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Giant mud crab (*Scylla serrata*) catches and climate drivers in Australia – a large scale comparison

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Abstract. Patterns in the Southern Oscillation Index (SOI) affect the life history of many aquatic organisms in the southern hemisphere. We examined the effect of this phenomenon and other factors (i.e. rainfall, river flow and sea surface temperature, SST) on the commercial harvest of the giant mud crab (*Scylla serrata*) in Australia, given the large inter-annual variations in the catch of this species over the last 15 years, particularly in the north. Regression models were applied to concurrent environmental and catch data for giant mud crab caught from 29 catchments that provided a combined harvest of >20 000 tonnes. Non-metric multidimensional scaling (nMDS) was also used to explore potential regional differences in catch trends. A combination of SOI, SST and rainfall/river flow explained 30–70% of the variability in commercial catches, with mean summer temperature being most influential at higher latitudes. The nMDS revealed distinct groupings of river systems that coincided with biogeographic regions. This work highlights the importance of climatic events on the harvest of giant mud crabs and reinforces the need to adopt a bioregional approach when assessing the performance of fisheries targeting this species.

Additional keywords: climate dependence, fisheries modelling, regional comparison.

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Introduction

The giant mud crab (*Scylla serrata*) is widely targeted in commercial and recreational Australian fisheries and also caught in south-east Asia (Walton *et al.* 2006). Estimates of the national, annual gross value of production (GVP) of fisheries targeting these species approaches AU$30 million in some years (Environment Australia 2002; NSW DPI 2008; Qld DPI 2009), with most (>99%) of product sold being the giant mud crab. Four distinct *Scylla* species commonly occur throughout tropical to warm temperate areas of the Indo-west Pacific and have been described based on morphological and genetic characteristics: *S. serrata*, *S. tranquebarica*, *S. olivacea* and *S. paramamosain* (Keenan *et al.* 1998). The giant mud crab is the largest and most common of the two species of *Scylla* harvested in Australian waters (Keenan 1999) where their distribution extends from Exmouth Gulf, Western Australia, through the Northern Territory and Queensland to southern New South Wales (Knuckey 1999). The other species, the orange mud crab, *S. olivacea*, constitutes zero or <1% of the total catch in most jurisdictions (i.e. NSW, the NT and Qld), the exception being Western Australia where it can constitute a much higher proportion of the catch). Significant inter-annual variations in catches and consequent impacts on the GVP are of concern to industry and other stakeholders, particularly in the NT and Qld, which support the largest commercial fisheries for these species. Much of this variability is due to fluctuations in fishing effort; however, catch per unit effort (CPUE) has shown the greatest relative change. This metric, although imperfect (owing to potential hyper-stability in catch rates) can provide some measure of the relative abundance of the giant mud crabs, particularly when similar patterns are observed over large temporal or spatial scales.

The abundance of giant mud crabs appears to be strongly linked to the prevailing environmental conditions during their early life history (Hill 1974; Heasman *et al.* 1985; Webley and Connolly 2007). Both rainfall and river flow, which are mediated through changes in the Southern Oscillation Index (SOI) in the southern hemisphere (Zhang and Casey 1992), have a range of direct and indirect effects (e.g. changes in salinity) on the giant mud crab (Chandrasekaran and Natarajan 1994; Robertson 1996; Ruscoe *et al.* 2004). River flow is critical in maintaining the delivery of nutrient and detrital inputs to estuaries, as well as preventing hyper-saline conditions (Blaber and Milton 1990; Robertson and Duke 1990; Forbes and Cyrus 1992). Assuming nutrient availability increases with river flow, it is reasonable to expect that higher flow rates culminate in greater primary, secondary and tertiary production, including that of giant mud crabs. Indeed, several works have shown positive relationships between commercial catches of the giant mud crab and river flow/rainfall in parts of eastern Australia (specifically Qld; Robins *et al.* 2005; Meynecke *et al.* 2006, 2007) (see Table S1 available as Supplementary Material to this paper). The timing of flow events may also affect the catchability of giant mud crabs (Poovichiranon 1992).

Another factor that influences the life cycle of giant mud crabs is temperature. Temperature affects all facets of the life history of this species from larval viability and development to the feeding activity and movement of adults (Hill 1974; Hill 1980; Hamasaki 2003). Poole *et al.* (2008) suggested an optimal larval survival temperature of 25–30°C, whereas the feeding activity of adult giant mud crabs is greatly reduced at water temperatures below 20°C (Hill 1980).

However, the influence of temperature on the life history of giant mud crabs varies between regions. For example, larvae of South African giant mud crabs exhibit high mortalities at temperatures above 25°C (Hill 1974), whereas Japanese giant mud crab larvae showed lowest mortality at 29°C (Hamasaki 2003). Regional differences in temperature optima are perhaps to be expected in a species with such a wide geographic distribution (i.e. across most of the Indo-west Pacific oceans; Keenan 1999). In general, temperature effects may become stronger and species interactions weaker at the latitudinal limits of a species (Myers and Mertz 1998). Other factors influencing the distribution and abundance of giant mud crabs include currents, tides, wind, lunar cycle and dissolved oxygen. Many of these variables are interlinked, so it is difficult to separate their individual effects. Furthermore, most of these factors operate on different temporal cycles to the (predominately monthly) reporting of giant mud crab catch data in Australia.

In the work presented here we tested two hypotheses: (1) that increased sea surface temperature and rainfall (or freshwater flow) during positive SOI episodes will enhance the catch rates of giant mud crabs in Australia; and (2) that the influence of sea surface temperature and rainfall on the catch rates of giant mud crabs will vary among regions. Relationships between catch rates and physical variables (in isolation and combination) were examined across several spatial scales (i.e. regional, jurisdictional and national) in an attempt to explain the mechanisms underlying catch variability in different areas.

Materials and methods

Study location

This study focussed on 29 catchments containing 52 river systems that support commercial giant mud crab fisheries in the NT, Qld and NSW, Australia (Fig. 1). Data from the commercial mud crab fishery in WA was not used owing to the small size and sporadic nature of the fishery, the prevalence of *Scylla olivacea* and uncertainties surrounding the identification/reporting of each species. The most productive river systems were selected on the basis of long-term catch data. These river systems provided the dominant contribution (>50%) to annual mud crab harvest in Australia (see Fig. S1 available as Supplementary Material to this paper), and allowed the examination of relationships between catch rates and physical factors under a range of climatic conditions along a latitudinal gradient.

Data

Mud crab catch data

Catch data (from trap (i.e. pot) fisheries only) were adjusted for effort using the number of fishing days recorded (CPUE, kg day^{-1}) (see Fig. S1 available as Supplementary Material to this paper). Adjusting the catch for effort using the number of days fished is a common practice for small-scale fisheries (Meynecke *et al.* 2006). Crab fishers in the NT and NSW are required to record the number of days fished per month, the average number of pots used on those days and how many times the pots were pulled twice (NT only). This information is then used to calculate the number of potlifts per month. Only crab fishers in Qld are given the option of recording the number of pots used on any given fishing day. Hence, it is possible that some fishers in the NT and NSW used more or fewer pots than average on some days, although this is not reflected in the data. For this reason we concentrated on fishing days as a measure for effort.

Monthly catch and effort data were selectively extracted from logbook records provided by the NT Department of Resources (DoR), the Qld Department of Employment, Economic Development and Innovation (DEEDI) and the NSW Department of Trade and Investment (DTI). River systems were selected based on the highest catch during the observation period (i.e. from 1984/85–2008) and the continuity of data, with the exception of the Daly River.

Environmental data

Mean monthly rainfall data within each catchment were selected using a 5 km rainfall grid for the period 1984–2008. Data were sourced from the Australian Government Bureau of Meteorology (BOM). The original ASCII data were converted into raster data in ArcGis 9.3, then transformed into point data and intersected with selected catchment areas to calculate rainfall data for each catchment. The mean of rainfall points per catchment area was used to calculate monthly average rainfall per catchment. The catchment area was based on Australian River Basin 1997 data provided by Geoscience Australia.

Daily freshwater flow data for each jurisdiction were screened for availability/continuity and compared with catchment rainfall (data courtesy of the NT Department of Natural Resources, Environment, The Arts and Sport (NRETAS), the Qld Department of Environment and Resource Management (ERM), the NSW Office of Water and the Sydney Catchment Authority). Flow rates in all river systems showed significant positive correlations with monthly average rainfall in the catchment area. In almost all cases, the strength of the relationship justified the use of catchment rainfall (mm) as a proxy for freshwater runoff. Catchment rainfall was a more consistent and continuous parameter when compared with freshwater runoff data from gauging stations.

Monthly SOI values (i.e. the difference in air pressure between Tahiti and Darwin) were obtained from the BOM website (www.bom.gov.au, accessed 18 August 2009). We used

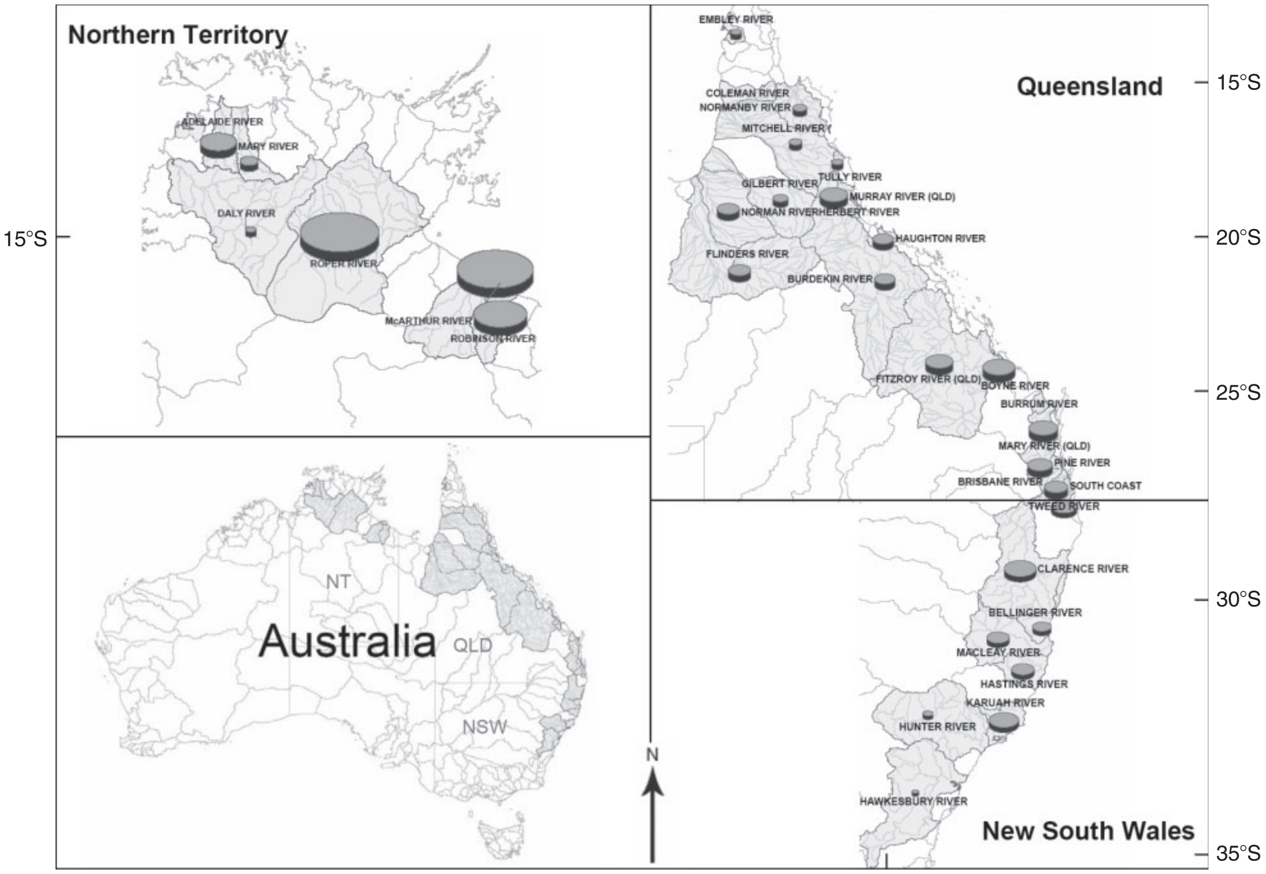

Fig. 1. Map of Australia showing the 29 selected catchments (grey) representing 52 major river systems. The relative proportion of total catch for the 29 catchments are indicated by the size of the discs for NSW (1997–2008), Qld, (1988–2008) and NT (1990–2008, Bynoe Harbour not included).

mean and maximum SOI values for our analyses. Negative values of the SOI are associated with El Niño conditions and below-average rainfall across north-east Australia. By contrast, positive SOI values are associated with a La Niña pattern in the central and eastern equatorial Pacific, and above-average rainfall for north-east Australia (Piechota *et al.* 1998).

Sea surface temperature (SST) was considered a more reliable source of temperature information than air temperature due to gaps in weather station data. We accessed SST data from NASA satellites (AVHRR Pathfinder V. 5 MODIS Aqua; http://poet.jpl.nasa.gov, accessed 14 January 2009), which provided a 4 km resolution of monthly daytime temperature information for the time period 1985–2007. The data were then converted into shapefiles in ArcGIS 9.3 and monthly average values calculated for each river system within a 20 km proximity of the river mouth.

Univariate analyses of individual river systems

Statistical analyses of giant mud crab catch and environmental data for NT, Qld and NSW were undertaken using forward regression and multiple regressions within the SPSS 17 software package (IBM, Armonk, NY, USA). The impacts of changing environmental conditions on fish communities can be estimated by running a regression of physical parameters such as rainfall or SOI (Beamish and Bouillon 1993; Aaheim and Sygna 2000). This method has been applied successfully in several studies and can provide insights into the relationships between physical parameters and catches of fish and invertebrates (Growns and James 2005; Gillson *et al.* 2009).

Forward linear regression was used to determine which environmental variables (i.e. the SOI, SST and rainfall/freshwater flow) explained the highest degree of variability in giant mud crab CPUE when configured as annual, monthly or seasonal datasets. Principal components generated to reduce autocorrelation resulted in similar outcomes when using log-transformed climatic variables but with slightly lower performance than for catch standardised for effort. Therefore, we targeted the analyses on a small number of variables and CPUE. To reduce autocorrelation (Pyper and Peterman 1998) between variables, we only selected parameters that were likely to be biologically relevant and have the strongest influence on the life cycle of giant mud crabs (e.g. temperature and rainfall/flow).

Other physical environmental factors such as moon phase, tidal range and currents were considered but not included in this analysis due to lack of local data or the temporal mismatch between these phenomena (that occur daily/fortnightly) and the reporting of commercial catch (monthly). We used a Bonferroni inequality adjustment to reduce the probability of making a

Type I error by creating a new α that had a lower significance than <0.05. The adjusted r^2 took into account co-linearity between variables and the degrees of freedom in the model. Giant mud crab catch data were reported differently between jurisdictions, so the datasets were not summarised; instead, a meta-analysis was performed using the results from each jurisdiction.

Multivariate and regional analyses

Non-metric MDS (using Primer 6.0; PRIMER-E Ltd, Lutton, UK; Clarke and Warwick 2001) was employed to describe similarities in annual giant mud crab CPUE, rainfall, temperature and flow (where available) between river systems and regions, using square-root transformed values and the Euclidean distance similarity measure. Trends between jurisdictions were observed by comparing the correlation values.

Results

Catch analyses

Giant mud crab catches in the NT increased from around 500 tonnes (t) in 1998 to just over 1100 t in 2001. This was followed by a sharp decrease in harvest over the next 2 years. The catch then increased to over 400 t in 2008. The Qld fishery experienced a steady increase in catch from 1988 to 2008, with a peak in 2004 of almost 1200 t. However, fluctuations of giant mud crab catches occurred between 2001 and 2005, similar to those experienced in the NT. During the period from 1985 to 1997, catches in NSW increased from 40 t to a peak of 160 t in 1991–92 followed by oscillating lows between 100 and 80 t per fiscal year and a peak of 110 t per fiscal year until 1996–97. Catch rates then decreased from 130 t to 80 t per fiscal year for the time period 1997–98 to 2007–08. In both cases, effort (as number of fishing days) followed a similar trend to catch with a change in logbook reporting after 1996–97 causing effort to drop (see Fig. S1 available as Supplementary Material to this paper). High catches occurred in all jurisdictions in 2001–02.

Regression analyses

Regression analyses using the NT giant mud crab CPUE and the climatic variables revealed significant relationships between seasonal rainfall (using average data for wet and dry seasons) lagged by one season and annual maximum SOI values. These two variables explained 30–40% of the catch variability for four of the seven river systems investigated. A summary of the total NT annual giant mud crab CPUE and a comparison with maximum SOI values highlights the possible influence of this variable on giant mud crab catch, with an r^2 of 0.32 ($P = 0.02$). The r^2 values for the positive relationship between maximum SOI and CPUE with a 2-year lag were slightly lower ($r^2 = 0.30$, $P = 0.04$). Higher r^2 values were found for the two rivers with continuous flow data, that is, the Adelaide and Roper Rivers (Fig. 2). Annual variability in the NT catch of giant mud crab was best explained by the maximum SOI and mean wet season rainfall 2 years before the catch.

The analyses of the Qld CPUE showed that the SOI and rainfall explained 30–50% of the variation in catch rate for six of the fourteen river systems examined. The wet season CPUE for the two river systems with continuous flow data was significantly related (Fig. 2). Small and sporadic catches from some rivers in the eastern Gulf of Carpentaria often led to non-significant results for these systems.

When giant mud crab CPUE was lagged by 2 years, data still showed significant r^2 values for most of the river systems, with rainfall and SOI being the most relevant drivers. Annual Qld giant mud crab catch was best explained by maximum SOI and mean annual rainfall. Significant relationships between Qld annual mud crab CPUE over 20 years of observation and annual maximum SOI values may explain 34% of catch variability. The Calliope, Normanby and Mary River systems showed no significant results (Tables 1, 2).

Results for NSW indicated that the best explanatory factor for giant mud crab CPUE was temperature, either in combination with SOI, or mean rainfall and SST. These factors explained 20–45% of the variation in monthly CPUE. When catchment rainfall was added as a covariate in the linear regression models, the r^2 values increased to 0.5–0.7 for some river systems (e.g. Tweed, Camden, Clarence Rivers). Linear regression of SST and mean giant mud crab CPUE, lagged by 2 years (for different seasons), found that the best explanatory factor was mean summer SST or mean spring SST (Table 2). This pattern was clearest in the 1985–97 dataset, where a positive relationship between mean autumn SST and giant mud crab CPUE was identified.

There were positive relationships between spring and summer SST (or rainfall/flow) and CPUE of giant mud crabs across most NSW rivers. This trend was most apparent in the Clarence and the Hunter Rivers (Table 1; Fig. 2). The strength of the relationship between CPUE and maximum SOI values was similar to NT and Qld ($r^2 = 0.30$) but slightly weaker and only evident for the time period 1984/85 to 1996/97. Annual catch patterns in NSW were best explained by mean summer SST and mean summer rainfall 2 years before catch. These positive relationships between CPUE and physical factors support our first hypothesis that increased SST and rainfall during positive SOI episodes enhances the catch rates of giant mud crabs in Australia.

Multivariate and regional analyses

Non-metric multidimensional scaling plots of giant mud crab catch, effort (fishing days), mean rainfall and mean sea surface temperature for the NT showed regional separation. The Adelaide, Daly and Mary Rivers, along with Bynoe Harbour, formed one distinct group whereas the Robinson, Wearyan and McArthur Rivers formed a second (Fig. 3*a*). In Qld, the data separated into three major groups: Gulf/northern Qld, central Qld, and southern Qld. The south-east and central Qld river systems overlapped and there were similar relationships between giant mud crab CPUE and environmental drivers for these river systems (Fig. 3*b*).

The nMDS plot for NSW separated rivers into two major groups: the Central and North Bioregions. As previously defined by Pease (1999) and expanded by Saintilan (2004), the Hunter and Hawkesbury Rivers fall within the Central Bioregion, with the others located in the Northern Bioregion.

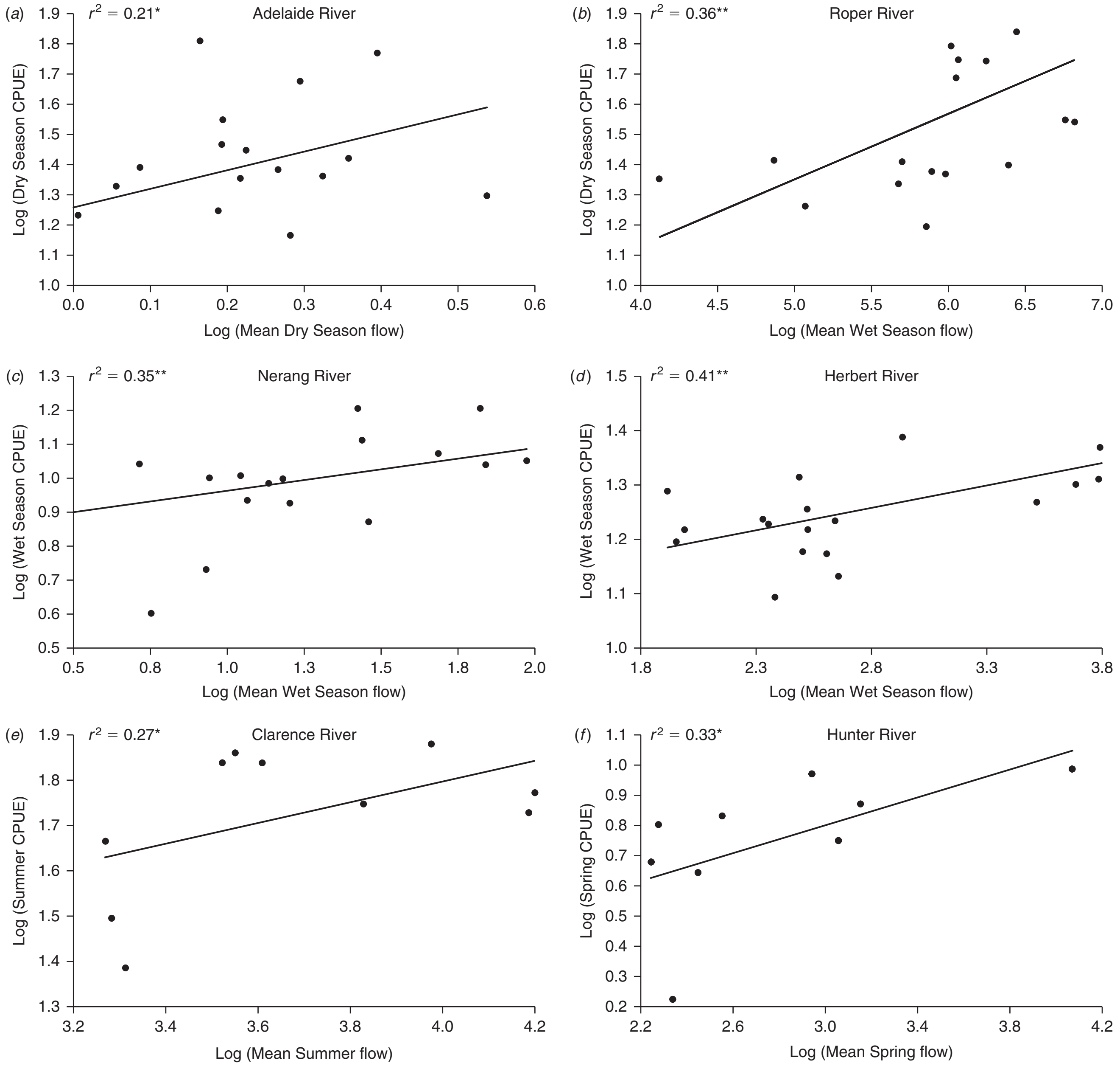

Fig. 2. Linear relationships between log-transformed seasonal mud crab catch per unit effort (CPUE) and mean seasonal flow for selected river systems in the NT ((*a*) Adelaide River: 1990–2008; (*b*) Roper River: 1990–2007), Qld ((*c*) Nerang River: 1989–2006; (*d*) Herbert River: 1989–2006) and NSW ((*e*) Clarence River: 1985–1997; (*f*) Hunter River: 1997–2006).**, $P < 0.01$; *, $P < 0.05$.

The differentiation within the dataset is driven by temperature, with cooler temperatures in the Central Bioregion and slightly warmer temperatures in the Northern Bioregion. Total catches (as indicated by the size of the circles in the nMDS plot) were also significantly different between Central and Northern Bioregions (Fig. 3*c*).

The multivariate analyses of CPUE, SST and rainfall, in conjunction with the higher r^2 values for the CPUE × SST relationships at higher latitudes, suggest that the linkage with SST becomes more significant towards the southern distributional limit of giant mud crabs. Northern river systems with high rainfall generally had higher catches, and there was a strong relationship between rainfall and giant mud crab CPUE. Conversely, river systems in the south typically yielded lower catches, with stronger linkages to temperature than rainfall (Fig. 4*a*, *b*). These results support our second hypothesis that the influence of temperature and rainfall on the catch rates of giant mud crabs varies among regions.

Table 1. Significant r^2 values ($P < 0.05$ and $P < 0.01$) from forward linear regressions between log-transformed giant mud crab catch per unit effort (CPUE), mean and maximum Southern Oscillation Index (SOI) values, mean and maximum catchment rainfall and mean sea surface temperature (SST) applied to seasonal data configurations (NSW: n = 11/12, NT: n = 18 dry/17 wet, Qld: n = 20)

Significance after Bonferroni adjustment indicated with * (Qld: 0.0003, NT: 0.0008, NSW: 0.0006). Note: Robinson/W, Robinson and Wearyan Rivers; NSC, not significant

Region	River system	Climatic parameter	Period	Adjusted r^2	*P*-value	Parameter	Adjusted r^2 2 year lag	*P*-value
NT	McArthur	Dry SOI	1990–2008	0.444	0.01	Dry SOI	0.636	0.00*
		Wet SOI	1990–2008	0.223	0.02	–	NSC	NSC
	Adelaide	Dry SOI	1990–2008	0.344	0.05	Dry SOI max	0.553	0.00*
		Wet SOI	1990–2008	0.372	0.03	–	NSC	NSC
	Mary	Dry SOI max	1990–2008	0.241	0.02	Dry SOI max	0.591	0.00*
	Bynoe H	Dry SOI	1990–2008	0.296	0.09	Dry SOI max	0.421	0.02
		Wet SOI	1990–2008	0.206	0.03	–	NSC	NSC
	Roper	–	1990–2008	NSC	NSC	Dry SOI	0.441	0.02
	Robinson/W	–	1990–2008	NSC	NSC	Dry SOI	0.441	0.02
Qld	Barratta	Wet rain/SST max	1988–2008	0.192	0.05	–	NSC	NSC
		Dry SOI/SST max/rain max	1988–2008	0.324	0.02	–	NSC	NSC
	Barron	Wet SOI	1988–2008	0.166	0.04	–	NSC	NSC
	Brisbane	Wet SOI/rain	1988–2008	0.233	0.04	–	NSC	NSC
	Burdekin	Wet SOI/rain/SST max	1988–2008	0.454	0.00	–	NSC	NSC
		Dry SOI/rain	1988–2008	0.243	0.03	–	NSC	NSC
	Callipse	–	1988–2008	NSC	NSC	Wet rain/SOI	0.258	0.03
	Gilbert	Dry rain/SST/SOI	1988–2008	0.401	0.01	–	NSC	NSC
	Herbert	Wet rain max/SST/SOI	1988–2008	0.294	0.03	–	NSC	NSC
		Dry SOI/rain/SST	1988–2008	0.397	0.01	–	NSC	NSC
	Marry	Wet SST/rain	1988–2008	0.170	0.05	–	NSC	NSC
	Embley	–	1988–2008	NSC	NSC	Wet rain max	0.175	0.04
	Brisbane	–	1988–2008	NSC	NSC	Dry SST	0.181	0.04
NSW	Clarence	Autumn SST	1985–97	0.439	0.01	Summer Rain	0.227	0.04
	Camden Haven	Autumn SST	1985–97	0.352	0.02	Summer Rain	0.337	0.02
	Macleay	Spring SST	1985–97	0.448	0.01	–	NSC	NSC
	Tweed	Summer Rain	1985–97	0.342	0.02	Spring SST	0.285	0.04
	P. Stephens	Summer SST	1985–97	0.393	0.01	Summer Rain	0.522	0.00*
	Hunter	Summer SST	1985–97	0.403	0.01	Spring Rain	0.716	0.00*
	Hawkesbury	Summer SST	1985–97	NSC	NSC	–	0.335	0.02

Discussion

This study defined regional patterns in giant mud crab catches across most of this species' Australian range and established distinct groupings of river systems using both univariate and multivariate analyses of CPUE, temperature, rainfall/river flow and the SOI. These groupings generally fell within recognised biogeographic regions (IBRA, Interim Biogeographic Regionalisation Australia). The hypothesis of a positive relationship between giant mud crab catch and temperature, rainfall and SOI in Australia (within certain bounds) was confirmed and at least one-third of the catch variation may be explained by these factors.

Biological links

SOI

Patterns in the SOI were a good predictor of giant mud crab CPUE in Qld, the NT (30–40% of the catch) and some parts of NSW (20–30%). The effects of this phenomenon were weaker in southern parts of Australia where the Indian Ocean Dipole (IOD) has a stronger influence on drought events (Ummenhofer *et al.* 2009). Relationships between the SOI (and rainfall) and mean annual CPUE lagged by 1 or 2 years were observed for all jurisdictions. This lag effect was shorter in the NT (18 months) and longer in NSW (24 month) – consistent with the different recruitment intervals in these regions. In northern Australia, the delivery of freshwater into estuaries increases during late spring and summer, depending on the seasonal summer monsoon trough reflected by the strength of the SOI (Zhang and Casey 1992). Given the relationship with SOI values throughout the datasets, a 4- to 7-year cycle of high catches would support the model that predicts highest catches when there is above average rainfall and temperature. A 15- to 20-year cycle with the Pacific Decadal Oscillation (PDO) would also be expected. Bayliss *et al.* (2008) found significant relationships between freshwater flow and the PDO using long-term datasets, but the data used here did not permit analyses over such a long interval.

Flow and catchment rainfall

Mean annual CPUE of giant mud crabs showed significant positive relationships with catchment rainfall (and when flow data was available) in many of the rivers examined. We believe that the explanation behind this trend is the same or similar for most north Australian systems; good wet seasons with higher

Table 2. Significant r^2 values from forward linear regressions between log-transformed giant mud crab catch per unit effort (CPUE), mean and maximum Southern Oscillation Index (SOI) values, mean and maximum catchment rainfall (flow has been used instead of rainfall when available) mean sea surface temperature (SST) applied to annual data (Qld: $n = 20$, NSW: $n = 11$ or 12, NT: $n = 18$) as well as annual mud crab CPUE lagged by 2 years

River systems that showed no significant r^2 values for both time lags were excluded from the table. Significance after Bonferroni adjustment indicated with * (Qld: 0.0007, NT: 0.002, NSW: 0.001); NSC, not significant

Region	River system	Climatic parameter	Period	Adjusted r^2	*P*-value	Parameter	Adjusted r^2 2 year lag	*P*-value
NT	Adelaide	SOI max	1990–2008	0.341	0.00*	Flow	0.266	0.02
	Mary	SOI max	1990–2008	0.380	0.00*	SOI max	0.259	0.02
	Bynoe H	SOI max	1990–2008	0.212	0.03	SOI max	0.139	0.05
	McArthur	SOI max	1990–2008	0.343	0.00*	–	NSC	NSC
Qld	Albert	–	1988–2008	NSC	NSC	Rain	0.201	0.04
	Barratta	SOI max	1988–2008	0.441	0.00	SOI max	NSC	NSC
	Brisbane	Rain max	1988–2008	0.230	0.02	Rain max	0.155	0.05
	Burdekin	SOI max	1988–2008	0.573	0.00*	SOI max	0.219	0.01
	Coleman	SOI max	1988–2008	NSC	NSC	Rain max	0.365	0.01
	Embley	Rain	1988–2008	0.323	0.01	Rain max/mean	NSC	NSC
	Fitzroy	SOI max	1988–2008	NSC	NSC	SOI max	0.492	0.00*
	Flinders	SOI max	1988–2008	NSC	NSC	SST	0.195	0.04
	Gilbert	SOI max	1988–2008	0.226	0.02	–	NSC	NSC
	Herbert	SOI max	1988–2008	0.589	0.00*	SOI max, SOI, flow	0.656	0.01
NSW	Camden	–	1985–97	NSC	NSC	Rain	0.321	0.03
	Clarence	–	1985–97	NSC	NSC	Rain	0.391	0.01
	Hastings	–	1985–97	NSC	NSC	SST	0.354	0.02
	Hawkesbury	Flow	1997–2006	0.307	0.04	–	NSC	NSC
	Hunter	SOI	1997–2006	0.549	0.01	Rain	0.347	0.02
		Flow	1985–97	0.391	0.01	–	NSC	NSC
	Macleay	Rain	1997–2008	0.227	0.04	SST (85–97)	0.274	0.04
	Port Stephens	–	1985–97	NSC	NSC	Rain	0.261/0.289	0.04
	Wallis Lake	SST	1997–2008	0.324	0.04	–	NSC	NSC
	Tweed	SOI	1985–97	0.300	0.04	–	NSC	NSC

than average rainfall increase river flow and flooding, thereby reducing salinity, increasing habitat availability and stimulating production by lower trophic levels leading to enhanced giant mud crab growth (Hill 1974; Hill and Williams 1982; Heasman *et al.* 1985; Le Vay *et al.* 2001). Anecdotal reports from fishers also suggest that high flow events can have temporary beneficial effects on CPUE for up to 2 weeks. This increase in catchability is probably due to the greater activity of giant mud crabs as they leave their burrows to find more saline waters. However, greater resolution in the catch data is needed to confirm these observations.

Positive relationships between rainfall and giant mud crab CPUE lagged by 5 and 6 months were evident in the NT and the eastern Gulf of Carpentaria (Qld). The probable cause was the combination of reduced fishing activity during the wet season (when the regions are inaccessible) and the influence of rainfall/flow on the development of giant mud crabs. Most river systems exhibited a positive lag effect on catch 2 years after above-average rainfall, likely enhancing the recruitment of giant mud crabs through increased productivity. Robins *et al.* (2005) found a positive correlation between the catch of the giant mud crab and summer freshwater flow; the inference here was that the influx of freshwater encourages seaward movement of adults and may trigger the spawning migration of females. This small-scale migration of adults could also increase the survival of juveniles by reducing cannibalism and competition for burrows, thereby increasing local productivity of the species. However, a negative 2-year lag effect of heavy rainfall events (causing major flooding) on CPUE was also evident. This may be due to the flood-induced removal or dieback of seagrass and consequent negative impacts on recruitment success of the giant mud crab (Webley *et al.* 2009). The rainfall-CPUE relationships indicate that the catch is not driven exclusively by total rainfall – spatial and temporal factors such as catchment area and the timing of rainfall, moulting and reproductive events also have a large part to play.

SST

We found strong positive relationships between monthly CPUE and temperature (SST) in some areas, particularly south-east Qld and NSW. Giant mud crabs, being poikilothermic, are less active and limit their foraging activities in the cooler dry season (south-east Qld) and winter (NSW). Most catches occur between February and April in these regions. A stronger dependence on temperature at the southern distribution limit of giant mud crabs can therefore be expected. In general, warm waters enhance productivity of estuarine systems (Cole and Cloern 1987) and accelerate the growth of giant mud crabs (Hill 1975). However, extreme high water temperatures (≥40°C) experienced when the incoming tide inundates shallow mud flats (Mounsey 1990) may suppress the activity and catch rate of giant mud crabs, the extent of this suppression being a

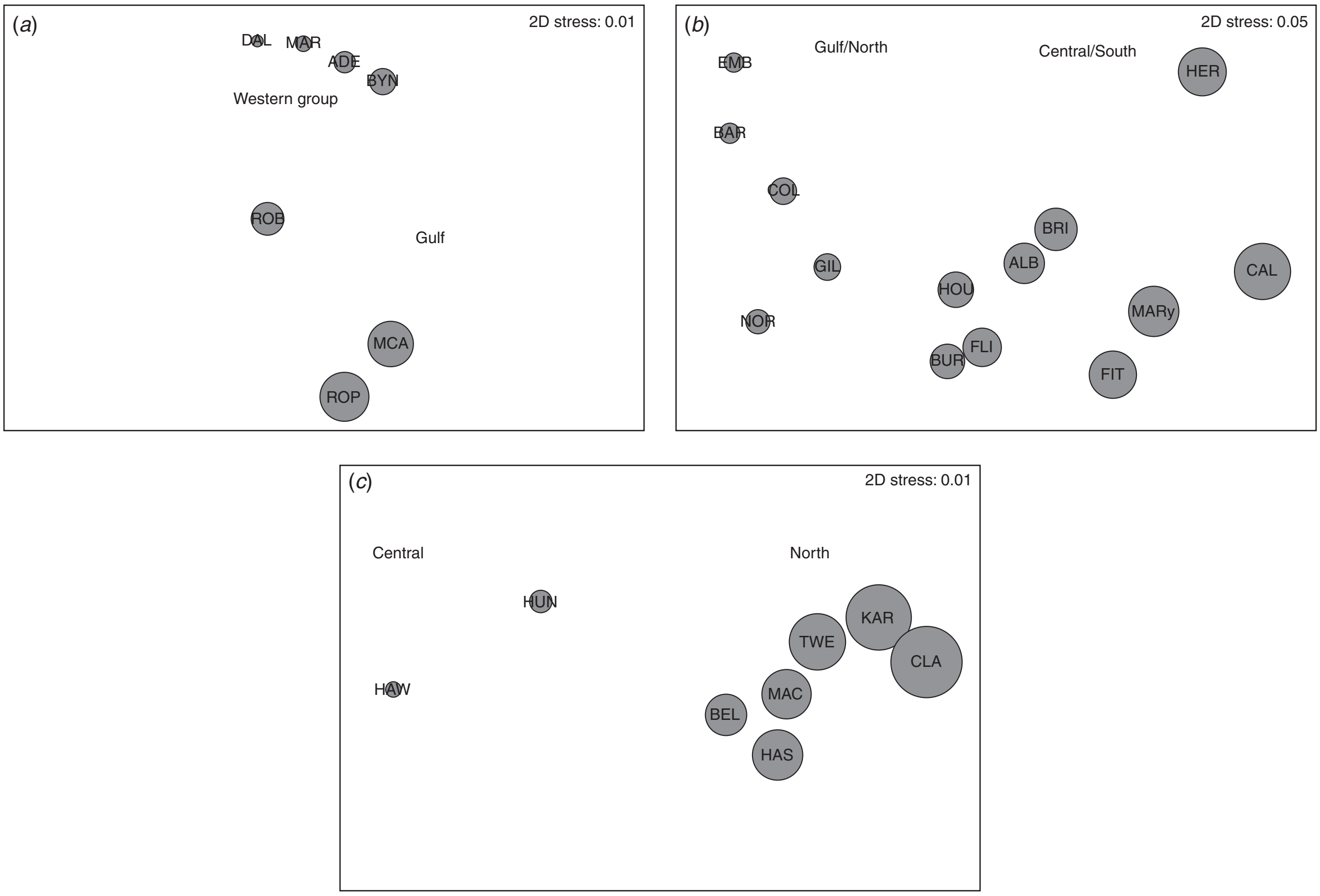

Fig. 3. An nMDS plot of seven river systems in the (*a*) NT (1990–2008), (*b*) 14 river systems (1988–2008) for Qld and (*c*) eight selected river systems (1997–2008) for NSW. The size of the circles indicates the size of the total catch. The plots are based on square-root transformed mean catch, effort, sea surface temperature (SST) and catchment rainfall using Euclidean distance.

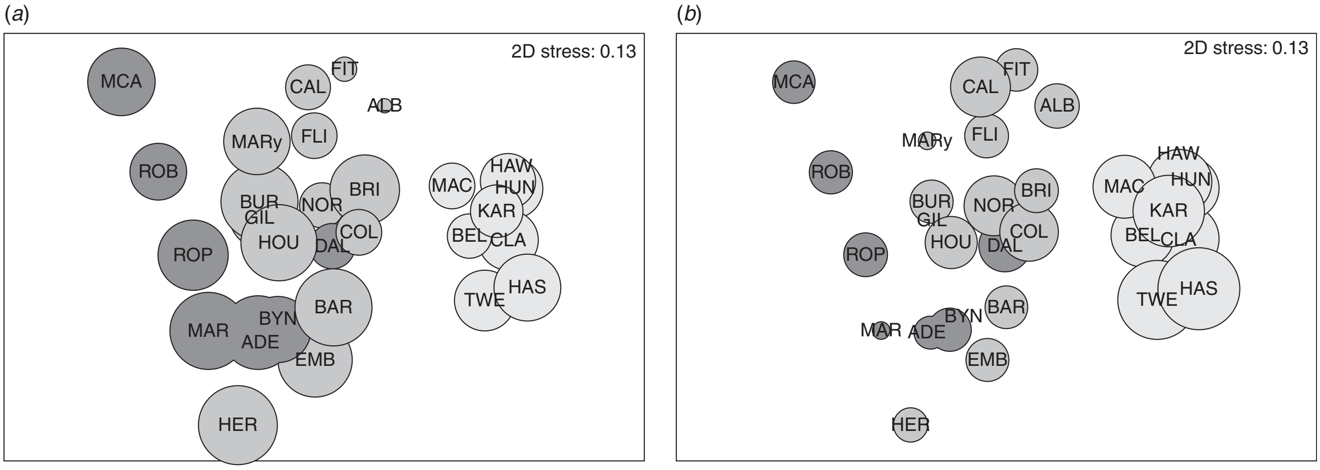

Fig. 4. An nMDS plot displaying the selected river systems for Australian mud crab catch analyses (excluding Wallis Lake in NSW). The size of the circles indicates the strength of the correlation between (*a*) rainfall and (*b*) sea surface temperature. The plot is based on standardised average catch, catch per unit effort (CPUE), sea surface temperature (SST) and rainfall for the relevant time periods from each state (NT in dark grey, Qld in grey and NSW in light grey) and transformed using Euclidean distance. HAW, Hawkesbury; HUN, Hunter; BEL, Bellinger; HAS, Hastings; MAC, Macleay; TWE, Tweed; KAR, Karuah; CLA, Clarence; NOR, Normanby; FLI, Flinders, Norman; EMB, Embley; GIL, Gilbert; COL, Coleman; Mitchell, FIT, Fitzroy, Raglan; CAL, Calliope, Boyne; HER, Herbert, Tully; HOU, Barratta, Houghton; BUR, Burdekin; BAR, Barron; ALB, Albert, Logan, Nerang, Coomera; BRI, Brisbane, North Pine; MARy, Burrum, Mary; MCA, McArthur; ROB, Robinson, Wearyan; ROP, Roper; ADE, Adelaide; BYN, Bynoe Harbour; DAL, Daly; MAR, Mary.

function of both local bathymetry and tidal range. The mortality rate of those conspecifics that do enter shallow set traps (which dry at low tide) during periods of extreme temperature will also be greater than usual. Giant mud crabs inhabiting mangrove-lined rivers are less prone to these events as they can either remain in the shade of the mangroves or move short distances into deeper, cooler waters.

Bioregion grouping

The nMDS plots revealed discrete groupings for all river systems. These groupings generally agreed with accepted bioregional boundaries. The nMDS plot for NT river systems separated them into a western group and a Gulf of Carpentaria group. This is likely due to known differences in the catch, rainfall and general habitat characteristics between the two regions (Hay *et al.* 2005). In Qld, the river systems showed a less distinct separation into eastern Gulf of Carpentaria/Far North Qld river systems and Central/South-east Qld river systems. Both the eastern Gulf of Carpentaria and Far North Qld river systems had lower catch rates (not a reflection of the productivity of the rivers, but rather, fishery accessibility) and generally higher temperatures/rainfall.

Central and south-east Qld bioregions had higher catch rates but lower temperature and rainfall, particularly in the dry season. The difference in CPUE between the eastern Gulf of Carpentaria and the east coast of Qld is also reflected in the results of the long-term mud crab monitoring program by Queensland DEEDI (Jebreen *et al.* 2008). River systems in NSW separated into two clear groups: the Central and Northern Bioregions. These groupings were mainly driven by catch and temperature, reflecting the oceanographic discontinuity around Port Macquarie (Pease 1999; Saintilan 2004).

The association between estuarine taxa, environmental factors and bioregions has previously been demonstrated for species such as barramundi (*Lates calcarifer*). Balston (2009) described the influence of climate variability including the SOI on the commercial barramundi fishery of north-east Queensland, Australia. The highest correlation between barramundi catch adjusted for effort and climate was with dry season rainfall. A study on barramundi in the central Queensland Fitzroy area attributed 41% of the variability in catch to summer (December–February) fresh water flow and 45% to summer rainfall (Robins *et al.* 2005).

Statistics and data consideration

The capacity of regression-based models to predict future catch has been questioned by some authors (e.g. Myers and Mertz 1998); however, linear models (LMs) provide a good grounding for supplementary modelling approaches (Wheeler and Hendon 2004). Attempts have been made to use LMs to predict prawn catch in the Gulf of Carpentaria and to use maximum likelihood estimation (MLE) for depletion analysis (Bedrick 1994; Loneragan and Bunn 1999; Burridge *et al.* 2003). Large fluctuations in effort and unknown parameters can make these models unreliable.

The use of regression models has been criticised because of: (1) the confounding effects of stock size and fishing pressure (Walters and Collie 1988); (2) the potential non-linearity of linking mechanisms (Baumann 1998) and the probability of multiple mechanisms; (3) the inability to prove causality (Quiñones and Montes 2001); and (4) their uncertain predictive capability as a consequence of long-term climatic variation or human-induced changes (e.g. habitat loss and pollution). However, the problems associated with point 1 can be lessened by only using catch data that provides consistent information. Points 2 and 3 can be mitigated by reducing autocorrelations (Pyper and Peterman 1998), meta-analyses and the selection of relationships that support current scientific and anecdotal knowledge. Points 3 and 4 are problems common to many (if not all) modelling approaches.

In recent years, hierarchical Bayesian models have been used for parameter estimation. Zhou *et al.* (2008) applied this type of model to the northern Banana Prawn (*Penaeus merguiensis*) fishery to assess abundance and catchability. This approach is likely to become increasingly popular, particularly for the assessment of short-lived invertebrates (Ives *et al.* 2009).

Changes to regulations and closure of fishing grounds influenced relationships between giant mud crab catches and environmental drivers but are difficult to factor into analyses of catch data. This includes factors like the different fishing type between jurisdictions (e.g. multispecies fisheries in Qld vs intensive mud crab fisheries in NT). Other factors, such as the construction of dams and river diversions, can also impact catch rates over time. Similar findings have been reported for the catch rate/flow relationships from other fishery species in NSW (Gillson *et al.* 2009). Weather-dependent road access to remote areas also influences the catch rates. For example, the Gulf of Carpentaria rivers catch records were concentrated over the dry season and were poorly, if at all, reported in the first years of reporting. River systems with significant gaps in the time series and/or low catch rates (e.g. Daly River; 74 out of 228 possible fishing months) require separate analyses. The non-significant results from the Daly River support the argument that CPUE is strongly influenced by environmental factors in areas where catches are high (potentially due to a greater density of giant mud crabs), whereas effort is more important in determining catch where the CPUE is low (and giant mud crabs are scarcer).

Future analyses of giant mud crab catch data should include a broader range of environmental variables (e.g. currents and salinity) as and when they become available for the areas fished. These analyses could be refined by examining catch relative to catchment size, flow volume instead of catchment rainfall, and also the inclusion of recruitment estimates and biogeographic information (e.g. mangrove, mud flat or salt pan area).

Conclusion

Similar to other near-shore fisheries in Australia (Gillson *et al.* 2009), the catch rate (i.e. CPUE) of giant mud crabs is affected by variations in freshwater flow (rainfall) and temperature. Such information is vital to the informed management of the giant mud crab resource as it demonstrates that fluctuations in total catch are not driven by fishing effort alone. Given the lack of direct evidence of cause and effect (which is an underlying issue with most ecological/climatic modelling) further work is needed to determine the exact causal mechanisms and document their influence on particular life history stages. Of particular importance is defining which physical cues (in isolation or combination) trigger moulting, spawning migrations, egg extrusion and hatching. The potential for regional differences in the factors which trigger these events must also be considered. The dynamics of ecosystems suggest that local recruitment anomalies are a common event in marine environments (Bay *et al.* 2008). Furthermore, information on growth rate, mortality and survival for a process-based ecosystem fisheries model are required to allow predictions of regional catch.

We believe that much of the 'noise' in our analyses was due to the temporal resolution of the catch data (i.e. monthly), and that this affected the strength of the relationships between CPUE and the environmental data. This being the case, we suggest that the relevant fisheries management agencies move towards finer-scale logbook reporting (both spatially and temporally) for domestic mud crab fisheries. This would provide a multitude of benefits for a range of different modelling approaches.

Finally, although depletion experiments provide the most accurate means of estimating giant mud crab abundance, and have been applied successfully to populations of giant mud crabs in Qld and the NT in the past (Hay *et al.* 2005), they are costly and logistically demanding, with the results specific to a particular time and place (thereby limiting their application to other areas and time periods). Hence, the likelihood of similar experiments being conducted in future is low. The advent of small, GPS-enabled devices such as smart phones and their potential application as 'electronic logbooks' is set to revolutionise catch reporting and may mitigate the need to conduct expensive field trials of this nature.

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