The influence of the La Niña-El Niño cycle on giant mud crab (*Scylla serrata*) catches in Northern Australia

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ABSTRACT

Mud crabs (*Scylla* spp.) are a high value commodity harvested in the Indo-West Pacific. Scylla species support important artisanal fisheries in south-east Asia and intensive commercial fisheries in Australia where the market demand and catch has increased markedly over the last decade. Overfishing of Scylla spp. has been observed at varying levels throughout its distribution. Fluctuations in catch rates and abundance are thought to be driven by climate parameters. Here we analyse monthly, seasonal and annual patterns in catch and effort data (from 1990 to 2008) for the commercial giant mud crab (*Scylla serrata*) fishery in the Northern Territory, Australia, with corresponding climatic data (rainfall, freshwater runoff, sea surface temperature) and the Southern Oscillation Index (SOI) as an indicator of La Niña/El Niño events. Between 30-40% of the variation in catch per unit effort can be explained by rainfall and SOI alone. This result was supported by linear mixed models which identified

27 SOI as the main contributor to the model. Spectral analyses showed that catch peaks

28 coincided with a four year La Niña cycle. One- and two-year time lags (consistent

29 with *S. Serrata's* life cycle) were also significantly correlated to SOI values and

30 rainfall. These outcomes may assist fishery managers in planning fishing exposure

31 period and duration. Furthermore, findings of this study provide information on the

32 vulnerability of *S. serrata* to fluctuations in environmental conditions and can help to

33 apply protective measures when and where necessary.

34

35 *Additional keywords:* giant mud crab, *Scylla serrata*, climate variability, multivariate

36 analysis, linear mixed models, Australia

37

1. Introduction

39 Mud crabs of the genus *Scylla* have a wide distribution in Indo-West-Pacific estuaries

40 supporting important fisheries in South Africa, Pakistan, Japan, Taiwan, Philippines,

41 Malaysia, Vietnam, China and Australia where their capture generates significant

42 revenue for coastal communities and forms an important component of small-scale

43 fisheries (Le Vay *et al*., 2001). The genus Scylla contains four recognised species: *S.*

44 *paramamosain, S. tranquebarica, S. olivacea* and *S. serrata*, (Keenan *et al.* 1998,

45 Imai *et al*., 2004) with the latter two found in Australian waters. A combination of

46 over-fishing and habitat loss has resulted in reduced landings and smaller mean size at

47 capture in several south-east Asian countries (Le Vay *et al.*, 2001), making Scylla

48 spp. potentially vulnerable to environmental stressors   (Hamasaki, 2003). The

49 fisheries dynamics have rarely been modelled or assessed throughout Scylla's wide

50 geographic range (Overton, 1997). Understanding more about ecological relationships

51 with *S. serrata* catches may be useful not only for managers but for understanding

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52   how this important species varies in its population characteristics and preferences for

53   environmental conditions throughout its range.

54   *S. serrata* abundance appears to be strongly linked with the prevailing

55   environmental conditions during their life history, especially during the larval and

56   juvenile phases (Ruscoe *et al.*, 2004). *S. serrata* fisheries are typically subject to high

57   fishing mortality rates, with little carry over of stock from one year's cohort to the

58   next (Lebata *et al.*, 2009). This combination of factors can result in extreme inter-

59   annual variation in *S. serrata* catches. For example, the years 2000 and 2001 saw

60   record *S. serrata* catches in northern Australia, presumably due to a combination of

61   high fishing effort and favourable recruitment in the preceding years. This peak was

62   followed by a significant decrease in catch. This phenomenon is thought to be due to

63   one or more environmental drivers, such as rainfall/river flow or water temperature.

64   Freshwater flow has a significant effect on estuarine fisheries production, with the

65   abundance and distribution of aquatic communities changing with seasonal and inter-

66   annual variations in flow (Robins *et al.*, 2005, Meynecke *et al.*, 2006, Gillson *et al.*,

67   2009).

68   The strong dependence of Scylla spp. on salinity is a world-wide phenomenon.

69   Bonine *et al.* (2008) reported for Micronesia that offshore migration in tropical *S.*

70   *serrata* populations is stimulated by a decrease in salinity. Similarly, seasonal changes

71   in salinity have been reported by Walton *et al.* (2006) from the Philippines as an

72   important factor in relation to recruitment of *S. paramamosain*. In India low salinity

73   (or 2-3 ppt) reduced catches of juvenile Scylla spp. to zero, though the species is

74   unclear (Chandrasekaran and Natarajan, 1994). Hill (1975) reported that heavy floods

75   (resulting in salinity of 2 ppt) greatly reduced mud crab catches (suspected *S. serrata*)

76   in two South African estuaries and in Australia *S. serrata* catch per unit effort (CPUE)

77 was negatively correlated with salinity (24-35 ppt) but positively correlated with

78 temperature (Williams and Hill, 1982).

79   Robins *et al.* (2005) also reported the effects of flow on *S. serrata*, and suggested

80 that flow affects recruitment supporting the results of Loneragan and Bunn (1999)

81 who proposed salinity change as the mechanism of adult movement. The downstream

82 movement of mud crabs (suspected *S. serrata*) following floods was also reported by

83 Stevenson and Campbell (1960). This small-scale migration of adult *S. serrata* may

84 reduce the severity of cannibalism (which is a strong mortality factor in brachyuran

85 crabs high-density environments), and burrow competition such that juveniles prosper

86 and overall *S. serrata* abundance increases (Møller *et al.*, 2008).

87   The difference in distributions of the four *Scylla* species is also suggested to be a

88 result of varying tolerances to salinity at larval or juvenile stages (Le Vay *et al.*,

89 2001). *S. serrata* in Australia is more dominant in oceans and mangroves with high

90 salinity (about 34 ppt), and may experience higher mortalities with sudden salinity

91 decreases associated with freshwater flooding. Conversely, the species dominant in

92 east and south-east Asia, *S. paramamosain*, prefers estuarine habitats where salinities

93 are lower than 33 ppt and maintains high catch rates through seasonal periods of low

94 salinity and freshwater conditions (Le Vay *et al*., 2001).

95   The optimal water temperature for *S. serrata* is between 28-32°C with significant

96 lower survival at temperatures < 20°C (Heasman *et al.*, 1985; Robertson, 1996;

97 Ruscoe *et al.*, 2004). The peak mating activity is usually in spring or at the end of the

98 dry season. Therefore, spawning is often linked to the wet season (e.g. Hill, 1994)

99 when the optimal water temperature for larvae of 28-30°C occurs (Baylon, 2010).

100 However, spawning can take place throughout the year depending on the region and

101 environmental conditions.

102   Here we aim to use the Northern Territory (NT, Australia), *S. serrata* catches as a

103   case study to define the most important climate drivers for *S. serrata* catch variability

104   and develop models capable of enhancing the prediction of *S. serrata* abundance. We

105   hypothesis that high sea surface temperature (SST) and high rainfall boost coastal

106   productivity, and consequently, result in a positive relationship between these

107   combined factors and *S. serrata* CPUE. Similarly, we expect maximum positive

108   Southern Oscillation Index (SOI) values indicating strong monsoonal effects (La Niña

109   phase) that result in high rainfall and warm temperatures in northern Australia, to be

110   positively correlated with *S. serrata* CPUE. However, prolonged flooding (in the

111   order of weeks to months), is expected to result in high mortality of juveniles, which

112   in turn would have a negative impact on subsequent recruitment. Depending on the

113   recruitment time of *S. serrata* to fisheries, there will be lag effect for physical

114   environmental driver/s and the resultant impacts on catch and estimated abundance.

115

116   **2. Methods**

117   *2.1. Conceptual model*

118   Temperature and salinity have the largest influence on the life history of *S. serrata*

119   (Hill, 1974) with the impact of environmental factors on *S. serrata* being greatest

120   during larval and juvenile stages (Nurdiani and Zeng, 2007). Catch data from adult *S.*

121   *serrata* therefore does not necessarily reflect an immediate response to temperature

122   and salinity fluctuations. The time lag between the environmental change and effect

123   on CPUE is expected to decrease with advanced life stages and also depends on the

124   movement. *S. serrata* has different movement phases during its life span where it can

125   be exposed to a wide range of environmental factors: 1) the movement of planktonic

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126 eggs and larvae to nursery areas; (2) a range of routine shelter and foraging

127 movements that maintain a home range; and (3) spawning migrations away from the

128 home range for dispersal (Pittman and McAlpine, 2003) (Fig. 1).

129 Other environmental factors that may influence the abundance, distribution and

130 ultimately catchability of *Scylla* spp. at the estuary and regional scales include

131 currents, tides, wind, lunar cycle and dissolved oxygen (linked with either temperature

132 or salinity). For example, *S. serrata* may be subject to hypoxic stress (Davenport and

133 Wong, 1987), especially during high temperatures. The lunar cycle probably affects

134 the on set of moulting and migration, but a definitive link is yet to be proven (Prasad

135 and Neelakantan, 1989). Currents, tides and wind also influence the dispersal of *S.*

136 *serrata* larvae and the subsequent abundance/distribution of juveniles (Webley *et al.*,

137 2009).

138

2.2. Study location

140 The Northern Territory (NT) is surrounded by relatively shallow tropical waters

141 with the Arafura Sea (50-80m depth) to the northwest and the Gulf of Carpentaria

142 (55-66m depth) to the east. The climate is characterised by a five-month warm, wet

143 season, (November to March, mean max. temperature of 32.2°C and 1500mm of

144 rain), and a seven-month cooler, dry season (April to October, mean minimum

145 temperature of 21.9°C and 214mm of rain) (McBride and Nicholls, 1998) (data for

146 Darwin accessed through BOM, 2011) These conditions mean that *S. serrata* often

147 experience wide annual, seasonal or daily, fluctuations in temperature and salinity.

148 Two *Scylla* spp. are caught in the NT, the giant mud crab, *S. serrata* and the orange

149 mud crab, *S. olivacea,* with the latter contributing < 1% of the total catch (Knuckey,

150   1999). Seven river systems in the NT, Australia were selected for this analysis (Fig.

151   2).

152

153   *2.3. S. serrata catch data*

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155   Monthly logbook data for the NT commercial *S. serrata* fishery were provided by

156   the Fisheries Division, NT Department of Resources (DoR). The data were entered

157   into an internal, proprietary Oracle data base, "Fishdat" and validated by checking the

158   accuracy of the entered data against the paper log sheet. The fishery is managed

159   through input rather than output controls (i.e. quota) and so catch data for the fishery

160   should reflect fluctuations in *S. serrata* catchability. The fishing season varies with

161   road access but usually extends from March to November. The highest volume of

162   catch is reported for March to June. Monthly catch data for the period 1990-2008 for

163   seven river systems were selected. These provided information on monthly catch per

164   area and grid code, monthly fishing days, number of pots used and potlifts. River

165   systems were selected based on the highest catch during the observation period and

166   the continuity of data (with the exception of the Daly River). The selected seven

167   catchments were each representing one major river system: the Roper, McArthur,

168   Robinson, Wearyan, Adelaide, Daly, and Mary Rivers. These systems accounted for

169   6,532t (75%) of the NT commercial *S. serrata* catch between 1990 and 2008. For

170   seasonal analyses, dates were split into a seven-month dry (April-October) and a five-

171   month wet season (November-March) (McBride and Nicholls, 1998).

172

173   *2.4. Environmental data*

174   *2.4.1 Rainfall data*

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176   We analysed mean monthly rainfall data (in mm) within each catchment area

177   using a 5-km rainfall grid for Australia, covering the years 1990 to 2008. Data were

178   provided by the Bureau of Meteorology (BOM). The original ASCII data were

179   converted into raster data in ArcGIS 9.3, then converted into point data and

180   intersected with selected catchment areas to calculate rainfall data for each catchment.

181   The mean of rainfall points per catchment area was used to calculate monthly mean

182   rainfall per catchment area. The catchment area was based on the Australian River

183   Basin 1997 information (Geoscience Australia, 2005).

184

185   *2.4.2. Freshwater flow data*

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187   Daily freshwater flow data for the river systems were provided by the NT

188   Department of Natural Resources, Environment, the Arts and Sport (NRETAS) in

189   either megalitres/day, cubic meters/day or height in m/day. A runoff model developed

190   for the Northern Australia Sustainable Yields Project by the Commonwealth

191   Scientific   and   Industrial   Research   Organisation   (CSIRO;

192   http://www.csiro.au/partnerships/NASY.html), provided additional information on flow

193   for the Roper River. These flow data were tested against mean catchment rainfall

194   (Table 1). Flow into north Australian estuaries increases during late spring and

195   summer, depending on the summer monsoon trough (Robins *et al.*, 2005).

196

197 *2.4.3. Southern Oscillation Index*

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199   Monthly SOI values were obtained from the BOM. Positive values of the SOI are

200 generally associated with a La Niña pattern in the central and eastern equatorial

201 Pacific and above average rainfall for north and northeast Australia. Negative values

202 of the SOI are associated with El Niño conditions and below average rainfall across

203 north and northeast Australia (Drosdowsky, 1996). We used mean and maximum SOI

204 values for annual or seasonal time period for the analyses.

205

206 *2.4.4. Sea surface temperature*

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208   Sea surface temperature (SST) was considered a more reliable source of

209 temperature information than air temperature from weather stations due to gaps in

210 weather station data or the often large distance between weather stations and river

211 mouths (i.e. > 50 km). We accessed free SST data from NASA

212 (http://poet.jpl.nasa.gov) satellites from AVHRR Pathfinder Version 5, which

213 provided a 4-km resolution of monthly daytime temperature information for the time

214 period 1990-2007. For 2008, SST data from MODIS Aqua with a 4-km resolution of

215 monthly daytime temperature were used. This information was downloaded as point

216 data in ASCII files with an original projection in WGS 1984. The data were then

217 converted into shapefiles in ArcGIS 9.3 and monthly mean values calculated for each

218 river system. It was assumed that water surface temperature in the estuaries was

219 similar to water temperature within a 20-km radial proximity to the river mouth.

220 Points with a 20-km buffer were generated along the river mouth and data points that

221 fell within this buffer were selected to generate monthly mean, minimum and

222 maximum SST.

223　*2.5. Statistical analyses*

224　Trends in *S. serrata* catch rate data and environmental factors were analysed using

225　linear mixed models (LMM), non-metric multi dimensional scaling (nMDS) and

226　spectral analyses using various temporal configurations (annual, monthly and

227　seasonal). Catch data (pot only) were adjusted for effort using the number of fishing

228　days recorded (CPUE, kg day^{-1}), which is a common practice for small-scale fisheries

229　(Gillson, 2011).

230　Initial exploratory analyses of relationships between selected physical

231　environmental drivers (covariates) and *S. serrata* CPUE were performed using

232　Pearson correlations and linear regression for each river system. Based on these

233　results, CPUE and mean annual rainfall were log(x+constant) transformed to ensure

234　linearity and homogeneity of variance for LMM analysis. Pearson correlation between

235　the covariates and log CPUE indicated that specific laggings of the covariates would

236　optimise these relationships. To investigate regional trends and variations within the

237　*S. serrata* fishery the total catch, mean annual rainfall, temperature, and flow (if

238　available) for each river system were used for an nMDS analysis using Primer 6.0

239　(Clarke and Warwick, 2001) based on the Euclidean dissimilarity measure.

240　Linear mixed models are an extension of linear models (i.e. ANOVA, regression)

241　in which random effects can be added to the linear predictor and the associated error

242　structure can be modeled independently of the residual error. The incorporation of

243　random effects generates a rich class of correlated data models that would be difficult

244　to specify directly (McCulloch and Neuhaus, 2005). Here we used a random intercept

245　– random slopes model with lagged SOI, lagged SST, and lagged log-transformed

246　rainfall as covariates and the river systems as subjects. Various models (not shown)

247　were investigated; for example, random intercepts only, random slopes for various

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248 covariates, with different types of variance – covariance matrices where appropriate.

249 The best model, obtained from a comparison of various goodness of fit statistics (-2

250 res log likelihood; AIC - Akaike Information Criterion; BIC - Bayesian Information

251 Criterion), contained a random intercepts term and a random slope term for lagged

252 SOI alone. Alternatively, the data was analysed using a fixed categorical variable, i.e.

253 seasons (wet and dry), instead of the random seasonal covariate terms; lagged SST

254 and lagged log rainfall.

255 Spectral (Fourier) analyses were undertaken to explore cyclical patterns in the

256 data. The purpose of the analysis is to extract cyclical components from complex time

257 series into a few underlying sinusoidal (sine and cosine) functions of particular

258 wavelengths (Shumway, 1988; Bloomfield, 2005) with the Fourier analysis being one

259 of the most important signal processing methods. Analyses of the monthly *S. serrata*

260 data were undertaken using SPSS 19.0.

261

262 **3. Results**

263

264 *3.1. Northern Territory catch*

265 Commercial *S. serrata* catch in the NT increased from 150t in 1990 to over 200t

266 in 1994. In 1995, the catch almost tripled and reached a peak, which was followed by

267 a slight drop in 1997. From 1998-2001 catches increased to over 1000t and then

268 dropped sharply to 350t in 2002. In the following years a gradual increase to >500t

269 was evident. We identified four periods of high catch rates consistent with the

270 1995/96, 1999-2001, 2004/05 and 2008/09 La Niña phases (Fig. 3). The initial

271 analyses showed large differences between systems, with the Gulf of Carpentaria

272 systems being most productive. The Roper River was exceptionally productive, with

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273 an estimated three million crabs being harvested between 1990 and 2008. On average,

274 half of the NT catches were derived from the Roper, McArthur and

275 Robinson/Wearyan Rivers (Fig. 2). The western regions only contributed a small

276 proportion to the total catch.

277

278 *3.2. Correlation analyses*

279   Significant positive correlations existed between *S. serrata* CPUE and

280 annual/seasonal catchment rainfall. The significance of this relationship increased

281 with a one-year lag and then decreased with a two-year lag. This coincides with the

282 estimated time of 18 months for *S. serrata* to recruit to the fishery. Significant

283 correlations were also detected for seasonal SOI values with distinct lag effects for all

284 river systems. There was an empirically determined lag effect of annual SOI on CPUE

285 of approximately six to nine months (Fig. 3). Monthly flow or, if this data were not

286 available, rainfall, showed a positive relationship when lagged by one wet season,

287 indicating that a good wet season translated to high catches in the following dry

288 season, as confirmed by anecdotal reports from fishers. Pearson correlation analyses

289 for annual, seasonal and monthly relationships between CPUE and SST revealed only

290 weak correlations for annual and seasonal data sets but significant relationships for

291 monthly SST data lagged by 6 months.

292

293 *3.3. Regression and linear mixed model analyses*

294   Regression analyses using NT log-transformed *S. serrata* CPUE for each river

295 system and the climate variables revealed significant relationships between seasonal

296 rainfall (using average data for wet and dry seasons) lagged by one season and annual

297 maximum SOI values (La Niña phases). These two variables explained 30-40% of the

298 catch variability for four of the river systems studied. Linear models for monthly *S.*

299 *serrata* catch data and three climate factors (temperature, rainfall and SOI) showed

300 similar regression slopes for the Gulf of Carpentaria systems. Relationships between

301 8-9 month lagged SOI and log-transformed CPUE ranged from $r^2 = 0.14$ for the

302 Robinson river to $r^2 = 0.32$ for the Mary river (Fig. 4a-c). A summary of total NT

303 annual *S. serrata* CPUE and comparison with maximum SOI values demonstrated the

304 possible influence of this variable on *S. serrata* catch, with an r^2 of 0.32 (p <0.05).

305 The r^2 value was slightly smaller for a two-year lag ($r^2 = 0.30$, p<0.05).

306 Linear mixed model analysis indicated that the slope for the fixed effects (lagged

307 SOI, lagged SST, and lagged log-rainfall) were significant (p=0.003, p<0.001, and

308 p=0.0187 respectively). The best model with a significantly (p<0.05) -2 Res Log

309 Likelihood fit statistic as well as a reduction in other fit statistics (AIC, BIC) was

310 provided by the random intercepts and a random lagged SOI slopes term, using an

311 unstructured variance-covariance matrix. The covariance between the random

312 intercepts term and the random lagged SOI slopes term was positive, indicating larger

313 intercepts had larger slopes. The addition of a random slopes term for lagged SST or

314 lagged log-rainfall did not significantly (p>0.05) add to the fit of the model. The

315 addition of a random lagged SOI slope term and its positive association with the

316 random intercepts term is basically due to the Bynoe Harbour location (-

317 0.0087±0.0025, p=0.0004) (Table 2, Fig. 4a-c). For all other locations the random

318 slope effects were small and not significant (p>0.05) from each other. The significant

319 random intercepts term is substantially due to the Bynoe Harbour location (-

320 1.82±0.38, p<0.0001). When Bynoe Harbour was excluded, the random intercept

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321 effect showed a significant separation between the two major regions

322 (difference=0.508± 0.041, p< 0.0001) – region 1: Adelaide River (-0.064±0.38), and

323 Mary River (0.182±0.38) vs. region 2: Robinson River (0.715±0.38), Roper river

324 (0.568±0.38), and McArthur River (0.418±0.38) (Table 2, Fig. 4). The use of the

325 fixed effect of season instead of various seasonal random effects (lagged SST and

326 lagged log rainfall) gave similar results as stated in the previous model above but with

327 lesser fitting.

328

3.3. Multi-analyses and spectral analyses

330 An nMDS plot using total catch, rainfall and SST produced a clear grouping of

331 rivers/regions, with the Adelaide, Daly and Mary Rivers and Bynoe Harbour forming

332 one group, and the Robinson, Wearyan and McArthur Rivers forming another (Fig.

333 5). Those systems with a lower mean annual rainfall supported higher average *S.*

334 *serrata* catches. This suggests that the catch was not driven by total rainfall, but by

335 the timing and magnitude of rainfall as well as other factors such as catchment size

336 and biological factors.

337 Spectral analyses showed a 3-5 year peak in *S. serrata* catch. Periods of high

338 catches also occurred every 6 months consistent with seasonal cycles in catch rates. A

339 smaller peak of high catches is also discernible every two years (Fig. 6).

340

4. Discussion

342 Temporal analyses of the NT commercial *S. serrata* fishery catch revealed

343 significant variation in catch rates. Such variations are most likely due to

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344 environmental factors affecting recruitment success over time and location throughout

345 *S. serrata* geographic distribution.

346   In the late 1990s and early 2000s, large increases in catch and CPUE occurred in

347 the NT. Similar patterns of fluctuation in recruitment and relative fishing effort (i.e.

348 up to eight-fold) would have been required to explain these inter-annual variations in

349 catch rates (Fig. 3) and are not particularly driven by effort in a pot-based fishery

350 (Robertson, 1989). Similar increases were experienced in the Queensland Gulf of

351 Carpentaria fishery (Meynecke and Lee, 2011). As hypothesised, we found positive

352 relationships between temperature, rainfall and *S. serrata* catch variability as well as a

353 positive relationship with SOI and lagged effects. Our results indicated that the best

354 environmental predictor for fluctuations in *S. serrata* catch variability was SOI with a

355 6-9 month lag. Negative impacts on *S. serrata* catches were observed after heavy and

356 prolonged flooding with a 1-2 year lag affect.

357

358 *4.1. Effect of the La Niña-El Niño cycle*

359   The results for the NT showed that monsoonal activities with high rainfall over

360 longer periods of time may explain between 30-40% of the catch variability. Such

361 monsoonal activities exist in many countries throughout the Indo-West Pacific. High

362 positive SOI values (indicating a La Niña event) in particular during the pre-wet

363 season (October-November) indicated strong monsoonal effects such as rainfall and

364 warm waters during the wet season. These factors most likely contributed to enhanced

365 productivity supported by increased material (organic matter and nutrients) movement

366 into estuaries (Grimes and Kingsford, 1996). There were also significant positive

367 Pearson correlations between seasonal CPUE and mean rainfall when lagged by one

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368 season. Good rainfall in the wet season appeared to stimulate overall productivity of

369 the river system which, in turn, stimulated higher catch rates five to six months after

370 the event. Overall SOI was a better predictor than catchment rainfall or temperature

371 for NT *S. serrata* catches. However, an improved resolution of flow and water

372 temperature data may result in stronger relationships with *S. serrata* catch. Similar

373 impacts of SOI on *S. serrata* catches are expected for some parts of Indonesia and

374 Papua New Guinea, which are under the same general influence of the La Niña-El

375 Niño cycle.

376 The lag effect of rainfall and SOI on *S. serrata* catches is resulting in a catch peak

377 after six to nine month and then followed by another positive peak of catch two years

378 after a wet season with greater than mean rainfall. However, if heavy rainfall events

379 occurred (causing major flooding), a negative two-year lag effect on *S. serrata* catch

380 was observed in the data. This may be explained by the associated dieback of

381 seagrass beds which are an important juvenile habitat (Hill and Williams, 1982,

382 Chandrasekaran and Natarajan, 1994) resulting in a negative effect on recruitment

383 success (Webley *et al*., 2009). Similarly the reduction in seagrass density can have

384 significant effects on the mortality of juvenile blue crabs, *Callinectes sapidus* (Wilson

385 *et al*., 1990). This can be seen in the 2001 floods in the McArthur and Wearyan River

386 systems, which destroyed seagrass beds in the area and was followed by catch

387 declines in the following years.

388 By contrast, moderate increases in freshwater flow can have positive short-term

389 effects by raising catches for up to two weeks after the rainfall events; however, these

390 were not covered by the monthly resolution of the data and therefore not revealed in

391 the analysis. Fishermen have reported this phenomenon, which can likely be

392   attributed to enhanced activity of *S. serrata* leaving their burrows to avoid low salinity

393   and thus increasing catchability.

394

395   *4.2. Effect of temperature*

396   There are both trophic and non-trophic mechanisms increasing *S. serrata* catches

397   (number and size of individuals) due to warmer waters. *S. serrata* is well adapted to

398   temperatures in tropical and subtropical regions. Adults are reported to reduce activity

399   at temperatures < 20°C (Hill, 1980, Heasman *et al*., 1985). When SST was high in

400   November and December catches were higher in the following dry season indicated

401   by a 6-month lag response with catch rates. This is most likely due to faster growth of

402   sub-adult *S. serrata* during the critical wet season period. Higher catches can also be

403   expected in warmer waters as an immediate response increasing activity and therefore

404   catchability. However, there were some indications from the analyses and anecdotal

405   reports that periods of very high temperatures had a negative effect on annual *S.*

406   *serrata* catches, particularly for regions where crabs are caught on intertidal flats

407   rather than in deep water. In this case, catches are generally reduced due to high

408   temperatures increasing mortality in the crab pots as well as increased post-harvest

409   mortality. Air temperature in excess of 40°C can also lead to hypoxic stress in

410   particular in shallow waters (Eggleston *et al.*, 2005).

411

412   *4.3. Meta-analyses and spectral analyses*

413   Two distinct groups were identified using nMDS plots based on catch, effort,

414   temperature and rainfall. These groups were the western group of river systems –

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415 Bynoe Harbour, Adelaide, Daly and Mary Rivers, and the Gulf of Carpentaria group

416 including Roper, Robinson/Wearyan and McArthur Rivers. This grouping pattern is

417 mainly caused by the distinct differences in catch and rainfall attributes. This is also

418 reflected in the general habitat differences between the Gulf of Carpentaria systems

419 and other river systems (Thackway and Cresswell, 1997). Such grouping of river

420 systems based on catch and environmental factors can be expected for other river

421 systems. It is therefore meaningful to develop models for each bioregion rather than

422 for administrative jurisdictions. This disconnect between spatial scales relevant to the

423 species and to their managers is supported by findings on artisanal mud crab fishery in

424 Micronesia, where Ewel (2008) suggested local management is necessary due to high

425 site fidelity.

426 Spectral analyses showed a 3-5 year repeat pattern of high catch rates that

427 coincided with strong Southern Oscillation events that occur on average every four

428 years in the NT (Zhang, 1992), generally the occurrence of La Niña event. A shorter

429 cycle of high catch rates also occurs every six and 12 months, describing the strong

430 seasonality of the catch data.

431

432 *4.4. Modeling*

433 The development and testing of models capable of predicting fisheries catch and

434 consequently fisheries species abundance is an important tool in ecosystem based

435 fisheries management (Ellis *et al.*, 2008). In many cases information is limited and

436 initially the development of a model based, at least partially, on simulated processes

437 of the actual system is needed. This allows the creation of more sophisticated models

438 by adding and adjusting potential natural drivers.

439   Following the regression analyses the annual *S. serrata* CPUE is best related to

440   wet season rainfall (November – April), two years prior to catch and SOI values from

441   the same year. The linear mixed model demonstrated a defined effect of SOI and a

442   seasonal relationship with temperature and rainfall. Rainfall and SST did not have

443   random slopes but the same value for all locations indicating that a similar mechanism

444   influences the *S. serrata* catches throughout the region as described in the conceptual

445   model (Fig. 1). The LMM showed that Bynoe Harbour was the main contributor to

446   the random slopes for SOI. The difference in intercepts e.g. the r^2 value for Mary and

447   Adelaide Rivers being lower than that for the Robinson, Roper and McArthur Rivers

448   was distinct between these regions reflecting the differences in catch between the Gulf

449   of Carpentaria and the Arafura Sea.

450   Attempts have been made to use linear models to predict prawn catch in the Gulf

451   of Carpentaria or maximum likelihood estimation (MLE) for depletion analysis based

452   on a more complete specification of the process (Schnute, 1983). However, large

453   fluctuations in effort and unknown parameters such as mortality rates made these

454   models unreliable.

455   In recent years, hierarchical Bayesian model approaches have been used for

456   parameter estimation in fishery models. Zhou *et al.* (2008) applied a hierarchical

457   Bayesian model to the Northern Banana Prawn (*Penaeus merguiensis*) Fishery to

458   assess abundance and catchability. Hierarchical Bayesian models are likely to become

459   increasingly popular, especially for the assessment of short-lived invertebrates.

460   However, they require careful choice of re-parameterisation and hyperpriors to

461   achieve convergence. Other possibilities to explore the use of a dynamic model to

462   simulate monthly catch rates of *S. serrata* include modeling programs such as

463   WinSAAM (www.winsaam.com) (Stefanovski *et al.*, 2003). This software supports

464 an array of flexible objects that allow the emulation of processes using constructs.

465 These processes can be direct conceptual counterparts of transition, and event,

466 processes of the actual system. WinSAAM was tested to simulate *S. serrata* catches

467 for the Roper River, and we found three distinct phases (0-70, 71-150, and 151-230

468 months) that demonstrated an underlying trend. This included 1) a linearly increasing

469 catch component varying from 0.059 kg/d per month for phase 1, to 0.170 kg/d per

470 month for phase 2, to, finally, 0.014 kg/d per month for phase 3, 2) a fixed catch rate

471 component of 6.230 kg/d and 3) a constant fractional decline of catch rate (reflecting

472 the suppression of excessively large catch rates) of 38.7% of the daily catch rate per

473 month. The phases followed a simplified SOI pattern that showed an extreme peak

474 coinciding with phase 2 of the described model supporting our findings.

475 It is possible under more tightly controlled conditions to automatically locate

476 transition points in the catch rate patterns using a delay system; however, the

477 resolution of the data precluded this approach (Stefanovski *et al.*, 2003). Further

478 refining, improved fitting and the combination with available models (Haddon *et al.*,

479 2005) would be needed to reflect biological links.

480

481 *4.5. Data issues and improvements*

482 Catch or catch adjusted for effort provides an indirect measure of the influence of

483 physical drivers. Therefore, catch data as an abundance measurement of a population

484 are limited, but often the only available information. Catchability can vary for reasons

485 associated with abundance, *S. serrata* behaviour, population biology including its

486 dynamics, but also the efficiency and magnitude of fishing effort, fishing strategy and

487 environmental conditions (Arreguin-Sanchez, 1996). For example, fishing effort can

488 be under-reported (i.e. people using pots in excess of the legal limit) (Groeneveld,

489 2003).

490   Analyses of the Daly River demonstrated that catch data with significant temporal

491 gaps are not suitable for the analysis. No significant results were obtained for this

492 river system; however, it is expected that the same relationship would have existed as

493 for the other systems if more and continuous catch data had been available. The

494 results of the Daly River were in line with the observation that in regions with high

495 catches (and therefore a high abundance of *S. serrata*), catch was more likely driven

496 by environmental factors, whereas in regions with low catch rates, effort was the most

497 important driver.

498   The use of mean rainfall as a proxy for freshwater runoff can give rise to a number

499 of problems. The smoothing effect of averaged data may hide important biological

500 trigger values e.g. negative effect of extreme rainfall events. Overall, the effect of

501 rainfall on the freshwater flow depends on the size of the catchment, soil saturation,

502 degree of urbanisation and other factors (Hassanizadeh *et al.*, 2002). When modeled

503 flow data from the Northern Australia Sustainable Yields Project were used for the

504 Roper River instead of the mean monthly catchment rainfall, the Pearson correlation

505 between monthly *S. serrata* CPUE and rainfall or flow rose from 0.40 to 0.53.

506

5. Conclusion

508   The lack of any real effort, throughout Scylla's wide geographic range, to model

509 the fishery dynamics of this species group, needs to be addressed in future research.

510 Here we have focused on *S. serrata* from northern Australia but the biology and

511 ecology of the four Scylla species seem to vary (although comparative data is next to

512 non-existent) so the impact of environmental fluctuations may differ requiring the

513 development of species-specific and location-specific models. Our case study

514 established the role and importance of the SOI for the NT *S. serrata* fishery as a case

515 study that CPUE was influenced by variations in temperature and rainfall (indicated

516 by the SOI) via changes in recruitment, movement and catchability. Similar trends are

517 expected in south-east Asia. A regional fisheries management strategy is supported by

518 the meta-analyses that demonstrated the existence of at least two distinct groups of

519 river systems in the NT. These findings can support predictions of *S. serrata* catch

520 rates for future modeling approaches and can be combined with currently available

521 models (Haddon *et al*., 2005, Jirapunpipat *et al*., 2009). This will allow fishers and

522 fisheries managers to adjust for increasing environmental fluctuations under climate

523 change and ultimately consequences of *S. serrata* catch and abundance.

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Figures and Tables

Fig. 1. Illustration of the role of salinity and rainfall as important drivers of *S. serrata* catch. The arrows from + to − indicate the strength of the impact of the environmental drivers from the larval to the adult life stage on *S. serrata* population indicators.

Fig. 2. Location of the study site. For six of the seven selected river systems (Bynoe Harbour not included), the relative proportion of total catch between 1990 and 2008 is represented by the size of the discs. The selected systems represent 75% of the total Northern Territory *S. serrata* catch between 1990 and 2008.

Fig. 3. Mean monthly (slim, black line) and annual (thick, black line) CPUE (kg/day) for the NT commercial *S. serrata* fishery from 1990 to 2008 and the mean monthly (thin, dotted line) and annual (thick, dotted line) maximum SOI values for the same period. Note the six- to twelve-month lag of *S. serrata* CPUE behind SOI variations. The SOI values explain 32% of the variation in CPUE. Arrows indicate La Niña years.

Fig. 4a-c. Plots of Northern Territory *S. serrata* CPUE (kg/day)with lagged SOI (a), SST (b) and log-transformed rainfall (c) for the period 1990-2008. The Daly River was excluded from the graphs due to extended data gaps. r^2 value are given in brackets. Fig. 4c includes months with no rainfall. ROP – Roper, MAR – Mary, ADE – Adelaide, BYN – Bynoe Harbour, ROB – Robinson, MCA – McArthur.

723

724 Fig. 5. nMDS plot displaying the seven selected river systems. The diameter of the

725 circles represents the mean rainfall. The plot is based on CPUE, SST and rainfall

726 1990-2008. Data were square-root transformed and Euclidean distance applied as

727 measure of similarity. The nMDS separated the data into a Gulf of Carpentaria group

728 and a western group of systems.

729

730 Fig. 6. Spectral Analysis of the NT monthly *S. serrata* CPUE data (1990-2008).

731 Periods of high catch occur every six months (seasonal pattern), every 12 months

732 (annual pattern), every two years (life cycle pattern) and approximately every 48

733 months (La Niña pattern).

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744 **Tables**

745

746   Table 1. Overview of selected river system and gauge stations as well as availability

747   of freshwater runoff information and its correlation with monthly average catchment

748   rainfall. All correlations were significant at p < 0.01.

749

750   Table 2. Parameter estimates (±S.E.) and their associated significance values are

751   tabulated based on a Mixed Model analysis of six river systems in the NT. The model

752   contained Log CPUE as the dependent variable and Lagged SOI, Lagged SST,

753   Lagged Log Rainfall as fixed covariant terms. Various models were used but the best

754   model, obtained from a comparison of goodness of fit statistics, contained a random

755   intercept term and a random Lagged SOI term with an unstructured variance-
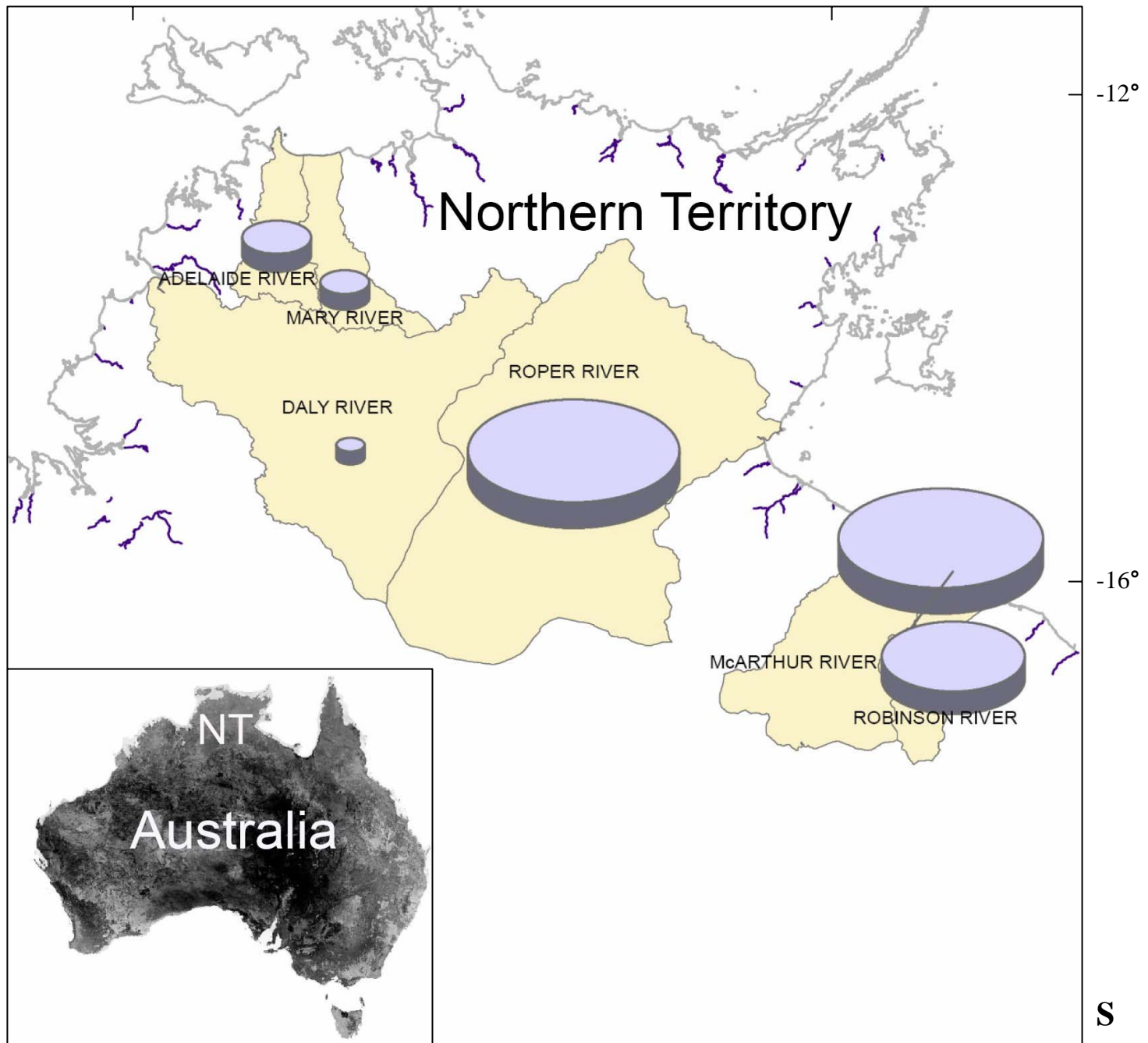
756   covariance matrix.
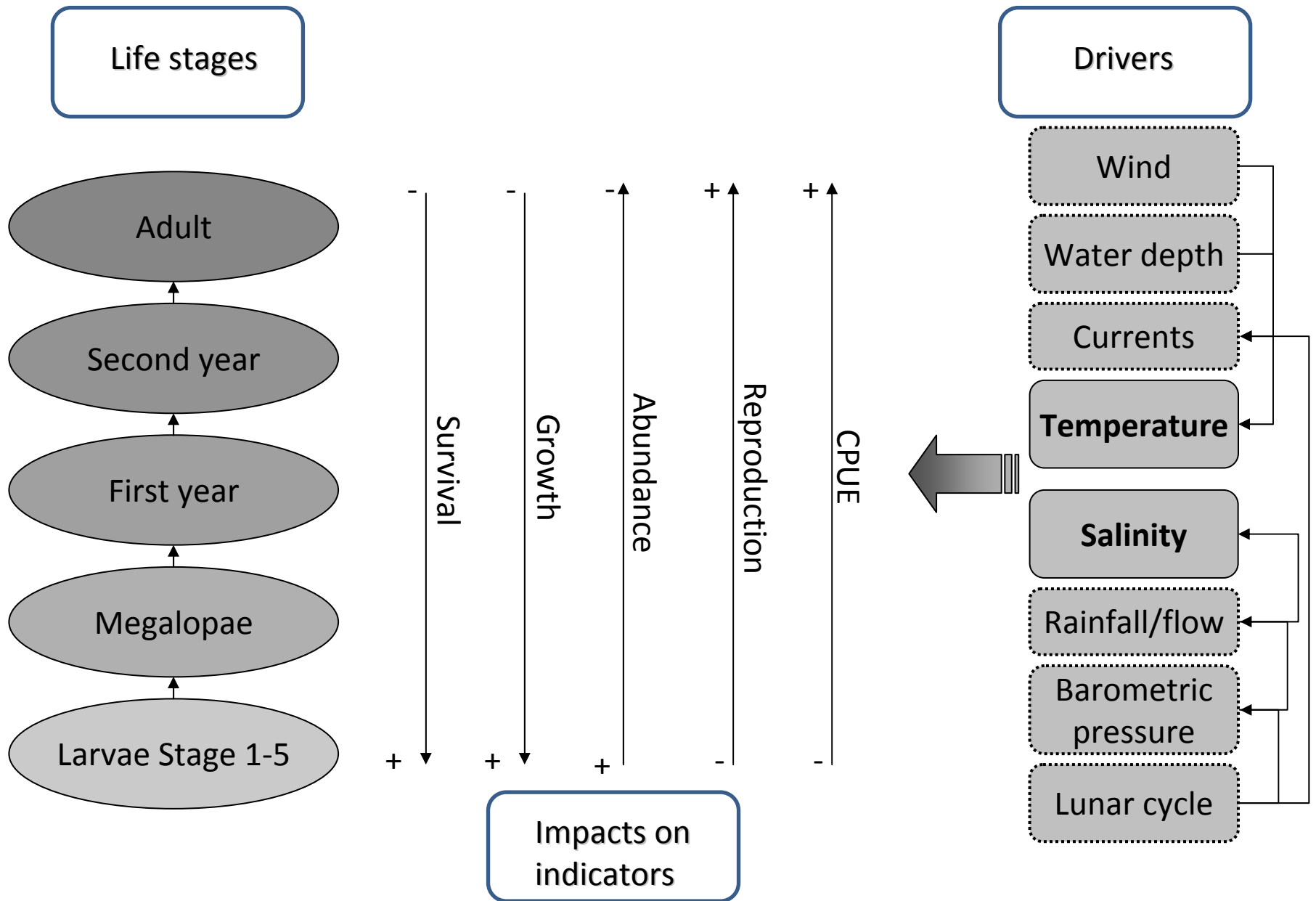
Figure 3

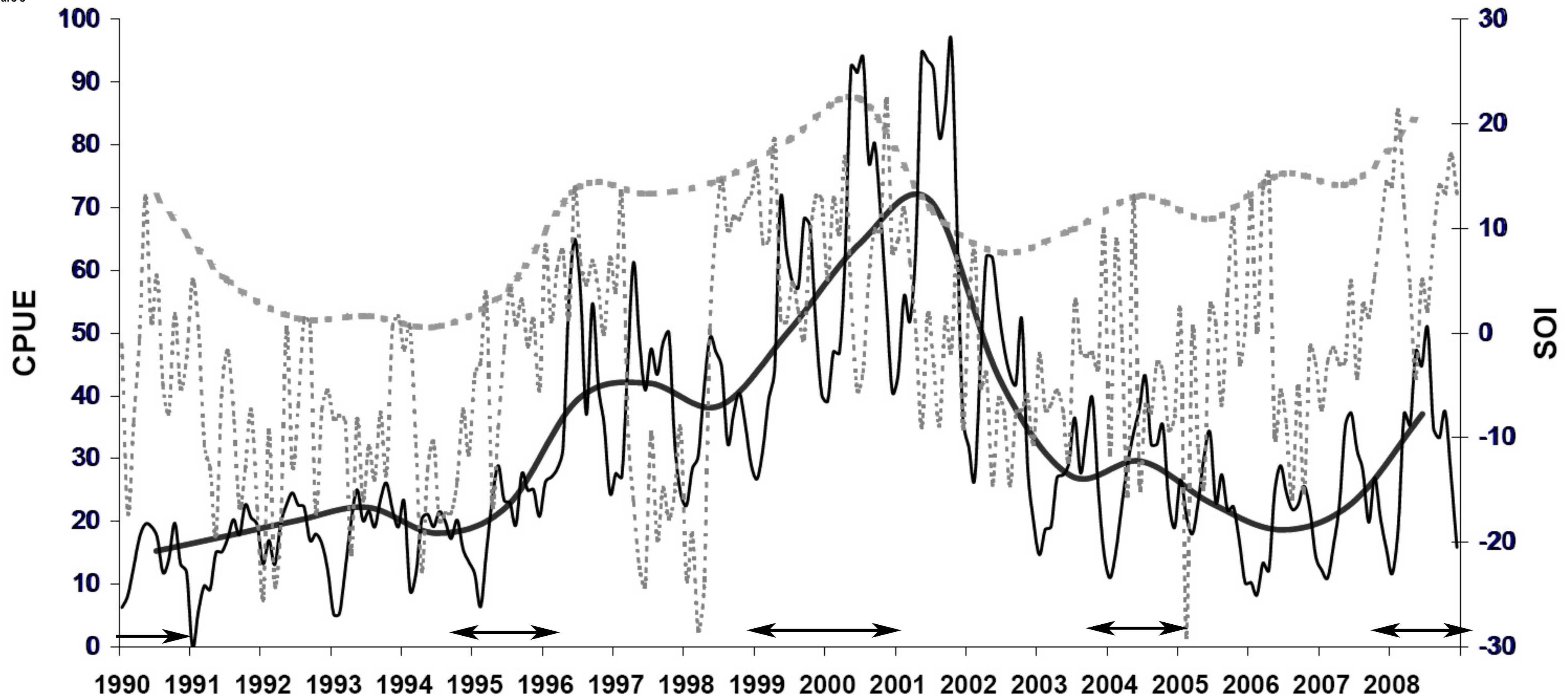**Figure 4**
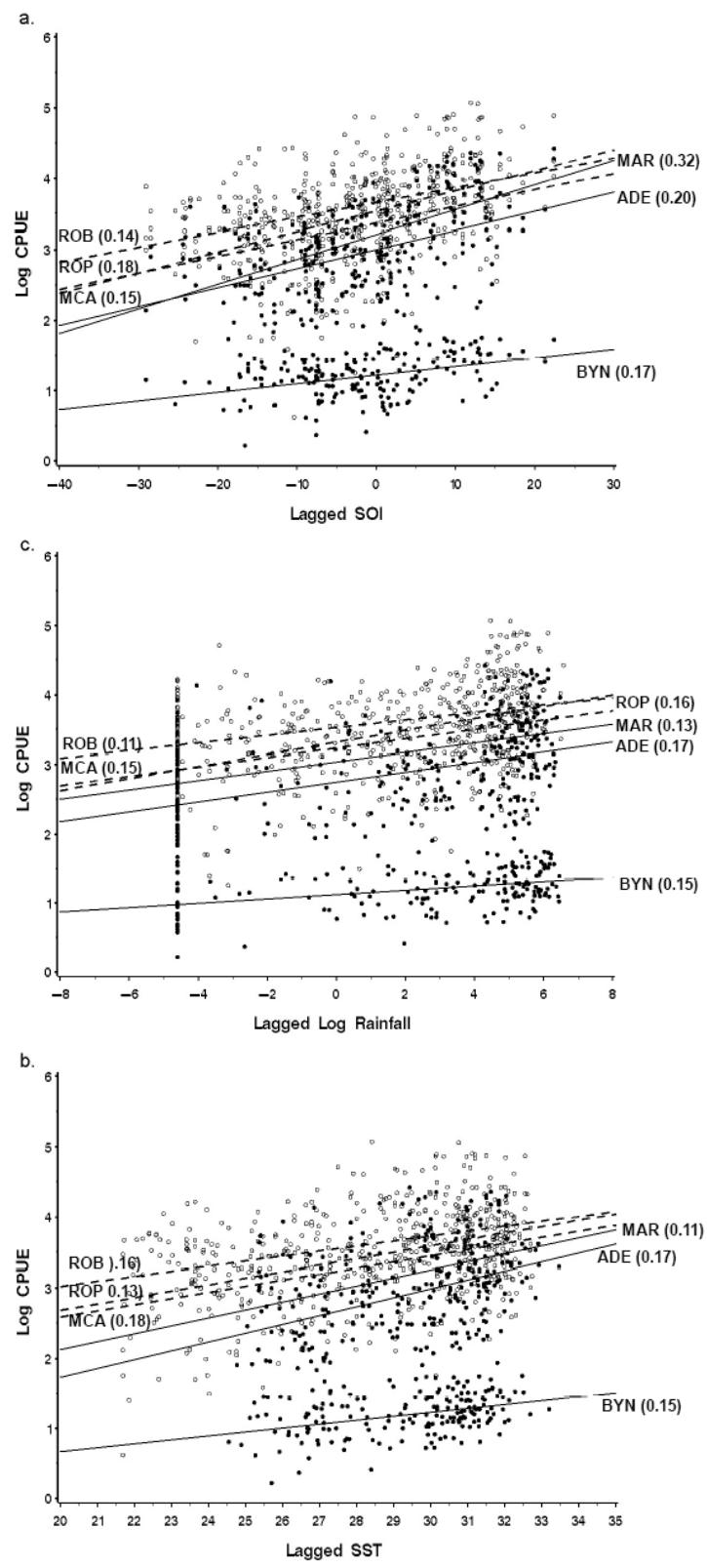
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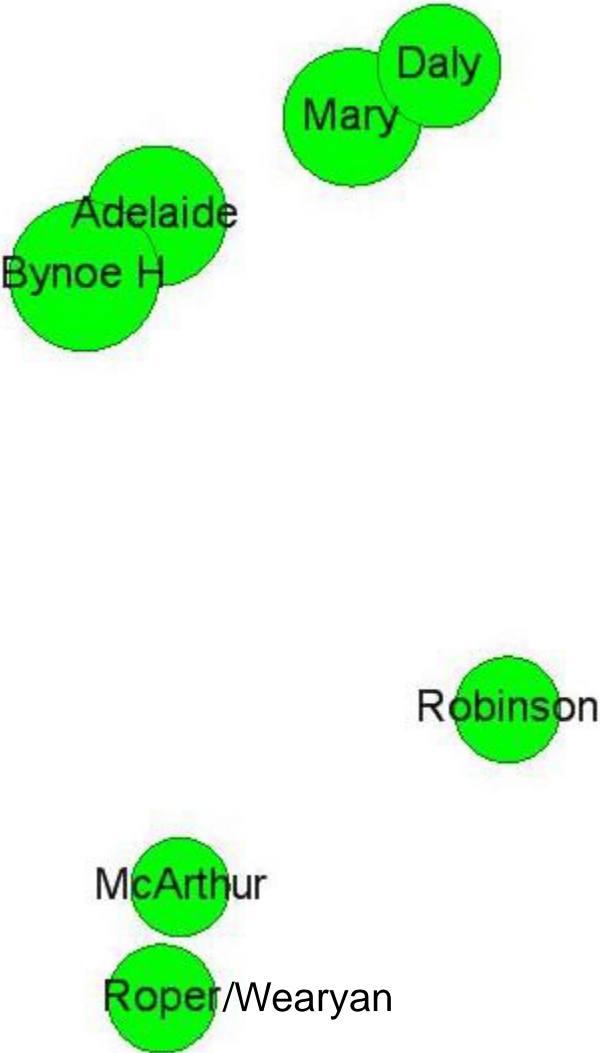
Figure 6
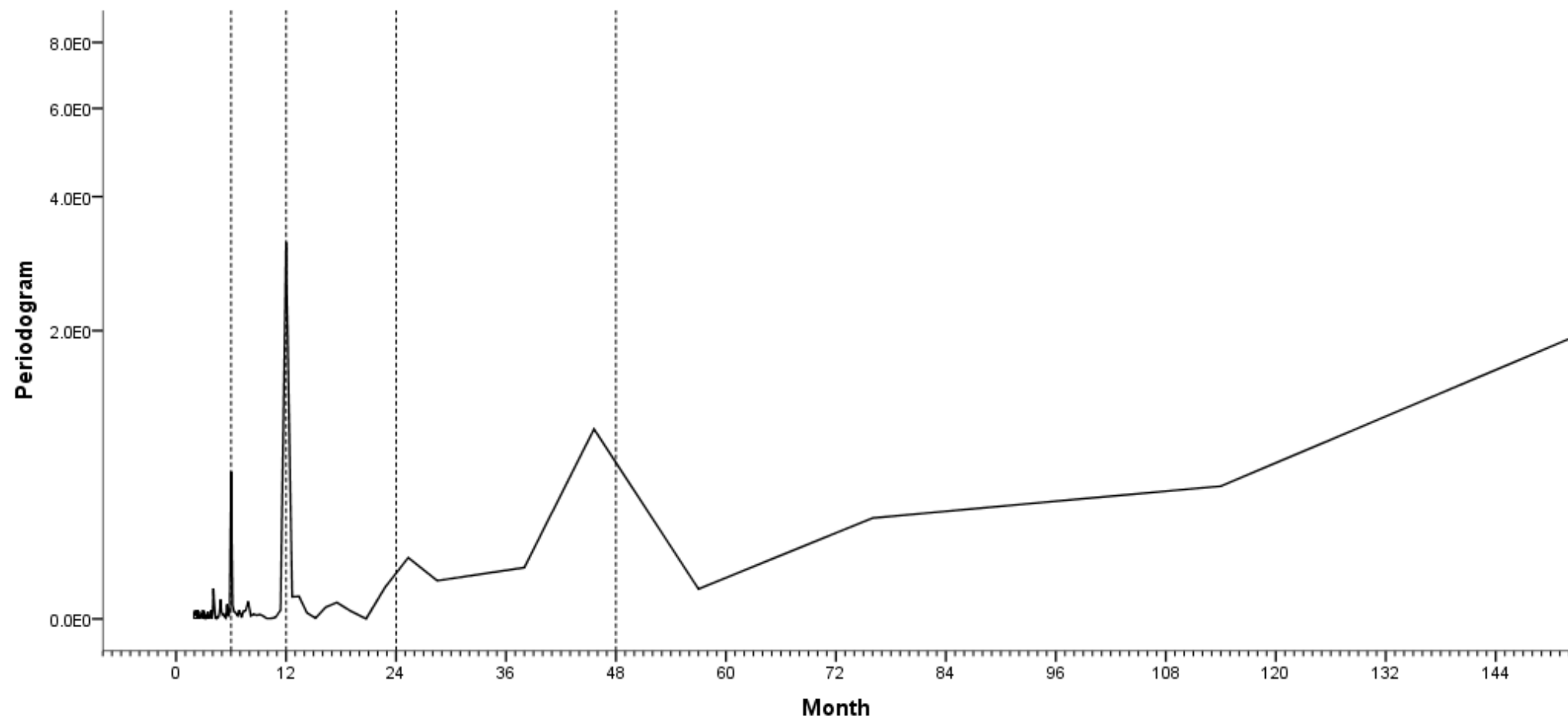
Table 1

River system State in brackets	Gauge ID	Available time period with minor data gaps	Pearson's r between average monthly flow and rainfall
McArthur (NT)	G9070142	1990-2008	.84
Mary (NT)	G8180085	1990-2008	.82
Adelaide (NT)	G817005	1990-2008	.81
Daly (NT)	G8140040	1990-2008	.60
Roper (NT)	G903250	1990-2008	.65

Table 2

Effect	Estimate (Fixed)	Estimate (Random)	Standard Error	P
Intercept	1.1568		±0.4629	0.0545
Adelaide River		-0.0642	±0.3827	0.8669
Bynoe Harbour		-1.8180	±0.3829	**<.0001**
Mary River		+0.1815	±0.3845	0.6371
McArthur River		+0.4176	±0.3828	0.2755
Robinson River		+0.7153	±0.3828	0.2755
Roper River		+0.5678	±0.3832	0.1388
Lagged SOI	0.0218		±0.0025	**0.0003**
Adelaide River		+0.0001	±0.0024	0.9676
Bynoe Harbour		-0.0087	±0.0025	**0.0004**
Mary River		+0.0021	±0.0025	0.3920
McArthur River		+0.0011	±0.0024	0.6560
Robinson River		+0.0026	±0.0024	0.6560
Roper River		+0.0028	±0.0025	0.2595
Lagged Sea Surface Temperature	0.0628		±0.0095	**<.0001**
Lagged Logged Averaged Rainfall	0.0168		±0.0072	**0.0187**