Understanding environmental and fisheries factors causing fluctuations in mud crab and blue swimmer crab fisheries in northern Australia to inform harvest strategies

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Cover photos: (i) commercial crab boats, Roper River, (ii) harvested Giant Mud Crabs, Northern Territory (source: M.Grubert NTDPI&R); (iii) satellite image of the Gulf of Carpentaria region on the 22/03/2016 PM (https://zoom.earth/#view=-14.025,136.833,7z/date=2016-03-22,pm) © Zoom Earth.

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Abbreviations

AIC	Akaike's Information Criterion
BOM	Bureau of Meteorology, Australia
CPUE	Catch per unit effort
C1	First crab instar
CUC	Commercially unsuitable crab
CW	Carapace width
DAF	Department of Agriculture and Fisheries (Qld)
DPI&R	Department of Primary Industries and Resources (NT)
DBN	Dynamic Bayesian network
EBS	Early benthic stage
FSSB	Female spawning stock biomass
GI	Gonosomatic index
GLM	Generalised linear model
GoC	Gulf of Carpentaria
HP	Horse power
ITQ	Individual transferable quota
MJO	Madden-Julian Oscillation
MLS	Minimum legal size
MSL	Mean sea level
MSY	Maximum sustainable yield
nm	Nautical miles
NT	Northern Territory
NTWGOCMCF	Northern Territory Western Gulf of Carpentaria Mud Crab Fishery
Qld	Queensland
PSMSL	Permanent Service for Mean Sea Level
RLR	Revised local reference
SOI	Southern Oscillation Index
SST	Sea surface temperature
STST	Selective tidal stream transport

Executive Summary

The current project investigated relationships between environmental factors and harvests of crabs in the Gulf of Carpentaria (GoC), northern Australia. This was in response to industry and managerial concerns about consistent declines in harvests of GoC Giant Mud Crab (*Scylla serrata*). In the Northern Territory (NT), declines occurred between 2009 and 2016, whilst in Queensland (Qld), declines occurred between 2013 and 2016. The declines occurred despite different management arrangements (e.g. NT harvests females, whereas Qld does not), suggesting common environmental factors were involved.

Background

Giant Mud Crabs support valuable commercial, recreational and indigenous fisheries in northern Australia. The GoC (NT and Qld combined) contributed, on average, about 25% of the reported commercial harvest of mud crabs in Australia between 2008 and 2017. The vast majority of mud crabs harvested in the GoC are the Giant Mud Crab (*Scylla serrata*), with the Orange Mud Crab (*S. olivacea*) only known to occur around Weipa (Keenan *et al*. 1998). The market price for mud crabs has increased over time, with an average price at the Sydney Fish Market of about $34 per kg in 2018/2019, up from about $23 in 2005/2006 (SFM 2019). When the project was initiated in 2016, Giant Mud Crabs were classed as sustainably fished in all management areas (despite declines in catch rates), with the exception of the NT Western GoC Mud Crab Fishery, which was classified as transitional-depleting. More recently in 2018, Giant Mud Crab stocks were classified as sustainably fished in all management areas, highlighting the likely resilience of this species.

Blue Swimmer Crabs (*Portunus armatus and P. pelagicus*), occur in the GoC (Kailola *et al.* 1993), but are not a significant component of the GoC crab harvest by commercial fishers. This is a function of animal size (i.e. many not reaching the Qld minimum legal size) and commercial viability (tonnage, value, and market access). In most years between 1990 and 2019, fewer than five licences reported a harvest of Blue Swimmer crabs, with the total annual harvest usually less than two tonne (QFish 2020). However, in 2016, about 10 tonnes of Blue Swimmer Crab was harvested from shallow inshore waters of the south-east corner of the GoC. At the same time and in the same locality, Giant Mud Crabs were in reduced abundance (QFish 2020). The influx of Blue Swimmer Crabs and reduction in Giant Mud Crabs suggested a major, short-term change to the inshore ecosystem of the south-eastern GoC, which warranted further investigation.

Aims and objectives

The current project focused on the GoC to:

(i) critically review and evaluate environmental factors affecting crab fisheries in this region;

(ii) apply stock assessment models at biologically appropriate scales to test the ability of model results to inform management of the relative importance of fishing pressure compared with environmental drivers; and

(iii) provide advice on reference point concepts suitable for adaptive harvest strategies for crab fisheries in northern Australia.

Methods

The project primarily focused on Giant Mud Crabs, given their greater importance (both catch and value) as a fishery species in the GoC. Knowledge and data for Blue Swimmer Crabs in the GoC is limited and is insufficient for quantitative analysis against environmental factors or for a quantitative stock assessment. However, as a first step in improving knowledge, samples of GoC Blue Swimmer Crabs were collected and assessed for species identification, to provide insight into which species was likely to have been unusually abundant in shallow coastal waters of the south-eastern GoC in 2016.

Using and sharing the available data, knowledge, and modelling expertise, fisheries scientists from the NT and Qld collaborated to investigate the evidence for large-scale ecosystem influences on populations of Giant Mud Crabs in the GoC. Temporal patterns in catch and effort at regional scales were analysed using generalised linear models of annual data and dynamic Bayesian networks of monthly data. Population modelling at regional scales was explored using the delay-difference model developed by scientists in the NT, as well as a catch-MSY approach applied by scientists in Qld. These modelling approaches were used to develop advice that could inform the harvest strategies for Giant Mud Crab fisheries in the GoC. The project also collaborated with a PhD candidate from Charles Darwin University to test hypotheses about the migration of ovigerous female Giant Mud Crabs and associated larval advection, using hydrodynamic and particle tracking modelling to inform the potential for connectivity of NT and Qld stocks.

Results

For the project's primary species, desktop correlative analyses clearly indicated that recent fluctuations in the catches of Giant Mud Crabs in the GoC are most likely driven by environmental factors including river flow, rainfall, temperature, evaporation, and sea level changes. It was unclear which of these factors, or their interactions were most important in any given year, and it remains unknown as to which processes affecting crab life history was impacted (i.e. recruitment, survivorship or catchability). However, results indicated that for the western to south-eastern GoC (i.e. Roper to Staaten rivers), high temperature negatively affected catch rates. Previous studies reported that rainfall was more important than temperature in northern Australia (Meynecke *et al.* 2010), but noted that high temperatures may cause mortality of Giant Mud Crabs harvested from shallow tidal areas. The declines in catches of Giant Mud Crabs in the GoC coincided with climate events that included a sequence of years with low rainfall, high temperatures and below average mean sea levels. This was also evidenced by an influx of Blue Swimmer Crabs, most likely *Portunus armatus*, in the south-eastern GoC, in 2016. This influx is likely to be indicative of major short-term, inter-year changes to the inshore ecosystem of the south-eastern GoC, and may be particularly indicative of high salinity in coastal waters resulting from sequential years of low freshwater input to the GoC.

The GoC may be atypical in the effects of environmental factors on populations of Giant Mud Crabs for several reasons. Firstly, the coastline of the western and southern GoC has an east-west layout, such that organisms cannot retreat southwards to avoid heat events. Secondly, the GoC has a mostly diurnal tidal regime resulting in the exposure of inter-tidal areas to the extremes of heat in summer and cold in winter. Thirdly, rainfall and associated flooding in the catchments of the GoC occurs during a relatively short wet season and the reliability of annual rainfall and flooding is relatively low. These environmental conditions occur especially in the western and south-eastern GoC, which can result in multiple years of low rainfall and hot dry conditions. We suggest that the GoC is an area where Giant Mud Crabs and their associated fisheries may be at high vulnerability to climate events, more so in the western and south-eastern regions (e.g. Roper and McArthur) than in the eastern and northern regions (e.g. Pormpuraaw and Weipa-Mapoon).

Patterns in the harvest of Giant Mud Crabs are a complex spatial interplay of population and fishing dynamics, with environmental factors impacting at multiple scales. Population modelling of Giant Mud Crab fisheries is challenging because of: (i) data limitations and uncertainties; (ii) large inter-annual variations in recruitment that are not necessarily linked to spawning stock size; (iii) variability in survivorship and growth; and (iv) difficulties in quantitatively separating the effects of fishing mortality from environmental effects. We applied two alternate modelling approaches to the harvest data for Giant Mud Crabs in the GoC. The results of both methods are heavily underpinned by their assumptions. The advantage of the delay-difference model is that it includes an explicit stock recruitment relationship and an estimated growth-survival function based on observed data. However, as a biomass-based model, it does not capture changes in management arrangements over time. Its application to Qld stocks was preliminary at best, as the no-female harvest policy of Qld provides limited evidence upon which to estimate female spawning stock biomass. The advantages of the catch-MSY model are its need only for catch data, as combinations of the population resilience (i.e. population intrinsic growth rate) and carrying capacity are evaluated for plausibility within the model. It intrinsically assumes that female spawning stock biomass is proportional to the modelled exploitable biomass, which is essentially what the delay-difference model explicitly assumes. Both models provided useful insights into patterns of Giant Mud Crab biomass over time. However, neither model was sufficiently numerically sophisticated to be able to include a temporally-varying recruitment effect that could be optimised to observed catch rate (delay-difference) or catch (catch-MSY).

As a step towards integrating environmental factors into a population model, the bias environmental factors may introduce to estimates of female spawning stock biomass and relative fishing mortality were investigated for the NT Western GoC Mud Crab Fishery, using the delay-difference model. Strong correlations occurred between the model estimated recruitment anomalies (in this context equal to the biomass of crabs entering the fishery i.e. "exploitable") and mean sea level (MSL) and cumulative heat index. Analyses, suggested that the relative spawning biomass (S/S_{msy}) was less sensitive than the relative fishing mortality rate (F/F_{msy}), to this potential bias.

The consistency of the declines in GoC Giant Mud Crab harvests across two jurisdictions, in which females are harvested in one (i.e. NT) but not the other (i.e. Qld), and commonality in environmental conditions across the GoC suggests that between 2009 and 2018 environmental factors may have been relatively more important than fishing pressure. Fundamental to sustainable fisheries management is the concept that there is adequate spawning stock remaining after fishing and natural mortality to provide sufficient recruits that subsequently become fishable biomass. The high fecundity (i.e. number of eggs) of female Giant Mud Crabs, high estimated natural mortality, and relatively short life span suggests that Giant Mud Crabs are a moderately resilient species - a characteristic explored in the catch-MSY analyses. These qualities suggest that Giant Mud Crabs could probably be fished to a relatively low spawning biomass and still recover. The Harvest Strategy for the NT Western GoC Mud Crab Fishery sets a secondary, biological performance indicator in which the target reference point is to retain at least 70 tonnes of estimated female spawning stock biomass. Increasing severity of management actions occur for various levels of estimated spawning stock biomass is below 70 tonnes, although the fishery is closed if the primary indicator (catch per unit effort in April/May) is less than 0.2 kg per pot day. Preliminary hydrodynamic and particle modelling of ovigerous females and larval movement, suggests that regions within the GoC may be heavily reliant on self-seeded larvae (i.e. regions are predominately autonomous), particularly in the western GoC. The hydrodynamic modelling suggests that, while Giant Mud Crabs have high fecundity which provides resilience, caution is needed regarding spawning stock levels of the Western GoC, because alternative larval replenishment from other GoC regions may be limited. Further work is needed to confirm these preliminary results.

Implications

The harvest of Giant Mud Crabs is known to fluctuate in response to environmental/climate conditions. The current project provides evidence supporting the assertion that poor harvests of Giant Mud Crabs in the GoC were likely driven by a combination of low rainfall and or river flows, high temperatures and sea level variations. Climate sequences as experienced in the last decade are likely to occur in the future, although the frequency and combination is highly unpredictable for the GoC. The implication of this for stakeholders in mud crab fisheries of northern Australia (i.e. fishers, licence holders, and management) is the need to have fishing businesses, fisheries management and harvest strategies that can be responsive and adaptable to these unpredictable events.

The influx of Blue Swimmer Crabs in 2016 to shallow inshore areas of the south-eastern GoC (Queensland jurisdiction) suggests that under certain climate (and possibly oceanographic) conditions, commercial harvests, probably of *Portunus armatus*, may be possible, but are currently unpredictable between years. This presents challenges for stock assessment and setting of a total allowable catch. In Queensland, the Blue Swimmer Crab Fishery is managed as a single, whole of state unit in the Harvest

Strategy for the Queensland Crab Fishery. As such, harvest data for Blue Swimmer Crabs from the GoC will continue to be collected as part of standard commercial reporting requirements. However, if the harvest of Blue Swimmer Crabs from the GoC stock becomes larger and more consistent over sequential years, separate regional management might be needed.

Recommendations

We reiterate the need for field-based studies on populations of Giant Mud Crabs, as per Brown (2010) and Meynecke *et al.* (2010), particularly in the GoC due to the area's inherent climate variability, with extreme events predicted to occur more frequently under climate change.

We recommend further work in the following areas:

- The collection and/or remote monitoring of empirical data to provide more accurate and representative data on environmental factors that directly affect Giant Mud Crabs in their estuarine and coastal habitats, such as water temperature, salinity, tidal inundation, and indices of "productivity" in mangrove habitats (e.g. chlorophyll-a and/or meiofauna abundance). We recommend collection at relevant regional scales, with a priority for the western GoC.
- Trialling a pre-season evaluation of regional environmental conditions, such as cumulative rainfall (or flow if available), cumulative heat, and sea level anomalies, to predict stock levels with an assessment of the likely risk to each region of having below or above average exploitable biomass, associated catchability and harvest.
- Within the NT, employ spawning biomass ratios (S/S_{msy}) rather than fixed spawning biomass values in the Harvest Strategy decision matrix, and explore a broader range of models used to assess the performance of the Western GoC Mud Crab Fishery.

We recommend further research into the movement of ovigerous female Giant Mud Crabs in the GoC and subsequent larval distribution (i.e. hydrodynamic modelling with field validation) to determine connectivity of regions, and to identify possible variation in larval distribution between years that may contribute to recruitment variation. It is possible that recruitment variation is affected at two key stages of the life-cycle: one during the offshore 'oceanic' phase of ovigerous females and planktonic larvae; the other during the inter-tidal habitat phase associated with seagrasses and mangroves. This is a fundamental knowledge gap that should be resolved.

Data collation, analysis and interpretation reinforced the need for:

- More accurate catch and effort data for both jurisdictions (including sex-specific catch data for the NT and size-specific catch data for Qld) as catch informs the biomass removed from the population, and catch per unit effort is used as an indicator of stock size. Both of these metrics are fundamental drivers of any stock assessment.
- Within Qld, to develop and monitor a metric of female Giant Mud Crab abundance to inform temporal variation in female spawning stock biomass (for stock assessment), given that females are not harvested and thus are not represented in the exploitable biomass.
- Ongoing liaison with commercial fishers and accurate harvest data for Blue Swimmer Crabs from the GoC, to enable early recognition of possible changes to the inshore ecosystem of the south-eastern GoC and to identify if or when regional management arrangements might need consideration.
- If the GoC fishery for Blue Swimmer Crabs significantly increases in quantity or consistency, then genetic differentiation of the species being harvested should be considered, as species identification based on morphometrics was problematic.

Keywords:

Giant Mud Crab, *Scylla serrata*, Blue Swimmer Crab, *Portunus armatus, Portunus pelagicus*, Gulf of Carpentaria, harvest strategy, environmental drivers, delay-difference model, catch-MSY, particle modelling

Introduction

Background

Giant Mud Crabs support valuable commercial, recreational and indigenous fisheries in northern Australia. The GoC (NT and Qld combined) contributed on average about 25% of the reported commercial harvest of mud crabs in Australia between 2008 and 2017. The vast majority of mud crabs harvested in the GoC are the Giant Mud Crab (*Scylla serrata*), with the Orange Mud Crab (*S. olivacea*) only known to occur around Weipa (Keenan *et al*. 1998). The market price for mud crabs has increased over time, with an average price at the Sydney Fish Market of about $34 per kg in 2018/2019, up from about $23 in 2005/2006 (SFM 2019). When the project was initiated in 2016, Giant Mud Crabs were classed as sustainably fished in all management areas (despite declines in catch rates), with the exception of the NT Western GoC Mud Crab Fishery (NTWGOCMCF), which was classified as transitional-depleting. More recently in 2018, Giant Mud Crab stocks were classified as sustainably fished in all management areas, highlighting the likely resilience of this species.

Blue Swimmer Crabs (*Portunus armatus and P. pelagicus*), occurs in the GoC (Kailola *et al.* 1993), but are not a significant component of the GoC crab harvest by commercial fishers and only occurs to a limited degree in the Qld jurisdiction. In most years between 1990 and 2019, fewer than five licences reported a harvest of Blue Swimmer Crabs, with a total annual harvest usually less than two tonnes (QFish 2020). The small to negligible harvest is a function of animal size (i.e. many not reaching the Qld minimum legal size) and commercial viability (tonnage, value, and market access). The harvest of Blue Swimmer Crabs in the GoC is insufficient for this stock to be included in the National Status of Australian Fish Stocks Report (Johnston *et al.* 2018*)*. Blue Swimmer crabs are also not commonly harvested from GoC waters by recreational or indigenous fishers (DAF 2020). However, in 2016, about 10 tonnes of Blue Swimmer Crab was harvested from the shallow, inshore waters of the south-east corner of the GoC, where Giant Mud Crabs are normally harvested, but were in reduced abundance (QFish 2020). The influx of Blue Swimmer Crab and reduction in Giant Mud Crab suggested a major, short-term change to the inshore ecosystem of the south-eastern GoC, which warranted further consideration.

The current project was developed in response to industry and managerial concerns over regionally significant changes in crab catches in the GoC, both in terms of tonnage and species composition. Consultation with fishers and managers indicated that changes in the catch rates and subsequent harvest of Giant Mud Crabs may be the consequence of, or exacerbated by, environmental factors (e.g. floods, droughts, elevated temperature, mangrove dieback or changes to seagrass abundance and distribution). Understanding the relative importance of environmental factors compared with fishing pressure on crab abundance and fishery catches supports better assessment of stock status and management.

At the start of the project, the NT was developing a Harvest Strategy for its Mud Crab Fishery and Qld was likely to do the same. Queensland has since reviewed the management arrangements of its Crab Fishery (i.e. C1 symbol – the endorsement required to commercially harvest Giant Mud Crabs in Qld), with the proposed Harvest Strategy including regional total allowable commercial catch and individual quota arrangements from a date yet to be approved.

In addition to fishing, current evidence indicates that the biomass of many crab fisheries vary as a consequence of environmental factors. This inherent variability needs to be accounted for in a harvest strategy, so that risks associated with environmental effects on the biomass can be identified, articulated to stakeholders and where necessary have pre-agreed management intervention.

The current project contributes to the FRDC National Priority 1 of ensuring that 'Australian fishing products are sustainable and acknowledged to be so' by increasing the knowledge of the influence of a broader suite of environmental factors on crab fisheries than previously studied, and enabling the inclusion of these influences (where possible) into population models and harvest strategies.

The project sought to build upon the significant work undertaken on Giant Mud Crab populations and their dependent fisheries in northern Australia over the past three decades including:

- FRDC 2000/142 - habitat area related to mud crab productivity (Hay *et al*. 2005)
- FRDC 2007/026 - priority areas for research, 2007 national mud crab workshop (Grubert *et al*. 2008)
- FRDC 2009/031 - female harvest strategy evaluation in Qld (Brown 2010)
- FRDC 2008/012 - correlative work on selected environmental drivers of mud crab catches (Meynecke *et al*. 2010)
- Assessment of the blue swimmer crab fishery in Qld (Sumpton *et al*. 2015)
- Delay-difference modelling of NT Western GoC crab stock (Walters 2016; Grubert *et al*. 2019).

Need

The work was needed to:

(i) Critically review the available literature on environmental factors influencing crab fisheries, particularly that relating to the GoC.
(ii) Update analytical relationships between catch and environmental factors to include the extreme climate events experienced in the past 10 years, and for a broader range of environmental factors than previously considered.
(iii) Expand jurisdictional stock modelling to a more biologically appropriate scale and support cross-jurisdictional collaboration.
(iv) Test the ability of model results to inform management of the relative importance of fishing pressure compared with environmental factors.
(v) Develop reference point concepts suitable for adaptive harvest strategies for Giant Mud Crab fisheries in northern Australia.

The project aimed to provide information at broad spatial scales (NT and Qld), as well as at regional scales for crab species with different life histories and potentially different responses to environmental factors. It aimed to compare the declining catches of mud crabs with the increasing catches of blue swimmer crabs in the GoC. Recent increases in Blue Swimmer Crab catches in the GoC needed investigation to clarify which species are present and to assess their vulnerability to fishing.

The adaptation of an existing crab population model was a case study that potentially could be applied to the Qld East Coast and other crustacean species.

However, the project primarily focused on Giant Mud Crabs, given their greater importance (both tonnage and value) as a commercial fishery species in the GoC. Knowledge and data for Blue Swimmer Crabs in the GoC is limited and was insufficient for quantitative analysis against environmental factors or for a quantitative stock assessment. However, as a first step in improving knowledge, samples of GoC Blue Swimmer Crabs were collected and assessed for species identification, to provide insight into which species was likely to have been unusually abundant in shallow coastal waters of the south-eastern GoC in 2016.

The current work aimed to assist in determining if the NT Western GoC Mud Crab Fishery warrants management intervention as a consequence of environmental factors. The previous closure of Blue Swimmer Crab fisheries in Western Australia highlights the potential of environmental factors to seriously impact a stock to the point where fishing needs to be suspended.

Objectives

1. Evaluate the role of a broad range of environmental drivers on catch variation in NT and Qld crab fisheries in the GoC.
2. Explore the relative importance of fishing pressure compared with environmentally driven variability using a population model of the GoC mud crab fishery.
3. Provide advice to support the development of harvest strategies appropriate for crab fisheries in northern Australia.

Chapter 1. Review of crab life histories, with specific reference to the Gulf of Carpentaria

J.B. Robins, M.A. Grubert, M.J. Campbell and W.S. Sumpton

Four species of mud crab are widely distributed throughout tropical and subtropical areas of the Indo-Pacific. They are *Scylla serrata*, the Giant Mud Crab; *S. olivacea* the Orange Mud Crab; *S. paramamosain* the Keeled Mud Crab; and *S. tranquebarica* the Purple Mud Crab, with some being significant aquaculture species across Asia. Two species (*S. serrata* and *S. olivacea*) are found in Australian waters (Keenan *et al*. 1998), with the Giant Mud Crab comprising the majority of the commercial harvest of crab fisheries in the GoC. The average harvest in this region over the last 10 years (2009 to 2018) was 200 tonnes for the NT Western GoC Mud Crab Fishery and 154 tonnes for the Qld GoC Crab Fishery.

In the GoC, Queensland jurisdiction only, Blue Swimmer Crabs (*Portunus* sp.) are opportunistically harvested by a handful of fishers. In most years, the reported annual catch is small (i.e., 18 kg to 2 tonne, Bayliss *et al*. 2014). However in 2016, about 10 tonnes of Blue Swimmer Crab was reported as harvested from Qld GoC Crab Fishery; a year when Giant Mud Crab harvests were unusually low in both the NT Western GoC and Qld GoC (i.e. 51 tonnes and 100 tonnes respectively).

The current project primarily focuses on Giant Mud Crabs, given their greater importance (both tonnage and value) as a commercial fishery species in the GoC than Blue Swimmer Crabs. Knowledge and data for Blue Swimmer Crabs in the GoC is limited. We briefly review the life history of Blue Swimmer Crabs to provide context to the work of the current project in identifying which species of *Portunus* was likely to have been unusually abundant in shallow coastal waters of the south-eastern GoC in 2016.

Giant Mud Crab

The Giant Mud Crab is a portunid crab with the distal segments of the last pair of walking legs flattened, such that they resemble paddles. The life-cycle of the Giant Mud Crab involves several stages and habitats, including offshore marine waters as well as mangrove-lined coastal mud flats and estuaries (Arriola 1940).

The GoC is a unique environment, with oceanic circulation that is quite different to that of other locations where Giant Mud Crabs are harvested, such as the Australian east coast and the Arafura Sea (Church and Forbes 1983; Wolanski 1993). Prevailing winds affecting GoC currents change from a south-easterly to north-westerly direction from December to April (Figure 1), which also leads to an increase in tidal height, and is coincident with the stronger influence of the Madden-Julian Oscillation (Ashbridge *et al*. 2016). Wind-driven currents in summer originate from the north-west and in the winter from the south-west (Forbes and Church 1983; Ashbridge *et al*. 2016).

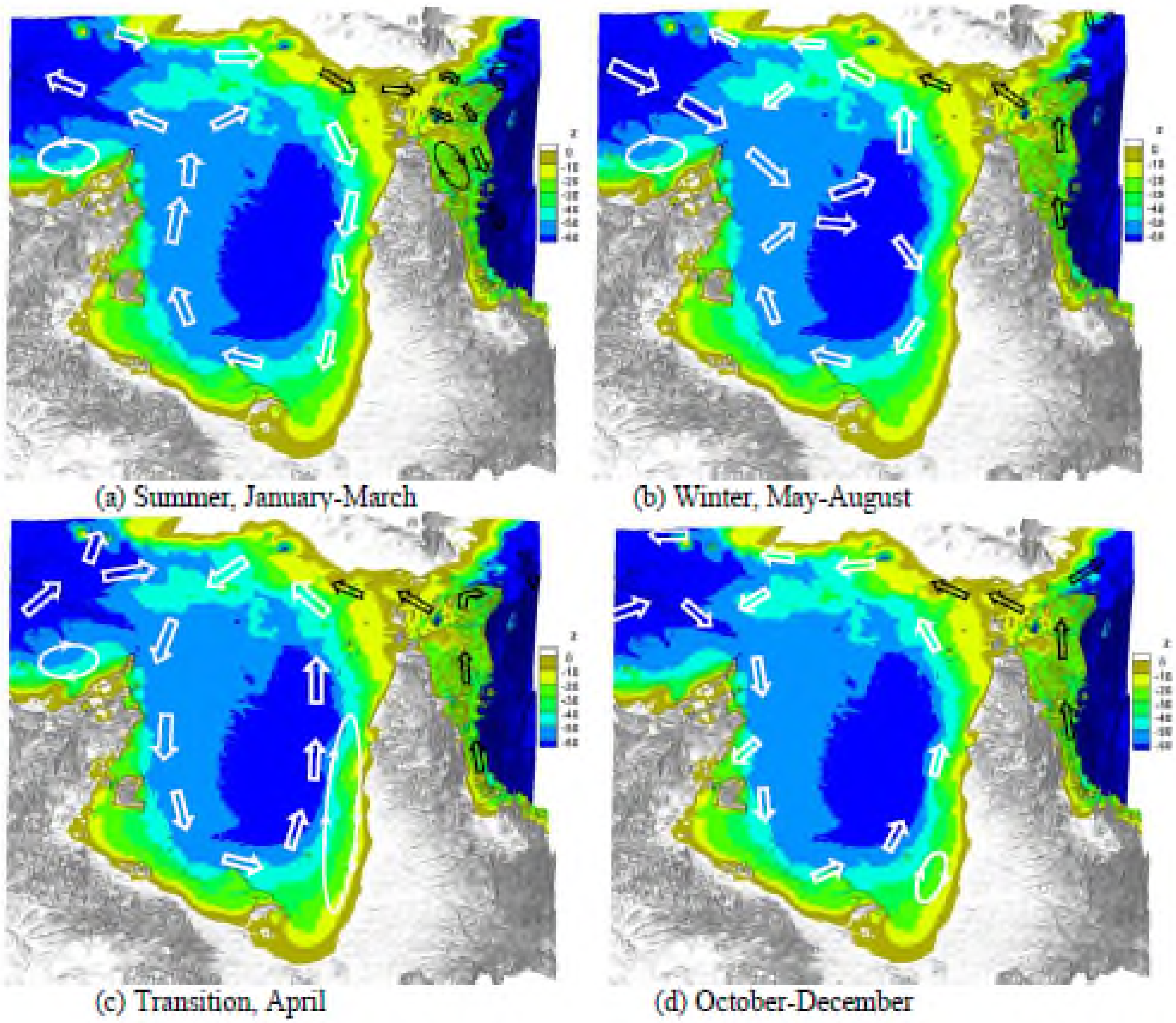


Figure 1. Schematic maps of generalised, wind-driven, seasonal circulation patterns in the Gulf of Carpentaria. Depth contours (m) are depicted by the colours as per the legend. Reproduced from Figure 17 of Li et al. (2006).

Offshore spawning

There is limited information on the spawning dynamics of Giant Mud Crabs in the GoC. In tropical Australia, mated ovigerous female crabs migrate to offshore waters, but the timing of the migration is uncertain. Hill (1994) suggests September to November, based on incidental captures (n = 390) of ovigerous females in the Northern Prawn Fishery between 1977 and 1987 (Figure 2). However, Knuckey (1999) suggests that the main spawning season is December to February. This was based on reduced female catches and increases in the mid-year catch of crabs (+1 years of age) in the NT Mud Crab Fishery (which includes the Arafura Sea) as well as the gonad index. Most ovigerous female mud crabs were trawl-captured within ~16 nm of the coast, although there were regional differences (Hill 1994). At Weipa, mean distance of capture from shore was 6.7 nm, while south of Groote Eylandt, the mean distance was 26 nm. Few ovigerous crabs were captured in offshore waters between Mornington Island and the Kirke River (14 ºS, Qld). This is possibly a sampling artefact because there was little or no trawling in this area during months when the offshore spawning migration is thought to occur.

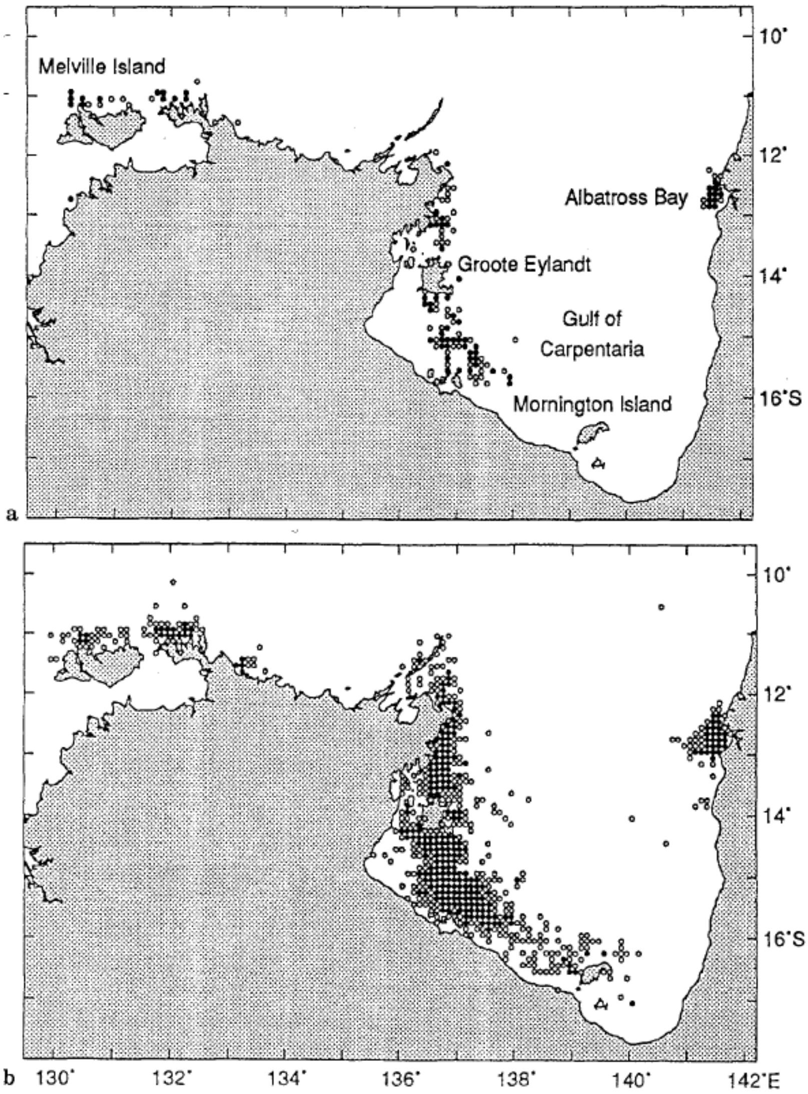


Figure 2. Gulf of Carpentaria: (a) reported locations of trawl-caught mud crabs; and (b) distribution of trawl effort in the Northern Prawn (trawl) Fishery in September, October and November in the years 1985, 1986 and 1987. Reproduced from Figure 1 of Hill (1994).

Undertaking an offshore spawning migration is an energy-demanding process. However, the potential benefits include a relatively stable environment (e.g. for salinity and temperature) for egg and larval development (Hill 1974; Quinn and Kojis 1987; Hill 1994; Alberts-Hubatsch *et al*. 2015), enhanced dispersal (Hill 1994), and genetic mixing (Gopurenko and Hughes 2002). Dispersal is reliant on currents in the GoC that occur at the same time as the pelagic larval phase (i.e. predominately October to December, see Figure 1).

Gopurenko and Hughes (2002) found evidence of genetic subdivision between Giant Mud Crab populations in the western (NT) and eastern (Qld) GoC. They speculated that the coastal boundary layer/current (modelled by Wolanski 1993 and anecdotally reported by GoC crab and net fishers) would effectively limit the mixing of estuarine and offshore waters and that substantial portions of mud crab larvae may be carried by currents close to their natal area. There is speculation that females return to inshore coastal waters and estuaries after spawning (Hill 1994).

Larval phases

The eggs of Giant Mud Crabs hatch after ~15 days at 28 ºC and become planktonic zoea larvae, which undergo five moults (stages I-V). Zoea I larvae are photopositive (Hill 1974; Holme *et al*. 2007). Survival and inter-moult period are strongly related to water temperature and salinity, with optimums of 26 to 32 ºC and 25 to 35 ppt, respectively (Hill 1974; Hamasaki 2003; Nurdiani and Zeng 2007; Baylon 2010). Temperature is thought to affect growth rates via stage duration, while salinity is thought to affect survival (Baylon 2010). Zoea larvae had high survival and metamorphosis at salinities of 25 to 35 ppt and temperatures of 26 to 32 ºC (Baylon 2010), suggesting a relatively narrow optimum range for metamorphosis from zoea to megalopa. Critical thresholds for zoea I larvae were 20 ºC (Baylon 2010) and 15 to 17.5 ppt (Hill 1974; Sara *et al.* 2006; Baylon 2010). It is possible that larvae from different regions have different temperature/salinity optima (Alberts-Hubatsch *et al.* 2015). However, it is unknown how this applies within the GoC.

Zoea 5 larvae metamorphose into demersal megalopae, which have a broader salinity tolerance (i.e. 15 to 45 ppt) for temperatures between 20 and 32 ºC (Webley and Connolly 2007). The development of functional gills (for salinity) and thicker integument (for temperature) in the more advanced larval stages is thought to provide the increased salinity and temperature tolerance (Baylon 2010). The megalopa stage lasts one to two weeks (Holme *et al.* 2007), with duration being temperature and nutrition dependent.

Zoea and megalopa stages have poor swimming ability, although selective tidal stream transport (STST) is likely to be important for larval dispersion, megalopae settlement and consequently juvenile crab recruitment (Sara *et al*. 2006). Selective tidal stream transport is a behavioural mechanism whereby larvae actively position themselves vertically within the water column to achieve horizontal movement utilising phases of the tide (Forward and Tankersley 2001). For the larvae of Giant Mud Crabs, this would enable movement from offshore to coastal and estuarine areas with mangrove and/or seagrass habitats suitable for the next life-history stages. Despite extensive sampling, few studies have successfully sampled *S. serrata* megalopae from the wild (Knuckey 1999; Sumpton *et al*. 2003; J. Webley pers. comm. 2017; although see Forbes and Hay 1988). However, the aquaculture literature reports the capture of "recruiting megalopa swarms" in southern China and Taiwan (Lucas and Southgate 2012).

Larval duration to the first crab instar (C1) is significantly related to temperature, being 16 days at 32 ºC, 21 days at 26 ºC and 50 days at 20 ºC (Baylon 2010). Therefore, effective contribution (after accounting for natural mortality) of larval Giant Mud Crabs to the fished population will be heavily influenced by the physical conditions offshore (e.g. temperature and salinity) as well as food availability encountered by larvae spawned in different months.

Crab stages

Megalopae metamorphose into crabs (C1), which have a broad tolerance to salinity (3 to 45 ppt). Salinity stress (i.e. too high or too low) can result in reduced survival, feeding and growth, and 'extended moulting' duration (Baylon 2010). The crab stage can be divided into four phases: (i) crablets (C1 to C5) also known as early benthic stage (EBS) with carapace widths (CW) of 3 to 30 mm, (ii) juveniles 30 to 80 mm, (iii) sub adults 70 to 150 mm, and (iv) mature adults with CW 130 mm and greater (Heasman 1980; Alberts-Hubatsch 2015).

Field studies have captured EBS crabs on sub-tidal mud flats in estuaries (Alberts-Hubatsch 2015 – Gold Coast, Qld, December 2012 to March 2013, 3 to 36 mm CW) and in saltmarsh wetlands behind mangroves (Knuckey 1999 – NT, February 1997, 10 to 20 mm CW, probably around 10 to 12 weeks old). Experimentally, small crabs have a strong preference for seagrass (Webley *et al.* 2009). Alberts-

Hubatsch *et al.* (2014) suggested that a muddy substrate into which EBS crabs can bury is important for successful settlement as it offers EBS crabs protection from predation, cannibalism and extreme physical conditions. In the GoC, especially the western and southern areas (Roper to Gilbert rivers; latitude ~14 °S to 16 °S), the near-shore coastal areas adjacent to the many estuaries are typified by shallow, inter-tidal mud banks, frequently with seagrass meadows of varying density. It is possible that megalopae and EBS crabs are broadly dispersed and settle across multiple habitat types. The final destination of megalopae and EBS crabs probably depends on behaviour associated with STST (i.e. water column placement), tide (e.g. large diurnal, night-time flood king tides coinciding with megalopa/EBS stage) and (local) wind-driven currents.

Grubert *et al*. (2008) interviewed crabbers from the Adelaide, Roper, McArthur and Wearyan River systems in the NT. Sightings of small (~58 mm) and smallest (~30 mm) crabs were most common from April to July/August. Large numbers of small crabs were seen from April to July (i.e. early dry season and the associated south-east trade winds). One fisher commented "that long wet seasons (in particular flood events) scour mud flats and remove seagrass" and were considered detrimental to the NT Mud Crab Fishery.

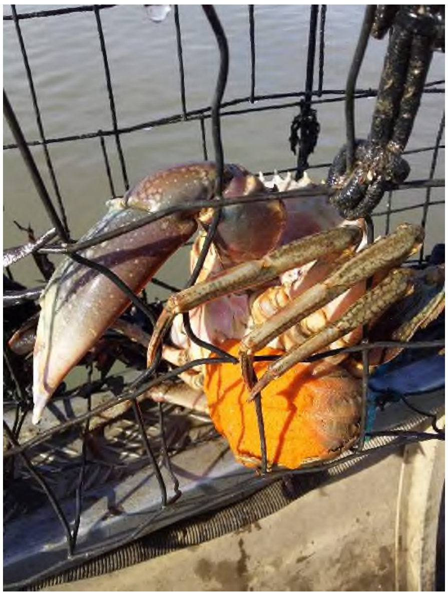
Under experimental conditions, adult Giant Mud Crabs showed varying levels of mortality after exposure to different salinities, but did not show an ability to discriminate between salinities (Davenport and Wong 1987). However, during these salinity preference experiments, crabs were only given 30 minutes to choose a preferred salinity, which may be an insufficient period for the crabs to react.

Juveniles and adult Giant Mud Crabs show some spatial separation in estuarine and coastal habitats (Hill *et al.* 1982). Juveniles tend to inhabit upper-tidal areas amongst mangrove forests and remain there during low tide. Adults tend to inhabit burrows in parts of the estuary that are influenced by tidal waters including the tidal flats and deeper channels. Most inferences on the spatial separation by size and sex of Giant Mud Crab within estuaries are based on observations from catch rates in passive pot fishing apparatus, and/or tag-recapture studies. In the GoC, the use of different habitats by different life history phases, sizes and sex classes is undocumented; particularly the size and sex of Giant Mud Crabs using the coastal tidal flats which are extensive, especially in the southern and western GoC adjacent to the Flinders, Norman, Roper and McArthur Rivers.

Reproduction

Giant Mud Crabs mature after about 18 to 24 months, depending on water temperature and food availability. Maturity occurs at 90 to 110 mm CW (Heasman 1980). However, Knuckey (1999) reported a pubertal moult size of 143 to 145 mm CW for NT crabs, which approximates to about 15 months of age (around May) and a second moult about six months later in November (at about 21 months of age), which aligns with the timing of the offshore spawning migration in November. The pubertal moult is often accompanied by broadening of the abdominal flap in females, because of the functional requirement to carry and protect fertilised eggs. Knuckey (1999) noted that the size-at-maturity for 50% of females varied between river systems – 131 mm in the McArthur River to 138 mm in the Adelaide River - and noted that "a large percentage of females undergo a second moult of maturity".

Mating occurs during the moult of the mature female when her shell is soft. The sperm are stored and become active when the eggs pass through the oviducts during extrusion. Knuckey (1999) recorded the incidence of male mating scars and found that most mating activity (based on scars) took place between August and November, with no new scars observed between February and March. This pattern is consistent with few females being harvested by the NT Mud Crab Fishery between December to February/March, and a low percentage of late inter-moult males. Peak female gonad condition occurred around December, indicating spawning was imminent. However, females with high gonad index (GI) and ripe ovaries were present in every month, suggesting that some spawning might occur throughout the year. Knuckey (1999) suggests that the predominant mating period (for the NT Western GoC) is in the middle of the year (May/June) based on mating scars, but that the main spawning period is December to February based on patterns in GI of females that had yet to migrate.



Female Giant Mud Crabs are highly fecund, carrying between two and five million eggs when berried, although up to eight million zoea have been successfully spawned by large (228 mm CW) females in captivity (D. Mann. Bribie Island Aquaculture Research Centre, pers. comm. 2019). Eggs are extruded by the female, attached to her pleopods and fertilised externally (Figure 3). When the majority of the egg mass hatches, females actively scrape off eggs, dispersing them (Hill 1974).

Figure 3. Ovigerous female Giant Mud Crab with an egg mass just a few days old (photo courtesy of Qld commercial fisher Port Alma, August 2019).

Genetics

In the context of the GoC, Gopurenko and Hughes (2002) reported indications of genetic subdivision, with populations from Weipa and Karumba (Qld GoC) displaying "near reciprocal differences in haplotype frequency" from populations from the Roper River (NT WGoC) and Adelaide River (NT Arafura Sea), suggesting limited genetic interchange between the western and eastern GoC.

Growth (and feeding)

Giant Mud Crabs have stepwise growth, moulting 13 to 15 times in their life span. A final or terminal moult is still assumed (in most of the literature) and marks the transition from juvenile to adult. It is thought that most crabs do not grow further after this terminal moult. The typical life span is thought to be three to four years of age. Direct ageing of Giant Mud Crabs via ossicles[1] is unreliable (Crook *et al*. 2018).

The growth and mortality of early benthic stage (EBS) crabs is optimal in warm (~30 °C), brackish (15 to 25 ppt) waters, with temperature the most influential factor affecting growth and survival (Ruscoe *et al*. 2004). Giant Mud Crabs have a lower thermal limit of 10 ºC (Hill 1980), but their upper thermal limit is uncertain either globally or for the GoC locally. An experimental study on the sequential exposure of Giant Mud Crabs to short-term (i.e. 30 minutes) extreme temperatures reported high survival of crabs to temperatures between 1 ºC and 55 ºC without water, and between 3 ºC and 45 ºC with water (Islam and Bhuiyan 1981), suggesting tolerance to high water temperatures, at least for short periods of exposure. However, commercial fishers from the GoC (from both NT and Qld jurisdictions) anecdotally report that Giant Mud Crabs are susceptible to extreme temperatures with mortalities noted at extremes of both hot and cold. Crab feeding activity, and thus movement and

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[1] Ossicles are small calcified teeth-like structures of the gastric mill of crustaceans, sometimes with apparent growth increments within the endocuticle layer.

catchability in passive fishing apparatus, is greatly reduced at water temperatures below 20 ºC (Hill 1980; Hill *et al*. 1984).

Estuaries in the southern GoC become hyper-saline by the end of the dry season, especially in years of low rainfall. For example, in December 2017 salinity in the Flinders River estuary 2 km upstream of the mouth was 39 ppt (M. Burford unpublished data). It is possible that growth and survival of EBS and juvenile crab stages may be suppressed by high temperatures and/or high salinity (Bayliss *et al.* 2014). Hill (1974) demonstrated an upper lethal salinity of 64.9 ppt. Estuaries in the GoC can also become hypo-saline during major/extreme flood events (e.g. south-east corner of the Qld GoC in 2009 when flooding of the Flinders and Norman rivers covered over 100 km of the coastline, with anecdotal reports of freshwater at the surface of the estuary for more than 30 days).

Growth, via moulting is closely linked to lunar and tidal cycles with most crabs moulting during the night high tides (Mirera and Mtile 2009); noting that in this study crabs were caged and placed in the intertidal zone, with high tides allowing the crabs to be covered with water. Crabs probably do moult in their burrows, based on the historical (but now banned) practice of 'hooking' soft crabs in their burrows. Hardening of the exoskeleton occurs within four to five days of moulting (Mirera and Mtile 2009).

The inter-moult duration increases with stage, being four to seven days for EBS C3 crabs (8 to 13 mm CW) under optimal conditions (Ruscoe *et al.* 2004), 18 days for juvenile crabs (~40 mm CW), and then 50 to 60 days for late-stage juvenile crabs between 50 and 65 mm CW (Catacutan 2002).

In the Philippines, captive-reared Giant Mud Crabs reached maturity within 146 days of hatching to the first crab stage (EBS C1), with the interval from egg to 'mature' crab, through 12 to 15 moults, taking about 186 days (Arriola 1940). Giant Mud Crabs in Moreton Bay, south-east Qld (~27 ºS) reached 120 mm CW at the end of their first year, and 150 mm CW at the end of their second year (Heasman 1980; Hill 1984).

Giant Mud Crabs are opportunistic omnivores that feed mostly at night and have an ontogenetic shift in diet. Small juvenile crabs feed on detritus, while large juveniles and adults are carnivorous, feeding on benthic invertebrates such as bivalves and gastropods, as well as fish. Heasman (1980) extrapolated a seasonal feeding efficiency curve for crabs in Moreton Bay which suggests that high feeding rates (and growth) occur from late November to the end of March and that water temperatures less than 18 ºC between June and August result in reduced food consumption. Feeding also ceases two to 14 days before moulting, but resumes when the mouthparts have hardened (i.e. two to four days post-moult).

Food items for cultured mud crabs include:

- Zoea 1 and 2: *Nannochloropsis* sp., which is food for *Brachionus* sp. rotifers
- Zoea 3 to 5: *Artemia* nauplii
- Megalopae: adult *Artemia*
- EBS crabs: fish, mussels, dead *Artemia*.

Movement

Once settled in an estuary, there is limited movement/interchange between neighbouring populations of juvenile and adult Giant Mud Crabs (Hyland *et al.* 1984). As such, fisheries for Giant Mud Crabs are dependent upon the number of crabs that settle in an area and reach legal size. Calogeras (2007) reported that most studies believed that juvenile mud crabs are most prevalent in inter-tidal habitats during the post wet season period.

Fishery relevant life-history

For a review of crab fisheries in the GoC, see Chapter 2. Commercial crab fisheries in northern Australia mostly use pots/traps that passively select (i.e. are biased) towards capturing crabs 150 mm CW or greater. It is thought that these crabs are 18 to 24 months old.

Environmental correlations

Fisheries for Giant Mud Crabs are associated mostly with estuaries and coastal mud flats. Anecdotally, commercial catches in the NT are 'slower' in August and September, and this is attributed by fishers to cooler water temperatures (Knuckey 1999). Queensland-based GoC commercial fishers report similar patterns. Within-year variation in catch rates of Giant Mud Crabs in Moreton Bay are similarly correlated with temperature, and the incidence of moulting (Hill 1982; Williams and Hill 1982). The size and sex composition of harvested NT mud crabs is monitored monthly by NT Department of Primary Industries and Resources (DPI&R), as harvested crabs are transported to Darwin before shipment further afield (e.g. Sydney and Melbourne). The NT Mud Crab Fishery predominately harvests the new cohort of 1+ year-old crabs (i.e. 12 to 23 months old) each fishing year (≅ calendar year). Numerical modelling suggests that at least 20% of the females in the population (1+ years-old) survive to the end of the fishing year (i.e. ~December) and potentially contribute to spawning (Knuckey 1999). Because the NT fishery is predominantly based on 1+ crabs, any recruitment failure is soon apparent (Knuckey 1999). In the NT, catch and catch rates drop rapidly at the end of the (calendar) year, with females virtually disappearing from the harvest and the fishing mostly ceases. A similar phenomenon is reported anecdotally for the Qld southern GoC. This intra-annual decline in catch and catch rates is probably determined by the complex interplay of the behaviour of mature male and female crabs, the behaviour of the commercial fishing fleet, and difficult fishing conditions that occur with the onset of the wet season (Knuckey 1999).

High inter-annual variation in fisheries yields is thought to be limited by recruitment rather than productivity (Heasman 1980; Grubert *et al.* 2008). Because of the extended breeding season, recruitment may occur as a series of small, indistinct and overlapping cohorts rather than as a single prominent cohort. In other words, recruitment maybe patchy in time and space. Heasman (1980) speculated that Giant Mud Crabs pass into the transient estuarine population (i.e. moving between inter-tidal and sub-tidal areas) at 50 to 60 mm CW, which is about 90 to 150 days after settlement as a crablet. Heasman (1980) also identified the following potential bottlenecks influencing the recruitment of megalopae and their subsequent survival during the inter-tidal juvenile phase:

- Precarious migration into upper inter-tidal mangroves especially in areas with high tidal range and wide mud flats, which is typical of some parts of the GoC
- Fierce and early competition for food and space from other crabs, especially grapsid crabs that inhabit inter-tidal habitats
- High rates of predation by fish and other swimming mangrove crabs (e.g. *Thalamita crenata*).

Meynecke *et al.* (2010) reported on a broad-scale, north Australian analysis of Giant Mud Crab catches (using logbook data to December 2008) and effects of environmental factors. This was determined by forward stepwise regression and multi-dimensional scaling. Different environmental factors were significant in different areas. For some rivers and associated estuaries, the annual wet season and subsequent runoff was a significant determinant of total catch one to two years later and was suggested to be related to recruitment strength. For NT rivers, the log-transformed catch per unit effort, where effort was expressed as days fished, was significantly correlated to rainfall and river flow in the Roper and McArthur rivers, but average monthly sea surface temperature (SST) and selected phases of the Madden-Julian Oscillation (MJO) were not (Meynecke *et al*. 2010). Severe floods in 2001 and 2004 were noted as destroying seagrass beds adjacent to the McArthur and

Wearyan rivers, having long-lasting negative effects. For the Flinders River in the Qld GoC, there was a 30 to 40% correlation between the Southern Oscillation Index (SOI) and subsequent commercial catches of Giant Mud Crabs. Meynecke *et al.* (2010) also noted anecdotal reports from fishers of short-term effects of river flows, whereby catches of Giant Mud Crabs were increased for up to two weeks after rainfall events. High temperatures were suggested to have a negative effect on CPUE of fishing apparatus set on tidal mud flats. Correlation coefficients for the Roper and McArthur rivers were only significant between the annual CPUE and annual rainfall one year prior to catch (correlation coefficient, $r = 0.49$ and 0.48 respectively). The best model for annual NT CPUE was log-transformed (total rainfall for November to April two years prior to catch) plus (maximum SOI in the same year as catch) minus (maximum river flow two years prior to catch). River flow had a higher correlation with CPUE than rainfall, but was not available for all catchments studied by Meynecke *et al*. (2010). The dry season in the NT was defined as between April and October and the wet season was between November and March.

Catch per unit effort in the Qld GoC was significantly related to SOI or rainfall in the Embley and Gilbert rivers, but not in the Flinders River. The best model reported by Meynecke *et al.* (2010) for the annual Qld CPUE was (SOI max same year) plus log-transformed (mean annual rainfall). Significant correlation coefficients between the annual CPUE (kg per day fished) and environmental variables for select rivers were:

- Flinders River –- SOI maximum two years prior to catch ($r = 0.51$)
- Gilbert River – no significant correlations
- Mitchell River – rainfall two years prior to catch ($r = 0.47$)
- Embley River – rainfall same year as catch ($r = 0.53$), annual rainfall one year prior ($r = 0.50$).

The dry season in Qld was defined as between May and October and wet season between November to April. High positive SOI values were indicative of higher rainfall and temperature, which Meynecke *et al*. (2010) attributes to enhancing estuarine productivity, with rainfall and flooding reducing salinity and enhancing crab growth and survival. Monthly average SSTs were calculated for each river system derived from NASA AVHRR Pathfinder V5 (1985 to 2007) and MODIS Aqua (2008) SST data that were within 20 km (= 10.85 nm) of the estuaries. Meynecke *et al*. (2010) suggested that extreme rainfall/flow events over many weeks had a long-term negative impact on CPUE, whereas flooding at the end of the wet season had a positive impact on CPUE two to three years later. Meynecke *et al.* (2010) concluded that SOI including rainfall was the most important explanatory environmental factors for Giant Mud Crab catches in the NT.

Further afield in Madagascar, recruitment success of Giant Mud Crabs was reported to be seasonally and inversely related to rainfall (Le Reste *et al*. 1976). However, flooding associated with cyclones had little measurable effect on the recruitment of megalopae in a South African estuary (Forbes and Hay 1988).

Giant Mud Crabs are known to move downstream with floods (Stephenson and Campbell 1960). Heavy flooding and low salinities (i.e. 2 ppt) eliminated and/or severely reduced the number of Giant Mud Crabs in two South African estuaries (Hill 1975). Anecdotally, commercial fishers in the Qld GoC attribute low catches of crabs to high migration rates 'out of fishing areas' and recruitment failure occurring as a consequence of extended periods of freshwater runoff (G. Ward in Bayliss *et al.* 2014). Several large floods in the years 2009 to 2011 in the south-eastern GoC reduced the catch of crabs, as the inshore waters tend towards a freshwater habitat (Figure 4) and Giant Mud Crabs migrate elsewhere due to their intolerance of very low salinities.

Figure 4. Flinders River estuary in flood, February 2009.

Catches of Giant Mud Crabs have also been positively correlated with summer freshwater flow in Moreton Bay (Loneragan and Bunn 1999), although Robins *et al.* (2005) reported ambiguous results for central Queensland east coast (i.e. Gladstone at ~23.5 ºS). Loneragan and Bunn (1999) suggested that freshwater flows might influence the catchability of crabs by stimulating their downstream movement away from low salinity water, thereby increasing their density in the fishing grounds. This may affect recruitment by increasing the survival of juveniles through reduced competition for burrows and increasing the survival of juveniles. Such increased juvenile survival would suggest that enhanced catches could occur in the following years (i.e. a lag effect), but lag correlations were not examined by Loneragan and Bunn (1999). Robins *et al.* (2005) reported significant relationships between catches of Giant Mud Crabs and autumn flow lagged by two years for central Queensland.

In summary

Based on the available information, Giant Mud Crabs in the GoC may be impacted by environmental factors at several life-history stages, either singularly or cumulatively. These include during:

(i) Larvae and megalopae stages in offshore waters, where non-optimum temperature and salinity may affect growth and survival; and where current-dependent transport may affect the regional distribution and survival, which influences the number/density recruiting to inter-tidal habitats.

(ii) Megalopae, EBS and juvenile crab stages in inter-tidal habitats, where temperature, salinity, food availability and tidal inundation may affect growth and survival.

(iii) Sub adult and adult stages in inter-tidal and sub-tidal habitats of estuaries and the coastal foreshores, where temperature, salinity and food availability may affect growth, survival and reproduction, as well as catchability in commercial fishing apparatus.

Each life-history stage has an optimal range of temperature and salinity. Temperature is a function of season, as well as climate conditions (including cloud cover) in any given year. Salinity is a function of the freshwater dilution of seawater, with hyper-salinity occurring when evaporative effects are greater than freshwater dilution. Freshwater is added to GoC estuaries and inshore coastal areas from both local coastal rainfall and river flow that results from rainfall higher up in the catchment. The large catchment areas of many of the Gulf rivers means that coastal rainfall and significant flooding of the estuaries through river flow is sometimes but not always co-incident.

Blue Swimmer Crab

The Blue Swimmer Crab belongs to the family Portunidae which is characterised by animals with the last pair of legs modified to flattened swimming paddles. Colouration is generally mottled blue on males and mottled brown on females but the intensity and pattern of colouration is variable. Mature male and female crabs are easily distinguished by the shape of the abdominal flap, being narrow and triangular in males, and broad and rounded in females. The *Portunus pelagicus* species complex was recently reviewed by Lai *et al.* (2010), with the Australian species considered to be *Portunus armatus* (A. Milne-Edwards 1861).

Growth

Blue Swimmer Crabs are considered to be fast growing, although there is considerable uncertainty in the growth rates due the inability to age the species (Sumpton *et al*. 2015; Lloyd-Jones 2016). While growth has been quantified for the Qld east coast stock (Sumpton *et al*. 2003), no information is available for stocks in the GoC. Blue Swimmer Crabs moult to grow, with the frequency of moulting decreasing with age. Crabs reach sexual maturity at about one year depending on latitude and location, with a maximum age in Qld of three years. Once maturity is reached, they moult and mate two or three times before death.

Weng (1992) reported on trawl-caught samples of Blue Swimmer Crabs (reported as *Portunus pelagicus*) from the southern GoC (Mornington Island, 8 to 40 m depth) collected in 1983 to 1984. Few of the Blue Swimmer Crabs sampled were of legal size, with this interpreted as GoC having slower growth rates compared to other areas within the species distribution. It also may have resulted from a lack of differentiation between *P. armatus* and *P. pelagicus* by the study.

Reproduction

Mating occurs immediately after moulting while the female's shell is still soft. Males can mate with many females, but females will only mate once at the beginning of each moult cycle. Females can store sperm for up to a year (Svane and Hooper 2004), fertilising several batches of eggs throughout the year. In the GoC, a high proportion of female Blue Swimmer Crabs exhibited moulting condition in May (Weng 1992). Mating is likely to occur at this time, with spawning occurring over subsequent months.

Blue Swimmer Crabs are highly fecund with females releasing up to 2.4 million eggs per spawning batch. Fecundity of smaller females (~100 mm CW) is about 250,000 and increases to over two million in larger (>180 mm CW) individuals (Zairion *et al*. 2015). Spawning appears to be dependent on salinity, with an Indian study reporting an optimal salinity of 35 ppt (Soundarapandian and Tamizhazhagan 2009).

Some spawning takes place year-round in tropical waters, with peak spawning occurring in spring (Weng 1992; Kunsook *et al*. 2014). In the GoC, the CW of ovigerous females ranges between 68 mm and 147 mm (Weng 1992). Female GI is generally highest in spring, although a high proportion of females are ovigerous in the GoC between July and October (Weng 1992). The average CW-at-maturity of female Blue Swimmer Crabs is 106 mm in the Gulf of Thailand (Kunsook *et al*. 2014) and 103 mm in Indonesia (Zairion *et al*. 2015). These results are consistent with Moreton Bay (Sumpton *et al*. 2003), where CW-at-maturity of female crabs was 110 mm.

Spawning occurs in oceanic and estuarine waters where salinity is oceanic. In the temperate Gulf of St Vincent (South Australia), ovigerous female Blue Swimmer Crabs migrate from shallow coastal and estuarine waters to deeper water (Bryars and Havenhand 2004), similar to the spawning migration of ovigerous female Giant Mud Crabs. However, the migration of Blue Swimmer Crabs in the GoC to spawn remains unsubstantiated. Females settle in the sand and extrude eggs, which become attached to pleopods under the abdominal flap. Eggs are incubated under the abdominal flap. The speed of egg development is dependent on water temperature (Svane and Hooper 2004; Tweedley *et al*. 2017).

Larval phases

The eggs hatch after approximately 15 days at 24 °C and 10 days for temperatures between 26 ºC and 29 ºC. Blue Swimmer Crab larvae are planktonic with high mortality rates (estimates of 98% to >99%). The larval phase has five stages, spending up to six weeks in the plankton before settling as megalopa in inshore areas.

Juvenile phase

Juveniles mostly live in inshore estuarine areas where they grow rapidly, moving into deeper water as they grow. Many migrate from estuaries to offshore waters as large juveniles or adults. While the distribution of juveniles is relatively well known for the major stocks in Australia (see Johnston *et al.* 2018), little is known about the distribution of juveniles in estuaries and inshore coastal waters of the Gulf of Carpentaria.

Habitat

Blue Swimmer Crabs live in a range of inshore and continental shelf areas including sandy, muddy, algal, or seagrass habitats, from the inter-tidal zone to 50 m deep. Female crabs are more often found on shallow sandy areas, whilst males prefer deeper gutters and lower slopes of sand banks. In the GoC, Blue Swimmer Crabs are commonly caught (but not retained) in the offshore trawl Fishery (i.e. Northern Prawn Fishery, M. Campbell pers. obs.), but are rarely of legal size (as noted by Weng 1992). In some locations the habitats of Blue Swimmer Crabs overlap with those of Giant Mud Crabs (e.g. southern Moreton Bay, see Webley 2008). Although based on limited records, the available information suggests that in the GoC, these species sometimes overlap (Jebreen *et al*. 2008), but probably not to the extent that they are in competition for habitat or food as is the case in southern Moreton Bay (Webley 2008).

Diet

Blue swimmer crabs are opportunistic bottom feeding omnivores. They feed on a wide range of benthic invertebrates, scavenge on dead pelagic animals, including fish and squid, and detritus. Wassenberg and Hill (1987) reported that animals discarded from prawn trawls constituted ~33% of the diet of Blue Swimmer Crabs caught in Moreton Bay.

Conclusion

The literature review on Giant Mud Crabs life-history drew on numerous studies conducted from a variety of locations, a small number of studies specifically from the GoC. Assuming GoC populations behave in a similar manner to others, Giant Mud Crabs in the GoC may be impacted by environmental factors at several life-history stages, either singularly or cumulatively. These include during:

(i) Larvae and megalopae stages in offshore waters, where non-optimum temperature and salinity may affect growth and survival; and where current-dependent transport may affect the regional distribution and survival, which influences the number/density recruiting to inter-tidal habitats.

(ii) Megalopae, EBS and juvenile crab stages in inter-tidal habitats, where temperature, salinity, food availability and tidal inundation may affect growth and survival

(iii) Sub adult and adult stages in inter-tidal and sub-tidal habitats of estuaries and the coastal foreshores, where temperature, salinity and food availability may affect growth, survival and reproduction, as well as catchability in commercial fishing apparatus.

The literature review on Blue Swimmer Crab life-history drew on numerous studies from a variety of locations, with only Weng (1992) including samples from the GoC. Like Giant Mud Crabs, each life-history stage of Blue Swimmer Crabs has an optimal range of temperature and salinity. Although in some localities (e.g., Moreton Bay), Giant Mud Crab and Blue Swimmer Crabs co-exist and compete as scavengers for food resources (including discarded bycatch from trawl fisheries). Determining the species and depth preferences of Blue Swimmer Crabs that inhabit inshore coastal areas of the GoC (see Chapter 3) may assist in determining whether competitive co-existence is likely or under what conditions it occurs.

The review confirmed that metrics of water temperature and salinity should be considered when evaluating the environmental factors affecting crab fisheries in the GoC, which is part of objective 1 and is reported upon in chapter 4. Temperature is a function of season, as well as climate conditions (including cloud cover) in any given year. Salinity is a function of the freshwater dilution of seawater, with hyper-salinity occurring when evaporative effects are greater than freshwater dilution. Freshwater is added to GoC estuaries and inshore coastal areas from both local coastal rainfall and river flow that results from rainfall higher up in the catchment. The large catchment areas of many of the Gulf rivers means that coastal rainfall and significant flooding of the estuaries through river flow is sometimes but not always co-incident.

Chapter 2. Crab fisheries of the Gulf of Carpentaria

J.B. Robins and M.A. Grubert

This chapter summarises the management arrangements of each jurisdiction for crab fisheries in the GoC and provides an overview of the temporal variability in catch and effort. Crab fisheries in waters west of 138 ºE are managed as part of the NT Mud Crab Fishery, while those in waters east of 138 ºE are managed as part of the Qld Crab Fishery. Although two species of mud crab occur in the GoC, the Orange Mud Crab (*Scylla olivacea*) appears to be restricted to the area around Weipa. This, and because very few Orange Mud Crabs reach the local minimum legal size (150 mm CW), means that over 99% of the mud crab harvest in the GoC is the Giant Mud Crab (*S. serrata*).

Blue Swimmer Crabs (*Portunus armatus and P. pelagicus*) occurs in the GoC (Kailola *et al.* 1993), but are not a significant component of the GoC crab harvest by commercial fishers. This is a function of animal size (i.e. many not reaching the Qld minimum legal size) and commercial viability (tonnage, value, and market access). In most years between 1990 and 2019, fewer than five licences in the Qld GoC reported a harvest of Blue Swimmer crabs, with the total annual harvest usually less than two tonne (QFish 2020). The scale of the fishery for Blue Swimmer Crabs in the GoC is insufficient to be included in the National Status of Australian Fish Stocks Report (Johnston *et al.* 2018). Blue Swimmer crabs are also not commonly harvested from GoC waters by recreational or indigenous fishers in most years (DAF 2020). However, in 2016, there was an influx of Blue Swimmer Crabs into shallow (5 to 10 m), inshore waters of the south-eastern GoC, resulting in a reported harvest of 11.5 tonne (QFish 2020). At the same time and in the same area, Giant Mud Crabs were reduced in their abundance. The harvest of Blue Swimmer Crabs from the south-eastern GoC should be considered as opportunistic, rather than a dedicated fishery. Further details are not provided in this chapter, as in most years, the catch and effort data for Blue Swimmer Crabs from the GoC is confidential as a consequence of the DAF 5-boat rule, which precludes disclosure in situations where fewer than five licences have operated (QFish 2020).

Over the last two to three decades, the market demand for Giant Mud Crabs has slowly increased. Hundloe (in Brown 2010) provides an overview of the economics of the Qld (mud) Crab Fishery (as at November 2009), whilst DPI&R (2017) provides an overview of the market for the NT Mud Crab Fishery. Most of the harvest of mud crabs from the GoC are not consumed close to the capture location; the few small towns in the GoC do not provide a large market for locally caught crabs. Giant Mud Crabs are transported mostly by road to either Darwin or a Qld east coast city (e.g. Cairns or Townsville). An unknown proportion is consumed in these cities, but price and demand suggest that many are transported by air to southern markets (e.g. Brisbane, Sydney, and Melbourne). Hundloe (in Brown 2010) details some of the complexity and seasonality of pricing of Giant Mud Crabs, which is linked to social celebrations (e.g. Christmas, New Year, Easter, Chinese New Year, and Chinese Mid-Autumn Festival). Limited economic data is available on the value of the Giant Mud Crab harvest from the GoC, but the annual reports of the Sydney Fish Market (https://www.sydneyfishmarket.com.au/Corporate/Company-Overview/Annual-Reports) provide some evidence of the trend of increasing value of Giant Mud Crabs, at least since 2006 (Figure 5). For comparison, the value of Blue Swimmer Crabs derived from the annual reports of the Sydney Fish Market also has been collated in Figure 5, and indicates: (i) lesser value per kg, and (ii) evidence of a trend of increasing value, at least since 2006. If considered with tonnage, these values highlight that GoC fisheries for Giant Mud Crabs are an order of magnitude more valuable than that for Blue Swimmer Crab, although for individual fishers, all harvested catch is valuable.

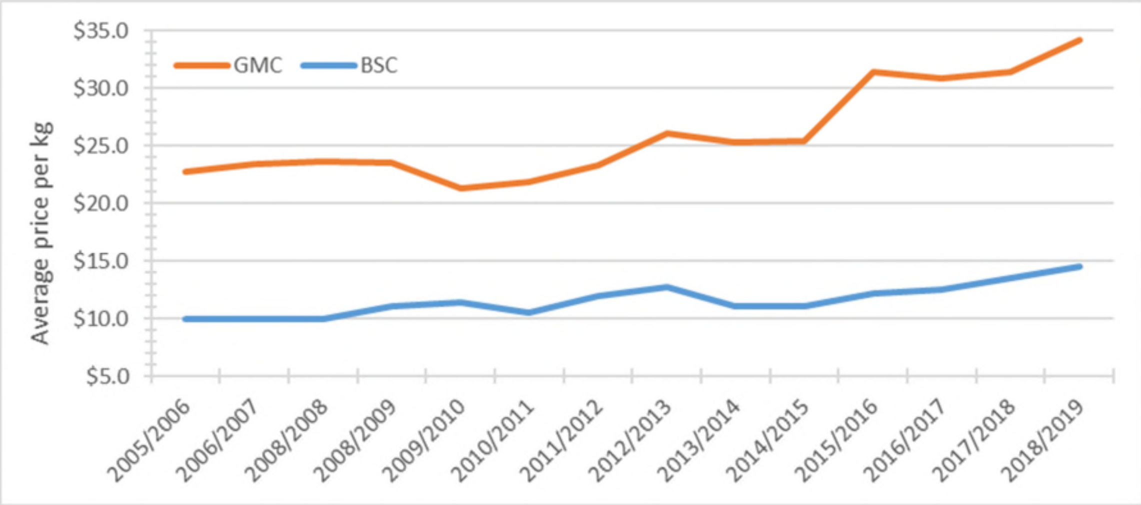


Figure 5. Annual average price per kg for mud crabs (GMC) and blue swimmer crabs (BSC) reported in the Sydney Fish Market Annual Reports

Northern Territory Western Gulf of Carpentaria

Giant Mud Crabs in the NT Western GoC Mud Crab fishery are predominately exploited by the commercial sector, with limited and poorly quantified harvest by the recreational sector. The recreational sector is estimated to take 6% of the mud crab harvest across the entire NT, with the commercial sector taking 88%, the traditional harvest taking 5% and the fishing tour sector taking the remaining 1% (Hay 2009; DPI&R 2017). Seventy per cent of the recreational harvest is estimated to occur in the Darwin region. The western GoC does not have large adjacent human populations (such as Darwin). Therefore, we assumed that the recreational harvest of Giant Mud Crabs was minor compared with the commercial harvest in the western GoC.

Management arrangements

For detailed description of the NT Mud Crab Fishery see Ward *et al*. (2008), the NT Harvest Strategy (DPI&R 2017) and Grubert *et al*. (2019). Key aspects relevant to the current work are that the fishery is input controlled, and has had several major management changes over time.

The NT fishery for mud crabs (predominantly the Giant Mud Crab) began in the early 1980s with considerable development over the next decade (Knuckey 1999). Prior to 1980, Giant Mud Crabs were harvested under a General Fishing Licence, with no restriction on the number pots used. A specific fishery for mud crabs was developed in 1980, with 61 licences issued, but pot numbers remained un-capped. A moratorium on the issue of new licences was applied in 1985 (capping licences at 55) and the number of allowable pots set at 60. In 1988, the number of licences was reduced to 49, where it remains today. In 2010, licences were spilt into two “units of entitlement” each of which permit the use of 30 pots. This arrangement provides greater flexibility for operators as they can now increase their gear holdings in multiples of 30 rather than 60 pots.

A minimum legal size (MLS) of 130 mm CW was applied to both sexes of mud crabs in 1985. The MLS for female mud crabs was then increased to 140 mm CW in 1996. A further change was implemented in 2006, with the MLS for commercially harvested mud crabs (only) increased by 10 mm; to 140 mm CW for males and 150 mm CW for females.

The "Commercially Unsuitable Crab (CUC)" rule (implemented in 2001) is unique to the NT and mandates that licensees must return recently moulted "soft" crabs to the water, to reduce post-harvest mortality and ensure a high degree of product quality.

Fishery

Steel weldmesh pots introduced in 1985 by crabbers of Cambodian and Vietnamese origin became standard throughout the fishery. Pots are rarely set closer than 100 m apart (Knuckey 1999). In the NT Western GoC, most licences operate from land-based dwellings near river mouths or coastal inlets, using 4 to 6 m aluminium vessels powered by 4-stroke outboard motors of between 100 and 150 horse power (HP). Consistent with inshore fisheries in other areas has been the adoption of 4-stroke outboard engines in preference to 2-stroke engines because of improved reliability and increasing HP; from 35 to 50 HP in 1989, 60 to 115 HP in 1999, and from 100 to 150 HP by 2017 (Knuckey 1999; DPI&R 2017).

The NT Western GoC Mud Crab Fishery is highly seasonal with 73% of the reported total catch harvested during the dry season i.e. May to October (Hay and Calogeras 2001; Hay *et al*. 2005). The onset of the wet season brings poor boating conditions from monsoonal storms, low catch rates (associated with Giant Mud Crab life-history), and limited/no road access to and from the main land camp areas on the Roper and McArthur rivers - creating problems in the transport of product to Darwin. Knuckey (1999) reported that the average number of months worked per year was 10, and the average number of days fished per month was 22. These are likely to be the practical limits of effort in the NT Mud Crab Fishery.

Monitoring and assessment

Catch and effort data in the NT Western GoC Mud Crab Fishery are reported via mandatory monthly logbooks, with a spatial resolution of 1^o x 1^o (Figure 6). Effort is recorded as days fished per month, number of pots used, and number of days the pots were lifted twice. This gives three metrics of effort in the NT Western GoC: (i) days fished, (ii) pot days = number of days fished by number of pots used, and (iii) pot lifts = number of days fished by number of pots used plus number of days the pots were lifted twice by number of pots used.

The DPI&R also monitor the size and sex-ratios of harvested Giant Mud Crabs at seafood processors in Darwin (Grubert *et al.* 2012). Sex ratios fluctuate throughout the year, reflecting the variable catchability of males and females. The percent of females is lowest in December to February at 10 to 20%, increasing to a peak of 60 to 80% between September and November.

Monthly catch and effort data were supplied to the current project by the DPI&R for the years 1983 to 2018 for fishery grids within the NT Western GoC Mud Crab Fishery. Although the data is non-validated, under reporting is considered minor (Knuckey 1999; Hay and Calogeras 2001; M. Grubert pers. obs.). The NT Western GoC was subdivided into regions for analysis of patterns in catch rate with environmental factors (Chapter 4) and mostly concurs with spatial areas noted in Knuckey (1999). Regions for the NT Western GoC were (Figure 6):

(i) Blue Mud Bay/Groote Eylandt – grids 1335, 1336, 1436
(ii) Roper – grids 1435, 1535
(iii) McArthur/Robinson – grids 1536, 1537, 1637

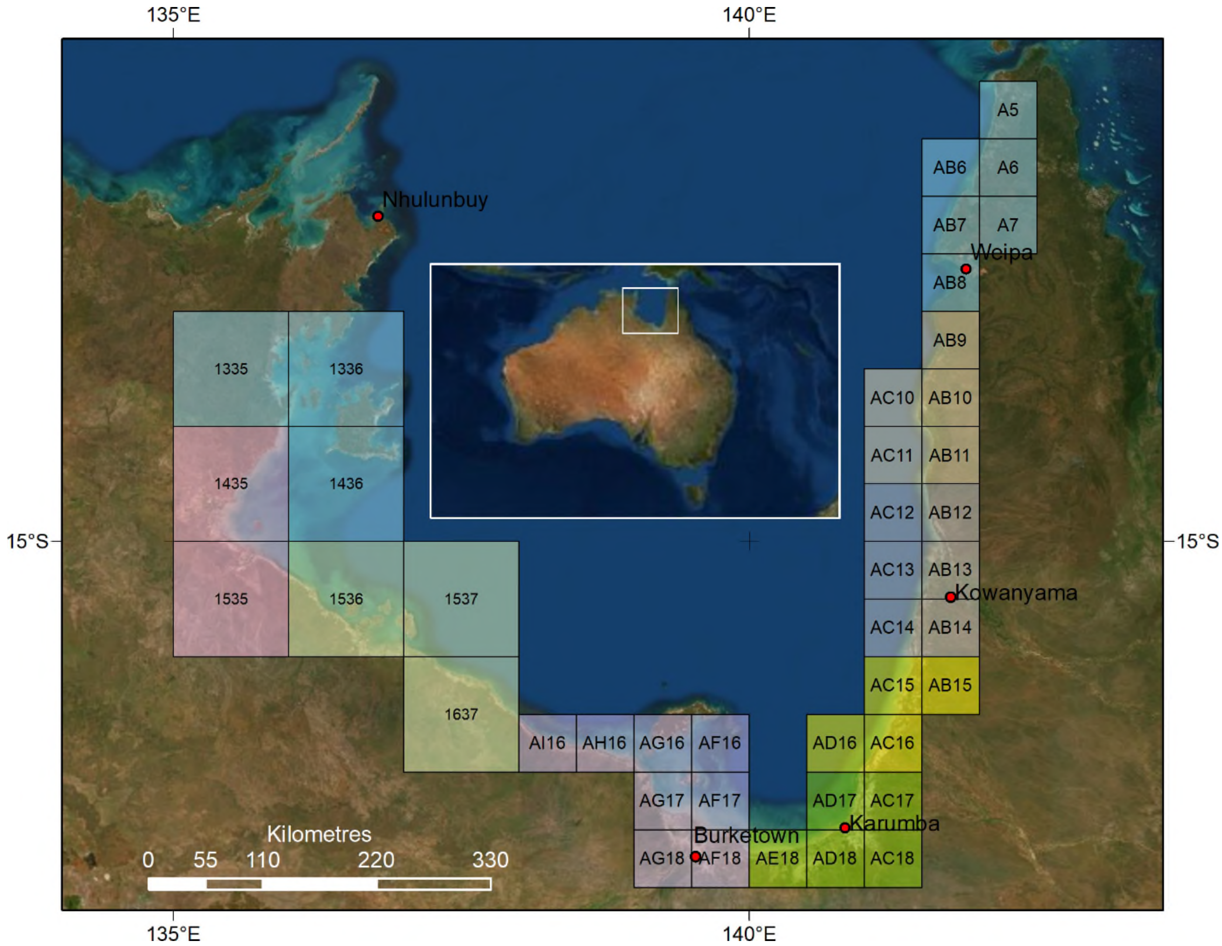


Figure 6. Fishery reporting grids in the Gulf of Carpentaria, noting that Northern Territory grids are 1^{o} by 1^{o}, whereas Queensland grids are 0.5^{o} by 0.5^{o}. Colours represent the aggregation of fishery reporting grids into regions for analysis, see text.

Since 1989, the harvest of Giant Mud Crabs from the NT Western GoC has fluctuated between a peak of 983 tonnes in 2001 to a low of 50 tonnes in 2016 (Figure 7). Whilst regional patterns are similar, there are slight differences in peaks and troughs in catch and catch rate.

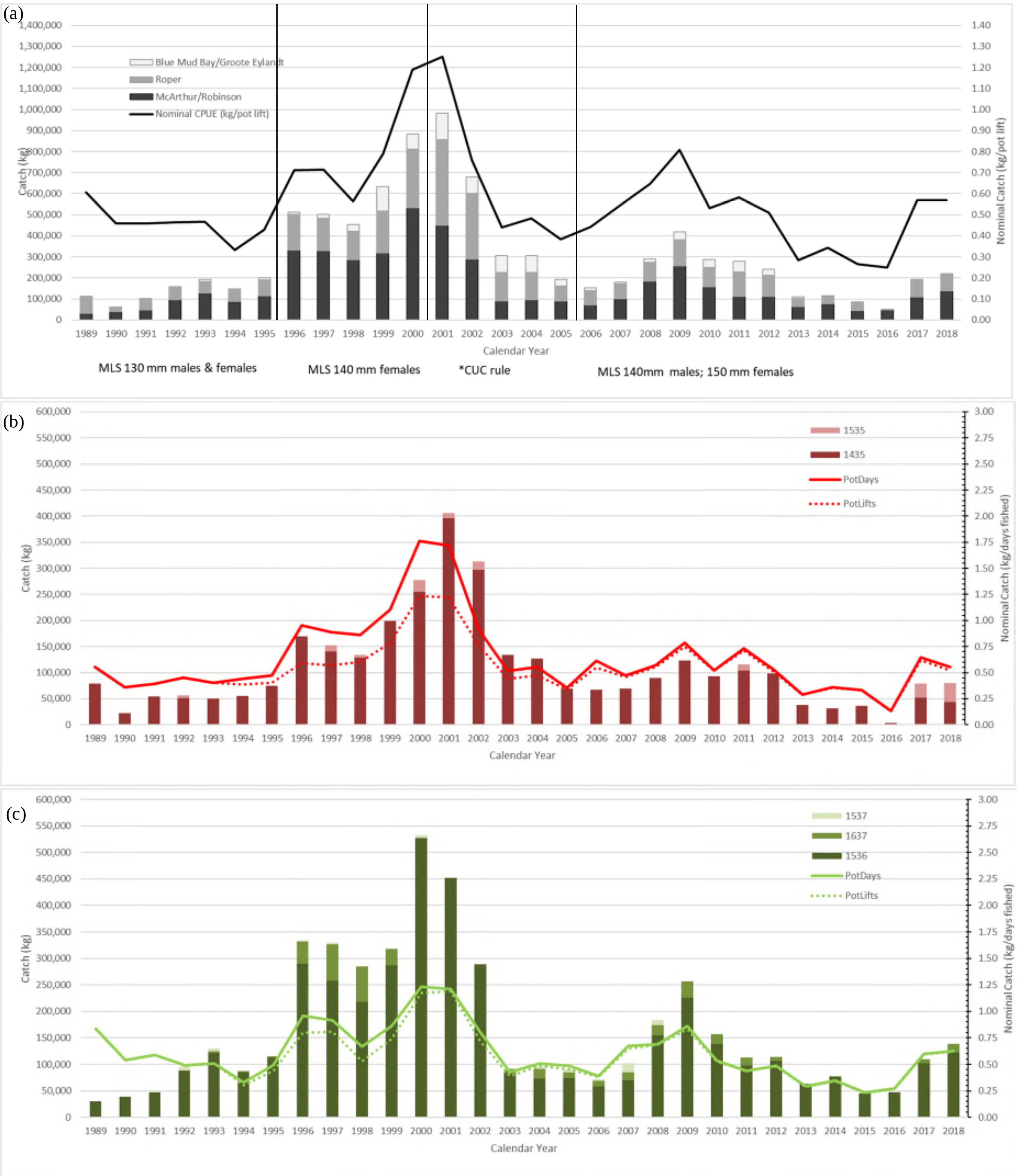


Figure 7. Harvest (kg) and nominal catch rate (kg/pot day or lift) of Giant Mud Crabs for NT Western GoC Mud Crab Fishery from: (a) all regions, (b) the Roper region and (c) the McArthur region.

The analysis of NT Western GoC catch and effort data in the current study only included data from 2006 to 2018, as this represents harvest under consistent management arrangements (i.e. MLS and Commercially Unsuitable Crab (CUC) rules). Under these conditions, variations in catch or catch rate are likely to be related to environmental factors, not management arrangements. The Blue Mud Bay/Groote Eylandt region was not considered further as changed effort patterns in the region after the Australian High Court's Blue Mud Bay decision (DPI&R 2017) may result in catch and effort not being representative of population abundance.

Yield (i.e. catch) was plotted against effort for the NT Western GoC Mud Crab Fishery (as per Brown 2010). In a hypothetical system in equilibrium (which assumes constant recruitment), the effort to yield relationship should be dome-shaped, indicating the level of effort resulting in maximum yield. Effort-to-yield plots require a fishery to heavily exploit the catchable biomass such that despite increasing effort, yield declines. Whilst recruitment is unlikely to be constant, the NT Western GoC Mud Crab Fishery is considered to be fully fished, with >90% of adult crabs estimated to be removed annually from the stock (Hay *et al*. 2005; Ward *et al*. 2008). Patterns in effort-to-yield were similar regardless of the effort metric (i.e. days fished, pot days or pot lifts) and were similar between the Roper and McArthur regions. The main difference between regions was the extreme decline in 2016 that occurred in the Roper region which was not as extreme in the McArthur region (Figure 8).

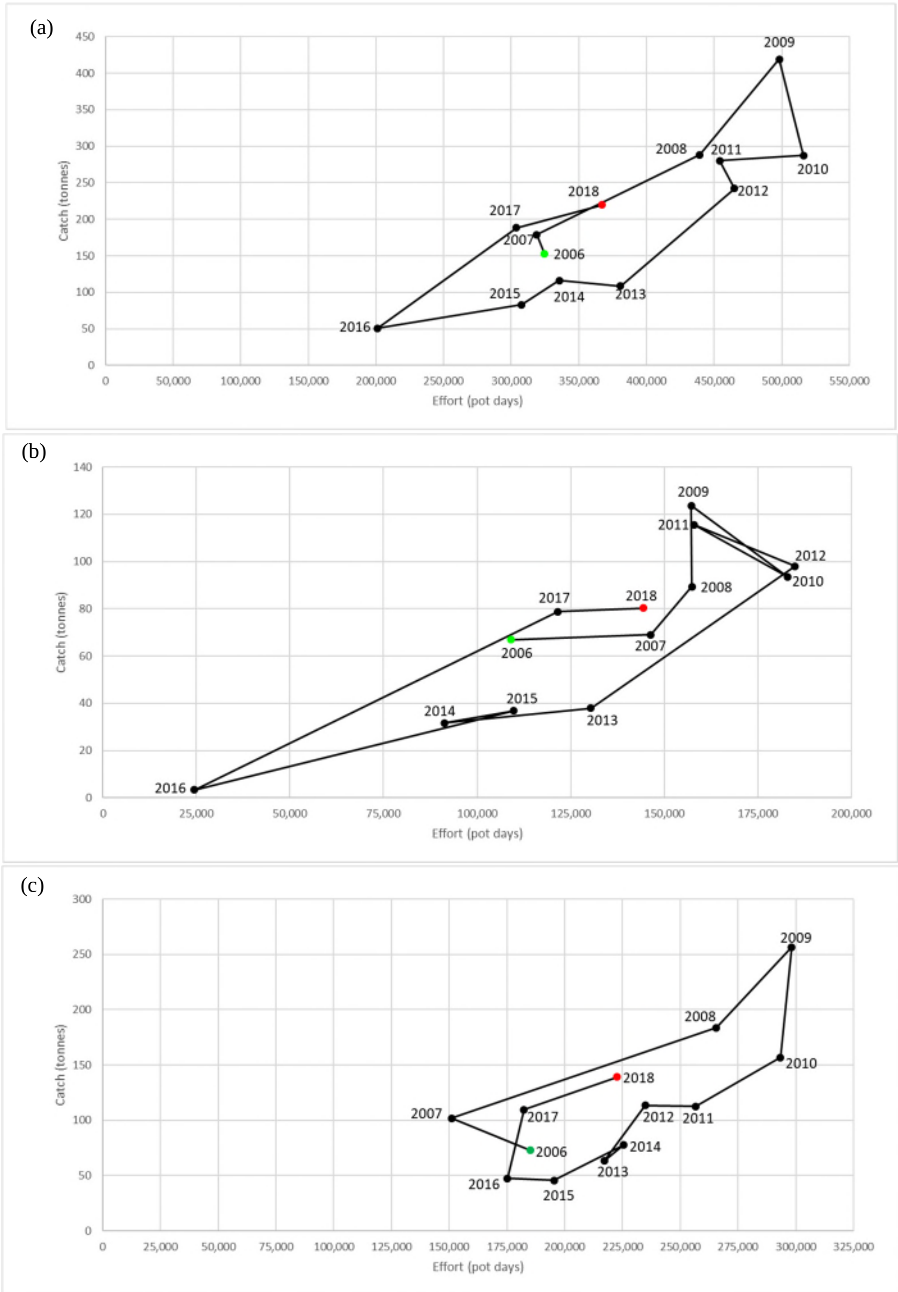


Figure 8. Effort-to-yield plots for the NT Western GoC Mud Crab Fishery, based on monthly logbook data, 2006 to 2018 from: (a) all regions, (b) Roper region and (c) McArthur region. Note different scales on x- and y-axes.

The NT Mud Crab Fishery has a long history of stock assessment, using a variety of approaches and models (Walters *et al*. 1997; Haddon *et al.* 2005; Ward *et al*. 2008; Grubert *et al*. 2013; Grubert *et al.*

2019). The stock assessment by Walters *et al.* (1997) indicated that the NT Mud Crab Fishery was fully exploited, with annual exploitation rates at 70 to 90% of the available stock, suggesting there was little room for further development. However, within 12 months, the commercial catch of the NT Mud Crab Fishery (Arafura-West and Western GoC stocks combined) doubled to 595 tonnes. Assessment using a novel monthly size-age-sex Stock Synthesis model (Grubert *et al*. 2013) indicated that the annual fishing mortality for Giant Mud Crabs is around 1.0 to 1.2, similar to that estimated by Knuckey (1999). The catch in any year consists (mostly) of 1+ year-old crabs that have recruited to the fishery between February and April (Knuckey 1999). Therefore, the fishery is very dependent on recruitment from the previous year, meaning that a poor year-class will be realised in the fishery within 18 months.

The assessments identified that catch-effort models and associated assessment methods may be influenced by the non-random fishing effort in mud crab fisheries (Walters *et al*. 1997). It is likely that commercial crabbers in northern Australia operate by systematically fishing then resting local areas over the fishing season. As such, they maintain a hyper-stable catch per unit effort (CPUE) at short time scales (i.e. weeks). However, annual patterns in catch and effort may not be as susceptible to these impacts because of the high overall fishing pressure.

Harvest strategy indicators

The NT has a formal management framework and Harvest Strategy for its Mud Crab Fishery (see https://dpir.nt.gov.au/fisheries/fisheries-strategies,-projects-and-research/harvest-strategy-policy-and-guidelines). The Harvest Strategy employs both primary and secondary performance indicators and four associated reference points (target, upper trigger, lower trigger, and limit).

The primary performance indicator is commercially retained CPUE in kg per pot day. The secondary performance indicator is female spawning stock biomass (FSSB) per stock (Arafura-West and Western GoC) estimated from a delay-difference model (Grubert *et al.* 2019).

Primary indicators are:

- Target reference point: Annual average CPUE = 0.6 kg per pot day
- Upper trigger reference point: Annual average CPUE = 0.7 kg per pot day
- Lower trigger reference point: April-May average CPUE = 0.3 kg per pot day
- Limit reference point: April-May average CPUE = 0.2 kg per pot day

The secondary indicator is the FSSB target reference point, set at 70 tonnes.

If the lower trigger reference point is exceeded, then a seasonal closure (of either 3, 6 or 13 weeks, beginning on 1 October) will be implemented, depending on the relative values of the primary and secondary performance indicators in a decision matrix.

Queensland Gulf of Carpentaria

Giant Mud Crabs in the Qld GoC Mud Crab are predominately exploited by the commercial sector, with limited and poorly quantified harvest by the recreational sector and indigenous sectors. The recreational MLS (male only fishery) is 150 mm CW, with a possession limit of 7 per person or 14 per boat (with 2 or more people on board). Recreational harvest of Giant Mud Crabs is thought to be concentrated adjacent to coastal ports (e.g., Karumba and Weipa). For the Qld GoC, the recreational sector is estimated to take about 12% of the annual mud crab harvest, with the commercial sector taking most of the remaining harvest, although there is likely a small but unquantified traditional harvest (Northrop *et al.* 2019).

Management arrangements

For a detailed description of the Queensland Crab Fishery, as it relates to mud crabs see Hill (1984) and Brown (2010). Key management arrangements for Giant Mud Crabs relevant to the current work are that the fishery is input controlled, and that the harvest of females has been prohibited since the early 1900s. The MLS for males was set at 6 inches CW in 1926 then converted to 150 mm CW during decimalisation in 1966.

Blue Swimmer Crabs are managed as part of the Queensland Crab Fishery and are taken under the same endorsement (C1 fishing symbol) as mud crabs (see Sumpton *et al.* 2015). Key management arrangements for Blue Swimmer Crabs relevant to the current work are that the fishery is input controlled, and that the harvest of females is prohibited. The MLS for male Blue Swimmer Crabs was 150mm maximum CW (i.e. distance between the tip of the lateral spines) until 2003 when the MLS was changed to 115 mm nominal CW (i.e. distance between the bases of the lateral spines). This equated to a decrease of the previous MLS to approximately 14 cm maximum CW.

Fishery

The fishery for Giant Mud Crabs in the Qld GoC has slight differences to that of its Qld east coast counterpart, although both are managed under the C1 fishing symbol (until the 2020 fishing year see https://www.daf.qld.gov.au/business-priorities/fisheries/sustainable/sustainable-fisheries-strategy/fishery-working-groups/crab-working-group). Key differences include the GoC’s remoteness and difficulty in accessing the large expanse of estuarine and coastal habitats where Giant Mud Crabs can be fished. Unlike the NT Western GoC, there are few land-camps. Most fishers who harvest operate out of a port (i.e. Karumba or Weipa) conducting day or overnight fishing trips or use larger live-aboard fishing vessels (with associated dories/tinnies) from which they conduct crabbing operations either full-time or as part of a mixed fishing operation (including netting). Effort is thus constrained by weather, much more so than in the NT Western GoC or most places on the Qld east coast. The Giant Mud Crab resource in the Qld GoC is mostly accessed by owner/operator fishers or lessee fishers, whereas the NT mud crab licences are mostly owned by investors or processors with sub-contractors undertaking actual fishing. This underpins differences in motivations to fish between the NT and Qld jurisdictions in the GoC, and combined with access differences, subtly changes the relationship between catch and effort, and how these relate to the abundance of Giant Mud Crabs.

The fishery for Giant Mud Crabs in the Qld GoC has expanded over time. Hill (1984) noted little development of the GoC crab fishery in 1984, with an estimated two master fishermen who were primarily crabbers. Gribble (2003) noted that the trends in catch and effort (between 1989 and 1997) for mud crabs in the Qld GoC were of a developing fishery with some areas at ‘maturity’ (e.g. around Karumba in the south-east corner) while others were newly exploited (e.g. Weipa, Mapoon). The expansion of the fishery for Giant Mud Crabs in the Qld GoC has been caused by the interplay of improved fishing capacity (including collapsible pots and more reliable 4-stroke motors), more fishers specialising in crabbing and the increasing market value of Giant Mud Crabs as a premium seafood product (Figure 5). Ryan (2003) notes that the (local) value of mud crabs in the early 2000s was $8 to 12 per kilogram.

Monitoring and assessment

Daily catch and effort data were supplied to the current project by Fisheries Queensland (Data Request 2796) for the years 1989 to 2018 for the Qld Crab Fishery. Only catches (and associated effort) west of 142.5 ºE were considered to have come from the Qld GoC stock. Queensland commercial catch and effort data is non-validated. Serious concerns about the accuracy of the catch and effort data (i.e. days fished and number of pots used) have been consistently raised in previous studies (Brown 2010, Wang *et al*. 2011). There have been several 'Investment Warnings' that potentially result in 'misreporting' of catch and effort: (i) for the GoC in 1997, (ii) for the Qld Crab Fishery in 2003, and (iii) for all Qld commercial fisheries in 2014. Wang *et al*. (2011) concluded that "A lack of confidence in the accuracy of catch-effort statistics from both recreational and commercial sectors" relates principally to the extreme difficulty in policing and recording the number of pots used by fishers. Associated with this is the widely-accepted view that many commercial operators use well in excess of the permitted number of pots, simply to cover losses due to pot theft and damage, and to maintain commercially viable harvests. The effects of various levels of over-potting (i.e. cryptic fishing effort or 'apparent efficiency') on stock density trends were examined in detail by Brown (2010). There was limited value in catch adjusted for misreporting or effort adjusted for over-potting, as any adjustments are broad-scale (i.e. generally applied equally across fishers) and require more non-validated assumptions.

Notwithstanding these concerns, the Qld catch and effort data in the current study were allocated to regions (Figure 6) to permit spatial analysis with environmental factors (see Chapter 4). The regions were based on commercial logbook fishery grids and were:

(i) South West – grids AI16, AH16, AG16, AF16, AG17, AF17, AG18, AF18
(ii) South East – grids AE18, AD18, AC18, AD17, AC17
(iii) Staaten and Gilbert – grids AD16, AC16, AC15, AB15
(iv) Pormpuraaw – grids AB14, AC14, AB13, AC13, AB12, AC12
(v) Aurukun – grids AC11, AB11, AB10, AC10, AC9, AB9
(vi) Weipa and Mapoon – grids AB8, AB7, A7, AB6, A6, A5

Since 1989, the reported harvest of Giant Mud Crabs from the Qld GoC has expanded, with a peak of 199 tonnes in 2012 and the most recent low of 98 tonnes in 2016 (Figure 9). Regional patterns in reported harvest are similar, but the South East region has the most variation. In the absence of validated data, and to use data with a similar level of fishing intensity (both in number of days fished and number of fishers fishing), the current project used the reported catch and effort data from 2000 to 2018. By this time, many operators in the Qld GoC had switched to collapsible trawl mesh pots, which are more readily moved between locations with the aim of maintaining high catch rates. Also, market prices for Giant Mud Crabs had risen to a value where fishers started to target Giant Mud Crabs specifically rather than treat them as an ancillary by-product to inshore finfish, such as barramundi.

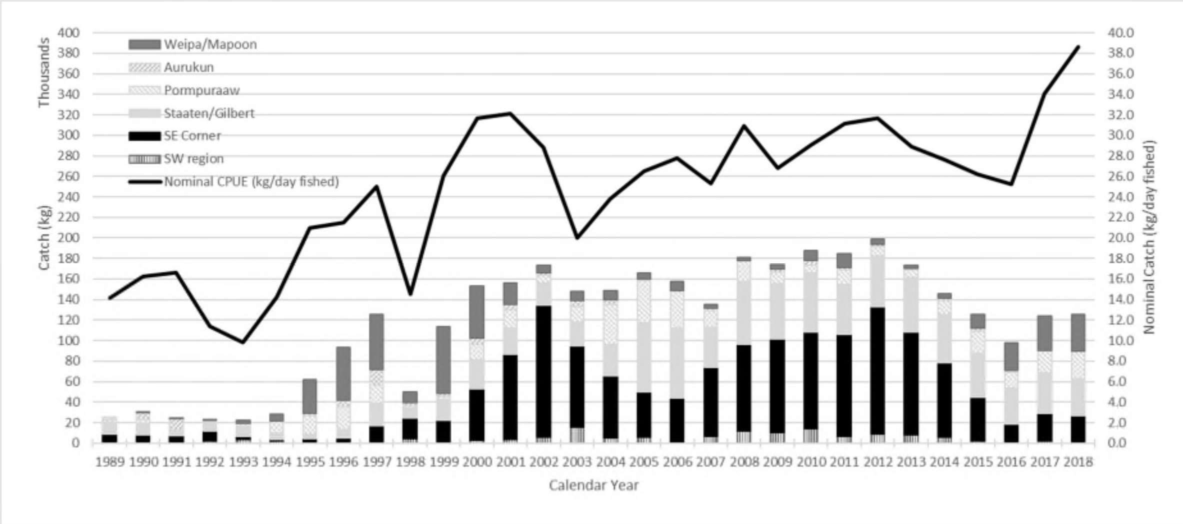
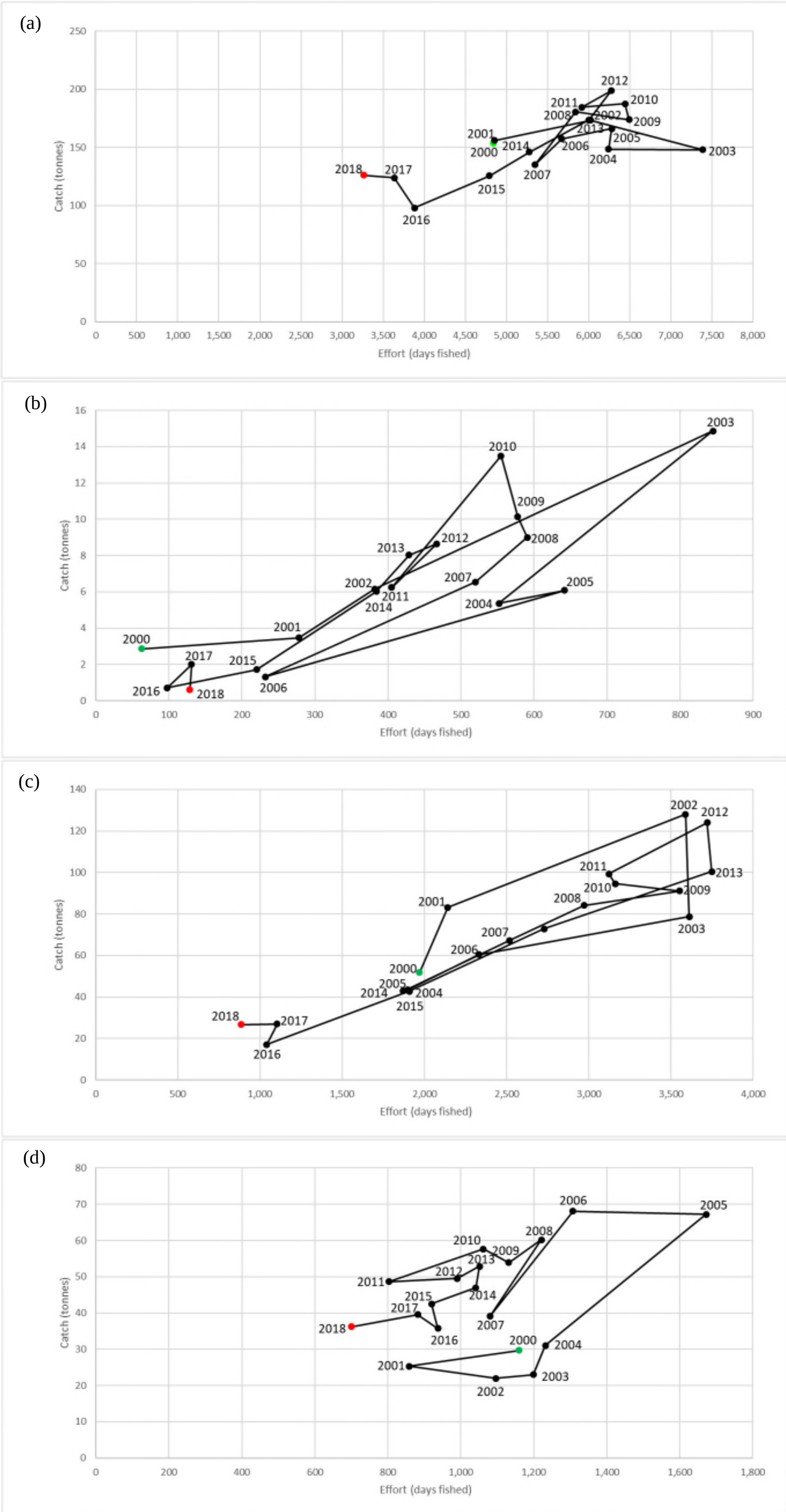


Figure 9. Harvest (kg) and nominal catch rate (kg/day fished) of Giant Mud Crabs for the Queensland Crab Fishery from regions within the Gulf of Carpentaria.

Yield (i.e. catch) against effort was plotted for the Qld GoC Crab Fishery to determine if there were patterns of yield against effort (Figure 10). For the Qld GoC as a whole, the 2003 data point (and to some degree the 2004 data) had higher effort for its level of catch. This is possibly an indication of the 'investment warning' effect (noted by Brown 2010), but was not consistently apparent across all Qld GoC regions (Figure 10).


(a)
Catch (tonnes)
Effort (days fished)
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
(b)
Catch (tonnes)
Effort (days fished)
(c)
Catch (tonnes)
Effort (days fished)
(d)
Catch (tonnes)
Effort (days fished)

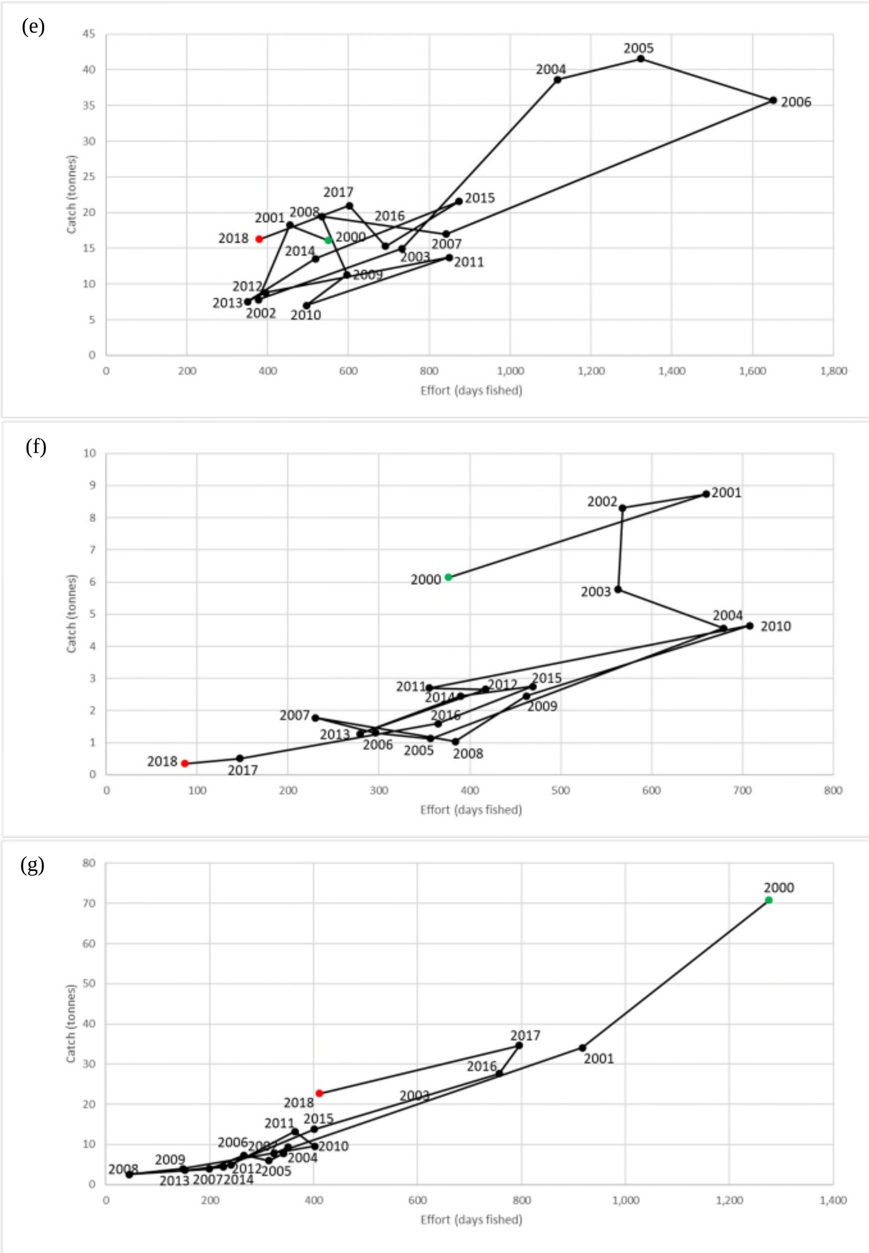


Figure 10. Effort-to-yield plots for the Queensland Gulf of Carpentaria Crab Fishery based on commercial logbook data between 2000 and 2018 from: (a) all regions, (b) South West, (c) South East, (d) Staaten-Gilbert, (e) Pormpuraaw, (f) Aurukun and (g) Weipa-Mapoon.

Harvest strategy indicators

The Sustainable Fisheries Strategy of the Queensland Government sets a management aim of a 60% exploitable biomass target (compared with unfished), as a proxy for Maximum Economic Yield, by 2027. The Harvest Strategy for the Qld Crab Fishery is still preliminary, but does propose a regional (i.e. GoC) total allowable catch (TAC); an approach that is consistent with other fisheries in Queensland. A lack of confidence in the catch data and no information on components other than the exploitable biomass has resulted in recommending a conservative TAC (Northrop *et al.* 2019, as recommended by Wang *et al*. 2010). Queensland's Harvest Strategy will establish recreational and commercial catch shares, and be guided by yield, to achieve target biomass (60%) from future stock assessments, should they become available. In the meantime, rules are in place to ensure a conservative TAC approximates the validated commercial harvest. The harvest strategy will be operational for five years, after which time it will be reviewed.

Catch data comparison of the Northern Territory Western Gulf of Carpentaria and Queensland Gulf of Carpentaria

It is often commented that overall patterns of catch and catch rate are similar in the NT Western GoC and the Qld GoC (e.g. Hay *et al*. 2005; Meynecke *et al*. 2010), despite a different MLS for males (i.e. 140 mm CW in NT and 150 mm CW in Qld), and the prohibited harvest of females in Qld. The similarity in overall patterns of harvest are hypothesised to reflect the influence of environmental factors on recruitment, growth and survival of Giant Mud Crabs at the scale of the GoC. It is possible that certain (broad scale) environmental conditions may have a greater effect on crab abundance than jurisdictional management arrangements.

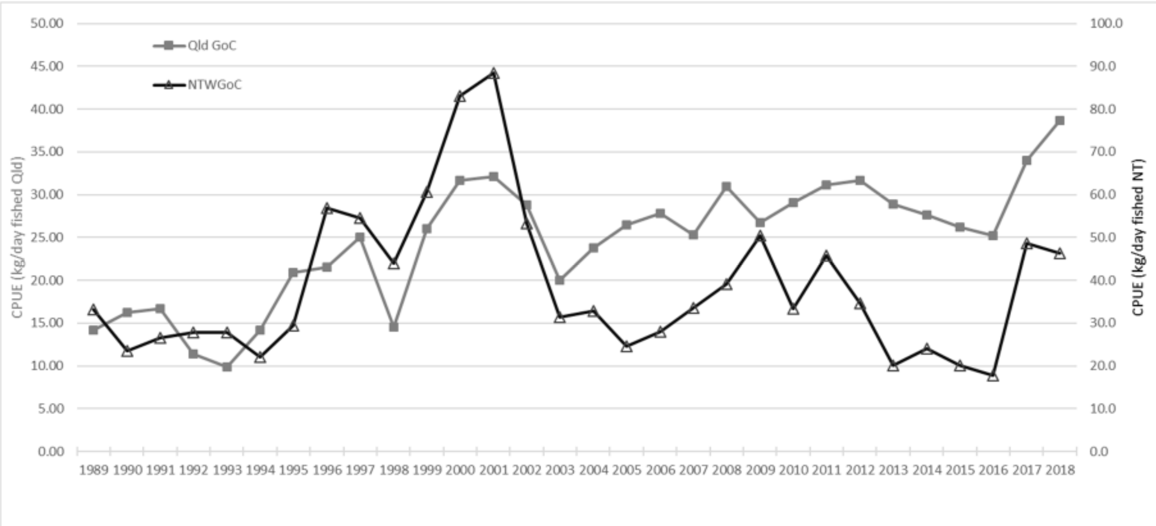


Figure 11. Nominal catch rates (kg/day fished) of Giant Mud Crabs in the Gulf of Carpentaria for Queensland and Northern Territory jurisdictions.

Whilst there were similarities in the temporal patterns of catch rates for Giant Mud Crabs in the NT and Qld GoC (Figure 11), the correlation between log-transformed nominal jurisdictional catch rates was significant, although low (adjusted $R^2 = 0.104$, $F = 0.046$). Considering only 2006 onwards (when NT regulations were temporally consistent), the correlation was significant and moderate (adjusted $R^2 = 0.313$; $F = 0.027$). Hay *et al*. (2005) speculated that some of the difference between NT and Qld GoC CPUE may be due to higher fishing pressure in the NT. High fishing pressure would effectively remove aggressive mature male and female crabs allowing smaller crabs increased access to habitat (i.e. burrows) and bait (estimated at ~300 tonnes of fish or red meat), which could improve growth and survival. In other words, NT Western GoC regions may be more productive than Qld GoC regions through an inadvertent cultivation effect, via the greater removal of large aggressive crabs from the habitat.

However, differences in patterns of CPUE may also be the consequence of the regional patterns in recruitment and subsequent survival of juvenile crabs into each fishery. Giant Mud Crabs are harvested across some ~2000 km of coastline in the GoC, and whilst there are some environmental factors that are common across areas (e.g. oceanographic influences such as sea level anomalies and broad scale climate patterns), there are many factors that act at regional scales (e.g. rainfall and temperature). The analyses in Chapter 4 aim to investigate regional patterns in catch rates and potential linkages with environmental factors.

Conclusion

Despite different management aims, a common need of harvest strategies for Giant Mud Crab fisheries is that the strategies accommodate the inherent variability in crab populations of northern Australia. Reference points need to responsive and adaptable, to ensure sufficient stock remains during periods of poor environmental conditions, but also to take advantage of exploitable biomass during periods of good environmental conditions. Future climate sequences are uncertain for the GoC. However, it is widely thought that 'extreme' events will be more commonplace than historically observed. The current Harvest Strategy for the NT Western GoC (implemented in 2017) is considered flexible and will be reviewed within the next two years to ensure this continues to be the case. The Harvest Strategy for the Qld Mud Crab Fishery is still evolving, but should ensure some level of flexibility, until more accurate harvest levels have been attained.

Chapter 3. Species identification of Blue Swimmer Crabs in the Gulf of Carpentaria

W.D. Sumpton, M. McLennan, and J.B. Robins

Introduction

Blue Swimmer Crabs have always been a very minor component of the harvest of crabs from the GoC region of the Qld Crab Fishery. They do occur in the GoC (Jebreen *et al*. 2008), but not to an extent (i.e., tonnage of legal size and market access and value) to support a targeted large-scale commercial fishery. Anecdotal reports from commercial fishers indicate that in 2016 Blue Swimmer Crabs were unusually abundant when Giant Mud Crab abundances were reduced. Blue Swimmer Crabs and Giant Mud Crabs occupy different ecological niches and associated habitats. Adult Giant Mud Crabs are abundant in mangrove creeks, estuarine areas and coastal foreshores, while Blue Swimmer Crabs are restricted to coastal foreshore areas and further offshore.

A recent taxonomic review (Lai *et al*. 2010) of the *Portunus* genus separated the Australian Blue Swimmer Crab as *Portunus armatus*, with the previously described *Portunus pelagicus* being endemic to waters of Southeast Asia. Lai *et al*. (2010) describe a number of features that separated the two species and provided a field-key to distinguish between the two species based largely on spination of the cheliped merus. The field-key to separate *P. armatus* from other *Portunus* species is based on an extra spine on the merus. However, Table 7 in Lai *et al.* (2010) acknowledges that on rare occasions three cheliped merus spines are present on *P. armatus.*

The objective of this component of the current study was to investigate the species composition of the Blue Swimmer Crabs likely to be harvested in the GoC. Specifically, to determine the number of species involved, and gather preliminary information on their broad distribution.

Methods

Portunid crabs were obtained from the GoC bycatch samples collected by the CSIRO as part of the annual prawn recruitment-index survey for the Northern Prawn Fishery (Kenyon *et al*. 2018). The annual CSIRO recruitment-index survey samples about 300 sites in five regions (i.e. Groote, Vanderlin and Mornington Islands, Karumba, and Weipa), that are further stratified by depth (shallow, medium and/or deep) and sub-region (North, South, East and/or West), generating 24 sub-strata (Figure 12, Table 1). Sampling occurred during January to early March 2018 using two commercial prawn trawlers each towing two 12 fathom tiger-prawn nets. The regions of Groote Eylandt and Vanderlin Islands provided samples from NT waters, while the regions of Mornington, Karumba and Weipa provided samples from Qld waters.

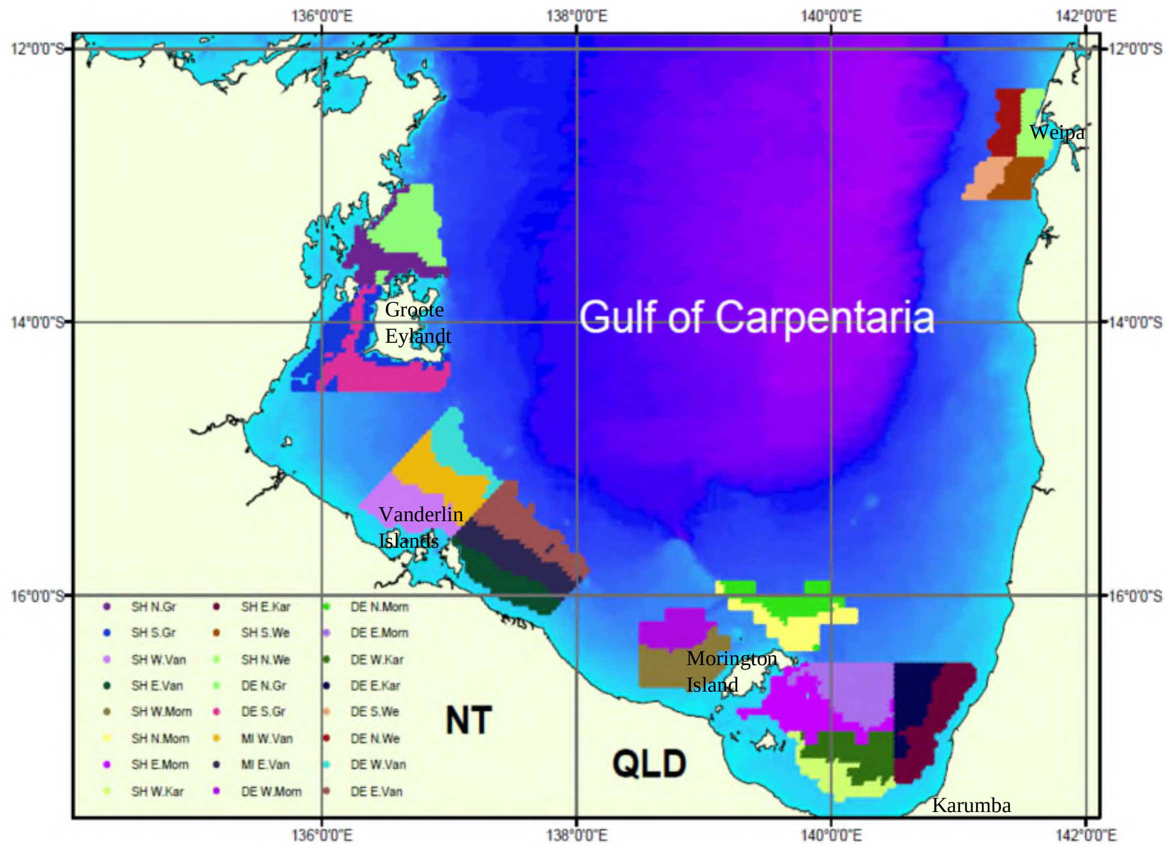


Figure 12. CSIRO recruitment-index survey regions, stratified by sub-region and depth. Sub-strata abbreviations are explained in Table 1. Map reproduced from Kenyon et al. (2018).

Table 1. Sub-strata for sampling Blue Swimmer Crabs from the Gulf of Carpentaria during the CSIRO recruitment-index survey.

Abbreviation	Sub-region	Shallow (SH)	Medium (MI)	Deep (DE)
N. Gr	North Groote	8-25 m		25–40 m
S. Gr	South Groote	8–20 m		20–40 m
W. Van	West Vanderlin	8–25 m	25–35 m	35–40 m
E. Van	East Vanderlin	8–20 m	20–30 m	30–40 m
W. Morn	West Mornington	8–25 m		25–33 m
N. Morn	North Mornington	14–35 m		35–44 m
E. Morn	East Mornington	8–20 m		20–36 m
W. Kar	West Karumba	8–15 m		15–24 m
E. Kar	East Karumba	8–12 m		12–20 m
S. We	South Weipa	8–30 m		30–40 m
N. We	North Weipa	7–25 m		25–40 m

Blue Swimmer Crabs from the *Portunus pelagicus* species complex (Lai *et al*. 2010) were mainly encountered from the shallow sub-strata reflecting their preferred depth range[2]. Not all crabs encountered from individual trawl shots were counted or retained and, as such, quantifying the relative spatial abundance of Blue Swimmer Crab across sampling regions was not possible. Crabs were frozen immediately after capture and returned to Brisbane where they were stored at -20 ºC prior to identification. Specimens were thawed in the laboratory and examined using the morphological key of Lai *et al*. (2010) to determine species identification. This taxonomic key relies mostly on the number of spines on the merus of the crabs' cheliped to separate species, with *P. armatus* having four spines compared with three for *P. pelagicus*.

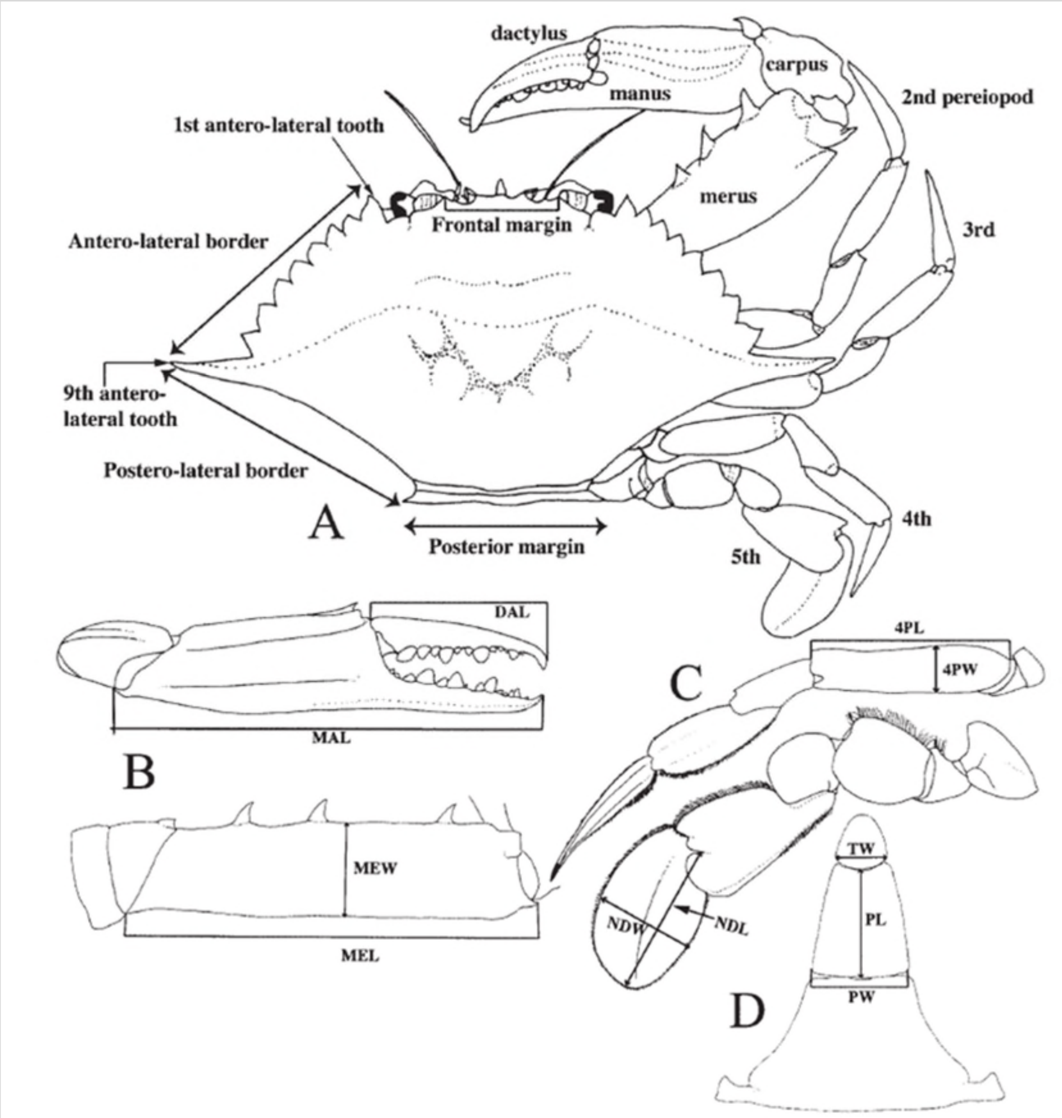


Figure 13. Schematic diagram of generalised Portunus pelagicus species complex *morphology, illustrating terms and measurements. Reproduced from Figure 1 of Lai et al. (2010).*

Other morphological features such as periopod merus shape, abdominal shape, branchial swelling and frontal carapace spination (Figure 13) as described in Lai *et al*. (2010) were also investigated as aids

[2] Note that the shallow sub-strata range in depth from 7 to 35 m. Anecdotally, Blue Swimmer Crabs are reported to occur in the 'deep' water (>8 m) of the south-eastern GoC, whereas Giant Mud Crabs occur in more shallow water (<8m).

to species identification. However, the differences in these features for the specimens from the GoC appeared subjective and variable. We found it difficult to use quantitative measurements or even subjective categorisation of particular morphological characters to aid in discriminating the species.

Results and Discussion

All Blue Swimmer Crabs sampled from the GoC in 2018 (that could be identified) were classified as either *Portunus armatus* or *Portunus pelagicus* on the basis of the count of spines on the merus cheliped (Table 2). None of the 842 specimens were classified as either of the other two species of the *Portunus* complex (i.e. *P. segnis* or *P. reticulatus*). The default of the field-key of Lai *et al.* (2010) is that four spines on the anterior margin of the cheliped merus indicates *P. armatus*, and for north eastern Australian regions, three spines indicates *P. pelagicus.* Accordingly, the majority of Blue Swimmer Crabs sampled in January to early March 2018 by prawn trawl were identified as *P. armatus,* with *P. pelagicus* present, but in lower proportion (Table 3, Figure 14).

We noted the presence of Blue Swimmer Crabs with four spines on one merus and three spines on another, which we refer to as 'mixed spination' (Figure 16). Lai *et al*. (2010) makes no mention of individuals with differing spine counts on the left and right cheliped merus, although they do note that *P. armatus* rarely has three spines and occasionally has five spines. Mixed spination was most common in the Weipa (21%) region, and less common in the Groote (12%) and Vanderlin (11%) regions, and uncommon in the Mornington (5%) and Karumba (5%) regions (Figure 14). We found a single crab that had five spines (Figure 15). This individual was a mature female, sampled in 20 m water depth around Groote Eylandt.

A complication in the current study (based on trawl sample collection) was that crabs had only one claw (26%) or had lost both claws (8%) making identification uncertain or not possible using the field-key. The extent of variation in the proportion of crabs that had only one claw across regions made statistical comparison of the species composition difficult.

Table 2. Proportion and classification of Portunus spp. crabs collected from five regions in the Gulf of Carpentaria, based on the field key of Lai et al. (2010).

		P. armatus		***P. pelagicus***	**Uncertain**	
Region	**Sample size**	**4 spines**	**Mixed spines***	**3 spines**	**3 spines, 1 claw****	**Unknown**
Groote	91	0.58	0.12	0.18	0.07	0.06
Vanderlin	297	0.73	0.11	0.04	0.05	0.07
Mornington	136	0.79	0.05	0.04	0.04	0.07
Karumba	138	0.88	0.05	0.01	0.01	0.04
Weipa	179	0.49	0.21	0.06	0.08	0.17

*According to the field-key of Lai *et al.* (2010), crabs with four spines on one cheliped should be considered as *P. armatus,* but these (which had three3 spines on the other cheliped) have been categorised separately as 'mixed spination'; ** samples where crabs only had one claw, but which had three spines on the merus cheliped and could be either P. *armatus* with mixed spination or *P. pelagicus* and thus were classified as uncertain.

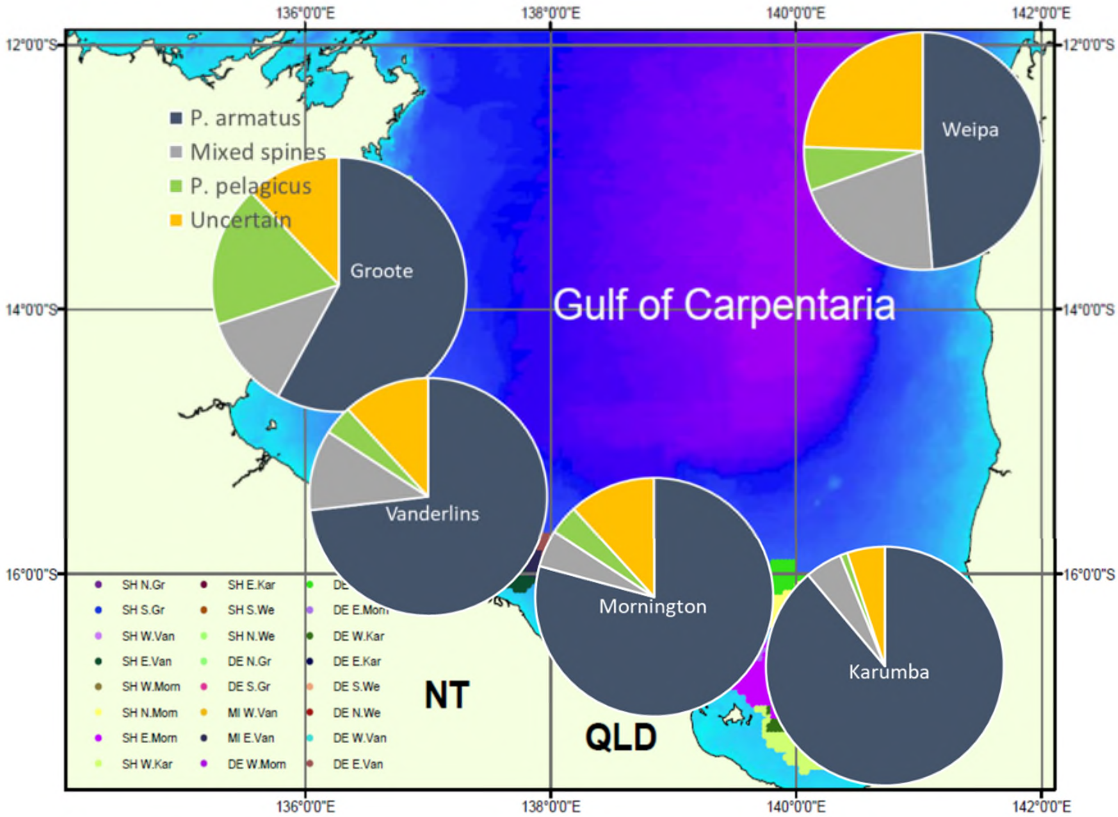


Figure 14. Regional proportion of Portunus spp. *crabs in the Gulf of Carpentaria classified based on the field key of Lai et al. (2010). Mixed spines were those crabs that had four spines on one cheliped and three spines on the other.*

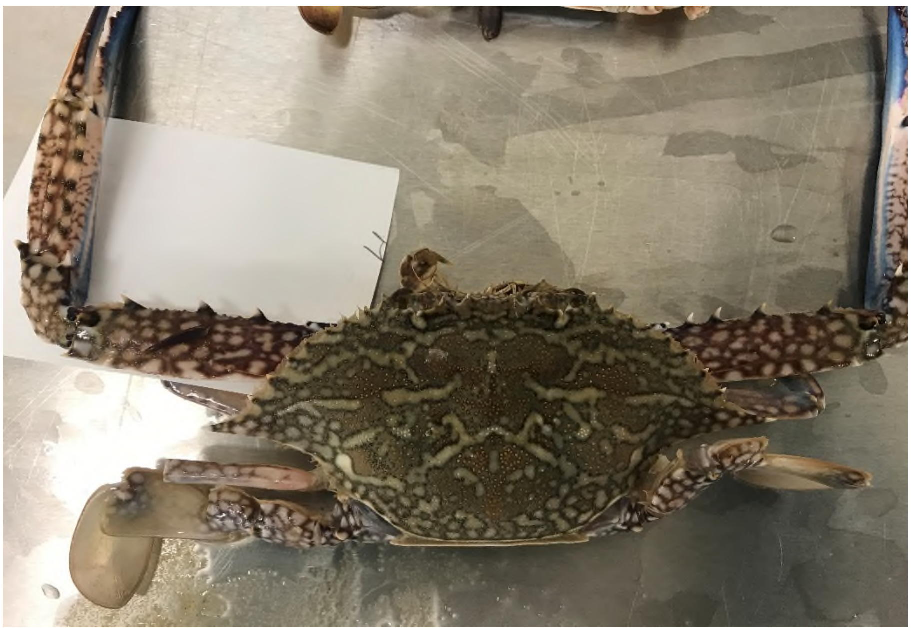


Figure 15. Male Portunus sp. with three spines on the left cheliped and four spines on the right cheliped. Classified as 'mixed spination'.

Figure 16. Female Portunus sp. with five spines on the right cheliped, classified as P. armatus.

There is considerable variation in the morphology and colour of the Blue Swimmer Crabs caught in the crab fishery in southern Queensland. Crabs with characteristics attributed to both species are harvested in this fishery (W. Sumpton pers. obs.). These variations can be seen at very small spatial scales within Moreton Bay and even within individual sampling apparatus (cylindrical pots) used by the fishery (W. Sumpton pers. obs.). It is likely that a more rigorous morphometric analysis of the crabs caught in the Moreton Bay fishery would reveal considerable variation in morphology over very small spatial scales.

We found it challenging to use morphological characteristics to identify with certainty the species of all Blue Swimmer Crabs sampled in the GoC. The reported morphological differences in periopod merus shape, abdominal shape, branchial swelling and frontal carapace spination were not useful in separating 10 to 205 specimens of *Portunus* spp. from regional areas within the GoC. The variations in merus spine count (on left and right chelipeds) was not uncommon, with one individual having five spines.

The misidentification of individual species in the *Portunus pelagicus* complex is a problem for fisheries management only if the respective life-history traits render the animals more vulnerable to fishing. There is limited information about the growth of what is now known as *Portunus pelagicus.* However, there are several studies on the biology and growth rate of *Portunus armatus,* which grows to the largest size in the *Portunus pelagicus* species complex (Lai *et al*. 2010). The results from the GoC highlight that from a scientific perspective, more work is required to discriminate between the species based on morphological features.

Despite the identification issues encountered during the current study, the data indicate that the main species likely to be harvested by the GoC component of the Qld Crab Fishery (using pot/trap apparatus) is *P. armatus*. The harvest is opportunistic and of relatively low tonnage. *Portunus armatus* is highly fecund (Sumpton *et al.* 2003), and the fishery for Blue Swimmer Crabs is conservatively regulated with a minimum size limit of 115 mm CW (notch to notch) for males and no harvest of females. Additionally, under proposed management arrangements, the Qld Crab Fishery will be managed under a total allowable catch (TAC) system for Blue Swimmer Crabs. Fishers are proposed to have individual transferable quotas (ITQs), based on catch history. This will restrict the harvest to a relatively small amount in the GoC and is likely to represent relatively low fishing pressure on the '*Portunus pelagicus* species complex' (Lai *et al*. 2010), which includes predominately *P. armatus* but also *P. pelagicus* in this region, at least from the Qld Blue Swimmer Crab Fishery. The species identification should not affect the TAC setting process. If the fishery for GoC Blue Swimmer Crabs significantly increase in quantity or consistency, then genetic differentiation of the species being harvested should be considered, as species identification based on morphometrics was problematic.

Notwithstanding this, the increase in the abundance and harvest of Blue Swimmer Crabs and the decrease in abundance and harvest of Giant Mud Crabs in the south-eastern GoC in 2016 is an interesting ecological phenomenon. It is likely to be indicative of major, short-term, inter-year changes to the inshore ecosystem as a consequence of a series of years with low freshwater input, more oceanic salinity levels and possible atypical current patterns that were more suited to *Portunus* species over *Scylla* species.

Conclusion

Work in the current chapter suggests that *Portunus armatus* is likely to be the main species of Blue Swimmer Crab intermittently harvested in the GoC. Monitoring of accurate harvest data for Blue Swimmer Crabs from the GoC may enable early recognition of possible changes to the inshore ecosystem of the south-eastern GoC.

Chapter 4. Analysis of Giant Mud Crab catch and environmental factors in the Gulf of Carpentaria.

J.B. Robins, A.R. Northrop, M.A. Grubert, and R.C. Buckworth

Introduction

The GoC is a shallow, semi-enclosed sea in northern Australia with a coastline of over 2 000 km, extending from Slade Point (Qld) to Cape Arnhem (NT). Around a dozen major catchments (and numerous coastal streams) flow into the GoC from a total catchment area of about 647 000 km^2 (BOM 2013).

Giant Mud Crabs have been commercially harvested from the GoC for over 30 years, with significant fluctuations in both catch and catch rates experienced during this time. Some of the variation in these metrics is a likely result of changes in fishing pressure and/or management arrangements over time (see Chapter 2) but it is difficult to quantify the relative importance of individual factors. There are different size limits in the NT to that in Qld, and the jurisdictions have different policies regarding the harvest of females (i.e. Qld has a no female harvest policy).

The possibility of large-scale environmental influences on Giant Mud Crab populations in the GoC was noted by Hay *et al*. (2005), Meynecke *et al*. (2010) and Grubert *et al*. (2019). Whilst not apparent in the catch data at the time, Knuckey (1999) noted that the fishery for Giant Mud Crabs would be vulnerable to recruitment variation because the fishery in the NT (and by assumption Qld) consists mostly of 1+ year-old crabs that recruit (i.e. moult up to legal size) to the fishery between February and April in the year of harvest. Therefore, recruitment variation (both weak and strong year-classes) will be realised by the fishery within 18 to 24 months. Previous studies have identified the following hypotheses in regards to environmental drivers on mud crab populations:

- Maximum positive SOI is an index high rainfall and warm SSTs in northern Australia associated with strong monsoonal effects, which boost coastal productivity and result in positive relationships with CPUE (Meynecke *et al*. 2010).
- Prolonged flooding negatively impacts recruitment and subsequent CPUE (Meynecke *et al*. 2010).

Within the GoC on an annual basis, and notwithstanding oceanographic distribution effects on larval dispersal, the review in Chapter 1 suggested that populations of Giant Mud Crabs are likely to be affected by combinations of: (i) rainfall (and subsequent evaporation) or alternatively river flow and (ii) temperature, probably positive to a point, then negative at the upper extreme.

The objectives of this chapter were to describe patterns between different environmental factors and the harvests of Giant Mud Crabs across the GoC to determine commonality, as well as regional differences, as recommended by Lawson *et al.* (2014).

The analyses follow on from Meynecke *et al*. (2010), who analysed data up to December 2008, but differ in the respect that the current analyses: (i) cover more years subsequent to May 2006 when minimum legal sizes were increased in the NT commercial fishery, and (ii) includes a number of recent extreme climate events. These include significant flooding over multiple years, and significant drought over multiple years. Additionally, 2015 and 2016 saw an unprecedented dieback of coastal mangroves along more than 1 000 km of the southern GoC (Duke *et al*. 2016; Accad *et al*. 2019). Whilst regional harvests and catch rates of Giant Mud Crabs declined coincidentally with the mangrove dieback, the severity of the decline in crab harvests and mangrove dieback was not universal across the southern GoC. Giant Mud Crabs are inherently associated with mangrove-lined estuaries and adjacent habitats. This association has not been explicitly analysed in the current work, but rather through the inclusion of key environmental factors that are suggested causes of these declines (i.e. rainfall/flow, temperature/evaporation, and sea level anomalies), see Duke *et al*. (2016) and Accad *et al*. (2019).

In addition to Generalised Linear Models (GLMs) of annual data, modelling of monthly data was also explored using Bayesian Network analysis as a means of discovering which abiotic variables impact on catch rates as a proxy for crab abundance. Bayesian Networks, also known as knowledge maps, probabilistic causal networks, probabilistic graphical models and directed acyclic graphs, are beneficial for discovering the structure of complex systems (Koller *et al.* 2009). In the past 10 years, Bayesian Networks have been widely adopted in fields such as fault diagnosis (Cai *et al.* 2017), educational assessment (Almond *et al.* 2015), and waterway resilience (Hosseini and Barker 2016). In fisheries research, examples include identifying ecosystem level change (Uusitalo *et al.* 2018), the impact of oil spills (Pascoe 2018), and fishery responses to management interventions (Underwood *et al.* 2016).

Bayesian Networks can be based entirely upon expert knowledge, entirely on data, or a combination of both. Bayesian networks represent a particular variable in the dataset as a “node”. The dependencies between the nodes are represented with an arc (Pearl 2014). The visual representation of the system is key in interpreting, and challenging, the resulting networks, providing an advantage over other artificial intelligence approaches such as neural networks. For predictive modelling, the variable of interest is referred to as the “target” variable.

A Dynamic Bayesian Network (DBN) is a Bayesian Network that models time series data. Random variables are modelled to show their influence on the future distribution of other variables (Weber and Jouffe 2003). In terms of the “supervised” Bayesian Networks used in the current analysis, relationships within the data may be discovered such that a particular target variable (e.g. crab catch rate) can be predicted by a combination of environmental variable states from the past.

Bayesian Network inference algorithms are useful for exploratory analysis when variables are correlated with each other, or when there are a large number of variables that make it difficult to employ traditional statistical modelling techniques. They are particularly powerful as they identify linear, non-linear, combinatorial and stochastic relationships (Yu *et al.* 2004). Thus, the Bayesian Network analysis offers an alternate means of identifying relationships between catches of Giant Mud Crabs and environmental variables in the GoC.

Methods

Catch and effort data

Northern Territory Western Gulf of Carpentaria

Catch and effort data for harvests of Giant Mud Crabs from the GoC were retrieved from the NT DPI&R, and are based on a monthly logbook return per licence which contains the following information: catch weight (kg), location of capture by 1º grid, number of days fished per month, number of days on which gear (i.e. pots) were pulled twice, and number of gear fished per day. From this information, estimates of fishing effort were derived (as per NT DPI&R protocols) in terms of: (i) days fished, (ii) pot days which is equal to days fished by number of gear used, and (iii) pot lifts which is equal to days fished by number of gear used plus number of days gear pulled twice by number of gear used. The Harvest Strategy for NT Western GoC Mud Crab Fishery has catch rate (kg per pot days) as a primary biological performance indicator (see Chapter 2).

In general, patterns in catch per day fished, catch per pot day and catch per pot lift were similar. Only harvest and catch rates from the calendar years 2006 to 2018 inclusive were considered in the current analyses, as these represent years when size limits were consistent (see Chapter 2). The NT Western GoC was divided into three spatial areas representing: (i) Blue Mud Bay and Groote Eylandt, (ii) Roper, and (iii) McArthur regions (Figure 6 in Chapter 2). The Blue Mud Bay/Groote Eylandt region was associated with a native title sea rights claim and subsequent High Court decision in 2008. It is likely that catch and effort in these grids (i.e. 1335, 1336 and 1436) may have been affected by the decision such that the commercial catch data is no longer indicative of the abundance of Giant Mud Crabs in this region. Thus, the Blue Mud Bay/Groote Eylandt region was excluded from further analysis.

Queensland Gulf of Carpentaria

Catch and effort data for harvests of Giant Mud Crabs from the pot fishery (i.e. C1 symbol) for the Qld GoC were retrieved from Fisheries Queensland, data request #DR2796. Catch and effort data in Qld are based on a daily logbook per commercial licence with the following information for *Scylla serrata*: retained whole weight derived (in kg, where number retained are converted to weight based on a conversion of one crab weighing one kg as per standard protocol), location of capture by 30' grid, noting that some records contain location of capture by 6' site), number of gear (i.e. pots deployed), and number of times gear used (≅ lifts). Incomplete fields and inconsistency in the interpretation of the gear fields by fishers, restricted the current study to using catch per day fished as the metric of CPUE (as per Brown 2010 and Meynecke *et al*. 2010).

Consistency in management arrangements in the Qld jurisdiction enabled data from 1989 to 2018 to be included in the analysis. However, we only considered data from 2000 to 2018 (Chapter 2) for reasons associated with targeted harvesting of Giant Mud Crabs and gear changes. The relationship between CPUE and biomass of Giant Mud Crabs in Qld waters may not be consistent over time and may vary regionally depending on the behaviour of local fishers. It was difficult to adjust for the likely changes in fishing efficiency without major and broad scale assumptions. This is a key limitation of the Qld catch data and results derived from its analysis. The Qld GoC Crab Fishery was divided into six regions representing: (i) South West, (ii) South East, (iii) Staaten and Gilbert, (iv) Pormpuraaw (including the Mitchell River), (v) Aurukun, and (vi) Weipa-Mapoon (Chapter 2).

Environmental data

Environmental factors were considered for inclusion in the analyses on the basis that they: (i) were ecologically relevant, (ii) had available data (or suitable proxies), and (iii) were as close to the biological process/hypothesis as possible (Dormann *et al.* 2012).

One of the constraints to working with the coastal fisheries of the GoC is the limited availability of environmental data against which to analyse patterns in the harvest of Giant Mud Crabs (see Grubert *et al*. 2019). Several of the environmental data sets (e.g. rainfall, evaporation, air temperature) were derived from an Australia-wide climate model constructed from observational records (i.e. raw meteorological data) of the Australian Bureau of Meteorology (BOM) to derive datasets that are spatially and temporally complete. The modelled data are referred to as SILO (see Jeffrey *et al*. 2001;

Jeffrey 2006), and were downloaded from https://www.longpaddock.qld.gov.au/silo/. SILO data have been used in numerous analyses as proxies for climate data (e.g. CSIRO 2009; Chamberlayne *et al.* 2019).

In the current study specifically of the GoC, the wet season was defined as October to April inclusive (i.e. seven months) so as to include early (build-up) and late rainfall and flow events. The dry season was defined as May to September inclusive (i.e. five months). This is consistent with the BOM definition of the (broad-scale) northern wet season year, and resulted in an annual cycle for environmental factors of October to the following September. The seasonality for the majority of the harvest of Giant Mud Crabs in the NT and Qld fisheries coincides with this temporal aggregation i.e. 90% and 85% of the harvest in the NT and Qld respectively occurs by the end of September each calendar year.

Flow

Gauged daily flow data were retrieved from https://nt.gov.au/environment/water/water-information-systems/water-data-portal for NT regions and from https://water-monitoring.information.qld.gov.au/ for Qld regions. Gauged flow data were checked against that available from the BOM (http://www.bom.gov.au/waterdata/) to minimise the number of days with missing data and to maximise data quality. Various aggregations of flow were considered e.g. monthly, and seasonal (i.e. spring/summer/autumn/winter). However, there are few biological reasons to justify subdividing annual flow patterns of GoC rivers to accommodate the life-history of Giant Mud Crabs. Therefore, for annual analyses, flow data (where available) were aggregated into annual totals corresponding to the northern wet season year (i.e. October to September), although the major rivers within each region were kept separate (Table 3).

Table 3. Major rivers and creeks within spatial regions of the Gulf of Carpentaria considered for the analysis of river flow with fishery catch rates of Giant Mud Crabs.

Regional rivers & Creeks	Data source
Roper (NT)	
Roper	G9030250 @ Red Rock; 14.6967 ºS, 134.4226 ºE; AMTD na; catchment area = 47400 km^2
Towns	No data
Limmen Bight	No recent data
McArthur/Robinson (NT)	
McArthur**	G9070121 @ Borroloola Xng; 16.0818 ºS, 136.3169 ºE; AMTD na; catchment area = 1570 km^2
Wearyan	No recent data
Robinson	No recent data
Calvert	No recent data
South West (Qld)	
Settlement Ck	No data
Nicholson	GS912101A @ Gregory Downs; 18.64190 ºS, 139.2523 ºE; AMTD 104 km; catchment area = 12690 km^2
Albert	No data
Leichardt	GS913007B @ Floraville Homestead; 18.2330 ºS, 139.8787 ºE; AMTD 100 km; catchment area = 23660 km^2
South East (Qld)	
Morning Inlet	No data
Flinders	GS915003A @ Walkers Bend; 18.1617 ºS, 140.8582 ºE; AMTD 103 km; catchment area = 106300 km^2
Norman	GS9160001B @ Glenore Weir; 17.8600 ºS, 141.1287 ºE; AMTD 102 km; catchment area = 39360 km^2
Walkers Creek	No recent data
Staaten-Gilbert (Qld)	
Gilbert*	GS917001D @ Rockfields; 18.2025 ºS, 142.8760 ºE; AMTD 276 km; catchment area = 10990 km^2
	GS917014A @ Burke Development Road; 17.1682 ºS, 141.7675 ºE; AMTD 102 km; catchment area = 39100 km^2
Staaten	GS918003A @ Dorunda; 16.5315 ºS, 142.0597 ºE; AMTD 95 km; catchment area = 6789 km^2
Pormpuraaw (Qld)	
Nassau	No data
Mitchell*	GS919009B @ Dunbar; 15.9424 ºS, 142.3743 ºE; AMTD 139 km; catchment area = 45870 km^2
Coleman	No recent data
Edward	No data
Aurukun (Qld)	
Holroyd	No recent data
Archer**	GS922001A @ Telegraph Crossing; 13.4176 ºS, 142.9207 ºE; AMTD 203 km; catchment area = 2828 km^2
Watson**	GS923001A @ Jackin Creek; 13.1280 ºS, 142.0526 ºE; AMTD 62 km; catchment area = 1001 km^2
Weipa/Mapoon (Qld)* **	
Embley	No recent data
Wenlock**	GS925001A @ Moreton; 12.4540 ºS, 142.6392 ºE; AMTD 156 km; catchment area = 3265 km^2
Ducie	GS926002A @ Dougs Pad; 11.8327 ºS, 142.4220 ºE; AMTD 50 km; catchment area = 332 km^2
Skardon	No data
Jackson	No data

* modelled flow data available; ** time series of data insufficient due to missing data; AMTD = adopted middle thread distance and was not available (na) for the NT gauging stations; catchment area is that upstream of the gauge. *** The Jardine River, although has significant flow, discharges into the Torres Strait and was not considered in the current study.

Rainfall

Collating appropriate rainfall data that are relevant to effects on populations of Giant Mud Crabs in estuarine and coastal waters of the GoC will always be an application of data that is assumed to be representative until better observational data is collected. The current analysis aimed to consider the effects of near coastal rainfall (via storms and rain events) rather than rainfall in the upper catchment that translates to seasonal flooding, and is represented in river flow. Coastal rainfall has been considered previously where rainfall was averaged for the coastal rainfall stations that were within 50 km of the coast and thus seaward of coastal mountain ranges in the study catchments (e.g. Robins *et al*. 2005; Balston 2009). In general, the coastal areas of the GoC are sparsely populated and poorly monitored for climate data. Locations that would provide data representative of estuaries and associated habitats are particularly data poor. Therefore, in the absence of wide-spread observed climate data with few missing values for the time-series of interest (2006 to 2018 for NT and 2000 to 2018 for Qld), we used interpolated rainfall at the coast adjacent to the main estuarine habitats of Giant Mud Crabs. These interpolated data (referred to as SILO, see Jeffrey *et al*. 2001) were derived from an Australia-wide climate model constructed from observational BOM records. SILO interpolates the raw data to derive datasets that are spatially and temporally complete. Beesley *et al*. (2009) provide a comparison of the SILO interpolated daily rainfall against the BOM Australian Water Availability Project.

For each region, SILO data were retrieved from https://www.longpaddock.qld.gov.au/silo/point-data/ for locations adjacent to the major rivers associated with the Giant Mud Crab fisheries in the GoC (Table 4). From daily interpolated rainfall (mm), the cumulative total across months, wet season (October to April), and wet season year (October to September), were calculated to capture the net rainfall effects. This differs from the approach of Meynecke *et al*. (2010), who used the monthly mean rainfall within each catchment area using a 5-km grid system.

Table 4. Locations of interpolated meteorological data retrieved from the SILO Australian climate database for river mouths within regions, and areas for selection of average, offshore, satellite-derived sea surface temperature data from MODIS Aqua.

Spatial region	**River**	**SILO patched point locations**		**MODIS Aqua area-averaged sea surface temperature user bounding box coordinates (~20 km offshore of the river mouth)**	
		Latitude (ºS)	Longitude (ºE)	Latitude (ºS)	Longitude (ºE)
Roper	Roper	14.75082	135.40399	14.8372 – 14.7535	135.5974 – 135.6963
McArthur	McArthur	15.80842	136.67877	15.6140 – 15.3119	136.8787 – 137.1808
South West	Leichardt	17.56600	139.77908	17.4927 – 17.3608	139.8175 – 139.9988
South East	Flinders	17.59563	140.59382	17.4927 – 17.3498	140.4877 – 140.3119
	Bynoe	17.50889	140.73183		
	Norman	17.46402	140.82213	17.3993 – 17.2510	140.5042 – 140.6909
Staaten - Gilbert	Gilbert	16.54739	141.27059	16.5949 – 16.5097	141.0013 – 141.0974
	Staaten	16.39331	141.29394	16.3959 – 16.2984	141.1015 – 141.1990
Pormpuraaw	Mitchell	15.19893	141.58902	15.1970 – 15.0995	141.4009 – 141.4970
Aurukun	Kirke	13.89762	141.46920		
	Archer	13.34206	141.64155		
Weipa - Mapoon	Embley	12.64825	141.81458	12.6441 – 12.7361	141.5012 – 141.5973
	Wenlock	11.91694	141.91818	11.8943 – 11.8009	141.8019 – 141.8967

Evaporation

Evaporation data were included in the interpolated climate data from SILO. Evaporation has not previously been considered in analyses between catch rates of Giant Mud Crabs and environmental factors (Meynecke *et al*. 2010). However, evaporation was considered as a contributing cause to the extensive mangrove dieback in the GoC in 2015 and 2016 (Duke *et al.* 2016; Accad *et al*. 2019). Giant Mud Crabs are sometimes referred to as mangrove crabs, because they rely predominately on mangrove habitats as juveniles. These habitats are usually tidal and thus are exposed at low tide to ambient air temperature, including its relative humidity and evaporative potential. The southern GoC is atypical in its tidal regime having diurnal tides (i.e. a single tide each day). In late spring and summer, the low tide occurs during the day, whilst in late autumn and winter the low tide occurs at night. If evaporation can affect mangroves, it is possible that, under extremes, evaporation may affect juvenile Giant Mud Crabs, which shelter amongst mangroves. From daily interpolated evaporation (mm), the cumulative total evaporation per month, dry season (May to September) and wet season year (October to September) were calculated to capture the net cumulative evaporative effects (i.e. to index how 'dry' the dry season was in any given year).

Water stress

For annual analyses using GLMs, an index of water stress was calculated to account for wet season effects of rainfall and subsequent dry season effects of evaporation. Water stress was the cumulative wet season rainfall (October to April in mm) minus the cumulative evaporation in the following dry season (May to September in mm) and is similar to the rainfall deficit metric generated in the Australian Water Resource Assessment (BOM 2013). A similar metric was also calculated in the Northern Australian Sustainable Yields project (CSIRO 2009).

Temperature (heat index)

Giant Mud Crabs inhabit areas of the GoC for which there are no direct measurement of water temperature in the estuaries of interest. Previous studies (Meynecke *et al*. 2010) accessed 4-km resolution, monthly-averaged daytime SST derived from AVHRR Pathfinder Version 5 and MODIS Aqua, to provide an index of temperature; assuming that surface water temperature within a 20-km proximity of the river mouth was similar to estuarine water temperature.

We accessed MODIS Aqua SST data via https://giovanni.gsfc.nasa.gov/giovanni/, downloading: (i) 8-day-averaged, 4-km night-time area-averaged SST, and (ii) 8-day-averaged, day-time area-averaged SST. Data were available from the week beginning 04/07/2002 until present. An area ~20 km offshore from the mouth of the main river in each region was defined for area-averaging of the SST (i.e. the user bounding box, see Table 4). Data with the shortest temporal resolution (i.e. 8-daily) was chosen for use in the analysis on the inference that critical temperature events are less likely to be apparent in monthly-averaged data. Day and night SST data were considered as it is unknown which have more critical effects on Giant Mud Crabs. We note that day SSTs are influenced by solar radiation and might not be as representative of the underlying patterns as night SSTs (Beggs 2019).

We also considered SILO-derived daily interpolated coastal air temperature in ºC, where maximum = T.max, minimum = T.min, and average = T.avg. Air temperature can be representative of patterns in estuarine water temperature, both within and between years, provided that the aquatic ecosystem in question is relatively shallow and well mixed (e.g. Kienzle *et al*. 2016). Patterns in interpolated coastal air temperature for 17.464 ºS, 140.822 ºE (Table 4, Norman River) were plotted against observed water temperature reported in Staples (1983) to check whether air temperatures were representative of water temperatures in the estuaries of the GoC. Correlations between air temperature and observed water temperature were all highly significant (see Appendix 3), indicating that air temperature was a reasonable proxy of patterns in estuarine water temperature.

Temperature is a key parameter affecting many aspects of the life history of Giant Mud Crabs (see Chapter 2), but few studies have analysed in-detail patterns of temperature and Giant Mud Crab 'abundance'. Therefore, we undertook a detailed screening of coastal air temperature data (replicated in each region) to investigate the most appropriate way of indexing temperature to capture its potential influence on the life-history of Giant Mud Crabs in GoC. The following metrics were screened:

- monthly average of the daily interpolated coastal T.avg
- monthly minimum of the daily interpolated coastal T.min
- monthly maximum of the daily interpolated coastal T.max
- monthly cumulative total of the daily interpolated coastal T.min
- the 7-day moving average of the daily interpolated coastal T.min to capture low-temperature events of several days duration
- the 7-day moving average of the daily interpolated coastal T.max to capture high-temperature events of several days duration
- counts of days per month per wet season year, when the 7-day moving average of the daily interpolated coastal T.min was below the following thresholds: 10 ºC, 11 ºC, 12 ºC, 14 ºC, 16 ºC, 18 ºC, and 20 ºC to capture low-temperature events of several days duration
- counts of days per month per year when 7-day moving average of the daily interpolated coastal T.max was above the following thresholds: 39.5 ºC to capture high-temperature events of several days duration
- cumulative total of the daily interpolated coastal T.max between: (i) October to March and (ii) November to March to index consistently hot wet seasons compared with consistently cool wet seasons.

Daily coastal air temperature were also calculated as an 8-day average for comparison with the 8-day area-averaged SST 20-km offshore derived from MODIS Aqua. Further calculations were:

- monthly average of T.min, T.avg and T.max per wet season year
- deviations of the monthly average from the 2002 to 2019 monthly average (i.e. anomalies) to identify months and years with unusual temperature regimes.

Although numerous measures of temperature were explored, further analyses used the cumulative total of the daily interpolated coastal T.max between November and March. This metric was considered to capture the effects of heat during months when juvenile crabs would be recruiting to inter-tidal mangrove habitats. Diurnal day-time low tides result in inter-tidal areas of the southern GoC being exposed for several hours to peak solar radiation. Extreme marine warming occurred in northern Australia in 2015 and 2016 (Benthuysen *et al.* 2018), and as discussed previously, heat has been suggested as one of the contributing factors to the mangrove dieback in the GoC (Duke *et al*. 2016). The cumulative coastal T.max provided a suitable index to compare heat over years and months.

Sea Level Anomalies

Low sea levels in 2015 has been speculated as a contributing factor to the wide-spread mangrove dieback in the GoC (Duke *et al*. 2016), and could possibly be a contributing factor to the declines in catch rates of Giant Mud Crabs in the GoC at around the same time. Tides and sea levels affect various components of the life-history and fishery harvest of Giant Mud Crabs via crab activity levels and associated catchability, as well as access by fishers to fishing areas and pot placement within the tidal range. Although most studies acknowledge the role of tides in catch rate variation (Hay *et al*. 2005), to the best of our knowledge, none have considered mean sea level nor sea level anomalies. In some places (e.g. the Qld east coast), the lunar cycle is a good approximation of tidal cycles, can be readily modelled and is usually included in catch standardisations (e.g. Wang *et al*. 2016). However, the GoC is unusual in that large areas of the coast have mostly diurnal tides (i.e. one high and one low tide per day, each of about 12 hours duration) rather than the normal semi-diurnal tides (i.e. two high and two low tides per day each of about six hours duration). In the GoC, the diurnal tidal pattern changes during the neap tides each fortnight when there are smaller 'double tides' (Figure 17). As such, the lunar cycle does not always reflect the tidal cycles in the GoC, and we caution its use in GoC analyses if its use is intended as a proxy of the coastal tidal regime.

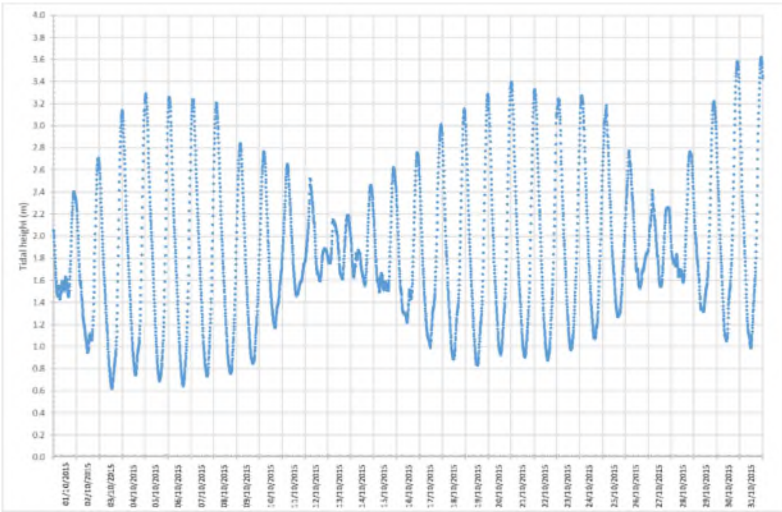


Figure 17. Tidal height (m) recorded every 10 minutes at the Karumba tidal gauge from 12 am 01/10/2015 to 12 pm 31/10/2015, illustrating the diurnal tidal patterns in the southern Gulf of Carpentaria. Each major vertical gridline is the start of a new day, with low tide during daylight hours.

As a shallow enclosed basin, the tides in the southern GoC are generated by tidal pulses through the Arafura Sea and Torres Strait, and also by localised wind, current, and barometric pressure events (Wolanski 1993). Near Karumba in the south-eastern GoC, fishers report that south-easterly winds can keep the tide offshore from the coastal flats, resulting in sea level that is lower than the tidal prediction, especially so in June and July. Alternatively, nearshore sea levels in the GoC can also be above the tidal prediction during extreme flood events when large volumes of freshwater discharge into the GoC (e.g. February 2009 during a major flood of the Flinders River).

There are only three long-term tidal gauging stations in the GoC: Milner Bay (Groote Eylandt), Karumba and Weipa. We obtained monthly sea level data from the Permanent Service for Mean Sea Level (PSMSL) available at https://www.psmsl.org/data/obtaining/ for Karumba (id 835), Weipa (id 1157) and Milner Bay (id 1160), see Holgate *et al*. (2013). Archived tidal data were also available from https://www.msq.qld.gov.au/Tides/Open-data. The data from PSMSL was used in analyses for consistency between jurisdictions and included monthly mean sea level (MSL) in mm at each station relative to the Revised Local Reference (RLR). We calculated the deviations (m) of the monthly MSL from the long term average monthly MSL to derive an index of MSL anomalies over time in the GoC. For Karumba, PSMSL data were available from 1985 to 2017 inclusive. For Weipa, PSMSL data were available for 1966 to 2017. For Milner Bay, PSMSL data were available from 1993 to 2019.

Although numerous measures of MSL were explored, further analyses used: (i) the average financial year MSL as per Lovelock *et al*. (2017), who used this metric to analyse the effects of sea level variation on mangrove dieback in Western Australia, and (ii) the average MSL anomaly for October to March, a period when early benthic stage (EBS) and small juvenile crabs are associated with inter-tidal mangrove habitats in the GoC may be most exposed to extremes of temperature and salinity effects. A 12-month moving average of MSL anomalies was also calculated (as per Wang *et al.* 2015) to assist in the visualization of the temporal patterns. We expected these MSL metrics to be highly collinear as October to March is a subset of the financial year. However, given uncertainty as to how variation in MSL affects population dynamics of Giant Mud Crabs or their associated fisheries, we retained both MSL metrics (one a 12-month average, the other a 6-month average of anomalies) in analyses, but never included both metrics with the same temporal component (i.e. lag of zero, one or two years) in the selected models.

In the absence of multiple local tidal gauges, it was assumed that patterns in MSL were representative of sea level variation experienced by Giant Mud Crabs in each region. Based on proximity and anecdotal advice from inshore commercial fishers in the GoC, MSL at Milner Bay was used for the Roper and McArthur regions, MSL at Karumba was used for the South West, South East, Staaten-Gilbert and Pormpuraaw regions, and MSL at Weipa was used for the Aurukun and Weipa-Mapoon regions.

Southern Oscillation Index

The Southern Oscillation Index (SOI) is a key atmospheric index, which provides a quantitative metric for the strength of El Niño and La Niña events that are linked to patterns in the Pacific Walker circulation (see http://www.bom.gov.au/climate/current/soi2.shtml). This index measures the difference in surface air pressure between Tahiti and Darwin. Although measured daily, average values of SOI over a monthly or greater time period (depending on purpose) are considered to better represent annual patterns, as SOI values can fluctuate markedly as a consequence of short-lived weather events, especially cyclones. A sustained SOI value of ± 8 is considered indicative of an event, with values ≥ +8 indicating a La Niña event and values ≤ -8 indicating an El Niño event (http://www.bom.gov.au/climate/enso/history/ln-2010-12/SOI-what.shtml). SOI values can be indicative of climate events in eastern and southern Australia, but less so in the GoC, where long-term weather and climate predictions are more uncertain. Annual maximum SOI has been positively related to catch rates of Giant Mud Crabs in the NT (Meynecke *et al*. 2012), with the inference that high SOI (=La Niña) increases productivity in coastal areas and estuaries brought on by warm SSTs and rainfall, which positively affect the occurrence and reproduction of Giant Mud Crabs.

The current study derived SOI values from the Australian BOM available at http://www.bom.gov.au/climate/current/soi2.shtml. Two metrics of SOI were calculated for use in analyses: (i) Maximum SOI values per calendar year (as per Meynecke *et al.* 2010, 2012); and (ii) average SOI values between June to November inclusive, which the Australian BOM uses as its' La Niña index.

Madden-Julian Oscillation

The Madden-Julian Oscillation (MJO) is another atmospheric index that has been linked to climate, wind and oceanographic conditions in the GoC preceding and during the Australian monsoon season (Oliver and Thompson 2011). The MJO describes an oscillating phenomenon, ranging in duration from 30 to 90 days, but usually associated with a 40-day wave. Data associated with the MJO include the categorisation of phases (between one and eight, with the GoC just south of the 'Maritime Continent', represented by phase 4 and phase 5) and an intensity value. The MJO reaches maximum intensity over the 'Maritime Continent' in December to February i.e. the austral summer. MJO-related wind stress during the Australian monsoon (or lack thereof) effects sea levels across the shallow GoC. When the MJO is in phase 6 and phase 7, the GoC experiences anomalous north-westerly winds and a rise in mean sea levels. When the MJO is in phase 1, 2 or 3, the GoC experiences anomalous south-easterly winds with a fall in mean sea levels. Meynecke *et al*. 2012 (following Balston's 2009 study of

Princess Charlotte Bay on the Qld east coast) considered the MJO as an indicator of timing of monsoonal activity rather than intensity. They used the number of days the MJO was in phase 2 as an index of significant suppression of rainfall for NT coastal areas, and the number of days the MJO was in phase 5 or 6 as an index of significantly enhanced rainfall in GoC catchments. Other studies suggest the use of MJO phase 4 intensity values, as these capture the intensity of the MJO roughly over the GoC region (Wheeler and Hendon 2004). Daily MJO data were downloaded from http://www.bom.gov.au/climate/mjo/.

In the current study, analyses considered: (i) the number of days during October to April inclusive (i.e. the wet season) when the MJO was in phase 2 (indicative of rainfall suppression), (ii) the number of days during October to April when the MJO was in phase 5 or 6 (indicative of rainfall enhancement), as well as (iii) the average intensity of the MJO phase 4 during October to April, and (iv) the number of days during the October to April when the MJO was in phase 4.

Analysis

Generalised linear models of annual data

Correlation coefficients were calculated between environmental factors. Annualised values of catch per unit effort (CPUE), flow, rainfall, evaporation, air temperature, and mean sea level were log-transformed prior to analysis to normalise variances. Water stress (= rainfall deficit), and anomalies of MSL, SOI and MJO indices were not transformed (consistent with Meynecke *et al.* 2010). All-subsets generalised linear models (GLMs) were used to explore potential relationships between the CPUE of Giant Mud Crabs and environmental factors using GenStat (2019). All-subsets GLM identifies the model that explains the greatest amount of variance (as per step-forward GLM) but also calculates all possible combinations of factors to identify a number of alternative regression models that can be evaluated by their explanatory power (adjusted R^2 and Akaike's Information Criterion (AIC)) and biological plausibility. Only models with no more than three environmental factors were selected to prevent overfitting and to ensure model results were biologically plausible.

Dynamic Bayesian networks of monthly data

The following regions (see Chapter 2) were considered for DBN analysis: (i) Roper, (ii) McArthur, (iii) South West, (iv) South East, (v) Staaten-Gilbert, and (vi) Weipa. The Aurukun and Pormpuraaw regions were excluded because of insufficient data for DBN analysis. Commercial catch and effort data for Giant Mud Crabs were extracted from commercial logbooks (see Chapter 2). Catch rate per month (crabs in kg per pot day for NT or days fished for Qld) were used as input to the DBN analyses.

Environmental factors used in the analysis, for a region from 1993 to 2018 when available, were:

- flow (see Table 3 for data source) - cumulative monthly value
- rainfall (SILO data) -cumulative monthly value in mm
- evaporation (SILO data) - cumulative monthly value in mm
- maximum temperature (SILO data) - mean average per month in ⁰C
- minimum temperature (SILO data) - mean average per month in ⁰C
- radiation (SILO data) - mean average per month in MJ/m^2
- relative humidity at maximum temperature (SILO data) - mean average per month
- relative humidity at minimum temperature (SILO data) - mean average per month

Dynamic Bayesian Networks modelled crab abundance at time points (time *t*), and corresponding past environmental variable states. This exploratory technique was used for generating hypotheses that could be tested or validated using more traditional techniques such as GLMs.

Data were manipulated in R (R Core Team, 2019). The raw monthly data were used as inputs into Bayesialab (Bayesia 2017, https://www.bayesia.com/), which is commercially available software. Missing values were imputed using the "most probable explanation" option (Conrady and Jouffe 2015). To control for seasonality, the "forecast" R package (Hyndman and Khandakar 2007) was then used with multiplicative de-seasonalisation on the resulting dataset. Using de-seasonalised data in a DBN is, to the authors' knowledge, a novel approach. Other seasonal adjustments were tested, though resulting DBNs were identical.

It was hypothesised that environmental variables up to 18 months previous may impact on catch rates of Giant Mud Crabs (see Chapter 1), via their impact on growth, survival and subsequent recruitment. For this reason, predictor variables were lagged by up to 18 months for input into the DBN.

The data were modelled in a "data-driven" DBN framework. One DBN was 'learnt' for each region using Bayesialab 7. A Markov blanket algorithm (Conrady and Jouffe 2015) was selected to 'learn' the conditional independencies and discard those that were not directly impactful on catch rates. All continuous factors were discretised in Bayesialab before learning conditional independencies. This allowed both continuous and categorical factors to be included in the analysis, as well as both linear and non-linear relationships to be determined. The DBN models in Bayesialab assume stationarity.

The measure of association used for factors was mutual information (Koller *et al.* 2009). That is, the amount of information gained about the target variable (e.g. catch rate) from information in the other variable (e.g. flow or rainfall). The G-test was used to report the significance of the relationships between nodes (Hoey 2012). The derivative of the target node with respect to the other variables, termed the total effect, was reported if the relationship was deemed linear. This value is somewhat analogous to the coefficient in a traditional linear regression. Overall precision provided a simple measure for model performance. This was the number of correct predictions of catch rate (discretised into low, medium or high) divided by the overall sample size.

Results

Characteristics of environmental factors

Summary information on the environmental factors across the eight regions of the GoC considered in the current study is provided to enable a comparison of the climatology of the regions, as well as to provide perspective of the longer term 'climate', given the limited previous work on GoC estuaries.

Flow

Flow data available to the project were daily discharge (cumecs) and/or river height, either gauged or modelled (Table 3). Daily river flow varies by several orders of magnitude between rivers, reflecting the catchment area of each river, as well as the geomorphology of each river bed. Flow data were inconsistent between regions in their completeness (i.e. missing data), duration (start and end dates) and position within the catchment (i.e. distance from end of system = coast). This made regional comparisons difficult. Overall, flow was variable between years and between regions. There were some consistencies; most rivers had high annual flow in 2009, whilst most rivers had low annual flow in 2015.

Rainfall

Rainfall indices were variable between years, within years and between regions (Figure 18). Western and southern GoC regions (i.e. Roper, McArthur, South West and South East) had the lowest median cumulative interpolated coastal rainfall, whilst Weipa and Mapoon had the highest. In any given year, rainfall near the coast occurs as a patchwork/mosaic across the estuaries of the GoC and is influenced by regional climate events (e.g. cyclones/troughs). All regions had high or the highest rainfall totals in the 2011 wet season, whilst most, but not all, regions had low or the lowest rainfall totals in the 2015 wet season (Figure 19). The 2016 cumulative wet season rainfall was low in the Roper, McArthur and South West regions but not the other regions.

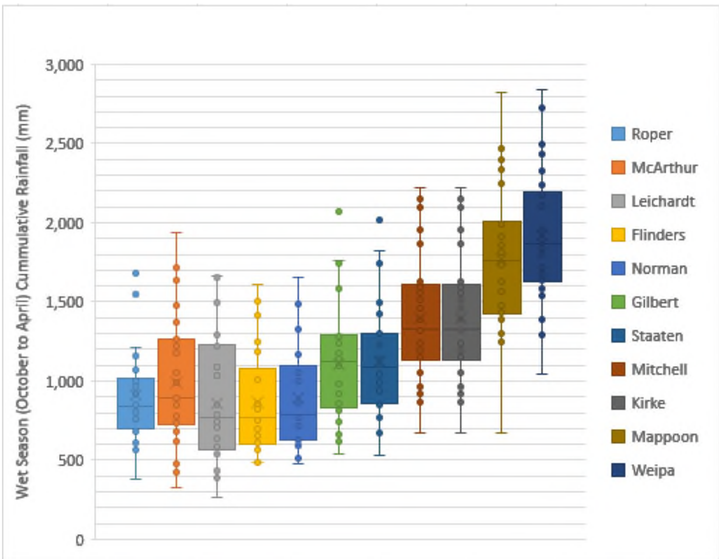


Figure 18. Box-Whisker plot of cumulative wet season (October to April) interpolated coastal rainfall (1989 to 2018) for locations within regions of the Gulf of Carpentaria (see Table 4).

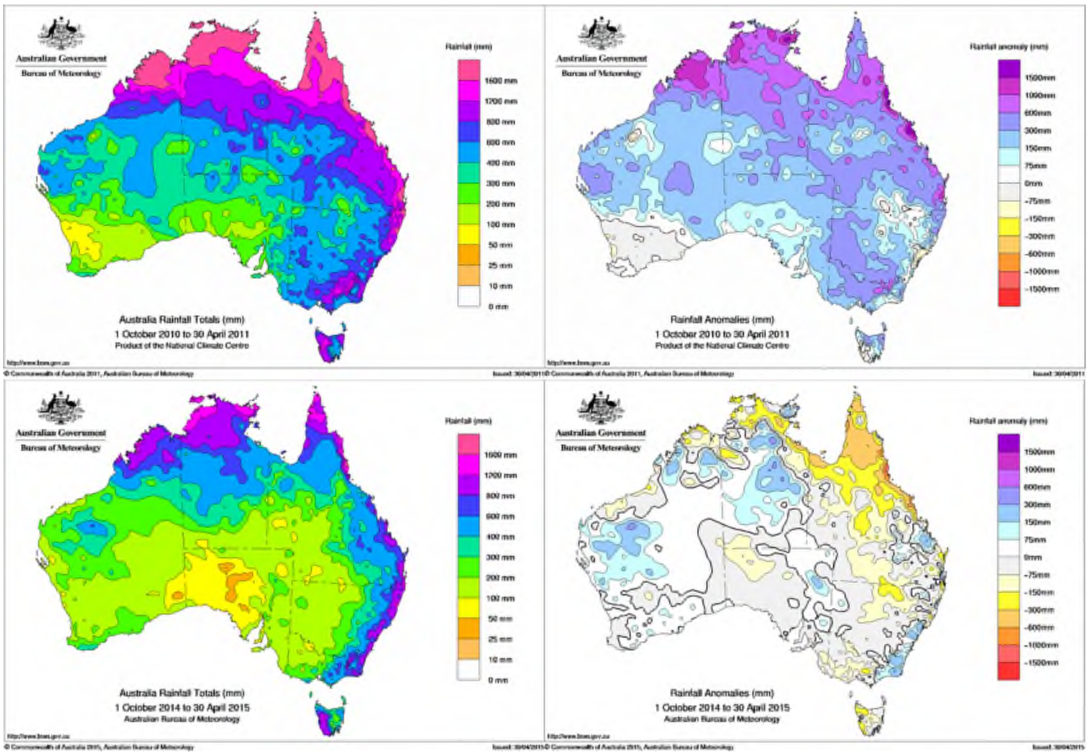


Figure 19. Cumulative rainfall totals and rainfall anomalies for the 2011 and 2015 wet seasons, as examples of high and low rainfall years for catchments of the Gulf of Carpentaria. Images sourced from http://www.bom.gov.au/jsp/awap/rain/index.jsp

Evaporation

Cumulative evaporation over the dry season (May to September) was less variable between years (and regions) than rainfall (Figure 20). The outliers for high cumulative evaporation in the Weipa and Mapoon regions were the 2016 dry season, whilst the outliers for the low cumulative evaporation were in the dry seasons of 1989, 1990 and 1991.

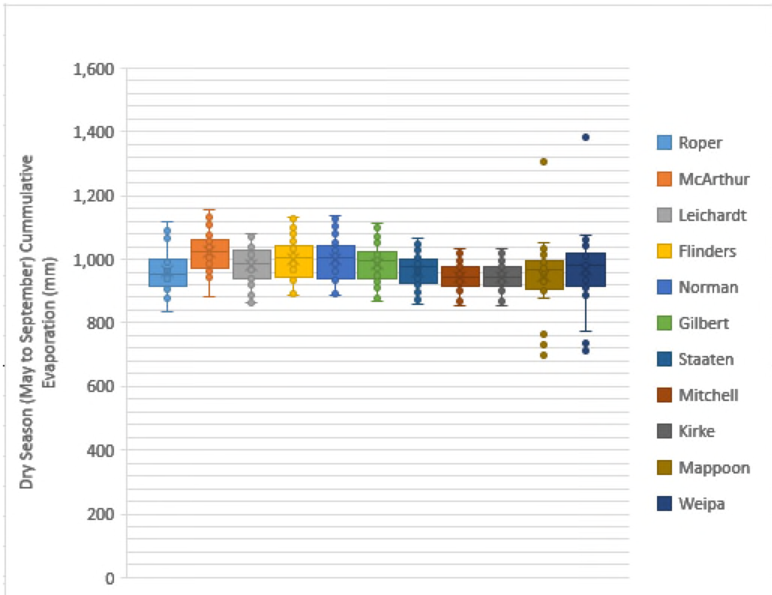


Figure 20. Box-Whisker plot of cumulative dry season (May to September) interpolated coastal evaporation (1989 to 2018) for locations within regions of the Gulf of Carpentaria (see Table 4).

Water stress index

The 'water stress' index was derived to account not only for wet season effects of rainfall but also dry season effects of evaporation. This index is mostly driven by the variability in wet season rainfall as dry season evaporation is relatively uniform. The western and south-eastern regions (i.e. Roper to Staaten) have more frequent years when wet season rainfall is much less than dry season evaporation (Figure 21). This is consistent with climate assessments, where the Carpentaria Coast is noted to have extreme rainfall deficits (BOM 2013). For all regions except Weipa and Mapoon, water stress for the 2015 wet season year (i.e. October 2014 to September 2015) was the most extreme of the data series examined. The outliers for strong negative water stress for the Weipa and Mapoon region were in 2016. Also of note is that the water stress index was strongly negative over multiple years (i.e. 2013, 2014, 2015 and 2016) for western and south-eastern regions.

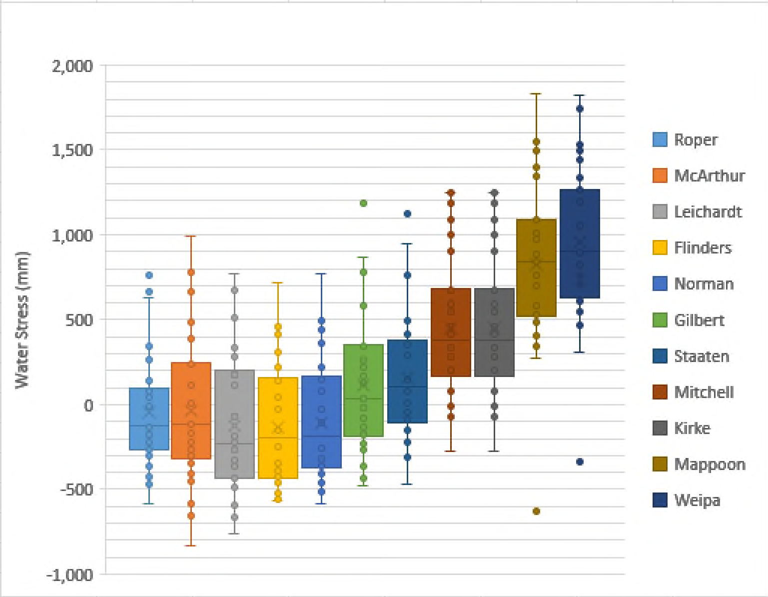


Figure 21. Box-Whisker plot of water stress (i.e. wet season rainfall minus dry season evaporation, 1989 to 2018) for locations within regions of the Gulf of Carpentaria (see Table 4).

Temperature – coastal air, offshore sea surface temperature, and heat index

Regardless of the data source and the metric considered (average, maximum, or cumulative), satellite-derived SST or interpolated coastal air are at best only an index of how temperature actually affected Giant Mud Crabs and associated fisheries in the GoC during the years of interest. Between-year patterns in annualised temperature metrics were consistent between satellite-derived offshore SST and interpolated coastal air temperature. Summarised data for each are provided below, but for consistency including adjustment for missing data, interpolated coastal air temperature data was used in GLM and DBN analyses.

Interpolated coastal air temperature

Cumulative heat was created to provide an index of consistently hot wet seasons compared with consistently cool wet seasons. It was less variable between years and regions (Figure 22) than rainfall (Figure 18). The high outliers for cumulative heat in the Roper region occurred in 2016, whilst the outliers for low cumulative heat occurred in 2011 for the McArthur, Leichardt, Flinders, Norman, Gilbert, Staaten and Mitchell regions and also for 2001 for the Roper, McArthur and Leichardt regions.

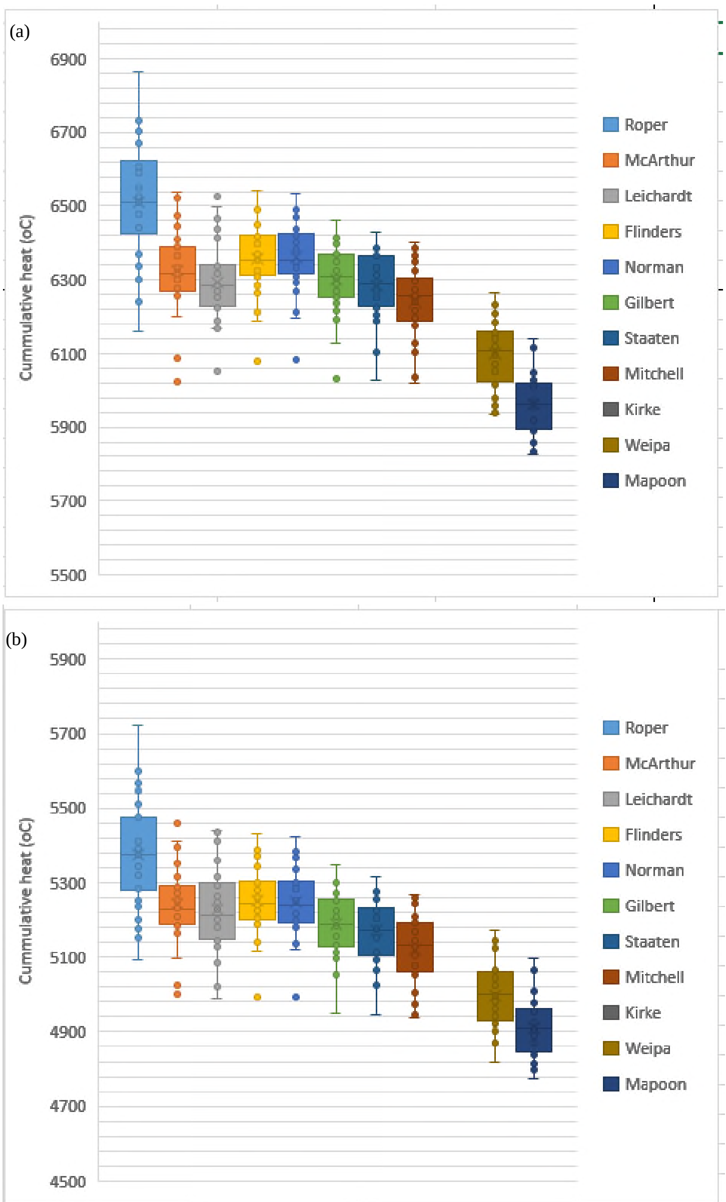


Figure 22. Box-Whisker plots of cumulative heat based on interpolated daily coastal (maximum) air temperature (1989 to 2018) for: (a) October to March; and (b) November to March; for locations within regions of the Gulf of Carpentaria (see Table 4).

Satellite-derived sea surface temperature 20 km offshore

Satellite-derived SST were available from July 2002 to present. Metrics of 8-day average day-time SST (i.e. October to March cumulative, average and maximum) were higher than metrics of 8-day average night-time SST (Figure 23), which is a consequence of solar radiation effects (Beggs 2019). The Roper region often recorded the highest SST metrics. For the study regions, the highest or near to highest values of SST were recorded for the 2016 wet season year (i.e. October 2015 to March 2016). This year was identified as having a marine heat wave event in northern Australia (Benthuysen *et al*. 2018). Most years had missing data for satellite-derived SST. The extent of missing data ranged from 10% to 29% for 8-day average night-time SST and 4% to 24% for 8-day average day-time SST. Missing data was less prevalent in low rainfall years as there were fewer cloud-obscured days. However, (weeks of) missing data resulted in unbalanced sample sizes between years for offshore SST and bias the metrics based on SST. Therefore, the current analyses used interpolated coastal air temperature (with no missing data) as a proxy for temperatures affecting Giant Mud Crabs.

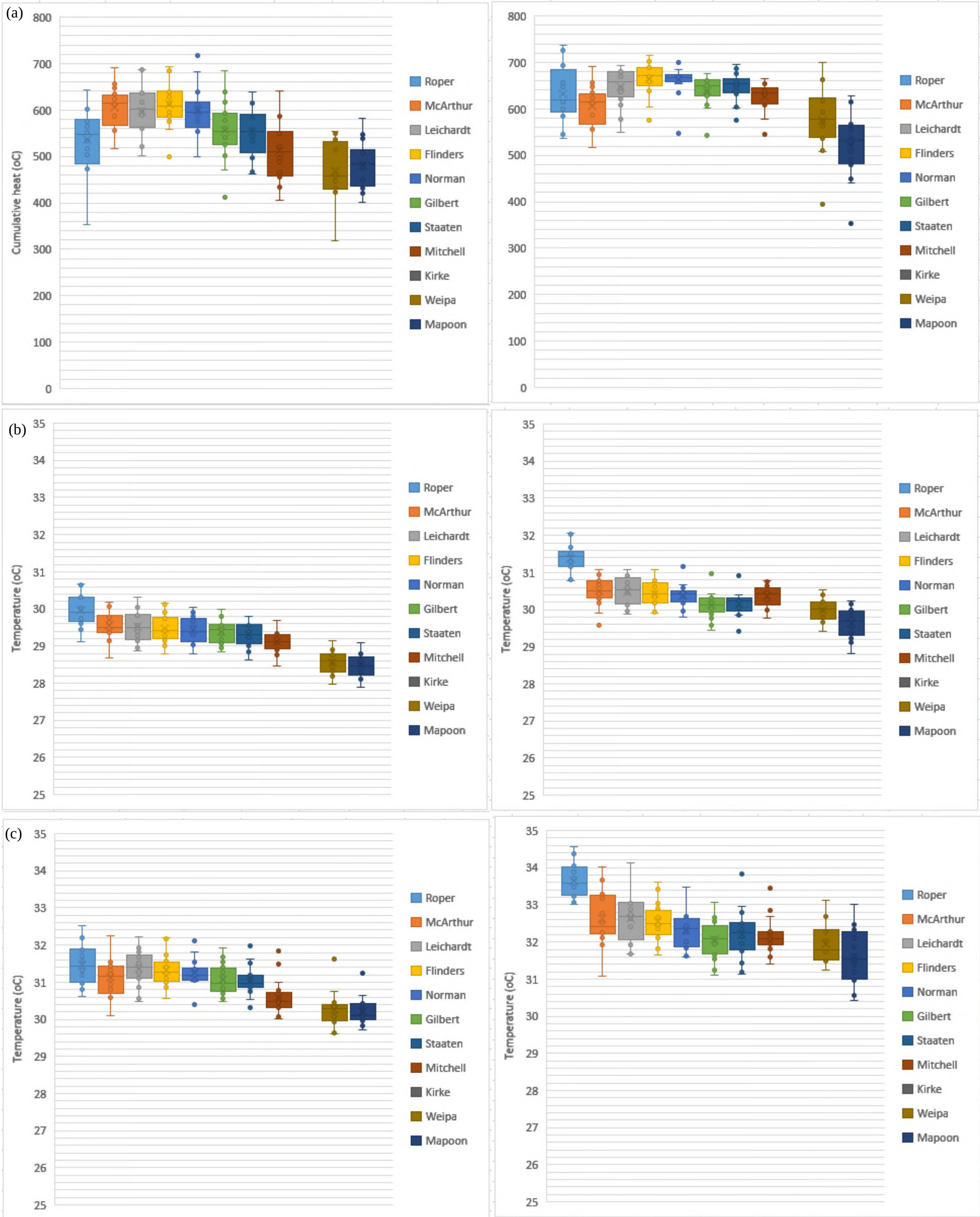


Figure 23. Box-Whisker plots based on satellite-derived 8-day average SST (October to March) for locations (see Table 4) within regions of the Gulf of Carpentaria for: (a) cumulative heat, (b) average of 8-day average SST, and (c) maximum 8-day average SST. Plots on the left are for night-time SST. Plots on the right are for day-time SST.

Sea level anomalies

Data downloaded from the Permanent Service for Mean Sea Level were minimum, maximum and mean of the monthly mean sea level (MSL). There was temporal variation between months in the MSL at all tidal gauging stations (Figure 24). The anomalies in MSL, particularly the 12-month moving average, highlights that by April 2016 the MSL had been below the long-term average at each gauge for about 14 months. The anomalies also highlight that extended periods of below average and above average MSL have occurred previously within the time series of the MSL data available. There was a large positive anomaly for February 2009 in the MSL data from the Karumba gauge, which coincided with an extreme flood event in the Norman River, where the gauge is located.

There were significant correlations in the monthly MSL between all gauging stations (adjusted R^2 90.4% Milner Bay ~ Karumba, 96.0% Milner Bay ~ Weipa, 94.9% Karumba ~ Weipa). There were also significant correlations in the anomalies of MSL between all gauging stations (adjusted R^2 68.0% Milner Bay ~ Karumba, 88.1% Milner Bay ~ Weipa, 73.7% Karumba ~ Weipa). These results indicate that trends in MSL are a GoC wide phenomena. This is consistent with more quantitative studies of sea level patterns in the GoC and their relationship with atmospheric forcing (e.g. Oliver and Thompson 2011; Wang *et al*. 2015; Colberg *et al*. 2019). The lesser coherence in the anomalies of MSL between gauging stations was probably the result of localised factors such as coastal winds and regional flooding. The southern and western GoC has extensive, shallow coastal inter-tidal mud-flats, with local fishers in Karumba reporting that strong offshore winds can keep the tide out, resulting in lower than expected tides.

As expected, the financial year mean MSL was highly collinear with the mean MSL anomaly for October to March for each tidal gauge, with *r* values of 0.95 for Milner Bay, 0.94 for Karumba and 0.96 for Weipa.

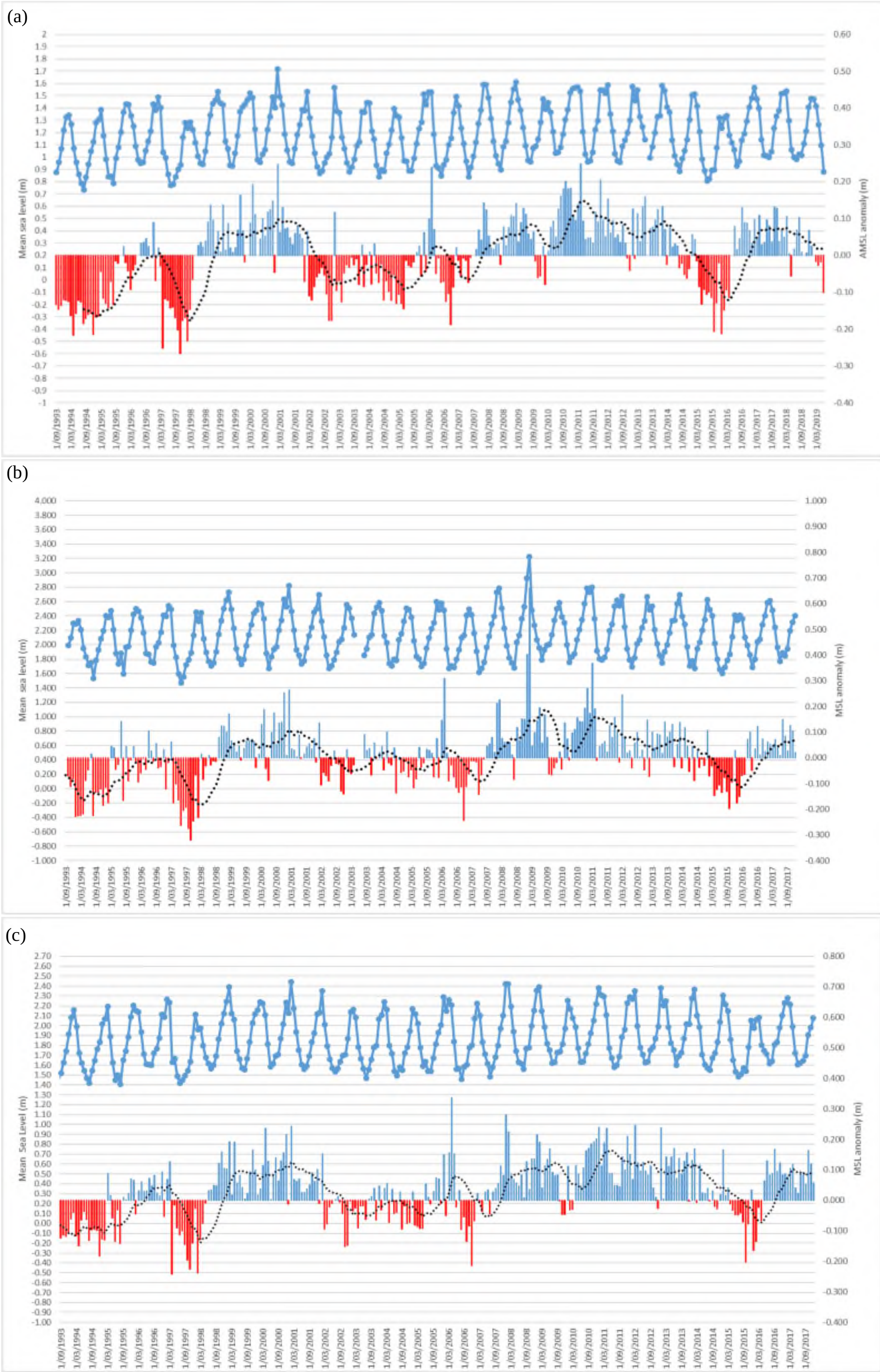


Figure 24. Monthly mean sea level (MSL, blue solid line), monthly anomaly in mean sea level (columns, blue are positive, red are negative), and the 12-month moving average of anomalies (black dotted line) for: (a) Milner Bay (Groote Eylandt), (b) Karumba, and (c) Weipa derived from the Permanent Service for Mean Sea Level.

Southern Oscillation Index

Monthly values of SOI have fluctuated dramatically over the past ~50 years (Figure 25). In the last 20 years, SOI values indicated strong La Niña conditions in 1999 to 2001, 2008/2009 and 2010 to 2012, and strong El Niño conditions in 1997/1998 and 2015/2016.

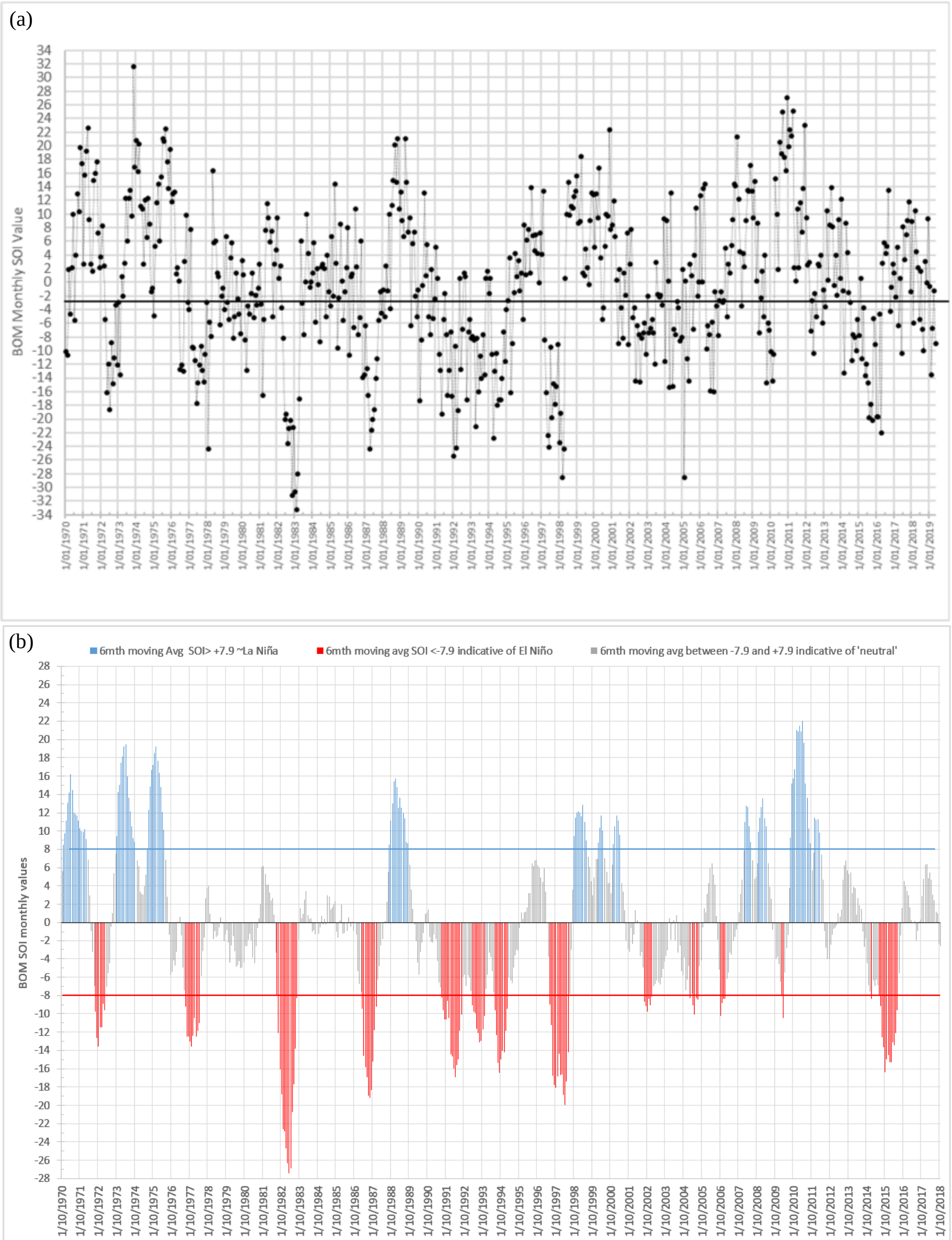


Figure 25. Values of the Southern Oscillation Index (SOI) from the Australian Bureau of Meteorology for: (a) monthly and (b) the six-monthly moving average, where values greater than 7.9 are blue (indicative of La Niña conditions), values less than -7.9 are red (indicative of El Niño conditions), and values in between are grey (indicative of 'neutral conditions').

The metrics used to represent SOI in the statistical analysis included the maximum in the Calendar year (as per Meynecke *et al.* 2010, 2012), and alternatively, average SOI values between June and November, as per the Australian BOM La Niña index (Figure 26).

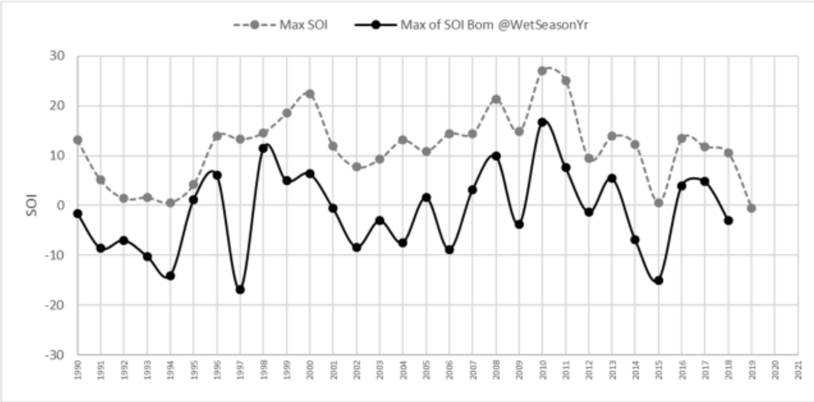


Figure 26. Annual indices of SOI for maximum per calendar year (grey dotted line) and average June to November (black solid line).

Madden-Julian Oscillation

Indices of the MJO have fluctuated between 1975 and 2019 (Figure 27).

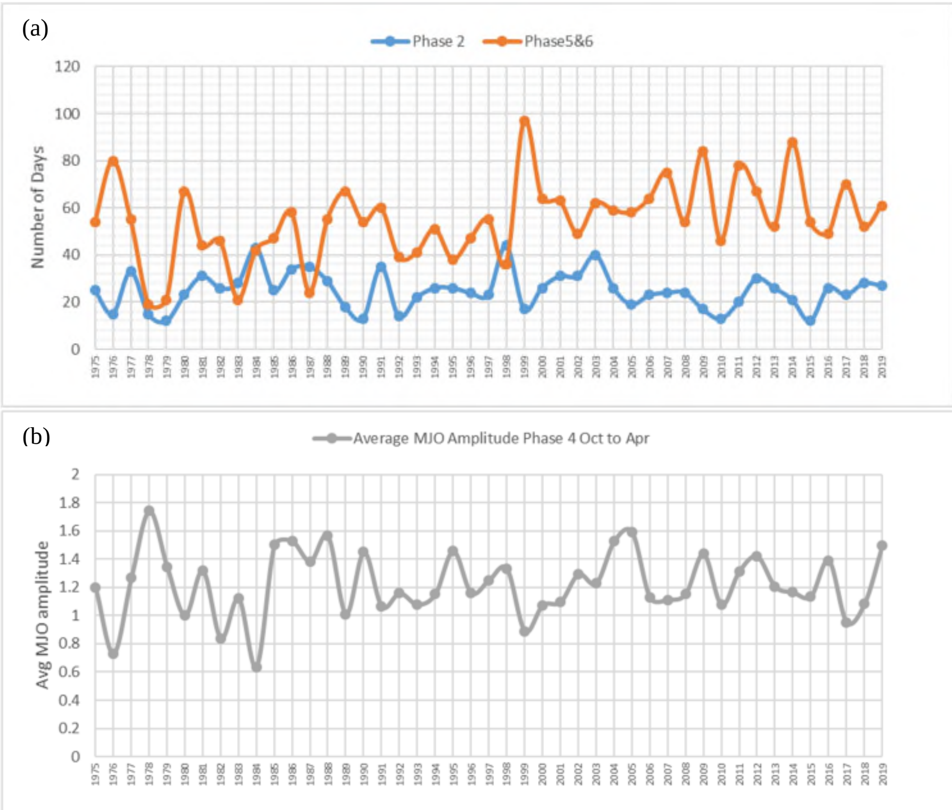


Figure 27. Annual indices for the Madden-Julian Oscillation (MJO) for: (a) number of days during the wet season (October to April inclusive) when the MJO was in phase 2 (blue solid line) and when the MJO was in phase 5 or 6 (orange solid line); and (b) the average amplitude during the wet season when the MJO was in phase 4.

Collinearity of environmental factors.

Many of the environmental factors in the current study were correlated, with high collinearity between some factors. Collinearity between environmental factors is a known, and almost unavoidable problem. Some of the observed collinearity was a function of the overlap in the temporal aggregations applied to the data (e.g. maximum calendar year SOI temporally overlaps with average SOI between May and September, but these were considered as alternatives rather than factors to be included in the same model). In other cases, the observed collinearity was probably a function of the dependence between factors (e.g. rainfall metrics were expected to be highly correlated to river flow) or may reflect intra-year broad scale climate forcing (e.g. temperature in summer, autumn and winter within a year or MSL anomalies). Rather than exclude environmental factors from regional GLM's, all factors were included in the all-subsets GLMs (to assist in identifying alternate factors potentially influencing Giant Mud Crabs). However, models containing two or more factors that were highly collinear (i.e. $r > 0.7$ as per Dormann *et al*. 2012) were excluded from the selection of plausible 'best' models.

Generalised linear models of annual data

Northern Territory - Roper region

For the Roper region, many of the environmental factors were correlated over the period considered in the current analysis (i.e. 2006 to 2018), with high collinearity between some factors (Table 5). Of note was the moderate correlation between flow and rainfall ($r = 0.51$), suggesting that patterns in interpolated coastal rainfall were similar but not always the same as flow in the Roper River at Red Rock. The Roper River has a large catchment (i.e. ~82 000 km^2), sharing boundaries with the Victoria, Daly, Liverpool and associated rivers of the NT Top End. (http://www.bom.gov.au/water/about/image/basin-hi_grid.jpg). In the Roper River, there can be flooding river flows to the estuary, but with limited coastal rain, or there can be heavy localised coastal rainfall, with limited river flows (and flooding). Alternatively, there can be both flooding river flows and heavy coastal rain. Either could provide a mechanism whereby nutrients are delivered to estuarine habitats to the benefit of juvenile crabs or lowering salinity that stimulates adult crabs to move downstream, enhancing their catchability.

The index of water stress was highly correlated with rainfall in the Roper region, but less so with evaporation, noting that both metrics were used to calculate the water stress index. The SOI indices were highly correlated to rainfall and water stress. The index of heat (cumulative temperature) was highly collinear (negatively) with water stress. This is possibly because higher daily temperatures are associated with lower rainfall years, via clear skies and increased solar radiation, compared with higher rainfall years where cloud cover is increased and solar radiation is decreased, resulting in lower daily temperatures.

Average financial year MSL was highly correlated to the average MSL anomalies between October and March ($r = 0.95$). As such, these MSL metrics should be considered as interchangeable, although they represent slightly different aspects of variation in MSL. Mean Sea Level indices were negatively correlated with the heat index in the Roper region (i.e. lower mean sea level was associated with higher cumulative temperature). This may be indicative of broader scale 'climate' phenomena, although none of the climate metrics considered (SOI or MJO) were highly correlated with the MSL metrics for the Roper region.

The average reported harvest (2006 to 2018) of Giant Mud Crabs for the Roper region was 71 tonnes, accounting for on average 35% of the harvest from the NT Western GoC Mud Crab Fishery. This region had the most dramatic fluctuations in catch, with a minimum catch of 3.3 tonnes (in 2016) and a maximum catch of 123.5 tonnes (in 2009, see Figure 7). Catch rates ranged from a minimum of 0.14

kg per pot day (in 2016) to a maximum of 0.79 kg per pot day (in 2009, see Figure 7). This is a much greater variation in catch than the adjacent McArthur region. In the Roper region analyses, 2016 was identified as a data point with high leverage and was often at an extreme in fitted model residual plots, even though CPUE was log transformed before analyses.

Best all-subsets GLM identified several alternate models that accounted for variation in the annual CPUE of Giant Mud Crabs in the Roper region. Only those factors that were significant in the GLM are presented in Table 6. Annual river flow was significant and positive, but only in the wet season immediately preceding the catch (i.e. there were no lagged effects). No metrics of coastal rainfall were detected as significantly related to catch. The heat index (i.e. cumulative maximum daily interpolated coastal air temperature) in the summer immediately preceding the catch year was a significant factor in several of the alternate models, being negatively related to catch, with no lag effects detected. Indices of MSL one or two years prior to catch were also significant, but negatively related to catch. Maximum SOI in the calendar year preceding catch was significantly related to catch, as was its alternative of the average SOI between May and September (i.e. the dry season) preceding the year of catch.

The 'best' three-term model, with the highest adjusted R^2 (86.6%) and lowest AIC (14.1), included cumulative heat November to March (negative effect), average MSL anomaly October to March two years preceding the catch year (negative effect) and total annual flow two years preceding the catch year. However, we were somewhat perplexed by the negative effect of the MSL anomaly two years preceding the catch year, as it is counter-intuitive to our expectations – i.e., that sea levels lower than average between October and March in the spawning year should result in higher CPUE two years later. As a biologically plausible alternative, 'best' all-subsets GLM identified a two-term model of lesser fit (both in terms of adjusted R^2 and AIC), with a strong positive effect of MSL anomaly in the Oct to Mar immediately preceding the catch year (i.e. low sea levels ~ low CPUE) and a negative effect of cumulative evaporation in the May to September of the catch year (i.e., high evaporation ~ low CPUE).

In general, the results for the analysis of a relatively short time series of CPUE and environmental factors for the Roper region provided evidence supporting the theory that the Western GoC experienced hot, dry conditions one to two years preceding 2016. It is possible (but not proven), that coupled with unusually low mean sea levels, these events contributed to the dramatically reduced harvest of Giant Mud Crabs in the Roper region in 2016.

The results at best provide hindsight into probable causes of reduced catches. However, the environmental input data and regression models (i.e. parameter estimates for environmental factors) are unlikely to be sufficiently robust to quantitatively predict future catches. Therefore, they should not be explicitly included in any harvest strategy until locally relevant environmental data (e.g. water and air temperature, salinity, sea level) are collected at the Roper River estuary and coastal foreshores where the fishery occurs.

Table 5. Correlation coefficients (r[*]) between environmental factors in the Roper region (2006 to 2018).

	Flow Oct to Sep	Cum rain Oct to Apr	Cum evap May to Sep	Water stress	Cum heat Nov to Mar	MSL avg fin yr	MSL anom Oct to Mar	Max SOI cal yr	Avg SOI May to Sep	MJO phase2 days	MJO phase 5 or 6 days	Avg MJO phase 4	MJO phase 4 days
Flow Oct to Sep	-												
Cum rain Oct to Apr	0.51	-											
Cum evap May to Sep	-0.30	-0.57	-										
Water stress	0.56	**0.98**	-0.66	-									
Cum heat Nov to Mar	**-0.70**	-0.64	0.62	**-0.73**	-								
MSL avg fin yr	0.39	0.44	-0.22	0.49	**-0.73**	-							
MSL anom Oct to Mar	0.41	0.29	-0.16	0.35	-0.69	**0.95**	-						
Max SOI cal yr	0.40	**0.75**	-0.46	**0.75**	-0.49	0.27	0.11	-					
Avg SOI May to Sep	0.15	0.61	-0.20	0.51	-0.17	0.07	-0.06	0.82	-				
MJO phase 2 days	-0.46	-0.18	0.05	-0.20	0.22	0.07	0.13	-0.12	0.07	-			
MJO phase 5 or 6 days	0.43	0.07	-0.26	0.17	-0.65	0.46	0.41	-0.02	-0.29	-0.04	-		
Avg MJO phase 4	-0.21	-0.35	-0.11	-0.30	0.10	-0.05	0.01	-0.10	0.05	0.42	0.10	-	
MJO phase 4 days	-0.25	-0.07	0.16	-0.04	0.45	-0.38	-0.39	-0.01	0.05	0.03	-0.55	0.09	-

[*] Values in bold type are indicative of high collinearity between factors as per the collinearity diagnostic critical value (i.e. $r > 0.7$) of Dormann *et al*. (2012).

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Table 6. Best all-subsets generalised linear models for annual CPUE (kg per pot day) of Giant Mud Crabs in the Roper region (2006 to 2018).

		Factors in Model								
Adj. R^2 (%)	**AIC**	Flow Oct to Sep	Flow Oct to Sep^{-2}	Cum evap May to Sep	Water stress	Cum heat Nov to Mar	MSL anom Oct to Mar	MSL anom Oct to Mar^{-2}	Max SOI cal yr^{-1}	Avg SOI May to Sep^{-1}
1 term										
68.3	21.8					<0.001				
43.3	35.8						0.009			
37.5	39.1	0.015								
31.5	42.4			0.027						
30.4	43.0				0.030					
52.7	31.5								0.003	
53.6	31.1									0.003
2 terms										
80.9	15.7					<0.001		0.016		
68.6	22.0			0.010			0.004			
3 terms										
86.6	14.1		0.049			<0.001		0.003		
78.8	17.7				0.012		0.006	0.007		

Factors in the GLM are positively related to catch unless indicated in red.

Northern Territory - McArthur region

For the McArthur region, many of the environmental factors were correlated over the period considered in the current analysis (i.e. 2006 to 2018), with high collinearity between some factors (Table 7). River flow in the McArthur River at Borroloola Crossing (although incomplete due to missing data) was highly correlated to rainfall indices ($r = 0.77$). This may reflect the closer association between river flow and rainfall in the catchments of the McArthur region, which back onto the Barkly and Wiso catchments of the Western Plateau drainage division (of central Australia, see http://www.bom.gov.au/water/about/image/basin-hi_grid.jpg). The water stress index was highly collinear with rainfall and to a lesser degree with evaporation. Indices of SOI were only moderately related to rainfall and to water stress index. The index of heat (cumulative temperature) was highly negatively collinear with river flow, rainfall and water stress, for similar reasons as in the Roper region (i.e. higher daily temperatures over spring and summer were associated with lower rainfall years). Indices of MSL were strongly negatively correlated with heat (i.e. lower mean sea levels were associated with higher cumulative temperature), but were not significantly correlated with SOI or MJO metrics (Table 7). The number of days the MJO was in phase 5 or 6 was significantly and negatively related to the cumulative heat index in both the McArthur (Table 7) and Roper regions (Table 5).

The average reported harvest (2006 to 2018) of Giant Mud Crabs for the McArthur region was 114 tonnes, accounting for on average 57% of the harvest from the NT Western GoC Mud Crab Fishery.

The minimum catch was 45.7 tonnes (in 2015) and the maximum catch was 256.5 tonnes (in 2009, see Figure 7). Catch rates ranged from a minimum of 0.23 kg per pot day (in 2015) to 0.86 kg per pot day (in 2009, see Figure 7).

Best all-subsets GLM identified several alternate models that accounted for variation in the annual CPUE of Giant Mud Crabs in the McArthur region. Only those factors that were significant in the GLMs are presented in Table 8.

Annual river flow was not detected as significantly related to CPUE. Coastal rainfall (two years preceding the catch year) was only a significant (and negative) effect when included in a 2-term model with cumulative evaporation in the dry season of the year preceding the catch year. The heat index (i.e. cumulative maximum daily interpolated coastal air temperature) in the summer immediately preceding the catch year had a significant (negative) effect only when included in a 2-term model with the average MSL anomaly October to March two years preceding the catch year (negative effect). No SOI or MJO metrics were significantly correlated to CPUE in the McArthur region between 2006 and 2018.

The 'best' model, with the highest adjusted R^2 (57.5%) and lowest AIC (16.5) included the MSL anomaly October to March^{-2} (negative effect, two years prior) combined with cumulative heat in the November to March immediately preceding the catch year (i.e. no lag, negative effect). The next 'best' 2-term model included cumulative rain October to April^{-2} and cumulative evaporation May to September^{-1} (both negative effects); but is equivalent (in terms of fit) with the 1-term model that only included average MSL anomaly October to March two year preceding the catch year.

In general, the GLMs accounted for less variation in CPUE for the McArthur region than could be accounted for in the Roper region, based on adjusted R^2 as well as the number of alternate models with significant effects. This may be the result of CPUE in the McArthur region being less variable between 2006 and 2018 than in the Roper region. The McArthur region is larger than the Roper region, has several rivers and estuaries and has more coastal foreshore along which Giant Mud Crabs are harvested. This gives fishers greater opportunity to search for productive fishing locations, which may maintain the annual CPUE (e.g. hyper stability), thus masking some of the signals between crab abundance and environmental factors.

Northern Territory - Roper and McArthur regions combined

Data for the Roper and McArthur regions combined and analysed by all sub-sets GLM (with region as forced term) to determine what environmental factors could be monitored to inform the Harvest Strategy (DPI&R 2017) for the NT Western GoC Mud Crab Fishery which is managed as a single stock. Only those factors that were significant in the GLM are presented in Table 9.

The 'best' models, with the highest adjusted R^2 (56.0%) and lowest AIC (16.5), contained average MSL anomaly between October and March two years preceding catch (negative effect), with the second term being preferentially cumulative heat between November and March (negative effect) or cumulative rainfall between October and April (positive effect) in the months immediately preceding the main fishing season (Table 9).

Heat and rainfall were highly but negatively correlated to each other ($r = -0.601$) across the Roper and McArthur regions combined. They are likely interchangeable as terms in the models, although the heat index accounted for more of the variation in CPUE. These results provide some insight into the recent declines in catches of Giant Mud Crabs in the western GoC. However, given the short time series analysed (2006 to 2018), the metrics highlighted by the correlative GLM analyses should be used cautiously for any predictive purposes.

The data for MSL at Milner Bay (Groote Eylandt), interpolated coastal air temperature and rainfall are readily available and could be monitored to trial their ability to forecast the likely harvest trends of Giant Mud Crabs in the NT Western GoC fishery. Other indices considered in the analysis could also be included. However, remotely inferred environmental data, whilst cost-effective in such a remote (and broad spatial) area as the GoC, should not be substituted for robust in-situ monitoring of environmental factors that are likely to impact the populations of Giant Mud Crabs and their associated fisheries – this would include estuarine water temperature, salinity, sea level and rainfall in the estuaries of the Roper and McArthur rivers.

Table 7. Correlation coefficients (r[*]) between environmental factors in the McArthur region (2006 to 2018).

	Flow Oct to Sep	Cum rain Oct to Apr	Cum evap May to Sep	Water stress	Cum heat Nov to Mar	MSL avg fin yr	MSL avg anom Oct to Mar	Max SOI cal yr	Avg SOI May to Sep	MJO phase 2 days	MJO phase 5 or 6 days	Avg MJO phase 4	MJO phase 4 days
Flow Oct to Sep	-												
Cum rain Oct to Apr	**0.77**	-											
Cum evap May to Sep	-0.48	-0.54	-										
Water stress	**0.83**	**0.96**	-0.64	-									
Cum heat Nov to Mar	**-0.77**	**-0.74**	**0.71**	**-0.79**	-								
MSL avg fin yr	0.69	0.63	-0.31	0.61	**-0.71**	-							
MSL anom Oct to Mar	0.54	0.46	-0.27	0.45	-0.62	**0.95**	-						
Max SOI cal yr	0.30	0.60	-0.43	0.58	-0.53	0.27	0.11	-					
Avg SOI May to Sep	0.00	0.37	-0.22	0.28	-0.21	0.07	-0.06	**0.82**	-				
MJO phase2 days	-0.19	0.20	-0.11	0.03	0.02	0.07	0.13	-0.12	0.07	-			
MJO phase 5 or 6 days	0.53	0.30	-0.27	0.32	-0.69	0.46	0.41	-0.02	-0.29	-0.04	-		
Avg MJO phase 4	-0.09	-0.21	-0.20	-0.27	-0.03	-0.05	0.01	-0.10	0.05	0.42	0.10	-	
MJO phase 4 days	-0.05	0.08	-0.12	0.11	0.29	-0.36	-0.31	-0.07	-0.13	0.08	-0.46	-0.04	-

[*] Values in bold type are indicative of high collinearity between factors as per the collinearity diagnostic critical value (i.e. r > 0.7).of Dormann *et al*. (2012).

Table 8. Best all-subsets generalised linear models for annual CPUE (kg per pot day) of Giant Mud Crabs in the McArthur region (2006 to 2018).

		Factors in model				
Adj. R^2 (%)	**AIC**	Cum rain Oct to Apr^{-2}	Cum evap May to Sep	Cum evap May to Sep^{-1}	Cum heat Nov to Mar	MSL anom Oct to Mar^{-2}
1 term						
39.6	20.4					0.013
24.5	24.5		0.049			
2 terms						
57.5	16.5				0.039	0.010
39.7	20.9	0.019		0.029		

Factors in the GLM were positively related to the catch unless indicated in red.

Table 9. Best all-subsets generalised linear models for annual CPUE (kg per pot day) of Giant Mud Crabs in the Roper and McArthur regions combined (2006 to 2018).

		Factors in model							
Adj. R^2 (%)	**AIC**	Flow Oct to Sep	Cum rain Oct to Apr	Cum evap May to Sep	Cum heat Nov to Mar	MSL anom Oct to Mar	MSL anom Oct to Mar^{-2}	Max SOI cal yr^{-1}	Avg SOI May to Sep^{-1}
1 term									
32.2	43.1				<0.001				
29.4	44.7			0.002					
28.8	45.0						0.003		
24.6	47.5					0.006			
13.0	54.1	0.040							
12.6	54.4		0.042						
32.2	47.0							0.001	
30.2	48.1								0.002
2 terms									
56.0	30.3				<0.001		<0.001		
51.9	32.6					0.002	0.001		
46.7	35.4		0.006				<0.001		
43.0	38.8			0.027	0.016				

Factors in the GLM were positively related to the catch unless indicated in red.

Queensland - South West region

For the South West region, there was high collinearity between some of the environmental factors over the period considered in the current analysis (i.e. between 2000 and 2018, see Table 10).

Flow in the Leichardt River at the Floraville gauge was highly correlated with interpolated coastal rainfall. Water stress was highly correlated with rainfall and to a lesser degree with evaporation. The index of heat (cumulative maximum daily temperature between November and March) was highly correlated (negatively) with rainfall and water stress, for similar reasons as the NT western GoC regions (i.e. higher daily temperatures over spring and summer are associated with lower rainfall years).

Like the Roper region, MSL indices in the South West region (based on data from the closest tidal gauge at Karumba) were only moderately negatively correlated with the heat index (i.e. where lower mean sea levels were associated with higher cumulative temperatures).

Metrics of the SOI were only moderately correlated to rainfall and water stress in the South West region, and were not correlated to river flow. The South West region, which backs onto the Lake Eyre drainage division, is a low summer rainfall area (BOM 2013), and derives most of its rainfall from episodic events such as cyclones. Neither of the climate indices (SOI or MJO) were highly correlated with MSL variation. The number of days the MJO was in phase 5 or phase 6 was significantly (and negatively) correlated to cumulative heat index (r = -0.66), a relationship that also occurred in the Roper and McArthur regions (Table 5 and Table 7).

The South West region was (and still is) fished intermittently and contributes a relatively small component (i.e. about 4% on average) to the harvest of Giant Mud Crabs from the Qld GoC. The average reported harvest between 2000 and 2018 for the South West region was six tonnes, but has ranged from a minimum catch of less than one tonne (in multiple years) to a maximum catch of 15 tonnes (in 2003, see Figure 9). Catch rates ranged from a minimum of 5.7 kg per day fished (in 2006) to 45.2 kg per day fished (in 2000, see Figure 9).

Detailed inspection of the reported catch and effort data for the South West region revealed unrealistic variations between the CPUE of licences that regularly fished this area throughout the GoC fishing season, compared with licences that were ‘transient’, in that they only fished for a short period in any given fishing season. It is unlikely that transient fishers should achieve much higher CPUE than fishers who work an area consistently. These variations were so great that it raises concern that whether CPUE may not be a reliable index of Giant Mud Crab abundance in this region.

Notwithstanding these concerns, best all-subsets GLM identified a number of alternate models that significantly accounted for variation in the annual CPUE of Giant Mud Crabs in the South West region (Table 11). The three ‘best’ alternate 2-term models had similar levels of fit (adjusted R^2 ~52% and AIC ~20.4), all included average MSL anomaly October to March one year preceding the catch year (positive effect) and either cumulative heat in the November to March immediately preceding the catch year, or the index of water stress two years preceding the catch year (positive effect) or cumulative rain in the October to April two years preceding the catch year (positive effect).

Overall, there was some consistency with the results for the South West region with those from the NT western GoC, whereby metrics of heat, dryness and MSL were significant. However, for the South West region, MSL anomalies were positively related to CPUE, whereas in NT regions, MSL anomalies were negatively correlated to CPUE. The analysis further highlights the need for validated catch and effort data in Qld crab fisheries, as well as appropriate environmental monitoring.

Table 10. Correlation coefficients (r[*]) between environmental factors in the South West region (2000 to 2018).

	Flow Oct to Sep	Cum rain Oct to Apr	Cum evap May to Sep	Water stress	Cum heat Nov to Mar	MSL fin yr	MSL anom Oct to Mar	Max SOI cal yr	Avg SOI May to Sep	MJO phase 2 days	MJO phase 5 or 6 days	Avg MJO phase 4	MJO phase4 days
Flow Oct to Sep	-												
Cum rain Oct to Apr	**0.66**	-											
Cum evap May to Sep	-0.24	-0.37	-										
Water stress	**0.68**	**0.97**	-0.46	-									
Cum heat Nov to Mar	0.23	0.14	0.38	0.07	-								
MSL fin yr	0.43	0.58	-0.15	0.62	-0.20	-							
MSL anom Oct to Mar	0.38	0.48	-0.16	0.54	-0.12	**0.94**	-						
Max SOI cal yr	0.21	0.52	-0.33	0.55	-0.27	0.34	0.22	-					
Avg SOI May to Sep	-0.09	0.27	-0.17	0.28	-0.19	0.08	-0.01	0.81	-				
MJO phase 2 days	-0.20	-0.11	0.00	-0.22	-0.38	0.02	-0.09	-0.23	-0.12	-			
MJO phase 5 or 6 days	0.33	0.51	-0.28	0.53	-0.05	0.42	0.43	0.08	-0.15	-0.11	-		
Avg MJO phase 4	0.01	-0.16	-0.23	-0.17	-0.19	-0.09	-0.05	-0.19	-0.07	0.12	0.00	-	
MJO phase 4 days	0.30	0.09	-0.40	0.10	0.08	-0.12	-0.13	0.24	0.19	-0.06	-0.36	-0.10	-

[*] Values in bold type are indicative of high collinearity between factors as per the collinearity diagnostic critical value (i.e. r>0.7) of Dormann *et al*. (2012).

Table 11. Best all-subsets generalised linear models for annual CPUE (kg per day fished) of Giant Mud Crabs in the South West region (2000 and 2018).

		Factors in model						
Adj. R^2 (%)	**AIC**	Cum evap May to Sep	Cum rain Oct to Apr^{-2}	Water $stress^{-2}$	Cum heat Nov to Mar	MSL anom Oct to Mar^{-1}	Max SOI cal yr^{-2}	Avg SOI May to Sep^{-2}
1 term								
30.3	26.6					0.009		
29.6	26.8			0.009				
28.8	27.1				0.010			
28.7	27.1		0.011					
19.5	30.1	0.033						
38.3	24.0							0.003
26.5	27.8						0.014	
2 terms								
52.9	20.4				0.008	0.007		
51.5	20.8			0.010		0.009		
51.2	20.9		0.011			0.009		

Factors in the GLM were positively related to catch unless indicated in red.

Queensland - South East region

For the South East region, many of the environmental factors were correlated over the period considered (i.e. 2000 to 2018), with high collinearity between some factors (Table 12). The South East region has two major rivers (the Flinders River and the Norman River) and associated lower tributaries and estuaries that create extensive habitat for Giant Mud Crabs in the south east corner of the GoC. Flow patterns were similar between the two rivers, with a correlation coefficient (r) of 0.82. River flows were highly correlated to rainfall indices, suggesting that patterns in interpolated coastal rainfall were similar to, but not always the same as, river flow patterns.

Similar to the Roper region, the estuaries of the Flinders and Norman rivers can flood from upstream river flow even though there has been limited coastal rain; or there can be heavy coastal rainfall with limited flood flows or both flooding river flows and heavy coastal rain. Either could provide a mechanism whereby nutrients are delivered to estuarine habitats to the benefit of juvenile crabs or lowering salinity that stimulates adult crabs to move downstream, enhancing their catchability.

The water stress index was highly correlated with rainfall but less so with evaporation. Only maximum calendar year SOI was positively related to coastal rainfall and water stress in the South East region. Cumulative heat between November and March was highly correlated (negatively) with water stress. Metrics of MSL were negatively correlated with cumulative heat between November and March (i.e. lower mean sea levels were associated with higher cumulative temperatures), a correlation also found for the Roper and McArthur regions of the NT western GoC. All correlations between MSL metrics and SOI or MJO metrics had *r* values <0.50, and were not statistically significant.

The South East region was (and still is) the most heavily fished region in the Qld GoC for Giant Mud Crabs as a consequence of its proximity to Karumba, the main port in the southern GoC. From Karumba, there is relatively 'easy' access to regional fishing grounds, supply of provisions (e.g. fuel) and market access (i.e. shipment of product to the east coast). The South East region consistently has the most number of licences reporting harvest data.

The average reported harvest (2000 to 2018) of Giant Mud Crabs for the South East region was 70 tonnes, accounting for on average 45% of the harvest from the Qld GoC. The annual reported harvest has ranged from a minimum of ~ 17 tonnes (in 2016) to a maximum of 128 tonnes (in 2002, see Figure 9). Catch rate ranged from a minimum of 16.5 kg per day fished (in 2016) to a maximum of 38.8 kg per day fished (in 2001, see Figure 9). Within the time series analysed (i.e. from 2000 to 2018), many fishers in the South East region have increased the number of pots used; some legally through the use of two C1 symbols on a commercial fishing licence (enabling 100 pots to be used), and some (illegally) through 'overpotting'. The increase in the number of pots used per day fished has been previously noted (Brown 2010) and will have impacted the assumed relationship between CPUE and population abundance. In theory, this should be accounted for prior to using CPUE as an index of abundance (such as through a catchability coefficient that increases with time, as considered by Brown 2010), but in reality, it is difficult to determine the appropriate adjustment.

Notwithstanding this issue, best all-subsets GLM identified a number of alternate models that significantly accounted for variation in the annual CPUE of Giant Mud Crabs in the South East region (Table 13).

Two 'best' alternate 2 term models had similar levels of fit (adjusted R^2 ~ 66% and AIC ~ 17). Both included the average MSL anomaly October to March immediately preceding the catch year (positive effect) and either cumulative rain in the October to April one year preceding the catch year (positive effect), or the index of water stress one year preceding the catch year (positive effect). These 2 term models only had slightly better fit than the 1 term model of cumulative rain in the October to April one year preceding the catch year (adjusted R^2 ~ 53.9% and AIC 19.8). The GLMs can only fit to the data supplied, and it should be noted that the time-series for the South East region includes the major rainfall / flood event of 2009 – which is so large that it can be seen in the monthly MSL data from the Karumba tidal gauging station (Figure 24).

Overall, there was some consistency with the results from the NT western GoC, whereby metrics of heat, dryness and MSL were significant in several alternate models. Like the South West region, MSL anomalies were positively related to CPUE, whereas in NT regions, MSL anomalies were negatively correlated to CPUE. The analysis again highlights the need for validated catch and effort data in Qld crab fisheries, as well as appropriate environmental monitoring.

Table 12. Correlation coefficients (r[*]) between environmental factors in the South East region (2000 to 2018).

	Flow Flinders Oct to Sep	Flow Norman Oct to Sep	Cum rain Oct to Apr	Cum evap May to Sep	Water stress	Cum heat Nov to Mar	MSL avg fin yr	MSL anom Oct to Mar	Max SOI cal yr	Avg SOI May to Sep	MJO phase 2 days	MJO phase 5 or 6 days	Avg phase 4 MJO	MJO phase 4 days
Flow Flinders Oct to Sep	-													
Flow Norman Oct to Sep	**0.82**	-												
Cum rain Oct to Apr	**0.71**	**0.86**	-											
Cum evap May to Sep	-0.25	-0.52	-0.44	-										
Water stress	0.66	**0.86**	**0.97**	-0.58	-									
Cum heat Nov to Mar	-0.55	**-0.71**	**-0.83**	0.35	**-0.83**	-								
MSL avg fin yr	0.46	0.59	0.59	-0.22	0.60	-0.68	-							
MSL anom Oct to Mar	0.47	0.61	0.52	-0.26	0.55	-0.64	**0.94**	-						
Max SOI cal yr	0.33	0.54	0.62	-0.34	0.64	-0.49	0.34	0.22	-					
Avg SOI May to Sep	0.08	0.25	0.35	-0.14	0.34	-0.28	0.08	-0.01	**0.81**	-				
MJO phase 2 days	-0.16	-0.22	-0.16	0.01	-0.21	-0.04	0.02	-0.09	-0.23	-0.12	-			
MJO phase 5 or 6 days	0.15	0.29	0.43	-0.30	0.43	-0.57	0.42	0.43	0.08	-0.15	-0.11	-		
Avg phase 4 MJO	0.09	-0.19	-0.22	-0.18	-0.18	0.09	-0.09	-0.05	-0.19	-0.07	0.12	0.00	-	
MJO phase 4 days	0.36	0.29	0.19	-0.38	0.20	0.25	-0.12	-0.13	0.24	0.19	-0.06	-0.36	-0.10	-

[*] Values in bold type are indicative of high collinearity between factors as per the collinearity diagnostic critical value (i.e. r > 0.7).of Dormann *et al*. (2012).

Table 13. Best all-subsets generalised liner models for annual CPUE (kg per day fished) of Giant Mud Crabs in the South East region (2000 to 2018).

		Factors in model									
Adj. R^2 (%)	**AIC**	Flow Flinders Oct to Sep^{-2}	Flow Norman Oct to Sep^{-1}	Cum rain Oct to Apr^{-1}	Water stress^{-1}	Cum heat Nov to Mar	Cum heat Nov to Mar^{-1}	MSL anom Oct to Mar	Max SOI cal yr^{-1}	Avg SOI May to Sep^{-1}	Avg SOI May to Sep^{-2}
1 term											
53.9	19.8			<0.001							
50.2	21.1				<0.001						
36.4	25.1						0.004				
27.7	28.0							0.012			
25.1	28.2		0.017								
22.1	30.7	0.024									
21.7	30.0					0.026					
45.3	22.7								0.001		
36.8	25.7									0.003	
2 terms											
66.3	16.8			<0.001				0.015			
65.7	17.1				<0.001			0.009			
55.4	20.4					0.011	0.002				
48.9	22.5	0.038					0.006				
40.5	25.2	0.034	0.024								
49.2	22.4									0.003	0.038

Factors in the GLM were positively related to the catch unless indicated in red.

Queensland - Staaten-Gilbert region

For the Staaten-Gilbert region, many of the environmental factors were correlated over the period considered (i.e. 2000 to 2018), with high collinearity between some factors (Table 14). There are two major rivers in this region (Staaten and Gilbert), with patterns in river flow highly correlated (r = 0.70). The Gilbert River is like other estuaries in the GoC, where a large catchment area can lead to flooding from river flows despite limited coastal rain, but the Staaten River is a much smaller catchment, and in general, flows coincide with coastal rainfall.

The water stress index was highly collinear with rainfall metrics. Indices of SOI were only moderately related to rainfall and flow metrics in the Staaten-Gilbert region. Heat indices were highly collinear (negatively) with water stress. Metrics of MSL were negatively correlated with heat (i.e. lower mean sea levels were associated with higher cumulative temperatures). This relationship was also found for the Roper, McArthur and South East regions.

The Staaten-Gilbert region had the least variation in reported catch and CPUE between 2000 and 2018. This region is less accessible than the adjacent South East region. The average reported harvest (2000 to 2018) of Giant Mud Crabs for the Staaten-Gilbert region was 44 tonnes, accounting for on average 28% of the harvest from the Qld GoC. The annual reported harvest has ranged from a minimum of 22 tonnes (in 2002) to a maximum of 68 tonnes (in 2006, see Figure 9). Catch rate ranged from a minimum of 19.2 kg per day fished (in 2003) to a maximum of 60.6 kg per day fished (in 2011, see Figure 9). Legal and illegal (overpotting) increases in the number of pots used is also an issue Staaten-Gilbert region (as it is for all Qld GoC regions), as is the over-reporting of harvest (see Brown 2010). In preliminary analyses of catch and effort, effort (in days fished) accounted for only 3% of the variation in reported harvest for 2000 to 2018, and the relationship between catch and effort was non-significant. This was an atypical result for the relationship between catch and effort of Giant Mud Crabs. In all other Qld GoC regions, effort (in days fished) accounted for at least 40%, up to a maximum of 90% of the variation in catch.

Notwithstanding the above major issues with catch and effort for this region, best all-subsets GLM identified a number of alternate models that significantly accounted for variation in the annual CPUE of Giant Mud Crabs in the Staaten-Gilbert region. Only those factors that were significant in the GLM appear in Table 15.

There was limited consistency in the results for the Staaten-Gilbert region compared with the southern and western GoC regions. Metrics for the MJO phase 2 were significant, as was cumulative rainfall between October and March immediately preceding the catch year. Mean sea level was not a significant term in any of the GLMs for the Staaten-Gilbert region. This may reflect how tides affect Giant Mud Crabs and fishing operations in the Staaten-Gilbert region, or it may reflect the reliability of the reported data. The analysis of the data for the Staaten-Gilbert region once again highlights the need for validated catch and effort data in Qld crab fisheries, as well as appropriate environmental monitoring.

Table 14. Correlation coefficients (r[*]) between environmental factors in the Staaten-Gilbert region (2000 to 2018).

	Flow Gilbert Oct to Sep	Flow Staaten Oct to Sep	Cum rain Oct to Apr	Cum evap May to Sep	Water stress	Cum heat Nov to Mar	MSL fin yr	MSL anom Oct to Mar	Max SOI cal yr	Avg SOI May to Sep	MJO phase2 days	MJO phase 5 or 6 days	Avg MJO phase 4	MJO phase 4 days
Flow Gilbert Oct to Sep	-													
Flow Staaten Oct to Sep	**0.70**	-												
Cum rain Oct to Apr	**0.71**	**0.86**	-											
Cum evap May to Sep	-0.45	-0.50	-0.41	-										
Water stress	**0.71**	**0.82**	**0.96**	-0.59	-									
Cum heat Nov to Mar	**-0.70**	**-0.73**	**-0.76**	0.48	**-0.80**	-								
MSL fin yr	0.57	0.52	0.54	-0.47	0.61	-0.69	-							
MSL anom Oct to Mar	0.63	0.53	0.52	-0.46	0.59	-0.68	**0.94**	-						
Max SOI cal yr	0.55	0.56	0.55	-0.42	0.56	-0.46	0.34	0.22	-					
Avg SOI May to Sep	0.42	0.33	0.36	-0.21	0.35	-0.31	0.08	-0.01	0.81	-				
MJO phase 2 days	-0.08	-0.01	-0.09	-0.17	-0.06	-0.05	0.02	-0.09	-0.23	-0.12	-			
MJO phase 5 or 6 days	0.20	0.50	0.44	-0.21	0.43	-0.53	0.42	0.43	0.08	-0.15	-0.11	-		
Avg MJO phase 4	0.08	-0.08	0.01	-0.04	0.06	0.08	-0.09	-0.05	-0.19	-0.07	0.12	0.00	-	
MJO phase 4 days	0.15	0.04	0.14	-0.22	0.11	0.31	-0.12	-0.13	0.24	0.19	-0.06	-0.36	-0.10	-

[*] Values in bold type are indicative of high collinearity between factors as per the collinearity diagnostic critical value (i.e. r > 0.7).of Dormann *et al*. (2012).

Table 15. Best all-subsets generalised linear models for annual CPUE (kg per day fished) of Giant Mud Crabs in the Staaten-Gilbert region (2000 to 2018).

		Factors in model			
Adj. R^2 (%)	**AIC**	Cum rain Oct to Apr	MJO phase 2 days	MJO phase 2 $days^{-1}$	MJO phase 2 $days^{-2}$
1 term					
17.2	38.4	0.044			
37.9	29.8		0.003		
23.3	35.8			0.021	
2 terms					
55.6	23.3		0.001		0.013

Factors in the GLM were positively related to the catch unless indicated in red.

Queensland - Pormpuraaw region

For the Pormpuraaw region, many of the environmental variables were correlated, with high collinearity between some factors (Table 16).

In the Pormpuraaw region, the estuary (and associated lower delta) of the Mitchell River creates extensive habitat for Giant Mud Crabs. Mitchell River flow was highly correlated with coastal rainfall (r = 0.76) even though this catchment often receives flood flows from high in the catchment, adjacent to the Wet Tropics. The water stress index was highly correlated with rainfall. The Maximum SOI calendar year index was highly correlated to Mitchell River flow, but only slightly related to coastal rainfall. The cumulative heat index was highly correlated (negatively) with flow, rainfall and water stress. The MSL indices were negatively correlated with the cumulative heat index (i.e. lower mean sea level was associated with higher cumulative temperatures), a correlation found for the Roper, McArthur, South East and Staaten-Gilbert regions.

The average reported harvest (2000 to 2018) of Giant Mud Crabs for the Pormpuraaw region was 19 tonnes, accounting for on average 12% of the harvest from the Qld GoC. Annual reported harvest ranged from a minimum of 7 tonnes (in 2010) and a maximum of 45 tonnes (in 2005, see Figure 9). Catch rates ranged from a minimum of 14.1 kg per day fished (in 2010) to a maximum of 42.7 kg per day fished (in 2018, see Figure 9). Like other Qld GoC regions, there were reliability issues with the catch and effort data, which was almost impossible to account for robustly without broad scale and generic assumptions.

Notwithstanding the reliability issues with catch and effort, the best all-subsets GLM only identified MSL metrics as significantly accounting for variation in crab CPUE within the Pormpuraaw region. Only those factors that were significant in the GLM appear in Table 17. Temperature, rainfall and river flow did not significantly improve the model fit, although MSL metrics were significant (with a negative effect). The SOI was not a significant term in any of the GLMs for the Pormpuraaw region. The analysis highlights the need for validated catch and effort data in Qld crab fisheries, as well as appropriate environmental monitoring.

Table 16. Correlation coefficients (r[*]) environmental factors in the Pormpuraaw region (2000 to 2018).

	Flow Mitchell Oct to Sep	Cum rain Oct to Apr	Cum evap May to Sep	Water stress	Cum heat Nov to Mar	MSL fin yr	MSL anom Oct to Mar	Max SOI cal yr	Avg SOI May to Sep	MJO phase 2 days	MJO phase 5 or 6 days	Avg MJO phase 4	MJO phase 4 days
Flow Mitchell Oct to Sep	-												
Cum rain Oct to Apr	**0.76**	-											
Cum evap May to Sep	-0.40	-0.50	-										
Water stress	**0.72**	**0.99**	-0.55	-									
Cum heat Nov to Mar	**-0.71**	**-0.71**	0.30	**-0.70**	-								
MSL fin yr	0.61	0.57	-0.24	0.55	-0.66	-							
MSL anom Oct to Mar	0.54	0.54	-0.28	0.54	-0.66	**0.93**	-						
Max SOI cal yr	**0.73**	0.36	-0.21	0.33	-0.48	0.38	0.26	-					
Avg SOI May to Sep	0.52	0.12	0.07	0.08	-0.38	0.15	0.06	0.85	-				
MJO phase 2 days	0.14	0.18	-0.05	0.13	-0.07	0.03	-0.09	-0.22	-0.11	-			
MJO phase 5 or 6 days	0.49	0.45	-0.37	0.48	-0.52	0.39	0.43	0.06	-0.17	-0.06	-		
Avg MJO phase 4	-0.09	-0.16	0.05	-0.14	0.02	0.04	0.09	-0.25	-0.09	0.12	0.09	-	
MJO phase 4 days	0.00	-0.05	-0.53	-0.03	0.22	0.06	0.04	0.27	0.13	-0.08	-0.34	-0.23	-

[*] Values in bold type are indicative of high collinearity between factors as per the collinearity diagnostic critical value (i.e. r > 0.7).of Dormann *et al*. (2012).

Table 17. Best all-subsets generalised linear models for annual CPUE (kg/days fished) of Giant Mud Crabs in the Pormpuraaw region (2000 to 2018).

		Factors in model	
Adj. R^2 (%)	**AIC**	MSL anom Oct to Mar^{-1}	MSL anom Oct to Mar^{-2}
1 term			
18.1	24.5	0.40	
2 terms			
32.1	22.0	0.021	0.049

Factors in the multiple regression were positively related to catch unless indicated in red

Queensland - Aurukun region

The average reported harvest (2000 to 2018) of Giant Mud Crabs for the Aurukun region was 2.5 tonnes, accounting for on average less than 2% of the harvest from the Qld GoC. Annual reported harvest ranged from a minimum of less than one tonne (in 2018) to a maximum of 9 tonnes (in 2001, see Figure 9), although 15 tonnes was reported harvested in 1991 and 1994. Catch rates ranged from a minimum of 2.7 kg per day fished (in 2008) to a maximum of 16.3 kg per day fished (in 2001, see Figure 9). The region is accessed by relatively few fishers (<10 since 2006, and in some years fewer than five fishers). As such, the data was considered inadequate for the GLM analysis as a single region.

Queensland - Weipa-Mapoon region

For the Weipa-Mapoon region, many of the environmental factors were correlated, with high collinearity between some factors (Table 18). There are several relatively short rivers that flow into the Weipa-Mapoon region including the Watson, Archer, Embley, Wenlock, Ducie, Skardon and Jackson rivers. Some have flow gauges, while others do not, and there were significant gaps in the flow data. As such, no flow index was compiled for the Weipa-Mapoon region. Interpolated coastal rainfall was assumed to be a reasonable proxy for river flow, given the relatively small catchment sizes.

Water stress was highly collinear with rainfall but less so with evaporation. None of the climate indices were strongly correlated to interpolated coastal rainfall. The heat index was moderately and negatively correlated to water stress. Despite its northerly latitude (at around 12 ºS), the Weipa-Mapoon region has a more moderate climate (i.e. lesser temperature range, and more consistent rainfall) than regions that are further south and west in the GoC (Figure 22, Figure 23).

Mean sea level (based on the tidal gauge at Weipa) was highly correlated with rainfall indices, and only moderately correlated with the cumulative heat index, which was the opposite of that found for other GoC regions.

None of the climate indices (SOI or MJO) were highly correlated with the MSL variation for the Weipa-Mapoon region.

The average reported harvest (2000 to 2018) of Giant Mud Crabs for the Weipa-Mapoon region was 14 tonnes, accounting for on average 10% of the harvest from the Qld GoC. Annual reported harvest ranged from a minimum of 2.5 tonnes (in 2010) to a maximum of 70 tonnes (in 2000, see Figure 9). Catch rates ranged from a minimum of 19.6 kg per day fished (in 2007) to a maximum of 56.8 kg per day fished (in 2008, see Figure 9). Anecdotal reports suggest that access and shipping of product to southern markets has played a major role in the fishing pressure on Giant Mud Crab populations in the Weipa-Mapoon region over time. In some years, as few as two fishers reported catch in the region.

Best all-subsets GLM failed to identify any models with environmental factors that significantly accounted for variation in crab CPUE for the Weipa-Mapoon region between 2000 and 2018. However, if only data from 2006 to 2018 were analysed, average MSL anomaly one year preceding the catch year accounted for some of the variation in CPUE (Table 19).

Queensland - all regions combined

In a similar manner to the NT, the combined data for Qld regions were analysed to determine what (if any) environmental factors could be monitored to inform the Harvest Strategy for the Qld GoC Crab fishery, which is proposed to be managed as a single unit by total allowable catch. Flow was not included in the all regions combined analysis, as some regions did not have suitable flow data available.

Only those factors that were significant in the GLM appear in Table 20. The ‘best’ model, based on adjusted R^2 (55.8%) and AIC (104.1), included cumulative heat between November and March (negative effect) and cumulative rainfall between October and April in the year preceding the catch year (i.e. some 16 to 18 months before crabs were harvested). Two other 2-term models had similar levels of fit, and included cumulative rainfall between October and April two years preceding the catch year and either cumulative rainfall one year preceding the catch year or average MSL anomaly between November and March immediately before the catch year (Table 20). However, a simpler 1-term model of only cumulative heat between November and March immediately preceding the catch year (negative effect) had a similar level of fit as the more complicated 2-term models. These results were similar to those for the NT western GoC combined regions analysis (Table 9). Cumulative heat between November and March and interpolated coastal rainfall were highly, but negatively, correlated (r = -0.57) across Qld GoC regions combined. They are likely interchangeable as terms in the GLMs, although the heat index accounted for slightly more variation in CPUE than cumulative rainfall.

The most consistent GLM result, across all regions, was the significant negative relationship between CPUE and cumulative heat between November and March immediately preceding the catch year. Interpreting the detailed results of the best all subsets GLM analysis is complex. An all subsets approach was taken, rather than a step forwards or step backwards GLM as a method of screening for likely biologically appropriate relationships, rather than identifying a particular model with statistically the best fit.

Table 18. Correlation coefficients (r[*]) of environmental factors in the Weipa-Mapoon region (2000 to 2018).

	Cum rain Oct to Apr	Cum evap May to Sep	Water stress	Cum heat Nov to Mar	MSL fin yr	MSL anom Oct to Mar	Max SOI cal yr	Avg SOI May to Sep	MJO phase 2 days	MJO phase 5 or 6 days	Avg phase 4 MJO	MJO phase 4 days
Cum rain Oct to Apr	-											
Cum evap May to Sep	-0.48	-										
Water stress	**0.99**	-0.56	-									
Cum heat Nov to Mar	-0.40	0.54	-0.45	-								
MSL fin yr	**0.73**	-0.26	**0.71**	-0.38	-							
MSL anom Oct to Mar	0.84	-0.32	0.81	-0.36	**0.96**	-						
Max SOI cal yr	0.12	-0.06	0.17	-0.51	0.33	0.20	-					
Avg SOI May to Sep	-0.13	0.18	-0.10	-0.28	0.14	0.01	0.81	-				
MJO phase 2 days	0.06	0.03	0.04	0.35	-0.13	-0.06	-0.23	-0.12	-			
MJO phase5 or 6 days	0.48	-0.31	0.49	-0.15	0.37	0.34	0.08	-0.15	-0.11	-		
Avg MJO phase 4	-0.05	0.07	-0.03	0.59	-0.28	-0.21	-0.19	-0.07	0.12	0.00	-	
MJO phase 4 days	-0.25	0.16	-0.25	-0.03	0.02	-0.05	0.24	0.19	-0.06	-0.36	-0.10	-

[*] Values in bold type are indicative of high collinearity between factors as per the collinearity diagnostic critical value (i.e. *r* >0.70) of Dormann *et al*. (2012).

Table 19. Best all-subsets generalised linear models for annual CPUE (kg per day fished) of Giant Mud Crabs in the Weipa-Mapoon region (2006 and 2018).

		Factors in Model	
Adj. R^2 (%)	**AIC**	MSL fin yr^{-1}	MSL anom Oct to Mar^{-1}
1 term			
28.2	13.4	0.036	
26.3	13.6		0.042

Factors in the multiple regression are positively related to catch unless indicated in red

Table 20. Best all-subsets generalised linear models for annual CPUE (kg per day fished) of Giant Mud Crabs in the Queensland Gulf of Carpentaria regions combined (2000 and 2018).

				Factors in model				
Adj. R^2 (%)	**AIC**	Cum rain Oct to Apr^{-1}	Cum rain Oct to Apr^{-2}	Cum heat Nov to Mar	Cum heat Nov to Mar^{-1}	MSL anom Oct to Mar	Avg SOI May to Sep^{-1}	MJO phase 5 or 6 $days^{-1}$
1 term								
54.3	106.2			0.001				
52.7	109.7		0.006					
51.6	109.9					0.018		
50.8	113.5				0.041			
50.7	113.6	0.043						
51.5	112.1						0.020	
50.9	113.3							0.037
2 terms								
55.8	104.1	0.048		0.001				
S54.2	107.4		0.015			0.049		
54.2	107.4	0.049	0.007					

Factors in the multiple regression were positively related to catch unless indicated in red

Dynamic Bayesian networks of monthly data

Environmental variables and catch rate of Giant Mud Crabs in the GoC had pronounced seasonal components. This means there were repeated peaks and troughs in the data from year to year. The seasonal patterns reflect the seasonality of fishing operations and associated catchability of Giant Mud Crabs (see Chapter 2). All data were de-seasonalised, which essentially resulted in an "index" rather than absolute values for all data. If season were not accounted for in the monthly analysis, all variables would spuriously show strong and significant relationships, simply due to the seasonal nature of the data (Erbas and Hyndman 2005). The resulting time series consisted of a "trend" and a random component (See Figure 28 and Figure 29). The trend is the long term movement of the time series (i.e. a smoothed version of the original series). The "random" component is the volatility in the series that remains once accounting for the long-term trend and seasonal components. Weipa was excluded from the analyses due to very poor model performance statistics. Note that catch per day for the NT is kg per pot day whereas for Qld is kg per day fished (see Chapter 2).

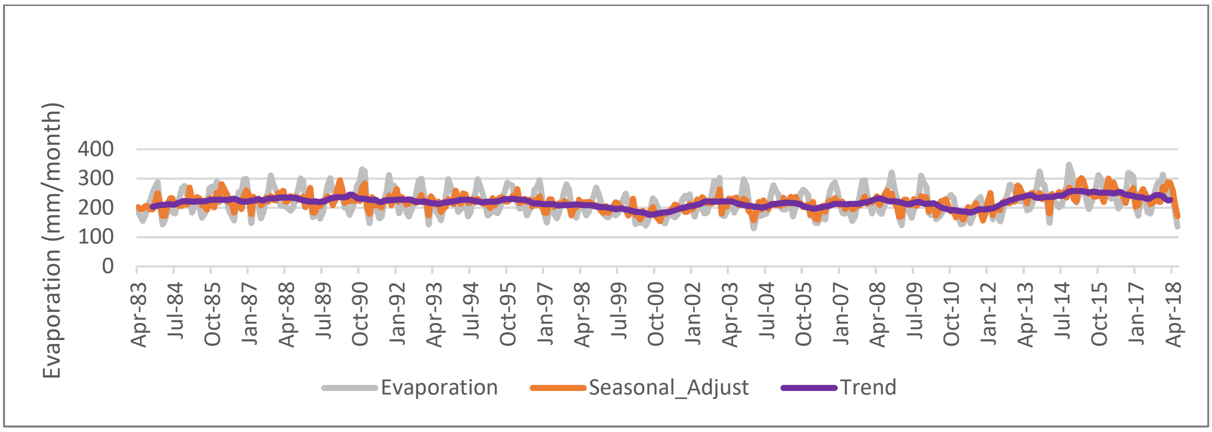

Figure 28. Raw, trended and seasonally adjusted evaporation data from the McArthur region.

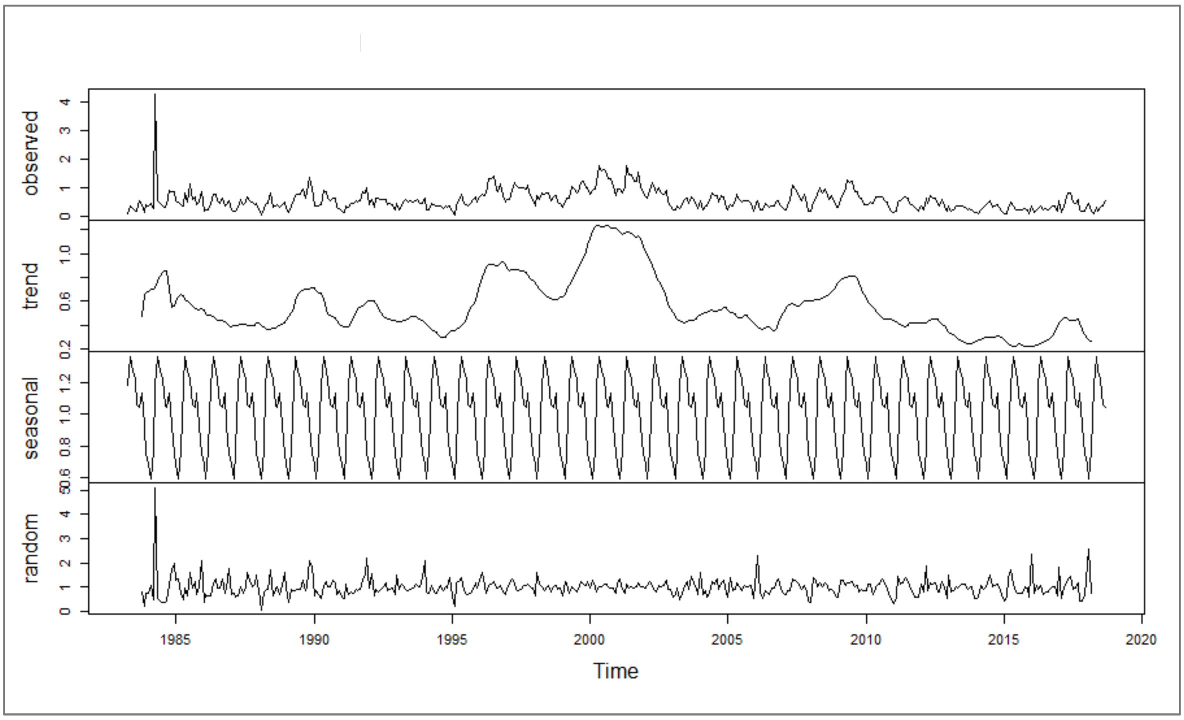

Figure 29. Catch per day of Giant Mud Crabs in McArthur region decomposed into trend, seasonal and random components using the multiplicative method.

Northern Territory - Roper region

Only variables with the highest predictive power for the catch rates of Giant Mud Crabs are reported (Table 21). Summary results include the mean value of each variable across the entire dataset, the test of the significance of the conditional dependencies (G-test), corresponding p-value and the total effect, which is analogous to the slope of the regression line. Previous maximum temperature, evaporation and relative humidity each had a significant relationship with the catch rate of Giant Mud Crabs for the Roper region. Notably, evaporation from 14 months previous, at around the time of hatching of the recruits (see Chapter 1), was one of the main drivers of catch rate. The overall precision for the model was 68%. Figure 30 shows the structure of the model. The probability distributions are shown in Figure 31.

Table 21. Dynamic Bayesian network analysis summary results for the Roper region of the variables that shared the most information with de-seasonalised catch rates of Giant Mud Crabs.

Node	Mutual information	Mean value	G-test	p-value	Total effect
Evapdata t^{-2}	0.145	199.76	60.86	<0.01	-0.00703
T_Max t^{-7}	0.117	35.73	49.37	<0.01	-0.11371
RHmaxT t^{-10}	0.109	48.61	45.84	<0.01	0.034269
Evapdata t^{-14}	0.109	199.04	45.65	<0.01	-0.00593
T_Max t^{-5}	0.089	35.73	37.25	<0.01	-0.10483
RHminT t^{-9}	0.084	92.58	35.41	<0.01	0.025228

Effects are positively related to catch rate unless indicated in red.

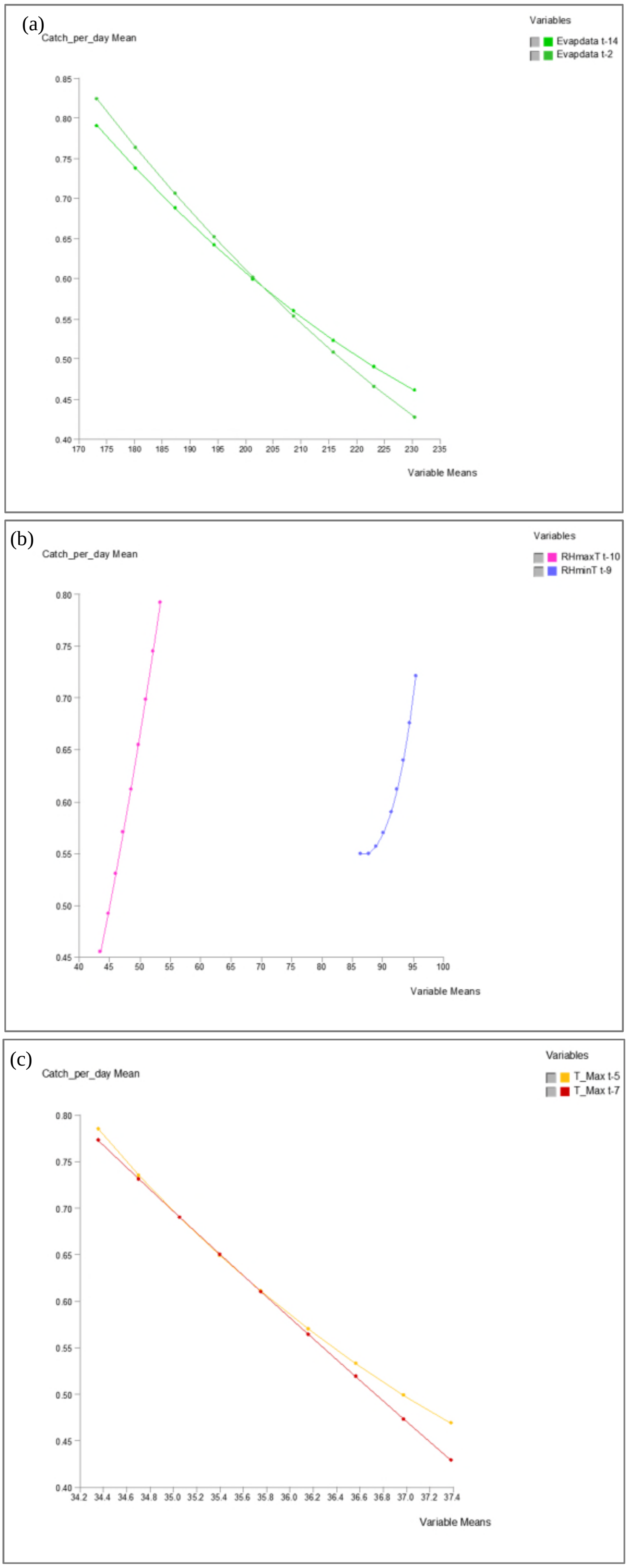

Figure 30. Key dynamic Bayesian network relationships for the Roper region – monthly catch rate as function of: (a) evaporation, (b) relative humidity, and (c) maximum temperature. All data are de-seasonalised.

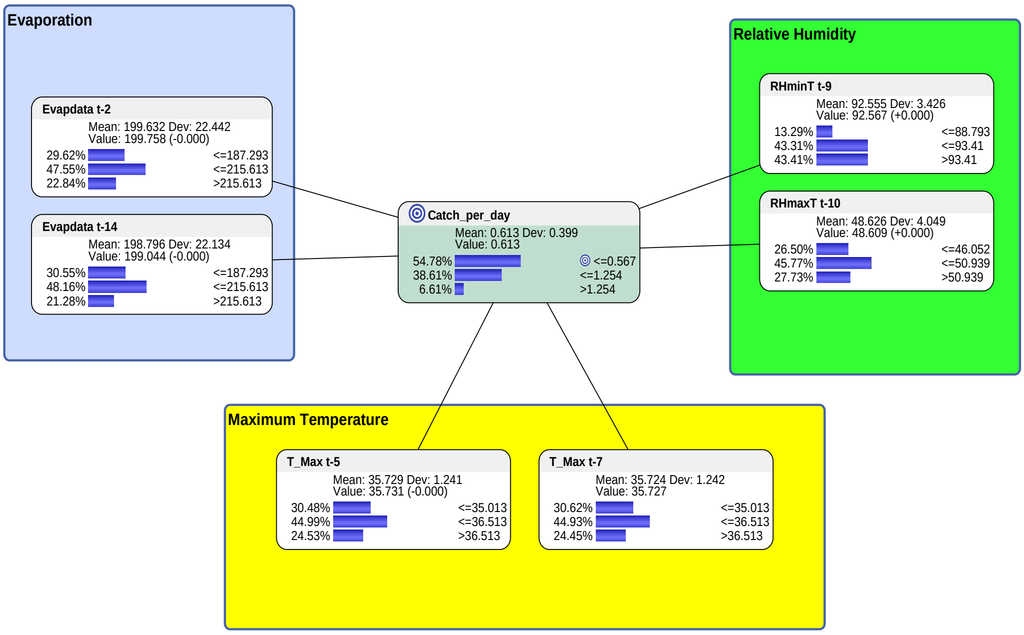

Figure 31. Dynamic Bayesian network analysis discovered structure and probability distributions for the Roper region of de-seasonalised monthly catch rates of Giant Mud Crab categorised into three levels.

Northern Territory - McArthur region

Only variables with the highest predictive power for the catch rates of Giant Mud Crabs are reported (Table 22). Summary results include the mean value of each variable across the entire dataset, the test of the significance of the conditional dependencies (G-test), corresponding p-value and the total effect, which is analogous to the slope of the regression line. Evaporation variables up to eight months previous to reported catch were found to have strong conditional dependencies on monthly catch rates in the McArthur region. De-seasonalised evaporation variables preceding monthly catches had a negative relationship with catch rates (see Total effect in Table 22). In other words, monthly catch rate will be lower than expected for particular month if evaporation one month (t^{-1}), four months (t^{-4}), five months (t^{-5}), and eight months (t^{-8}) previous was higher than usual (see Figure 32). The overall precision for the model was 56%. The relatively low precision was largely due to the model correctly classifying a “high” catch rate (>0.903 kg per pot day de-seasonalised) only 38% of the time. However, it was relatively accurate at classifying low and medium catch-rates. The probability distributions are shown in Figure 33.

Table 22. Dynamic Bayesian network analysis summary results for the McArthur region of the variables that shared the most information with de-seasonalised monthly catch rates of Giant Mud Crabs.

Node	Mutual information	Mean value	G-test	p-value	Total effect
Evapdata t^{-1}	0.083	219.05	49.06	<0.01	-0.00347
Evapdata t^{-4}	0.063	219.24	37.47	<0.01	-0.00330
Evapdata t^{-5}	0.062	219.28	36.85	<0.01	-0.00330
Evapdata t^{-8}	0.062	219.06	36.46	<0.01	-0.00347

Effects are positively related to catch rate unless indicated in red

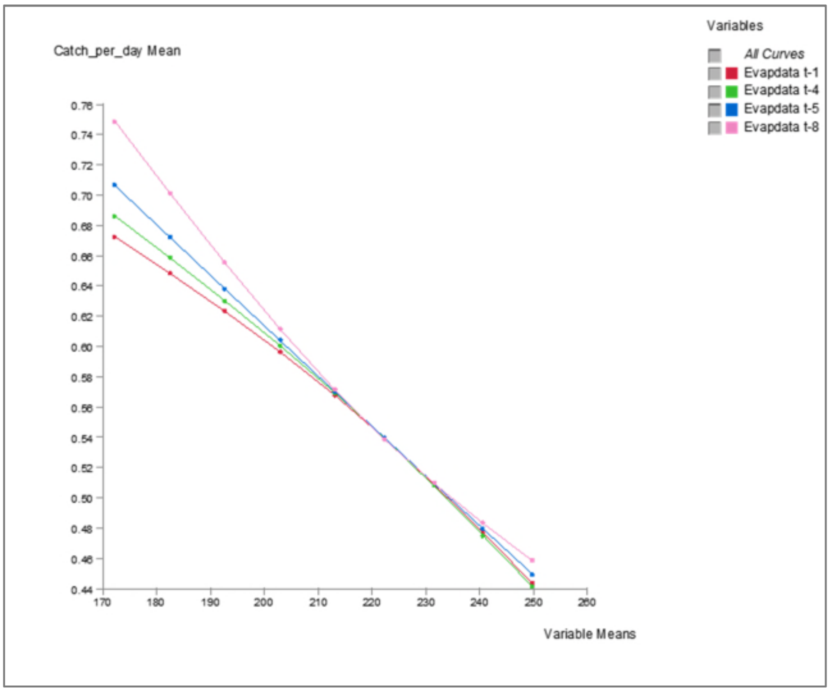

Figure 32. Key dynamic Bayesian network relationships for the McArthur region –monthly catch rate as a function of evaporation. All data are de-seasonalised.

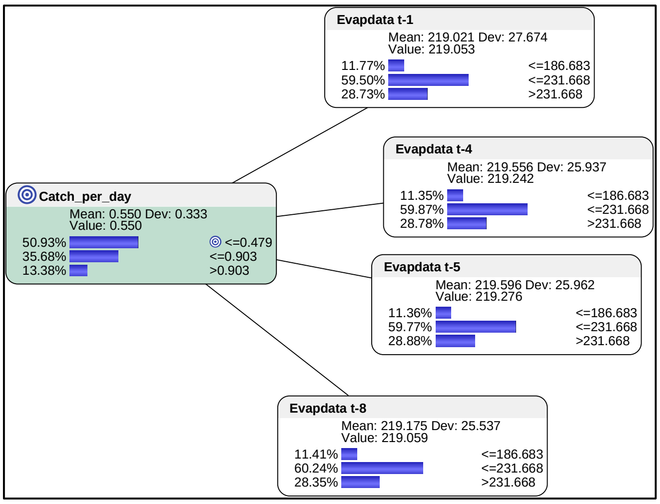

Figure 33. Dynamic Bayesian network analysis discovered structure and probability distributions for the McArthur region of de-seasonalised monthly catch rates of Giant Mud Crab categorised into three levels. Evapdata is the de-seasonalised cumulative evaporation value for a month.

Queensland - South West region

Only variables with the highest predictive power for the catch rates of Giant Mud Crabs are reported (Table 23). Summary results include the mean value of each variable across the entire dataset, the test of the significance of the conditional dependencies (G-test), corresponding p-value and the total effect, which is analogous to the slope of the regression line. The model had overall precision of 70% in the South West region. De-seasonalised minimum temperature and flow from the Leichardt River 16 months previous (around the time of hatching or just previous to it, see Chapter 1) had a significant relationship with catch rate (Table 23). The total effect values were positive for flow, and negative for minimum temperature. Figure 34 shows the structure of the model. The exact nature of the relationships are shown in Figure 35.

Table 23. Dynamic Bayesian network analysis summary results for the South West region of the variables that shared the most information with de-seasonalised monthly catch rate of Giant Mud Crabs.

Node	Mutual information	Mean value	G-test	p-value	Total effect
Flowdata_Leichardt t^{-16}	0.048	189601	22.02	<0.01	-1.83485
T_Min t^{-16}	0.033	21.38	15.08	<0.01	1.2E-06

Effects are positively related to catch rate unless indicated in red.

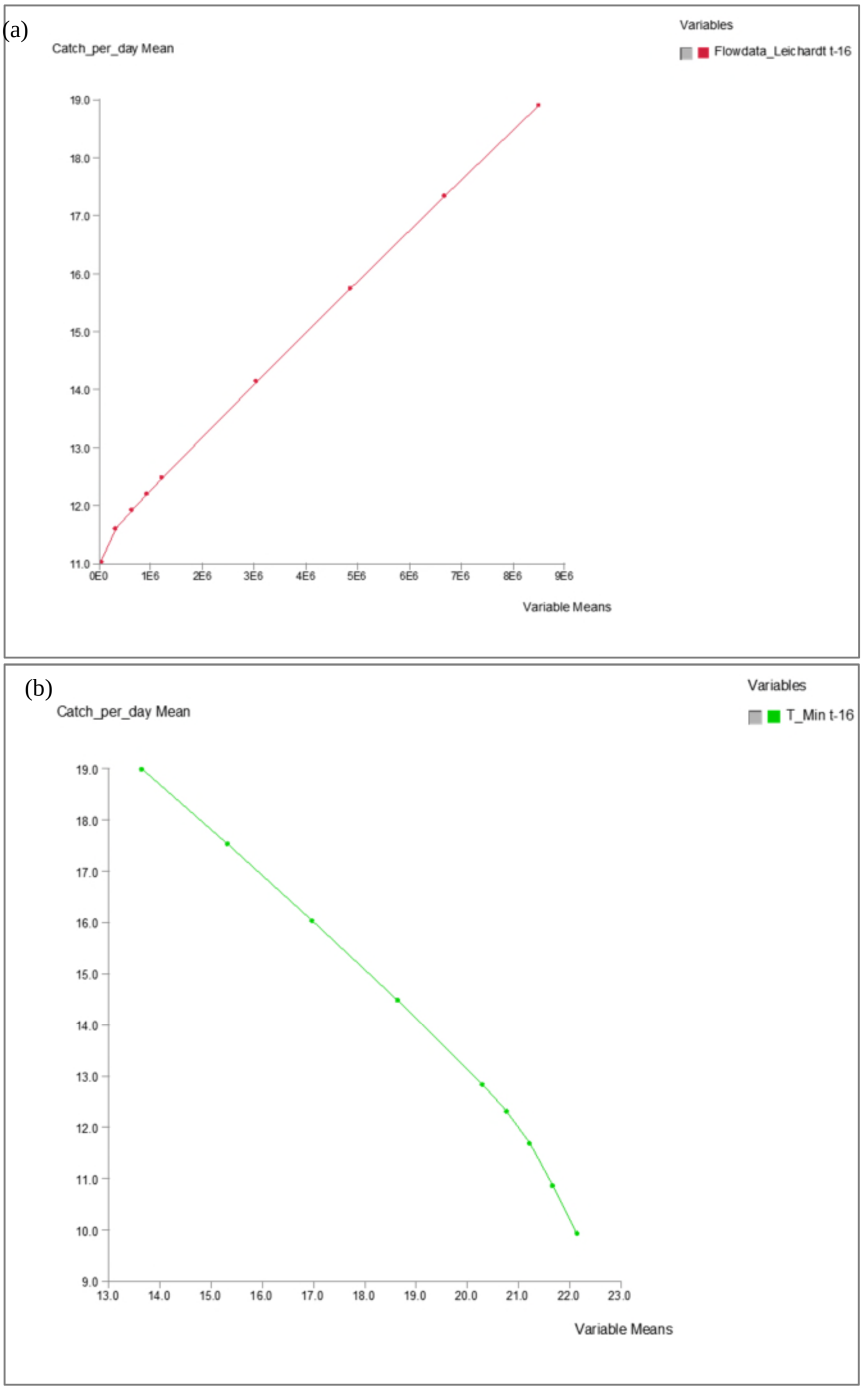

Figure 34. Key dynamic Bayesian network relationships for the South West region – monthly catch rate and its relationship with: (a) flow in the Leichardt River and (b) minimum temperature, both 16 months previous to catch. All data are de-seasonalised.

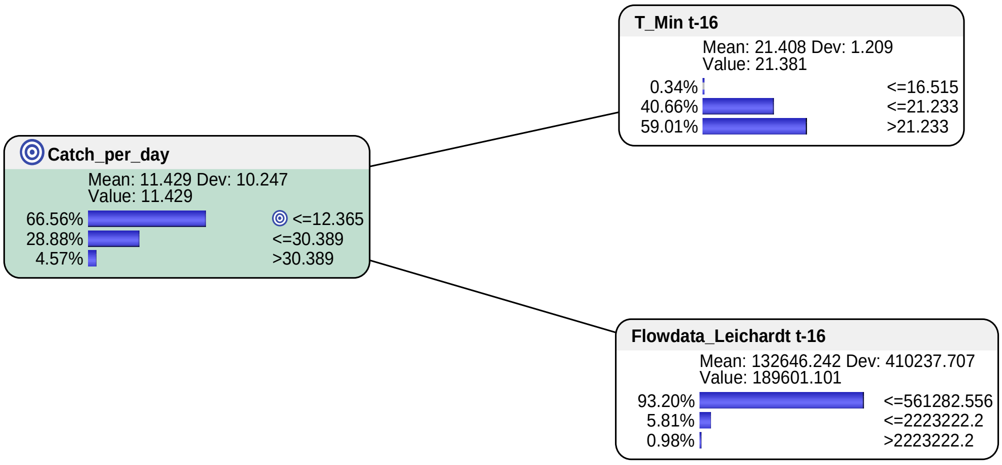

Figure 35. Dynamic Bayesian network analysis discovered structure and probability distributions for the South West region of de-seasonalised monthly catch rates of Giant Mud Crab categorised into three levels.

, Queensland - South East region

Only variables with the highest predictive power for the catch rates of Giant Mud Crabs are reported (Table 24). Summary results include the mean value of each variable across the entire dataset, the test of the significance of the conditional dependencies (G-test) and corresponding p-value. The total effect values, which is analogous to the slope of the regression line, are also reported. Evaporation variables in month t, t^{-4}, t^{-9} and t^{-12} had a significant but negative relationship with catch rate. Results for this region were similar to model results for the McArthur region. Overall precision for the model was 64%. Figure 36 shows the structure of the model. The exact nature of the relationships are shown in Figure 37.

Table 24. Dynamic Bayesian network analysis summary results for the South East region of the variables that shared the most information with de-seasonalised monthly catch rates of Giant Mud Crabs.

Node	Mutual information	Mean value	G-test	p-value	Total effect
Evapdata t^{-12}	0.132	212.91	65.57	<0.05	-0.18601
Evapdata t	0.097	213.13	48.024	<0.05	-0.14912
Evapdata t^{-9}	0.092	212.97	45.60	<0.05	-0.14161
Evapdata t^{-4}	0.074	213.02	36.71	<0.05	-0.12218

Effects are positively related to catch rate unless indicated in red

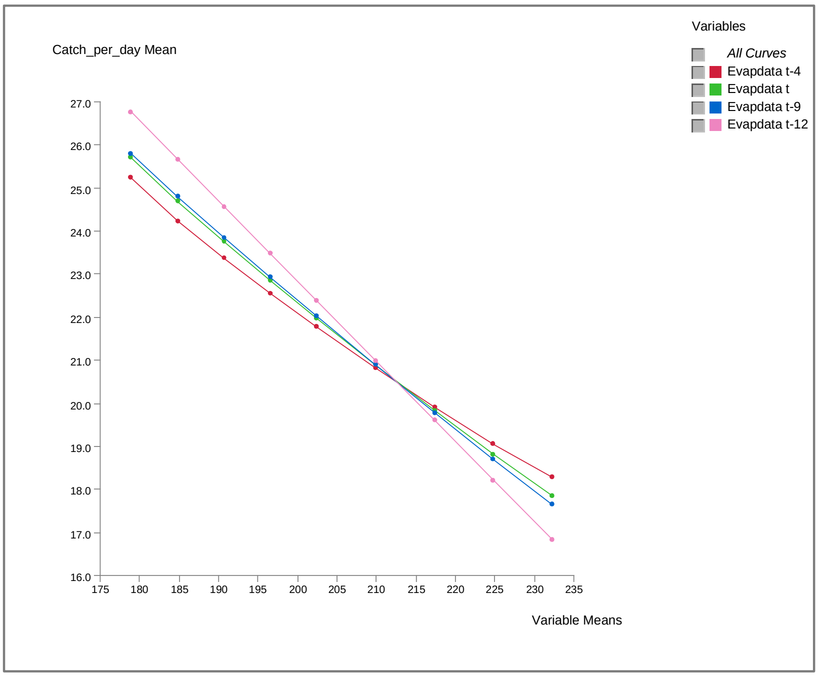

Figure 36. Key dynamic Bayesian network relationships for the South East region – monthly catch rate as a function of evaporation. All data are de-seasonalised with evapdata being the de-seasonalised cumulative evaporation value for a month.

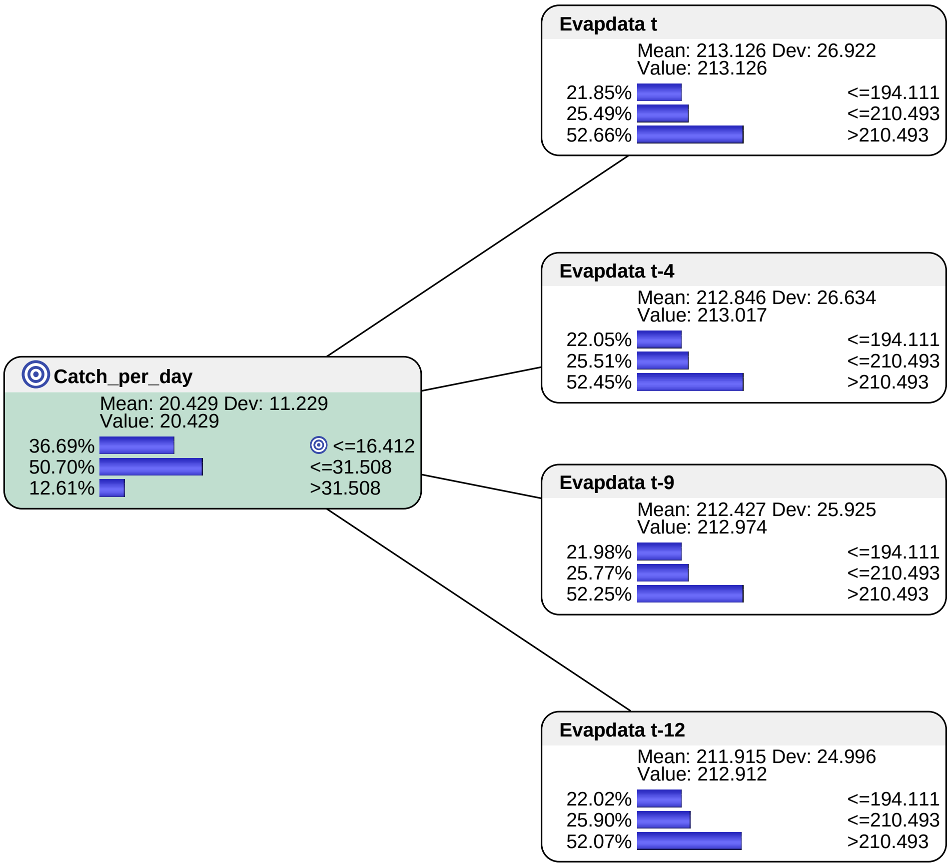

Figure 37. Dynamic Bayesian network analysis discovered structure and probability distributions for the South East region of de-seasonalised monthly catch rates of Giant Mud Crab categorised into three levels.

Queensland - Staaten and Gilbert region

Only variables with the highest predictive power for the catch rates of Giant Mud Crabs are reported (Table 25). Summary results include the mean value of each variable across the entire dataset, the test of the significance of the conditional dependencies (G-test), corresponding p-value and the total effect, which is analogous to the slope of the regression line. Flow variables from the Staaten and Gilbert Rivers appeared to have a significant postive impact on catch rate. The overall precision was 55%, with the model struggling to predict the reported high catch rates. Figure 38 shows the structure of the model. The exact nature of the relationships are shown in Figure 39.

Table 25. Dynamic Bayesian network analysis summary results for the Staaten-Gilbert region of the variables that shared the most information with monthly de-seasonalised catch rates of Giant Mud Crabs.

Node	**Mutual information**	**Mean value**	**G-test**	**p-value**	**Total effect**
flowdata_Gilbert t^{-2}	0.059	364321	26.70	<0.05	1.76E-05
flowdata_Staaten t^{-7}	0.057	153484	25.53	<0.05	2.46E-05
flowdata_Staaten t	0.056	151200	25.29	<0.05	5.17E-06

Effects are positively related to catch rate unless indicated in red.

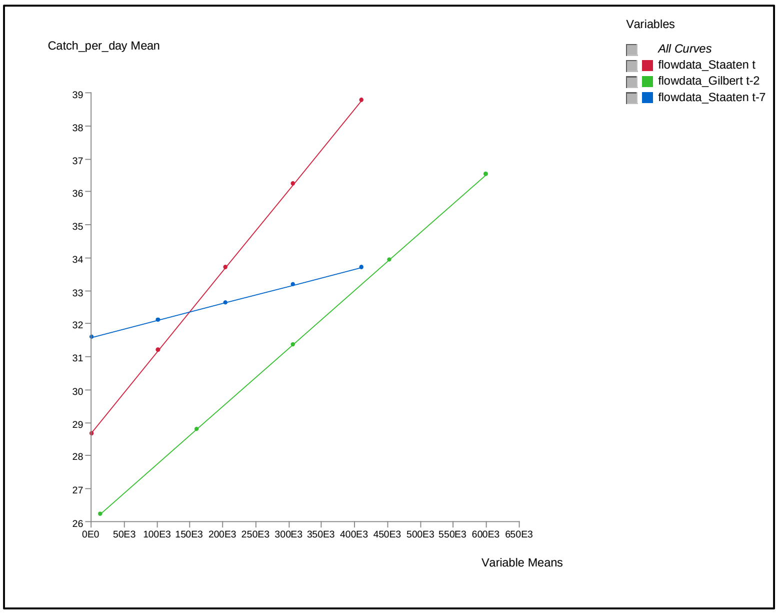

Figure 38. Key dynamic Bayesian network relationships for the Staaten and Gilbert region – monthly catch rate and its relationship with flow of the Staaten and Gilbert Rivers. All data are de-seasonalised.

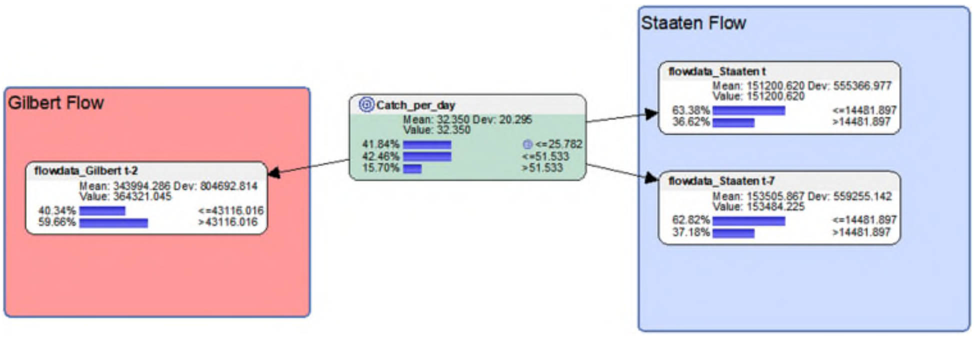

Figure 39. Dynamic Bayesian network analysis discovered structure and probability distributions for the Staaten-Gilbert region of de-seasonalised monthly catch rates of Giant Mud Crab categorised into three levels.

Discussion

We evaluated the role of a broad range of environmental factors on the catch variation of fisheries harvesting Giant Mud Crabs in the GoC. Annual analyses by traditional GLMs and monthly analyses by novel Bayesian network data-driven machine learning were used. Long-held concerns regarding the accuracy of reported catch and effort information from licensees operating in the Qld GoC strongly suggest that CPUE estimates derived from these records may not accurately represent fluctuations in the abundance of Giant Mud Crabs, especially at regional scales.

Notwithstanding this issue, both techniques identified environmental factors that accounted for significant variation in the catch rates of Giant Mud Crabs. Consistently across both techniques, rainfall, flow, evaporation and temperature in the preceding months and year were key factors affecting catch rates. In some regions, evaporation, flow and temperature around the time larval and EBS stages had a significant relationship with catch rates of those same crabs when they recruited to the fishery.

The inclusion of sea level metrics in the annual GLM analyses of mud crab catch data (not available at the time of the DBN analyses) were novel. Although most studies acknowledge the role of tides in catch rate variation (Hay *et al*. 2005), to the best of our knowledge, none have considered mean sea level nor sea level anomalies before. Tides and sea levels affect various components of the life-history and harvest of Giant Mud Crabs via crab activity levels and associated catchability, as well as access by fishers to fishing areas and pot placement within the tidal range. Low mean sea levels in 2015, speculated as a contributing factor to the wide-spread mangrove dieback in the GoC (Duke *et al*. 2016), could also be a contributing factor to the declines in catch rates of Giant Mud Crabs in the GoC at around the same time. While MSL was frequently a factor significantly related to Giant Mud Crab, results were inconsistent in terms of the direction of effect (i.e. both positive and negative effects were fitted) and timing (i.e., immediately, one year prior and two years prior were fitted). We can naively speculate that lower MSL might decrease CPUE (i.e. a positive relationship) through less access to intertidal habitats (possibly of poorer quality) and thus increased natural mortality. Although lower MSL might reduce the area in which crabs are distributed and thus at some temporal scale, increase the catchability of crabs to the fishery. This might be a reason that would support lower MSL leading to increased CPUE (i.e. a negative relationship). The GoC is a very large semi-enclosed sea that has an unusual diurnal tide regime (i.e. one high and one low tide per day, each of about 12 hours duration), which is more pronounced in the south-eastern GoC than the western or north eastern GoC. Better tidal inundation data and improved understanding of the consequences of tidal inundation in the inter-tidal habitats of GoC estuaries used by Giant Mud Crabs would better inform analyses such as those conducted in the current study.

Consistently in the analyses, temperature was an important factor related negatively to catches and catch rates for regions in western to south-eastern GoC i.e. Roper to Staaten-Gilbert regions, from which the majority of GoC Giant Mud Crabs are harvested. Previous studies reported that rainfall was more important than temperature in northern Australia (Meynecke *et al.* 2010), but noted that high (water) temperatures may cause mortality of Giant Mud Crabs harvested from shallow tidal areas. It is likely that high temperatures in recent years (2015, 2016 - notably associated with low rainfall and river flow) are the main driver of this result, as temperatures were lower in the time-series considered by Meynecke *et al.* (2010).

Dynamic Bayesian network analysis was a useful exploratory technique to uncover complex relationships between environmental variables and Giant Mud Crab catch rates based on observational data in remote areas where records are lacking. The networks in the current analysis were discovered entirely through data-driven machine learning, rather than through expert knowledge, albeit some initial boundaries on factors to include and time limits were set by the life-history review. Bayesian Networks, similar to any modelling technique, can only truly model within the data ranges provided. This means if something peculiar were to happen outside of these ranges, the model may not accurately predict the outcome. When “wet season year” was included in the analysis, it was found to be the most informative variable for Giant Mud Crab abundance. An analysis at an annual level probably would be more informative than a monthly level, but Bayesian networks require hundreds of data points, which is impractical for annual mud crab catch and effort. Evaporation in the past had a negative relationship on de-seasonalised monthly catch rates in both the

McArthur and the South East regions. A few hypotheses could be tested in the future with regards to this insight. One of these is that increased evaporation and/or low freshwater input affects mud crab habitats by increasing salinity levels beyond the optimal range (see Chapter 2). High salinities are not well tolerated by juvenile crabs. When not considering the effect of evaporation in the analysis, variables such as radiation and humidity became important, presumably as proxies of evaporation.

Conclusion

In the current chapter, we evaluated environmental factors affecting the major fishery for crabs in the GoC (i.e. Giant Mud Crabs) at regional scales, informed by the critical literature and fishery reviews (of Chapters 1 and 2). The results, whilst complex, consistently indicated that cumulative heat had a negative impact on catch rates of Giant Mud Crabs, more so than flow, rainfall or MSL. Cumulative heat is a simple index of what is probably a more complex interplay of factors that directly affect Giant Mud Crabs through various processes at multiple life history stages. Cumulative heat (and/ or other metrics such as rainfall/evaporation/MSL) maybe appropriate proxies for the GoC in the absence of better observational data. Cumulative heat data (and others) are readily available and could be trialled to test their ability to forecast the likely harvest trends of Giant Mud Crabs in the GoC. Other indices considered in the analysis could also be included. However, remotely inferred environmental data, whilst cost-effective in such a remote (and broad spatial) area as the GoC, should not be substituted for robust in-situ monitoring of environmental factors that are likely to impact the populations of Giant Mud Crabs and their fisheries. This would include estuarine water temperature, salinity, sea level, rainfall and coastal productivity (e.g. chlorophyll a or meiofauna abundance) in each of the main regions where Giant Mud Crabs are harvested (i.e., Roper, McArthur, and South East).

Reduced catches and catch rates of Giant Mud Crabs in the GoC coincided with climate events that include a sequence of years with low rainfall, high temperatures (resulting in high evaporation) and below average mean sea levels. The GoC may be an atypical area in terms of environmental drivers on populations of Giant Mud Crabs as a consequence of several factors:

(i) the east-west layout to the coastline of the southern and western GoC such that the crabs cannot retreat southwards to avoid heat events;
(ii) a mostly diurnal tide regime resulting in the exposure of inter-tidal areas to the extremes of heat in summer and cold in winter; and
(iii) inconsistent rainfall/flooding patterns of catchments and associated rivers that provide freshwater and nutrients to the estuarine and near coastal habitats important for mud crabs.

We suggest that the GoC is an area where Giant Mud Crabs and their associated fisheries may be at high risk to climate ‘events’, more so in the western and southern regions (i.e. Roper and McArthur regions of the NT jurisdiction) than the eastern and northern regions (i.e. Qld jurisdiction). This should be of concern to fisheries stakeholders and warrants monitoring of environmental conditions in the habitats that support Giant Mud Crabs.

Chapter 5. Population models of Giant Mud Crab fisheries in the Gulf of Carpentaria.

A.R. Northrop, J.B. Robins, R.C. Buckworth and M.A. Grubert

Introduction

The harvest of Giant Mud Crabs is a complex interplay of spatial population and fishing dynamics, with environmental factors impacting at multiple scales. In addition to this complexity, modelling of mud crab populations is also challenging because of data limitations and uncertainties, unmeasured high inter-annual variation in recruitment, growth and survivorship, and the difficulty in separating effects of fishing mortality from environmental effects. The NT has a long history of quantitative assessment of its Mud Crab Fishery and most recently, applied a simplified model (i.e. annualised delay-difference model) to assess the risk of recruitment overfishing (Walters 2016, Grubert *et al*. 2019).

We applied two alternate ways of modelling fished populations to the annual harvest data for Giant Mud Crabs in the GoC: (i) delay-difference and (ii) catch-MSY.

The delay-difference model 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-recruitment relationship (in the current case for Giant Mud Crabs, females provide recruits two years hence), an estimated growth-survival function based on empirical data. It assumes that the growth-survival function is representative of the population over time, but as a biomass-based model, does not explicitly capture the selectivity changes resulting from changed management arrangements over time (relevant to NT but not Qld). The no-female harvest policy of Qld required assumptions (with a limited evidence base) about the biomass of females for the spawning stock recruitment-relationship.

Catch-MSY is a model-assisted data-poor assessment method for species where a time series of catch is available, but there is limited information on, or uncertainty about, other life-history and fishery parameters. The concept of the model is that catch is removed each year of fishing from the population biomass. Biomass in the following year is the post-catch biomass plus a response to that biomass level, which implicitly represents the net effect of natural survival, growth and recruitment. As such, catch-MSY is fundamentally similar in many ways to the delay-difference model. However, in catch-MSY, the spawning stock-recruitment relationship is implicit in this response. Catch-MSY models possible biomass trajectories of the stock based on some simple assumptions, which include: (i) the prior ranges for resilience of the stock, (ii) the carrying capacity, and (iii) the exploitable biomass ratio (to unfished) in the first year of the catch series (Martell and Froese 2013). Resilience is represented by one parameter (*r*), which is the intrinsic rate of population growth. *K* represents the carrying capacity of the stock and is analogous to the unfished exploitable biomass. These can be used to calculate the range of possible sustainable harvest levels (e.g. MSY). The advantages of the catch-MSY is its use of only catch data as input. The catch is assumed to be produced by an available biomass with a certain productivity (i.e. resilience by carrying capacity). Therefore the model can estimate the biomass that could have produced the catch under combinations of *r* and *K* evaluated by the model.

Methods

Delay-difference model

When the current project was developed, our aim was to adapt the delay-difference model developed for the NT Western GoC Mud Crab Fishery to the Qld GoC jurisdiction (Walters 2016), noting that there were challenges to be overcome, such as the absence in Qld of an index of female abundance (and thus the female spawning stock biomass) due to their prohibition from harvest.

Detailed model description and the equations used in the delay-difference model can be found in Grubert *et al*. (2019).

The NT DPI&R supplied an Excel version (December 2018) of the delay-difference model to the project, which was then replicated in Matlab (see Appendix 3). The model was applied to regions of the NT western GoC to better visualise regional patterns of recruitment variation and then to the Qld catch and effort data. A Kobe plot was also added to visualise the estimated trajectory of biomass versus fishing pressure.

In light of the regional influences of environmental factors (Chapter 4), preliminary results from the hydrological larval particle modelling that indicated separate regional stocks (Chapter 7), as well as the innate difference in how catch data relates to a relative index of abundance in the Northern Territory (males and females harvested) compared with Qld (males only harvested, larger MLS), we determined that it was unsuitable to build a single GoC wide delay-difference model (i.e. NT plus Qld data combined). While we have confidence in the general qualitative results of analyses between environmental factors and regional catch and effort of Giant Mud Crabs, we considered the desk-top based analyses insufficient to provide a quantitative link between environment data and population parameters such as the combined growth-natural survival factor (*g*).

There is a dearth of population biology information for Giant Mud Crabs from the Qld portion of the GoC. In the absence of observational data, we assumed that populations of Giant Mud Crabs were more like other GoC populations than Qld east coast or populations overseas (e.g. Asia). Therefore, the parameter estimates from the NT western GoC were used for the Qld GoC with the following adjustments: effort, in days fished, rather than pot lifts (scaled as per model requirements). The harvest rate and predicted catch were adjusted for the prohibition of female harvest. We assumed a 1:1 male to female ratio in the biomass (standard for the NT model), but the harvest rate of females was set to zero with a small percentage for discard mortality (i.e. 10% for females).

Catch-MSY model

The aim was to apply a modified catch-MSY model to mud crab fisheries in the GoC on a regional basis to estimate the current biomass ratios as: (i) an alternate population modelling approach to the delay-difference model; and (ii) to predict the impact of a variety of total allowable catch scenarios on biomass ratio levels.

Harvest information from the NT Western GoC Mud Crab Fishery and Qld GoC Crab Fishery were used as input into a modified catch-MSY model (Haddon *et al*. 2018). This model has been recently applied to Giant Mud Crab fisheries (at broad scales) in Qld (Northrop *et al*. 2019). The model quantified the current biomass within levels of certainty. The model was further used to generate future biomass predictions based upon hypothetical future catch limit scenarios.

Northern Territory western Gulf of Carpentaria

Commercial logbook data

Monthly commercial logbook data from the NT Western GoC Mud Crab Fishery between 1983 and 2018 (calendar years) were provided by NT DPI&R. Numerous changes to the management of the NT Mud Crab Fishery have occurred (DPI&R 2017), but the most relevant to an analysis of catch over time are in: 1985 –

the introduction of a minimum legal size (MLS) of 130 mm carapace width (CW); 1996 – an increase to the MLS of females to 140 mm CW; 2001 – a Commercially Unsuitable Crabs (CUC) rule effectively limiting the harvest to A-grade crabs; 2006 – an increase in MLS for males to 140 mm and for females to 150 mm. Harvest, and how it relates to the abundance of Giant Mud Crabs, will be influenced by these changed management arrangements. Therefore, only harvests from 2006 to 2018 were considered in the analysis for NT data for catch-MSY, as this time series has consistent harvest rules, especially for the size of crabs able to be legally harvested (i.e. the exploitable biomass).

The data were aggregated spatially to enable investigation of trends in harvest and biomass at regional scales that may be influenced by environmental factors (see Chapter 2). The regions were:

(i) Blue Mud Bay/Groote Eylandt – NT grids 1335, 1336, 1436
(ii) Roper – NT grids 1435, 1535
(iii) McArthur –NT grids 1536, 1537, 1637, which includes the Robinson and Wearyan Rivers.

Given the scale of the regional commercial harvests, the current catch-MSY analysis focused on the Roper and McArthur regions, as they account for about 90% of the Giant Mud Crab harvest in the NT western GoC between 2006 and 2018.

Recreational harvest estimates

The NT Western GoC Giant Mud Crab fishery is predominately exploited by the commercial sector, with limited and poorly quantified harvest by the recreational sector. The recreational sector is estimated to take 6% of the mud crab harvest in the NT, with the commercial sector taking 88%, the traditional harvest taking 5% and the fishing tour sector taking the remaining 1% (Hay 2009; DPI&R 2017). Seventy per cent of the recreational harvest is estimated to occur in the Darwin region. The Roper and McArthur regions do not have large adjacent human population (such as Darwin). Therefore, for the catch-MSY analysis, we assumed that the recreational harvest of Giant Mud Crabs was negligible compared with the commercial harvest for these regions.

Queensland Gulf of Carpentaria

Commercial logbook data

The Qld data is as per Northrop *et al*. (2019) for the GoC, except that the data were divided spatially to enable investigation of trends in harvest and biomass at regional scales that may be influenced by environmental factors. The regions were:

(i) Aurukun/Weipa/Mapoon – Qld grids AB10, AB11, AB9, AC10, AC11, AC9, A6, A7, AB6, AB7, AB8
(ii) Pormpuraaw/Staaten/Gilbert – Qld grids AB12, AB13, AB14, AC12, AC13, AC14, AD13, AB15, AC15, AC16, AD15, AD16
(iii) South East Corner/South West – Qld grids AE18, AD18, AC18, AD17, AC17, AI16, AH16, AG16, AF16, AG17, AF17, AG18, AF18

Analysis

A catch-MSY (Martell and Froese 2013) using the R package *simpleSA* (Haddon *et al.* 2018) was used to model the exploitable biomass levels of Giant Mud Crabs. The catch-MSY uses a Schaefer (1954) surplus-production model at its core. A range for the initial depletion levels are specified, as well as the number of replicates (many thousands) to be tested within the range. Initial depletion is the ratio of the size of the stock in the year of first available data, and the size of the stock before crabbing began. Stock reduction analyses are then used (Kimura *et al.* 1984) for each replicate to generate an array of feasible trajectories of the stock biomass over the harvest period. An adaption of the catch-MSY for Giant Mud Crabs was the use of a logistic growth curve (i.e. the Schaefer model) for the likely stock-recruitment relationship using the Schaefer stock-recruitment function specified in Haddon *et al*. (2018). Male Giant Mud Crabs are extremely competitive for habitat with other males. Therefore, it is likely that an equilibrium is reached at a certain male stock size.

Assumptions of the model were:

(i) The potential ranges for carrying capacity are very wide, between the maximum harvest and 60 times the maximum harvest (Haddon *et al*. 2018).

(ii) The initial depletion (i.e. the biomass of the stock in 2006 compared with the unfished biomass) ranged from 0.15 (i.e. heavily depleted) to 0.70 (i.e. lightly depleted) for all regions.

Catch-MSY is based on the Schaefer model, which assumes density-dependent growth in population size. Though only the exploitable component of the stock was modelled, a density-dependent relationship was deemed a reasonable assumption. Male Giant Mud Crabs are extremely territorial, and after a certain biomass is reached in an area, there will be high competition for habitat, food and females, resulting in decreases in male population growth, as previously speculated by Hay *et al.* (2005). Catch-MSY was considered an appropriate alternative model to more complex and data intensive models (e.g. Grubert *et al*. 2013; Grubert *et al*. 2019) as more complex models rely on more assumptions and may not necessarily provide more precise results.

Analyses were conducted to determine the catch-MSY model sensitivity to various resilience parameters, alternate initial depletion levels, and the default assumption that stocks cannot increase higher than their initial carrying capacity. Future catch limits were tested and compared against the likelihood of obtaining 50% biomass ratio levels.

Results

Delay-difference model

Only results in addition to that of Grubert *et al*. (2019) are provided below, for contrast with results those for Qld. The delay-difference model is deterministic (not optimised), so results should be considered as explorations of alternate possibilities rather than the most likely from an optimised model with uncertainty included in fitted parameter estimates. Plots of reconstructed biomass (harvestable males plus unharvested females) are presented in Figure 40 for alternate values of *q* (catchability) for harvests of Giant Mud Crab in the Qld GoC. Plots of estimated anomaly patterns in recruitment and nominal catch per unit effort (CPUE) are presented in Figure 41.

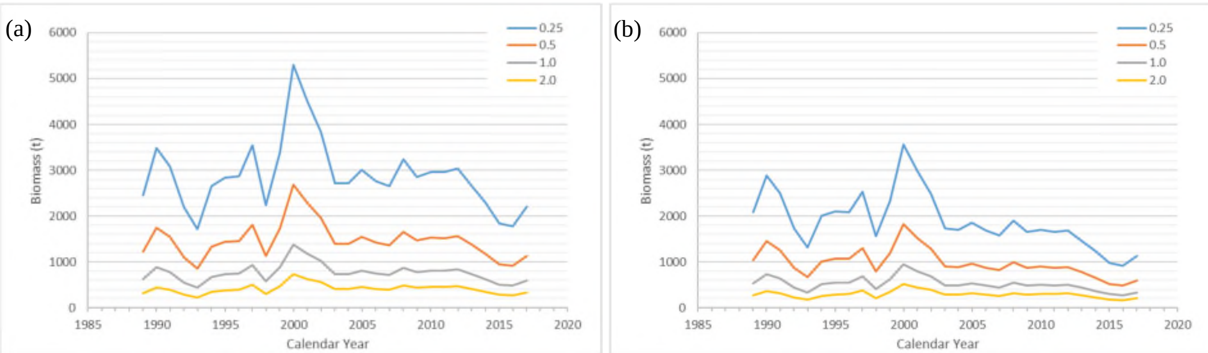

Figure 40. Delay-difference model reconstructed biomass (harvestable males plus unharvested females) of Giant Mud Crabs from the Queensland Gulf of Carpentaria for: (a) different assumed values of constant q (i.e. catchability) and (b) where q doubles over the time series from the initial different assumed values.

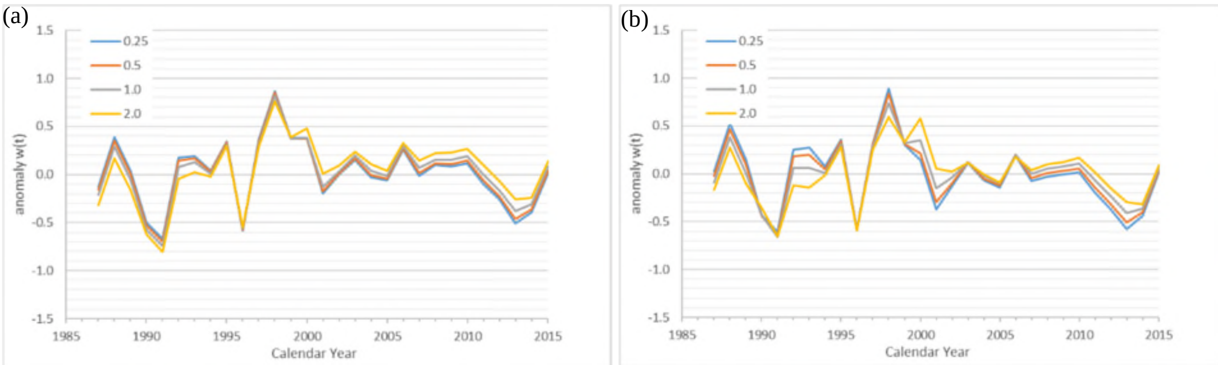

Figure 41. Delay-difference model estimated recruitment anomaly patterns (ωt) around the average Ricker stock recruitment relationship for Giant Mud Crabs from the Queensland Gulf of Carpentaria for: (a) different assumed values of constant q, and (b) where q doubles over time series from the different assumed initial values.

Kobe plots, which are based on MSY calculations, are limited for Giant Mud Crabs stocks in that they are inherently based on average conditions; in this case average relative recruitment which is unlikely to represent the reality of variable recruitment. Notwithstanding this limitation, the Kobe plots derived from the delay-difference model highlight the different fishing pressures on the stocks of Giant Mud Crabs in the NT and Qld jurisdictions of the GoC (Figure 42). Regardless of whether catchability has stayed consistent (top plots) or doubled (bottom plots), the Qld jurisdiction was estimated to be mostly in the low risk panel (i.e. green area, as expected), except for the last two to four years of the time series (2013 to 2017), which probably represent low stock size derived from low recruitment.

In contrast in the NT jurisdiction, fishing pressure was at times mostly in the moderate risk parts of the Kobe plot (yellow areas), which is consistent with a fishery where >90% of the exploitable biomass was estimated to be harvested each year (Hay *et al*. 2005; Ward *et al*. 2008).

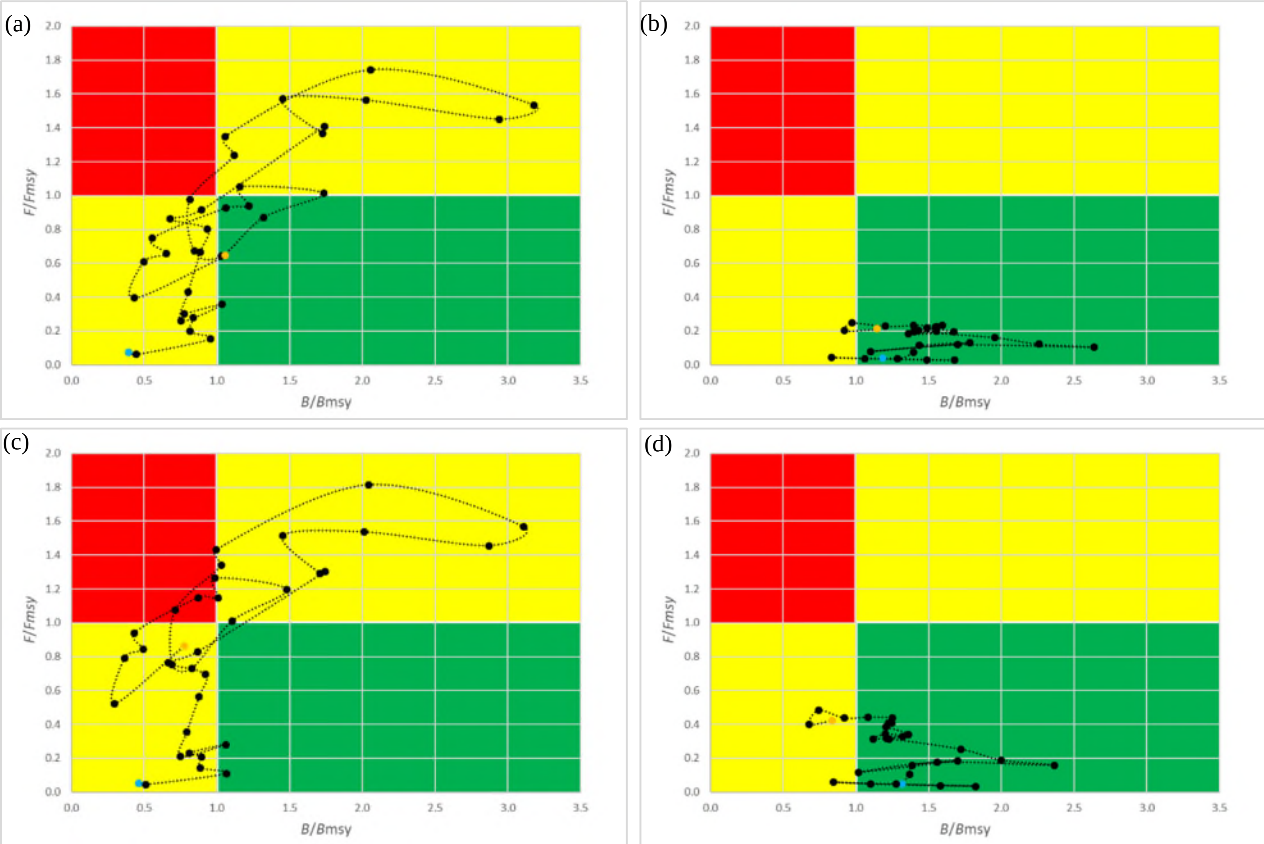

Figure 42. Kobe plots of estimated annual Biomass/Biomass$_{MSY}$ against F/F$_{MSY}$ from the delay-difference model (assuming average relative recruitment in MSY calculations) for: (a), (c) Northern Territory Western Gulf of Carpentaria Mud Crab Fishery; and (b), (d) Queensland Gulf of Carpentaria Mud Crab Fishery (assuming 1:1 male to female spawning stock biomass, but with no female harvest). (a) and (b) assumed constant catchability (q). (c) and (d) assumed q doubled over the time series. The blue point is 1983 for Northern Territory and 1989 for Queensland. The orange point is 2017.

Modified catch-MSY

Northern Territory - Roper region

The modified catch-MSY produced mean values of *r* (resilience) and *K* (carrying capacity) of 0.59 and 531 tonnes respectively for the Roper region, which are indicative of a moderately resilient stock (Table 26, Figure 43). The estimated biomass trajectories indicated that at the start of 2019 calendar year, the mean biomass ratio was 0.55 compared with unfished, with the median estimated at 0.60 (Table 26, Figure 44, Figure 45).

Table 26. Estimated catch-MSY model parameters for the Roper region.

	Lower 97.5% CI	Mean	Upper 97.5% CI	Percentiles 2.5th	5th	50th	95th	97.5th
r	0.40	0.59	0.86	0.38	0.41	0.61	0.77	0.78
K	414.4	531.2	680.9	407.6	422.7	540.3	629.1	633.6
MSY (tonnes)	57.9	78.4	106.1	57.9	60.8	78.3	100.8	105.9
Biomass ratio B_{2019}/B_{0*}	0.29	0.55	0.82	0.22	0.27	0.60	0.69	0.70

Where *r* is the intrinsic rate of growth, *K* is the carrying capacity of the stock, MSY is the maximum sustainable yield, and B_{0*} is unfished biomass.

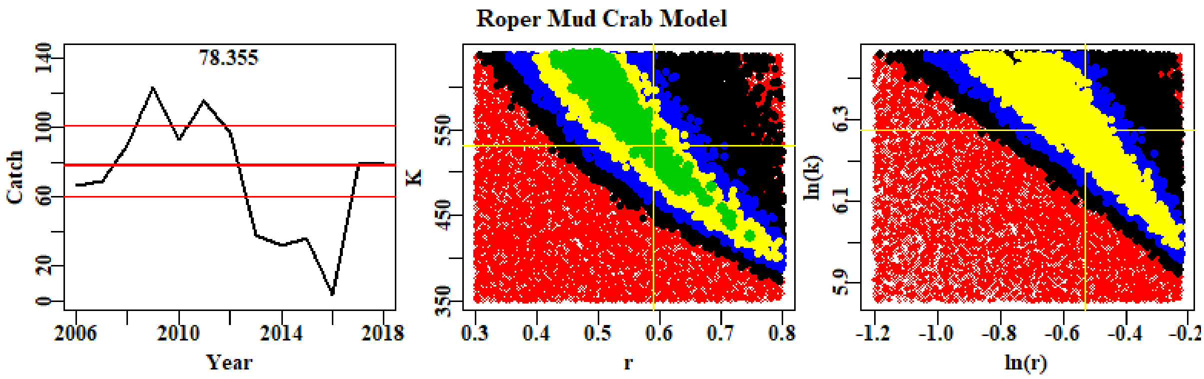

Figure 43. Summary outputs of the catch-MSY for Giant Mud Crabs from the Roper region. The left plot shows reported catch (tonnes) from 2006 to 2018. The estimated mean and 90th percentiles are shown as parallel red lines. The middle and right plots show r-K combinations (left plot standard, right plot log transformed), where red dots are non-successful r-K combinations, and dots coloured black to green denote successful r-K combinations. The yellow lines indicate the mean values for r and K.

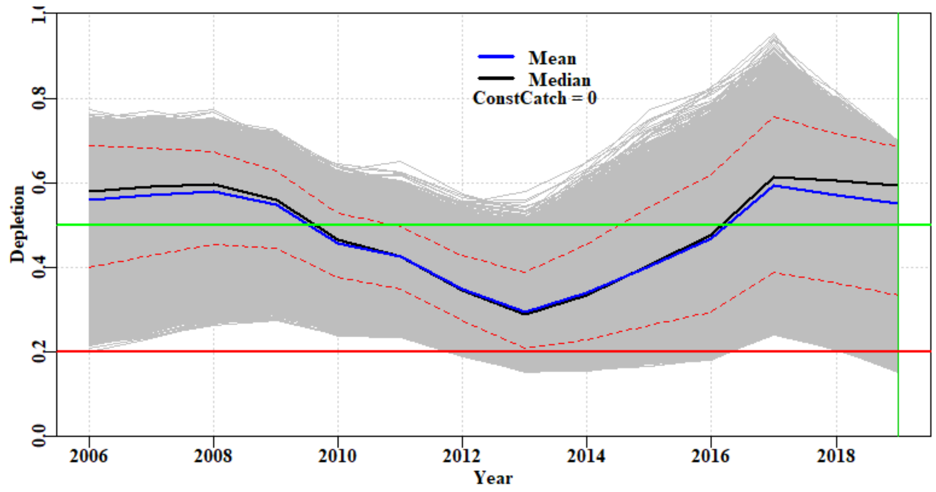

Figure 44. Trajectories of depletion (B_{year}/B_0) estimated for Giant Mud Crab exploitable biomass from the Roper region. The blue line represents the mean, the black line the median. The red dashed lines represent the 90th percentile confidence intervals. The green line represents the 50% depletion level.

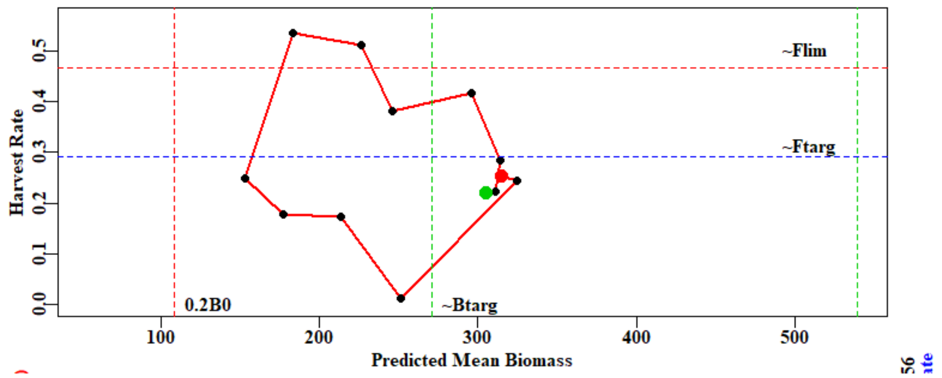

Figure 45. Phase plot of the estimated mean biomass and harvest rate for Giant Mud Crabs from the Roper region. The green point is biomass and harvest in 2006. The red point is biomass and harvest in 2018.

After fitting the model, four harvest levels were explored (Figure 46) to determine potential trajectories of the exploitable biomass of Giant Mud Crabs to 2029 in the Roper region. The constant harvest scenarios of 78 and 70 tonnes resulted in more than 10% of the depletion trajectories going below the 0.20 limit reference point of Sainsbury (2008). The constant harvest scenarios of 50 and 60 tonnes resulted in the lowest probability of depletion trajectories going below the 0.20 limit reference point (i.e. 5% and 8% of depletion trajectories were below the 0.20 biomass ratio by 2029 respectively). The broad confidence intervals are likely related to high uncertainty in the parameter values of *r* and *K*.

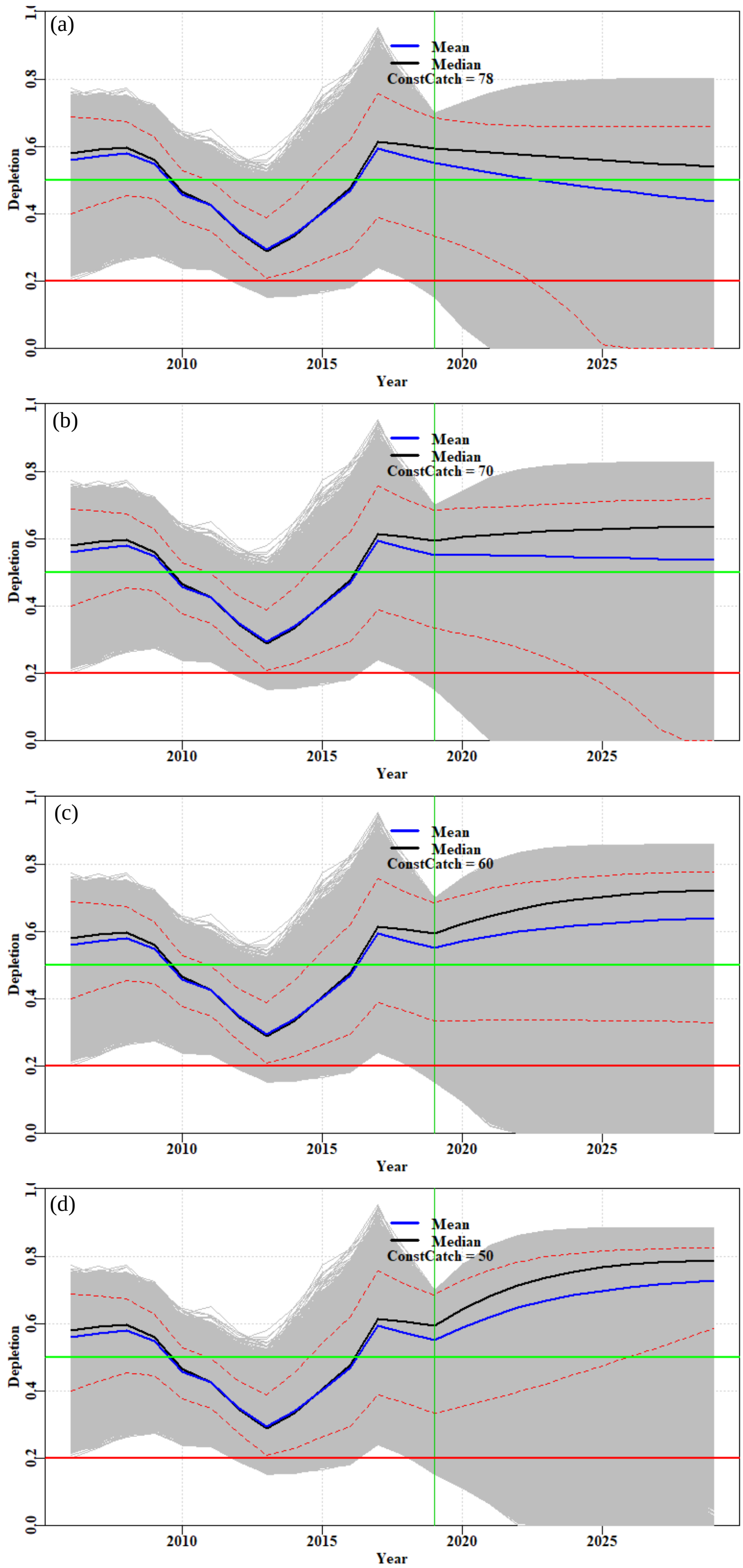

Figure 46. Trajectories of predicted biomass ratios for Giant Mud Crabs from the Roper region for constant future annual catches of: (a) 78 tonnes, (b) 70 tonnes, (c) 60 tonnes and (d) 50 tonnes.

Northern Territory - McArthur region

The modified catch-MSY produced mean values of *r* (resilience) and *K* (carrying capacity) of 0.56 and 876.6 tonnes respectively for the McArthur region, which are indicative of a moderately resilient stock (Table 27, Figure 47). The estimated *r* value was similar to that estimated for the Roper region. The estimated biomass trajectories indicated that at the start of 2019, the mean biomass ratio was 0.54 (compared with unfished), with the median estimated at 0.59 (Table 27, Figure 48, and Figure 49).

Table 27. Estimated catch-MSY model parameters for the McArthur region.

	Lower 97.5% CI	Mean	Upper 97.5% CI	Percentiles				
				2.5th	5th	50th	95th	97.5th
r	0.38	0.56	0.84	0.36	0.38	0.58	0.75	0.77
K	677.7	876.3	1133.1	673.4	692.9	894.9	1044.5	1052.5
MSY (tonnes)	91.3	123.1	165.8	90.2	94.2	124.5	155.3	160.6
Biomass ratio B_{2019}/B_{0*}	0.25	0.54	0.83	0.19	0.23	0.59	0.69	0.7

Where *r* is the intrinsic rate of growth, *K* is the carrying capacity of the stock, MSY is the maximum sustainable yield and B_{0*} is unfished biomass.

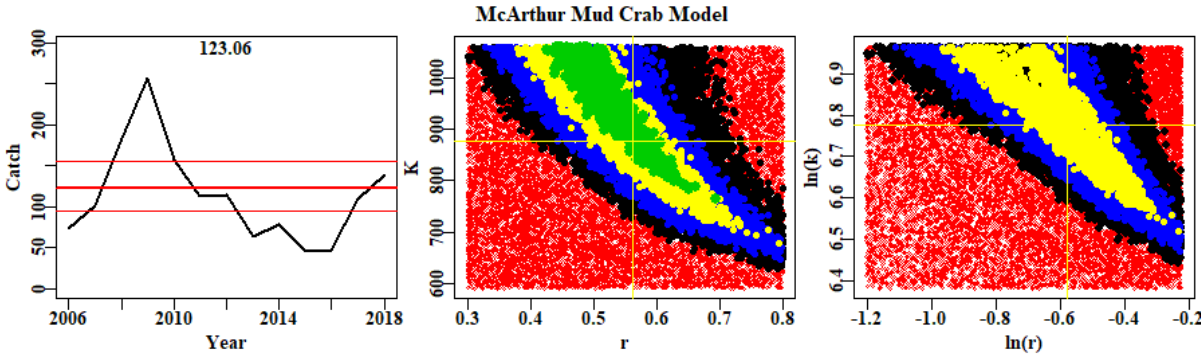

Figure 47. Summary outputs of the catch-MSY for Giant Mud Crabs from the McArthur region. The left plot shows reported catch (tonnes) from 2006 to 2018. The estimated mean and 90th percentiles are shown as parallel red lines. The middle and right plots show r-K combinations (left plot standard, right plot log transformed), where red dots are non-successful r-K combinations, and dots coloured black to green denote successful r-K combinations. The yellow lines indicate the mean values for r and K.

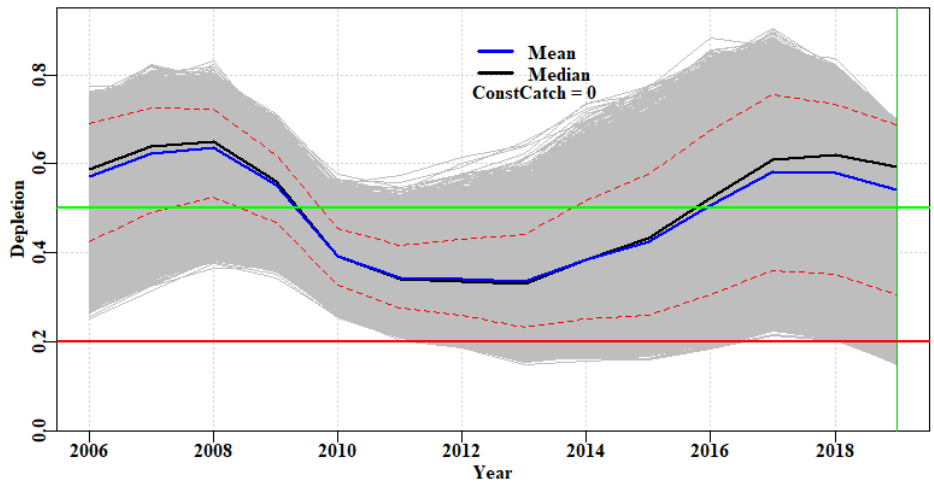

Figure 48. Trajectories of depletion (B_{year}/B_0) estimated for Giant Mud Crab exploitable biomass from the McArthur region. The blue line represents the mean, the black line median. The red dashed lines represent the 90th percentile bounds. The green line represents the 50% depletion level.

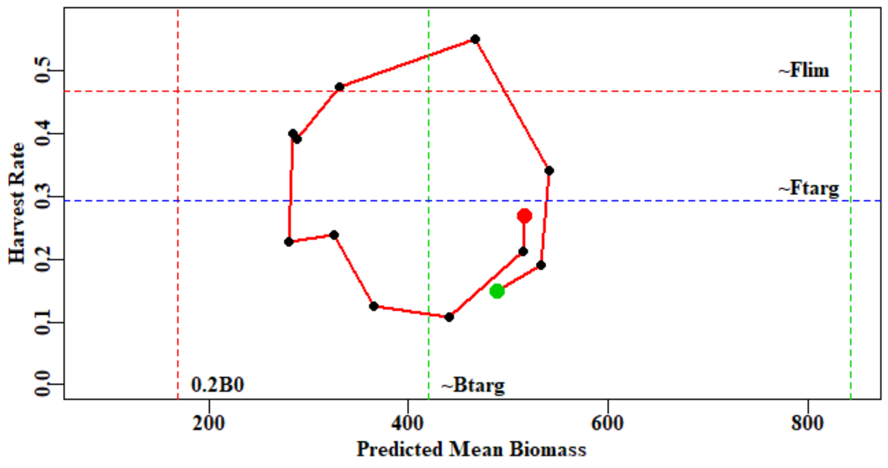

Figure 49. Phase plot of the estimated mean biomass and harvest rate for Giant Mud Crabs from the McArthur region. The green point is 2006 .The red point is 2018.

After fitting the model, four constant annual harvest levels (123, 110, 100 and 90 tonnes) were explored to determine potential trajectories of the biomass to 2029. All but one of the future catch limit scenarios showed more than 10% of trajectories going below the limit reference point (i.e. 0.2 B/B_0, Sainsbury 2008) sometime in the future (Figure 50). The 90 tonne scenario showed the least probability of trajectories going below the limit reference point (i.e. 7% of projections were below the 0.20 biomass ratio).

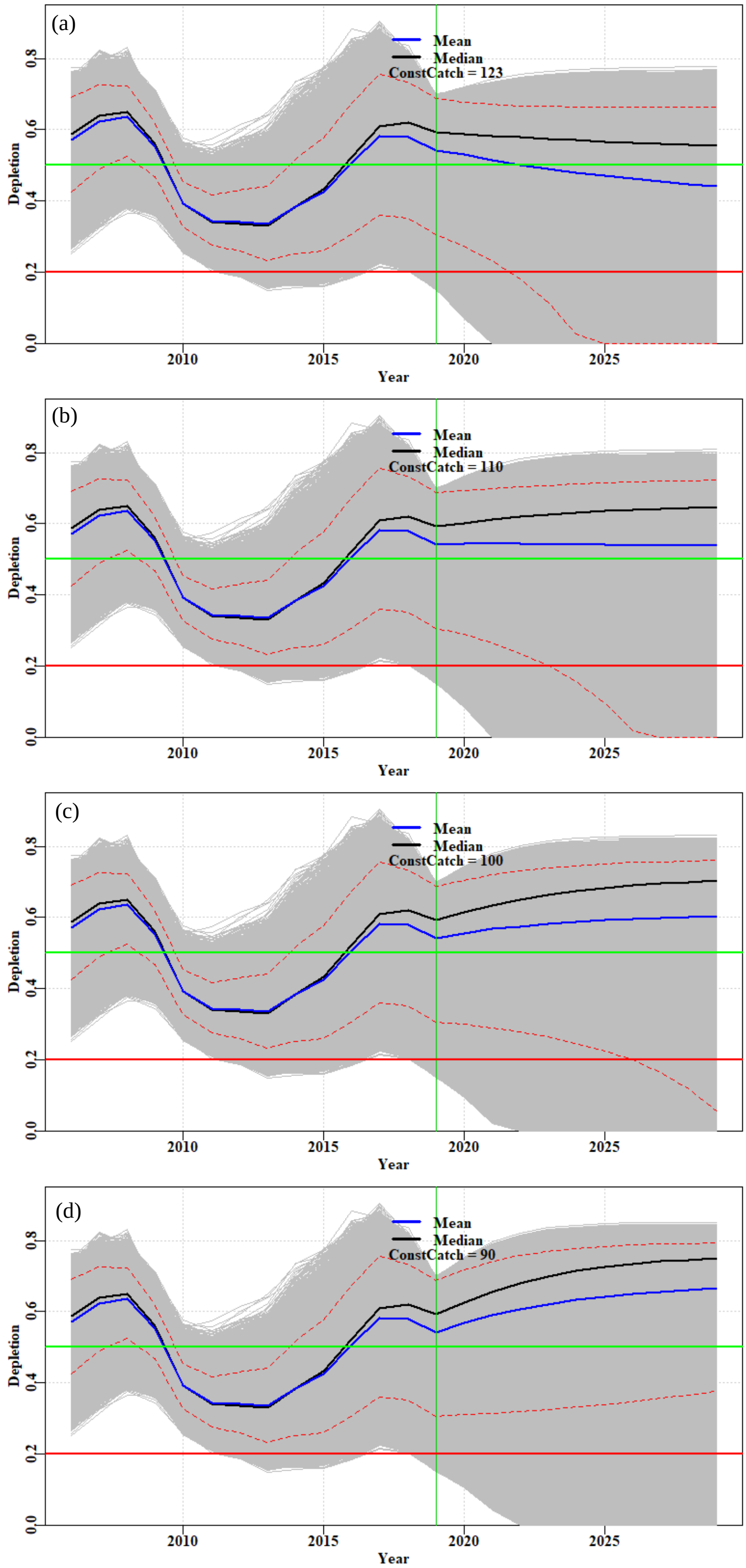

Figure 50. Trajectories of predicted biomass ratios of Giant Mud Crabs from the McArthur region, for constant future annual catches of: (a) 123 tonnes, (b) 110 tonnes, (c) 100 tonnes and (d) 90 tonnes.

Queensland - South East and South West regions combined (South Gulf)

The South East and South West regions were combined into a 'South Gulf' region, and the modified catch-MSY applied to the commercial and recreational harvest data for this region. On average, about 50% of Qld GoC Giant Mud Crabs are reported harvested from the South Gulf region (see Chapter 2). The mean values of *r* (resilience) and *K* (carrying capacity) were 0.50 and 511.2 tonnes respectively (Table 28, Figure 51), which are indicative of a moderately resilient stock. The estimated exploitable biomass trajectories for this region indicated that at the start of 2018/19, the mean biomass ratio was 0.32, with the median estimated at 0.34 (Table 28, Figure 52, Figure 53).

Table 28. Estimated catch-MSY model parameters for the South Gulf region.

	Lower 97.5 % CI	Mean	Upper 97.5 % CI	Percentiles				
				2.5^{th}	5^{th}	50^{th}	95^{th}	97.5^{th}
r	0.33	0.5	0.77	0.35	0.36	0.49	0.74	0.77
K	373.6	511.2	699.6	370.3	381.8	524.1	634.1	639.6
MSY (tonnes)	55.3	64.4	74.9	54.3	55.6	65.3	71.5	72.2
Biomass ratio $^{**}B_{2018}/B_{0*}$	0.08	0.32	0.57	0.08	0.10	0.34	0.49	0.49

Where *r* is the intrinsic rate of growth, *K* is the carrying capacity of the stock, MSY is the maximum sustainable yield and B_{0*} is unfished biomass. $^{**}B_{2018}$ represents the 2018/19 financial year.

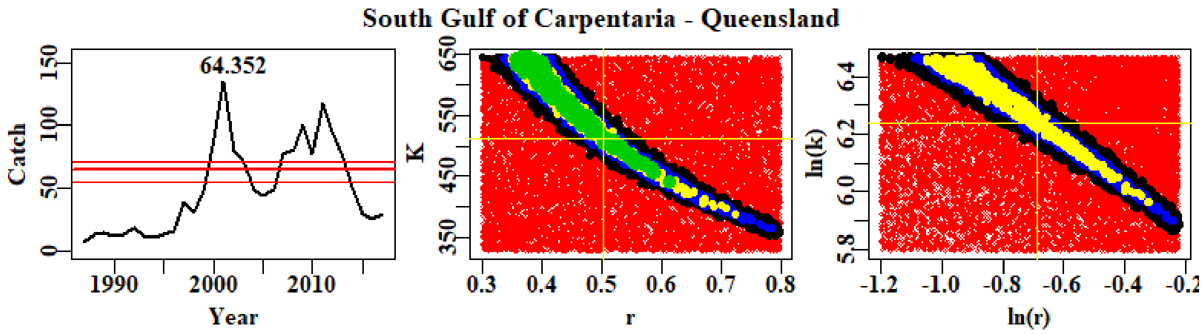

Figure 51. Summary outputs of the catch-MSY for Giant Mud Crabs from the South Gulf region. The left plot shows reported catch (tonnes) from 1988/89 to 2018/19. The estimated mean and 90th percentiles are shown as parallel red lines. The middle and right plots show r-K combinations (left plot standard, right plot log transformed), where red dots are non-successful r-K combinations, and dots coloured black to green denote successful r-K combinations. The yellow lines indicate the mean values for r and K.

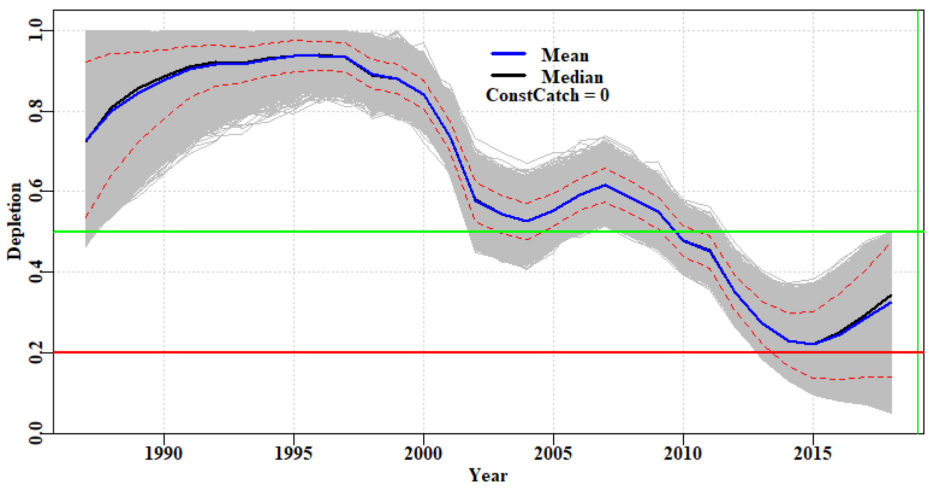

Figure 52. Trajectories of depletion (B_{year}/B_0) estimated for Giant Mud Crab exploitable biomass from the South Gulf region. The blue line represents the mean, the black line the median. The red dashed lines represent the 90th percentile bounds. The green line represents the 50% depletion level.

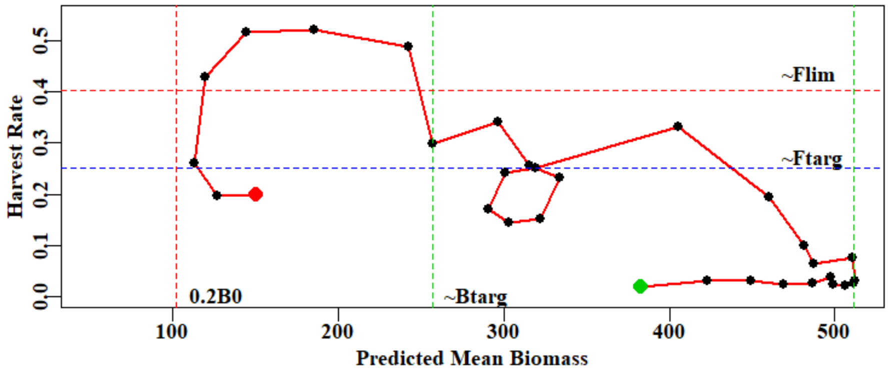

Figure 53. Phase plot of the estimated mean biomass and harvest rate for Giant Mud Crabs from the South Gulf region. The green point is 1989/90. The red point is 2018/19.

After fitting the model, four harvest levels (64, 55, 45 and 35 tonnes) were simulated to determine potential trajectories of the exploitable biomass of Giant Mud Crabs to 2028/29 in the South Gulf region (Figure 54). All scenarios had more than 10% of trajectories below the 0.20 limit reference point by 2028/29.

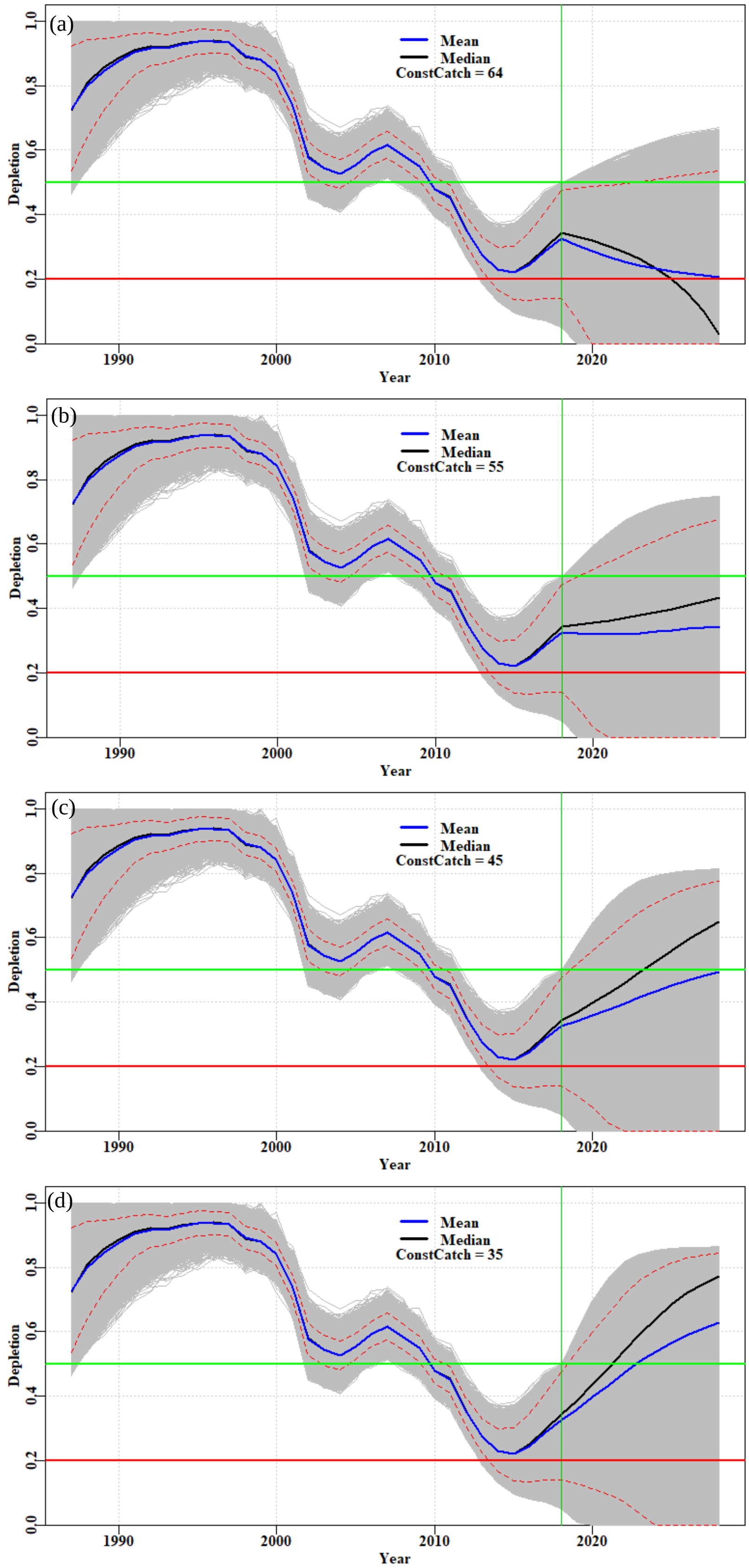

Figure 54. Trajectories of predicted biomass ratios of Giant Mud Crabs from the South Gulf region for constant future annual catches of: (a) 64 tonnes, (b) 55 tonnes, (c) 45 tonnes and (d) 35 tonnes.

Queensland - Pormpuraaw, Staaten and Gilbert regions combined

On average, about 40% of Qld GoC Giant Mud Crabs are reported harvested from the Pormpuraaw-Staaten-Gilbert region (see Chapter 2). The modified catch-MSY produced mean values of *r* (resilience) and *K* (carrying capacity) were 0.96 and 212 tonnes respectively (Table 29, Figure 55) for the Pormpuraaw-Staaten-Gilbert region, indicative of very high resilience, and is atypical compared to results for other regions. The estimated biomass trajectories for this region indicated that at the start of 2018/19, the mean biomass ratio was 0.60, with the median estimated at 0.65 (Table 29, Figure 55, Figure 56, Figure 57).

Table 29. Estimated catch-MSY model parameters for the Pormpuraaw-Staaten-Gilbert region.

	Lower 97.5 % CI	Mean	Upper 97.5% CI	Percentiles				
				2.5^{th}	5^{th}	50^{th}	95^{th}	97.5^{th}
r	0.67	0.96	1.38	0.68	0.71	0.96	1.31	1.36
K	185.2	212.0	316.0	188.9	193.1	244.4	295.6	298.1
MSY (tonnes)	48.6	58.1	69.4	48.7	49.7	58.6	66.4	67.4
Biomass ratio $^{**}B_{2018}/B_{0*}$	0.39	0.60	0.82	0.29	0.35	0.65	0.70	0.70

Where *r* is the intrinsic rate of growth, *K* is the carrying capacity of the stock, MSY is the maximum sustainable yield and B_{0*} is unfished biomass. $^{**}B_{2018}$ represents the 2018/19 financial year.

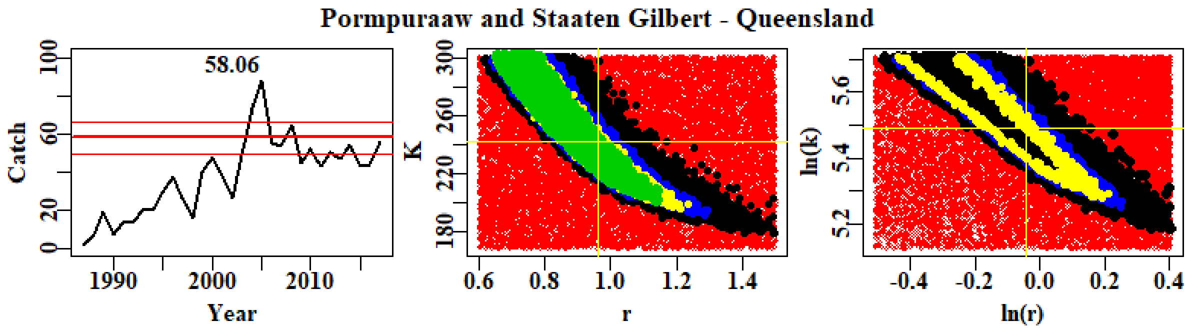

Figure 55. Summary outputs of the catch-MSY for Giant Mud Crabs from the Pormpuraaw-Staaten-Gilbert region. The left plot shows reported catch (tonnes) from 1988/89 to 2018/19. The estimated mean and 90th percentiles are shown as parallel red lines. The middle and right plots show r-K combinations (left plot standard, right plot log transformed), where red dots are non-successful r-K combinations, and dots coloured black to green denote successful r-K combinations. The yellow lines indicate the mean values for r and K.

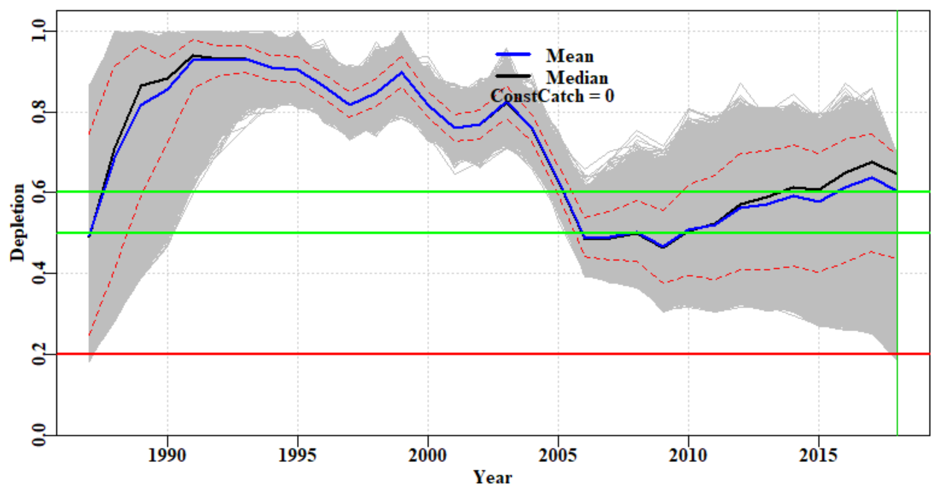

Figure 56. Trajectories of depletion (B_{year}/B_0) estimated for Giant Mud Crab exploitable biomass from the Pormpuraaw-Staaten-Gilbert region. The blue line represents the mean, the black line the median. The red

dashed lines represent the 90th percentile bounds. The green lines represent the 50% and 60% depletion levels.

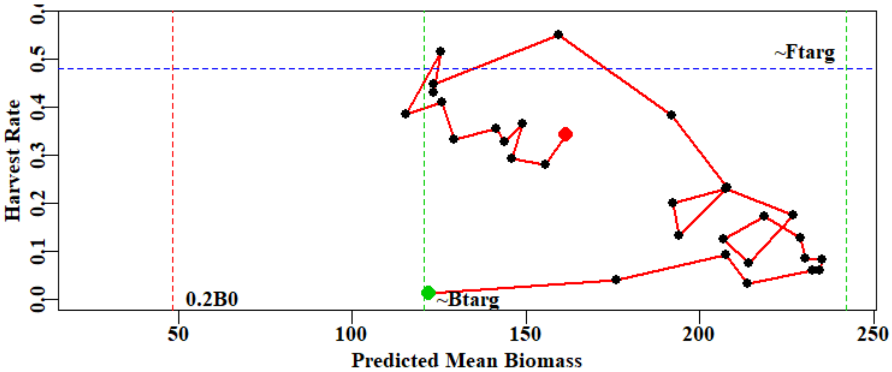

Figure 57. Phase plot of the estimated mean biomass and harvest rate for Giant Mud Crabs from the Pormpuraaw-Staaten-Gilbert region. The green point is 1988/89. The red point is 2018/19.

After fitting the model, four harvest levels (58, 50, 40 and 30) were explored to determine potential trajectories of the exploitable biomass of Giant Mud Crabs to 2028/29 in the Pormpuraaw-Staaten-Gilbert region (Figure 58). The 58 tonne constant harvest scenario resulted in more than 10% of the depletion trajectories going below the 0.20 limit reference point (Sainsbury, 2008). The 50, 40 and 30 tonne scenarios resulted in the lowest probability of trajectories going below the 0.20 limit reference point (i.e. 7%, 2% and 0% of trajectories were below 20% in 2028/29 respectively).

(a)

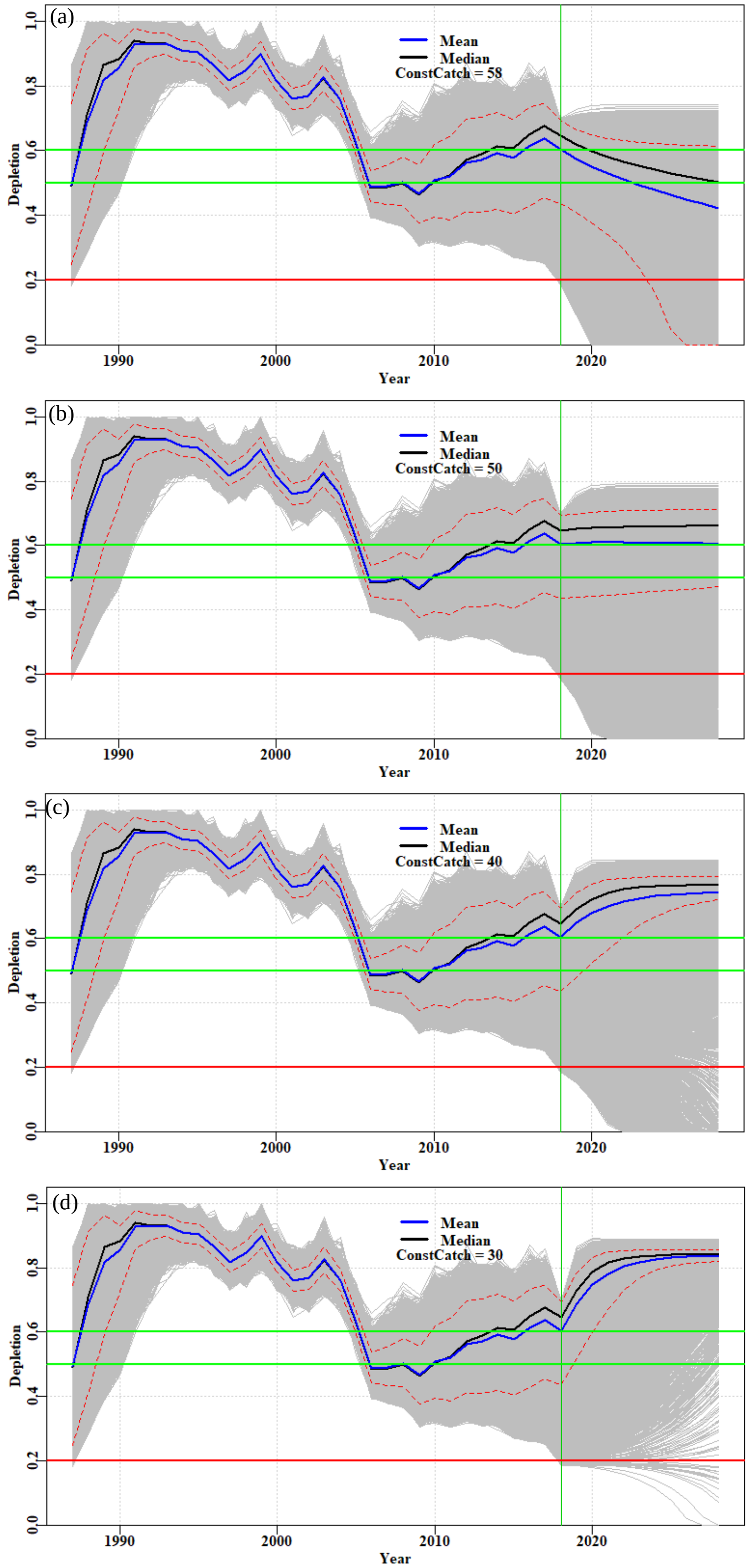

Figure 58. Trajectories of predicted biomass ratios of Giant Mud Crabs from the Pormpuraaw-Staaten-Gilbert region for constant future annual catches of: (a) 30 tonnes, (b) 40 tonnes, (c) 50 tonnes and (d) 58 tonnes.

Queensland stocks – Aurukun, Weipa, Mapoon regions combined

On average, about 10% of Qld GoC Giant Mud Crabs are reported harvested from the Aurukun-Weipa-Mapoon region (see Chapter 2).The modified catch-MSY produced mean values of *r* (resilience) and *K* (carrying capacity) of 0.21 and 452.0 tonnes respectively (Table 30, Figure 59) for the Aurukun-Weipa-Mapoon region, and were considerably lower than estimated mean values for the NT regions. The estimated biomass trajectories for this region indicated that at the start of 2019, the mean biomass ratio was 0.33, with the median estimated at 0.34 (Table 30, Figure 60, Figure 61).

Table 30. Estimated catch-MSY model parameters for the Aurukun-Weipa-Mapoon region.

	Lower 97.5% CI	Mean	Upper 97.5% CI	Percentiles				
				2.5^{th}	5^{th}	50^{th}	95^{th}	97.5^{th}
r	0.12	0.21	0.4	0.12	0.12	0.21	0.36	0.37
K	330.4	452.0	618.2	330.6	339.0	462.8	561.4	566.6
MSY (tonnes)	16.7	24.2	35.0	15.8	16.7	25.2	31.0	31.7
Biomass ratio $^{**}B_{2018}/B_{0*}$	0.1	0.33	0.56	0.1	0.12	0.34	0.49	0.49

Where *r* is the intrinsic rate of growth, *K* is the carrying capacity of the stock, MSY is the maximum sustainable yield and B_{0*} is unfished biomass. $^{**}B_{2018}$ represents the 2018/19 financial year.

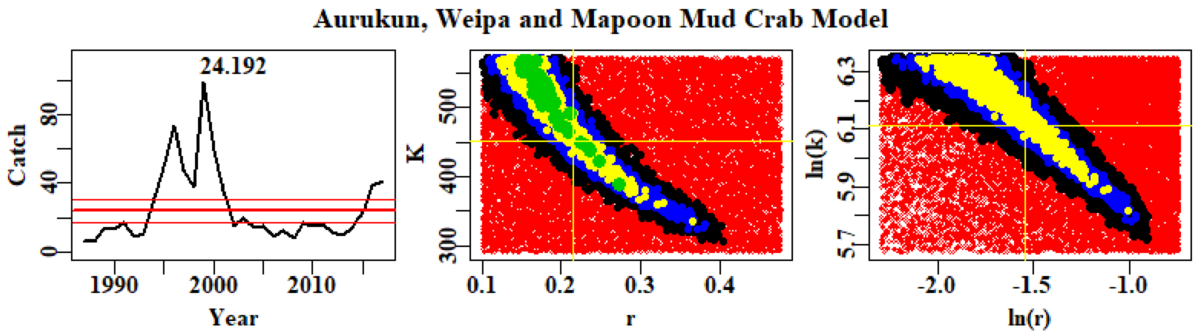

Figure 59. Summary outputs of the catch-MSY for Giant Mud Crabs from the Aurukun-Weipa-Mapoon region. The left plot shows reported catch from 1988/89 to 2018/19. The estimated mean and 90th percentiles are shown as parallel red lines. The middle and right plots show r-K combinations (left plot standard, right plot log transformed), where red dots are non-successful r-K combinations, and dots coloured black to green denote successful r-K combinations. The yellow lines indicate the mean values for r and K.

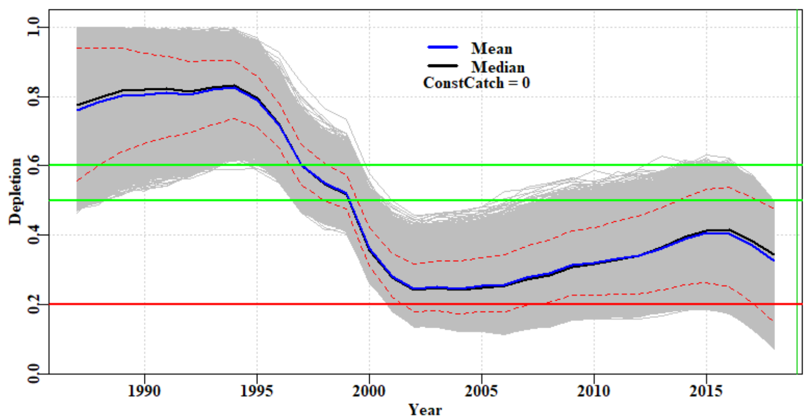

Figure 60. Trajectories of depletion (B_{year}/B_0) estimated for Giant Mud Crab exploitable biomass from the Aurukun-Weipa-Mapoon region. The blue line represents the mean, the black line the median. The red dashed lines represent the 90th percentile bounds. The green lines represent 50% and 60% depletion levels.

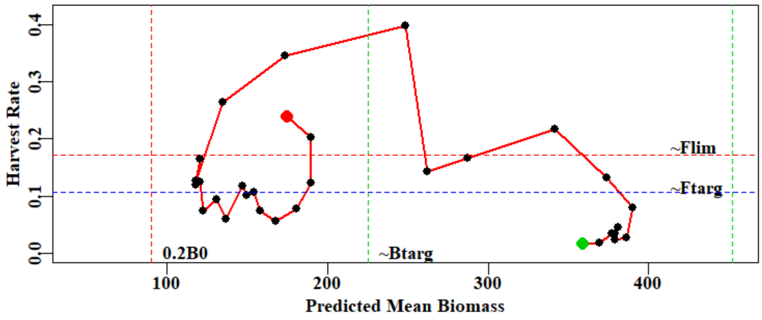

Figure 61. Phase plot of the estimated mean biomass and harvest rate for Giant Mud Crabs from the Aurukun-Weipa-Mapoon region. The green point is 1988/89. The red point is 2018/19.

After fitting the model, four harvest levels (24, 20, 15 and 10 tonnes) were explored to determine potential trajectories of the biomass to 2028/29 (Figure 62). The 24, 20 and 15 tonne constant harvest scenarios resulted in more than 10% of the depletion trajectories going below the 0.20 limit reference point (Sainsbury 2008). The 10 tonne scenario resulted in the lowest probability of trajectories going below the 0.20 limit reference point (i.e. 10% of trajectories were below 0.20 in the 2028/29 financial year).

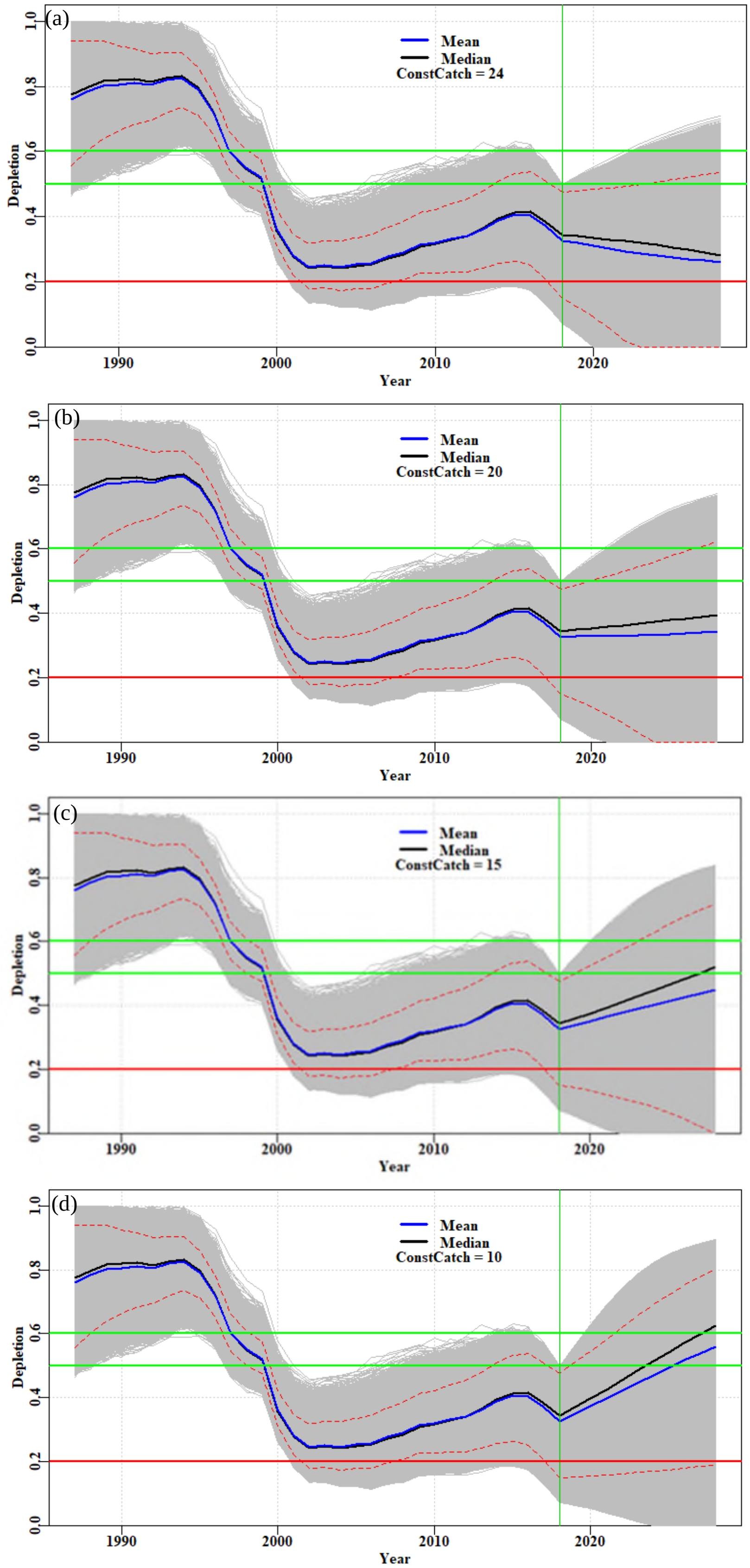

Figure 62. Trajectories of predicted biomass ratios of Giant Mud Crabs from the Aurukun-Weipa-Mapoon region for constant future annual catches of: (a) 24 tonnes, (b) 20 tonnes, (c) 15 tonnes and (d) 10 tonnes.

Discussion

The main purpose of modelling fisheries populations is to estimate stock status and evaluate the response of populations to fishing. Additionally, model outputs may be used to advise on appropriate management and to provide clear recommendations on catch or effort levels. The two jurisdictions that manage populations of Giant Mud Crabs in the GoC have different management aims.

The primary concern of the Harvest Strategy for the NT Western GoC Mud Crab Fishery is to determine when populations are low, based on catch rates as proxies of biomass, and avoid the possibility of overfishing. This is pertinent given that harvesting females is legal and the estimated exploitation rate is high (>90%). The primary aim of the Harvest Strategy for the Qld GoC Mud Crab Fishery is to have an exploitable biomass ratio, compared with the theoretical unfished population, of 60% as a proxy for Maximum Economic Yield by 2027. These very different management objectives are supported by the different means of assessment that each jurisdiction has chosen (i.e. a delay-difference model for the NT compared with (initially at least) a catch-MSY model for Qld).

There are challenges in applying each of these modelling approaches. In both the NT and Qld fisheries, the harvest comprises mostly of crabs above the age and size at first maturity as recruitment to the fishery occurs at the minimum legal size, which equates to about 18 months of age (Knuckey 1999). The populations of Giant Mud Crabs are heavily fished, especially in the NT western GoC. Natural mortality rates are high, even in unfished populations, as few crabs survive beyond three years of age (Knuckey 1999). Therefore, there is little increase in the fished population's biomass via somatic growth. Consequently, fluctuations in population biomass from year to year, and accordingly the fishery harvests, will largely be due to recruitment. This suggests that MSY might represent something like the mean recruitment. Most catches in the fishery are likely to be comprised of new recruits (i.e. 1+ year old crabs of mostly a single year-class). The fluctuations in fishery harvests from year to year thus mostly reflect recruitment variation, with the effects of various environmental factors apparent.

The delay-difference model is currently deterministic, explicitly includes fishing effort, and tests various scenarios (e.g. catchability) to determine possible outcomes. This is sufficient for the NT Harvest Strategy catch rate and female spawning stock biomass reference points. For the NT fishery, changes in management (e.g. changes in MLS, the introduction of a requirement to release commercially unsuitable crabs) are difficult to incorporate. Catchability (q) is a poorly quantified parameter, and the model outputs are sensitive to different levels of assumed q. The resulting biomass estimates for the NT Western GOC Mud Crab Fishery differ by an order of magnitude (i.e. about a thousand tonnes, Grubert *et al. 2019*). Such an approach would not assist the Qld policy framework of setting total allowable catches and managing by individual transferable quotas, which need a smaller range of biomass estimates.

The delay-difference model was applied to the Qld GoC fishery, assuming 1:1 ratio of males to females to generate an index of females necessary for the spawning stock recruitment relationship explicit in this model. Without information on the relative abundance of the mature female crabs in the Qld GoC, its representativeness is uncertain. As a consequence of an all-male harvest, fishing intensity and spatial separation of crabs in estuaries (Hill *et al*. 1982), observed sex ratios in Qld show large variation between estuaries (Jebreen *et al*. 2008; Alberts-Hubatsch 2016; Flint *et al*. 2017), although Knuckey (1999) reported an overall sex ratio close to 1:1 for the NT GoC.

A challenge in applying the catch-MSY model to the harvests of Giant Mud Crabs in the Qld GoC, was that the catch time series is only for the harvest of male crabs, which is assumed to be indicative of the abundance of female crabs. The model then represents the response of the population to fishing from year to year under various combinations of population resilience (r) as well as regional carrying capacity (K). In the real world, recruitment of Giant Mud Crab each year depends upon the abundance of the (mostly unfished) female crabs. Thus it should be questioned, as to how catches from one year to the next might be related when fishing mortality predominately applies only to males. We propose, that in the absence of evidence for sex-specific mortality[3] for Giant Mud Crabs below the minimum legal size, that the abundance of male and female crabs should be strongly related just prior to the size of recruitment of males to the Qld GoC fishery. Thus, as catch is assumed to be related to male abundance, it is also assumed to be related to female abundance. This relationship is strongest at the size crabs recruit to the fishery (before fishing mortality removes crabs). And moreover, should be strongest when most of the exploitable biomass population is harvested (i.e. high fishing pressure), as is the case for the NT Western GoC Mud Crab Fishery; noting that no effort metric is considered in catch-MSY.

Despite different management aims, a common need of harvest strategies for Giant Mud Crab fisheries in northern Australia is that they are routinely reviewed, such that reference points remain responsive and adaptable, as future climate sequences are unpredictable. It is widely thought that 'extreme' events will be more commonplace than historically observed. The current Harvest Strategy for the NT Western GoC (implemented in 2017) is considered flexible and will be reviewed within the next two years to ensure this continues to be the case.

The Harvest Strategy for the Qld Crab Fishery is still preliminary, with a higher priority to quantify and validate the harvest and associated effort. Lack of confidence in the catch and effort data (confirmed in the current study) and no information on components other than the exploitable biomass has resulted in conservative reference points (Northrop *et al.* 2019, as recommended by Wang *et al.* 2010). Nevertheless, the tools and outputs produced by the current project will be available to inform development of TACs. Queensland plans to revise the Harvest Strategy for the Crab Fishery in 2025, and should be better placed to include adaptive reference point concepts for Giant Mud Crabs, notwithstanding the State's management aim of a 60% exploitable biomass target (compared with unfished) by 2027, in the absence of estimates of maximum economic yield.

Reference points could consider more than catch rate targets (such as those considered in the NT) or quantitatively estimated biomass targets (such as in Qld), if pre-recruit monitoring were common practice, as recommended by Webley (2005). Survey information including (relative) female and recruit abundances at appropriate temporal and regional scales would provide valuable information if the intention was to adequately monitor the stock. This would be required, in particular, to produce a defensible biomass estimate. Given the observations above, that the fishery in any year is largely comprised of new 1+ year-old crabs, recruitment monitoring could be a powerful management tool. As a minimum, data required for a stock assessment should have information that can be assembled to represent an index of population abundance, and a catch-history. Brown (2010) recommended improved monitoring systems to track changes in mud crab abundance. A survey that can yield catch rate information and data on pre-recruits, length-frequency and sex ratio would provide key pieces of information for a robust stock assessment.

Whilst not quantitatively modelled for a number of reasons, the consistency of the decline across two jurisdictions in which females are harvested in one (i.e. NT) but prohibited from harvest in the other (i.e. Qld) and commonality in environmental conditions over the broad spatial scale of the GoC suggests that between 2009 and 2018 environmental factors may have been relatively more important than fishing pressure. Fundamental to fisheries management is the concept that there is 'sufficient' spawning stock to provide recruits that subsequently become the fishable biomass. The high fecundity of female mud crabs, high estimated natural mortality, and relatively short life span suggests that Giant Mud Crabs are a moderately resilient species (a characteristic explored in the catch-MSY analyses), that could probably be fished to a relatively low spawning biomass yet still recover rapidly. Recover would be dependent on environmental conditions being favourable.

The NT Harvest Strategy sets a secondary reference point of retaining at least 70 tonnes of female spawning stock biomass (FSSB) at the end of the fishing season for the Western NT GoC Mud Crab Fishery. Management intervention (i.e. closure) is increasingly severe as levels of FSSB decrease below 70 tonnes, although if the primary reference point of April/May CPUE is less than 0.2 kg per pot day, then the fishery is

[2] Excluding sex-specific mortality that may be associated with the migration of ovigerous females to offshore areas

automatically closed. Whilst not conclusive, the preliminary hydrodynamic and particle modelling of ovigerous females and larvae (see Chapter 6), suggests that stocks may be heavily reliant on larvae produced by the remaining females in a region, particularly so in the Western GoC. This indicates that while the species is resilient, some caution about spawning stock levels is needed as larval replenishment from other regions is unlikely, although further work is needed to confirm this.

Conclusion

In the current chapter, we applied two relatively simple stock assessment models to regional fisheries of Giant Mud Crabs in the GoC. Current (and past) assessments of Giant Mud Crabs are based predominately on trends in catch or catch rate. However, commercial CPUE may not represent changes in population abundance due to variable catchability, hyper-stability and serial depletion. The consistency of decline in the harvest of Giant Mud Crabs across two jurisdictions in which females are harvested in one (i.e. NT) but prohibited from harvest in the other (i.e. Qld) and commonality in environmental conditions over the broad spatial scale of the GoC, suggests that between 2009 and 2018 environmental factors may have been relatively more important than fishing pressure.

Giant Mud Crabs are assumed to be a moderately resilient fishery species, based on high fecundity of female mud crabs, high estimated natural mortality, and relatively short life span, that can be fished to a relatively low spawning biomass yet still recover rapidly. This presumes suitable environmental conditions exist. Recent climate-driven events in the GoC are likely to occur more frequently under most climate change projections. Temporal monitoring of the non-exploited parts of Giant Mud Crab populations (i.e. pre-recruit index or even simply female abundance in the Qld GoC) would improve our ability to separate fishing mortality from environment-related recruitment variation. If collected annually, a pre-recruit index could identify poor catch seasons with 6 to 12 months' notice; allowing management and fishers to adjust their harvest arrangements.

Chapter 6. Incorporating environmental factors into the NT delay-difference model to inform the harvest strategy

R.C. Buckworth

Summary

In this Chapter, I focus on the effects of environmental drivers on the NT Western GOC Mud Crab Fishery, specifically for the Roper and McArthur regions (as defined in Chapter 2). The analyses of the previous chapters identified environmental factors which have the greatest impact on catch rates of mud crabs. I first provide some visualisation and simple analysis of catch per unit effort versus mean sea level anomalies (MSL) and the cumulative heat index (Heat) (see Chapter 4). These variables are negatively correlated with CPUE. The analysis might be applied to inform management, pre-season, of the expected abundance in the fishery.

I use a delay-difference model (Grubert *et al*. 2019) to evaluate the impact of bias in estimates of female spawning stock biomass. Such bias could arise from environmentally driven changes in catchability and recruitment. The bias could have an important impact on the relative fishing mortality ratio, but the relative spawning biomass (spawning biomass/spawning biomass at MSY) was relatively resilient to the bias. The harvest strategy for the NT mud crab fisheries should be updated so that relative spawning biomass is used as a performance measure rather than estimated spawning biomass. I use the relative fishing mortality rate versus relative spawning biomass plotted by year (Kobe plots), to illustrate the performance of the NT Western GOC Mud Crab Fishery over time, in terms of those key performance measures.

Correlations between model-estimated recruitment anomalies and environmental factors were also evaluated. Parameter values to inform the delay-difference model stock-recruitment relationships, that explicitly include environmental drivers, were derived using regression analysis. This will support future exploration of the fisheries dynamics and the impact of environmental drivers on fishery harvest strategy policy.

Policy implications of the analyses are discussed, and I make suggestions as to how monitoring information, analysis and management might be improved in the NT Western Gulf of Carpentaria Mud Crab Fishery.

Introduction

Giant Mud Crab (*Scylla serrata*) catches in the Northern Territory (NT) have varied significantly over the last two decades. However, the magnitude of this variation has differed between areas. For example, annual catches in the GoC region have ranged almost 20-fold (i.e. 51 to 984 tonne), in response to a four-fold variation in effort, whereas those along the remainder of the NT coast have shown around two-fold variation (i.e. 61 to 157 tonne), in response to a similar variation in effort. This variation is unlikely to all be a population response to fishing, and environmental drivers are known to be important in mud crab fisheries (e.g. Meynecke *et al*. 2012). Effects of environmental factors appear to vary in magnitude from region to region.

Such variations were recognised during the development of the harvest strategy for the NT Mud Crab Fishery (DPI&R 2017) and led to the implementation of two discrete management units: the Arafura-West Mud Crab Fishery (AWMCF) and the Western Gulf of Carpentaria Mud Crab Fishery (WGOCMCF), with the point of separation being Cape Grey (13°00’S, 136°39’E).

Environmental factors act on catches and catch rates of mud crabs via many complex mechanisms that affect mud crab ecology, such as the distribution, size and number of crabs in the population, from recruitment of small crabs into the fishery, to the survival and growth of adult crabs as well as their reproduction. Environmental factors might also act on the ways in which crabs and fishers interact - catchability - via, for example, impacts on behaviour of both crabs and fishers.

The previous chapters of this report investigated the potential relationships between environmental factors and catch rates of mud crabs. For the NT mud crab fisheries of the Western Gulf of Carpentaria (GOC), I further investigate the effects on the fishery and population processes of important environmental factors indicated in Chapter 4: mean sea level, cumulative air temperature and river flow.

I first provide some visualisation and simple analysis of catch per unit effort versus mean sea level anomalies and the cumulative heat index (see Chapter 4) and suggest a means for application of the analysis in a management context.

Grubert *et al*. (2019) used structurally simple delay-difference modelling to visualise key performance measures for the mud crab fishery relative to harvest strategy policy, evaluating, in particular, the effect of various assumptions about catchability (q). I extend the application of this model to investigate whether variations in the spawning stock remaining after fishing in each year S_t, might be environmentally affected, and thus be influential on outputs that inform the management of the fishery.

Building on these analyses, I investigated the effects of environment on recruitment, defined here as the biomass of crabs entering the fishable (or “exploitable”) biomass of the population. Correlations between recruitment anomalies and environmental drivers, using the Grubert *et al*. (2019) delay-difference model framework were explored. Linear regressions were used to parameterise environmental factors within the stock-recruitment relationship. Given the strong relationships between catch rates and environmental factors demonstrated in Chapter 4, this has the potential to improve the utility of the model in evaluation of the fisheries’ performance and in further exploring the fisheries’ dynamics.

I discuss the policy implications of the results in the current chapter and provide advice on how the Harvest Strategy for the NT Western Gulf of Carpentaria Mud Crab Fishery might be adapted. I also make recommendations on further monitoring and analyses, as well as management actions.

Methods

Environmental factors

Environmental factors for the analyses in the current chapter, were chosen based on the GLM results for the Roper and McArthur regions given in Chapter 4. Environmental factors identified as having strong significant effects on mud crab catch rates in both the Roper and McArthur regions were “Cumulative heat”, the cumulative maximum daily interpolated coastal air temperature between November and March (abbreviated hereafter to “Heat”) lagged by one year, and the average of the mean sea level anomaly lagged by two years (“MSL”) for October to March. Annual river flow was also identified as important for the Roper region. Cumulative rain and cumulative evaporation were identified as important in the McArthur region but given inter-correlations between these factors and river flow (see Table 7, Chapter 4), the application of the three chosen factors (Heat, MSL, and Flow) provides consistency between the analyses of the Roper and McArthur regions, and supports analyses for the Combined region (i.e., Roper and McArthur combined), which equates to the majority of the harvest from the NT Western GoC Mud Crab Fishery.

The data series applied were those used in Chapter 4, noting the data series were extended back to 1983, where available. For the Combined region, the mean of the annual values for environmental factors was used, noting that the MSL is the same, as it is based on data from Milner Bay.

Delay Difference Model

The Deriso (1980)-Schnute (1985) delay-difference model structure was applied as detailed in Grubert *et al*. (2019), with readers referred to that article for model description. Below, details of the model are included only when necessary for clarity, or where modified. We updated the model with catch and effort data for the period 1983 – 2019, derived from the NT DPI&R logbook data system. Separate models were constructed for the Roper and McArthur regions as well as a ‘Combined’ region model, in which the data simply the sum of the catch and effort data for the Roper and McArthur regions[4] in each year. Apart from the catch and effort data series, input parameters for the models were identical, and are detailed in Grubert *et al*. (2019).

Spawning stock size S_t in year t, was calculated as the difference between annual exploitable biomass B_t and annual catch, C_t

$$S_t = B_t - C_t \qquad \text{(Eq. 6.1)}$$

Where B_t was calculated as in Grubert *et al*. (2019, equation 6) using input catchability and logbook effort information, and C_t was from logbook catch data. For analyses of the effect of variation in S_t from the definition (Eq. 6.1), I simply multiplied by a coefficient d, so that the “calculated” spawning stock size in year t was $d * S_t$. Thus, for example, if $d < 1.0$ then the calculated spawning stock would be smaller than estimated using equation 6.1 and this smaller input would be used in the calculation of the stock-recruitment relationship parameters, F_{msy} and other performance measures for the fishery.

The series of historical recruitment anomalies, ω_t, were calculated as in Grubert *et al.* (2019) (their equation 10):

$$\omega_t = Ln\left(\frac{R_{t+2}}{S_t}\right) - a + bS_t. \qquad \text{(Eq. 6.2)}$$

Here, R_t and S_t are respectively recruitment and spawning stock size in year t. It is important to note that in this chapter, “recruitment” is defined as entry into the fishery, i.e. into the exploitable biomass. Productivity at low stock size (a) and density dependence (b) are the parameters of the Ricker stock-recruitment relationship (S-RR), estimated by regression within the model. Note that the calculation of the anomalies for year t requires recruitment information for year $t + 2$, so that with logbook data for 1983-2019, it is only feasible to calculate anomalies to 2017.

The anomalies ω_t were related to an environmental factor I, embedded in the Ricker stock-recruitment relationship (Maunder and Watters 2003)

$$R_t = S_t \exp(a - bS_t) \exp(\beta I_t + \omega_t + \alpha). \qquad \text{(Eq. 6.3)}$$

We applied this relationship by regressing I_t on ω_t. The regression constants can be used to parameterise β and α in further application of the model.

Spawning biomass is defined in the delay-difference model simply as the exploitable population remaining after fishing, as in Equation 6.1

Model input parameters

Catchability, q, was given an initial value of 1.0 (as in Grubert *et al*. 2019), doubling over the period 1983 to 2019. The growth-natural survival factor (g) was 0.36, as in Grubert *et al*. (2019; their equation 3).

[4] This differs from the GLM analysis in Chapter 4, where each region retained its data, but region was a forced term in the model.

Results

Simple analysis of annual catch per unit effort against environmental factors

To visualise the impact of environmental factors on catch rates, annual catch per unit effort (CPUE, kg pot lift^{-1}) was plotted against MSL for 1996-2018, and against Heat for 1983-2018.

For the Combined data set, CPUE varied between a maximum of 1.25 kg pot lift^{-1}, in 2001, and a series minimum of 0.25 kg pot lift^{-1}, with the median CPUE being 0.52 kg pot lift^{-1}. MSL (m) data are identical for both the Roper and McArthur regions, being derived from data collected at Milner Bay on Groote Eylandt. Heat, being a cumulative index, ranged between 5046 and 5590 ºC, with the median value of 5306 ºC.

Annual CPUE values are clearly influenced by the environmental factors (Figures 63, 64, and 65), as expected from Chapter 4. Put simply, high Heat and high MSL coincide with low CPUE; when MSL and Heat are low, CPUE tends to be high. As described in Chapter 4, the relationship between CPUE and these two environmental factors was negative, with higher than average CPUE typically occurring when MSL was low, and lower than average CPUE at high MSL but in this respect the high catch rate of 2001 is a strong outlier. However, as shown in the plot of CPUE against Heat, in each figure, higher CPUE occurred usually when Heat was at the lower end of the range, with the best catches when Heat was less than about 5200 ºC. The series maximum CPUE in 2001 was at the lowest end of the range of Heat values, at 5096 ºC. Low catch rates occurred when Heat exceeded about 5450 ºC. Note that several of the below-trend points in Figure 63b, indicated with orange symbols, are from among the 10 points for which MSL was highest. For most of the other 'blue' points below the trend line in Figure 63b are for years prior to 1996 for which MSL data are not available. The lowest CPUE occurred when the MSL (anomaly) was greater than about 0.10 (m); CPUE values were high when the MSL (anomaly) was less than -0.15 (m), but noting the outlier of the 2001 high CPUE at 1.25 kg pot lift^{-1}.

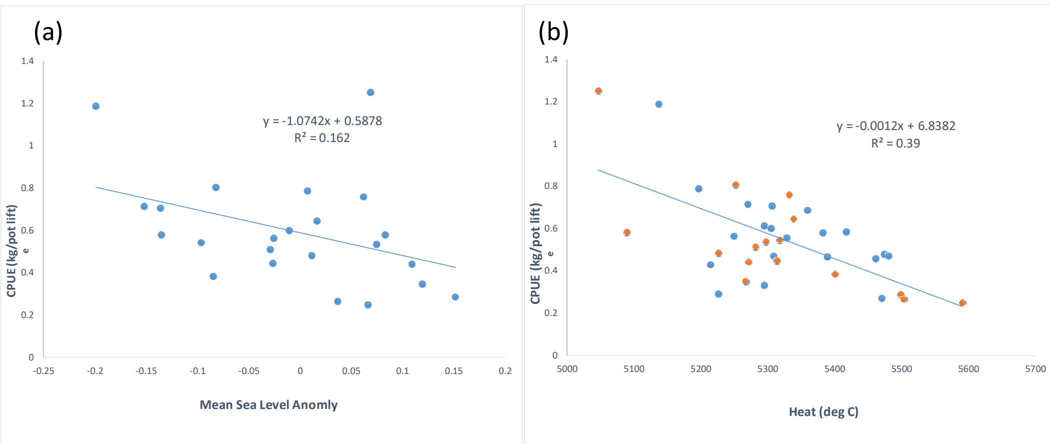

Figure 63. Relationships between catch rates and environmental factors in the NT Western Gulf of Carpentaria Mud Crab Fishery Combined region (Roper and McArthur). (a) Annual CPUE versus Mean Sea Level anomaly, 1996-2018; (b) Annual CPUE versus Cumulative Heat, 1983-2018. The orange symbols in (b) indicate the 10 years in which the Mean Sea Level anomaly was highest.

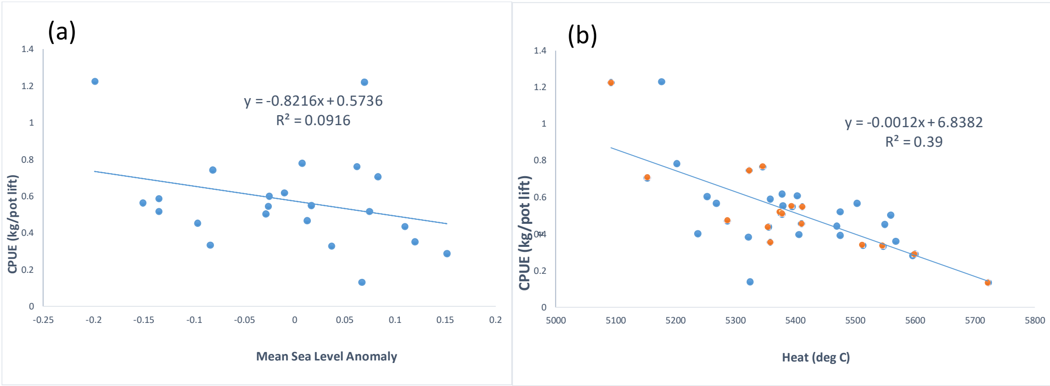

Figure 64. Relationships between catch rates and environmental factors in the NT Western Gulf of Carpentaria Mud Crab Fishery for the Roper region (a) Annual CPUE versus Mean Sea Level anomaly, 1996-2018; (b) Annual CPUE versus Cumulative Heat, 1983-2018. The orange symbols in (b) indicate the 10 years in which the Mean Sea Level was highest.

For the Roper region, annual CPUE varied between 0.14 and 1.23 kg pot lift^{-1}, with the median being 0.51 kg pot lift^{-1}. MSL was as above and Heat was between 5092 and 5721 ºC, with a median value of 5377 ºC. Again, the high CPUE of 2001 was a strong outlier in the otherwise negative relationship between CPUE and MSL anomaly and is indicated in Figure 64(b), many data points beneath the trend line of CPUE against Heat were when MSL values were higher.

For the McArthur region, CPUE varied between 0.25 and 1.25 kg pot lift^{-1}, with the median being 0.52 kg pot lift^{-1}. MSL was as described above and Heat was between 5145 and 5459 ºC, with a median value of 5238 ºC. The high CPUE of 2001 was a strong outlier in the relationship between CPUE and MSL, is indicated in Figure 65(b), and was again in the low range of Heat.

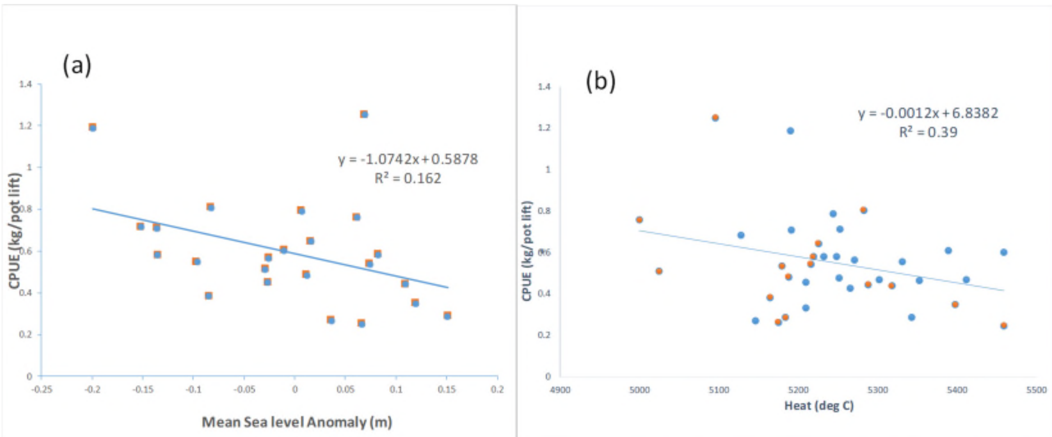

Figure 65. Relationships between catch rates and environmental factors in the NT Western Gulf of Carpentaria Mud Crab Fishery for the McArthur region (a) Annual CPUE versus Mean Sea Level anomaly, 1996-2018; (b) Annual CPUE versus Cumulative Heat, 1983-2018. The orange symbols in (b) indicate the 10 years in which the Mean Sea Level was highest.

Variation in apparent spawning stock size, S_t

I multiplied the S_t series by a range of values of d in the delay difference model, calculating the effects on the estimates of key parameters (Table 31).

The propagation of erroneous estimates of S_t begins with the calculation of the S-RR coefficients. When $d <$ 1.00, the spawning stock is apparently smaller (than the base case of when d = 1.00), but recruitment is calculated to be larger (to sustain the historical catch series), and the stock thus appears more productive than the ‘reality’ of the base case (i.e. d = 1.00). This is reflected in the decreasing value of the a parameter of the

S-RR as *d* increases (Table 31). The estimates of spawning stock size at maximum sustainable yield, S_{msy} increase with *d*. As increasing *d* leads to apparent lower productivity, it would be necessary to maintain a higher stock size to explain historic catch patterns.

Increasing *d* led to the model interpreting the fishery as being less productive, producing reduced estimates of the parameters B_{msy}, U_{msy} and F_{msy}, and the S-RR parameter *a*.

Table 31. Effects of varying annual effective spawning biomass size S_t on estimates of key parameter values in the NT Western Gulf of Carpentaria Mud Crab Fishery derived from the delay-difference model

	d **coefficient**			
Parameter	**0.50**	**0.75**	**1.00***	**1.25**
S_{msy}	157	201	227	238
B_{msy}	548	517	478	433
U_{msy}	0.71	0.61	0.52	0.45
F_{msy}	1.25	0.94	0.74	0.60
MSY	391	316	251	195
a	1.94	1.50	1.19	0.94
b	-0.0051	-0.0035	-0.0028	-0.0024
Bias in F/F_{msy} relative to d = 1.0	0.59	0.79	1.00	1.24

d = 1.00 is termed as the "base case"

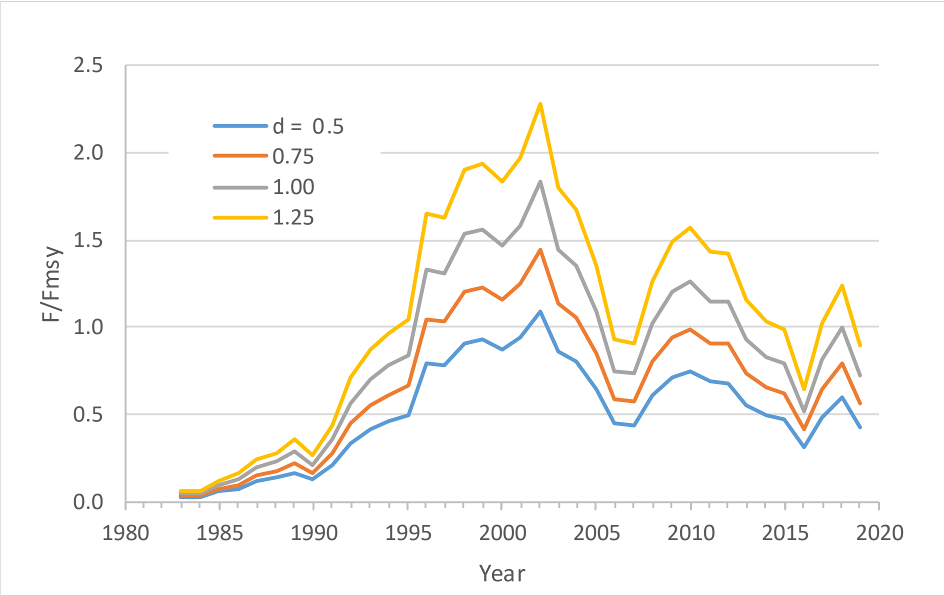

Figure 66. Effects on the apparent trajectory of F/Fmsy, of varying annual spawning biomass size St, by multiplying by different values coefficient d

Applying the different values of *d* to the spawning biomass produced markedly different trajectories of the relative fishing mortality rate (F/F_{msy}), which is the ratio of the estimated fishing mortality rate to the fishing mortality rate at maximum sustainable yield (Figure 66). The trajectories were biased by consistent multiples (Table 31), close to the multiplying *d* value, implying that the relative error in the estimate of F/F_{msy} corresponds to the bias in estimating the spawning stock size. A consistent over-estimate of the stock size in the model, and correspondingly under-estimating productivity, would tend to be conservative (in a management sense) in estimation of F/F_{msy}. Note that when *d* = 1.25 (light orange trajectory in Figure 66), F/F_{msy}.is consistently estimated to be greater than for when *d* = 1.00. The latter represents the trajectory given accurate input estimates of spawning stock size (grey line). The apparent trajectories for when *d* < 1.00 (blue and dark orange trajectories in Figure 66) consistently under-estimate F/F_{msy} compared to the base case.

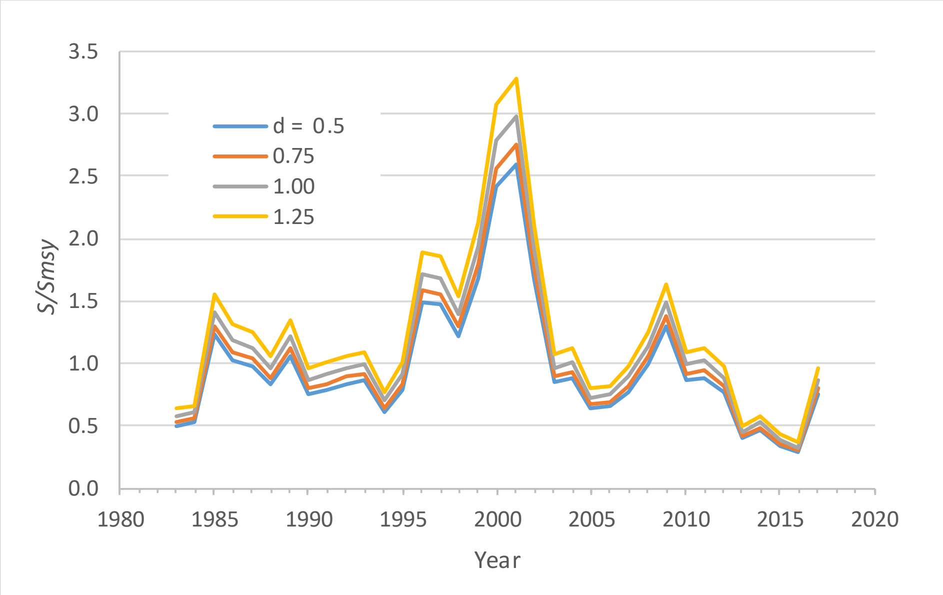

Figure 67. Effects on the apparent trajectory of S/S_{msy} estimates, of varying annual spawning biomass size S_t, by multiplying by different values coefficient d.

In contrast, the trajectories of the estimates of the relative spawning biomass (S/S_{msy}), which is the ratio of the current spawning biomass to spawning biomass at maximum sustainable yield, were more consistent with the trajectory when d =1.00 (Figure 67). This suggests that presenting these measures as a ratio muted the effects of the introduced bias. Over-estimating input (S_t) d >1.00 led to consistent but small over-estimation of the S/S_{msy}, and when d < 1.00, S/S_{msy} was under-estimated. In the management sense, over-estimation of the spawning biomass was slightly conservative.

The trajectory of F/F_{msy} plotted against S/S_{msy} for d = 1.00 (a Kobe Plot, Figure 68a), indicates that, in 2007, the NT Western Gulf of Carpentaria Mud Crab Fishery was in a good state (green part of the plot), with F/F_{msy} < 1.0 and S/S_{msy} >1.0. However, in subsequent years, there was overfishing (F/F_{msy} >1.0) which continued as S/S_{msy} declined. Despite a reduced relative fishing mortality (F/F_{msy} < 1.0) since 2013, the fishery has had a spawning biomass below the target (S/S_{msy} <1.0).

The interpretation of the trajectory of F/F_{msy} plotted against S/S_{msy} for d = 0.75 (Figure 68b), also indicated that the fishery was in a good state in 2007. However, the spawning biomass in the fishery subsequently declined, and even though fishing mortality rates were not excessive (F/F_{msy} < 1.0), with S/S_{msy} < 1.0 persisting for the remainder of the time series.

The interpretation of the trajectory F/F_{msy} plotted against S/S_{msy} for d = 1.25 (Figure 68c), again indicated that the fishery was in a good state in 2007. However, there was overfishing in the following five years and the spawning biomass was consequently fished down. The fishery recovered somewhat to cycle around target levels for the last three years of the time series.

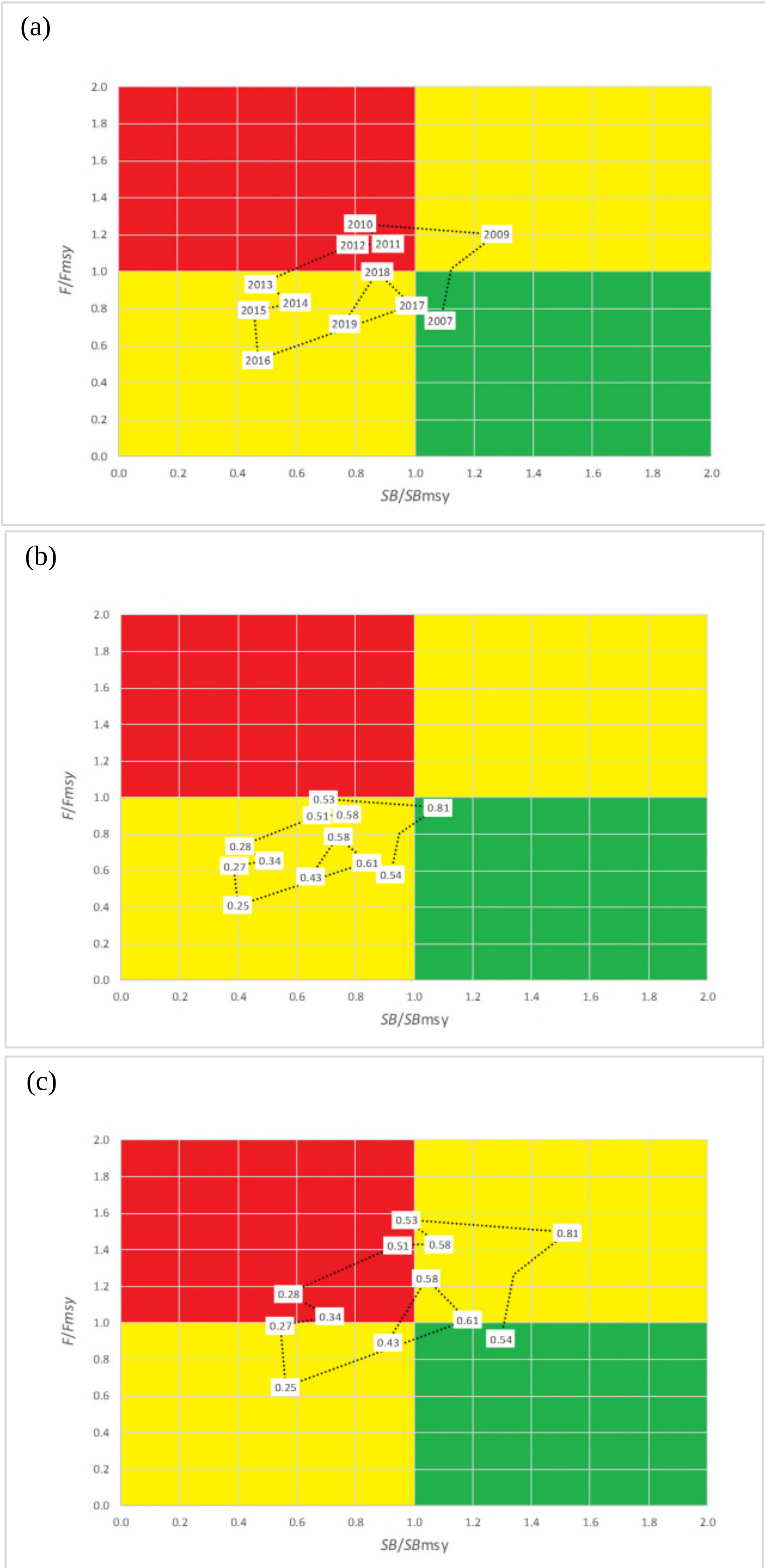

Figure 68. Trajectories of relative fishing mortality F/Fmsy plotted against relative spawning biomass S/Smsy in the NT Western Gulf of Carpentaria Mud Crab Fishery, 2007-2019. (a) coefficient d = 1.00 considered as the "base case"; (b) d= 0.75; (c). d=1.25. Point labels in sub-plot (a) are years, whereas point labels in sub-plots (b) and (c) are annual CPUE values.

Correlations and regressions between recruitment anomalies and environmental factors

Correlations between recruitment anomalies from the delay-difference model and environmental factors, each lagged at zero, one and two years, were analysed and regression coefficients calculated (Table 32). Recruitment anomalies were calculated for the full time series (1983) for each model (Combined, Roper and McArthur regional models) with separate analyses conducted, for the period 1983 to 2017, or shorter periods if data were not available, and for 2006 to 2017 (for which data were available for all environmental factors). The Mean Sea Level data series begins in 1994 and the annual flow data series for the McArthur River does not begin until 2003, so the latter comparisons used restricted data sets. Where $P \leq 0.10$ (indicated in Table 32), correlations were selected for potential further analysis.

Most correlations were poor (and so are not shown). However, for the ‘Combined’ data set, there was a moderate negative correlation between Heat (lag-1 year) and stronger relationships between MSL (lag-0) and MSL (lag-2), all negative, for the 1983-2017 comparison. There were also strong negative correlations with MSL (lag-0, lag-2) for the 2006-2017 time series (Table 32). There were no meaningful correlations with Flow.

For the Roper region, there was a moderate negative relationship between recruitment anomalies with Heat (lag-1) and stronger correlations with MSL (lag-0 and lag-2), for the 1983 to 2017 comparison (Table 32). There were no relationships between the anomalies and environmental factors for the short time series, nor with Flow.

For the McArthur region, strong correlations were evident between recruitment anomalies and MSL (lag-0 and lag-2) and Flow (lag-0), for the 1983 to 2017 comparison. For the shorter time series, there was a moderate correlation between recruitment anomalies and MSL (lag-0), and also with Flow (lag-0) (Table 32).

Table 32. Correlation and regression analyses of recruitment anomalies estimated from the delay-difference model against environmental factors for Combined, Roper and McArthur regions. Two data series are analysed: (i) 1983 to 2017 and (ii) 2006 to 2017. Note that data series for MSL began in 1994, and the annual Flow data series for the McArthur River began in 2003. P values are shown where there was a moderate or stronger correlation, P ≤ 0.10.

	Combined			**Roper**			**McArthur**		
	lag-0	lag-1	lag-2	lag-0	lag-1	lag-2	lag-0	lag-1	lag-2
Heat 1983-2017									
Pearson *r*	-0.193	-0.333	0.001	0.046	-0.295	-0.014	0.061	0.074	0.151
R^2	0.037	0.111	0.000	0.002	0.087	0.000	0.004	0.005	0.023
P value		**0.051**			**0.086**				
alpha	5.792	9.177	0.964	-0.942	13.380	1.651	-0.760	-1.089	-3.510
beta	-0.001	-0.002	0.000	0.000	-0.002	0.000	0.000	0.000	0.001
Heat 2006-2017									
Pearson *r*	0.403	-0.105	0.363	0.396	-0.347	0.125	0.498	0.083	0.405
R^2	0.163	0.011	0.132	0.157	0.120	0.016	0.248	0.007	0.164
P value							**0.099**		
alpha	-7.489	2.904	-7.919	-24.756	22.603	-9.052	-10.224	-1.039	-9.245
beta	0.002	0.000	0.002	0.005	-0.004	0.002	0.002	0.000	0.002
MSL 1983-2017									
Pearson r	-0.511	-0.292	-0.566	-0.429	-0.148	-0.386	-0.649	-0.341	-0.506
R^2	0.261	0.085	0.320	0.184	0.022	0.149	0.421	0.116	0.256
P value	**0.011**		**0.006**	**0.037**		**0.076**	**0.001**		**0.015**
alpha	1.095	1.069	1.054	-5.852	-2.030	-5.525	1.044	1.008	0.987
beta	-3.303	-1.872	-3.727	0.986	0.966	0.947	-4.303	-2.185	-3.288
MSL 2006-2017									
Pearson *r*	-0.678	-0.077	-0.594	-0.428	0.029	-0.423	-0.766	-0.149	-0.460
R^2	0.459	0.006	0.353	0.183	0.001	0.179	0.586	0.022	0.212
P value	**0.015**		**0.042**				**0.004**		
alpha	0.884	0.765	0.857	-8.831	0.565	-9.356	0.949	0.815	0.881
beta	-4.209	-0.441	-3.956	0.875	0.601	0.846	-4.958	-0.898	-3.195
Flow 1983-2017									
Pearson *r*	-0.341	0.029	-0.346	0.001	0.026	-0.037	-0.595	-0.015	-0.246
R^2	0.117	0.001	0.120	0.000	0.001	0.001	0.354	0.000	0.061
P value							**0.019**		
alpha	1.007	0.760	1.015	0.999	0.967	1.048	1.249	0.813	1.025
beta	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Flow 2006-2017									
Pearson *r*	-0.381	-0.042	-0.357	-0.030	0.156	0.078	-0.554	-0.050	-0.316
R^2	0.146	0.002	0.128	0.001	0.024	0.006	0.307	0.002	0.100
P value							**0.062**		
alpha	1.036	0.784	1.000	0.671	0.327	0.458	1.245	0.835	1.039
beta	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Discussion

It is clear from Chapters 4 and 5 of this report that environmental factors impact catch rates of mud crabs in the GoC. Suggested by the strength of results in the GLMs and DBN analyses, it is evident that environmental factors are important drivers of recruitment and probably catchability in the crab fisheries. We undertook further analyses of the relationships between environmental factors and CPUE in the NT Western Gulf of Carpentaria Mud Crab Fishery, as well as modelled recruitment anomalies. The impact that bias driven by environmental factors could cause in performance indicators applied in the fishery's Harvest Strategy was evaluated.

A simple correlation analysis of annual CPUE focussed on two environmental factors that were identified as being the most important in Chapter 4 - specifically, Heat (which appears to be the most important in this analysis) and MSL. The intention here was to visualise and to communicate simple approaches that might provide guidance for the NT Western Gulf of Carpentaria Mud Crab Fishery for future application in the harvest strategy for the fishery.

Based on these results, a qualitative approach to the prediction of broad categories of catch rates in coming seasons is possible. The environmental factors considered here, Heat and MSL, precede the fishery catch by two and one years respectively, and thus might be used in planning for the fishery and in combination with the decision rules of the fishery harvest strategy.

The intent of the approach below is to provide guidance to the management of the fishery rather than support knife edge decision rules. Very good, as well as very bad, catch rate years are probably best managed with prior warning. We show how some knowledge of the environmental drivers in the fishery might be simply applied. But we also caution that some data series we have used are relatively short, and our understanding of processes involved are deficient. The interplay of environmental drivers is often complex and may change over time. It was noted in Chapter 4 that the negative impact of temperature on catch rates is in contrast to previous studies, where temperature had not reached a limiting effect.

The current categorisation of CPUE as "good", poor" and "average" is arbitrary, and if the approach described below is used in the Harvest Strategy, levels should be chosen carefully by management and stakeholders.

The approach described below relies on the observation that extremes of catch rates coincide with extremes of environmental factors (see Plagányi *et al*. 2020). Thus, high CPUE values were achieved in both regions when Heat was low and MSL (anomaly) was low, noting that both drivers were lagged. Low CPUE values tended to be when the two environmental drivers were at the low ends of their respective ranges. Average catch rates were usually achieved when these drivers were not at their extremes.

I illustrate this further for both river regions combined.

1. If Heat < 5200 : CPUE good to high
2. If Heat < median (5306) and MSL < median (0.007) : CPUE average to good
3. If Heat < median (5306) and MSL > median (0.007) : CPUE poor to average
4. If Heat < median (5306) and MSL < median (0.007) : CPUE poor.

The NT Western Gulf of Carpentaria Mud Crab Fishery relies largely on a single year-class of crabs. As such, a primary objective of the Harvest Strategy for the fishery is to ensure that spawning biomass remaining after fishing (mostly of the recruiting year-class) is at levels that meet the fishery management goals. Given the assumption that CPUE is indicative of population biomass, then a mechanism similar to that above could employed to inform expectations of relative spawning biomass levels.

It is not known whether the environmental factors considered in the simple analysis above impact mostly on recruitment or catchability. However, the two-year lag that was applied with MSL (anomaly) suggests that MSL impacts on the spawning process or the survival of eggs, larvae or juveniles i.e. recruitment processes. It is more conceivable that temperature effects, even lagged by year, might impact on catchability (for example by impacting the distribution of crabs). However, temperature might also impact recruitment via the survival of juvenile and pre-recruit crabs.

The analysis was based on relatively sparse data, and it is not uncommon for apparently tight relationships with environmental factors to be disrupted. I thus note that the qualitative predictions should be applied with care. Even so, some prediction of the performance of the fishery, even in qualitative terms, should be a valuable planning tool, and this method could be applied for each region of the fishery. The development of a more-formal statistically based approach, such as the use of tree regression techniques as in Plagányi *et al*. (2020) is recommended. Such an approach would have the potential to include more data (including more factors) and provide greater objectivity and rigour. It would also provide a formal framework to support learning from decisions, as well as the inclusion of new data (catch rate and environmental factors).

Environmental factors may affect both catchability and recruitment, and in ways that are not obvious. They might affect not only real spawning stock biomass (S_t), but also our ability to estimate this important population attribute. There are many ways in which estimates of S_t might be biased, including natural mortality that is different to that assumed in the model (via the growth-survival parameter g), or a change in reproductive capacity after the annual fishery, that effectively alters S_t. This could be, for example, through the relative survival rates of females during the fishing year, or their subsequent survival to spawn after fishing.

Changes in catchability such as range changes, might also occur with a segment of the population becoming unavailable/more available to fishing or becoming economic/uneconomic to fish. All of these causes might have environmental drivers that create such a bias for one or a series of years. Additionally, environmentally driven change could be compounded by, and confounded with, unaccounted fishing mortality, such as discard mortality or illegal fishing, that could also bias estimates of S_t. For example, the implementation of the Commercially Unsuitable Crab' (CUC) rule in 2001 (which mandates that recently moulted "soft" crabs must be returned to the water) and the 10 mm increase in the commercial minimum legal size for mud crabs in 2006 mean that discard rates now approach 70% in some areas (Ward *et al*. 2008; Grubert 2019). Survival rates of discarded crabs are not known.

The levels of bias (*d)* that we have applied in our analysis of the estimation of spawning biomass could quite reasonably be realistic, so that a strong observation arising from the analyses in this chapter is the importance of good monitoring information.

The ratios F/F_{msy} and S/S_{msy} are frequently used as performance measures in harvest strategies for many fisheries, with F/F_{msy} indicating whether overfishing is occurring, and the S/S_{msy} ratio indicating whether the fishery is overfished (relative to the reference point S_{msy}). Given this emphasis, it is important to understand that bias is likely to impact on the performance of management by either under or over estimating these values, given poor input information. The analyses indicated that bias in the input S_t values led to corresponding bias in F/F_{msy} but bias in the estimation of S/S_{msy} was relatively muted, with the bias largely cancelling out in the ratio. This is a good reason to express the fishery performance measure as a ratio rather than absolute number, and I suggest that the Harvest Strategy for the NT Mud Crab Fishery be changed in this way.

Kobe plots neatly summarise and provide a visual time-series trajectory of the ratios of F/F_{msy} versus S/S_{msy} and can be a valuable tool in management decisions. Interestingly, although the trajectories of Figure 68 appear to differ substantially, all point to the fishery being below target biomass S_{msy} for much of the last decade, so that the expected management direction would be to encourage measures to improve S/S_{msy}. However, the extent to which the trajectories might be interpreted as a consequence of overfishing, the influence of environmental factors or the assessment process would differ between each of the d scenarios. To emphasise that these trajectories arise from the same catch and effort data series, Figure 68b and Figure 68c are labelled with the annual CPUE values. Relatively small changes in input variables can produce large differences in model outputs. This observation might be used as an excuse to deride the value of the model outputs but in reality, by exposing uncertainty, it indicates the value of both better inputs and the value of using multiple analyses to inform management decision making.

This bolsters the argument to widen the suite of models used in assessments of the fishery and reinforces the need to improve data inputs. A limitation of the current implementation of the delay-difference model (Grubert *et al.* 2019) is that, as a policy model, it does not estimate precision (such as confidence intervals) around outputs, which perhaps limits acceptability to stakeholders.

The analyses comparing catch rates and environmental factors (Chapter 4 and in the current Chapter), demonstrate that catch rates are related to environmental factors. The analyses of correlations between recruitment anomalies and environmental factors MSL and Heat indicate that one path by which catch rates are affected by the environmental factors is via the impact on recruitment and subsequently, abundance. We have additionally produced regression coefficients that will enable further exploration of the impacts of climate drivers on management policy for the NT Western Gulf of Carpentaria Mud Crab Fishery.

In the analysis, recruitment anomalies were strongly correlated with MSL (lagged at zero and two years). Changes in MSL indicate variation in circulation and tidal flow, the importance of which is described in Chapter 7. The two-year lag corresponds with the spawning process, and the survival and shoreward transport of larvae and juvenile crabs. The variation in recruitment with MSL suggests that this early life stage is impacted. Variations in circulation indicated by zero and two year lags could reflect local ecological effects engendered by changes in circulation or tidal patterns, impacting the coastal and estuarine habitats of adult crabs but what these impacts might be are not known. The positive relationship between recruitment anomalies and Flow for the McArthur region could reflect the improved productivity and extent of habitat that increased river flow provides. It was perhaps surprising that this was not also as important for recruitment in the Roper.

Future work could apply the regression coefficients in exploring the impact on recruitment of prolonged directional change to environmental factors such increased variation in MSL, Heat and Flow, as may occur under climate change (Welch *et al*. 2014). The consequence of such impacts, particularly if prolonged (e.g. extended hot and dry), on harvest strategy policy performance for the NT Western Gulf of Carpentaria Mud Crab Fishery (and the Qld Crab Fishery) should be considered.

There are many other ways in which the Grubert *et al.* (2019) delay-difference model might be employed to explore the relationships between environmental factors and various aspects of fishery performance. One possibility is that environmental factors affect the growth and survival of crabs. However, we explored varying the growth-natural survival factor (g) in the model to mimic the impact of environmental factors, but found that it had little effect on outputs i.e. the model was quite resilient to variation in g, a property also observed by Walters and Parma (1996). The potential impacts of those factors on the spawning biomass were, however, captured in our analyses.

Catchability is not explicitly monitored in the NT Mud Crab Fishery but the potential impact of environmentally driven changes to catchability could be explored further with the delay-difference model by regressing calculated annual catchability values against an environmental factor, in an analogous approach to that used above for recruitment analyses. A more rigorous approach could be adopted within an integrated assessment model, as in the estimation of environmental impacts on recruitment (Maunder and Watters 2003; Maunder and Thorson 2018).There are other changes that could be implemented in the delay-difference model to improve its representation of the crab fishery. For example, vulnerability schedules could be developed to reflect the changes in minimum legal size. However, one of the advantages of the delay-difference model is its relative simplicity and any changes implemented should note that increasing complexity may reduce utility.

I reiterate the observation by Grubert *et al*. (2019) that the improvement of input data is probably more important than the implementation of more sophisticated models. The fishery would benefit by ensuring the quality of monitoring data, and development of means of monitoring recruitment and catchability would be desirable. One approach could be to use the changing sex composition of fishery catches as a means of indexing performance or estimating harvest rates in-season. The collection of such data has been demonstrated as feasible with 45% of catches reported by sex in 2019. This is a laudable industry effort that nevertheless, could be improved upon, to ensure fine scale spatial and temporal effects are captured.

Results in the current chapter demonstrate that environmental factors impact strongly on the mud crab fisheries of the NT western GoC. And how this is likely to impact on the interpretation and analysis of observations for the fishery was further explored. Suggestions were made on how the information might be implemented in policies of the Harvest Strategy for the NT Western GoC Mud Crab Fishery. I tabulate below, further monitoring, analysis and management recommendations.

Monitoring recommendations:

1) There is a strong need to collect better environmental data e.g. fitting environmental sensors to fishing vessels and transmitting the data through VMS units;
2) Work with other agencies to expand the network of near-shore marine monitoring stations in northern Australia;
3) Develop fishery independent means for estimating recruitment and survival, such as tagging programs, or independent survey;
4) Use the information from the market monitoring program in additional models to inform the harvest strategy (e.g. sex and length and weight composition data from market monitoring); and
5) Seek ways of providing monitoring information on catchability, such as through a tagging program.

Analysis Recommendations:

1) Use the delay-difference model to predict spawning biomass at the end of the current fishing year, with the value of future recruitment anomalies set according to recent environmental conditions;
2) Expand the range of models used to assess the performance of the fishery to at least three (including the delay-difference model), to ensure that different aspects of the fishery's processes and status, including uncertainties, are captured;
3) Where applicable, develop an approach to account for the effects of fishery closures (to protect spawning biomass) on subsequent modelling exercises, otherwise the protected biomass may be overlooked by the model/s;
4) Improve the utility of catch rate information (catch per unit effort, CPUE) as an index of abundance, by investigation of standardisation of catch rates, including an emphasis on environmental factors, applying statistical modelling such as General Linear Models (GLMs) or General Additive Modelling (GAMs); and
5) Future development and application of an integrated assessment model, with a finer time step, is suggested. This could include environmental factors within the model as suggested by Maunder and Watters (2003).

Management recommendations:

1) Employ spawning biomass ratios (i.e. S/S_{MSY}) rather than fixed spawning biomass values in the harvest strategy decision matrix;
2) Encourage increased catch reporting by sex, to detect temporal changes in catch composition (outside of the norm) and improve the validity of fishery models. This should be accompanied by analysis and extension to ensure that the stakeholders in the fishery are aware of the value of reporting catches by sex;
3) Consider the practicalities of catchment scale management, given that all commercial crabbing vessels are now fitted with VMS;
4) Specify minimum effort thresholds below which the performance assessment process is not required; and
5) Improve logbook data (better definition and recording of effort, more accurate and sex specific catch recording) and look for ways to enhance the speed of logbook returns.

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Chapter 7. Preliminary investigation of hydrodynamic and particle tracking modelling of female and larval stage Giant Mud Crabs in the Gulf of Carpentaria

R.G. Patterson

Introduction

Scylla serrata is an important species for fisheries in both Qld and the NT, but is managed differently in each jurisdiction. Queensland and NT coastlines meet in the central southern GoC – a shallow, semi-enclosed sea. In the GoC, access difficulties make field work and in-situ surveys expensive. However, desk-based computational modelling can be used to address questions about geospatial and temporal connectivity and guide field research.

Model description

Hydrodynamic and particle tracking modelling is an ideal way to test hypotheses and direct future field investigations. A hydrodynamic and particle tracking model has been developed using the freely available open access and open source program SLIM (Second generation Louvain-la-Neuve Ice-ocean Model). SLIM GoC is a barotropic model forced by tides at the Arafura and Torres Strait boundaries and wind across the model domain. SLIM resolves the 2-dimensional equations of shallow water flow using bathymetry and an unstructured, high resolution mesh at 15 minute time steps. This model is the first of its kind to be developed for the GoC. The model has been calibrated for tides in the coastal regions, and simulates currents, sea level and dynamic particle movement. Particles can be programmed to move under controlled biological situations such as directional swimming and selective tidal stream transport.

Hypothesis Testing

The following hypotheses were tested for this study:

Hypothesis 1*: *The connectivity[5] of S. serrata in the GoC is independent of the distance of female crabs from the shoreline at the time of spawning.

Hypothesis 2*: *The connectivity[5] of S. serrata in the GoC is independent of the month of year of spawning.

Hypothesis 3*: *The GoC is uniformly connected between QLD and NT fisheries jurisdictions.

Methods

A high resolution (minimum mesh size 400 m), unstructured grid, barotropic hydrodynamic model of the GoC was run for 12 months using tides from 1st August 2000 until 1st August 2001. Selecting a tidal year as the base hydrodynamic model run is common practice for modelling scenarios where seasonal or monthly changes are important. Generally, the tides during calendar months are similar irrespective of the year. The model was previously calibrated against reconstructed, field derived, tidal harmonics and performed well. The model is driven by tidal harmonics at the Arafura Sea and Torres Strait boundaries, and surface winds.

[5] connectivity is defined as the number of either females or larvae which cross into another jurisdictional block

NCAR wind reanalysis was averaged over the past two decades (2008 – 2018) with a temporal resolution of six hours and spatial resolution of 2.5 by 2.5 degrees. This ensured that the general hydrodynamics for each month tested will be an ‘average’ month. This also dilutes spatial variability in the short term and localised events such as cyclones and/or unseasonable storms. Therefore, this study was tested under generally mild wind conditions. Specific cyclone events could similarly be tested in further studies.

Component A – ovigerous female movement

To test *Hypothesis 1*, female adult crabs were seeded in the model as ‘bunches’ (10 individuals) of particles where major and minor surface hydrology lines and mangrove forests intersected. A total of 3,040 adult females were released from 304 different locations where mangrove and streams intersect along the GoC coastline (Table 33).

Table 33. Number of start locations, female adults and larvae released per region in hydrodynamic and particle modelling of Giant Mud Crabs in the Gulf of Carpentaria.

Region	Number of female start locations	Female adult particles	Larval particles
Blue Mud Bay/Groote	82	820	8,200
Roper	31	310	3,100
McArthur	64	640	6,400
South West	62	620	6,200
South East	42	420	4,200
Staaten and Gilbert	4	40	400
Pormpuraaw	7	70	700
Aurukun	2	20	2,000
Weipa	10	100	1,000

Major and minor streams were sourced from the Australian national surface hydrology lines (available at: https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/83130). Mangrove forest extent was derived from the global Mangrove Watch repository 2010 (available at: https://www.globalmangrovewatch.org/datasets/).

Adult Giant Mud Crabs use selective tidal stream transport (STST) to move large distances. Female adults are thought to migrate toward meso-euryhaline conditions to spawn during the months September to January in the GoC. The particle tracking model simulates female adult crab particles by using an attraction or repulsion formula with a switch to determine the direction of swimming:

$$\text{if } u_w + v_w > 0\,; \quad p_{vel} = \sqrt{(u_w)^2 + (v_w)^2} \times swim_p \qquad \text{(Eq. 7.1)}$$

$$\text{if } u_w + v_w < 0\,; \quad p_{vel} = 0 \qquad \text{(Eq. 7.2)}$$

where u_w and v_w are the vector components of currents at a point that determines the particle movement direction either towards the coastline (positive) or away from the coastline (negative); $swim_p$ is the swimming speed of females.

During component A, which modelled female movement, three scenarios were tested to explore the distance from shore that females might move (Table 34). In Scenario 1, females actively swam towards an attractor depth contour, either 35 m or 21 m. These values were based on Hill (1994), who reported that 72% of female mud crabs being trawl-caught in the GoC were captured from depths of 21 to 35 m. Females were assumed to swim at a rate of 0.12 ms^{-1}. In Scenario 2, females did not actively swim, but rather relied on STST to be repulsed away from the coastline and move toward the 20 m depth contour.

Table 34. Scenarios of movement for adult females (model component A) and larvae (model component B) considered in hydrodynamic and particle modelling of Giant Mud Crabs in the Gulf of Carpentaria.

Component A – adult females				Component B - larvae
Scenario	**Depth contour attractor**	**Swim speed**	**Duration (including incubation period)**	**Duration of larval STST**
Scenario 1 (i)	35 m*	0.12 ms^{-1}	15 days	28 days
Scenario 1 (ii)	21 m*	0.12 ms^{-1}	15 days	28 days
Scenario 2	Inshore (20 m)	No active swimming	15 days	28 days

*Based on 72% female mud crabs caught between 21 and 35 m depth contours (Hill 1994)

Component B – larval movement

During component B, 10 larval particles were released (to simulate hatching) from the last position of the female adult particle to simulate hatching (Table 33). Thus, a total of 30,400 larval particles were released for each for each of the scenarios modelled in component A.

To test *Hypothesis 2*, STST of larvae toward the coastline was programmed to start immediately after the simulated egg hatching. The particle tracking model simulates larvae moving towards the shoreline, which was in the opposite direction to the adult female crabs. Therefore, the positive direction for larvae was towards the coastline (unlike in component A, where the positive direction for adult females was away from the shoreline). Component B was run for each scenario of component A, with female's movement initiated in each month between September and January inclusive.

Adult crab particles were released approximately near the start of an outgoing spring tide cycle. Adult and juvenile release times were checked against tide for five different locations around the Gulf: Cape Grey, Milner Bay, West Island, Karumba and Pennefarther River, for each month. Release times were the same across the Gulf, as the tides were similar throughout.

Table 35. Adult and juvenile particle release times in hydrodynamic and particle modelling of Giant Mud Crabs in the Gulf of Carpentaria.

Month	**Adult release date**	**Juvenile release date**
September	6th September 2000, 18:00	21st September 2000, 18:00
October	3rd October 2000, 16:00	18th October 2000, 16:00
November	13th November 2000, 13:00	28th November 2000, 13:00
December	10th December 2000, 10:00	25th December 2000, 10:00
January	7th January 2001, 9:00	22nd January 2001, 9:00

Initial results were screened to identify representative scenarios to develop further, as constraints on model run-time for this preliminary investigation did not permit all scenarios by all release months to be fully implemented. Scenarios selected were: (i) Scenario 1, with a depth contour attractor of 35 m representing females actively migrating offshore, for release months of October and January; and (ii) Scenario 2, representing females passively migrating offshore, for release months of October and January.

Scenario 1 was the largest movement simulated for adult female crabs, and Scenario 2 was the closest to shore that the female adult crabs travelled. Scenario 2 was also thought to be the most likely biologically, under the logic that STST allowed ovigerous females to move sufficiently offshore within the allocated time (i.e. 15 days), whilst allowing them to conserve energy by not swimming. Preliminary results from Scenario 2 showed that STST alone could transport the particles far enough offshore where salinity and temperature conditions were likely to be appropriate, without an added swim speed. Release months of October and

January were chosen to represent early versus late spawning migration as well as representing likely changes in seasonal circulation patterns that occur in the GoC (see Chapter 2).

Statistical analysis and result interpretation

Simple connectivity analyses were undertaken to compare the results of October and January from Scenario 1 model runs with those from Scenario 2. Each adult female crab particle was assigned a start region corresponding to where they were seeded (Figure 69). Each larvae carries the start region label of its adult female crab particle. At the end of the 28 day component B modelling, the total number of larvae and their end region were counted and tabulated into a connectivity matrix.

A connectivity matrix (e.g. Figure 70) shows the level of connectivity between regions. The row-wise start region and column-wise end region allow directional connectivity to be inferred. A column-wise, or 'end region' normalisation was implemented, so that the proportion of larvae in each end region can be attributed a 'start region'. For example, in Figure 70 for all the particles that ended in the Roper region, 69% started in the Roper region, and 31% started in the McArthur River region.

The results were also represented spatially using connectivity networks (e.g. Figure 71). An arrow from the McArthur River node points towards the Roper node with the number '0.31' near the head of the arrow. Conversely, 10% of the larvae ending in the McArthur river region started in the Roper region.

Larvae particles that did not return to a region were not accounted for in these matrices.

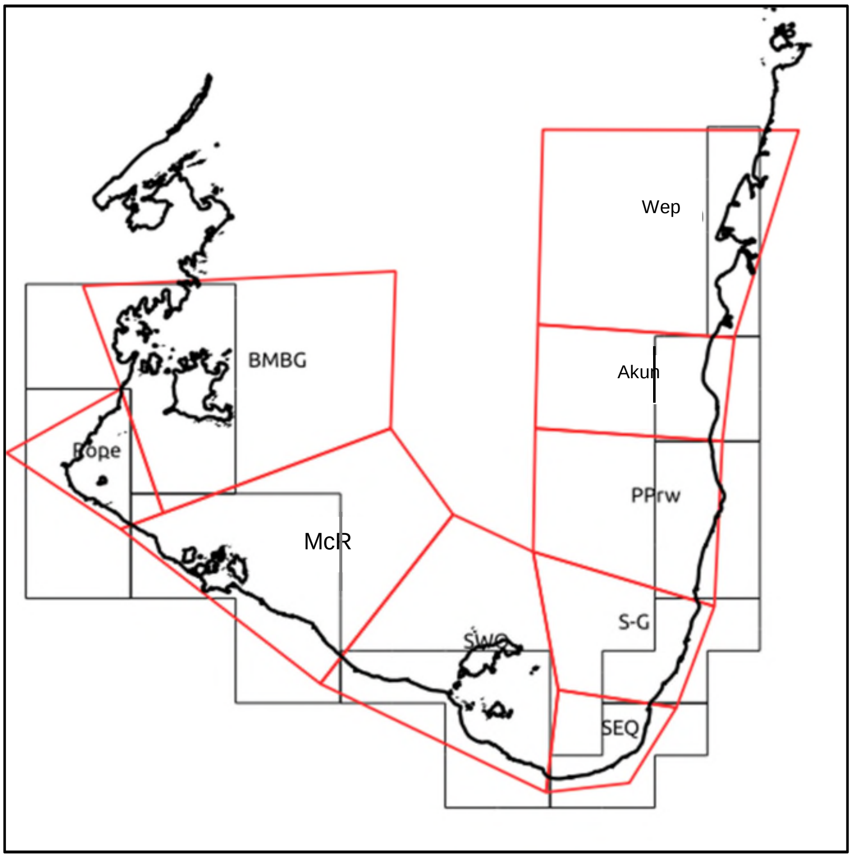


Figure 69. Fisheries reporting regions (black polygons) and adapted hydrological regions (red polygons) for the hydrodynamic and particle tracking model of Giant Mud Crabs in the Gulf of Carpentaria.

Results

The model outputs were in the form of a series of simulation videos for each scenario and month, and are available from the authors on request. To assist in interpretation, results from the simulation videos were summarised in a connectivity matrix and connectivity network. Each connectivity matrix explains one generation of movement for each scenario run. Each scenario is represented as a connectivity matrix with a corresponding connectivity network, run for 15 days for adult female particles, and 28 days for larval particles.

Scenario 1 – females actively swim offshore towards a depth contour

In general, the proportion of particles that started and ended in the same region (indicated by the red cells in Figure 63) was consistent for most of the regions regardless of the release month (i.e. October or January), except for Aurukun and Weipa. Corresponding directional connectivity networks are represented spatially for October and January (Figure 71).

(a) October release

Start region \ End region	BMBG	Rope	McR	SWQ	SEQ	S-G	PPrw	Akun	Weip
BMBG	0.76	0	0	0	0	0	0	0	0
Rope	0.24	0.69	0.10	0	0	0	0	0	0
McR	0	0.31	0.90	0	0	0	0	0	0
SWQ	0	0	0	0.75	0.08	0	0	0	0
SEQ	0	0	0	0.25	0.87	0.30	0	0	0
S-G	0	0	0	0	0.05	0.58	0.06	0	0
PPrw	0	0	0	0	0	0.12	0.93	0.10	0
Akun	0	0	0	0	0	0	0.01	0.90	0.27
Weip	0	0	0	0	0	0	0	0	0.73

(b) January release

Start region \ End region	BMBG	Rope	McR	SWQ	SEQ	S-G	PPrw	Akun	Weip
BMBG	0.50*	0	0	0	0	0	0	0	0
Rope	0.49*	0.70	0.08	0	0	0	0	0	0
McR	0	0.30	0.91	0	0	0	0	0	0
SWQ	0	0	0	0.73	0.04	0	0	0	0
SEQ	0	0	0	0.27	0.90	0.37	0	0	0
S-G	0	0	0	0	0.06	0.55	0.05	0	0
PPrw	0	0	0	0	0	0.08	0.93	0.29	0
Akun	0	0	0	0	0	0	0.02	0.71	0.10
Weip	0	0	0	0	0	0	0	0	0.90

Figure 70. Connectivity matrix between start region (rows) and end region (columns) for Scenario 1, where females actively swam offshore towards the 35 m depth contour and larvae used selective tidal stream transport to move towards the coast for up to 28 days for release months of: (a) October and (b) January.

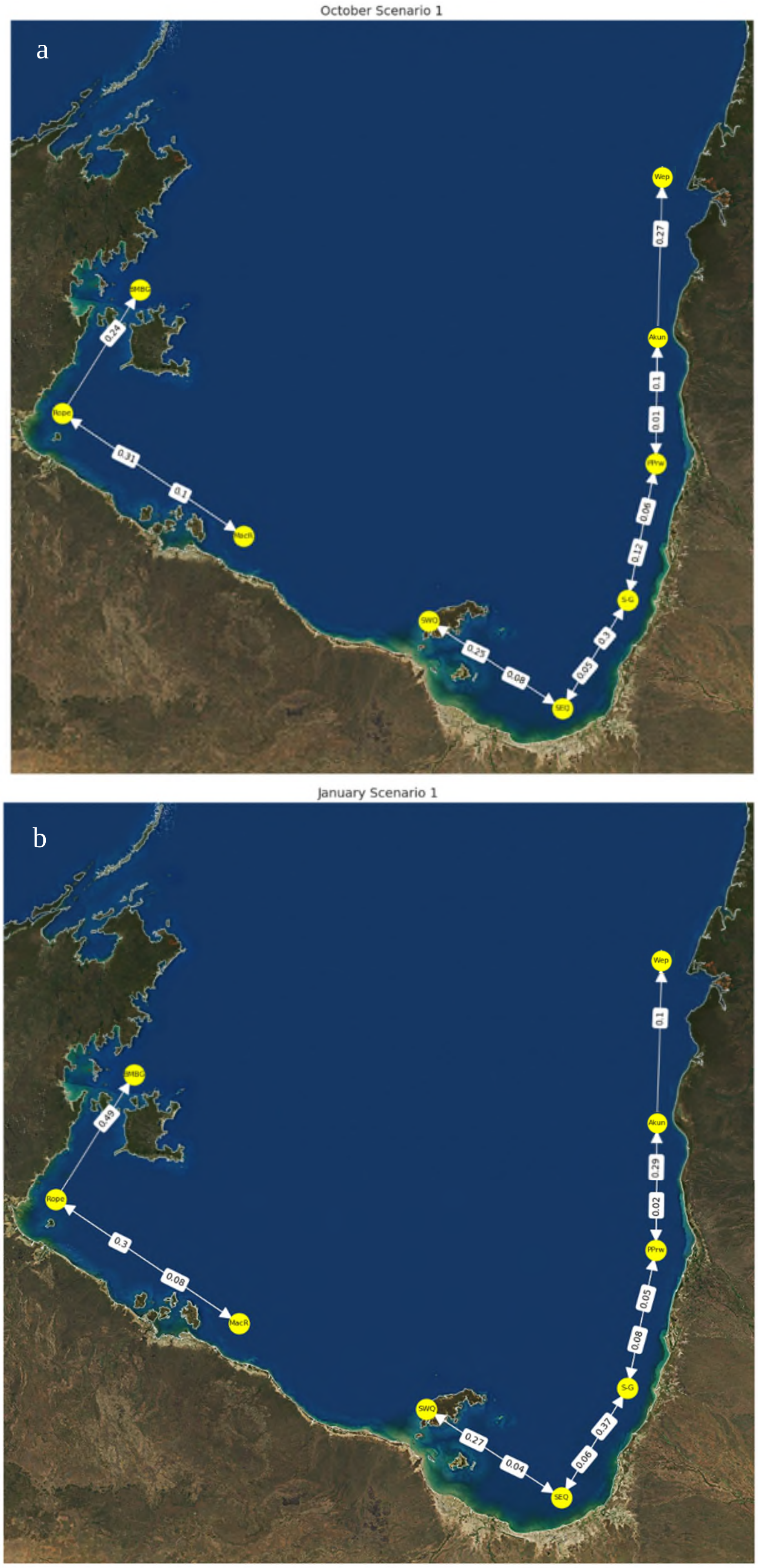


Figure 71. Connectivity network for Scenario 1 for release months of: (a) October and (b) January; where females actively swam offshore towards the 35 m depth contour and larvae used selective tidal stream transport to move towards the coast for up to 28 days. The numbers in the white boxes are the proportion of larvae (i.e. particles) that are derived from the adjacent region, with the direction of movement being toward the closest arrow.

Scenario 2 – females passively move offshore using selective tidal stream transport

Results for Scenario 2 were less consistent for months of release for several regions and were different to results for Scenario 1. In the connectivity matrix (Figure 72), red cells indicate the proportion of particles that started and ended in the same region. The most notable difference in the results for Scenario 2 was for the Staaten-Gilbert region, which under Scenario 2, received most of its larval particles from the South East start region (Figure 73). The results for Scenario 2 were also more aligned with the general change in circulation that happens in the GoC between October and January, depending on weather events, when the circulation changes from clockwise to anti-clockwise (Lui *et al*. 2014).

(a) October release

Start region \ End region	BMBG	Rope	McR	SWQ	SEQ	S-G	PPrw	Akun	Weip
BMBG	0.87	0	0	0	0	0	0	0	0
Rope	0.13	0.91	0	0	0	0	0	0	0
McR	0	0.09	1.00	0	0	0	0	0	0
SWQ	0	0	0	0.93	0.14	0	0	0	0
SEQ	0	0	0	0.07	0.85	0.62	0	0	0
S-G	0	0	0	0	0	0.37	0.05	0	0
PPrw	0	0	0	0	0	0.02	0.95	0.10	0
Akun	0	0	0	0	0	0	0	0.86	0.14
Weip	0	0	0	0	0	0	0	0.04	0.86

(b) January release

Start region \ End region	BMBG	Rope	McR	SWQ	SEQ	S-G	PPrw	Akun	Weip
BMBG	0.83	0	0	0	0	0	0	0	0
Rope	0.17	0.92	0	0	0	0	0	0	0
McR	0	0.08	1.00	0	0	0	0	0	0
SWQ	0	0	0	0.92	0.11	0	0	0	0
SEQ	0	0	0	0.08	0.88	0.63	0	0	0
S-G	0	0	0	0	0.01	0.34	0.09	0	0
PPrw	0	0	0	0	0	0.03	0.91	0.26	0
Akun	0	0	0	0	0	0	0	0.74	0.12
Weip	0	0	0	0	0	0	0	0	0.88

Figure 72. Connectivity matrix between start region (rows) and end region (columns) for Scenario 2, where females passively move offshore using selective tidal stream transport for 15 days and larvae used selective tidal stream transport to move towards the coast for up to 28 days for release months of: (a) October and (b) January.

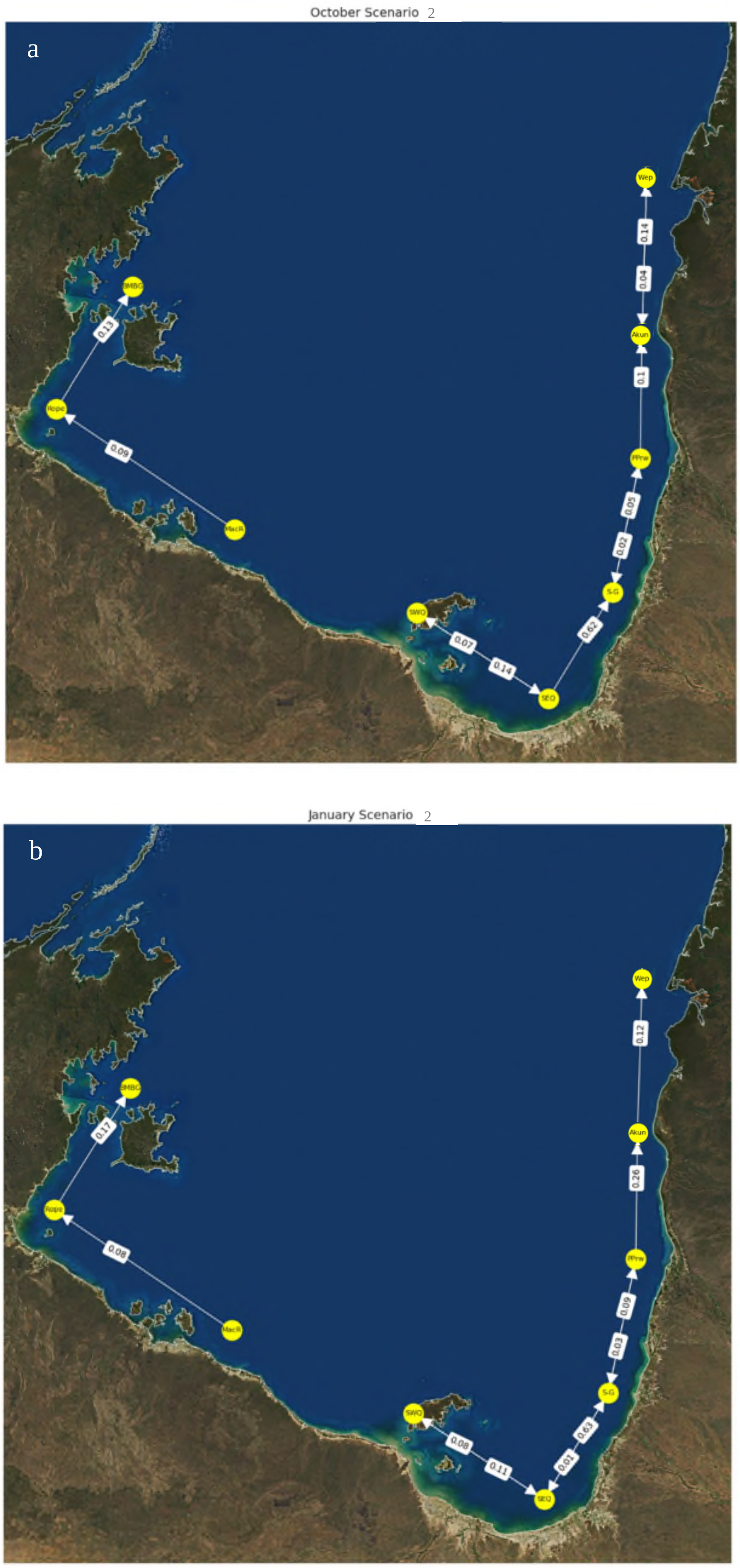


Figure 73. Connectivity network for Scenario 2 for release months of: (a) October and (b) January, where females passively moved offshore using selective tidal stream transport for 15 days and larvae used STST to move towards the coast for up to 28 days. The numbers in the white boxes are the proportion of larvae (i.e. particles) that are derived from the adjacent region, with the direction of movement being toward the closest arrow.

Model limitations and possible improvements

Hydrodynamic and particle tracking models are limited by the assumptions used during the model setup, several of which were made for the current simulation. Many of these assumptions could be improved with further time and resources than was available for this preliminary modelling exercise (Table 36).

Table 36. Limitations and suggested improvements of hydrodynamic and particle modelling of Giant Mud Crabs in the Gulf of Carpentaria.

Model and study limitations	Model improvement
Mud crab particle movement depends on the modelled crab behaviour (equations 7.1 and 7.2) as a function of the currents.	Equations 1 and 2 could be replaced by a more realistic interpretation of selective tidal stream transport that uses sea surface elevation, rather than current direction.
The setup used for the selective tidal stream transport (equations 7.1 and 7.2) caused artefacts in the model results, particularly for the larvae movement toward the coast.	This could be improved by using a different set of movement behavioural triggers, e.g. using either sea surface elevation for a pressure induced stimuli, or time of day for a light induced stimuli.
Mud crabs behind islands could not in some cases 'find' their way around the island. Crabs were therefore 'stuck' behind islands in initial model runs. This was resolved by moving seeded locations of adult female crabs to a logical location (e.g. following the main current) out from behind the island. The assumption was that crabs are able to navigate around islands.	
Temperature and salinity are not modelled in SLIM.	Another, more complex 3-dimensional model of similar scale ($^{1}/_{50}$ ^{o} grid) is available for use. However, this model is a structured mesh, unlike SLIM which is unstructured, so is less realistic for movement of particles around coastlines. Other models also have limitations.
A 35 m contour was used as an attractor for the swimming movement of adult female mud crabs offshore, based on the results of Hill (1994).	A pre-defined temperature or salinity gradient may be more appropriate to use as a minimum distance a female mud crab is likely to travel offshore.
The model assumed 15 days for female adult movement offshore, based on an egg incubation period (Hamasaki 2003).	Female mud crabs are able to carry sperm for months before self-fertilizing. Realistically, female mud crabs could leave the coastline and exist in pelagic water for months, although this poses risks from predation. Model sensitivity to pelagic residence time could be explored using a series of alternate scenarios.

The particle model was seeded based on the assumption that mud crabs exist where mangroves and streams intersect. The sparsity of seeds in some fisheries blocks (e.g. Weipa and Staaten and Gilbert – Table 33) are likely to have influenced the connectivity of some of these regions.	Model trials testing particles seeded at even intervals along the coastline (e.g. every 5, 10, 15 and 20 km) may show the sensitivity to the network connectivity results to the distance between the seeded particles.
The number of seeded particles was 3,040 for female crabs, each of those seeding 10 larvae, producing a total of 30,400 larvae released at 'hatching'. This relatively small number of larval particles were chosen to enable all 30 model runs to be undertaken in the time frame given for this study. Large particle quantities significantly slow model run times.	The model is capable of releasing more particles than was implemented in this study. Female egg masses can contain between two and five million eggs, and perhaps a more appropriate larval release number per female would be > 100,000. This current study has shown that running each of the 30 models is unnecessary. Therefore, fewer (monthly) scenarios with a larger number of particles but longer running time per model run could be justified.
Significant wind events were not accounted for in this study.	The model is capable of running higher resolution wind reanalysis for specific cases of extreme winds. Connectivity for extreme wind scenarios would be useful for determining the likely range of connectivity under stronger wind conditions.
Mud crabs simulated in this study were assumed to move only with the currents.	Anecdotal reports by fishers suggest that female mud crabs move at the surface of the water column. If this is the case then a small wind drift could be applied to model runs to determine whether this has any effect on the connectivity between fisheries blocks.
Mortality or survival algorithms were not used in this study.	The particle tracking modelling software allows implementation of generic mortality rates which can be based on temporal or spatial factors. Mortality factors can also be implemented as a probability function. An example of a temporal factor may be the incubation period of the larvae, after which time individual larvae randomly die off linearly over a specified period of time. An example of a spatial factor driving mortality could be water depth or benthic habitat at time of larval maturation. An orchestra of temporal and/or spatial mortality rates can be implemented simultaneously.

Discussion

Network connectivity mapping results clearly showed two distinct networks for Giant Mud Crab larvae in the GoC, irrespective of season or distance female crabs move from the coast. One network is on the western GoC coastline in the NT, and the other is on the eastern GoC coastline in Qld, with Mornington Island appearing to create a barrier to interchange between the two networks. Although preliminary, results show that irrespective of swimming behaviour, any crab using STST will remain in either the NT or Qld jurisdictional waters, if the female adult was seeded there under the assumptions of the current study. Thus *Hypothesis 3* that *the Gulf of Carpentaria is uniformly connected between QLD and NT fisheries zones* is rejected. These results are consistent with genetic studies that indicated limited genetic interchange between the western and eastern GoC (Gopurenko and Hughes 2002).

Generally, particles appear to move northwards in both networks except in three cases highlighted in green in Figure 70.

In the NT, northward movement appears to start at the McArthur region, which seeds larvae to the Roper region, which in turn seeds larvae to the Blue Mud Bay and Groote Eylandt region. The reverse is only true for the Roper region seeding larvae to the McArthur region in Scenario 1 (10% in October and 8% in January) – noting that this is under ‘average’ wind conditions. Therefore, the distance that the female crab moves away from the coast is important for north-west to south-east connectivity between the Roper and McArthur regions, with respect to rejecting *Hypothesis 1* that *the connectivity of S. serrata in the Gulf of Carpentaria is independent of the distance of female crabs from the shoreline at the time of spawning.*

In Qld, particles appear to be sequentially connected from south to north starting from the South West region and ending in the northern most region of Weipa. In most cases, the connectivity moving eastward (for South West and South East) and northward was stronger in the eastern and northern directions. It is difficult to quantify the influence of the Arafura Sea and Torres Strait currents and wind on particle dispersion given that the model domain does not include those areas, and there are few and in some cases no, current or wind records for these regions to compare against the model output.

There are two exceptions (highlighted in green in Figure 70) to the general connectivity in Qld of moving eastward (southern regions) and northward.

Firstly, in Scenario 1, the north westerly movement from the South East region to the South West region was stronger (i.e. 25 to 27 %) than in Scenario 2, where the reverse direction was stronger (i.e. 11 to 14%). In this case, the distance the female crab particles moved away from the coast was important with respect to *Hypothesis 1* in determining whether the South East region provided larvae to the South West region or vice versa.

Secondly, in Scenario 1, the southward connection from the Pormpuraaw region to the Staaten and Gilbert region was stronger (i.e. 8 to 12%) than in Scenario 2, where the reverse direction was stronger (i.e. 5 to 9%). In this case, the distance the female crab particles moved away from the coast was important with respect to *Hypothesis 1* in determining whether the Pormpuraaw region provided larvae to the Staaten and Gilbert region or vice versa.

Generally, the results showed that the month when ovigerous females migrate offshore had little effect on the broad scale connectivity of the larvae (and thus populations) in the GoC. However, month may have a greater influence on connectivity at smaller spatial scales, especially for some regions of the Qld jurisdiction. There appears to be no consistent pattern that shows either October or January having stronger connectivity than the other. However, month may be an important variable if wind driven seasonality in connectivity is examined in further work.

The most outstanding result was the directional connectivity from the Roper region to the Blue Mud Bay/ Groote Eylandt region, marked with an asterisk in Figure 70. However, these results were likely due to model limitations in the way the particles were set to move (equations 7.1 and 7.2). Other notable results were the south to north connection between Pormpuraaw to Aurukun regions, which was stronger in January (26 to 29%) than in October (10%). However, the south to north connection between Aurukun to Weipa was stronger in October but only in Scenario 1, where the female crabs move further offshore. *Hypothesis 2* that *the connectivity of S. serrata in the Gulf of Carpentaria is independent on the month of year of spawning,* therefore cannot be rejected from the preliminary tests undertaking in this study.

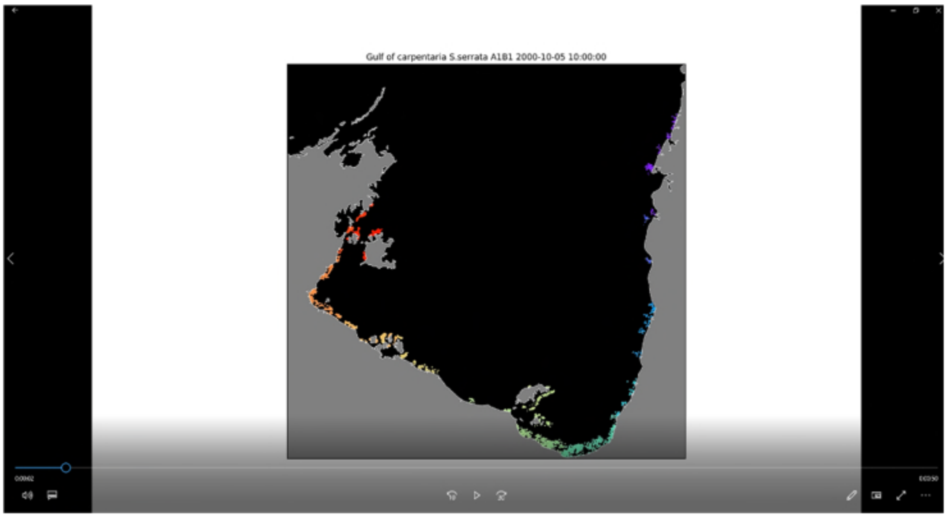
Conclusion

In the current chapter, preliminary particle modelling was undertaken to investigate the geospatial and temporal connectivity of Giant Mud Crabs (via female spawning movement and larval transport) in the GoC. This is, to the knowledge of project collaborators, the first study of its kind applied to GoC Giant Mud Crabs. The results provide preliminary evidence on the appropriate spatial scale of mud crab population dynamics, useful to Objective 2 of the project. The particle modelling (albeit preliminary) highlights possible limited larval exchange between some regions of the GoC and is particularly pertinent to the NT Western GoC Mud Crab Fishery, its associated Harvest Strategy and its secondary indicator of residual Female Spawning Stock Biomass.

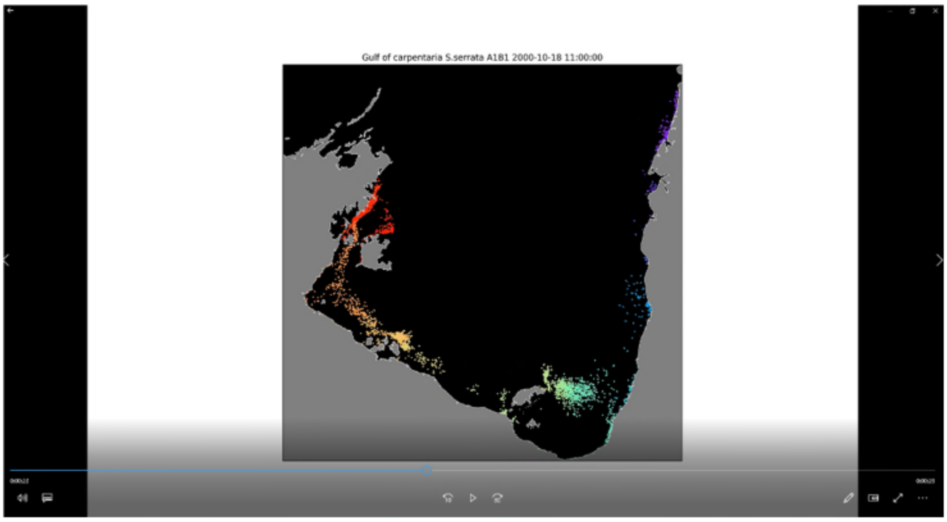
Acknowledgements

This preliminary work was undertaken under a PHD program for Ruth Patterson at Charles Darwin University. Time and resources were made available by Assoc. Prof. Hamish Campbell (Charles Darwin University, Darwin). Dr Jonathan Lambrechts (Université Catholique de Louvain, Belgium) was instrumental in the development of the model. Prof. Eric Wolanski (James Cook University, Townsville) provided logical arguments for the general development of the study, including the hydrodynamic model development and the assumptions for mud crab particle movements. Dr Julie Robins (DAF) provided mud crab literature and knowledge, as well as valuable discussion and guidance on the biological and ecological bases of the mud crab movement assumptions. Prof. Eric Deleersneijder (Université Catholique de Louvain, Belgium) suggested the use of management blocks to quantify particle connectivity.

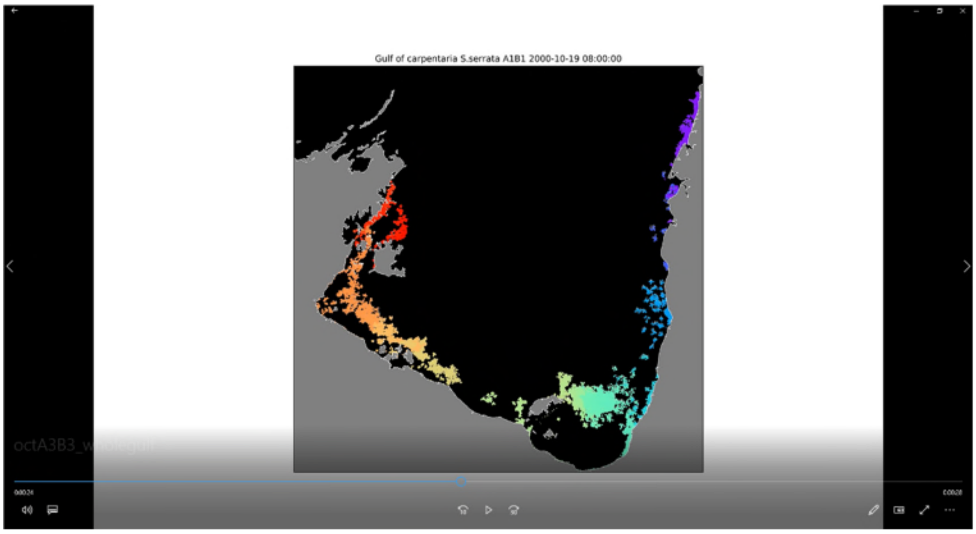
Chapter 7, Appendix. Selected screen shots showing examples of the simulation videos of particle movement for Scenario 1, October release month.



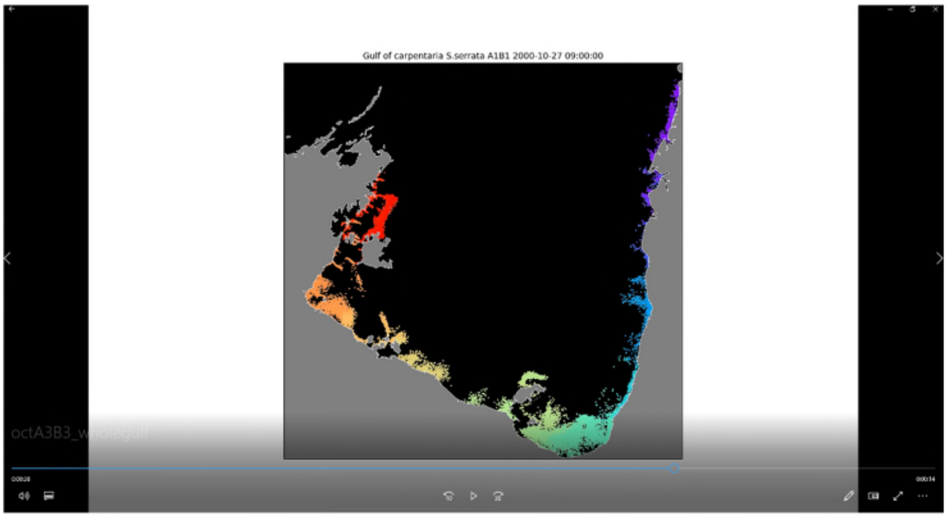
Females start migration from coastal estuaries based on density of mangroves and freshwater drainages (i.e. streams and rivers).



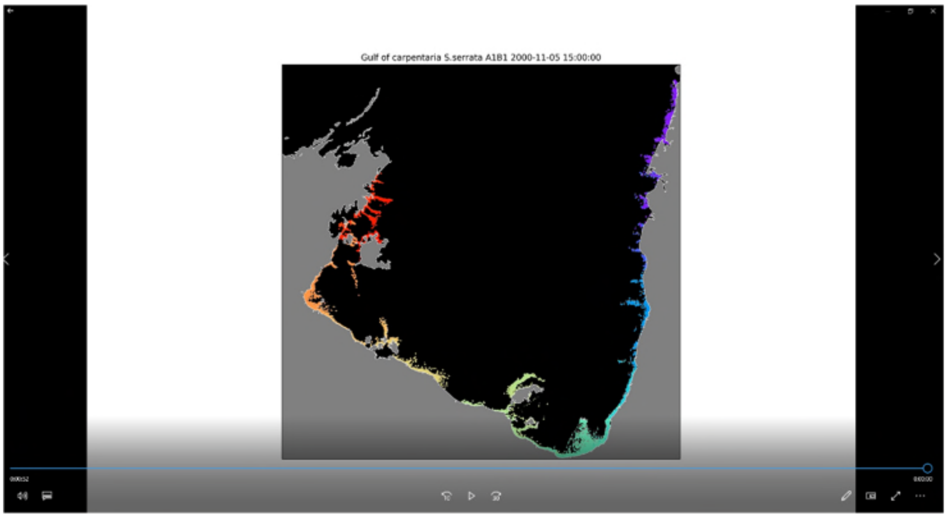
Females migrate offshore towards the 35m depth contour, as per Hill (1994).



Eggs hatch (after 15 days) at location where migrating females had reached.



Zoea larvae move towards the coastline using selective tidal streaming transport (STST).



Megalopa settle (or die) at location after 28 days of STST.

Chapter 8. Conclusion

Fisheries scientists from Qld and the NT collaborated by sharing data, knowledge and modelling expertise to investigate the evidence for large scale ecosystem influences on populations of Giant Mud Crabs in the GoC.

The environmental factors potentially influencing crab fisheries in the GoC were critically reviewed. Analytical relationships between catch and environmental factors were updated to include the extreme climate events experienced between 2009 and 2018, and highlighted the regional variation in these relationships within the GoC. The western and southern regions were identified as being at the greatest risk of climate extremes (within the time series examined). These results are further evidence that low-latitude areas may host species that are close to their thermal tolerance and exemplifies an ecosystem vulnerable to heatwaves where individuals can not physically move to a cooler location (Babcock *et al.* 2019).

Portunus armatus was identified as the probable main species of Blue Swimmer Crab harvested opportunistically in the south-eastern GoC in 2016. The change in abundance of crab species (i.e. increase in *Portunus* and decrease in *Scylla*) was likely indicative of major, inter-year changes to the inshore ecosystem in 2015 and 2016 as a consequence of several years of low freshwater input to the south-eastern GoC, resulting in more oceanic salinity levels and possible atypical current patterns that suited Blue Swimmer Crabs over Giant Mud Crabs.

Cross-jurisdictional collaboration enabled the delay-difference modelling approach of the NT to be explored for the Qld GoC crab stock, and the catch-MSY modelling approach of Qld applied to regions of the NT Western GoC stock.

Collaborative work with a PhD candidate from Charles Darwin University, provided preliminary evidence that NT and Qld stocks of Giant Mud Crabs have limited connectivity, but more scenario testing and empirical data is required to confirm this.

Without further field work, the relative importance of fishing pressure compared with environmental factors remains correlative. However, it appears that environmental conditions can result in significant declines in the abundance (and catchability) of Giant Mud Crab populations in the GoC. It is likely that Gulf populations are more exposed to climate extremes (drought/heat/sea level anomalies) than other northern Australian populations (e.g. Qld east coast), although this also requires further research.

A common need of harvest strategies for Giant Mud Crab fisheries in northern Australia is that they are routinely reviewed such that reference points remain responsive and adaptable, as future climate sequences are unpredictable. The Harvest Strategy for the NT Western GoC (implemented in 2017) is considered flexible, and will be reviewed within the next two years to ensure this continues to be the case.

The Harvest Strategy for the Qld Crab Fishery is preliminary, with a high priority to quantify actual harvest and associated effort. Queensland plans to revise its Harvest Strategy for the Crab Fishery in ~ 2025, and should be better placed to include adaptive reference points for Giant Mud Crabs, notwithstanding the state’s policy of a 60% exploitable biomass target (compared with unfished) by 2027. Reference points could consider more than catch rate targets or quantitatively estimated biomass targets, if pre-recruit monitoring (at appropriate temporal and regional scales) were common practice.

Chapter 9. Implications

The Gulf of Carpentaria is a remote and relatively poorly studied ecosystem in northern Australia, supporting productive and important fisheries for prawns, finfish (e.g. barramundi, threadfins, mackerels and snapper) and crabs. Harvested crabs are predominately the Giant Mud Crab (*Scylla serrata*).

Life-history reviews and desktop analyses of catch and environmental data provide correlative evidence supporting speculation that recent fluctuations of Giant Mud Crab harvests in the GoC were driven by a combination of low rainfall, low river flow, high temperature and sea level variation. Climate sequences as experienced between 2009 and 2018 are likely to occur in the future, although the frequency and combination is unpredictable. The implications for mud crab fisheries in northern Australia is that fishing businesses, fisheries management and harvest strategies need to be structured such that they can respond and adapt to these unpredictable environmental events.

Whilst not quantitatively modelled for a number of reasons, the consistency of the decline across two jurisdictions in which females are harvested in one (i.e. NT) but prohibited from harvest in the other (i.e. Qld) and commonality in environmental conditions over the broad spatial scale of the GoC suggests that between 2009 and 2018, environmental factors may have been relatively more important than fishing pressure. Fundamental to fisheries management is the concept that there is adequate spawning stock to provide recruits that subsequently become the fishable biomass. The high fecundity of mature females, high estimated natural mortality, and relatively short life span suggest that Giant Mud Crabs are a moderately resilient species (a characteristic explored in the catch-MSY analyses), that could probably be fished to a relatively low spawning biomass and still recover. However, this is dependent upon environmental conditions being suitable.

The Harvest Strategy for the NT Mud Crab Fishery sets a secondary reference point of retaining at the end of the fishing year at least 70 tonnes of female spawning stock biomass (FSSB) for the Western NT GoC Mud Crab Fishery. Management intervention (i.e. duration of fishing season) is based on the combination of CPUE in April/May and FSSB estimated from the delay-difference model (Grubert *et al.* 2019), with CPUE having the greater influence (see DPI&R 2017). Management intervention is increasingly restrictive as levels of FSSB decrease below 70 tonnes. A 3-month closure will be implemented irrespective of FSSB if CPUE is less than 0.20 kg per pot day.

Whilst not conclusive, the preliminary hydrodynamic and particle modelling of ovigerous females and larvae, suggests that stocks may be heavily reliant on larvae produced by the remaining females in a region at the end of the fishing year, particularly in the western GoC. This indicates that while resilient, some caution about spawning stock levels is needed as larval replenishment from other regions appears unlikely, although further work is needed to confirm this.

Chapter 10. Recommendations

Desk-top studies are limited by available data. Like previous studies, we reiterate the need for field based studies of Giant Mud Crabs, particularly in the GoC due to the area's inherent climate variability, including extreme events, with are likely to occur more frequently under climate change.

We recommend further work in the following areas:

- Collection and/or (remote) monitoring of empirical data to provide more accurate and representative data on environmental factors that directly affect Giant Mud Crabs in their estuarine and coastal habitats, such as water temperature, salinity, tidal inundation, and indices of "productivity" in mangrove habitats (e.g. chlorophyll-a and/or meiofauna abundance). We recommend collection at relevant regional scales, with priority for the western GoC.
- Trialling a pre-season evaluation of regional environmental conditions to provide predictors of stock levels, such as cumulative rainfall (or flow if available), cumulative heat, and sea level anomalies, with an assessment of the likely risk to each region of having below or above average biomass (and/or catchability) and thus associated harvest.

Data collation, analysis and interpretation reinforced the need for:

- More accurate catch and effort data for both jurisdictions (including sex-specific catch data for the NT and size-specific catch data for Qld) as catch informs the biomass removed from the population, and catch per unit effort is an indicator of stock size. Both of these metrics are fundamental drivers of any stock assessment.
- Within the NT, improve the temporal resolution of CPUE from moving from monthly to weekly catch and effort reporting, which could be most efficiently achieved through electronic means. Currently, crabs are weighed at seafood processors, after transport to Darwin from the Roper and McArthur regions; usually several days after the crab was first captured. Estimation of daily CPUE by number is theoretically possible, but this would place a much greater onus on crabbers who have a limited operational window of a few hours around high tide.
- Within Qld, to develop and monitor a metric of female Giant Mud Crab abundance to inform temporal variation in female spawning stock biomass (for stock assessment), given that females are not part of the exploitable biomass in Qld.
- Within Qld, ongoing liaison with commercial fishers and accurate harvest data for Blue Swimmer Crabs from the GoC stock, to enable early recognition of possible changes to the inshore ecosystem of the south-eastern GoC and to identify if or when separate regional management arrangements might need consideration.

Further development

We recommend further research into the movement of ovigerous female Giant Mud Crabs in the GoC and subsequent larval distribution (i.e. hydrodynamic modelling with field validation) to determine connectivity of regions and stocks, and to identify possible variation in larval distribution between years that may contribute to recruitment variation between regions. Recruitment variation may be affected at two key life history stages: (1) during the oceanic phase of ovigerous females and planktonic larvae; and (ii) during the inter-tidal habitat phase associated with seagrasses and mangroves. This is a fundamental knowledge gap that should be resolved.

Improve (and validate if possible) hydrological and particle modelling of ovigerous females and larvae. Preliminary modelling of the possible movements of ovigerous females and subsequent recruitment of crab megalopae indicates the potential for limited dispersal and cross-regional supply of larvae. This should be investigated further to include the time series for which wind and tide data are available for the GoC, and, if possible, all months during which ovigerous female migration and larval transport may take place. The number of larvae 'lost' per region per year could also be a useful metric to identify how 'risky' recruitment of larval mud crabs may be in various regions over time.

Chapter 11. Extension and Adoption

A media statement was released at the start of the project on the 23/03/2018.

Project staff have kept the crab fishery management committees in the NT and Qld (Crab Working Group) informed of project progress during meetings in 2018 and 2019.

Rik Buckworth presented at the National Estuaries Network meeting in Darwin, June 2018, illustrating environmental factors thought to affect NT catches of Giant Mud Crabs.

Julie Robins presented a summary of the project to the annual Gulf Fishermen's meeting in Karumba in October 2018.

Julie Robins and Mark Grubert attended the Territory NRM Annual Conference (poster presentation) and the Mini-Symposium on fisheries and oceanographic research in the GoC (oral presentations), both held in Darwin on the 14^{th} and 15^{th} of November 2018.

Results will be disseminated when the final report has been finalised. These will include a formal presentation to the Fisheries Queensland Crab Working Group when it next meets, a social media post on Fisheries Queensland Facebook page, a webpage summarising results on the DAF Agri-Science site, and a meeting with industry members from the Gulf to discuss results, when restrictions associated with covid-19 permit.

Project materials developed

Products from the project (i.e. scientific papers, factsheets) are still in development.

We propose to submit for publication aspects of Chapter 4 and Chapter 7 (manuscripts currently in draft).

We propose to develop a four-page project factsheet summarising key information, including data for key environmental factors, for distribution (hard copy and electronically) to active crab fishers in the NT and Qld jurisdictions of the GoC.

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(in alphabetical order)

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Ms Amanda Northrop, Senior Fisheries Scientist, Fisheries Queensland

Dr Julie Robins, Principal Fisheries Biologist, Fisheries & Aquaculture

Dr Wayne Sumpton, Senior Fisheries Biologist, Fisheries & Aquaculture (now retired)

Department of Primary Industries and Resources

Dr Mark Grubert, Senior Fisheries Scientist, Fisheries Research

Dr Thor Saunders, Principal Scientist, Fisheries Research

Charles Darwin University

Dr Rik Buckworth, University Professional Fellow, RIEL/ (Director, Sea Sense Australia Pty Ltd)

Ms Ruth Patterson, PhD Candidate

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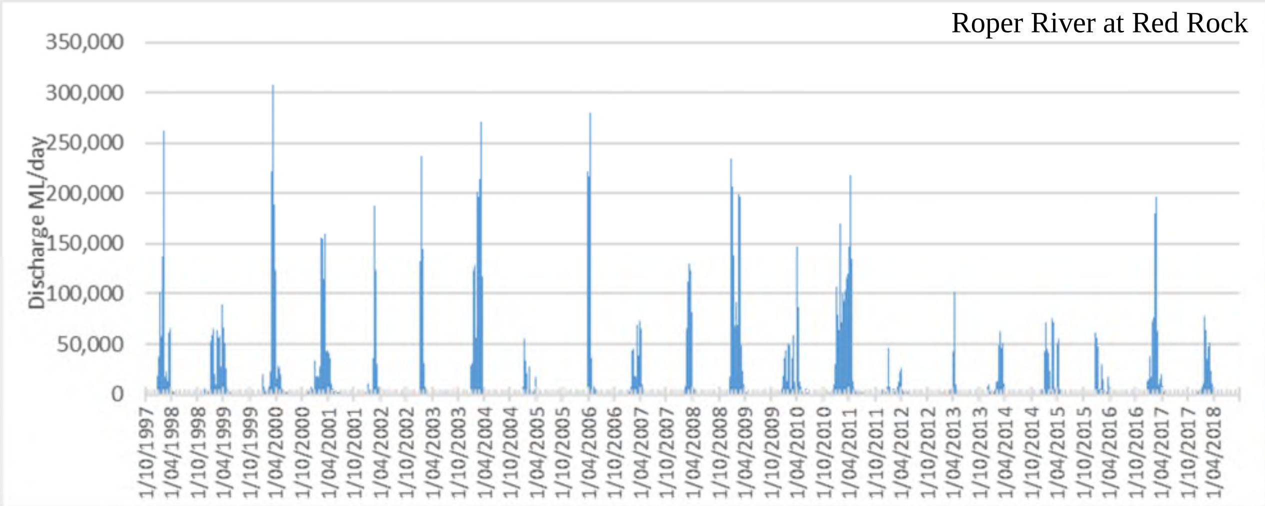
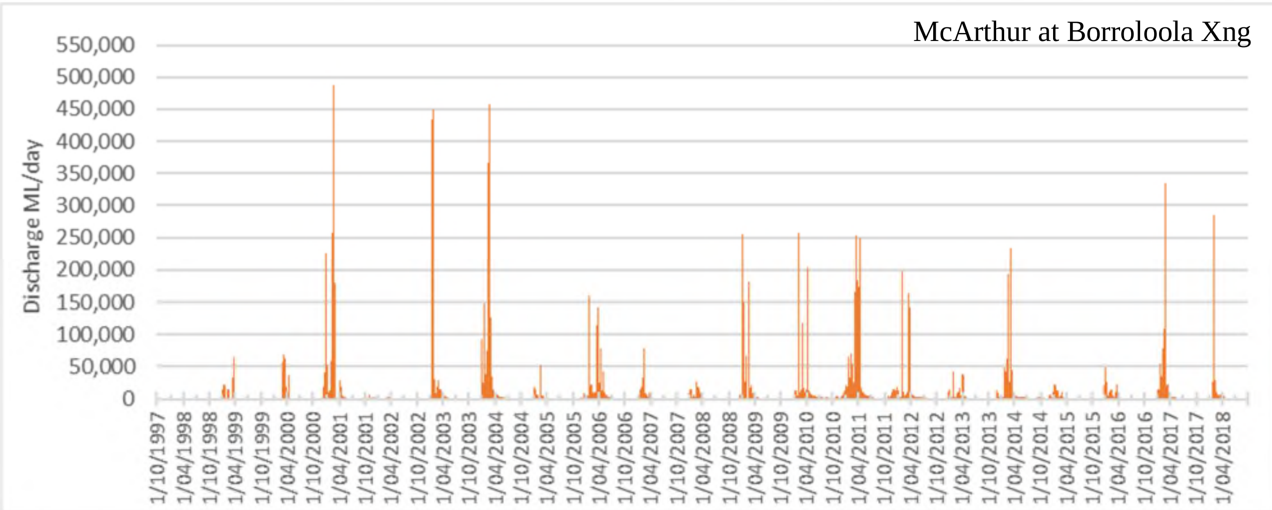
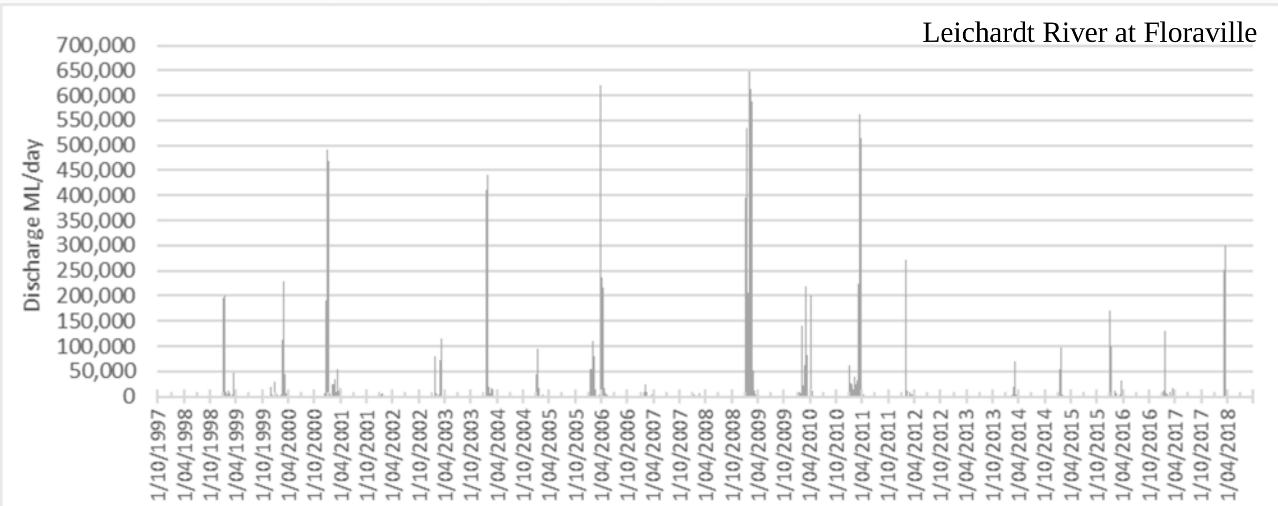
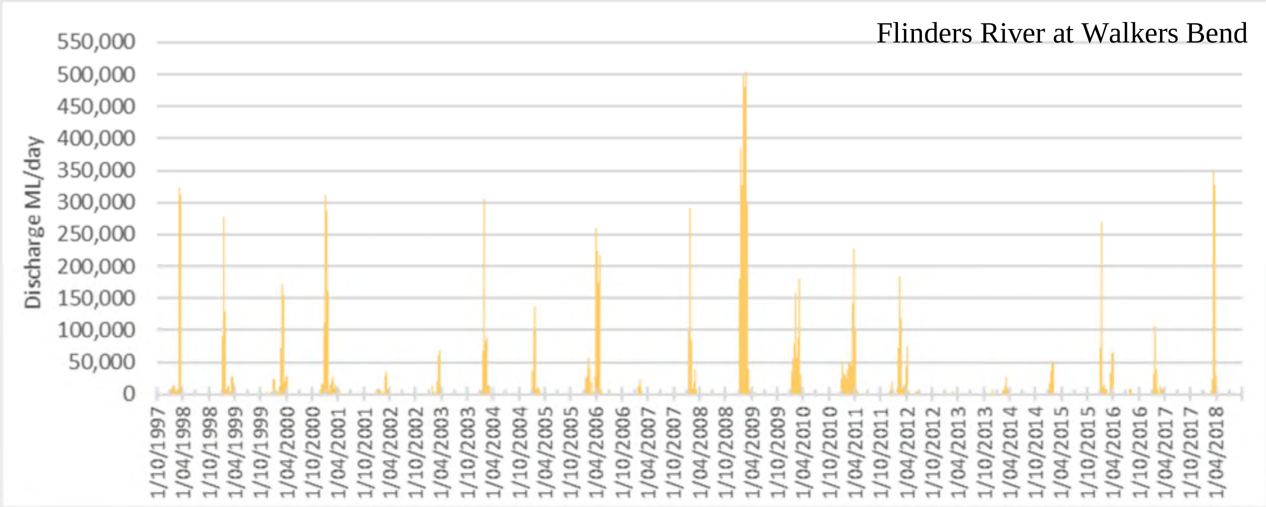
Appendix 3. Additional information

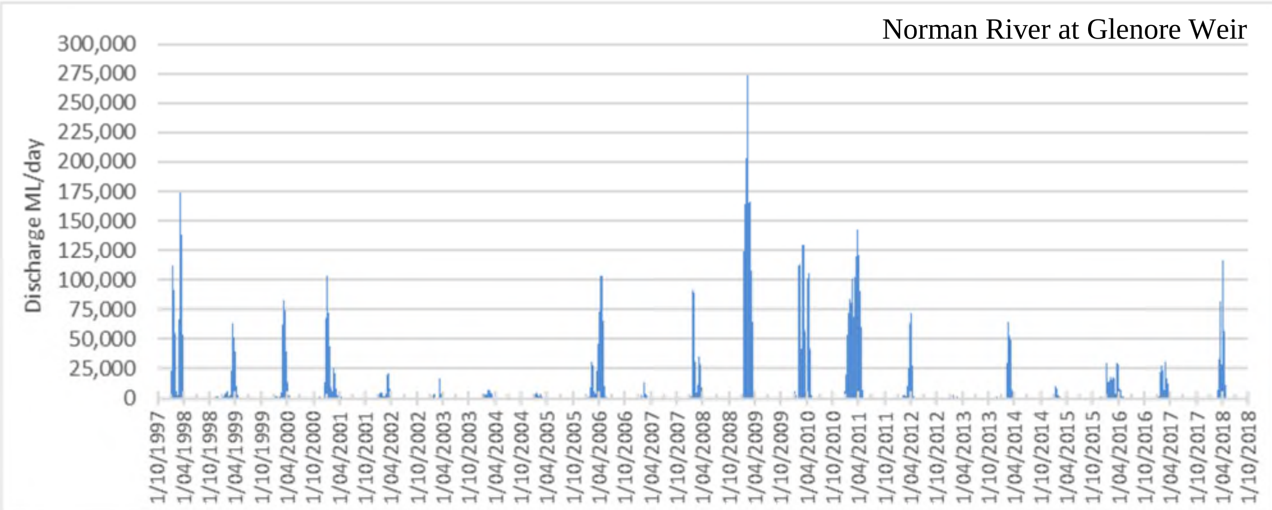
Plots of river flow for major rivers in each region of the Gulf of Carpentaria.

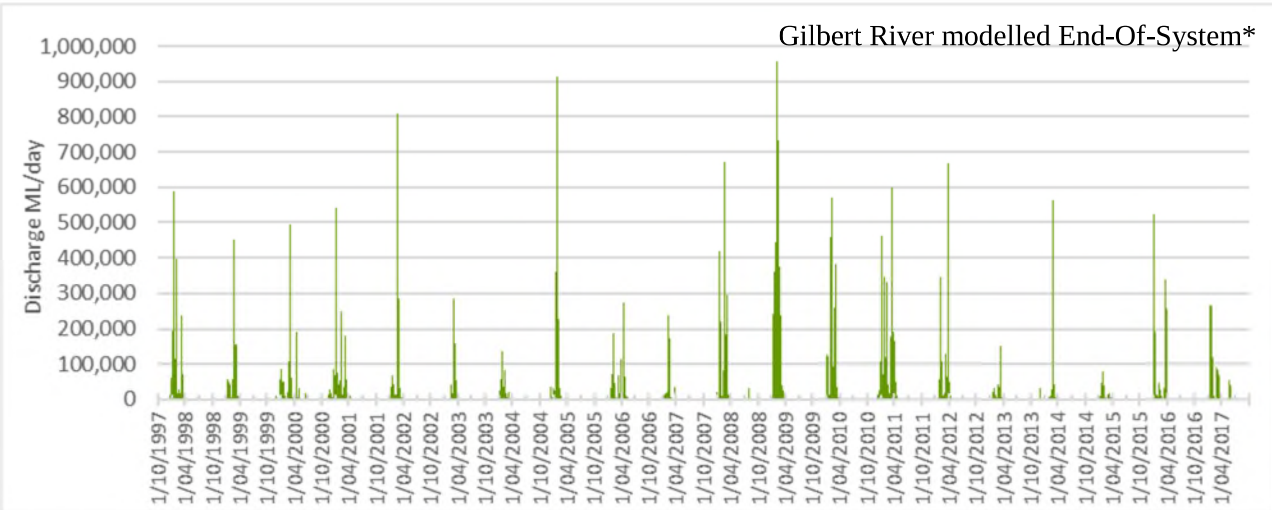







Flinders River at Walkers Bend
Discharge ML/day
550,000
500,000
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0


Norman River at Glenore Weir
Discharge ML/day
300,000
275,000
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0


Gilbert River modelled End-Of-System*
Discharge ML/day
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0

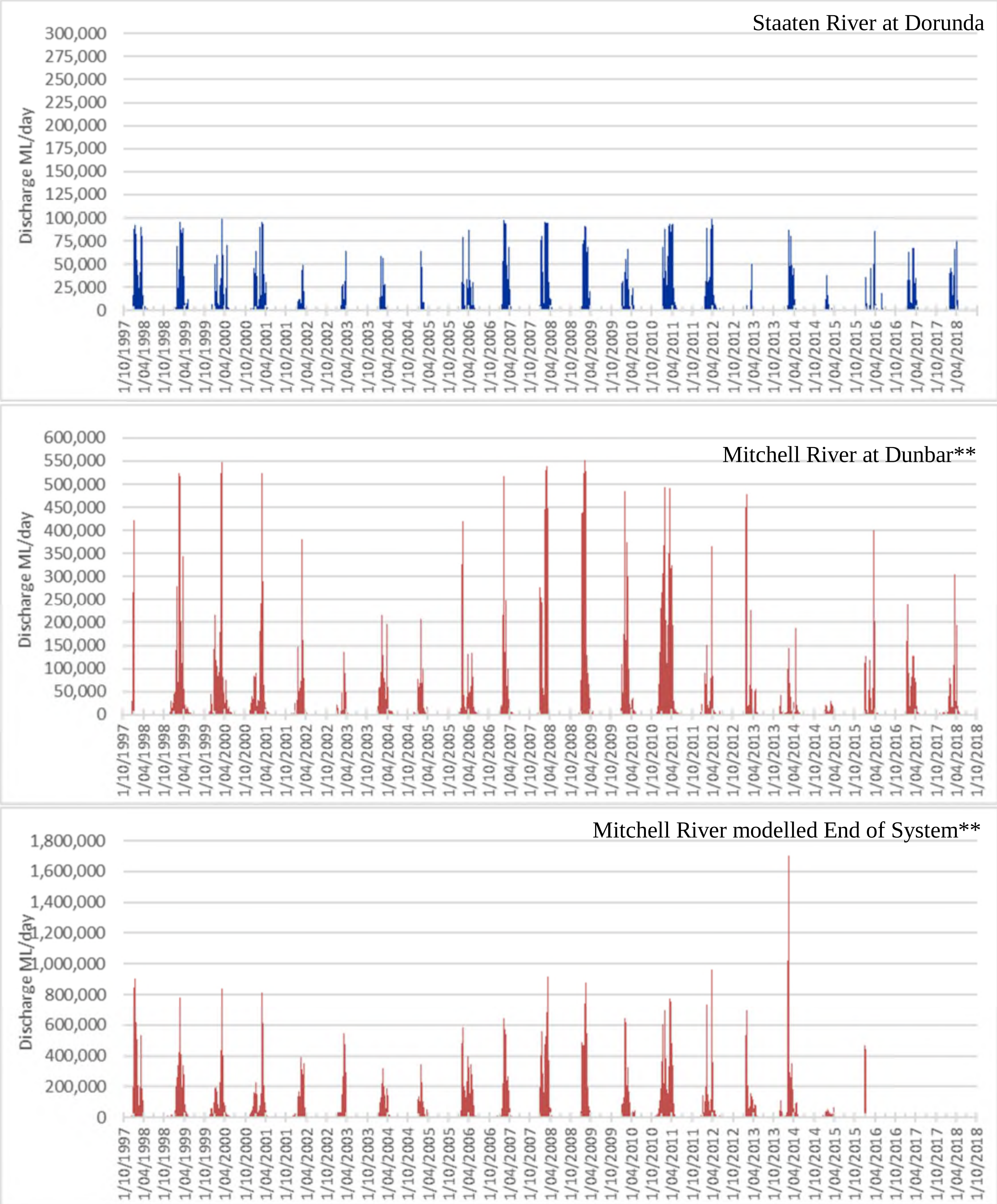


Figure A3.1.Temporal patterns in daily discharge for the major rivers per regions of the Gulf of Carpentaria. No discharge data is presented for the Aurukun or Weipa-Mapoon regions. See text for details.

Patterns in interpolated coastal air temperature against historic in-water observed and offshore satellite-derived sea surface temperature (SST).

Staples (1983) provides mean monthly water temperature in the Norman River for September 1976 to August 1979. This was compared with interpolated coastal air temperature for 17.464 ºS, 140.822 ºE downloaded from https://www.longpaddock.qld.gov.au/silo/point-data/. Monthly metrics of the interpolated coastal air temperature were calculated (average, minimum and maximum) and compared against the data in Staples (1983), see Figure A3.1. All monthly metrics derived from the interpolated coastal air temperature data were significantly correlated ($p < 0.001$) to the observed monthly water temperatures reported in Staples (1983), see Table A3.1.

Table A3.1. Correlation coefficients (*r*) between interpolated coastal air temperature (from SILO) and observed mean monthly water temperature in the Norman River reported by Staples (1983).

Avg T.Avg	Min T.Min	Avg T.Min	Max T.Min	Min T.Max	Avg. T.Max	Max T.Max
0.96	0.94	0.97	0.95	0.68	0.85	0.77

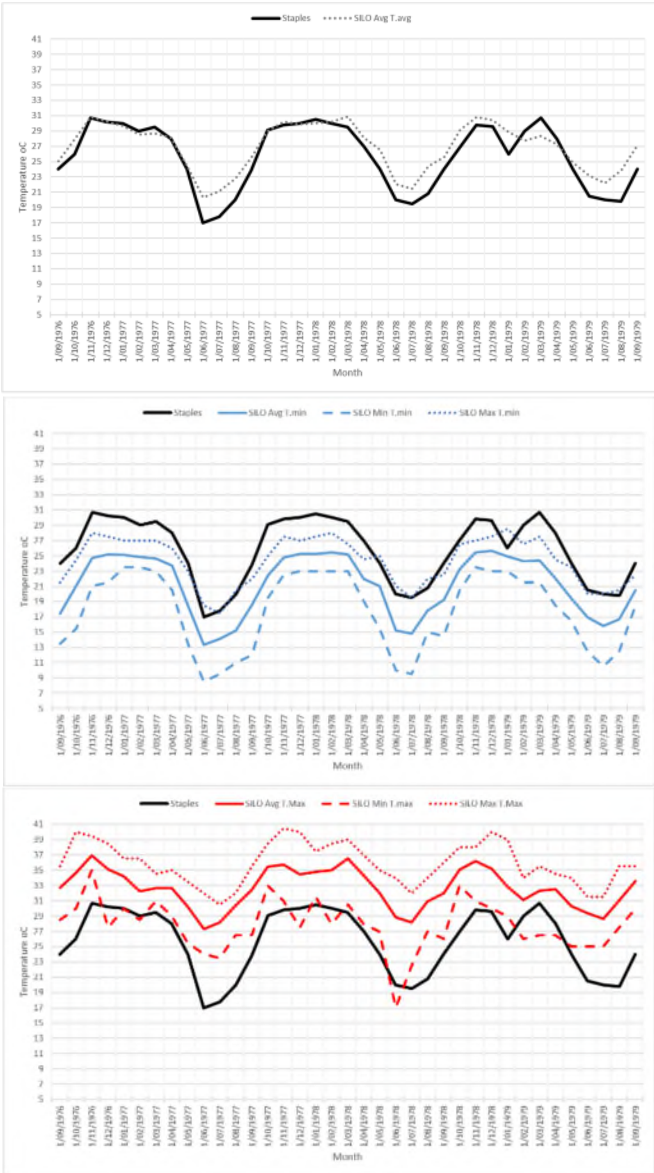


Figure A3.2. Patterns in interpolated coastal air temperature against offshore sea surface temperature.

SST data derived from MODIS aqua (8-day average, both day and night) showed few records with temperature below 20 ºC or above 32 ºC (see Figure A3.2).

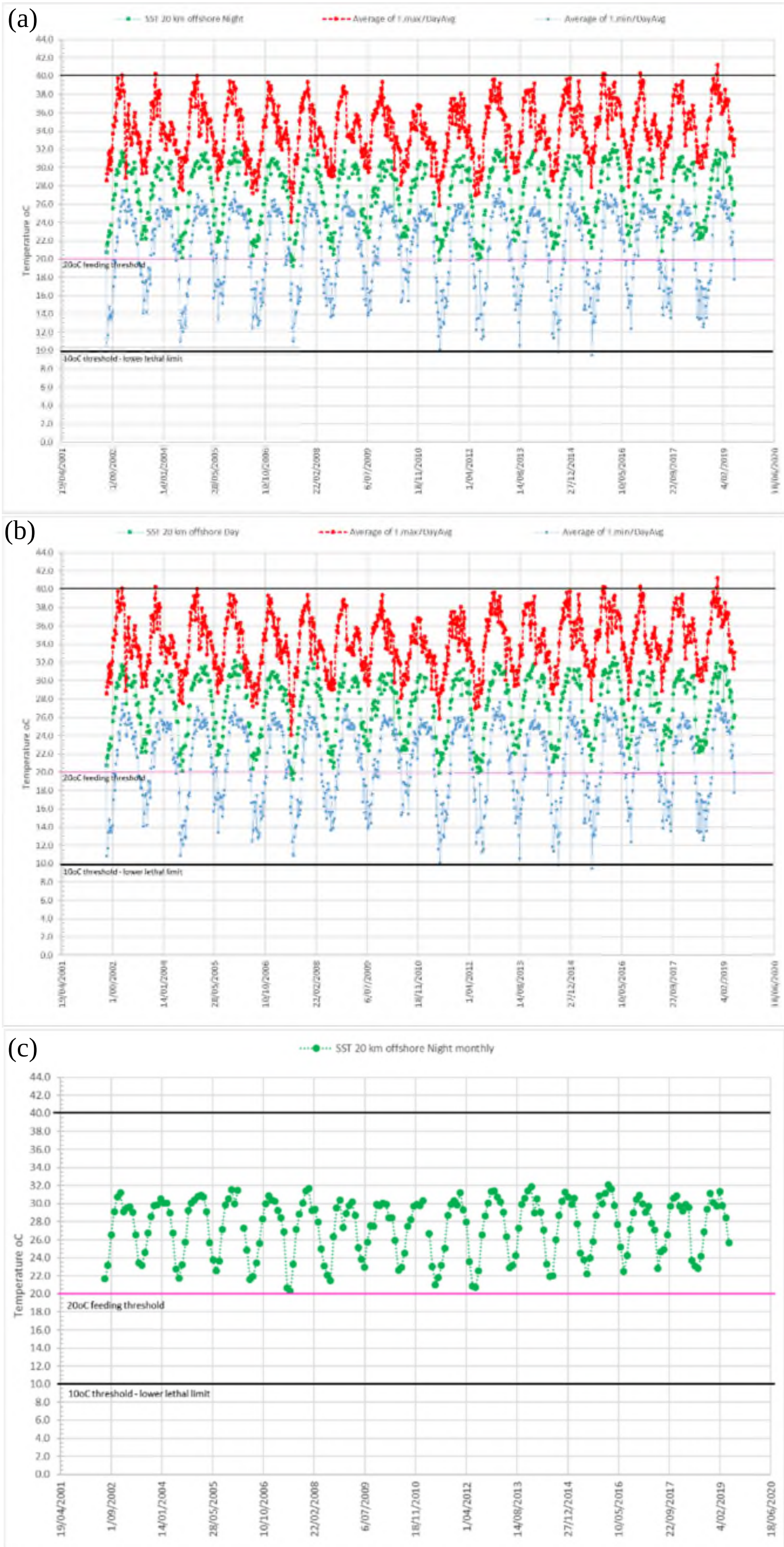


Figure A3.3. Sea surface temperature (SST) and interpolated coastal air temperature – example shown for the Roper region for: (a) 8-day average night-time SST, (b) 8-day average day-time SST, and (c) monthly average night-time SST.

Matlab code of annual delay-difference model for Northern Territory Western Gulf of Carpentaria Mud Crab Fishery

```
%% Stock assessment mudcrab fishery: data inputs.
% Note -this replicates "GOC mud crab model 2017 data.xlsm" which was sent
% by NT Fisheries on the 14th March 2018 as the most recent and accurate
% file; based on Grubert et al. (2019).

% Authors: A. R. Northrop
% Created: 12 March 2018

%
%% Select working directory and fishery data to load

%% Load all data.

T = readtable('NT Mudcrab v2.xlsx');  %year, Effort and Catch loaded

%These are hardcoded

q   = 1.5           % Catchability coefficient in first year of fishing (1983)
before taking into account fishing power
amax=   2           % How much the fishing power has increased in 2015 relative
to 1983.  A value of 2 means crabs are now twice as catchable than in 1983. A
value of 1 means no change in q
futanom=    0       % Future anomalies
Bhalfq= 1.00E+20    % Scaling factor


% g is worked out from NT data, see Grubert et al 2019 for details.
g = 0.36  % Growth of surviving individuals


cpue = T.Catch./T.Effort
Minyear = min(T.year)
Countyear = length(T.year)


%This is an estimate of fishing power - currently assumed fishing
%power was double in 2017 than that of 1983, and increased linearly between
%those years
relq = 1+(amax-1).*(T.year-Minyear)/(Countyear-1)


%Predicted "U" where U(t) = 1-exp(-q*E(t))

predu = zeros(Countyear,1);
predu(1)= 1-exp(-q*relq(1)/1000*T.Effort(1))

%Needs an estimate of predu(1) to get biomass(1), then biomass(1) used to
%calculate the rest of the predu's

Bt = zeros(Countyear,1);
Bt(1) = T.Catch(1)/predu(1);

 for y=1:Countyear-1
    predu(y+1) = 1-exp(-q*relq(y+1)/1000.*T.Effort(y+1)./(1+Bt(y)/Bhalfq))
    Bt(y+1) = T.Catch(y+1)./predu(y+1)
```

```
  end

%Survivors for the year

St = Bt-T.Catch

%Recruits for 2 years ahead
%Rtplus2=zeros(Countyear,1);


for y=1:Countyear-2
    Rtplus2(y) = Bt(y+2)-g*St(y+1)
end

%Include final 2 NaNs to get vectors the same length
Rtplus2(34:35) = NaN;
Rtplus2 = transpose(Rtplus2);

%Recruits from t+2 / Survivors from current year - this is the Y to the
%regression for estimates of a and b - where a estimates productivity at low
stock size

lnrtp2dvS = log(Rtplus2./St);

%Get slope and intercept

X = St(1:Countyear-2);
Y = lnrtp2dvS(1:Countyear-2);

coefs = polyfit(X,Y,1);

a = coefs(2) %intercept
b = coefs(1) %slope

%Weights - ie recruitment anomalies

wt =Y-(a+b.*X)+1 %Could be compared against environmental explanatory variables

%MSY estimates and maximums
Smsy = Sm(a,-b,g)  %Level of survivors at MSY
Bmsy=Smsy*exp(a+futanom+b*Smsy)+g*Smsy
Umsy = 1-Smsy/Bmsy
Fmsy = -log(1-Umsy)
umax = max(predu)
Fmax = -log(1-umax)
Smax = max(St)

%Stock recruitment
SbySmax = 0:0.05:1
S = Smax*SbySmax
R = S.*exp(a+b.*S)

%Plot actual recruitment versus expected recruitment

figure
plot(S, R, 'r')
axis([0 500 0 1800 ])
```

```
hold on
s=scatter(St, Rtplus2, 'k')

xlabel('S(t)')
ylabel('R(t+2)')
title('Stock Recruitment Relationship')

hold off

forgr = ones(Countyear-2,1);
%Plot recruitment anomalies
figure
plot(T.year(1:Countyear-2),wt, 'r')
axis([1983 2018 0 2.5 ])
hold on
plot(T.year(1:Countyear-2),forgr, 'b')
hold off
xlabel('Year')
ylabel('W(t)')
title('Historical Recruitment Anomalies')
```