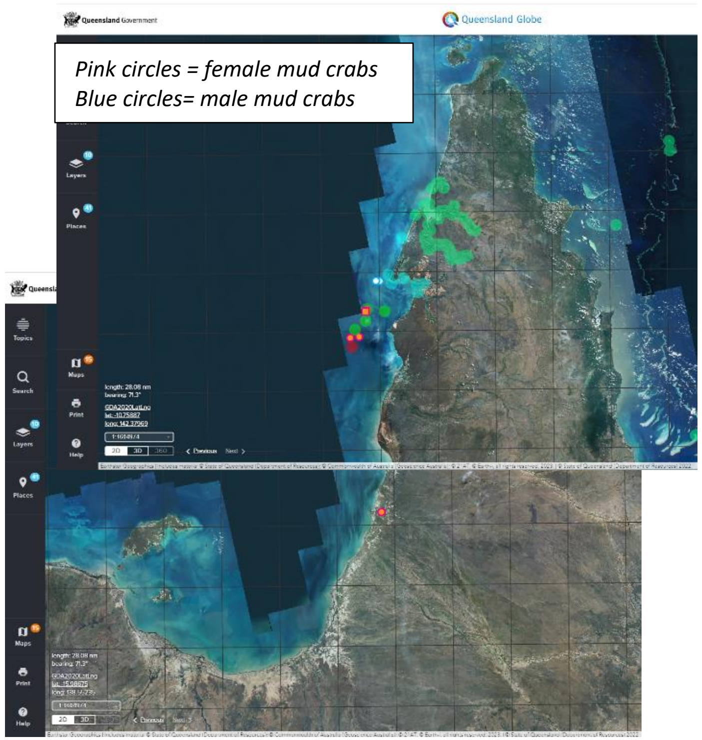
Figure 5. Marine skin tagging system developed for continuously tracking animal movement and environmental parameters such as temperature, pressure and salinity. (reproduced from Nassar et al. 2018).

Appendix 6. Review of acoustic and satellite tags to better understand the spawning migration of female mud crabs

Advanced ovary development externally visible in abdomen

Purpose

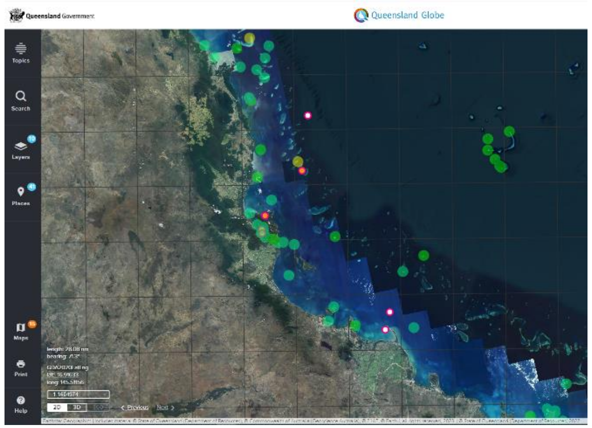
- Apply to mature female mud crabs, preferably with externally visible ovary in the abdomen, as this indicates late-stage ovary development, spawning migration 'imminent', unlikely to moult before spawning, triggers for migration uncertain.
- Collect data on details of the 'offshore movement' of spawning female mud crabs.
    - Does migration occur at surface or at bottom or a combination? Depth information required.
    - Does migration take advantage of prevailing currents and or tides? Pathway / geolocation required.
    - If geolocation data recovered, estimate speed, and infer mode of migration (walking, swimming tidal transport).
    - Determine possible fate of post spawn females (i.e., post egg hatch). Do female mud crabs remain offshore, do they mostly die (predation, lost) or survive? Do they migrate inshore back to the same or different estuary?
- Potential tags
    - Satellite - microPATs (if available) otherwise miniPATs
    - Acoustic - V9TP-2X (depth and temp) or V9P-2X (depth)



Potential Localities

- Port Musgrave (GoC north)
    - High density of acoustic receivers in vicinity (Wenlock, Ducie, Albatross Bay, Pera Head).
    - Known occurrence of female mud crabs moving offshore (Hill 1994)
    - Crabs could be caught on flats in Port Musgrave.
    - High feasibility. Moderate potential for data return.
- Karumba coastal flats (GoC south)
    - Low density of acoustic receivers in vicinity, 2 on new DPI FADS.
    - Suited for satellite tagging, not acoustic due to lack of acoustic receiver density.
    - High likely occurrence of female mud crabs moving offshore, although undocumented.
    - High feasibility. Moderate potential for data return
    - Preferred timing of satellite tagging Sept for an Oct, Nov, Dec offshore spawning migration.

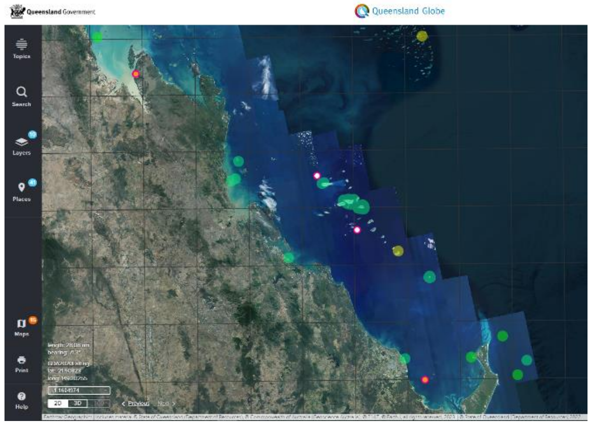
- Hinchinbrook Channel /Benjamin flats / (North Qld east coast)
    - Known occurrence of female mud crabs egg bearing within the Channel.
    - Females more prevalent on the flats (including those outside of creeks just south of Lucinda i.e., Taylors Beach, Halifax Bay, Cattle Creek, especially in April).
    - Crabs can be caught on flats external to creeks and rivers.
    - Extensive acoustic receivers (11) – conducive to acoustic tags.
    - High feasibility. Moderate potential for data return.



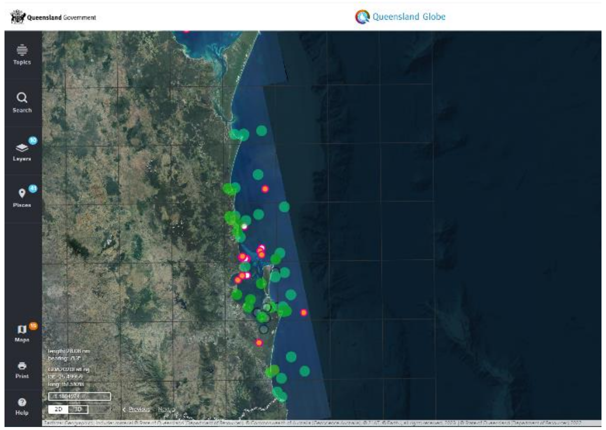
- Missionary Bay, Hinchinbrook Island (North Qld east coast)
    - Conservation area, yellow zone so ltd commercial potting, ltd rec potting except in holidays.
    - Known occurrence of female mud crabs non & egg bearing.
    - Crabs can be caught on flats external to creeks of the bay.
    - Limited acoustic receivers, more suited to satellite tags
    - High feasibility. Moderate potential for data return.
- Bowling Green Bay (North Qld east coast)
    - Conservation area, yellow zone so limited commercial and recreational crabbing effort
    - Known occurrence of female mud crabs moving offshore, non-egg bearing.
    - Crabs can be caught on flats external to creeks and rivers.
    - Limited acoustic receivers, more suited to satellite tag.
    - Moderate feasibility. Moderate potential for data return.

Eurimbula Creek (Central Qld east coast)

- Limited fishing pressure as a ‘mud crab sanctuary’.
- Bimonthly sampling by CQUniversity, location of CQU PhD student’s research.
- Males and female crabs will be acoustically tagged with V9’s for small scale spatial study.
- CQUniversity to install numerous within estuary receivers (69Hz) include one at estuary mouth to monitor ‘offshore’ movement.
- Known occurrence of female mud crab in offshore waters non & egg-bearing, captured in trawls.
- Extensive, localised acoustic arrays on Heron Island and One Tree Island of Capricorn bunker Group.
- Moderately logistically doable – estuary exit receiver to be installed and maintained by CQUniversity.

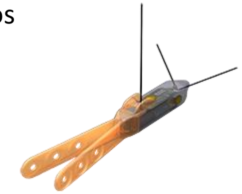
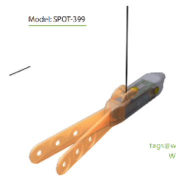


- Northern Moreton Bay (south east Qld east coast)
    - Known occurrence of female mud crabs moving offshore, non & egg-bearing, captured in BSC gear.
    - Moderate density of acoustic receivers in vicinity – north, east & south.
    - Potential data recovery of acoustic tags – moderately good.
    - Useful to confirm if females in from main SEQ habit do similar migration to NSW females.
    - High feasibility. High potential for data return.
    - Presumed spawning migration – Oct to Feb.
- Southern Moreton Bay (South Qld East Coast)
    - Known occurrence of female mud crabs moving offshore, non & egg-bearing.
    - Low density of acoustic receivers in immediate vicinity. need to deploy a receiver at Jumpinpin.
    - High feasibility. Moderate potential for data return by acoustic tags.
    - Useful to confirm if females in from main SEQ habit do similar migration to NSW females.
    - Presumed spawning migration – Oct to Feb.

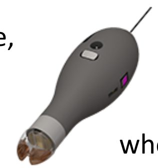


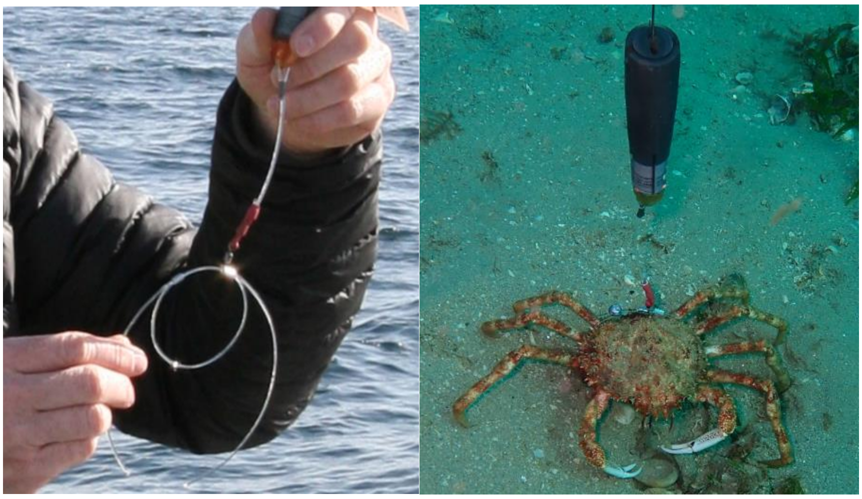
Summary of acoustic and satellite tags for potential application to Scylla serraya to provide information on spawning migration, preferred tags in blue

Model	**Parameters**	**Battery (days)**	**Size (mm)**	**Price $AUD (add 10% import duty)**	**Comments**
InnovaSea V9TP-2x	Temp and Pressure 2g	410 to 730 days	31 x 9 mm	$977 ($895 CAD)	no archive time series of depth or temp – only that at the time the crab is a passing an acoustic receiver and tag transmitting
V9P-2x	Pressure	410 to 730 days	31 x 9 mm	$893 ($815 CAD)	
V9T-2x	Temp	410 to 730 days	27.5 x 9 mm	$526 ($480 CAD)	used by Alberts-Hubsatch
V9-1x, 2x	No sensor, just occurrence	410 to 730 days	24 x 9 mm	$449 ($410 CAD)	used by Hewitt, will be used by CQUniverisity PhD study at Eurimbula Creek
Splash10-F-392	Fastloc Depth Temp Light 66g	50	74 x 28 x 24	$7250	antennae must be exposed above the surface of the water; data collected, summarised and compressed for Argos transmission, full archive on tag recovery 

SPOT horizontal movement of free ranging animals	Argos locations, time-at-temperature histogram, % dry time				only transmit when at surface, consecutive transmission received in a single satellite pass used to calculate the location of the transmitter can be customised to suit purpose, potentially fin mount , include recovery UHF pinger, tracked using a direction antenna and receiver
SPOT-376 towed	Argos Temp 45g	300	107 x 18 x 21	$2190 ($1450 USD)	in mrPAT style pop up tag could float behind crab 
SPOT-275	Argos Temp 40g	170	86 x 17 x 18	$2190 ($1450 USD)	recommended by Rowan as best glue on option for mud crabs but no depth information, geolocation questionable in GoC, 
SPOT-F-398 (Fastloc) For animals that surface quickly	Argos locations Time-at-temp histogram % dry time 65 g	70m days	180 x 19 x 26	$4756 ($3150 USD)	accurate GPS locations in <1sec, transmitted thru Argos works best on animals that surface regularly fin mounted for sharks or fish only successful locations save and transmitted UHF pinger, tracked using a directional antennae and receiver 
SPOT-399	 65 g	300 days	180 x 019 x 26	$2569 ($1700 USD)	

MiniPAT-348 *MicroPAT* Pop-up satellite archival tag with an Argos transmitter large scale movement & behaviour	Depth (±0.5m) Temp Light – geoloc Argos loc Wet/dry sensor 61g wt	800 days 63 MB memory Sample Interval (secs) 10 mins or less; determines no. data pts per day	118 x 38 plus antennae	$5670 ($3950 USD) Excluding Argos satellite charges - $180 USD	preferred sat tag (but in micro form); full data archive if recovered, summary of archived depth and temp transmitted when tag at surface after pop off; includes a radio tracking recovery; release on a date, interval or if detected at surface; corrodible pin for release on a pre-programmed date, attachment glue to carapace then tether to miniPAT applied to 18 porcupine crabs (900m) Canada, 2 mm polytube (Floy tags) tied around carapace between 3rd and 4th leg, secured with 3 mm crimps. miniPAT leader line (1.8 mm mono) secured to polytube, crimped with 1.6 mm oval crimps 
MicroPAT Pop-up satellite archival tag with an Argos transmitter	Light & SST for geolocation Depth		95 mm x 33 mm, plus antennae		depth – transmit empirical cumulative distribution, include min, and 6 hr summaries; depth time series for 4 days prior to release, full archive of depth, temp and light if tag retrieved, large scale movement & behaviour
sPAT 407	Argos loc Archive Depth Temp Light – geo 61g	60 day	118 x 38	$2989 ($2000 USD) Include Argro satellite charges	used for large scale movement & behaviour release on a date, interval or if detects at surface summary of archived data transmits to Argos when tag at surface, time series depth for the end of deployment to help determine the fate of the animal, full data archive available on recovery corrodible pin for release on a pre-programmed date - 30, 45 or 60 days or conditional release, attachment by tether ONLY SUITABLE FOR VERY LARGE FEMALES 
sPAT-355 short-term survival Pop-up satellite archival tag	Argos loc Archive Depth Temp Light -geo loc 60 g	60 days	124 x 38	$2870 ($2000 USD)	used for large scale movement & behaviour , release on a date, interval or if detects at surface, summary of archived data transmits to Argos when tag at surface, full data archive available on recovery corrodible pin for release on a pre-programmed date - 30, 45 or 60 days or conditional release attachment by tether ONLY SUITABLE FOR VERY LARGE FEMALES 

with an Argos transmitter)					
mrPAT location Pop-up coordinates upload via the Argos satellites	Argos loc Date/time mark and release Temp 40 g	730 days	127 mm x 28 mm	$2265 ($1500 USD)	tag releases at a pre-set date from application – corrodible pin, conditional release; daily min/max temperature for 100 days prior to release; daily difference between min/max tilt for 100 days prior to release  includes pinger for radio tracking recovery ONLY SUITABLE FOR VERY LARGE FEMALES applied to 15 Giant spider crabs Port Phillip Bay, data recovered from 12 secured using a harness of a 2 mm fluorocarbon line around the crab's carapace between the 3rd and 4th legs and secured with 3 mm crimps. satellite tag leader line (10 cm) secured to crab harness with 3 mm crimps. 10g lead weight fitted to leader line so tag slightly positively buoyant. longest deployment 4 mths. Tags programmed to transmit continuously every 90 secs for the duration of battery life mrPAT applied to porcupine crabs (900m) Canada
sPAT-354 benthic Pop-up satellite tag	Argos transmitte	Up to 96 days			survivorship; includes 'tilt' to measure activity in benthic species; wet-dry sensor, acceleration, knockdown archive, Argos location, orientation; pop-up date and location via Argos; release on a date, interval or if detects at surface; summary of archived data transmits to Argos  when tag at surface, full data archive if recovered
PSAT PTT-100			167 mm x 40 mm, 17 cm antennae		
X-tag Microwave telemetry			122 x 33 mm, 18 cm antennae	$4200 USD	



Vic Fisheries report. Green *et al.* 2022. Monofilament harness prepared to be fitted on to a Giant spider crab (left); Giant spider crab fitted with the harness and mrPAT satellite tag (right). Harness may not be suitable for a spawning female, which needs to be able to open her abdominal flap, extrude and carry eggs.

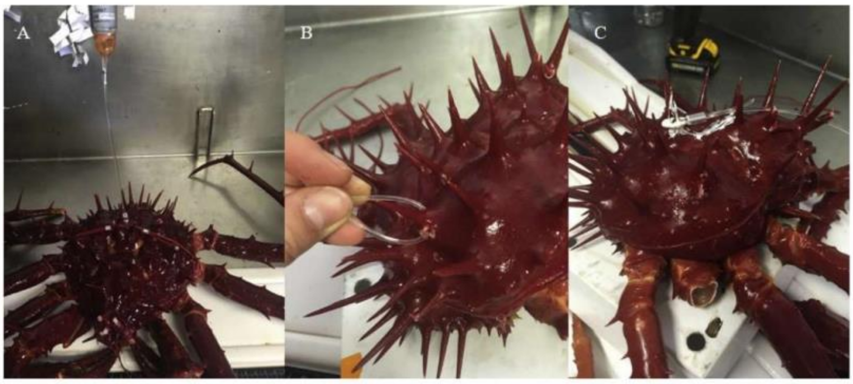


Fig. 2. Three tag attachment methods for administering pop-up archival tags on porcupine crabs: A) harness method around carapace B) drill method through spine C) epoxy attachment on carapace. Method A was formally tested and selected as the most appropriate technique.