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Size-selective fishing of *Palaemon serratus* (Decapoda, Palaemonidae) in Wales, UK

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1 **Title:** Size-selective fishing of *Palaemon serratus* (Decapoda, Palaemonidae) in Wales, UK: implications of
2 sexual dimorphism and reproductive biology for fisheries management and conservation.

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10 **Key words:** Caridea; Ecosystem based management; Prawn; Sex-bias; Size at maturity

11 **Abstract**

12 *The common prawn (Palaemon serratus) supports a small-scale but economically important seasonal static-*
13 *gear fishery in Cardigan Bay, Wales (UK). Due to a lack of statutory obligation and scientific evidence, the*
14 *fishery has operated to date without any harvest-control-rules that afford protection from overfishing. In*
15 *response to fluctuations in landings and in pursuit of increased economic returns for their catch, some*
16 *members of the fishing industry have adopted a size-selective harvesting regime, which we evaluate here*
17 *using baseline data. Monthly samples were obtained from fishers operating out of five ports between*
18 *October 2013 and May 2015 (n = 4,233). All prawn were sexed, weighed and measured, whilst the fecundity*
19 *of females was estimated for 273 (44%) individuals. Peak spawning occurred during the spring and females*
20 *were estimated to undergo a 'puberty moult' at a carapace length (CL) of 7.7 mm, whilst functional maturity*
21 *was estimated at a CL of 9.9 mm. The sampled population exhibited sexual dimorphism, with females*
22 *attaining a greater size than males. The current harvesting regime results in a sex bias in landings as even*
23 *large mature males remained under the recruitment size to the fishery, unlike the large mature females. The*
24 *temporal trend in sex-ratio indicates a continual decrease in the catchability of female prawn through the*
25 *fishing season; however, whether this is caused by depletion via fishing mortality or migratory behaviour is*
26 *yet to be resolved. Here, we provide a comprehensive baseline evaluation of population biology and discuss*
27 *the implications of our findings for fisheries management.*

28 INTRODUCTION

29 The fishery for the common prawn, *Palaemon serratus* (Pennant 1777; Neal 2008), is relatively small
30 compared to other European “prawn” fisheries (*Nephrops norvegicus* and *Pandulus borealis*); however, in
31 the UK it has significant regional economic importance. In Cardigan Bay (Wales), the fishery accounts for
32 ~76% of total UK landings (estimate from 2013; MMO, 2015). Commercial exploitation of prawns in
33 Cardigan Bay is exclusively an inshore static-gear pot fishery, with most vessels working within six nautical
34 miles of the coast. The fishery begins to target prawn in early autumn and continues through to the following
35 spring (Cardigan Bay Fishermen’s Association (CBFA) *pers comm.*). The fishing season is dictated by the
36 reproductive migrations of *P. serratus*, which are thought to move inshore to release larvae during the
37 summer and then move offshore in winter. Similar seasonal migrations are reported in a range of palaemonid
38 species, including for *P. serratus* in other regions (Guerao & Ribera, 2000; González-Ortegón *et al.*, 2006).
39 The seasonal migration of prawns inshore in the summer decreases static gear catches to levels that are no
40 longer economically viable (CBFA *pers comm.*). Nonetheless, the Cardigan Bay prawn resource is integral in
41 maintaining the economic viability of many fishing businesses as it provides income during a time of the
42 year when the catchability of other target species, such as European lobster (*Homarus gammarus*), is low.
43 The fishery is therefore an important element in a necessarily diverse static-gear sector.

44 Commercial demand for a larger-sized prawn has resulted in the introduction of voluntary size-grading of
45 catch by fishers. Since 2008, many Cardigan Bay fishers have used a 10 mm bar-spacing riddle (CBFA *pers*
46 *comm.*). Prawns that fall through the bars and into the sorting box are discarded overboard, whilst prawns
47 retained by the riddle are stored onboard, usually within small viver systems.

48 As with many small-scale artisanal fisheries, the Welsh prawn fishery is considered data-poor, with little
49 information pertaining to the fisheries biology of the species. Combined with limited management and the
50 lack of a formal stock-assessment, there is considerable uncertainty about the future sustainability of the
51 fishery. Indeed, fluctuations in inter-annual landings in the Irish fishery (Fahy & Gleeson, 1996; Kelly *et al.*,
52 2009) suggest a variable biomass that may be vulnerable to periodic overfishing or recruitment failure in the
53 absence of management. Understanding the interaction of fishing activities with the species biology is
54 necessary to inform future evidence-based management of the fishery and more generally, understanding the
55 reproductive biology of a fished species is critical information when considering ‘supply-side’ ecology of
56 benthic populations with economic value (Underwood & Fairweather, 1989; Anger, 2006).

57 The common prawn is patchily distributed throughout European inshore waters (Kelly *et al.*, 2009) and
58 occurs between the Mediterranean Sea in the south and the temperate coastal waters of the United Kingdom
59 and Ireland in the north (Forster, 1951). Although the longevity of the species has been speculated to be up to
60 five years (Cole, 1958; Forster, 1959), *P. serratus* are more likely to have a relatively short life span, with
61 individuals persisting for between two to three years (Forster, 1951; Fahy & Gleeson, 1996). Similar to other
62 palaemonids, *P. serratus* is sexually dimorphic, with adult females attaining significantly larger sizes
63 (Forster, 1951; Berglund, 1981). Sexual dimorphism may influence mortality rates between the sexes, from
64 both size-selective commercial exploitation and natural mortality through predation (Berglund & Rosenqvist
65 1986). For female palaemonids, a larger body size also allows for increased fecundity (Guerao *et al.*, 1994).
66 Compared to other similar species, *P. serratus* broods contain larger eggs with high nutritional values
67 (Morais *et al.*, 2002), which are thought to reflect environmental conditions and increase successful
68 recruitment through the larval phase (Parker & Begon, 1986). The planktonic larval phase is characterised by
69 temperature dependent periods of incremental growth and metamorphosis (Reeve, 1969a; Kelly *et al.*, 2012),
70 while salinity has been shown to influence mortality rates during the early life stages (Kelly *et al.*, 2012).

71 The aim of this research was to fill the knowledge gaps for this data-poor fishery by presenting baseline
72 catch and population biology characteristics (length frequency, sex ratio, size at maturity) during the adult
73 stage of the species life-history and to highlight several potential implications of a mandatory technical
74 conservation measure of riddling catches at 10 mm.

75 MATERIALS AND METHODS

76 In August 2013, six commercial fishermen operating from five different ports in Cardigan Bay, Wales, were
77 each given three standard prawn traps (referred to hereafter as “science pots”). The cylindrical pots were
78 fitted with 8 mm mesh on all sides with 35 mm circular entrance at both ends. Once a month, when possible,
79 each fisher recorded the date and GPS location of a haul and the entire contents of each science pot were kept
80 separate and stored frozen. Samples were retained for scientific analysis during two fishing seasons (2013-
81 2014 and 2014-2015), ending in May 2015.

82 <figure 1>

83

84 Scientific pot samples were assessed in the laboratory using a dissecting microscope. All animals caught in
85 the science pots were identified, weighed and measured. Palaemon species were identified according to the

86 illustrated key published by González-Ortegón & Cuesta (2006). Sex was recorded; male prawns were
87 identified by the presence of an appendix masculina on the second pleopod pair. All morphometric
88 measurements were recorded to the nearest 0.1 mm and included the carapace length (CL; the distance
89 between the posterior of the eye-orbit to the posterior of the cephalothorax carapace segment), carapace
90 width (CW; the widest point of the cephalothorax carapace) and pleura width (PLW; the widest section of
91 the second abdominal pleura). The reproductive state (ovigerous or not) was also noted for female prawns
92 and the fecundity of ovigerous females were calculated from a subsample of 10% of the entire egg mass (wet
93 weight). The fecundity was estimated using the following formula (1); where Y indicates the subsample
94 calculated as a proportion of the total eggs mass (T), which was then used to calculate fecundity (F).

$$95 \quad Y_{(\text{approx.}=0.1)} = \frac{\text{Weight}_{\text{subsample}}}{T_{\text{weight}}}$$
$$96 \quad F = \frac{\text{Count}_{\text{subsample}}}{Y} \quad (1)$$

97 All statistical analyses were run in “R” (R Core Team, 2014). Prior to statistical modelling data were tested
98 for normality using the Kolmogorov-Smirnov test and inspected visually using a Q-Q plot.
99 Heteroskedasticity was tested using Levene’s test and a Cook’s distance plot was used to check for outliers.
100 A Hartigan’s dip test was used on length distribution data for non-unimodality. The likelihood of the sample
101 having a 1:1 sex-ratio was tested using a G-test. Since we were not able determine size-at-age for the
102 sampled population, age cohorts are inferred from the observed length distribution. A mixed population
103 approach was used to determine statistical differences between sexes and cohorts within a mixed bi-modal
104 dataset. Using the R packages “MIXTOOLS v1.0.3” (Young *et al.*, 2015) and “MIXDIST v0.5-4”
105 (Macdonald & Du, 2011), the mean and standard deviation of the two modes in aggregated male and female
106 length distribution data is presented alongside a goodness-of-fit Chi-square test. We use the results to
107 evaluate the length distributions of immature and mature populations as well as sexual dimorphism within a
108 single mixed-population cohort.

109

110 The size of functional maturity was estimated by relating growth parameters (CL) and ovigerous status
111 (binary variable, where 0 = no eggs and 1 = gravid) of females using a logistic regression model (Roa *et al.*,
112 1999) reformulated by Walker (2005) to give:

$$113 \quad P_i = \left\{ 1 + e^{-\ln(19) \left(\frac{CL_i - CL_{50}}{CL_{95} - CL_{50}} \right)} \right\}^{-1} \quad (2)$$

114 where P_i is the proportion of the female population gravid at a given CL. Model parameters were estimated
 115 using generalized linear model with logit link function and a binomial error structure. Confidence intervals
 116 were added by bootstrapping the generalized linear model (1000 runs). The base R code was constructed by
 117 Harry (2013) and is available online.

118 To describe morphometric maturity and determine at what CL positive allometry occurs, an iterative search
 119 procedure was used whereby PLW is modelled against CL for male and female populations separately using
 120 piecewise linear regression. The analysis examines the linear morphological relationship (CL:PLW) and
 121 searches for significant deviations between male and female growth patterns, indicating sex-specific
 122 morphological changes in preparation for sexual reproduction described as a “puberty moult” (Hartnoll,
 123 2001). The method searches each potential “breakpoint” or “inflection” (c) within a predetermined range
 124 until the model has found the point at which the total residual mean standard error is minimised (Crawley,
 125 2007). The model simulation then produces a value (CL) at which the linear models above and below the
 126 breakpoint c show the statistically strongest inflection. The model applied to both male and female datasets is
 127 described mathematically using the equation 3.

$$128 \quad y_i = \begin{cases} \beta_0 + \beta_1 CW_i, & CW_i < c \\ \beta_2 + \beta_3 CW_i, & CW_i \geq c \end{cases} \quad (3)$$

129 where y_i is the CL of individual i , c is a breakpoint (inflection) between linear relationships applying above
 130 and below the value of carapace length equal to c , and the β parameters are the intercepts and slopes of the
 131 two linear relationships.

132 In order to relate the morphological estimate of population characteristics, fisheries catches (CL) results are
 133 converted to CW using the following equations (4) produced by linear regression ($p < 0.05$):

$$134 \quad CW_{\text{Male}} = 0.563CL_{\text{Male}} + 0.643$$

$$135 \quad CW_{\text{Female}} = 0.6389 CL_{\text{Female}} - 0.297 \quad (4)$$

136 Individuals with a CW < 10 mm are assumed to be discarded through the use of a 10 mm spaced riddle.

137 RESULTS

138 Severe weather conditions during the 2013 and 2014 fishing seasons limited the fishing opportunities and the
139 number of individual prawns that could be sampled within that season (n = 765). In total, fishers returned 82
140 pot-samples and 4,233 *P. serratus* underwent laboratory analysis (table 1).

141 <Table 1>

142

143 **Sexual dimorphism and riddling**

144 Sexual dimorphism was evident in the length distributions of all samples. Moreover, prawn populations
145 showed bimodal distributions when data was aggregated by fishing season and location (Hartigan's dip-test;
146 $D_{\text{Male}} = 0.95$, $D_{\text{Female}} = 0.04$, p-value < 0.001). The majority of male prawns and the smaller sized cohort of
147 female prawns caught in the small mesh science pots were of a size that would be discarded using the 10
148 mm riddle employed by Cardigan Bay fishers (Fig 2).

149 <figure 2>

150

151 Carapace width varied significantly between sexes and two cohorts were identified using a mixed population
152 cohort analysis (1⁺ and 2⁺; summary statistics and ANOVA results in Table 2a). Table 2b compares
153 dimorphism highlighted by Forster (1951) and the present study. A higher proportion of the males (78.3 %)
154 caught were smaller than 10 mm CW compared to the females (39.7 %) in catches.

155 <Table 2>

156 The maximum size observed in the sampled population showed females grew to a size considerably greater
157 than males, whilst the length distribution of catches show that the average male prawn within the 2⁺ cohort
158 does not reach a size at which it recruits into the Cardigan Bay prawn fishery.

159

160 **Sex ratio**

161 The sex-ratio of catches varied significantly from the expected 1:1 ratio, with both male and female directed
162 skews being observed throughout the sample period (Fig 3a)

163 <figure 3>

164

165 For all locations sex-ratios were female skewed in autumn and winter samples, with a higher proportion of
166 males caught in spring. Where an extended time-series was available from a single location, data exhibited
167 strong temporal trends in the sex-ratio and declining abundance of females as the fishing season progressed
168 in New Quay (3b); however, the data trend was less clear in the samples from Aberystwyth (Fig 3c).

169 **Size at maturity (SOM)**

170 Using an iterative search procedure, an inflection point was detected in the linear relationship between CL
171 and PLW in the female dataset. The data suggests that for pleura morphometrics, males display an isometric
172 growth pattern and females an allometric growth pattern. For females, the CL:PLW inflection point was
173 detected at 12.5 mm CL (Fig 4).

174 <figure 4>

175

176 **Size at maturity (L_{50})**

177 Maturity is expressed as L_{50} , which is the size (CL) at which 50% of the females were observed to be gravid
178 (carrying eggs). The maximum likelihood estimate of L_{50} estimated by the generalised linear model with a
179 binomial distribution was 15.9 mm CL (upper and lower confidence intervals = 16.4 mm and 15.4 mm CL
180 respectively; Fig 5).

181 <figure 5>

182

183 **Fecundity**

184 Of the 616 gravid prawn that were captured by scientific pots, 273 (44%) were analysed for fecundity using
185 the equation described (1). Prawn ranged in size from 14.2 mm to 25 mm (CL) and produced fecundity
186 estimates of between 221 and 5,121 eggs per animal.

187 <figure 6>

188 A Spearman's correlation was run to assess the relationship between CL and fecundity. There was a strong
189 positive correlation, which was statistically significant ($r_s = 0.48$, $p < 0.001$) and is explained by the power
190 relationship below (figure6; equation 5). The fecundity data exhibits a high degree of variability with CL

191 explaining just 22.2% of the variation in fecundity. Data points shown as triangles represent available
192 fecundity data from Forster (1951).

$$193 \text{ Fecundity} = 92.546 e^{0.1465 CL} \quad (5)$$

194

195 DISCUSSION

196 **Sexual dimorphism**

197 Our results confirm that *P. serratus* in Cardigan Bay are sexually dimorphic, with females occupying a
198 broader length-distribution than males in the sampled populations. These results mirror the sexual
199 dimorphism that has been reported elsewhere for *Palaemon serratus* (Guerao & Ribera, 2000) and many
200 other *Palaemon* spp, with typically slower growth rates and smaller sizes in males. (e.g. Berglund, 1981; Ito
201 *et al.*, 1991; Bilgin *et al.*, 2009; Al Maslamani *et al.*, 2013).

202 The evolutionary cause for dimorphism in this species is likely to have resulted from selection based on the
203 differing reproductive roles of the sexes (Shine, 1989). The current size-selective exploitation and resulting
204 pressure on mature females could potentially result in evolutionary responses that change growth and
205 reproductive patterns at a genetic level (e.g Conover & Munch, 2002; Walsh *et al.*, 2006; Swain *et al.*, 2007).
206 Given the short life span of *P. serratus*, fishery-induced responses such as decreasing size-at-maturity and
207 size-at age may occur over a timescale of years or decades (Reznick *et al.*, 1997; Thompson, 1998; Koskinen
208 *et al.*, 2002; Stockwell *et al.*, 2003), a phenomenon that has been demonstrated in a number of other
209 exploited populations (e.g Grift *et al.*, 2003; Olsen *et al.*, 2004; Barot *et al.*, 2004). Indeed, the selection
210 pressure towards large females and potential decrease in growth rates may have a negative effect on the
211 value of the species in the long term, which runs contrary to the larger prawns desired by the market. Hence
212 it is important to continue monitoring these life history characteristics, in order to determine any long term
213 changes, particularly in females. It would also be valuable to compare populations with varying degrees of
214 commercial exploitation.

215 **Length frequency and commercial fishing**

216 At present, the fishery is not subject to any statutory harvest-control-rules or technical-measures that aim to
217 encourage sustainable exploitation of prawn populations in Welsh waters in addition to the requirement for

218 commercial fishers to hold a shellfish license. The voluntary riddling of catch using either a 10 mm riddle or
219 > 10 mm pot mesh by some fishers ensures both a better market price and may return as many as 40% of
220 females to sea including sexually immature individuals. Since the grading of prawns is an entirely voluntary
221 practice, it is not possible to determine the relative proportion of common prawn landings in the UK that
222 have been graded at sea, on the quayside or not at all. Whilst the mortality rate amongst prawns discarded at
223 sea is still to be determined, personal observations indicate a very high level of mortality when prawns are
224 graded on the quayside. The absence of information on discard mortality rates calls into question the real
225 value of the riddling practice, particularly since the mortality rate is likely to be high. If the rate of mortality
226 amongst discarded prawn is at a significant level, the sex-specific consequences of riddling may not be as
227 severe as the data suggests. Nonetheless, there is a need to ensure that riddling is done at sea over fishing
228 grounds and habitat from which the prawn were removed. Some fishermen argue that a larger mesh size on
229 the fishing gear is a more appropriate conservation measure. We suggest that a gear comparison trial be
230 conducted to determine the gear design that maintains catchability whilst promoting the escape of undersized
231 prawn. Importantly the interaction between riddling and size-selectivity (i.e that a riddle will retain prawn
232 only of a size ≥ 10 mm) is an assumption in this study and not empirically validated. Future research needs to
233 collect data on retention rates of a known size distribution of animals being graded in order to evaluate the
234 real the real size and sex specific implications of the technical measure.

235 In 2008, when voluntary measures were adopted by some Cardigan Bay fishers, it was hoped that the
236 discarding of small prawn at sea would provide additional ecological and economic value by improving
237 market prices and releasing immature prawns to improve yield-per-recruit and spawner-per-recruit
238 respectively (CBFA *pers. comm.*). Our results show that by applying a size-selective harvesting regime, the
239 Cardigan Bay prawn fishery subjects the female population to a much higher level of removal relative to the
240 male population. Indeed, the immediate consequence of the quasi-minimum-landing-size would have been
241 the discarding of approximately 78% of male prawns caught in pots, compared to a female discard rate of
242 approximately 40% on average throughout the fishing season. The bi-modal distribution of size-frequency
243 data was present in all spatial and temporal combinations, representing a strong indication that two cohorts of
244 prawns are present during fishing the season. With the assumption that commercial activities select prawn at
245 a size 10 mm CW under the voluntary MLS, data shows females are recruiting into the fishery in their

246 second year at a mean size of 12.32 mm CW (SE \pm 1.22). However, fewer 2+ males are recruited into the
247 fishery, as the average male in their second year is 9.64 mm CW (SE \pm 0.84).

248 Our study shows similar patterns in length-cohort distribution to previous studies. Forster (1951) reported
249 female population attaining a greater modal size than males within the 2+ cohort ($TL_{M_0}^{\text{♀}} \approx 92.5$ mm; $TL_{M_0}^{\text{♂}} \approx$
250 77.5 mm). The above values are comparable to those reported in this study; however, the historical data
251 indicates a smaller average size of prawn within the 1+ group than we observed in this study (see table 2b),
252 although the difference is unlikely to be significant. The difference in 1+ size is likely to be as a consequence
253 of differing sampling methods employed by the two studies; Forster (1951) using fishery independent trawl
254 surveys in contrast to the present study, which used fishery-dependent ‘science pots’, which were fished
255 alongside commercial gear and therefore targeted the larger prawns.

256 **Sex bias in the fishery**

257 A consequence to size-selective fishing and higher rates of removal of female prawn may be evident in the
258 temporal trend of sex-ratios (Figure 3a), representing sex-overfishing on a regional scale. However, Fig 3b
259 and 3c shows that decreasing catchability of female prawn is location specific, with samples from
260 Aberystwyth showing a near 1:1 sex ratio late into the fishing season in comparison to fishing grounds to the
261 south, although the proportion of females in spring is still lower than during winter. The decreasing
262 abundance of females in catches marks the end of the prawn season as it is perceived by fishers as a
263 weakening fishery that yields less marketable catch. Seasonal variation in sex-ratios have been observed in a
264 range of palaemonid species (see Kim, 2005; Al-Maslamani *et al.*, 2013) and has been attributed to
265 differential migration patterns, seasonal habitat preferences and possibly mortality between males and
266 females (Berglund, 1981). Female *P. serratus* are known to migrate between habitats to release larvae in
267 Wales (Haig *et al. unpublished data*) and hence it is unsurprising that we observe temporal and spatial
268 changes in sex-ratio as the fishing season progressed in Cardigan Bay as this may reflect localised
269 differences in timing of migration or habitat availability.

270 On a regional scale, fishing behaviour follows an inter-annual pattern whereby fishers in the south
271 experience the onset of the fishing season, with fishing opportunities gradually opening in a northward
272 direction along the Cardigan Bay coast (*pers. obs.* and CBFA *pers comms.*). Similarly, fishing opportunities
273 decline earlier in the south relative to the north, with fishermen from Aberystwyth and Aberdovey continuing

274 to fish for months after fishing has ceased to be commercially viable in Fishguard and New Quay (*pers. obs.*
275 and CBFA *pers. comm.*). Fishermen therefore hold the view that females migrate in a northerly direction,
276 sustaining different rates of catch in different areas through the season. The scientific evidence presented
277 here neither validates nor disproves this view on the migratory behaviour of prawn in the region. Further
278 fisheries independent research (ideally using mark recapture methods) is required to determine if the
279 observed patterns in female catch indicate sex-overfishing, decreasing catchability as a result of seasonal
280 migration by females, or a cumulative response to both of these.

281 The potential for sex-overfishing identified by this study may have consequences on recruitment levels in the
282 future, although the life-history of palaemonids (highly fecund and typically multiple broods per season) may
283 safeguard it against depletion events. The data show female skewed catches in the early period of both
284 fishing seasons (Emmerson *et al.*, 2014), which indicates the population has a degree of resilience in
285 sustaining size-selective fishing at present effort levels, the research presented here cannot draw a conclusion
286 with regards to sex-overfishing in the absence of both long-term datasets and evidence pertaining to adult
287 migration patterns.

288 **Size at maturity**

289 Crustacean fisheries are most commonly managed in the UK using a minimum landing size (MLS),
290 appropriated by maturity characteristics. In order to determine a valid MLS in decapod crustaceans, maturity
291 indicators such as morphological sexual maturity and functional maturity can be applied (Waddy and Aiken,
292 2005; Pardo *et al.*, 2009). Size at maturity has been determined from allometric growth parameters (*e.g.*
293 Hartnoll, 1974; Little & Watson III, 2005; Claverie & Smith, 2009) and specifically the CL:PLW
294 relationship in Palaemonidae species (Cartaxana, 2003). In this study, the pleura has been shown to undergo
295 allometric growth in female *P. serratus*, which expand the brood chamber in preparation for egg carriage at a
296 size $CW = 7.7$ mm. At this point, females undergo an expansion in the PLW relative to males as they
297 continue to grow. It is highly likely that this dynamic allometry amongst females represents a physical
298 change of the abdomen in preparation for egg bearing and thus a sign of sexual maturity. Only 1.5% ($n = 9$)
299 of ovigerous females were observed at a size below our estimate of morphological size at maturity, implying
300 a high degree of confidence in the results of the iterative search procedure used. A total of 18.6 % of females
301 ($n = 361$) captured by scientific pots throughout this study had a $CW < 7.7$ mm and were assumed to be

302 sexually immature. With a CW < 10 mm, immature female prawn that have yet to develop their brood
303 chamber and are released by Cardigan Bay fishers onto the fishing ground from where they were captured.

304 The size at morphological sexual maturity supports the results from this study's estimate of functional
305 maturity (L_{50}), with the results implying that female prawn undergo a puberty moult at an estimated size CW
306 = 7.7 mm, whilst 50% of females are able to contribute to the reproductive capacity of the population by the
307 size CW = 9.9 mm (15.9 mm CL). In this way, the voluntary measure of releasing prawn below CW = 10
308 mm by CBFA fishers has been shown to be a potentially valuable conservation measure. The CL_{50} reported
309 here is greater than that reported in similar studies elsewhere for the species (Ireland; CL_{50} = 12.5mm; Kelly,
310 2009), though similar to previous estimates for the Welsh population (CL_{50} = 16.5; Huxley, 2011).

311 **Fecundity**

312 *P. serratus* were found to carry between 221 and 5,121 eggs at any one time (mean average = 1,916). This is
313 similar to estimates published by Forster (1951), who found large prawn (TL = 105 mm) carry up to 4,282
314 eggs and within a similar range of other Palaemonidae species (Corey & Reid, 1991). The fecundity (number
315 of eggs carried) of female prawns was positively correlated with body size (CL); however, there was a high
316 degree of variability between individuals and CL only explained ~23% of the variation. Studies of similar
317 species (*P. elegans*, *P. adspersus* and *P. xiphias*) report R^2 values > 0.95 (Guerao *et al.*, 1994; Cartaxa, 2003;
318 Bilgin & Samsun, 2006). Different methodologies for estimating fecundity may be the reason behind the
319 variable R^2 values reported here and in the published literature. In particular, previous fecundity estimates
320 were derived from the number of eggs at stage 1 (e.g Guerao *et al.*, 1994) in order to account for egg loss
321 during incubation, which can be the result of mechanical stress or parasites (Glamuzina *et al.*, 2014) and has
322 been reported to be as high as 38% in this species (Reeve, 1969 in Zimmermann *et al.*, 2015). Egg counts by
323 developmental stage were unavailable in this study, which is the likely explanation for the high variability in
324 the fecundity estimate. Nonetheless, the results are within the range reported for the species, as shown in
325 figure 6, and provide an important baseline from which to further understand the reproductive capacity of the
326 Welsh *P. serratus* population by providing an estimate between the numbers of eggs laid on pleopods during
327 spawning and the total that eventually hatched.

328 Fecundity can be influenced by temporal-spatial variations of environmental factors such as depth (e.g *P.*
329 *naval*; Thessalou-Legakiand, 1992), mean bottom temperature (e.g *P. borealis*; Parsons & Tucker, 1986) and

330 habitat (e.g. *E. modestus* and *P. gravieri*; Oh & Park, 2000). We recommend future studies pay particular
331 attention to the problem of egg loss during brooding on pleopods by staging eggs using the criteria outlined
332 in Guerao and Ribera (1995). Preservation of samples would permit a more accurate estimate of real
333 fecundity, which should incorporate egg stage, size-dependent egg losses and egg-quality into the fecundity
334 estimate. The limited scope and resources dedicated to the present study has constrained the data available
335 for our fecundity estimate; however, it provides a useful baseline from which to continue monitoring.

336 **Management**

337 The aim of this research was to provide a series of region-specific indicators that can be used by fisheries
338 managers in the Cardigan Bay prawn fishery to guide biologically appropriated management measures. The
339 voluntary measures employed by some fishing industry members in Cardigan Bay are effective at protecting
340 50 % of the female brood stock in their catch providing the discard mortality rate is low. The process of
341 grading prawn on the deck of a commercial fishing boat can be resource intensive and fishers have
342 engineered bespoke riddle systems or replaced gear for larger mesh traps that may increase the efficiency of
343 the gear in selecting larger prawn. While the results presented here demonstrate the potential ecological
344 benefits of using either a larger mesh size, or a riddle in the prawn fishery, many commercial operations do
345 neither (CBFA *pers. comm.*). Given the potential economic and ecological value of increasing the size prawn
346 reaching the market and the reluctance of some industry members to alter their fishing strategy, a
347 comprehensive analysis of technical options should be explored. This might include the effectiveness of
348 escape panels and minimum mesh-sizes (Fothergill, 2006), which would allow animals to escape before
349 being exposed to increased stress and mortality rates associated with handling.

350 The limited evidence presented here suggests that there has not yet been an observable effect of overfishing
351 on size-at-maturity of females in Cardigan Bay. However, declining CPUE in other exploited populations on
352 the coast of Ireland suggest that overfishing can occur (Fahy & Gleeson, 1996) and hence long term
353 monitoring of any changes should be included as part of ongoing fisheries management. At present, there are
354 no statutory requirements to collect size at maturity data on *P. serratus* despite it being recognised as an
355 important parameter for fisheries management. Ideally, these investigations would be replicated at an
356 appropriate temporal scale; and given the short-life span of *P. serratus*, we recommend biennial replication.
357 Given the potential for sex-overfishing within a size-selective harvesting regime in the Welsh prawn fishery,

358 the extent of which is yet to be fully understood, affording a scientifically-validated level of protection to
359 juvenile females via a MLS would be a valuable safeguard against recruitment failures in the future.

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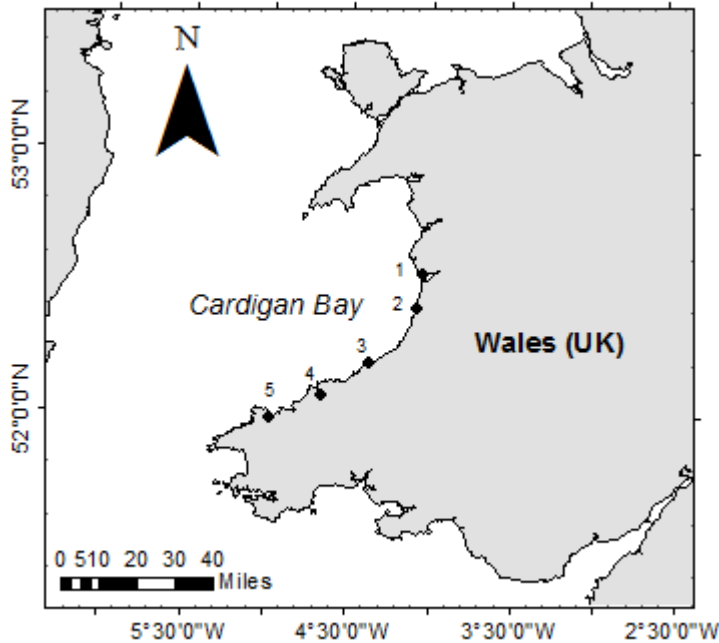
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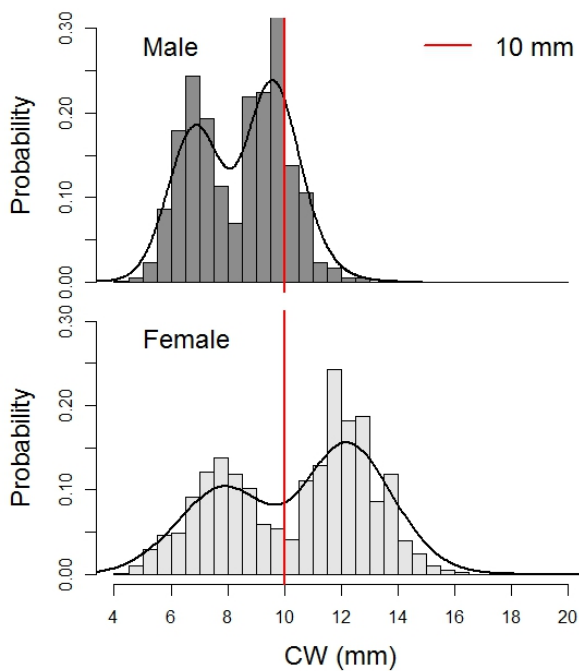
511 FIGURE LEGENDS

512 **Fig 1** The homeports for the six active *Palaemon serratus* fishers in Cardigan Bay, Wales; who
513 contributed monthly samples (when possible) during the prawn fishing seasons from 2013, 2014
514 and 2015. Ports are numbered north to south and are as follows: 1, Aberdovey (2 fishers); 2,
515 Aberystwyth; 3, New Quay; 4, Cardigan; 5, Fishguard



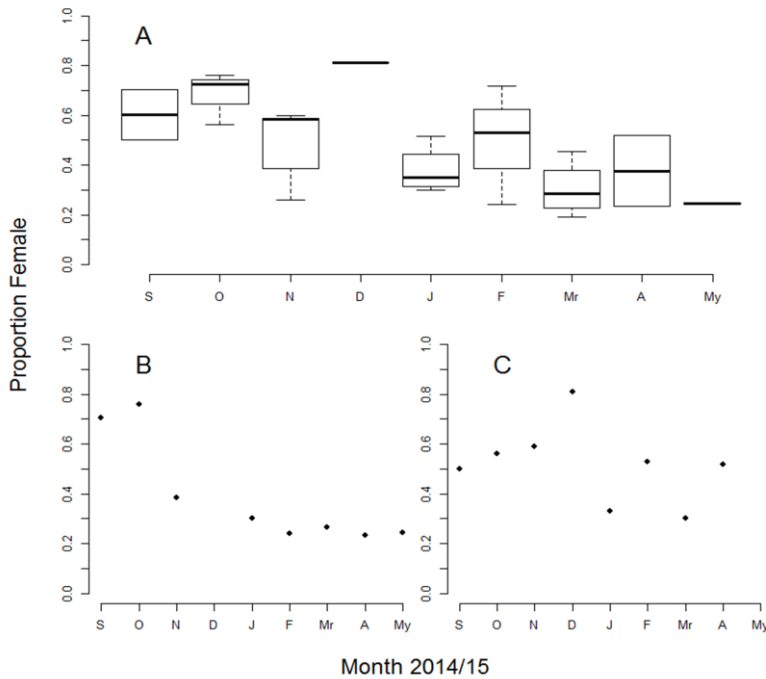
516

517 **Fig 2** A length frequency histogram with a probability density function for male (above) and
518 female (below) *Palaemon serratus* caught in science pots during the 2013-2015 *Palaemon serratus*
519 research period in Cardigan Bay. The solid vertical red line represents the voluntary sorting size
520 (10 mm CW) used by many fishers in Cardigan Bay



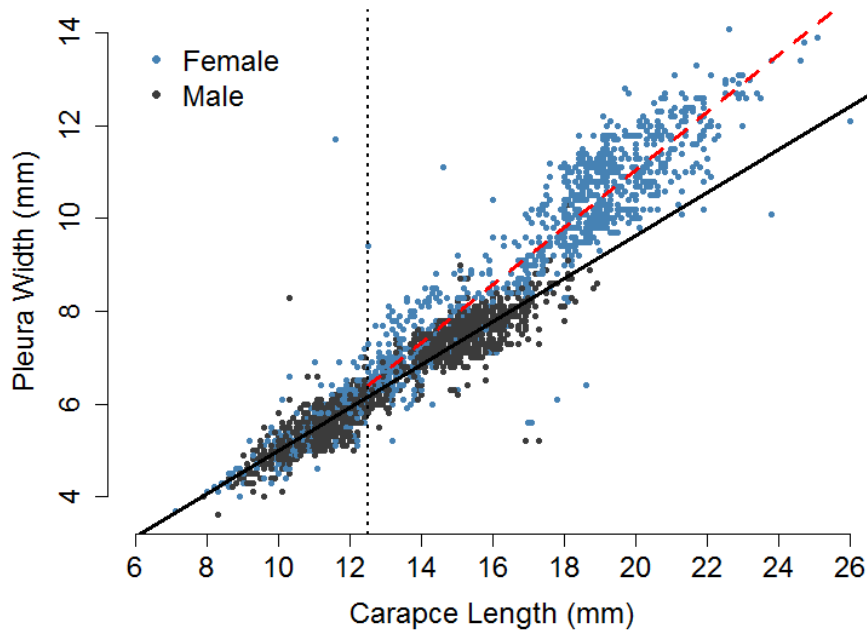
521

522 **Fig 3a** The sex-ratio of prawn (*Palaemon serratus*) caught in science pots from during the 2014 /
 523 2015 in Cardigan Bay and **3b** the sex ratio of catches in localised datasets from New Quay and **3c**
 524 Aberystwyth



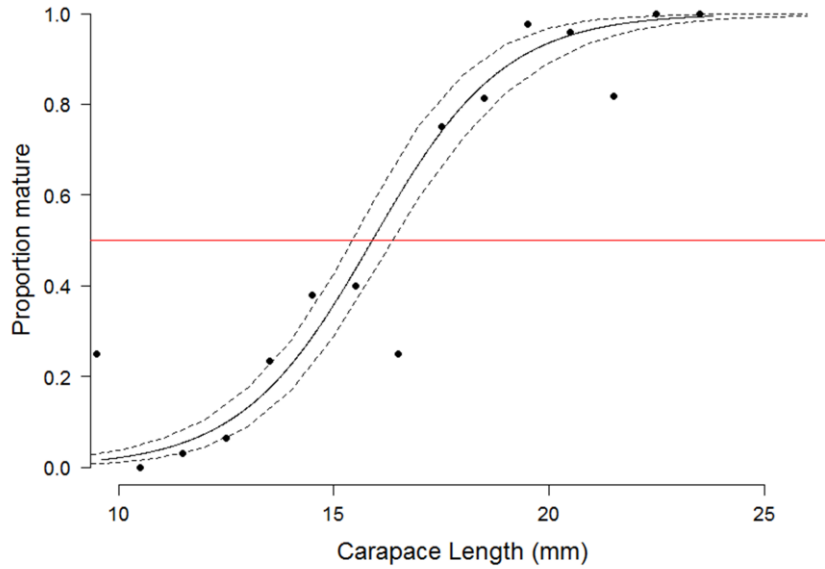
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526 **Fig 4** Inflection point indicating allometric growth based on morphometric variance between
 527 iterative tests on linear models of PLW and CL for the prawn *Palaemon serratus*. The dotted
 528 vertical line is the value with the lowest mean standard error (12.5 mm CL). Solid black line shows
 529 the linear male relationship. Hashed line shows the allometric female relationship after inflection
 530 event



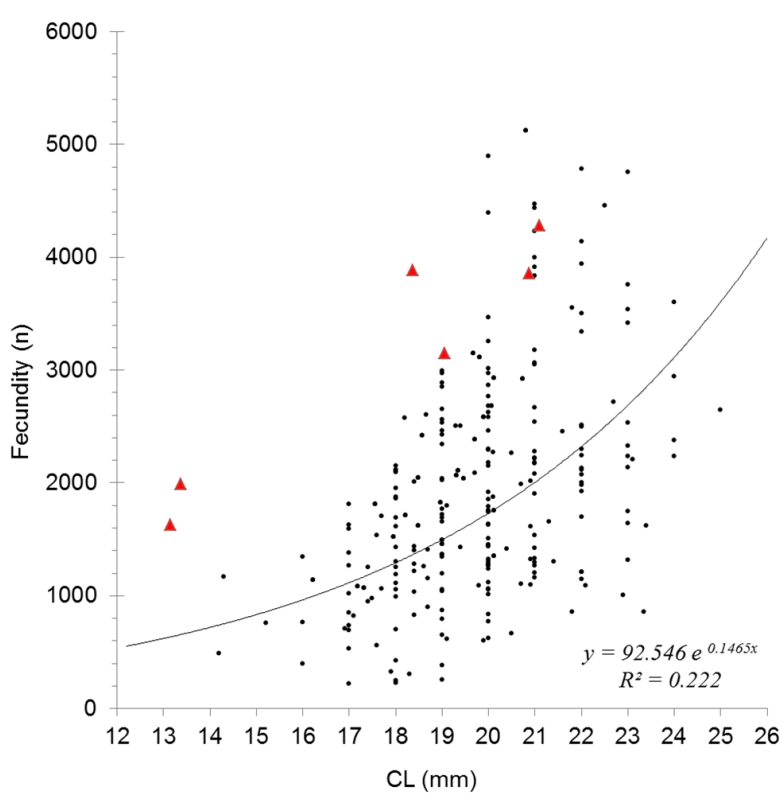
531

532 **Fig 5** Functional maturity model fit for female prawn (*Palaemon serratus*) from Cardigan Bay
 533 (Wales) with 95% CIs as indicated by the presence or absence of eggs. The horizontal line
 534 represents L_{50} (15.9 mm CL) for the females sampled within period of peak spawning (April; n =
 535 544)



536

537 **Fig 6** Fecundity of gravid prawn (*Palaemon serratus*) from Cardigan Bay (Wales) with size (CL)
 538 (n = 273). The solid line shows the power relationship between the correlating variables CL and
 539 Fecundity ($p < 0.001$; $R^2 = 0.222$). The red triangle points and associated hashed trendline show
 540 the fecundity data available from Forster (1951).



541