1 **Abundance and Spatial Distribution of Brown Crab (*Cancer pagurus*) from Fishery-**

2 **Independent Dredge and Trawl surveys in the North Sea**

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13 Exploration of the Sea (ICES) Shellfish Symposium (under the session "Assessment and
14 population dynamics of shellfish"), which took place in November 2019 in Tromsø, Norway.

Abstract

Spatial information is important to understand the distribution, population structure and dynamics of commercially important marine species. Brown crab (*Cancer pagurus*) is a crustacean that supports important commercial fisheries along the British coastline. There have been no specific studies based on fishery-independent surveys documenting the habitat preferences of brown crab around Scotland. This paper provides an analysis of dredge and trawl fisheries surveys in the North Sea (2008-2018) with the aim of describing the spatial distribution of brown crab and developing abundance and recruitment indices for the species. The distribution of brown crab is investigated using geostatistical methods, and generalized additive models (GAMs) are used to model crab catch rates in relation to a number of explanatory variables (depth, distance to coast, sediment type and year). Brown crab catch rates were higher in coastal areas. The male and female crab distribution was relatively similar and juvenile crabs (<100 mm) showed a very clear inshore distribution along the shoreline up to 20 km from the coast. The total abundance as estimated from the dredge survey varied between years, from 34 to 86 million crabs from the dredge survey. The annual trawl catch rate, which provides an index of relative abundance, ranged between 16 and 65 animals/km^2. The dredge and trawl indices were correlated, showing a similar trend of increasing catch rates in the early years of the time series up to 2016, and a subsequent reduction. A recruitment index was also estimated, showing a gradual increase in captured juvenile crabs up to 2014, followed by a steep decrease with the lowest estimated value being reached in 2018. The advantages and limitations of using active fishing methods rather than passive gears such as traps for obtaining standardized catch rates are discussed. The results obtained provide baseline information on abundance, distribution and habitat for a widely distributed species and could be used in future stock assessments, informing the management of this important species.

Keywords: brown crab, geostatistics, survey, fishery-independent data, dredge, trawl, spatial distribution, creel fisheries, Scotland

Introduction

The brown crab (*Cancer pagurus*) is a decapod crustacean which inhabits sandy and rocky seabeds of northwestern Europe (Edwards, 1979), from the littoral zone, to depths of over 100 m (Shelton and Hall, 1981). Like other crustaceans, the growth of brown crab takes place by moulting the shell, with moult frequency decreasing with age. The species reaches the minimum landing size (MLS) in Scotland of 150 mm carapace width (CW) at an age of around 6 years (Mill *et al.*, 2009). The brown crab is considered to be a slow-growing species with a lifespan of approximately 20

53   years, reaching an asymptotic size (L∞) of between 220 and 246 mm in Scottish waters (Bennett,

54   1974; Tallack, 2002; Mill *et al.*, 2009).It is a commercially valuable species with annual landings

55   into Scotland in excess of 10,000 tonnes and a first sale value of £26.8 million in 2018 (Scottish

56   Sea Fisheries Statistics, 2018). Pot fisheries for brown crabs occur along almost the entire length

57   of the British coastline and traditionally these fisheries have been essentially inshore (Eaton *et al.*,

58   2001). Since the late 1980's, offshore crab fisheries have developed, rapidly becoming the largest

59   pot fisheries both in the North Sea and west coast of Scotland. More recently, the expanded

60   demand for this species from European and emergent Asian markets makes an evaluation of its

61   status more important (Mesquita *et al.*, 2017).

62   Concerns about increased landings and uncertainty over the level of exploitation have

63   highlighted gaps in the current understanding of brown crab stocks (Bennett, 1995; Smith and

64   Addison, 2003). Information on spatial distribution is important for understanding the population

65   structure and dynamics of commercially valuable marine resources (Hunter *et al.*, 2013), but there

66   have been very few studies documenting habitat preferences of brown crab. Juveniles from

67   different crab species prefer nursery habitats close to the shore, presumably to avoid predation

68   before moving to different habitats, potentially representing a major source of recruitment for

69   offshore fisheries (Edwards, 1979; Robinson and Tully, 2000; Beck *et al.*, 2001). Brown crabs are

70   known to be associated with rocky substrates but also inhabit mixed coarse, sand and soft

71   sediments, particularly offshore where they dig into mud in search of food, or bury themselves to

72   avoid strong currents (Hall *et al.*, 1993).

73   Abundance indices are generally lacking for decapod crustaceans in European waters.

74   Fisheries-dependent data obtained from vessels using pots are difficult to interpret due to problems

75   in standardizing catch rates, which are affected by, for example, pot design, gear saturation, soak-

76   time and types of bait (Miller, 1990). The problems with commercial catch data can be avoided by

77   using fisheries-independent research surveys which provide estimates of abundance and catch

78   composition across the geographic range of a species (Hilborn and Walters, 1992). Given the

79   occurrence of brown crabs in a wide variety of sediment types, the species is often found in the

80   same habitat as other commercial species such as scallops and demersal fish (Jenkins *et al.*, 2004;

81   Öndes *et al.*, 2016). Many nations have long-term scientific research surveys which contribute to

82   fisheries assessment and management (Jouffre *et al.*, 2009). The brown crab is not currently

83   targeted by any specific fishery-independent survey and there are currently no estimates available

84   of abundance or recruitment for populations around Scotland. Despite this, catches of brown crab

85   are routinely recorded during a number of fisheries surveys conducted by Marine Scotland Science

86   (MSS). There are no studies documenting brown crab catch rates from surveys using mobile gears

87   such as dredges or trawls. It is expected that analysing catch rates from these surveys may contain

88   relevant information on habitat preferences of the species, for example in relation to substrate type,

89   depth distribution or distance to coast.

90   This study provides an analysis of catch rates of brown crab between 2008 and 2018 in two

91   fisheries-independent surveys taking place in the North Sea: a dredge survey directed at the main

92   king scallop fishing grounds (Dobby *et al.*, 2017); and the International Bottom Trawl Survey

93   (IBTS) developed for demersal fish species (ICES, 2018). The aims of this study were to: (i)

94   determine the spatial distribution of brown crab by size and sex; (ii) model crab catch rates in

95   relation to explanatory variables (depth, distance to coast, sediment type and year); (iii) derive

96   abundance and recruitment indices for brown crab. The work represents the first study directed at

97   understanding the abundance, distribution and important habitat features of brown crab in the North

98   Sea using fisheries-independent data.

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101   **Methods**

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103   Study area and sampling

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105   The study area was located in the western North Sea, off the east coast of Scotland. Brown

106   crab data were collected during 11 dredge surveys and 11 trawl surveys (2008-2018, Table 1). The

107   surveys were carried out by MSS in summer (between May and September) on-board the Scottish

108   research vessels FRV "Alba na Mara" (dredge) and FRV "Scotia" (trawl) covering fishing stations

109   around the east coast of Scotland (Figure 1a).

110   The scallop dredge survey was directed at king scallop stocks and took place at fixed

111   stations. The dredge gear consisted of a mixture of standard commercial dredges (9 tooth bar, 80

112   mm internal diameter belly rings) and smaller dredges (11 tooth bar, 60 mm internal diameter belly

113   rings) aimed at capturing smaller scallops (Dobby *et al.*, 2017). The North Sea IBTS quarter 3 (Q3)

114   is an internationally coordinated survey carried out in August each year to collect data on a range

115   of demersal species in ICES Division 3a and Subarea 4 (ICES, 2018).The fishing gear consisted of

116   a GOV (Grand Ouverture Vertical) bottom trawl with standard ground gear as described in ICES

117   (2018). The survey followed a repeat station survey design based on an initial stratified-random

118   allocation, with at least two stations in each ICES statistical rectangle (1 degree longitude × 0.5

119   degree latitude).

120   At each station, the fishing gear was towed for approximately 30 minutes at a speed of 2.5

121   knots (dredge) or 4 knots (trawl) and any identified brown crabs were counted, sexed and measured

122   to the nearest millimetre below. Catch rates were standardized for gear size and tow length by

123   calculating a swept area for each station, i.e. the product of the tow length and the gear width. In

124   the dredge survey, gear size was measured as the total dredge width. For the trawl survey, the

125   horizontal opening of the mouth of the net (wingspread) was used as a measure of the gear width.

126   Catch rates were calculated for each station as numbers of crabs caught per square metre ($N.m^{-2}$).

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130   Environmental variables

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132   Bathymetry datasets for the areas considered were obtained from the UK Hydrographic

133   Office and supplied to MSS by OceanWise Ltd at a resolution of 6 arc second (OceanWise, 2015)

134   (Figure 1b). The sediment layers were obtained from the British Geological Survey (BGS) (Cooper

135   *et al.*, 2013) based on the Folk sediment classification (Folk, 1954). Four sediment strata covering

136   the survey areas were considered: mud, sand, gravelly sand and gravel (Figure 1c). At each station,

137   the geodesic distance to the nearest point in the UK coast (including islands) was computed (in

138   km), referenced to the World Geodetic System 1984 (WGS84).

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140   Spatial distribution

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142   To examine the spatial structure of brown crab distribution, geostatistics (Rivoirard *et al.*,

143   2000) were applied to analyse catch rates in the dredge and trawl surveys (2008-2018). The

144   analysis focused on all brown crabs caught on both dredge and trawl surveys. For the dredge

145   surveys, where a higher number of stations were completed and larger numbers of crabs were

146   sampled (Table 1), the analysis was performed separately for females, males, and juvenile crabs

147   under 100 mm CW. Due to the skewed nature of crab catch rates in both surveys, with many zeros

148   (no crabs caught during a haul), and to reduce the influence of the largest values (Petitgas *et al.*,

149   2017), a logarithmic transformation was performed on the data as follows:

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151        $$C_{ij} = log\left(\frac{r_{ij}}{\bar{r}_j} + 1\right),$$

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153   where C_{ij} is the log transformed catch rate (response variable), r_{ij} is the catch rate in station i and

154   year j and $\bar{r}_j$ is the mean catch rate in year j. Given that the analysis combines several years,

155   dividing the catch rate by $\bar{r}_j$ ensures the data are mean standardized by year.

156   Variograms can be used to quantify the mean variability (semi-variance) of a regionalized

157   variable as a function of the distance between any two points (Petitgas *et al.*, 2017).

158   Omnidirectional empirical variograms were computed for the transformed catch rates for both

159   dredge and trawl surveys in each year (2008-2018) using the estimator (Matheron, 1963):

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161        $$\gamma(h) = \frac{1}{2N(h)}\sum_{i=1}^{N(h)}[Z(x_i) - Z(x_i + h)]^2,$$

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163   where γ is the calculated semi-variance for each dataset, $Z(x_i)$ the catch rate of brown crabs at

164   sampled station x_i, $Z(x_i + h)$ is the catch rate value separated from x_i by a lag distance h (measured

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as a straight line, in km) and $N(h)$ is the number of observation pairs separated by h. A distance h of 10 km was used for the dredge survey and 25 km for the trawl survey (number of lags = 15) (Table 2).

The variograms for each survey/year were combined to obtain an experimental mean variogram standardized by the yearly sample variance following the approach proposed by Rivoirard et al. (2000). Four mean variograms were obtained from the 11 years of data for the dredge survey (all crabs, females, males, juveniles) and one mean variogram for the trawl (all crabs) survey. Visual inspection of the resulting mean variograms (Figure 2a) suggested that spherical models provided a good fit for the dredge data and a linear model was appropriate for the trawl data. Spherical models were fitted to the variograms using a non-linear regression to obtain model parameters, resulting in estimates of a sill, range and nugget (Bivand *et al.*, 2008). The range is the distance at which the semi variance (sill) becomes asymptotic. The nugget is the discontinuity from the origin at a distance of zero, due to measurement error and small scale variability (Rivoirard *et al.*, 2000; Petitgas *et al.*, 2017). For the trawl data, a nested model consisting of a nugget and a linear model, weighted by the number of observation points in each lag, was fitted using ordinary least squares (Pebesma, 2004). The estimated variogram models were used to interpolate the data by kriging (Matheron, 1963; Rivoirard *et al.*, 2000; Bivand *et al.*, 2008).

A number of predictor variables for the study area were available (distance to coast, depth and BGS sediment type), allowing the application of kriging with external drift whereby some of the variance of the data is attributed to the variable in question (Rivoirard *et al.*, 2000; Oliver and Webster, 2014). Data exploration of crab catch rates, in relation to different predictor variables, led to the selection of depth and distance to coast as important variables to explain the spatial distribution of crabs in the dredge surveys. The same variables were used for the trawl surveys with the addition of BGS sediment type, which was found to have an effect in the trawl-caught catch rates. The interpolated catch rate predictions were computed onto an equally spaced grid (3 nautical miles resolution) of the survey area and two-dimensional density maps were generated for each dataset on both surveys. The validity of the variogram models and kriging interpolations was evaluated using a leave-one-out cross-validation procedure (Bivand *et al.*, 2008). A routine was implemented whereby each point was removed from the dataset, using the remaining data to predict the omitted density value and the residuals were computed and spatially plotted for inspection and validation of the model applied to each dataset.

Abundance and recruitment indices

To estimate temporal trends and an abundance index of brown crab in the study area, GAMs were applied to the survey data using the catch rate per haul (numbers of crabs caught per square

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203 metre) as the response variable. Two sets of models were fitted separately, for the dredge and trawl

204 surveys. Large numbers of zero observations were present in both survey datasets, as no crabs were

205 recorded in many of the sampled stations. To deal with zero observations and considering the

206 response variable was markedly right-skewed, a GAM was applied assuming a Tweedie

207 distribution (Tweedie, 1984; Dunn and Smyth, 2005) with a log link. Tweedie models belong to the

208 exponential family of distributions and include a power mean-variance relationship, $V(\mu) = \mu^p$,

209 where $V()$ is the variance function, μ is the mean of the distribution and p is a parameter ($1<p<2$),

210 where $p=1$ implies a Poisson distribution and $p=2$ a gamma distribution (Dunn and Smyth, 2005).

211 The parameter p was estimated for each survey during the fitting procedure with the *tw* function in

212 the mgcv R package (Wood, 2011).

213   The size data available for brown crabs caught in the dredge and trawl surveys were

214 compared to develop a recruitment index for the east of Scotland. A size of 100 mm CW was

215 chosen as a cut-off point to separate juvenile crabs from mature adults, based on the lowest

216 estimates of gonadal size at maturity in Europe (Haig *et al.*, 2016). A preliminary analysis of the

217 length information showed that very few crabs below 100 mm CW were captured in the trawl

218 surveys. Consequently, the recruitment analysis in the study area was focused only on data from

219 the dredge survey, during which smaller crabs were frequently caught. The response variable was

220 the catch rate of crabs (N.m^{-2}) under 100 mm CW. GAM models assuming a Tweedie distribution

221 were fitted to the defined recruitment index but model diagnostics based on the residuals showed

222 generally a poor fit. Therefore, a two-part hurdle model (Mullahy, 1986; Zeileis *et al.*, 2008; Zuur

223 *et al.*, 2009) was used to model the recruitment index of juvenile crabs. In the first part, a binomial

224 GAM (logit link) was used to model the probability that a zero is observed in each sampled station.

225 Positive recruitment index values were plotted and compared with several distributions (Delignette-

226 Muller and Dutang, 2015) and shown to follow a gamma distribution. Therefore, in the second part

227 of the model, non-zero values were modelled with a GAM using a gamma distribution with a log

228 link.

229   The explanatory variables considered for the two abundance models and for the recruitment

230 hurdle model (both parts) were: sediment type (BGS data, categorical variable with 4 levels),

231 depth, distance to coast, year (2008-2018) and geographical position (latitude and longitude plus an

232 interaction term between these) at each sampling station. A backwards stepwise model selection

233 was used to build the GAMs starting with a full model containing all explanatory variables and

234 removing non-significant variables one at a time. The degrees of freedom of each smooth function

235 in the GAM models were not constrained and the convergence of the smoothness selection

236 optimization was inspected for each model. Testing of the fitted models was based on analysis of

237 deviance. Marginal F-tests (Wood, 2006) were used to compare nested GAM models, and chi-

238 squared tests (Chambers and Hastie, 1992) applied to compare nested binomial models, selecting

239 the simpler model if no differences were found (at a significance level of $\alpha=0.05$). The model

240 selection procedure is summarized in Table 3.

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241   Model validation was performed by visually inspecting the residuals obtained for each model

242   which were plotted against each explanatory variable to assess the presence of patterns. The final

243   selected models were used to estimate the abundance and recruitment indices by year. For the

244   hurdle model, estimates of the part 1 binomial GAM (probability of a non-zero event) were

245   multiplied by estimates of the zero-truncated part 2 (gamma GAM) to obtain a final combined

246   estimate. Predictions were made for each grid cell within a 3×3 nautical mile grid and averaged for

247   each survey year over the scallop survey area (Figure 1a). The relative abundance indices derived

248   from the dredge model ($N.m^{-2}$) were raised to the total dredge area (26,600 km^2) to generate an

249   absolute index of abundance and recruitment. The trawl model was used to produce a relative index

250   of abundance ($N.m^{-2}$) estimated inside the dredge area and this was compared with the dredge

251   absolute abundance index for the period 2008-2018.

252   All statistical analysis was implemented in the R statistical programming environment (R

253   Core Team, 2018). The computing of variograms, model fitting, kriging and cross validation were

254   performed with the gstat package v. 1.1-6 (Pebesma, 2004). GAM models were fitted with R

255   package mgcv v. 1.8-23 (Wood, 2011). The probability distribution of survey catch rates was

256   evaluated using functions provided by package fitdistrplus v. 1.0-11 (Delignette-Muller and

257   Dutang, 2015).

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260   **Results**

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262   The two surveys considered in the study are part of MSS research vessel program where the

263   east coast of Scotland dredge survey is generally carried out one month before the IBTS Q3 trawl

264   survey. The same vessels were involved in the data collection for each survey with consistent gear

265   and sampling procedures. The mean number of stations sampled in each year inside the study area

266   was 108 stations in the dredge surveys and 46 stations in the trawl surveys (Table 1). The dredge

267   survey area, where sampling effort is higher (1 station per 248 km^2) is approximately 22% of the

268   larger trawl area where sampling was sparser (1 station per 2609 km^2).

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270   Spatial distribution

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272   The spherical model fitted to the dredge surveys gave a range estimate between 59 and 93

273   km and sills ranging from 0.82 to 0.91 (Table 2). The nuggets varied between 0.53 and 0.76 which

274   is indicative of relatively high variance at short ranges compared with the overall variability at the

275   regional scale (sill). The variograms for all individuals and male crabs were similar with

276   comparable sills and lower estimated nuggets than those found in other scenarios (Figure 2a). For

277   the trawl survey, which only used catch rates for all crabs combined, a linear variogram with a 0.63

278   nugget (intercept) and a 4.07×10^{-4} slope was estimated as the best fit (Table 2). This implies that

279 the variance in the trawl survey increases without bounds unlike the dredge survey where the

280 variance is bounded at the sill.

281   The predicted catch rate for all crabs in the dredge survey was higher in coastal areas

282 particularly in the south of the Moray Firth and along the south east coast towards the Firth of Forth

283 (Figure 2b). In the southern area off the Firths of Forth and Tay, the higher predicted catch rates

284 extended further offshore to the east. Catch rates from the trawl survey had a similar distribution

285 pattern to that found for the dredge survey, although the prediction area of the former was larger.

286 Trawl catch rates showed that the high density area in the south found in the dredge survey may

287 have extended further to the southeast and, in addition, showed a region of medium to high

288 densities estimated to the north of the Orkney Islands corresponding mostly to gravel grounds

289 (Figure 1c). The male and female distribution (derived from the dredge survey) were found to be

290 relatively similar, the main difference being the fact that females were more often found in the

291 inshore waters south of Orkney and to the east side of the survey area. Juvenile crabs <100mm CW

292 showed a very clear inshore distribution along the shoreline up to ~20 km from the coast, except in

293 the north of the survey area where catch rates were low both inshore and offshore.

294   The kriging prediction variances on the five scenarios presented were lowest at and around

295 the observation points and highest in areas where the number of stations was low. Higher predicted

296 mean variances were estimated for the female (0.81) and juvenile (0.78) models in relation to the

297 males and all crabs models (0.61 and 0.62 respectively) (Table 2). Cross-validation analysis

298 performed to verify the validity of spherical and linear variogram fits and kriging predictions

299 supported the suitability of the models used. Spatial plots of the residuals for each scenario showed

300 no spatial patterns in the data.

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302   Abundance indices

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304   Selected GAMs to model catch rates of all crabs (abundance index) and juvenile crabs

305 (recruitment index) are summarized in Table 4. As part of the model validation, visual inspection

306 indicated no obvious patterns in the residuals when plotted against each explanatory variable. The

307 deviance explained for the dredge and trawl models was 45.7% and 61.6%, respectively. The

308 Tweedie parameter p was estimated as 1.14 for the dredge survey and 1.02 for the trawl survey.

309 Explanatory variables "year", "distance to coast", "depth" and "longitude × latitude" were selected

310 for the dredge and trawl models in the abundance index. The "sediment" (BGS) covariate was

311 found to be not significant in the dredge model (p=0.181) based on the analysis of deviances, while

312 in the trawl model, this variable had a significant effect (p=0.04) (Table 3). The trends of the

313 smooth functions and the BGS parametric term in the trawl model fitted to the catch rates are

314 illustrated in Figure 3. The response variable for both the dredge and trawl surveys showed an

315 approximate gamma distribution (positive values) but also contained a large proportion of zeros

316 (21% in the dredge survey; 78% in the trawl survey) supporting the use of a Tweedie distribution to

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model the data (Table 4, Figure 3a). The estimated crab catch rates from the dredge survey (1300-3200 animals/km^2) were 1-2 orders of magnitude greater than those from the trawl survey (16-65 animals/km^2) as recorded catches of crabs were much higher in the former (Table 1). The smooth functions fitted for both models showed mostly non-linear responses to the different covariates used. The exception was the covariate "distance to coast" in the trawl model for which a linear (d.f.=1) decrease of catch rates was estimated over the range of distances which were recorded up to 160 km from the coast. The model applied to the dredge data also showed a decrease of catch rates with distance to coast (although non-linear), in particular within 30 km from the coast where most stations were located with data becoming sparser and larger confidence intervals estimated for distances above 40 km up to the maximum value of 67 km (Figure 3c). In both surveys, the abundance of crabs seemed to be affected by depth with lower catch rates found generally at greater depths. Crab catch rates showed a non-linear decrease with depth in the dredge survey where the depth range was 23-84 m. A similar pattern was observed in the trawl surveys (depth range 42-192 m) but only for depths shallower than ~150 m (Figure 3d). Smoothed plots for year effects were also clearly non-linear (Figure 3b). The plot of the effect of BGS sediment (trawl model only) shows that crab catches in the trawl survey increased gradually from softer to harder grounds with catch rates peaking in the "gravel" sediment type (Table 4, Figure 3e). An absolute abundance index was derived from the dredge model and compared with the relative index from the trawl model. These were compared inside the scallop dredge area where the two surveys overlap (Figure 4). The total abundance as estimated by the dredge model varied between 34 and 86 million of crabs in the 2008-2018 period (trawl catch rates ranged between 16 and 65 crabs per square kilometre). The dredge and trawl indices resemble the respective year effects (Figure 3b) and seem to be correlated showing a very similar trend of increasing catch rates in the early years of the time series up to 2016 and a subsequent reduction.

Recruitment index

The dredge survey captured smaller crabs (median=134 mm, mean=135.9 mm) than the trawl survey (median=160 mm, mean=154.5). The median size per year was found to be significantly correlated (Pearson correlation=0.83, p=0.002) in the two surveys, but fluctuated with no trend throughout the study period (Figure 5). Because animals below 100 mm were seldom caught in trawl surveys, the recruitment index was based on dredge data and was modelled with a two-part hurdle model. The results from the first part of the model (binomial GAM) showed that the variables year, distance to coast and geographical position were significant (p<0.05) for explaining the probability of juvenile crabs being captured in the dredge survey (Table 4). The depth smoother was borderline insignificant (p=0.054, also included in the model) implying a slightly lower likelihood of finding juvenile crabs away from the coast and in depths greater than

354   50 m. A χ^2 test showed that including the type of sediment (p=0.254) as an explanatory variable did

355   not improve the model significantly and this was not included in the final model (Table 3).

356   The second part of the hurdle model used a GAM assuming a gamma distribution of the

357   response variable, i.e. the catch rate of juvenile crabs caught in each dredge station where juveniles

358   were recorded (positive catch rates). The results from this model showed that only variables "year"

359   and geographical position were significant (p<0.05) (Table 4). Juvenile crabs in the dredge survey

360   were mostly found in stations close to the coast in shallow waters, as shown by the geostatistical

361   analysis (Figure 2a). The variables depth (p=0.276), sediment (p=0.277) and distance to coast

362   (p=0.079) did not significantly improve the second part of the model and were excluded during the

363   stepwise selection (Table 3). A predicted recruitment index obtained from combining the two

364   model parts in the dredge survey area is shown in Figure 6. The recruitment index shows a gradual

365   increase in juvenile crabs up to 2014 (0.58 million crabs), followed by a recent steep decrease with

366   the lowest value estimated (0.15 million) observed in 2018.

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368
369   **Discussion**

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371   There is an increasing demand from fisheries managers and stakeholders to obtain

372   information on stock status of exploited marine species. Detailed information on the distribution

373   patterns of species is often missing in fisheries science. Mapping is an important tool to identify

374   habitats and the distribution range of important marine resources. Fishery-independent surveys at

375   sea provide high quality data, as sampling and collection are scientifically designed and

376   standardized (Pennino *et al.*, 2016). Despite the fact that the two surveys analysed in this study

377   were aimed at other species such as scallops (dredge) and demersal fish (trawl), data collected on

378   the distribution of brown crab was informative and useful abundance estimates were derived.

379   Hilborn and Walters (1992) list a number of limitations of fisheries surveys that may lead to

380   unrepresentative sampling, including the location of sampling stations in relation to the target

381   species and the timing of the survey and its relation to the seasonal cycle. The dredge survey

382   analysed is mostly carried out around the coast, following the scallop fishing distribution in the

383   East of Scotland which often overlaps with the inshore crab and lobster fishery (Öndes *et al.*,

384   2016). The trawl survey includes the area of the dredge survey but also extends further offshore to

385   the east and northern North Sea. The dredge survey has a much higher sampling effort resulting,

386   not only in more stations per area, but also in much higher catch rates than the trawl surveys, given

387   that brown crabs are mostly found in the inshore grounds of the North Sea. The timing of the

388   dredge and trawl surveys is similar as both take place in summer, making the two surveys

389   comparable.

390   Brown crabs have previously been reported to be caught more frequently by scallop dredges

391   than trawls (Kaiser *et al.*, 1996). The different catchabilities of the gears may be related to the

392   different types of operation, including the way these gears interact with the sediment and the

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393   towing speed (higher in the trawl survey). The teeth on scallop dredges are able to go deeper in the

394   sediment, capturing crabs that are buried, whereas trawls are more likely to catch only those crabs

395   that are active on the surface of the seabed (Öndes *et al.*, 2016). For example, dredges have been

396   shown to be more efficient than trawls to capture blue crabs (*Callinectes sapidus*) in the western

397   Atlantic given that these species remain inactive and partially buried in the sediment during winter

398   months (Vølstad *et al.*, 2000). Brown crabs are also known to lie in the sediment partially buried

399   (Edwards, 1979; Howard, 1982) making them less available to trawl gears.

400

401   Spatial distribution

402

403   Geostatistics were used to describe the patterns of spatial distribution of brown crab in the

404   North Sea around the East coast of Scotland. Kriging with external drift is a common way to handle

405   a trend in non-stationary geostatistics, taking advantage of auxiliary variables that are known across

406   the study area including the sampling stations (Petitgas *et al.*, 2017). In this study, the predictors

407   used in the kriging analysis included depth and distance to coast (dredge and trawl), and BGS

408   sediment type (trawl model only). Results of variographic analyses of the dredge survey suggest

409   that in the four scenarios (all crabs, females, males, and juveniles) the underlying covariate

410   function is represented by a spherical model, showing that there is spatial autocorrelation in crab

411   density estimates at stations located within small distances of each other. The spherical model has

412   been widely used in fisheries geostatistics given its properties of linear behaviour at the origin

413   stabilizing on a sill, implying the model is bounded and, therefore, associated with stationary

414   covariance (Rivoirard *et al.*, 2000; Petitgas *et al.*, 2017). For the trawl data (which uses all crabs)

415   the nugget effect is higher than for the dredge survey (all crabs scenario) and the semivariance

416   increases linearly with distance, corresponding to non-stationary covariance, which implies a trend

417   in the distribution. The spatial distributions of males and female crabs in the dredge survey were

418   found to be quite similar but there is some evidence of higher female catch rates in the north of the

419   survey area. Several studies based on tagging provide evidence that female brown crabs move more

420   frequently and over longer distances than male crabs e.g. in the North Sea (Edwards, 1979),

421   English Channel (Bennett and Brown, 1983; Hunter *et al.*, 2013), Bay of Biscay (Latrouite and Le

422   Foll, 1989), Sweden (Ungfors *et al.*, 2007) and north of Scotland (Jones *et al.*, 2010; Coleman and

423   Rodrigues, 2016). Edwards (1979) describes an inshore movement of crabs in spring for hatching,

424   moulting and mating, and an offshore movement in the autumn (in particular females) for

425   spawning. The sediment type may also play a role during spawning as female crabs seem to prefer

426   softer substratum (more likely found offshore) in order to scoop out a hollow to rest the lower

427   abdomen and ensure attachment of the eggs to the pleopods (Brown and Bennett, 1980).

428   This study clearly demonstrates that juveniles have a strong preference for inshore grounds

429   as catch rates peak at small distances from land and most crabs below 100 mm were recorded

430   within 20 km from the coast. This agrees with previous descriptions of juvenile brown crabs which

431   have been found to live mainly in shallow inshore waters (Bennett, 1974; Bennett, 1995; Robinson

432   and Tully, 2000) indicating selective habitat preferences possibly related to favourable

433   environmental and ecological conditions (Pallas *et al.*, 2006; Pardo *et al.*, 2007; Dickens, 2012).

434   Heterogeneous habitats such as those found inshore may be selected by crabs as a response to the

435   selective pressure of predation. Structurally complex habitats may result in reduced predation rates

436   by the provision of refugia/shelter to juvenile animals or by decreasing the chances of encounters

437   between prey and predators (Harrison and Crespi, 1999).

438

439   Abundance indices

440

441   Abundance indices were estimated from the survey data using GAM models assuming a

442   Tweedie distribution. Tweedie models are natural candidates for modelling continuous non-

443   negative variables where many zeros are present in the data (Dunn and Smyth, 2008). Tweedie

444   distributions have been used as a modelling approach in a diverse range of fields including fisheries

445   (Candy, 2004; Shono, 2008; Arcuti *et al.*, 2013). In this study, a value of between 1 and 2 was used

446   for the *p* parameter as the Tweedie model was represented by a mix of distributions with a positive

447   mass around zero, given the high number of stations where no crabs were captured. Results from

448   the GAM models applied to the dredge and trawl survey data showed a significant effect of

449   covariates depth and distance to coast in predicting brown crab catch rates. These effects (with the

450   exception of distance to coast in the trawl survey) were non-linear but reflected a general decrease

451   in catch rates at greater depths and away from the coast. This study represents a first insight into

452   the distributional pattern and potential effects of depth and distance to coast on the distribution of

453   brown crab in the North Sea during the summer. However, these results may not applicable to other

454   times of year or other stocks because the distribution of brown crab varies with season and locality,

455   and the trawl surveys in the present study included few hauls at depths greater than 150 m (while

456   the dredge survey was restricted to areas of <100 m depth). For example, female brown crabs

457   support a large fishery in offshore grounds to the north and west of Scotland at depths between 100

458   and 200 m (Mesquita *et al.*, 2017). More recently, numerous individuals of adult brown crab were

459   observed at more than 400 m depth (well over the depths normally reported for the species) on the

460   coast of Norway using video transects (Bakke *et al.*, 2019). In the English Channel, larger adult

461   crabs tend to be caught in the fishery at greater depths while juveniles and smaller crabs were

462   mostly reported inshore (as described in this study) but no standardized catch rates were available

463   (Brown and Bennett, 1980). A study in the Isle of Man found that the catch per unit of effort of

464   brown crab caught in traps increased with depth but the study was limited to a small inshore area

465   with depths up to 65 m (Öndes *et al.*, 2019).

466   Depth and location preferences of brown crabs may also be associated with substrata

467   preference. An important difference between the dredge and trawl models was that the latter

468   included sediment type as an explanatory variable. GAM models applied to the trawl data showed

that sediment type was a significant variable for explaining crab catch rates, with higher rates found in the harder sediment type (gravel) in comparison with the softer sandy and muddy sediments. This explains the relatively high catch rates predicted in the trawl geostatistical analysis for the areas to the north of the Orkney Islands where gravel sediment is predominant. This contrasts with the results obtained for the dredge survey where sediment was not found to be significant, although the amount of gravel inside the dredge area is restricted to some small patches mostly found in the south of Moray Firth and to the south of Orkney. The limited amount of stations within the gravel sediment in the dredge survey in relation to the other sediment types was perhaps not sufficient for the model to find a significant effect. It is also possible that the physical interaction of dredges and trawls with each substrate is distinct, implying potential differences in catchability by sediment type. Crabs are known to live in a variety of different sediment types (Shelton and Hall, 1981) and habitat preferences may depend on several factors including the migratory and reproductive cycle, which is thought to differ between males and females.

The GAM models for both dredge and trawl catch rate included a significant year effect, which was used to estimate abundance indices for both gears inside the scallop dredge area. It was clear that the dredge survey is more efficient at catching brown crabs than the trawl survey and for this reason we propose a (minimum) absolute abundance estimate for the dredge survey and a relative abundance index for the trawl survey (used for comparison). Different biases may arise from the proposed catch rates in the two surveys. The dredge survey only covers an inshore area off Scotland, although its station density is relatively high. The trawl survey covers a larger area than the dredge survey but has a lower station density and also a catch rate bias (given its lower catchability). An absolute abundance estimate for the whole area could potentially be extrapolated from the dredge survey but caution is needed when interpreting the results, given the absence of dredge data in the offshore areas.

Estimation of absolute abundance from surveys is difficult because it typically requires assumptions about gear efficiency (Miller *et al.*, 2018). An absolute abundance estimate implies, for example, assumptions that crabs are not able to swim over the dredge/nets and that no herding takes place. Crabs of both sexes are known to converge for the reproductive season to facilitate mating encounters (Edwards, 1979; Orensanz and Gallucci, 1988) but there is no evidence of large mating aggregations (Hartnoll, 1969), implying that the assumption of no herding is reasonable. Catch rates estimated from the dredge survey in this study ranged between 1300 and 3200 animals/km^2. These estimates are comparable to the catch rate for the same species, of 2100 animals ≥ 70 mm/km^2, estimated from a mark-recapture model applied to a population of crabs in the east coast of England (Bell *et al.*, 2003). There is a very clear similarity in the crab abundance signal estimated from the two surveys in the present study. The fact that the surveys show the same signal in terms of crab abundance trends indicates that active gear surveys can be used to estimate the distribution of brown crabs, even though dredging/trawling are not the main methods employed by the fishery to capture the species.

14

508   Recruitment index

510   The median size of crabs caught during the study period was shown to be correlated in the
511 two surveys. No crabs below 35 mm were caught by any of the surveys. This is not surprising,
512 given the habitat preferences of smaller crabs, which are mainly found very close to shore and
513 outside the areas covered by the surveys. The dredge survey generally captured smaller individuals
514 than the trawl survey, including juvenile animals below 100 mm CW, suggesting that small crabs
515 are also more likely to escape trawling and the dredge survey is a better choice to detect
516 recruitment pulses. Brown crab recruitment estimates were produced for the dredge study area
517 using a two-part hurdle model. The difficulties associated with fitting a Tweedie model to the
518 recruitment data may be explained by the high percentage of zeros (87%) in the dredge data, i.e.
519 individuals below 100 mm CW were only caught in a small percentage of sampled stations. Some
520 authors have described a poor performance of Tweedie models in handling extremely unbalanced
521 zero data (around 90% or more zeros), in which case, hurdle models are considered reliable
522 alternatives to analyse the data (Shono, 2008; Zhou *et al.*, 2018). Two-part GAMs (first part:
523 presence and absence; second part: catch rates given presence) have been used in fisheries and
524 ecology studies to describe trends in abundance and geographic distribution in fisheries
525 (Maravelias, 1997; Murase *et al.*, 2009; Goetz *et al.*, 2012). The hurdle model applied to the
526 recruitment data showed that several covariates (year, depth, distance to coast) were important in
527 determining juvenile crab presence (part 1) while only year was significant for juvenile crab catch
528 rates (given presence) (part 2), although this may be at least in part an artefact of the much smaller
529 sample size for presence records. From the first part of the model, there was a greater probability of
530 juvenile crabs being present close to the coast between 40 and 50 m depth, as previously shown by
531 the geostatistical analysis. When considering only the stations where juveniles were present in the
532 second part of the model (shallow areas closer to the coast), there was not enough contrast in the
533 data to detect an effect of depth or distance to coast. The combination of the two parts of the hurdle
534 model results in a recruitment index peaking in 2014. The highest recruitment estimate was
535 detected two years before the abundance peak of 2016 on both the dredge and trawl surveys
536 suggesting that the higher recruitment signal detected in 2014 may have contributed to the higher
537 estimates two years later. The low recruitment estimated in 2018 suggests that the abundance
538 decline recently observed is likely to continue in the coming years. Growth studies based on
539 tagging in the North Sea suggest that it takes around 2 years for a 70 mm crab to reach 115 mm
540 (Edwards, 1979), although growth may vary with the frequency of moult increments, which is
541 likely to be related with temperature and may be subject to interannual variability.

545   Future work

546

547   This study demonstrated that spatial modelling may be used to create brown crab distribution

548   maps and abundance indices from fisheries survey data, allowing for the detection of trends in the

549   crab fishery. The deviance explained by the GAM models (33- 62%) could be improved by the

550   inclusion of other potentially influential variables not considered in this study, e.g., bottom water

551   temperature or current strength. These abiotic factors related to environmental and oceanographic

552   conditions are strongly associated with the spatial distribution of crustacean assemblages (Basford

553   *et al.*, 1989; Fariña *et al.*, 1997).

554   One advantage of using dredge and/or trawl gears instead of passive gears such as traps for

555   obtaining standardized catch rates, is that the catchability of the former is not affected by factors

556   such as season, bait, current strength/direction (affecting the spread of the bait plume) and soak

557   time. Additionally, catch rates calculated from mobile gears eliminate issues related with animals

558   which avoid traps, such as berried females (Howard, 1982), and are not affected by saturation

559   effects related to the behaviour of the first animals entering the traps. The main limitation

560   associated with the use of active gear surveys applied to benthic crustaceans is that towed nets or

561   dredges are limited to trawlable seabed, which may introduce some biases considering that

562   crustaceans may also live in rocky habitats (Smith and Tremblay, 2003). For this reason, the

563   abundance estimates provided in this study should be interpreted with caution given the

564   assumptions (no herding and crabs unable to escape by swimming over the nets/dredge) and should

565   be regarded as a minimum estimate. Abundance data may be used in stock assessment models and

566   when combined with other sources of data such as effort, landings and catch composition (e.g.

567   length) may be able to provide information on the dynamics of the stock (Maunder and Piner,

568   2014). There have previously been no abundance indices available for the Scottish brown crab

569   fisheries. The methodology developed here was applied to the North Sea but could potentially be

570   extended to other areas in Europe covered by scallop and dredge surveys. This approach has the

571   potential to be used in stock assessment to determine stock status and provide future advice on

572   sustainable levels of catches, contributing to the management of the brown crab fisheries around

573   Scotland and elsewhere.

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585   **References**

586

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772

Table legends

774

775 Table 1. Summary information for dredge and trawl surveys in the present study: vessel used, year,

776 month, numbers of stations and crabs sampled.

777

778 Table 2. Variogram models fitted to the dredge and trawl surveys including type of model (Sph-

779 spherical, Lin-linear), lag distance information, model parameters (range, sill, nugget and slope),

780 goodness of fit (RSS-residual sum of squares) and mean predicted variance.

781

782 Table 3. Variable selection for the abundance (dredge and trawl) and recruitment index models

783 using a backwards stepwise approach. Hypothesis testing was performed with marginal F-tests

784 (GAMs) and χ^2 tests (binomial GAMs).

785

786 Table 4. Selected models for estimating abundance (dredge and trawl GAMs) and recruitment

787 (hurdle). For the BGS sediment effect (trawl model only), gravel is used as the reference type. The

788 significance of parametric model terms was tested with t-tests. The p-values associated with the

789 GAM smothers for each model term were derived from Wald tests (Wood, 2012).

790

Figure legends

Figure 1. (a) Study region on the east coast of Scotland with the dredge and trawl survey areas and stations sampled (2008-2018). (b) Bathymetry map of the study area (depth in metres). (c) Distribution of marine sediments in the study area from the British Geological Survey (Cooper *et al.*, 2013).

Figure 2. (a) Variograms estimating semivariance (γ) with spherical (parameters: range-*rg*, sill-*si*, nugget-*ng*) and linear (parameters: intercept/nugget-*ng*, slope-*sl*) models. (b) Kriged maps showing predicted catch rates (in the transformed log scale). The five analysis scenarios considered are displayed from top to bottom: 1.all crabs (dredge), 2.females (dredge), 3.males (dredge), 4.juveniles (dredge) and 5.all crabs (trawl).

Figure 3. Results for the abundance and recruitment indices derived from the dredge model (top panel), trawl model (second panel) and hurdle models (third and bottom panels) applied to brown crab catch rates. (a) Distribution of the response variable; (b) partial effect of "year"; (c) partial effect of "distance to coast"; (d) partial effect of "depth"; (e) parametric effect of BGS sediment type (trawl model only; gravel is used as the reference type). The dashed lines give the standard errors around the parametric and smooth effects (shown in the scale of the linear predictor).

Figure 4. Brown crab abundance indices by year estimated from GAMs applied to dredge (solid line, left vertical axis) and trawl (dashed line, right vertical axis) surveys (2008-2018) with 95% confidence intervals. The abundance index for the dredge model is an absolute estimate (millions of individuals) while the trawl index is relative ($N.m^{-2}$). Predictions are averaged for grid cells within the dredge survey area (Figure 1a).

Figure 5. Length frequency distribution of brown crabs captured in the dredge and trawl surveys (2008-2018). The medians and means in each year are represented by the full and dotted vertical lines respectively.

Figure 6. Brown crab recruitment index by year with 95% confidence intervals. The recruitment index is an absolute estimate calculated as the number (millions) of juvenile crabs <100mm CW. Recruitment estimates were derived from a hurdle model applied to dredge surveys (2008-2018). Predictions are averaged for all grid cells within the dredge survey area (Figure 1a).

Tables

828

829　Table 1

Survey	Vessel	Year	Month	N stations*	N crabs*
Dredge	FRV Alba na Mara	2008	Jun-Jul	92	241
Trawl	FRV Scotia	2008	Aug	38	7
Dredge	FRV Alba na Mara	2009	Jul	99	176
Trawl	FRV Scotia	2009	Aug	41	11
Dredge	FRV Alba na Mara	2010	Jun-Jul	114	261
Trawl	FRV Scotia	2010	Aug-Sep	46	14
Dredge	FRV Alba na Mara	2011	Jun-Jul	113	272
Trawl	FRV Scotia	2011	Jul-Aug	43	14
Dredge	FRV Alba na Mara	2012	May-Jun	117	404
Trawl	FRV Scotia	2012	Jul-Aug	40	8
Dredge	FRV Alba na Mara	2013	Jul	116	324
Trawl	FRV Scotia	2013	Jul-Aug	38	12
Dredge	FRV Alba na Mara	2014	Jun	107	610
Trawl	FRV Scotia	2014	Jul-Aug	41	19
Dredge	FRV Alba na Mara	2015	May-Jun	90	327
Trawl	FRV Scotia	2015	Jul-Aug	51	39
Dredge	FRV Alba na Mara	2016	May-Jun	115	544
Trawl	FRV Scotia	2016	Aug	57	35
Dredge	FRV Alba na mara	2017	Jun	119	345
Trawl	FRV Scotia	2017	Aug	50	42
Dredge	FRV Alba na Mara	2018	Jul	109	284
Trawl	FRV Scotia	2018	Jul-Aug	56	20

830　*Number of stations and crabs sampled during each survey within the dredge and trawl
831　areas used for this study shown in Figure 1a

832

833

834　Table 2

	Dredge				Trawl
	All	Females	Males	<100mm	All
Model	Sph	Sph	Sph	Sph	Lin
Lag distance (km)	10	10	10	10	25
Range (km)	71	93	91	59	-
Sill	0.82	0.91	0.84	0.86	-
Nugget	0.53	0.76	0.54	0.71	0.63
Slope	-	-	-	-	4.07e-04
RSS	8.61	4.62	10.29	11.32	1.45
Mean variance	0.62	0.81	0.61	0.78	0.66

835

836

837　Table 3

Models	Model type (assumed distribution)	Covariates	Dropped	p-value	Test
Dredge					
Model 1	GAM (Tweedie)	*Year, Distance, Depth, BGS, Lon*Lat*			
Model 2^		*Year, Distance, Depth, Lon*Lat*	*BGS*	0.181	F
Trawl	GAM (Tweedie)				
Model 3^		*Year, Distance, Depth, BGS, Lon*Lat*	-	-	
Recruitment index	Hurdle GAM1 (Binomial)				
Model 4	catch rate (0,1)	*Year, Distance, Depth, BGS, Lon*Lat*			
Model 5^		*Year, Distance, Depth, Lon*Lat*	*BGS*	0.254	χ^2
Model 6		*Year, Distance, Depth, BGS, Lon*Lat*			
Model 7	Hurdle GAM2 (gamma)	*Year, Distance, BGS, Lon*Lat*	*Depth*	0.276	F
Model 8	catch rate > 0	*Year, Distance, Lon*Lat*	*BGS*	0.277	F
Model 9^		*Year, Lon*Lat*	*Distance*	0.079	F

838　^ Selected parsimonious model
839　Lon*Lat includes variables longitude, latitude and an interaction term between these.

840

841

842　Table 4

843

	Abundance index					Recruitment index					
	Dredge			Trawl		Dredge					
						Hurdle					
Model	GAM			GAM		GAM1			GAM2		
N	1191			501		1191			155		
Perc. zeros (%)	20.9			77.8		87.0			0		
Family	Tweedie			Tweedie		Binomial			Gamma		
Link function	log			log		logit			log		
P	1.14			1.02		-			-		
Dev. explained (%)	45.7			61.6		32.5			41.6		
GVC/UBRE score	3.606e-04			1.957e-05		-0421*			0.323		

| Model terms	Est.	d.f.	p-val	Est.	d.f.	p-val	Est.	d.f.	p-val	Est.	d.f.	p-val
Smoothers												
Year	-	8.7	<0.001	-	3.6	<0.001	-	7.7	<0.001	-	7.5	0.005
Distance	-	6.9	<0.001	-	1	<0.001	-	5.2	<0.001	-	-	-
Depth	-	7.4	<0.001	-	7	<0.001	-	5.3	0.054	-	-	-
Lon*Lat	-	25.3	<0.001	-	28.1	<0.001	-	14.7	0.001	-	13.1	0.012
Parametric terms												
Intercept	-9.084	1	<0.001	-11.78	1	<0.001	-2.859	1	<0.001	-9.487	1	<0.001
BGS												
Gravelly Sand	-	-	-	-1.472	1	0.009	-	-	-	-	-	-
Sand	-	-	-	-1.729	1	0.005	-	-	-	-	-	-
Mud	-	-	-	-1.901	1	0.022	-	-	-	-	-	-

844　*GCV was used as the prediction error criteria for all models except the binomial GAM where the scale parameter is known and an Un-Biased Risk
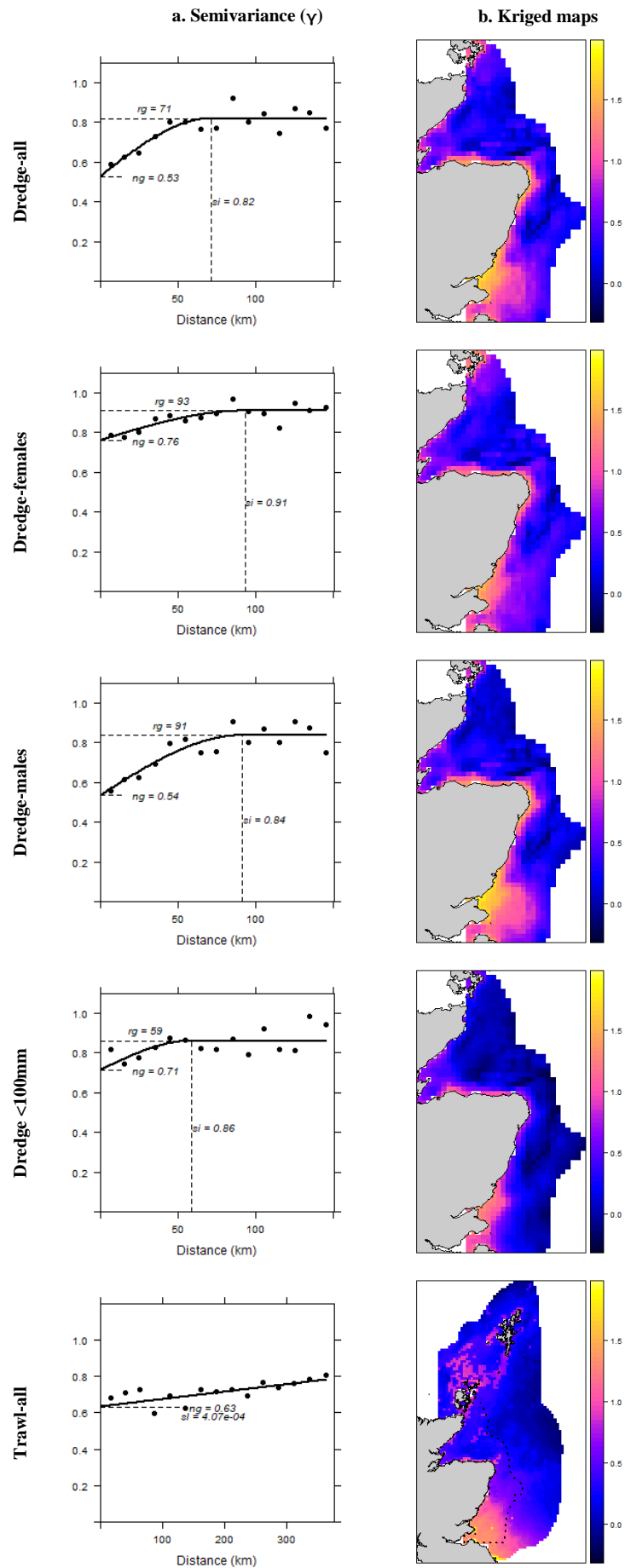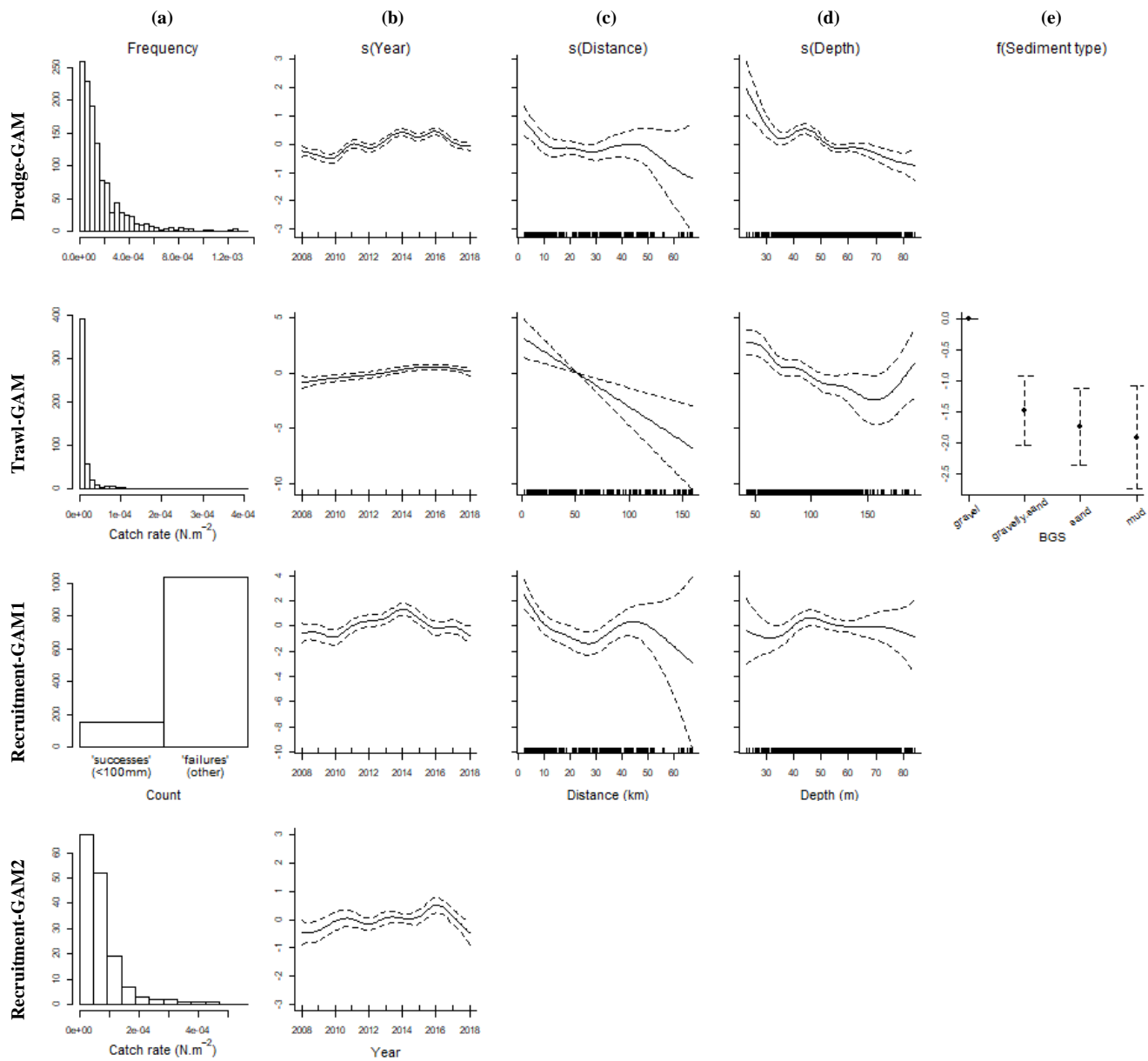845　Estimator (UBRE) is used instead (Wood, 2011).

846

Figures

Figure 1

849   Figure 2

a. Semivariance (γ)   b. Kriged maps

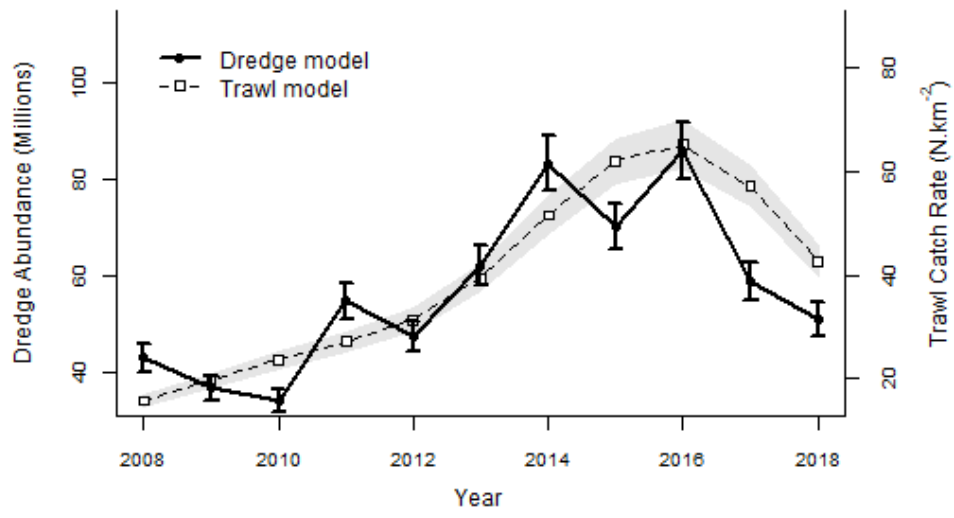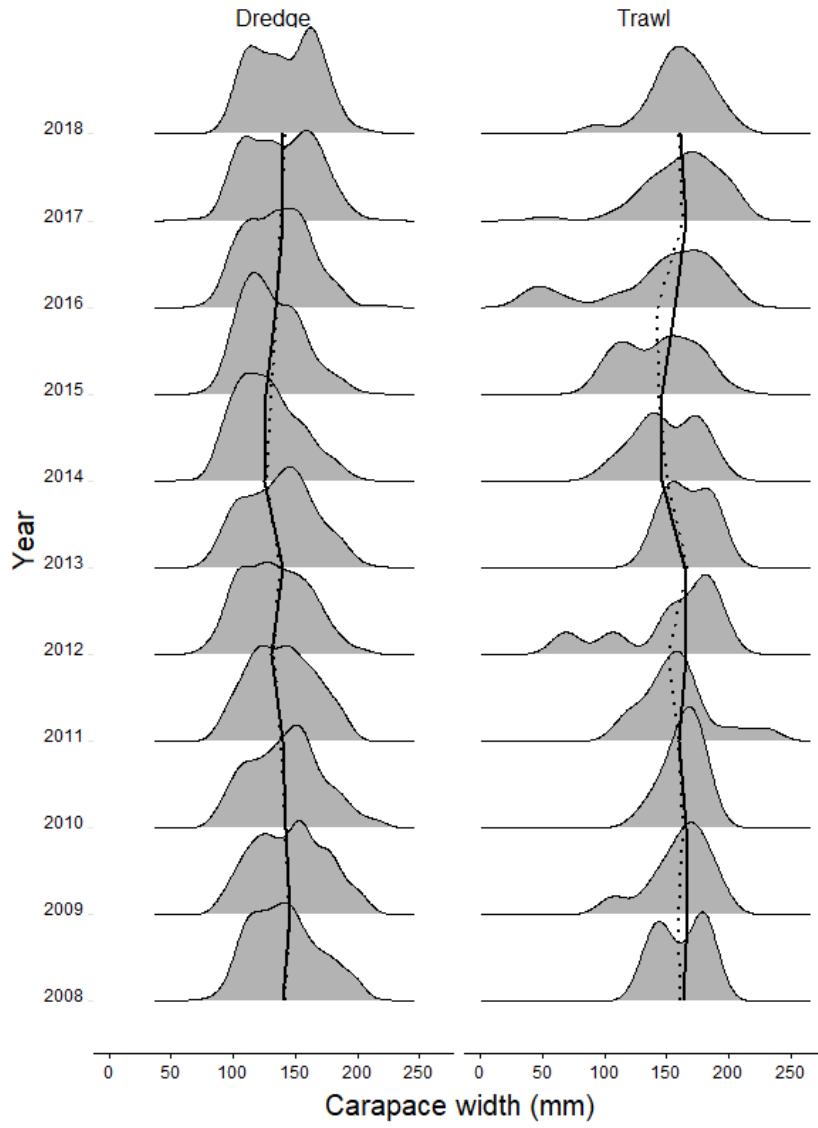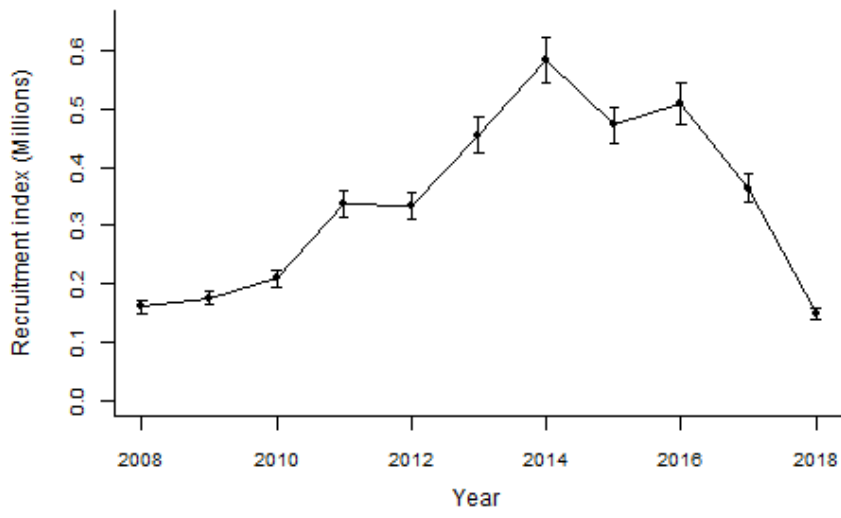850

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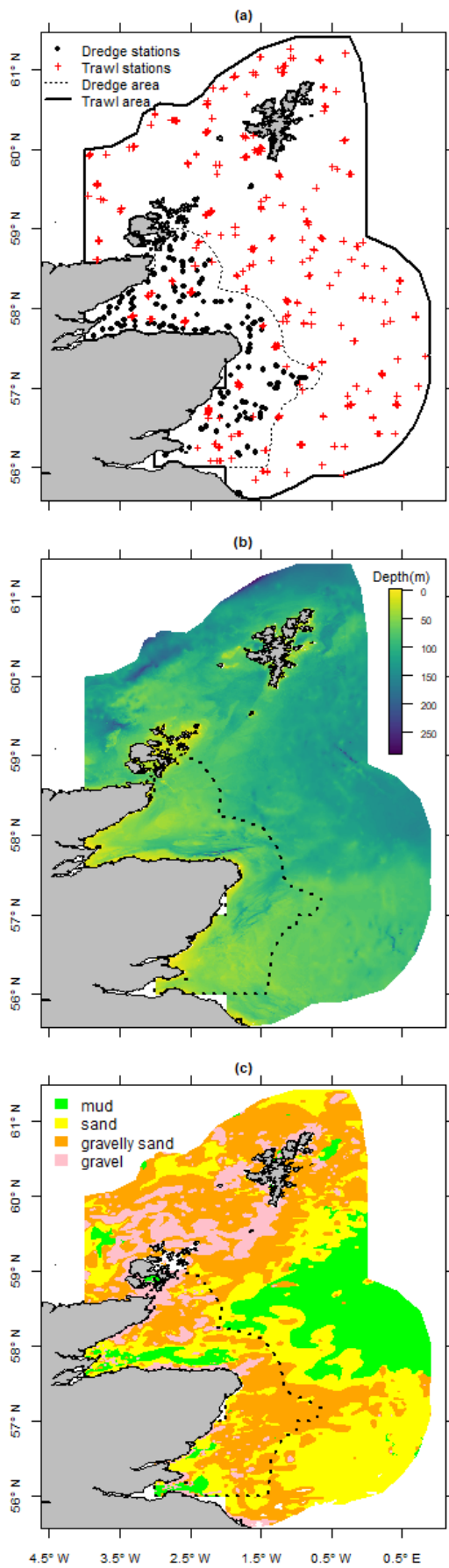
851   Figure 3

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855 Figure 4

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858   Figure 5

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861   Figure 6

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