Nuclear power and coastal birds: predicting the ecological consequences of warm-water outflows

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ABSTRACT

Local alteration of species abundance in natural communities due to anthropogenic impacts may have secondary, cascading effects on species at higher trophic levels. Such effects are typically hard to single out due to their ubiquitous nature and, therefore, may render impact assessment exercises difficult to undertake. Here we describe how we used empirical knowledge together with modelling tools to predict the indirect trophic effects of a future warm-water outflow on populations of shorebirds and wildfowl. Of the main potential benthic prey used by the birds in this instance, the clam *Macoma balthica* was the only species suspected to be adversely affected by a future increase of temperature. Various scenarios of decreases in prey energy content, simulating various degrees of temperature increase, were tested using an individual-based model, MORPH, in order to assess the effects on birds. The survival and body condition of eight of the 10 bird species modelled, dunlin, ringed plover, turnstone, redshank, grey plover, black-tailed godwit, oystercatcher and shelduck were shown to be not influenced even by the most conservative prey reduction scenarios. Most of these species are known to feed primarily on polychaete worms. For the few bivalve-feeding species, the larger size-classes of polychaete worms were predicted to be a sufficient alternative food. Only knot was predicted to have a lower survival under the two worst case scenario of decreased *M. balthica* energy content. We believe that this is the first time such predicted cascade effects from a future warm-water outflow have been shown.

Keywords: Thermal pollution; Individual-based model; Shorebirds; Benthic invertebrates; Temperature sensitivity; Cascade effects

1.INTRODUCTION

Guaranteeing energy security whilst ensuring the transition to a low carbon economy will be a key challenge for all the nations in the 21st century. The world's economies need to change the way energy is produced so that a greater proportion of it comes from low-carbon sources (IPCC, 2014). As a consequence, nuclear energy is on the policy agenda of many countries with projections for new build exceeding those in the early years of nuclear power, to the point that the term "*nuclear renaissance*" has been used to refer to the potential increase of the nuclear industry (World Nuclear Association, 2015).

Coastal sites are the preferred location for new nuclear build (NNB), as a reliable supply of water for cooling is often a prerequisite for operations. The cooling systems for nuclear power stations can produce considerable volumes ($>100 m^3 s^{-1}$) of heated seawater (>10°C above ambient). The potential increase of nuclear power operations makes it pressing to assess the impact of such heated seawater discharge on the marine environment (Crema and Bonvicini Pagliai, 1980). The region of elevated temperature may extend for up to 10km (Suh, 2014), with bathymetry, tides and winds determining the rate of dispersion.

All species have a preferred temperature range and a local change can potentially lead to changes at population, species and community-levels. Benthic species, with a fixed location on the seabed and limited possibilities for avoidance, are exposed to more prolonged thermal effects than any other ecological compartments (Blake et al., 1976; Cowie, 2007; Robinson, 2010; Schiel et al., 2004). At any given location, benthic communities are likely to include some species that are close to either their minimum or maximimum thermal limits of distribution. It would then be expected that local temperature increase due to thermal effluent would potentially benefit the former and adversely affect the latter (Bamber, 1995). This could lead to a structural reorganisation of the community following local species depletion or loss and subsequent consequences through bottom-up cascading (or secondary) effects (Pimm, 1980) *via* compensation among competitors and interactions among trophic level. A recent review of empirical studies shows that cascading extinctions that result from loss of a focal species tend to be more likely if the species is highly connected in the food network as well as more severely affecting species at higher trophic levels when the loss is at low trophic levels (Duffy et al., 2009).

The aim of the investigations described by this paper is to explore the ecological consequences of a large thermal discharge on wading birds, including shorebirds and wildfowl. Using high spatial and temporal resolution benthic data and the output from a separately validated numerical

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70   hydrodynamic model, these investigations explore how to predict which low-trophic level species

71   (i.e. benthic invertebrate) are most likely to be affected by a direct local thermal discharge over an

72   intertidal mudflat and how best to estimate the cascading, secondary consequences for their main

73   avian predators further up the food chain. We answer these questions in two steps: first, by using an

74   empirical understanding of benthic invertebrate physiology and ecology coupled with the outputs of

75   a validated hydrodynamic model to assess the potential consequences of a local temperature

76   increase on the benthic community; second, by using an understanding of bird physiology and

77   behaviour in individual-based model to predict the knock-on consequences for the birds of changes

78   in their invertebrate prey.

79   2 METHOD

80   2.1 Study site and context

81   The Severn Estuary (UK) is one of the largest estuaries in Europe and has the third largest tidal range

82   in the world. It encompasses several sites supporting bird populations that are of national or

83   international importance. Although the estuary is thought of as species-poor, prey items are found

84   at very high densities across wide areas of intertidal mudflats and sandbanks (Boyden and Little,

85   1973; Mettam et al., 1994; Warwick and Somerfield, 2010; Warwick et al., 1991) which support

86   considerable numbers of wading birds during the winter (Burton et al., 2010). The largest of these

87   areas is Bridgwater Bay, which is composed of two main intertidal mudflats, Stert and Berrow flats

88   respectively on the south and the north side of the River Parret (**Figure 1).** Adjacent to the bay,

89   Hinkley Point (HP) is the location of two existing nuclear power stations (HPA – no longer operating

90   and HPB – operational) and permission has recently been granted for a third (HPC), the operation of

91   which could have impacts on the local marine fauna and flora, including the wading bird and their

92   preys.

93   2.2 Identification of the potential thermal impact on benthic invertebrate species

94   The benthic invertebrate species *Corophium volutator*, *Hediste diversicolor*, *Macoma balthica* and

95   *Peringia (Hydrobia) ulvae* are among the key biological features of the intertidal mudflats (Boyden

96   and Little, 1973; Warwick et al., 1991). These species are known to form a component of shorebird

97   diets (Goss-Custard et al., 2006; Langston et al., 2007) and the birds have been observed to actively

98   utilise the mudflats to obtain the majority of their diet from the mudflat infauna (Burton et al., 2010;

99   Clark and Prys-Jones, 1994). The trophic link between the birds and their infaunal prey means that

100 any NNB activities potentially affecting the mudflat habitat may have direct implications for the

101 benthic prey and knock-on secondary consequences for the bird populations at higher trophic levels.

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102   2.2.1 Assessment of the sensitivity to elevated temperature for the main benthic taxa

103   The putative effect of a temperature increase on benthic taxa was first assessed by a literature

104   review. Two elements were specifically sought: (i) the area of distribution where the species has

105   been recorded and (ii) any specific physiological features tested *via* (e.g.) field or lab experiment or

106   monitoring studies **(Table 1)**. Only *M. balthica* showed evidence of temperature sensitivity. The clam

107   is a cold-water species with a latititunal distribution along the eastern Atlantic ranging from the

108   Arctic Pechora Sea to the Gironde estuary (Hummel et al., 1997) and various laboratory experiments,

109   long-term monitoring and correlative studies have provided evidence to suggest that *M. balthica*

110   might be sensitive to increasing seawater temperature (e.g. Honkoop and Van Der Meer, 1998;

111   Honkoop et al., 1998; Philippart et al., 2003). The species is also thought to currently be experiencing

112   a range contraction in western Europe primarily due to warming temperature in the southern limit

113   of its distribution (Bachelet et al., 1990; Beukema et al., 2009; Jansen et al., 2007).

114   2.2.2 Thermal sensitivity of *M. balthica*

115   Growth of *M. balthica* is thought to cease at 15°C (de Wilde, 1975), in the Wadden sea its main

116   growth period has been observed to be between the time of first spawning in early spring and the

117   time at which mean seawater temperatures reaches the 15°C threshold. At other places however,

118   populations have shown dual growing seasons during both spring and autumn, when food

119   availability is sufficient to support a second growth in the latter part of the year (Beukema and

120   Desprez, 1986). Nevertheless, the single annual growing season in spring and early summer appears

121   to be the rule in western Europe, while the dual growing season exceptions are thought to be

122   restricted to the southern limit of distribution (south of ~50°N) (Beukema and Desprez, 1986). With

123   the assumption that the Severn Estuary populations follow the single growing season rule, future

124   thermal effluents in the study area are expected to bring forward the 15°C threshold, with an overall

125   shortening of *M. balthica*'s only annual growth period and retarding biomass gain. As *M. balthica* is

126   assumed to exhibit a linear growth (Beukema and De Bruin, 1977; Beukema and Desprez, 1986), an

127   estimate of thermally-induced reduction of the growth period can therefore be used to predict

128   resulting effects on biomass accrual using linear modelling (**Figure 2**).

129   2.3 The individual-based model

130   2.3.1 Rationale

131   The selection of an appropriate model for investigating the trophic interactions between the birds

132   and their infaunal preys requires consideration of aspects of the birds' ecology. Mortality and

133   reproductive rate of the birds are the two most important demographic factors to assess (Stillman

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134 and Goss-Custard, 2010). Individual-based models (IBM) are considered to be appropriate tools for
135 such tasks since they consider important aspects of species interaction such as interference and
136 competition and incorporation of individual variations (Stillman and Goss-Custard, 2010).

137 MORPH is a flexible IBM platform designed to be used with a wide range of species and
138 environmental issues (freely available at: http://individualecology.bournemouth.ac.uk/index.html).
139 The tool is described in detail in Stillman (2008). Briefly, the basic principles of MORPH are as
140 follows: Time progresses in discrete, fixed duration time-steps, the birds arrive on site on their
141 species-specific arrival day, they remain at the same location during a time-step, either on a feeding
142 patch or travelling between patches but cannot move between time-steps. They alter their location
143 and the food they consume in order to maximise their perceive fitness and finally leave the site on
144 their species-specific departure day. During the model period, each day, each model bird aims to
145 meet its temperature-related energy demand by selecting feeding locations, times of the day and
146 tidal zones where the intake rate is highest. Survival is then determined by the balance between
147 daily consumption rate and energy demands.

148 2.3.2 The model global environment

149 The model simulations were run over a generic period from 1st September to 31st March,
150 encompassing the major overwintering period of most shorebirds in the UK. The time step was set to
151 one hour and environmental conditions assumed to remain constant during each time step.

152 2.3.3 The model patches

153 Ten profiles covering the full tidal range were defined over Bridgwater Bay (A to K, from south to
154 north), using site-specific information on the resources available over the modelled area (Bolam et
155 al., 2011; Musk et al., 2011a, 2011b, 2010a, 2010b). Each of these zones was divided into three areas
156 according to their tidal elevation (low, mid or high tide). A low-lying sandbar in the mouth of the
157 Parrett River was also defined as a patch, as was a supratidal roosting area (where the birds can go
158 when the tide covers the entire feeding area). The modelled area of Bridgwater Bay was thus divided
159 into 31 feeding and 1 roosting patches **(Figure 1** and **Appendix A)**.

160 2.3.4 Patch resources

161 *Benthic data source*

162 A seasonal survey of the intertidal benthic community was conducted in 2010/2011 with one visit
163 per season (April, July and November 2010 and January 2011). For each species ash-free dry weight

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164 was calculated either individually or at the species level. Additionally, shell length/total length in mm

165 was measured for most polychaetes and mollusc taxa collected.

Prey size class

167 Common shorebird species forage mainly across a particular prey size range (Goss-Custard et al.,

168 2006). In order to classify the potential dietary sources in an ecologically realistic manner, the

169 invertebrate species were grouped by size. All taxa whose average length was less than 10mm were

170 attributed to one of the resource categories with no size differences (**Appendix B**); the majority of

171 species recorded from the mudflats belonged to this category. Species whose lengths exceeded

172 10mm – the bivalve *M. balthica* and the polychaetes *H. diversicolor*, *Eunereis longissima*, *Nephtys*

173 *hombergii*, *Nephtys cirrosa* and *Eteone longa/flava* - were divided into resource-specific size-classes,

174 based on published information on size range of prey handling by different bird species (Goss-

175 Custard et al., 2006). Thus, bivalves were divided into two (<10mm and >10mm) and polychaetes

176 into four (<10mm, 10-20mm, 20-50mm and >50mm) size classes (**Appendix B & C**).

Resource identity and density at the start of the model period

178 The birds' prey-specific intake rates are not fully defined with respect to all macro-invertebrate

179 species present in the mudflat. Fortunately, they were still available for the most abundant species

180 (Goss-Custard et al., 2006). We however chose not to ignore the potential extra sources of energy

181 from the other, rarer species but, in so doing, had to simplify the prey-species input in MORPH by

182 arranging all species into functional resource groups, referred to as 'resource group' hereafter. Apart

183 from the bivalve group which exclusively contains *M. balthica,* the resource groups were based on

184 the most abundant taxa on site: *P. ulvae*, *Pygospio elegans*, *C. volutator*, *H. diversicolor* and the

185 oligochaete family Enchytraeidae and the remaining species were grouped with one of the closest

186 abundant taxa according to shape, size and life form (**Appendix B**). Their respective initial density

187 was then calculated using the July 2010 abundance data (**Appendix C**). These resource groups[1] were

188 named and defined as follow:

189 - "PolErr" (Polychaeta Errantia or motile worms, e.g. *Hediste* spp, *Nephtys* spp): 4 size-classes

190   (<10mm – PolErr0to10, 10-20 – PolErr10to20, 20-50 – PolErr20to50 and >50mm –

191   PolErr50plus)

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[1] The resource groups do not follow taxonomical convention since they are composite groups that may include different taxa or/and specific size-classes. In order to avoid any confusions, the resource groups names are underlined hereafter, e.g. PolErr0to10 resource group.

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192   -   "PolSed" (Polychaeta Sedentaria or sessile or discretely motile worms, e.g. *P. elegans*): 1

193   size-class

194   -   "Interstitial" (Interstitial worms and small motile worms, e.g. Nematoda): 1 size-class

195   -   "Crustacea" (small crustaceans, e.g. *C. volutator*, *Diastylis* spp): 1 size-class

196   -   "Macoma" (*M. balthica only*): 2 size-classes (<10mm – Macoma0to10 and >10mm –

197   Macoma10plus)

198   -   "Gastropoda" (gastropod, e.g. *P. ulvae*): 1 size-class

199   *Prey energy content at the start of the model period*

200   -   Benthic invertebrates

201   Ash-free dry weight (AFDW) was used as the proxy for the prey individual energy content. As with

202   the calculation of faunal density, for all resource groups AFDW was calculated using the July 2010

203   data. Average AFDW per individual of each resource group was calculated for each feeding patch.

204   -   Microphytobenthos

205   The microphytobenthic (MPB) biofilm is also known to be used as a food source for some bird

206   species (e.g. Kuwae et al., 2012, 2008; Mathot et al., 2010). Inspection of multispectral Landsat

207   images from the period 1999-2010 has shown that the mid to upper shore of Bridgwater Bay has a

208   region of enhanced infra-red reflectance indicative of dense MPB cover (van der Wal et al., 2010).

209   Unfortunately, no representative MPB samples were available for the site, so an indirect estimation

210   based on sediment grain size was utilised. Muddy sediments are known to always support a higher

211   MPB biomass than sandy sediments and dense surface biofilms only occur when the silt content is

212   high (Paterson, 1989).

213   The grain size of the sediment where infauna samples were collected was therefore used as an

214   indicator of the biofilm food resource, with an assumed inversely proportional relationship between

215   chlorophyll and increasing grain size converted to an algal equivalent AFDW per m^2, assuming the

216   following relations:

217   -   1mg chl *a*=50x1mgC (de Jonge, 1980)

218   -   1mg AFDW=0.4x1mgC (Finlay and Uhlig, 1981).

219   However, the way the ingestion rate of birds changes with MPB density (i.e. functional response see

220   **section 2.3.6**) is unknown which prevents direct inclusion of MPB as an independent resource group

221   in MORPH. Therefore, MPB was linked to the benthic resource groups, assuming that invertebrate

222   prey physically covered with MPB would display a higher energy value than would the same type of

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223 prey not covered by MPB. Larger individuals are able to burrow deeper in the sediment, but MPB

224 biofilms are mainly found in the upper 2mm of sediment. With this in mind, only the small group

225 resources were considered to benefit from this supplementary energetic value. The average MPB

226 AFDW/m^2 was apportioned between the six smallest resource groups presented above (i.e.

227 PolErr0to10 resource group, Gastropoda resource group, Interstitial resource group, PolSed resource

228 group, Macoma0to10 resource group and Crustacea resource group) (see **Appendix C**).

229 *Resource dynamics*

230　　-　Densities

231 It was difficult to determine the shape of the relationship between resource groups abundance and

232 time with measurement at four intervals through the year; we chose to assume a constant

233 proportional loss of prey per day that followed an exponential model decrease. A second problem

234 was related to the extent to which the non-predation mortality (i.e., mortality not caused by birds)

235 affects the resource groups. We used a conservative estimate by considering the difference in

236 density between July 2010 and the average of January 2011 and April 2010 (**Figure 3a**) to be only

237 due to non-predation mortality. In summary, the resource group densities were considered to

238 decrease throughout the winter by the resource group-specific proportions shown in **Table 2**.

239　　-　Average Ash-free dry weight per individual

240 Similarly to the density dynamic, the exact nature of the individual weight change was difficult to

241 characterise. Zwarts and Wanink (1993) made a seasonal study of body weight of *M. balthica*,

242 *Scrobicularia plana*, *Cerastoderma edule* and *Mya arenaria* and found a linear decrease of 28%

243 between May/June and November to March. We assumed that all of the resource groups followed a

244 similar linear decrease; the difference in average individual AFDW content between the average of

245 the month of January and April data (end point) and the July data (starting point) were used to set

246 the extent of the decrease (**Table 2** and **Figure 3b**). No seasonal data were available for the MPB,

247 therefore only the energy content that relates to the benthic species was considered.

248 2.3.5 The bird assemblage

249 The bird assemblage data needed to parameterise MORPH are overall mean monthly count, arrival

250 day and departure day for each forager species. Data used for the present MORPH model were

251 obtained from the Wetland Bird Survey (WeBS) Core Counts scheme

252 (http://www.bto.org/volunteer-surveys/webs/taking-part/core-counts, data obtained in August

253 2010). In Bridgwater Bay bird data were available from four areas (Berrow flats, Berrow, Burnham-

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254 on-Sea and Bridgwater Bay). These areas have been surveyed for several consecutive years and have
255 been summarised in order to build a generic September to March period.

256 The WeBS dataset provided the bird counts as a monthly average per species per area. Ten species
257 of birds were considered to be the most important species in terms of overwintering in Bridgwater
258 Bay (Burton et al., 2010) and feeding off the intertidal zone (Goss-Custard et al., 2006): dunlin
259 (*Calidris alpina*), ringed plover (*Charadrius hiaticula*), turnstone (*Arenaria interpres*), knot (*Calidris*
260 *canuta*), redshank (*Tringa totanus*), grey plover (*Pluvialis squatarola*), black-tailed godwit (*Limosa*
261 *limosa*), oystercatcher (*Haematopus ostralegus*), curlew (*Numenius arquata*) and shelduck (*Tadorna*
262 *tadorna*) (**Table 3**). Relevant bird data were extracted from the database and, for each species, the
263 monthly averages were summed across the four areas to give monthly averages for the whole of the
264 Bridgwater Bay (**Table 3** and **Figure 4**). MORPH does not allow for the temporal variation of bird
265 number, only an arrival, a departure date and a mean of monthly counts. Between the arrival and
266 the departure, no bird individual can be added to the site and any removal only occurs by death of
267 the individuals if they cannot meet their energy requirements. Therefore, in order to capture some
268 of the temporal variation in bird population changes, any monthly count below 10% of the winter
269 maximum was ignored and average bird numbers were calculated from the remaining months of
270 data. Similarly, a bird species was considered absent if the 10% threshold was not reached. In this
271 way, it was possible to estimate the arrival and departure dates parameters for each species (**Table 3**
272 and **Figure 4**).

273 2.3.6 Forager feeding ecology

274 The following sections describe the derivation of forager feeding parameter values specific to the
275 present MORPH version. The other, more generic, parameter values are given in **Appendix D**.

276 *Diet*

277 There is an abundant literature on feeding of coastal birds (see e.g. Anders et al., 2009; Evans, 1987;
278 Goss-Custard et al., 2006; Quaintenne et al., 2010; Scheiffarth and Nehls, 1997; Zwarts and Wanink,
279 1993). This information was used to characterise a bird-specific diet for all the forager species
280 selected in the model based on a specific selection of the resource groups, in other words, a bird diet
281 group[2] was defined as a combination of one or more resource groups (**Table 4a and b**).

282 *Day and night variation in foraging efficiency*

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[2] The bird diet groups do not follow taxonomical convention since they are composite groups that includes one or more resource groups which in turn may include one or more taxa and or specific size-classes. The diet groups names are underlined hereafter, e.g. PolErr20plus diet group

283 Many species of waders forage extensively at night, but there is little information on the relevance
284 of this behaviour for the energy budget of waders wintering in estuarine wetlands. In the present
285 model the relative rates at which waders could feed during the day and night were derived from
286 Lourenço et al. (2008) and Sitters (2000) (**Appendix E**). In their paper, Lourenço et al. (2008)
287 calculated night-time efficiency as the proportion of day time energy consumption obtained during
288 the night for four species: ringed plover (49%), redshank (95%), grey plover (100%) and black-tailed
289 godwit (87%). It is unclear whether grey plover obtains more energy at night (Kalejta, 1992) or
290 during the day (Turpie and Hockey, 1993); as a consequence, a value of 100% was used for this
291 species. For oystercatchers, night-time efficiency has been calculated at 100% of daytime for
292 individuals opening prey using the stabbing feeding method and 62% of daytime for individuals
293 opening prey using the hammering feeding method (Sitters, 2000); as we do not know the specific
294 mechanism used by oystercatchers in this instance, we used the average of these two values (81%).
295 No other estimation of night-time efficiency was available to our knowledge, so the average of the
296 values given above was used (82%) for the remainder of the species.

297 *Bird functional response*

298 The functional response parameter utilised within MORPH is a mathematical formulation describing
299 the way a species ingestion rate varies with respect to food density. In theory, a functional response
300 is species-specific but in practice species with similar feeding behaviour and prey items can share
301 similarities in their functional response. As such the shorebird species included in MORPH (i.e.
302 dunlin, ringed plover, turnstone, knot, redshank, grey plover, black-tailed godwit, oystercatcher and
303 curlew) share a common formulation of the functional response while shelduck, being a wildfowl, is
304 expected to be different.

305   -   Shorebirds

306 The functional responses utilised in the model are based on body mass, using the equation of Goss-
307 Custard et al. (2006):

$$IFIR = f \, \frac{IFIR_{max} \, B}{B_{50} + B}$$

308 Where $IFIR$= Interference-free intake rate (mg.s^{-1}), f= foraging efficiency of the focal individual, B=
309 patch biomass density of prey within the size range consumed (mg.m^{-2}), $IFIR_{max}$= maximum intake
310 rate when prey are superabundant and B_{50}= prey biomass density at which intake rate is 50% of its
311 maximum. Values of f, B and B_{50} were taken from Goss-Custard et al. (2006) and $IFIR_{max}$ was
312 related to shorebird body mass and prey mass with the following equation:

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$$\ln(IFIR_{max}) = -2.802 + 0.245 \ln M_{bird} + 0.365 \ln rM_{prey}$$

313   Where M_{bird} = average body mass (g) of the bird species at the start of the model period, M_{prey} =

314   mean ash-free dry weigh (mg) of prey within the size consumed and r=1.05 (assumed ratio of size of

315   prey consumed to size in patch) (Goss-Custard et al., 2006)

316   -   Shelduck

317   Using the shorebird functional response equation "as it is" for shelduck was inappropriate because it

318   was developed for shorebirds but shelduck is a wildfowl and this would result in an underestimation

319   of its intake rate calculation. However, since no functional response value existed for shelduck, we

320   adapted the shorebird equation to account for the different way of feeding. The classic shorebirds

321   functional response follows the general forms of the 'disc equation', which is a theoretical model of

322   a decelerating rate of intake (see e.g., Goss-Custard et al., 2006, Hiddink, 2003 and Smart and Gill,

323   2003) where the maximum (or asymptotic) intake rate is determined by how long it takes the

324   forager to capture and swallow prey items, the 'handling time'. At the asymptote of the functional

325   response, the prey items are so abundant that the forager finds another prey immediately after it

326   swallows the preceding, the intake rate being only limited by the rate at which the gut can process

327   food. However, instead of probing or pecking for individual prey items as shorebirds do, shelduck

328   sweeps the surface of the mud in broad arcs ('scything') which results in an omnivorous diet (Ferns

329   and Reed, 2009) that may include MPB (Meininger and Snoek, 1992), *P. ulvae*, young *M. balthica*,

330   young mussels, young cockles and many kind of worms (including *H. diversicolor*) (Anders et al.,

331   2009; Ferns and Reed, 2009; Leopold et al., 2004a, 2004b). Additionally, shelduck is the largest

332   species of all the birds considered in the present study and feeds on rather small prey sizes with

333   respect to its own body mass. This is a very wildfowl-specific characteristic since amongst the

334   shorebirds, the larger the bird species, the larger the prey size (Goss-Custard et al., 2006; Johnson,

335   1985). The long-term trend of shelduck winter counts suggests a slightly increasing overwintering

336   population in Bridgwater Bay (Burton et al., 2010); this means that the current observed survival for

337   the species in the area must be high. Consequently, the shorebird equation, which underestimates

338   shelduck intake rate (and overestimate its mortality), was corrected by progressively increasing to

339   the value of the $IFIR$ until the resulting modelled survival reached values very close to 100% - this

340   happened after a 50% increase of the $IFIR$ coefficient for shelduck.

341   2.4 Simulation procedures

342   Each simulation was run for one autumn-winter period. The simulation predictions vary each time it

343   is run, due to the particular characteristics of the individuals in each run. Five simulations for each

344   combination of parameter values were therefore run.

345   Site carrying capacity was measured by assessing bird survival against prey biomass densities

346   (gAFDW.m^{-2}) variation from 0 to 250% of the current condition.

347   The only intertidal invertebrate species in Bridgwater Bay considered to be potentially adversely

348   sensitive to increasing seawater temperature is *M. balthica*. A temperature rise due to thermal

349   effluents can be expected to shorten the growth period and retard biomass gain (**Figure 2**). Thus, we

350   modelled the effect of reductions in the growth period of the species on its bird predators.

351   The length of the growing season was estimated using bottom water temperature values from a run

352   of an existing validated and calibrated numerical hydrodynamic model utilising the General Estuarine

353   Transport Model (GETM, the model was obtained from https://www.getm.eu) (Stips et al., 2004).

354   This model was run in 3D with 100m resolution and 15 depth intervals, providing simulated

355   temperature outputs for the intertidal areas covering periods of both immersion and emersion. The

356   3D domain included the Severn Estuary and the inner Bristol Channel up to the line between

357   Minehead and Cowbridge. The elevation and current boundary conditions were supplied from a

358   larger 2D GETM run and the meteorological forcing from ECMWF (European Centre for Medium-

359   Range Weather Forecasts: http://www.ecmwf.int/en/research/climate-reanalysis/era-interim) ERA

360   interim reanalysis data. The GETM model was run at 1.5 second internal time steps for one full year

361   and includes the cooling water discharge from HPB power station, which has a flow of 33m.s^{-1} and a

362   temperature increase at the outfall of 11°C. The GETM model was successfully validated against

363   measurements from tidal gauges in the Severn and Acoustic Droppler Current Profilers (ADCP) data

364   and temperature sensors previously deployed in the Bridgwater Bay area. For more details of this

365   model and its corroboration see Fernand et al. (2011).

366   The GETM model output allowed for a determination of the the extent of the spring growth period

367   as the number of Julian days between mid-March, the estimated start of the growth period

368   (Beukema et al., 1985) - Julian day number 80 - and the point at which 15°C was achieved for two or

369   more consecutive days. The baseline length of the growth period was based on the current situation

370   (**Table 5**). The GETM model was used to calculate the potential reduction in the length of the

371   growing season in *M. balthica* exposed to the thermal plume.

372   The reduction in biomass accrued over a single growing season was translated into MORPH by

373   decreasing the average AFDW content of individual *M. balthica* and therefore the temperature

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374 effect concerns only the two model resource groups including this species (Macoma0to10 resource

375 group and Macoma10plus resource group). Three scenarios of biomass reduction were simulated (B,

376 C and D in **Table 5**) and compared against the reference conditions (A in **Table 5**).

377 3.RESULTS

378 3.1 Corroboration of the MORPH model

379 The principle of a model corroboration, as defined by Grimm et al. (2014), is to compare model

380 predictions against data recorded in a separate independently collected data set not utilised in the

381 development of that model. Here we compared model estimates and actual observations of (1) the

382 overall proportion of time foraging by the birds and (2) the distribution of wading birds around

383 Bridgwater Bay.

384 The field observation data came from EDF/NNB Genco Entec Ltd dataset (described in EDF/NNB

385 Genco Entec UK Ltd, 2009). These data classify observed activities into a number of different types.

386 After removing the "activity unclear", five main activities remained: "Commuting", "Flushed",

387 "Foraging", "Loafing" and "Roosting". MORPH does not provide such detailed outputs of bird

388 behaviour since "Foraging" and "Roosting" are the only possible activities of modelled birds.

389 Observed bird activities were thus rearranged into "Foraging" and "Not Foraging" (the latter

390 including "Commuting", "Flushed", "Loafing" and "Roosting"). An "observed" average proportion

391 value of birds "Foraging" and "Not Foraging" was then compared to the "predicted" value emerging

392 from MORPH along with their respective 95% confidence interval (**Figure 5**).

393 For eight (8) of the bird species, the predicted foraging time was within the 95% confidence interval

394 of the mean of those observed. The two bird species for which modelled and observed foraging

395 times were different, oystercatcher and curlew, are predicted to spend more time feeding than

396 observed.

397 For testing the spatial predictions of the model, field observations were taken from WeBS low tide

398 counts (http://www.bto.org/volunteer-surveys/webs/taking-part/low-tide-counts data obtained in

399 August 2012).

400 The primary purpose of the WeBS scheme is to investigate relative distributions averaged over

401 several dates, which makes it an ideal dataset for validating spatial prediction. The observed winter

402 low tide counts (November 2009 to February 2010) were compared against predicted bird

403 distribution on the patches (i.e., A, B-C, D-E, F, G, H, I, J, K) (**Figure 6)**. Most modelled bird species

404 show the same pattern of distribution spending most of their time on the same two main patches, a

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405 primary and a secondary one. Overall, MORPH runs predicted the bird distribution among patches
406 with a high degree of accuracy especially for the primary feeding patches. The two main
407 discrepancies concern: (i) knot, for which the model predicted foraging on Berrow flats (i.e. I and K)
408 whilst observations showed that the actual preference was for Stert flats (i.e. A, B-C and D-E) and (ii)
409 oystercatcher for which the primary feeding ground was predicted to be Stert flats whilst
410 observations showed a preference for Berrow flats (i.e. from patch G to K). Additionally, the
411 observed secondary feeding patches on Berrow flats by curlew (~10%) and shelduck (~20%) were
412 not well predicted by the model.

413 For all species except knot, Stert flats (B-C and D-E) was observed to be the predominant foraging
414 habitat which is in accordance with MORPH predictions.

415 3.2 Model simulations outputs

416 3.2.1 Bird survival and prey selection

417 Food availability, as average biomass density (i.e. mean biomass multiplied by the density), mainly
418 controls the survival and body condition (respectively expressed as the percentage of the number of
419 birds alive / total and the final average bird mass / target mass – the average mass of a healthy bird)
420 of the birds on site. These bird-specific values recorded at the end of the winter season are two of
421 the major outputs of MORPH (**Table 6**). With an average of 14.49 gAFDW/m^2 of benthic
422 invertebrates and MPB prey supply, Bridgwater Bay is predicted to sustain in excess of 97% of the
423 overall overwintering bird population under reference (i.e. current) conditions. Of the 10 bird
424 species selected, 7 had a survival rate of over 99% and body condition over 98%. Of the 3 remaining
425 species, MORPH predicted shelduck, oystercatcher and curlew body condition to be 91, 90 and
426 73.3% and survival rates to be 100, 91.6 and 64.7% respectively.

427 Half of the bird species were predicted from MORPH outputs to feed on only one type of resource
428 while the other half were expected to have a more diverse diet (**Figure 7**). The PolErr resource
429 groups (mix of size-classes) were predicted to sustain the majority of the bird species, exclusively for
430 grey plover and black-tailed godwit (PolErr20plus diet group), oystercatcher and curlew
431 (PolErr50plus diet group) and in majority for turnstone and redshank (PolErr20plus diet group) and
432 shelduck (PolErr50plus diet group). Dunlin and ringed plover were predicted to mainly use the
433 Crustacea diet group and knot were predicted to feed on the large Macoma10plus diet group.
434 Resources composing the Gastropoda diet group and Worms0to10 diet group are not expected to be
435 major dietary items for the birds.

436 3.2.2 Effects of changes in prey biomass across all patches

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437   In order to test how sustainable Bridgwater Bay is for the bird feeding on the mudflats, prey biomass

438   densities, encompassing all resource groups, were varied between 0 and 250% of the current (2010)

439   mean (in gAFDW/m^2) to determine the threshold below which survival would be adversely affected

440   (**Figure 8**). As a result, dunlin, turnstone, knot, redshank, grey plover and black-tailed godwit were

441   predicted to show a survival rate >94% until the food supply was reduced to 25%. Ringed plover

442   remained at 100% survival when food supply was reduced to 75%. Shelduck survival was shown to

443   decrease immediately after the food supply was reduced (83% survival rate at 75% AFDW). Finally,

444   survival for oystercatcher and curlew within Bridgwater Bay was predicted to be lower than 100%

445   with the current food supply (100%). Oystercatcher reaches 100% survival with an extra 25% food

446   supply but even with up to 250% of the reference biomass condition curlew survival only reaches

447   97%. Thus, for all species except oystercatcher and curlew, the available data suggest that the

448   current observed food supply within Bridgwater Bay is sufficient or more than sufficient to support

449   the observed number of birds. Shelduck and ringed plover are predicted to be the most sensitive

450   species to reductions in food supply.

451   3.2.3 Effects of changes in prey biomass due to warm-water outflow

452   The body condition and survival of dunlin, ringed plover, turnstone, redshank, grey plover, black-

453   tailed godwit, oystercatcher, curlew and shelduck are not predicted to be adversely impacted by

454   reductions in *M. balthica* average AFDW brought on by any of the four tested scenarios (**Figures 9 &**

455   **10**). Knot, on the other hand, is predicted to be slightly affected by scenario B (1.2% reduction in

456   survival), C (1.5% reduction in survival) and D (3% reduction in survival).

457   Resources consumed by the birds are predicted to remain similar under all three scenarios

458   considered. This is not surprising as, according to the model (**Figure 10**), dunlin and knot are the only

459   two predators using *M. balthica* as a resource. Scenario C is predicted to be sufficient to trigger a

460   switch in dunlin foraging activity from Macoma0to10 diet group to the PolErr10to50 diet group. Knot

461   on the other hand, is predicted to feed on Macoma10plus diet group under every scenario.

462   4.DISCUSSION

463   4.1 Predicting the ecological consequences of a warm-water outflow

464   In this paper, we used empirical evidence coupled with two models, a previously validated

465   hydrodynamic model and an IBM – MORPH – to predict the secondary consequences of a future

466   heated effluent on bird populations. Efforts were made to incorporate observational data on all of

467   the main bird species overwintering on our study site, Bridgwater bay; this includes shorebirds and

468   wildfowl. Additionally, the model was implemented using high spatial and temporal resolution

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469   benthic data and a microphytobenthic component was included in order to build the most accurate

470   estimation of prey stock and change through time for MORPH use. Model outputs for a reference

471   case were also corroborated against independantly sourced field data not utilised in model

472   development. To our knowledge, this is the first time that this has been done. We first endeavoured

473   to qualitatively identify potential temperature sensitivity among the prey species living on the

474   mudflat (i.e. benthic invertebrate). Then, an existing validated and calibrated numerical

475   hydrodynamic model (GETM) was used to assess the quantitative extent of the thermal and seasonal

476   sensitivity and its inherent consequences on the populations of the clam *M. balthica*, the only

477   species suspected to be adversely affected by a warm-water outflow. The biological link between

478   benthic prey species and their avian predators was formalised by implementing a Bridgwater Bay-

479   specific version of MORPH. GETM outputs which described *M. balthica* growth period shortening

480   were then fed into MORPH and different prey decrease scenarios were thus simulated. MORPH

481   predicted that a local temperature increase due to the the proposed power station development

482   (HPC) would cause little difference for worm-feeding birds and that even primarily bivalve-feeding

483   species would have the ability to shift to a more worm-based diet if necessary.

484   4.2 Understanding the effects of thermal impact on benthic invertebrates

485   Depending upon the precise disposition of the discharge and the local tidal regime, warm-water

486   discharges from coastal power stations can be expected to have an effect that extends to local

487   intertidal areas. Infaunal communities living between the low and the high water marks will already

488   experience daily variations in environmental stress (e.g. wave-induced sediment remobilisation,

489   temperature, salinity, dessication) (Raffaelli and Hawkins, 1996) and this can be even more

490   pronounced if the area is also located in or close to an estuary due to the presence of and variance

491   in freshwater discharge (Little, 2000) or where the tidal range is extreme leading to higher levels of

492   superficial sediment disturbance (Raffaelli and Hawkins, 1996). Consequently, most benthic species

493   living on the intertidal mudflats are ecologically adapted to such varying environments.

494   Understandably, all dominant benthic species in Bridgwater Bay are euryhaline and eurythermic and

495   present some form of resistance to most stresses caused by their intertidal and estuarine medium

496   (Little, 2000). As a result these species are not expected to be readily sensitive to thermal stress

497   unless they are already close to their warmer limit of geographic distribution and are already

498   undergoing some sort of stress (temperature or otherwise), whereby an extra thermal pressure

499   during a critical period of the year could "push them over the edge". In first considering possible

500   thermal effects of a new power station development on the intertidal area of Bridgwater Bay,

501   through published evidence from field and laboratory studies and due to its reported southern limit

502 of distribution (see **section 2.2.1**), we identified the cold-water clam *M. balthica* as potentially

503 temperature sensitive. The study that has been reported here suggests, however, that this will not

504 be of great concern because the direct thermal impact on the *M. balthica* population will be

505 somewhat local (mostly on Stert flat) and the indirect effect on its bird predators attenuated by the

506 availability of alternative choices of prey. Beside, competitive realease means that this local loss may

507 lead to a structural reorganisation of the community *via* compensatory mechanisms (Duffy et al.,

508 2009; Ernest and Brown, 2001); the outcome of which cannot be known for certain until it occurs

509 but scenarios of benthic succession along various environmental gradient, together with the

510 knowledge of the other locally dominant species suggest that a shift to polychaetes-dominated

511 community might happen (Rosenberg, 2001). This, in turn, could potentially account for the extra

512 predatory pressure forecast by the model on these taxa. In Bridgwater Bay *M. balthica* is not

513 predicted to be the main prey for the birds normally present, hence the negligible cascade effects on

514 bird predators. It cannot, however, be assumed that this will consistently remain the case since

515 prey/predator linkages are known to differ between sites. For example, a study in the Wash,

516 England, showed that a similar local depression of two clams the cockle *Cerastoderma edule* and the

517 mussel *Mytily edulis* (due to fishery activity) progressively changed the population of birds from a

518 bivalve-diet species to a worm-based species thus qualitatively changing the bird populations

519 (Atkinson et al., 2010).

520 4.3 Model corroboration

521 IBMs like MORPH are relatively complicated, but they still represent a considerable simplification of

522 real ecosystems. In considering potential impacts on a localised area such as Bridgwater Bay it is

523 important that they consider the main drivers of the processes at stake in order to make accurate

524 and usable simulations. They must represent the best compromise between simplification and

525 accuracy of the processes modelled. IBMs have been shown to accurately predict or postdict survival

526 rate in shorebirds at a range of sites (e.g., Stillman et al., 2007), and both survival (Goss-Custard et

527 al., 2004) and behaviour (Stillman et al., 2010) have been accurately postdicted in a site nearby, the

528 Burry Inlet. MORPH has also been used and validated in a variety of estuarine and coastal systems

529 where applications emcompassed site-quality monitoring and scenario testing in relation to habitat

530 loss or creation, tidal barrages, human disturbance, shell-fishing or climate change (e.g. the Humber

531 estuary, Stillman et al., 2005; Pool Harbour, Dit Durell et al., 2006; the Bay of Somme, Dit Durell et

532 al., 2008 or the Bay of Seine, Dit Durell et al., 2005).

533 In Bridgwater Bay, predictions were corroborated with field data from different sources than those

534 used in developing the model itself. Overall, MORPH accurately predicted the present-day

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535   distribution of dunlin, ringed plover, turnstone, redshank and black-tailed godwit between the two

536   main mudflats. However, knot, oystercatcher and, to a lesser extent, shelduck and curlew

537   distributions were less well predicted. Modelled knot were predicted to feed entirely in high shore

538   Berrow flats due to a high density of the <u>Macoma10plus diet group</u> in these areas. Observations,

539   however, show that knot primarily fed on Stert flats which would have corresponded to a

540   preferential use of the <u>PolErr10to50 diet group</u> and/or <u>Gastropoda diet group</u>. High-density patches

541   of bivalves may have been missed despite our high spatial resolution surveys since *M. balthica*

542   density has been observed to vary widely over a rather short spatial scale in other intertidal

543   locations (Azouzi et al., 2002) and the medium-large *M. balthica* standing-stock of Stert flats could

544   have been underestimated. Oystercatcher, curlew and shelduck's main feeding patches were

545   correctly predicted but some of the secondary ones much less so. Realistically, not all parameters

546   included in MORPH can be site-specific and some had to be derived from generic relationships

547   defined with data from other areas (see **section 2.3.6** and **Appendix D**) (Stillman and Goss-Custard,

548   2010). These relationships, combined with the uncertainties of food abundance records, can explain

549   some of the differences between predictions and observations. This is consistent with previously

550   published applications, where MORPH sometimes failed to predict spatial occupation of some

551   species, curlew and oystercatcher in Poole Harbour (Dit Durell et al., 2006) and dunlin and curlew in

552   the Humber estuary (Stillman et al., 2005). These shortcomings have not prevented these models to

553   make useful predictions.

554   The EDF/NNB Genco Entec UK Ltd (2009) data used to estimate the time spent foraging was derived

555   from part of the model area only (Stert flats). Most of the bird species considered here primarily fed

556   in this zone. As a consequence, the observed data, despite being partial, was considered to be a

557   good proxy for the overall bird foraging effort across the whole area. Model outputs were in good

558   agreement with observations. Though modelled birds seem to be foraging more than they do in

559   nature, most of the predicted foraging is within the 95% confidence interval of the observed

560   foraging, except for two species – oystercatcher and curlew. The observed time spent foraging for

561   oystercatcher was less than that predicted by MORPH and this could potentially be explained by the

562   discrepancy of coverage area between observations and model data. Modelled oystercatcher fed for

563   only 50% of their time on Berrow flats and observations are lacking to explain a more complete

564   account of the bird activities. The situation is similar for curlew as this species may also feed on

565   other types of habitat besides intertidal mudflats, such as fields, saltmarsh, grasslands or freshwater

566   areas at high tide (Del Hoyo et al., 1996). Such supplementary feeding grounds are not allowed for in

567   MORPH, and this gap may explain why curlew was observed feeding more frequently than predicted.

568   With only one main discrepancy for each test, we consider that MORPH provided a reasonable

569 representation of the real system in this instance with perhaps a slight over-estimation of the energy

570 needs when compared with what happens in nature.

571 4.4 Site quality

572 Inter-specific competition across bird species in MORPH only occurs through the depletion of shared

573 resources (Stillman, 2008). More depletion will happen if many birds feed in the same area, i.e. if the

574 area is perceived as attractive for maximising bird fitness. The predicted survival and body condition

575 is a results from an indirect inter-specific competitions *via* shared food resources and direct intra-

576 specific competition through variation in dominance and interference (Stillman et al., 2002, 2000;

577 Triplet et al., 1999). Under the current conditions observed in Bridgwater Bay, curlew and

578 oystercatcher had the lowest survival and body condition; all the other birds selected apart from

579 shelduck were predicted to show a 100% survival rate and retain >98% of their body condition.

580 Shelduck was predicted to have the same survival but at a slightly lower condition. Being a wildfowl,

581 shelduck physiology might not be properly implemented in MORPH, the model having essentially

582 been developed for shorebirds. However, shelduck survival and body condition predictions in this

583 instance fell within the range of the other bird species considered and for which we have a higher

584 modelling confidence. Moreover, no obvious higher mortality of shelduck was observed on the site

585 since a consistently large population overwinters in Bridgwater Bay on an annual basis and, unlike

586 curlew, shelduck is not known to forage on grounds other than mudflats (Bryant and Leng, 1975;

587 Olney, 1965; Thompson, 1981). Additionally, the observed data on the overall proportion of time

588 spent foraging and the distribution of shelduck within Bridgwater Bay confirmed the validity of the

589 predictions. As a result we are confident that the shelduck-specific coefficient modification we

590 applied to the shorebirds equation in this instance in order to account for its different feeding

591 behaviour was a reasonable approximation of ecological reality. Even within the shorebirds group

592 there are some species-specific differences in the observed functional responses (Goss-Custard et

593 al., 2006) and yet case studies have shown that the functional equation considered in MORPH is

594 powerful enough to account for these differences (e.g. Dit Durell et al., 2006; Stillman et al., 2005).

595 The low natural survival predictions for curlew in this instance were not unexpected: in a recent

596 unpublished model of the Severn Estuary its predicted survival on the basis of mudflat use alone was

597 around 50% (Stillman, Com. Pers). In reality curlew are also expected to feed on other grounds

598 besides mudflats (Del Hoyo et al., 1996). A simulation of Poole Harbour (Dit Durell et al., 2006)

599 confirmed that larger shorebirds require terrestrial feeding habitats. The curlew population

600 observed within Bridgwater Bay could likely feed on such habitat at high tide in order to meet the

601   energetic requirements which seem to be unsustainable by the mudflats alone, a behaviour that has

602   indeed been observed within the Severn Estuary by Stillman (Com. Pers.).

603   In contrast, oystercatcher was predicted by MORPH to reach maximum survival and body condition

604   with an additional 25% of food availability and should be able to survive with only the mudflat as a

605   feeding ground. The predicted mortality with the current food conditions could be the natural

606   mortality rate which is, indeed, expected to be in the range of 2-10% (Cramp and Simmons, 1983).

607   Additionally, the night-time efficiency set for this bird – 81% - was derived from observations made

608   in the Tejo Estuary in Portugal (Lourenço et al., 2008) and the efficiency could different in the Severn

609   Estuary.

610   Overall the model predicted that there was more food available in Bridgwater Bay than that required

611   by the birds; we are also confident that predictions for shorebirds and wildfowl have a similar level

612   of accuracy. This implies that the bird community observed was not operating at the limit of the

613   carrying capacity in Bridgwater Bay; this is consistent with the predictions of other MORPH

614   applications (Stillman and Goss-Custard, 2010).

615   4.5 Effect of warm-water outflows on birds

616   The MORPH model simulated the effects of reduced *M. balthica* individual average AFDW due to a

617   contraction of its growth period resulting from a warm-water discharge from a proposed new

618   nuclear build within Bridgwater Bay. The exact effect of the future thermal impact on the clam's

619   population dynamics cannot be confirmed until the station begins to operate. Some assumptions

620   used in the present paper were not based on local field observations but instead on the authors'

621   knowledge on the species' physiology, previously published temperature-related population

622   dynamic studies and existing numerical hydrodynamic model outputs: one result was that we were

623   obliged to use a wide range of potential AFDW decreases from that model to bracket the possible

624   impact of the thermal influence on that particular parameter value. The simulation scenarios show

625   that (i) eight of the 10 bird species included in the model did not differ in their survival and body

626   condition under even the most conservative impact scenarios, most of these species being found to

627   feed predominantly on worms and (ii) the progressive decrease of *M. balthica* attractiveness

628   triggered a switch to the PolErr resource group (mix size-classes). The only bird species amongst

629   those selected whose survival was predicted to be reduced by a *M. balthica* AFDW decrease was

630   knot. Knot has been observed to feed on the worm *H. diversicolor*, but only on individuals ranging

631   from 10 to 59mm (Goss-Custard et al., 2006); an older study even states that this species cannot

632   feed on such prey larger than 30mm (Zwarts and Blomert, 1992). The model did not show knot

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633 turning to *H. diversicolor* to compensate for the loss of *M. balthica*. This could be because large *M.*
634 *balthica* may be a better quality food source than small and medium size-classes of *H. diversicolor*.
635 The drop in predicted survival was mild , at 3%, but is consistent with other studies documenting
636 cases of bird species switching from *M. balthica* to *H. diversicolor* when the bivalves are depleted
637 (Atkinson et al., 2010, 2003; Ens, 2006). The corroboration of the model with observed foraging data
638 suggests that these predictions could be a slight over-estimation compared to what happens in
639 nature since modelled birds seem to be having more difficulty meeting their energy requirements
640 than real birds but even then, the predicted impact of a rising water temperature is small.

641 5 CONCLUSION

642 In this paper we have demonstrated how modelling tools and empirical evidence can be combined in
643 a holistic manner to assess the environmental effects of a thermal discharge. The model predicts
644 that the bird population involved in this instance is generalist enough to withstand the impact of a
645 potential decrease of prey quality. This finding is, however, suspected to be a site-specific situation
646 and a similar protocol applied to another site may not yield the same outcomes. Benthic
647 communities living on intertidal areas and particularly those in estuaries are expected to be tolerant
648 of variations of temperature, but this tolerance will vary from one species to another and this aspect
649 may becomes critical whenever the site is close to the species' geographical limit of distribution.
650 Temperature tolerance of species highly connected within a trophic network must be thoroughly
651 addressed together with the level of specialism of the bird species involved; the relatively simple
652 network studied in this instance allows for a realistic understanding of these two fundamental
653 mechanisms and allowed us to test different impact scenarios resulting from the warm-water
654 discharge of a coastal power station development.

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934 TABLES

935 **Table 1**. Review of the temperature sensitivity of the main intertidal benthic taxa in Bridgwater Bay.

Species	Distribution	Physiology measured	Sensitive?	References
Hediste diversicolor	North east Atlantic to Mediterranean and Black Sea lagoons	Reproduction Metabolism	Unlikely	(Fritzsche and von Oertzen, 1995; Hartmann-Schröder, 1996; Ozoh and Jones, 1990; Smith, 1977)
Corophium volutator	North east Atlantic to Mediterranean and Black Sea lagoons, Azov sea	Osmoregulation Growth rate	Unlikely	(Dobrzycka-Krahel et al., 2014; Kater et al., 2008; Lincoln, 1979; Meadows and Ruagh, 1981; Wilson and Parker, 1996)
Peringia (Hydrobia) ulvae	Northern Norway to Senegal	Metabolism	Unlikely	(Hylleberg, 1975)
Macoma balthica	Eastern Atlantic, Pechora Sea to the Gironde estuary	Fecundity Recruitment Stress conditions	Likely	(Honkoop and Beukema, 1997; Honkoop and Van Der Meer, 1998, 1997; Honkoop et al., 1998; Hummel et al., 1997; Philippart et al., 2003)

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944   **Table 2**. Modelled decrease in density and individual energetic value of group resources throughout

945   the model period.

Resource group	Density curve	Mortality	AFDW curve	AFDW decrease
PolErr0to10	Exponential	29.20%	Linear	0%
PolErr10to20	Exponential	29.20%	Linear	0%
PolErr20to50	Exponential	29.20%	Linear	0%
PolErr50plus	Exponential	29.20%	Linear	0%
Crustacea	Exponential	25.52%	Linear	4.71%
Gastropoda	Exponential	0%	Linear	62.1%
Macoma0to10	Exponential	0%	Linear	71.02%
Macoma10plus	Exponential	26.49%	Linear	22.65%
PolSed	Exponential	11.81%	Linear	87.27%
Interstitial	Exponential	0%	Linear	44.99%

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947   **Table 3**. Bird population descriptive parameters.

Forager	Scientific name	Population number	Model number	Arrival day	Departure day
Dunlin	*Calidris alpina*	4695	7803	62	182
Ringed plover	*Charadrius hiaticula*	29	29	1	212
Turnstone	*Arenaria interpres*	43	43	1	212
Knot	*Calidris canuta*	313	358	31	212
Redshank	*Tringa totanus*	354	354	1	212
Grey plover	*Pluvialis squatarola*	93	108	31	212
Black-tailed godwit	*Limosa limosa*	18	42	1	92
Oystercatcher	*Haematopus ostralegus*	139	139	1	212
Curlew	*Numenius arquata*	614	614	1	212
Shelduck	*Tadorna tadorna*	977	977	1	212

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953 **Table 4.**

954 (a) Relation between group resource and bird diet.

Diet	Resource
PolErr10to50	PolErr10to20
PolErr10to50	PolErr20to50
PolErr20plus	PolErr20to50
PolErr20plus	PolErr50plus
PolErr50plus	PolErr50plus
Gastropoda	Gastropoda
Macoma0to10	Macoma0to10
Macoma10plus	Macoma10plus
Crustacea	Crustacea
Worms0to10	PolErr0to10
Worms0to10	PolSed
Worms0to10	Interstitial

955 (b) Diet matrix of bird species. PE: PolErr, G: Gastropoda, M: Macoma, C: Crustacea and W: Worms

Forager	PE10-50	PE20+	PE50+	G	M0-10	M10+	C	W0-10
Dunlin	√	X	X	√	√	X	√	X
Ringed plover	√	X	X	√	X	X	√	X
Turnstone	X	√	X	√	√	√	√	X
Knot	√	X	X	√	X	√	X	X
Redshank	X	√	X	√	√	√	√	X
Grey plover	X	√	X	√	X	√	X	X
Black-tailed godwit	X	√	X	X	X	√	X	X
Oystercatcher	√	X	√	X	X	√	X	√
Curlew	X	X	√	X	X	√	X	X
Shelduck	√	X	√	√	√	X	√	√

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960 **Table 5.** Modelled input scenarios for *M. balthica* average energy content in proportion per
961 individual.

Scenario	Decrease in *M. balthica* energy content (%)	
	Stert Flats	Berrow Flats
A – Current conditions	0	0
B	9	3
C	50	10
D	50	20

962

963 **Table 6.** Survival and body condition of each bird species and on average at the end of the winter (in
964 percentage) in relation to food availability.

Forager	Resources (gAFDW/m^2)	Survival (%)	Body condition (%)
Dunlin	7.79	100	99.9
Ringed plover	5.80	100	98.5
Turnstone	8.71	100	99.2
Knot	5.92	100	99.08
Redshank	8.71	100	99.29
Grey plover	6.84	100	99.17
Black-tailed godwit	3.79	100	99.9
Oystercatcher	8.35	90.64	91.76
Curlew	3.79	64.7	73.31
Shelduck	13.27	100	96.86
Total	14.49	97.75	91.64

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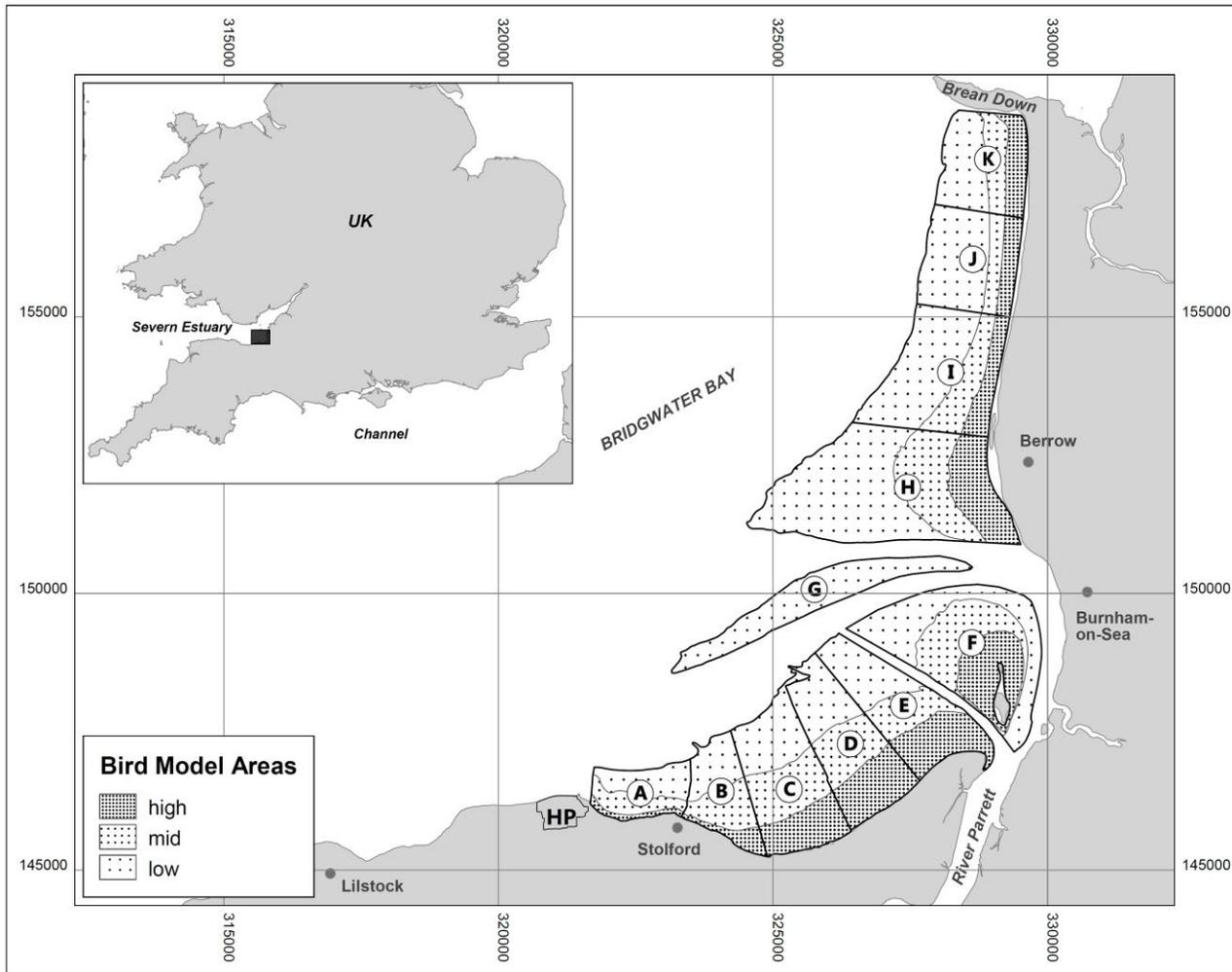
968   **Figure 1.** Bridgwater Bay and the 16 feeding patches defined by the combination of profile zones based on benthic invertebrates data (e.g. A, B) and broadly
969   shore-parallel divisions based on tidal elevation areas (High, Mid, Low). Stert flats: Profile zones from A to F; Berrow flats: Profile zones from H to K; HP:
970   complex of power stations at Hinkley Point.

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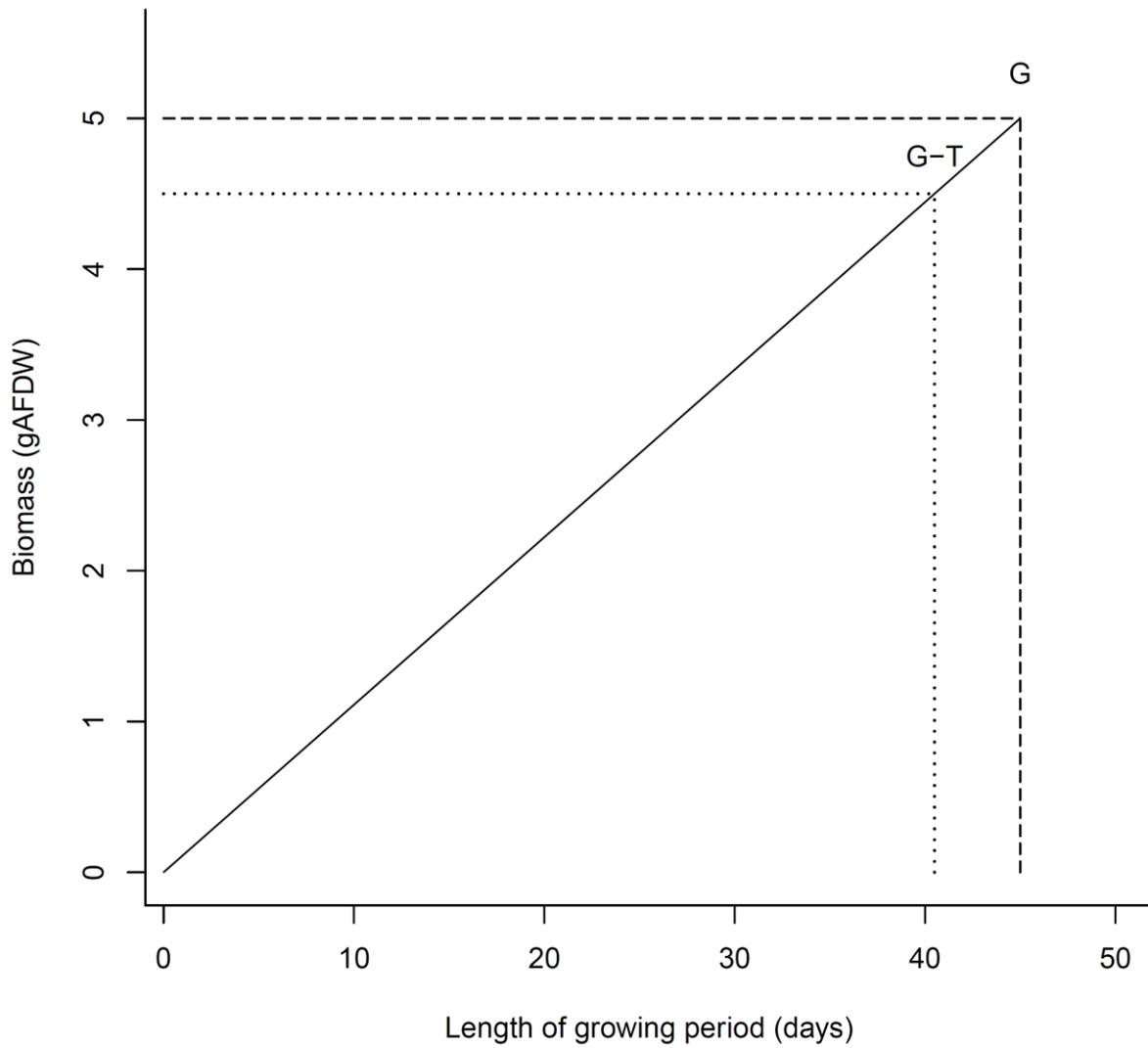
Figure 2. Conceptual diagram of the effects of increased seawater temperature on biomass accrual by *Macoma balthica*. AFDW: ash-free dry weight; G: dashed line: growth period in current conditions; G-T: dotted line: growth period shortened by an extra thermal pressure. Calculations are based on a linear growth rate.

a

Crustacea

PolErr

Gastropoda

Macoma0to10

Macoma10plus

PolSed

Interstitial

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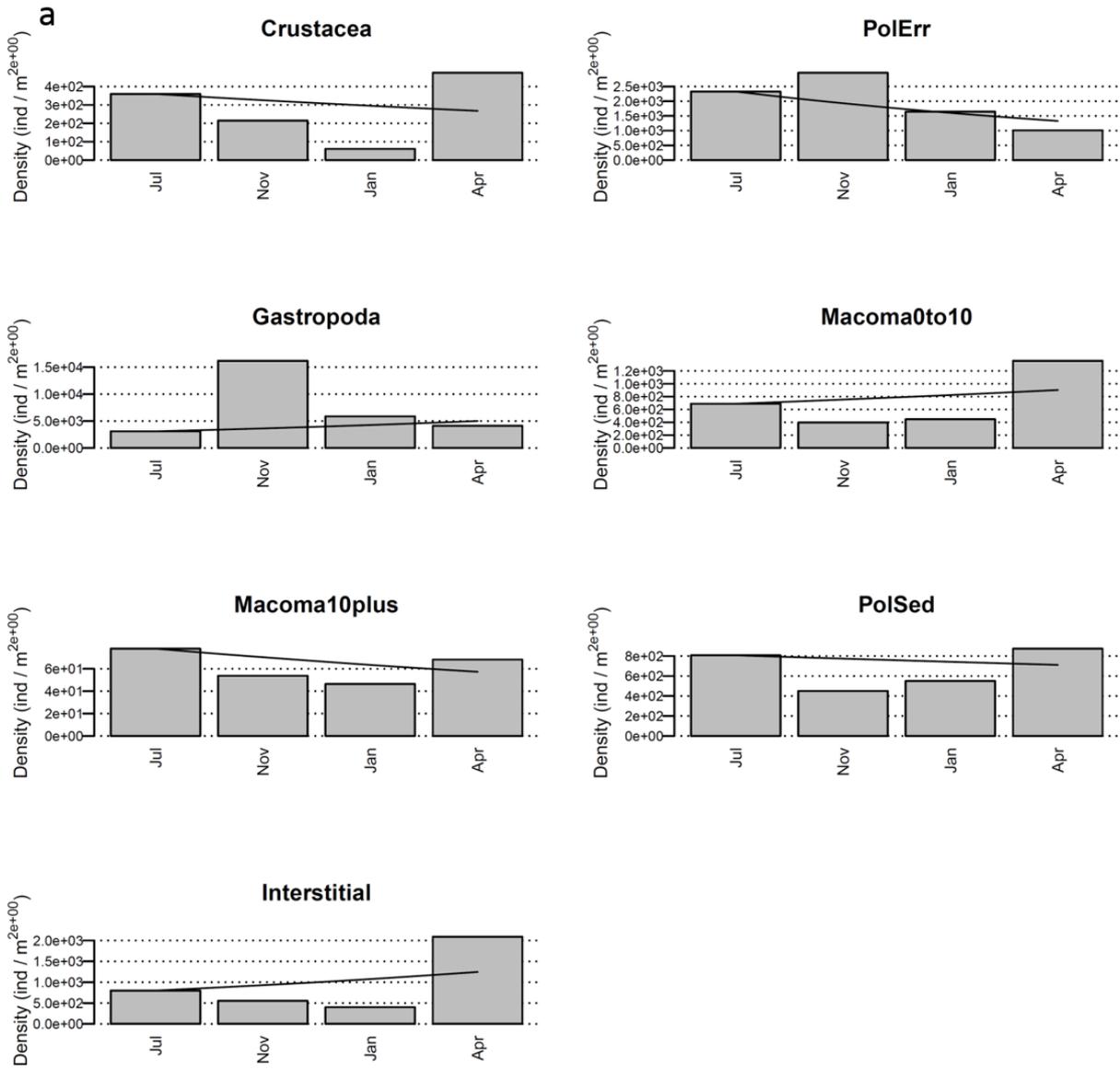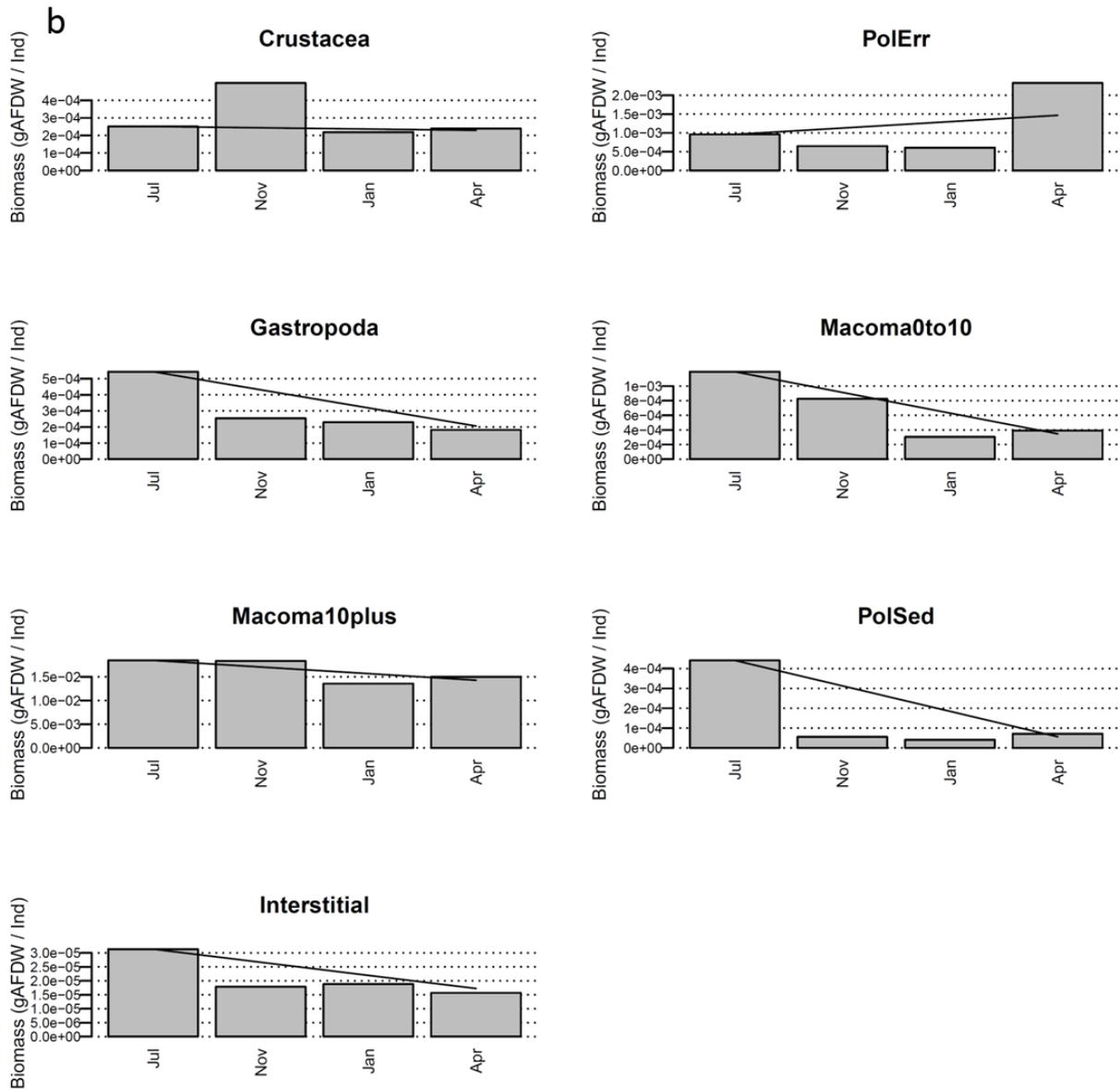
Figure 3. Generic temporal dynamics of the (**a**) density and (**b**) average individual biomass of each functional resource group throughout the model period. The solid line represents the decrease coefficient used in the model: the decrease follows (**a**) an exponential and (**b**) a linear model respectively.
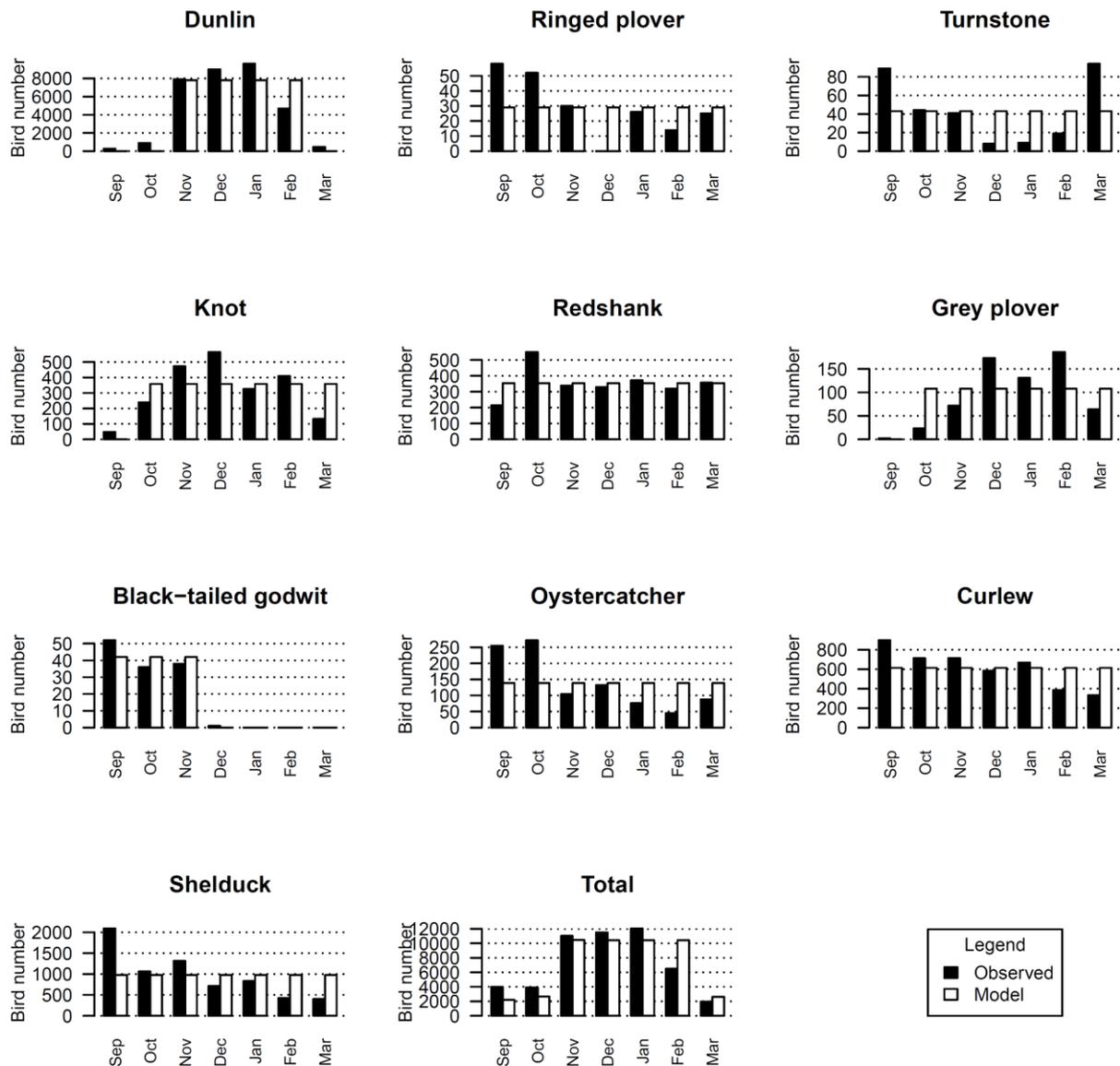
Figure 4. Bird counts as a monthly average per species. Observed numbers (black bars) were modified (open bars) (see **section 2.3.5**) in order to best describe the population changes throughout the model period.
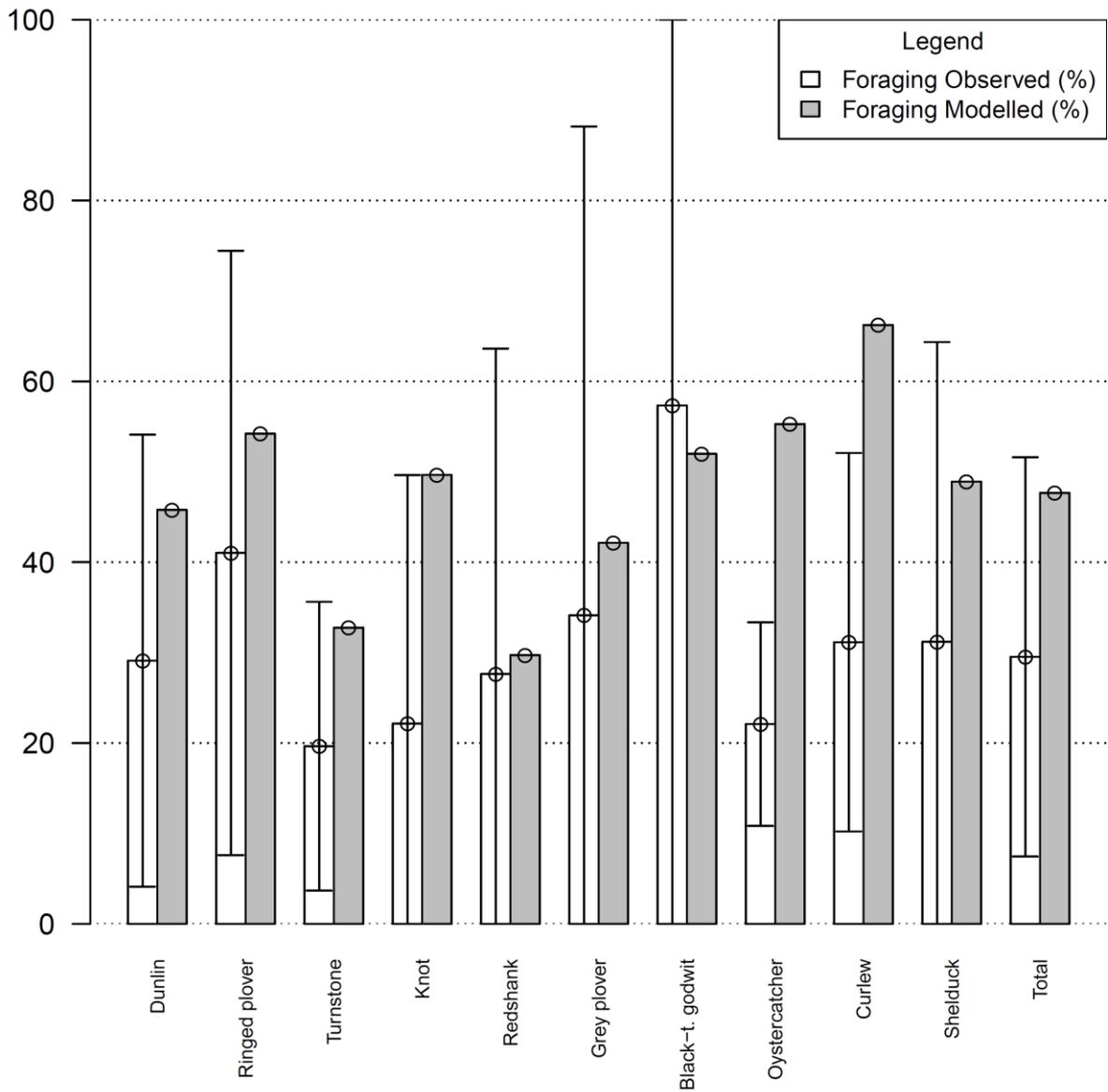
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987 **Figure 5.** Observed (open bars) and predicted (grey bars) proportions of bird time spent foraging.
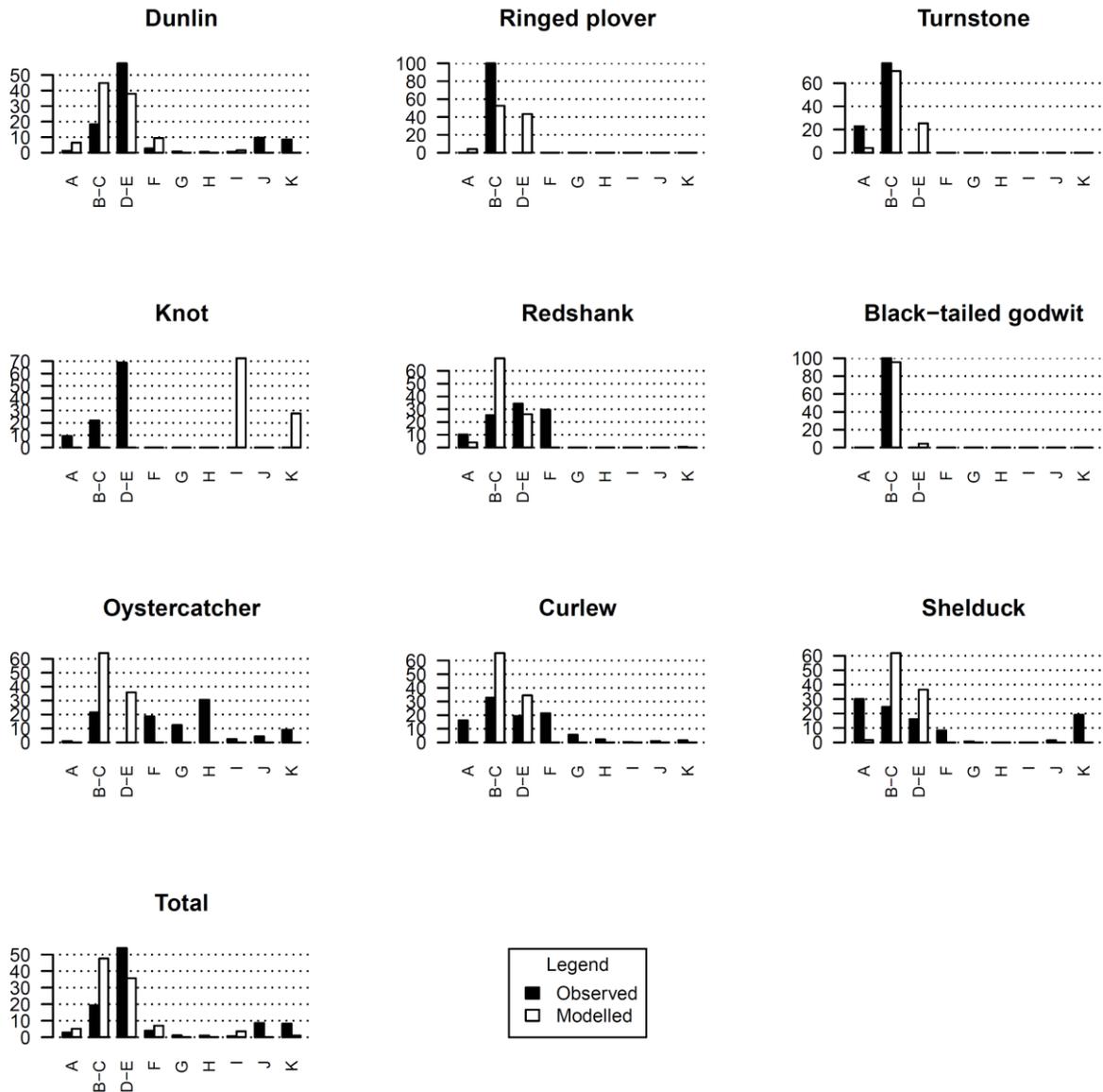
Figure 6. Observed (black bars) and predicted (open bars) average distribution of birds across the different feeding patches.
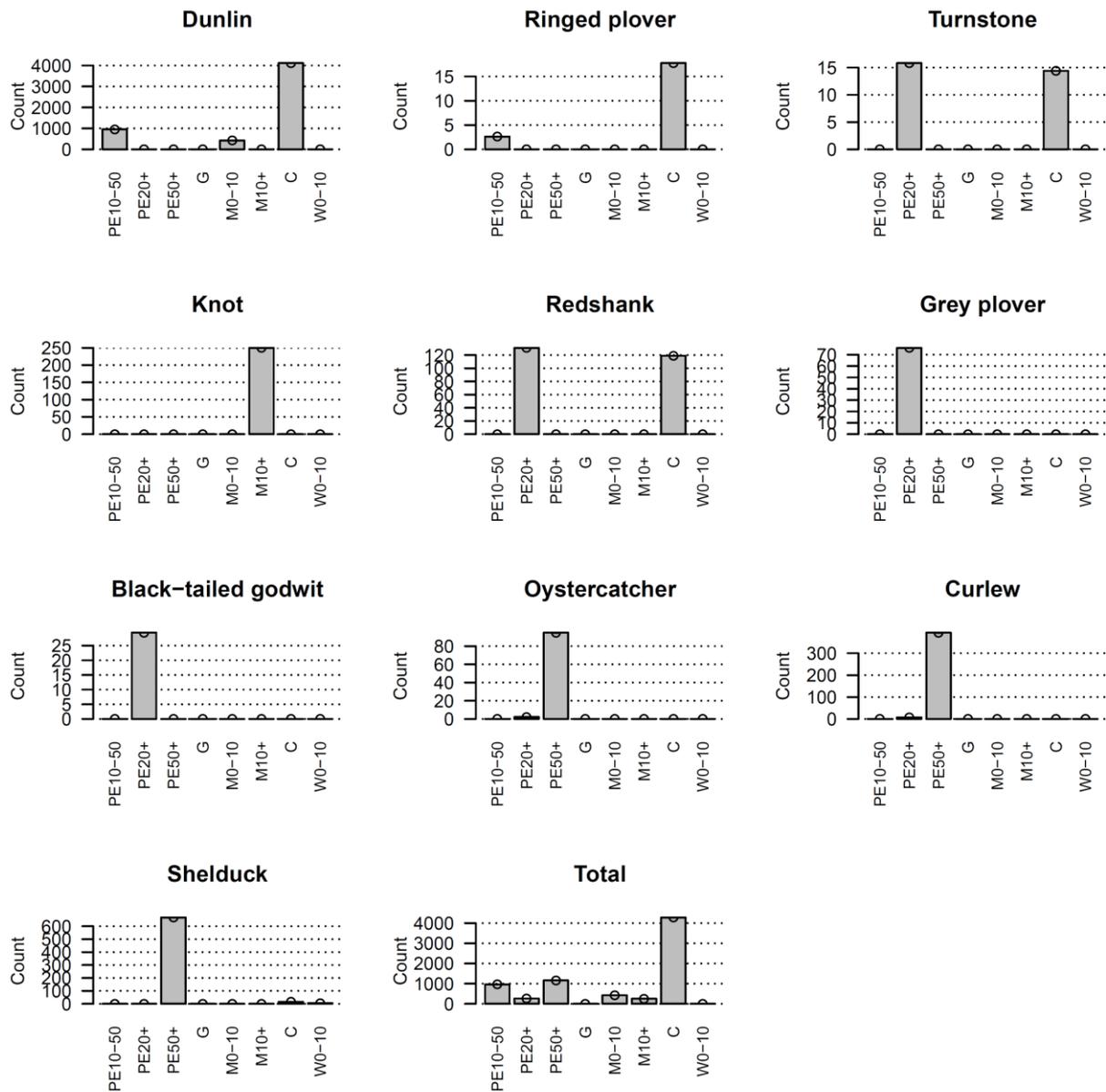
Figure 7. Functional diet groups for each bird species and in total (in number of birds feeding) as predicted by the model. PE10-50 (PolErr10to50 diet group), PE20+ (PolErr20plus diet group), PE50+ (PolErr50plus diet group), G (Gastropoda diet group), M0-10 (Macoma0to10 diet group), M10+ (Macoma10plus diet group), C (Crustacea diet group) and W0-10 (Worms0to10 diet group)

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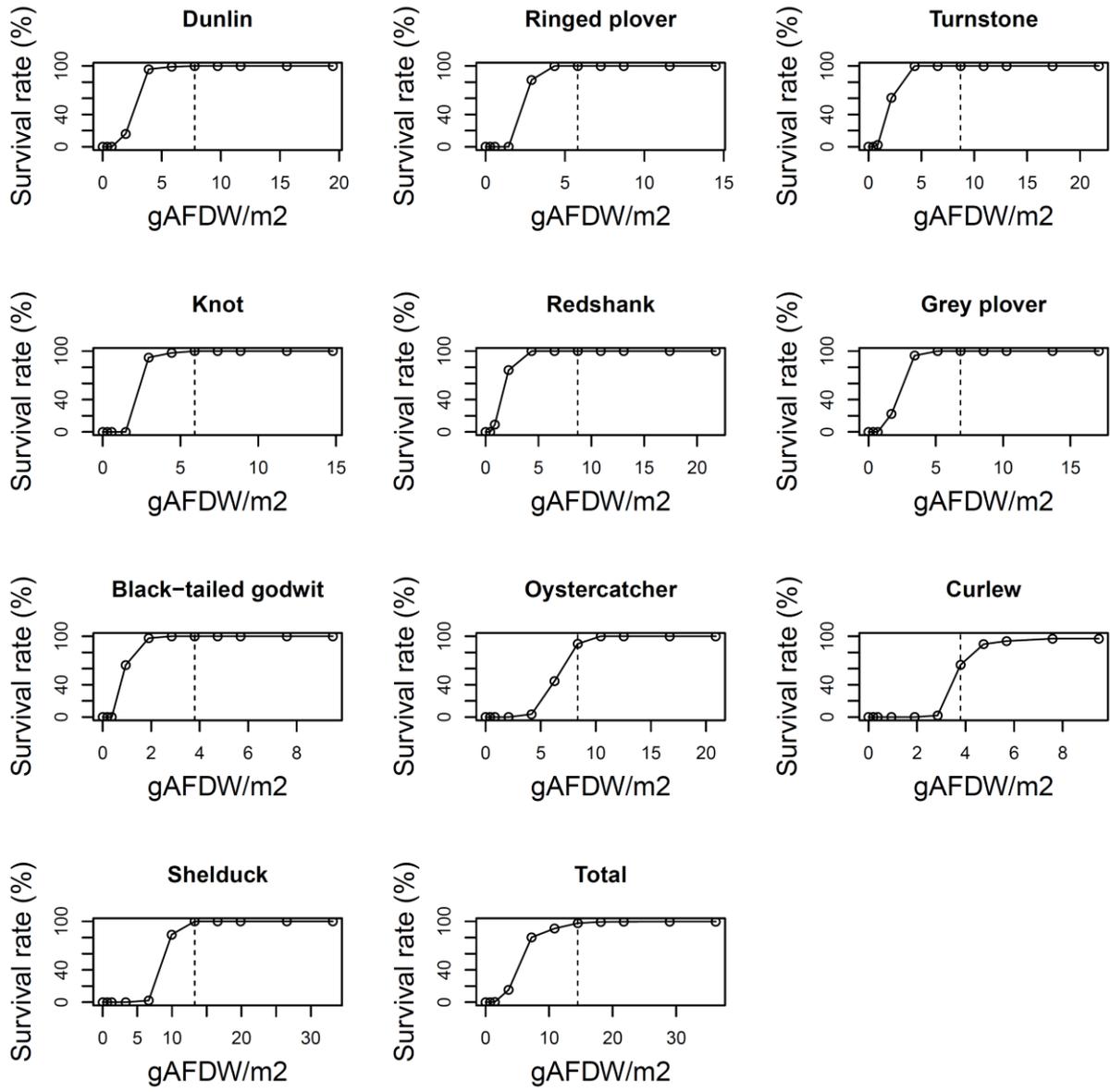
Figure 8. Predicted effects of change in prey biomass densities on overwinter survival rate of the selected bird species in Bridgwater Bay (in percentages). The vertical dashed line represents the actual prey biomass density values.

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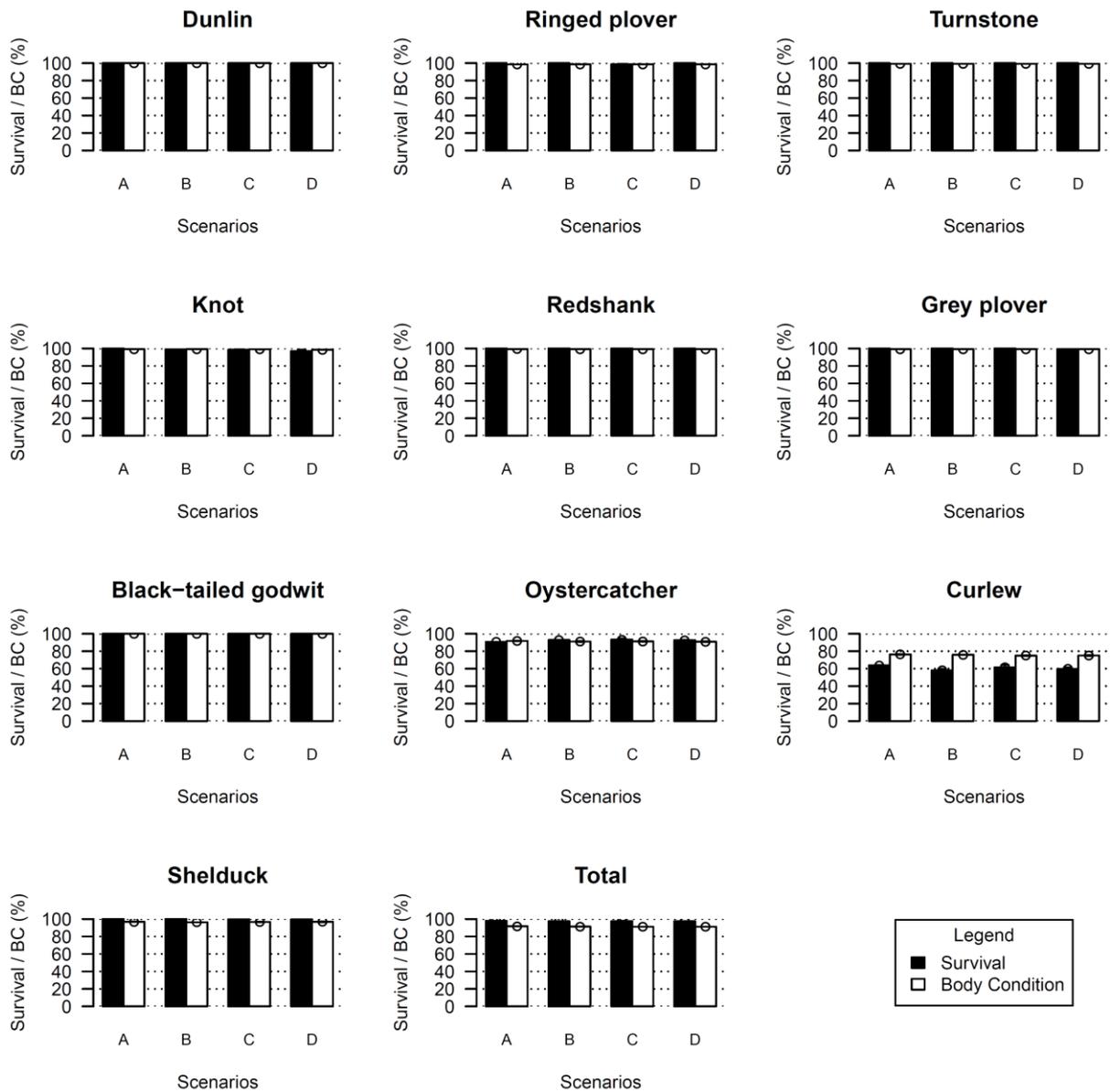
Figure 9. Predicted annual survival rate and body condition change (in percentages) of the selected birds under three scenarios of decrease in *M. balthica* energy content on Stert flats and Berrow flats respectively (in %). A: current (reference) conditions, B: 9% and 3%, C: 50% and 10% and D: 50% and 20%.
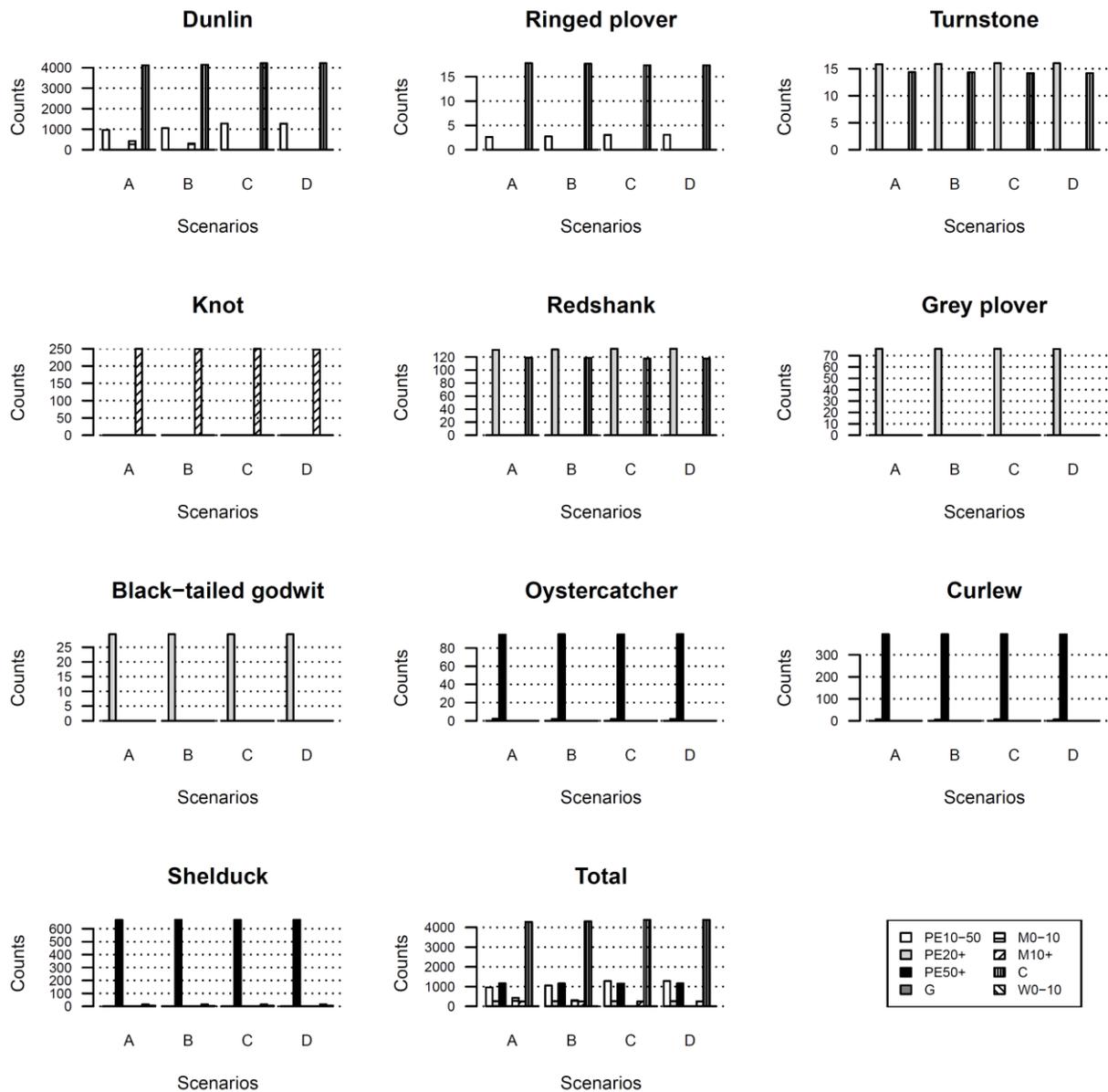
Figure 10. Predicted change in functional diet groups selection under scenarios B, C and D compared to the reference condition A. A: current (reference) conditions, B: 9% and 3%, C: 50% and 10% and D: 50% and 20%.

1011   GLOSSARY

1012   Cascade (secondary) effects: The effects of species depletion (or loss) on subsequent depletion (or

1013   loss) of additional species.

1014   Diet (MORPH): Collection of one or more resources from a patch consumed simultaneously by a

1015   forager.

1016   Forager (MORPH): Animal which forage within the system consuming diets and assimilating energy.

1017   Here the foragers are the nine species of shorebird and the wildfowl.

1018   Global environment (MORPH): State variables which apply throughout the modelled system.

1019   Overwintering: Process by which some organisms pass through or wait out the winter season (or the

1020   period of the year) when winter-like conditions make normal activities and survival difficult.

1021   Patch (MORPH): Locations with local, patch-specific state variables containing resources and

1022   foragers.

1023   Resource (MORPH): The food consumed by the foragers.

1024   Shorebird/Wader: Bird species members of the Charadriiformes order that includes plovers,

1025   sandpipers, godwit or curlews; excluding the more marine web-footed seabird group (gulls). They

1026   are a group of various ground-nesting bird of small to moderate size that live near the water.

1027   Wildfowl: Bird species members of the Anatidae family that includes ducks, geese and swans. These

1028   birds are adapted for swimming, floating on the surface, and in some cases diving in shallow water.

1030   **Appendix A.** Patch-specific variables. The patch names combine the profile zones (e.g. A, B) and elevation areas (high, mid, low). Shore levels are relative to

1031   British National Grid (Ordonnance Datum Newlyn).

Patch number	Patch name	Shore level (m)	Patch area (m^2)	Patch number	Patch name	Shore level (m)	Patch area (m^2)
1	Roost	>5	1000000	17	Fhigh	1 – 5	1391447
2	Ahigh	1 – 5	166834	18	Fmid	-1 – 1	1682610
3	Amid	-1 – 1	527362	19	Flow	<-1	2433889
4	Alow	<-1	848064	20	Glow	<-1	2538660
5	Bhigh	1 – 5	317716	21	Hhigh	1 – 5	1411444
6	Bmid	-1 – 1	774230	22	Hmid	-1 – 1	1748902
7	Blow	<-1	806393	23	Hlow	<-1	4513673
8	Chigh	1 – 5	1053357	24	Ihigh	1 – 5	674536
9	Cmid	-1 – 1	1285203	25	Imid	-1 – 1	1038085
10	Clow	<-1	1381339	26	Ilow	<-1	2671851
11	Dhigh	1 – 5	1216332	27	Jhigh	1 – 5	524879
12	Dmid	-1 – 1	1046195	28	Jmid	-1 – 1	459288
13	Dlow	<-1	1154361	29	Jlow	<-1	2107134
14	Ehigh	1 – 5	1272711	30	Khigh	1 – 5	684267
15	Emid	-1 – 1	857551	31	Kmid	-1 – 1	664495
16	Elow	<-1	1267852	32	Klow	<-1	1374216

1032   **Appendix B.** List of the benthic species from the 2010 - 2011 surveys included in the functional

1033   resource groups.

Taxa	Resource group	Abundance (%)	Number of class
Eteone longa/flava	PolErr	0.049529	1
Hediste diversicolor	PolErr	8.927601	4
Nephtys (juvenile)	PolErr	3.244149	2
Nephtys hombergii	PolErr	7.145522	4
Nereididae (juvenile)	PolErr	0.074293	1
Hydrobia ulvae	Gastropoda	49.5909	1
Retusa obtusa	Gastropoda	0.60673	1
Macoma balthica	Macoma	11.28023	2
Tellinoidea (juv)	Macoma	0.297174	1
Bathyporeia pilosa	Crustacea	0.012382	1
Bathyporeia sarsi	Crustacea	1.10202	1
Corophium volutator	Crustacea	1.832573	1
Cumopsis goodsir	Crustacea	0.024764	1
Diastylis rathkei	Crustacea	0.037147	1
Gastosaccus spinifer	Crustacea	0.012382	1
Idotea neglecta	Crustacea	0.012382	1
Melita spp	Crustacea	0.012382	1
Pontocrates altamarinus	Crustacea	0.012382	1
Sphaeroma monodi	Crustacea	0.024764	1
Arenicola (juvenile)	PolSed	0.024764	1
Arenicola marina	PolSed	0.012382	1
Aricidea minuta	PolSed	0.916286	1
Capitella sp	PolSed	1.844955	1
Eupolymnia nebulosa	PolSed	0.024764	1
Levinsenia gracilis	PolSed	0.012382	1
Polydora cornuta	PolSed	0.136205	1
Pygospio elegans	PolSed	2.538361	1
Sabellaria spinulosa	PolSed	0.123822	1
Scoloplos armiger	PolSed	0.061911	1
Streblospio shrubsolii	PolSed	0.841993	1
Enchytraeidae	Interstitial	5.770128	1
Grania spp	Interstitial	0.198116	1
Nematoda	Interstitial	0.829611	1
Nemertina	Interstitial	0.235263	1
Tubificoides amplivasatus	Interstitial	2.117364	1

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Appendix C. Resources per patch (individuals per m^2) and by ash-free dry weight (g per individual) (* denotes groups with added microphytobenthic
biomass).

Patch	Resource	ind. /m2	AFDW/ind g	Patch	Resource	ind. /m2	AFDW/ind g	Patch	Resource	ind. /m2	AFDW/ind g
Roost	PolErr0to10*	0	0	Amid	Macoma10plus	51.96	0.018463	Chigh	PolErr20to50	1094.00	0.009509
Roost	PolErr10to20	0	0	Amid	Crustacea*	25.98	0.047569	Chigh	PolErr50plus	320.33	0.045279
Roost	PolErr20to50	0	0	Amid	PolSed*	684.16	0.002238	Chigh	Gastropoda*	4598.60	0.000874
Roost	PolErr50plus	0	0	Amid	Interstitial*	34.64	0.03552	Chigh	Macoma0to10*	1117.17	0.002559
Roost	Gastropoda*	0	0	Bhigh	PolErr0to10*	1082.93	0.002137	Chigh	Macoma10plus	51.96	0.018463
Roost	Macoma0to10*	0	0	Bhigh	PolErr10to20	1444.29	0.000868	Chigh	Crustacea*	51.96	0.029538
Roost	Macoma10plus	0	0	Bhigh	PolErr20to50	617.49	0.009509	Chigh	PolSed*	701.48	0.002611
Roost	Crustacea*	0	0	Bhigh	PolErr50plus	179.80	0.045279	Chigh	Interstitial*	818.39	0.001891
Roost	PolSed*	0	0	Bhigh	Gastropoda*	1195.12	0.001616	Clow	PolErr0to10*	551.00	0.003602
Roost	Interstitial*	0	0	Bhigh	Macoma0to10*	77.94	0.017644	Clow	PolErr10to20	383.27	0.000868
Ahigh	PolErr0to10*	207.85	0.009126	Bhigh	Macoma10plus	207.85	0.018463	Clow	PolErr20to50	65.96	0.009509
Ahigh	PolErr10to20	597.56	0.000868	Bhigh	Crustacea*	0.00	0.000251	Clow	PolErr50plus	26.03	0.045279
Ahigh	PolErr20to50	77.94	0.009509	Bhigh	PolSed*	181.87	0.00749	Clow	Gastropoda*	259.81	0.005157
Ahigh	PolErr50plus	0.00	0.045279	Bhigh	Interstitial*	77.94	0.016479	Clow	Macoma0to10*	207.85	0.006964
Ahigh	Gastropoda*	39438.82	0.000575	Blow	PolErr0to10*	558.59	0.003647	Clow	Macoma10plus	51.96	0.018463
Ahigh	Macoma0to10*	1896.60	0.001845	Blow	PolErr10to20	363.73	0.000868	Clow	Crustacea*	25.98	0.046389
Ahigh	Macoma10plus	51.96	0.018463	Blow	PolErr20to50	77.94	0.009509	Clow	PolSed*	935.31	0.001723
Ahigh	Crustacea*	0.00	0.000251	Blow	PolErr50plus	0.00	0.045279	Clow	Interstitial*	272.80	0.004426
Ahigh	PolSed*	1532.87	0.001243	Blow	Gastropoda*	2121.76	0.001124	Cmid	PolErr0to10*	582.97	0.005132
Ahigh	Interstitial*	51.96	0.023691	Blow	Macoma0to10*	320.43	0.005042	Cmid	PolErr10to20	483.68	0.000868
Alow	PolErr0to10*	940.71	0.002751	Blow	Macoma10plus	51.96	0.018463	Cmid	PolErr20to50	92.41	0.009509
Alow	PolErr10to20	110.48	0.000868	Blow	Crustacea*	25.98	0.047679	Cmid	PolErr50plus	8.81	0.045279
Alow	PolErr20to50	14.00	0.009509	Blow	PolSed*	5715.77	0.000657	Cmid	Gastropoda*	1047.89	0.00233
Alow	PolErr50plus	0.05	0.045279	Blow	Interstitial*	1039.23	0.001217	Cmid	Macoma0to10*	164.54	0.012574
Alow	Gastropoda*	3325.54	0.000996	Bmid	PolErr0to10*	415.69	0.004651	Cmid	Macoma10plus	95.26	0.018463
Alow	Macoma0to10*	623.54	0.00361	Bmid	PolErr10to20	389.71	0.000868	Cmid	Crustacea*	25.98	0.072308
Alow	Macoma10plus	155.88	0.018463	Bmid	PolErr20to50	25.98	0.009509	Cmid	PolSed*	64.95	0.029264
Alow	Crustacea*	25.98	0.058169	Bmid	PolErr50plus	0.00	0.045279	Cmid	Interstitial*	441.67	0.00427
Alow	PolSed*	259.81	0.006233	Bmid	Gastropoda*	1130.16	0.001605	Dhigh	PolErr0to10*	298.78	0.012342
Alow	Interstitial*	86.60	0.017407	Bmid	Macoma0to10*	389.71	0.004275	Dhigh	PolErr10to20	324.76	0.000868
Amid	PolErr0to10*	493.63	0.004067	Bmid	Macoma10plus	116.91	0.018463	Dhigh	PolErr20to50	181.87	0.009509
Amid	PolErr10to20	389.71	0.000868	Bmid	Crustacea*	25.98	0.046423	Dhigh	PolErr50plus	51.96	0.045279
Amid	PolErr20to50	51.96	0.009509	Bmid	PolSed*	25.98	0.046614	Dhigh	Gastropoda*	1247.08	0.002482
Amid	PolErr50plus	0.00	0.045279	Bmid	Interstitial*	51.96	0.023118	Dhigh	Macoma0to10*	155.88	0.016706
Amid	Gastropoda*	16445.83	0.000618	Chigh	PolErr0to10*	1606.08	0.001788	Dhigh	Macoma10plus	25.98	0.018463
Amid	Macoma0to10*	1125.83	0.002288	Chigh	PolErr10to20	2115.07	0.000868	Dhigh	Crustacea*	2130.42	0.001385

Appendix C *(continued).*

Patch	Resource	ind. /m2	AFDW/ind g	Patch	Resource	ind. /m2	AFDW/ind g	Patch	Resource	ind. /m2	AFDW/ind g
Dhigh	PolSed*	0.00	0.000441	Elow	Gastropoda*	1402.96	0.001368	Fmid	PolErr0to10*	2248.76	0.001003
Dhigh	Interstitial*	1688.75	0.001463	Elow	Macoma0to10*	415.69	0.00398	Fmid	PolErr10to20	361.09	0.000868
Dlow	PolErr0to10*	719.31	0.003131	Elow	Macoma10plus	0.00	0.018463	Fmid	PolErr20to50	38.42	0.009509
Dlow	PolErr10to20	254.97	0.000868	Elow	Crustacea*	0.00	0.000251	Fmid	PolErr50plus	1.77	0.045279
Dlow	PolErr20to50	43.30	0.009509	Elow	PolSed*	25.98	0.044984	Fmid	Gastropoda*	545.60	0.002259
Dlow	PolErr50plus	0.00	0.045279	Elow	Interstitial*	25.98	0.044574	Fmid	Macoma0to10*	259.81	0.0048
Dlow	Gastropoda*	2260.33	0.001134	Emid	PolErr0to10*	1122.49	0.001909	Fmid	Macoma10plus	0.00	0.018463
Dlow	Macoma0to10*	402.70	0.004513	Emid	PolErr10to20	1025.65	0.000868	Fmid	Crustacea*	129.90	0.007458
Dlow	Macoma10plus	25.98	0.018463	Emid	PolErr20to50	470.38	0.009509	Fmid	PolSed*	2156.40	0.000875
Dlow	Crustacea*	51.96	0.025957	Emid	PolErr50plus	114.99	0.045279	Fmid	Interstitial*	129.90	0.007238
Dlow	PolSed*	51.96	0.026148	Emid	Gastropoda*	1493.89	0.001317	Glow	PolErr0to10*	0.00	0.000388
Dlow	Interstitial*	558.59	0.002423	Emid	Macoma0to10*	337.75	0.004619	Glow	PolErr10to20	0.00	0.000868
Dmid	PolErr0to10*	412.38	0.009049	Emid	Macoma10plus	0.00	0.018463	Glow	PolErr20to50	0.00	0.009509
Dmid	PolErr10to20	444.99	0.000868	Emid	Crustacea*	1325.02	0.001123	Glow	PolErr50plus	25.98	0.045279
Dmid	PolErr20to50	77.94	0.009509	Emid	PolSed*	25.98	0.044934	Glow	Gastropoda*	103.92	0.001671
Dmid	PolErr50plus	0.00	0.045279	Emid	Interstitial*	4325.80	0.000299	Glow	Macoma0to10*	0.00	0.001196
Dmid	Gastropoda*	1913.92	0.001807	Fhigh	PolErr0to10*	2248.76	0.001279	Glow	Macoma10plus	0.00	0.018463
Dmid	Macoma0to10*	571.58	0.005426	Fhigh	PolErr10to20	361.09	0.000868	Glow	Crustacea*	51.96	0.002505
Dmid	Macoma10plus	77.94	0.018463	Fhigh	PolErr20to50	38.42	0.009509	Glow	PolSed*	25.98	0.004951
Dmid	Crustacea*	51.96	0.04678	Fhigh	PolErr50plus	1.77	0.045279	Glow	Interstitial*	25.98	0.004541
Dmid	PolSed*	25.98	0.093499	Fhigh	Gastropoda*	545.60	0.003031	Hhigh	PolErr0to10*	161.32	0.018105
Dmid	Interstitial*	38.97	0.06207	Fhigh	Macoma0to10*	259.81	0.00642	Hhigh	PolErr10to20	163.43	0.000868
Ehigh	PolErr0to10*	1205.74	0.001803	Fhigh	Macoma10plus	0.00	0.018463	Hhigh	PolErr20to50	56.51	0.009509
Ehigh	PolErr10to20	1557.67	0.000868	Fhigh	Crustacea*	129.90	0.010697	Hhigh	PolErr50plus	8.45	0.045279
Ehigh	PolErr20to50	914.79	0.009509	Fhigh	PolSed*	2156.40	0.001071	Hhigh	Gastropoda*	11743.31	0.000708
Ehigh	PolErr50plus	114.99	0.045279	Fhigh	Interstitial*	129.90	0.010478	Hhigh	Macoma0to10*	4104.96	0.001668
Ehigh	Gastropoda*	1584.83	0.001272	Flow	PolErr0to10*	2248.76	0.00047	Hhigh	Macoma10plus	25.98	0.018463
Ehigh	Macoma0to10*	259.81	0.005641	Flow	PolErr10to20	361.09	0.000868	Hhigh	Crustacea*	0.00	0.000251
Ehigh	Macoma10plus	0.00	0.018463	Flow	PolErr20to50	38.42	0.009509	Hhigh	PolSed*	1117.17	0.002173
Ehigh	Crustacea*	1325.02	0.001122	Flow	PolErr50plus	1.77	0.045279	Hhigh	Interstitial*	155.88	0.012442
Ehigh	PolSed*	0.00	0.000441	Flow	Gastropoda*	545.60	0.000773	Hlow	PolErr0to10*	482.42	0.001141
Ehigh	Interstitial*	8625.62	0.000165	Flow	Macoma0to10*	259.81	0.001679	Hlow	PolErr10to20	69.95	0.000868
Elow	PolErr0to10*	1039.23	0.002033	Flow	Macoma10plus	0.00	0.018463	Hlow	PolErr20to50	6.07	0.009509
Elow	PolErr10to20	493.63	0.000868	Flow	Crustacea*	129.90	0.001216	Hlow	PolErr50plus	0.14	0.045279
Elow	PolErr20to50	25.98	0.009509	Flow	PolSed*	2156.40	0.000499	Hlow	Gastropoda*	233.83	0.001596
Elow	PolErr50plus	0.00	0.045279	Flow	Interstitial*	129.90	0.000996	Hlow	Macoma0to10*	1727.72	0.001339

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Appendix C *(continued)*.

Patch	Resource	ind. /m2	AFDW/ind g	Patch	Resource	ind. /m2	AFDW/ind g	Patch	Resource	ind. /m2	AFDW/ind g
Hlow	Macoma10plus	116.91	0.018463	Imid	PolErr20to50	12.14	0.009509	Jmid	PolSed*	389.71	0.001148
Hlow	Crustacea*	51.96	0.004985	Imid	PolErr50plus	0.28	0.045279	Jmid	Interstitial*	324.76	0.00088
Hlow	PolSed*	0.00	0.000441	Imid	Gastropoda*	1584.83	0.000632	Khigh	PolErr0to10*	142.01	0.002145
Hlow	Interstitial*	0.00	3.14E-05	Imid	Macoma0to10*	883.35	0.001354	Khigh	PolErr10to20	159.43	0.000868
Hmid	PolErr0to10*	1110.87	0.000543	Imid	Macoma10plus	168.88	0.018463	Khigh	PolErr20to50	90.79	0.009509
Hmid	PolErr10to20	93.98	0.000868	Imid	Crustacea*	1182.13	0.000369	Khigh	PolErr50plus	15.50	0.045279
Hmid	PolErr20to50	14.13	0.009509	Imid	PolSed*	220.84	0.001074	Khigh	Gastropoda*	1905.26	0.000632
Hmid	PolErr50plus	2.11	0.045279	Imid	Interstitial*	311.77	0.000479	Khigh	Macoma0to10*	2381.57	0.001267
Hmid	Gastropoda*	2000.52	0.000602	Jhigh	PolErr0to10*	36.02	0.006684	Khigh	Macoma10plus	259.81	0.018463
Hmid	Macoma0to10*	597.56	0.001391	Jhigh	PolErr10to20	0.00	0.000868	Khigh	Crustacea*	259.81	0.000901
Hmid	Macoma10plus	0.00	0.018463	Jhigh	PolErr20to50	0.00	0.009509	Khigh	PolSed*	346.41	0.000929
Hmid	Crustacea*	51.96	0.002493	Jhigh	PolErr50plus	0.00	0.045279	Khigh	Interstitial*	6105.48	5.9E-05
Hmid	PolSed*	0.00	0.000441	Jhigh	Gastropoda*	1299.04	0.000662	Klow	PolErr0to10*	18.01	0.122607
Hmid	Interstitial*	0.00	3.14E-05	Jhigh	Macoma0to10*	1861.96	0.001279	Klow	PolErr10to20	0.00	0.000868
Ihigh	PolErr0to10*	0.00	0.000388	Jhigh	Macoma10plus	86.60	0.018463	Klow	PolErr20to50	0.00	0.009509
Ihigh	PolErr10to20	0.00	0.000868	Jhigh	Crustacea*	6451.89	0.000274	Klow	PolErr50plus	0.00	0.045279
Ihigh	PolErr20to50	0.00	0.009509	Jhigh	PolSed*	389.71	0.000835	Klow	Gastropoda*	3983.72	0.000918
Ihigh	PolErr50plus	0.00	0.045279	Jhigh	Interstitial*	303.11	0.000538	Klow	Macoma0to10*	433.01	0.004637
Ihigh	Gastropoda*	25.98	0.005919	Jlow	PolErr0to10*	155.35	0.013117	Klow	Macoma10plus	0.00	0.018463
Ihigh	Macoma0to10*	493.63	0.001479	Jlow	PolErr10to20	548.82	0.000868	Klow	Crustacea*	1926.91	0.001024
Ihigh	Macoma10plus	311.77	0.018463	Jlow	PolErr20to50	84.30	0.009509	Klow	PolSed*	129.90	0.011912
Ihigh	Crustacea*	2338.27	0.00031	Jlow	PolErr50plus	1.92	0.045279	Klow	Interstitial*	86.60	0.017237
Ihigh	PolSed*	415.69	0.000777	Jlow	Gastropoda*	909.33	0.002015	Kmid	PolErr0to10*	108.06	0.023474
Ihigh	Interstitial*	571.58	0.000276	Jlow	Macoma0to10*	129.90	0.0115	Kmid	PolErr10to20	0.00	0.000868
Ilow	PolErr0to10*	870.26	0.002351	Jlow	Macoma10plus	0.00	0.018463	Kmid	PolErr20to50	0.00	0.009509
Ilow	PolErr10to20	108.73	0.000868	Jlow	Crustacea*	173.21	0.007978	Kmid	PolErr50plus	0.00	0.045279
Ilow	PolErr20to50	8.09	0.009509	Jlow	PolSed*	0.00	0.000441	Kmid	Gastropoda*	4893.05	0.000889
Ilow	PolErr50plus	0.18	0.045279	Jlow	Interstitial*	1212.44	0.001135	Kmid	Macoma0to10*	541.27	0.004316
Ilow	Gastropoda*	1623.80	0.001256	Jmid	PolErr0to10*	126.07	0.003616	Kmid	Macoma10plus	0.00	0.018463
Ilow	Macoma0to10*	714.47	0.002815	Jmid	PolErr10to20	0.00	0.000868	Kmid	Crustacea*	4373.43	0.000637
Ilow	Macoma10plus	25.98	0.018463	Jmid	PolErr20to50	0.00	0.009509	Kmid	PolSed*	4568.29	0.000811
Ilow	Crustacea*	25.98	0.044766	Jmid	PolErr50plus	0.00	0.045279	Kmid	Interstitial*	303.11	0.0056
Ilow	PolSed*	25.98	0.044957	Jmid	Gastropoda*	1104.18	0.000793				
Ilow	Interstitial*	1195.12	0.000999	Jmid	Macoma0to10*	1039.23	0.001461				
Imid	PolErr0to10*	1621.61	0.000515	Jmid	Macoma10plus	86.60	0.018463				
Imid	PolErr10to20	184.63	0.000868	Jmid	Crustacea*	3290.90	0.000334				

1040 **Appendix D.** Foragers feeding parameters not specific to the Bridgwater Bay version of MORPH.

Feeding parameters	Principle	Reference
Competition	Interference is assumed to reduce intake rate when the number of birds is above 100 birds per hectare with less interference for dominant birds.	(Stillman et al., 2002, 2000; Triplet et al., 1999)
Foraging efficiency	Assumed to follow a normal distribution in absence of competitors with a standard deviation of 0.125	(Stillman et al., 2000)
Dominance	Uniform distribution value that influence the sensitivity of foraging efficiency to other competitors	(Stillman et al., 2000)
Maximum intake rate	Limits the maximum amount of food a bird can consume within a time-step	(Kirkwood, 1983)
Metabolic rate	Amount of energy expended per time-step per bird	(Nagy et al., 1999)
Energy density of birds	Amount of energy (KJ) contained in a gram of bird fat reserve (33.4 KJ.g^{-1})	(Kersten and Visser, 1996)
Assimilation efficiency	Proportion of energy within the prey consumed that is assimilated into the bird's body: 0.75 for all resources for each bird except 0.85 for Macoma and Peracarida for oystercatcher	(Dit Durell et al., 2006; Stillman et al., 2005)

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1042 **Appendix E.** Night-time foraging efficiency coefficient used in the model, *information found in the
1043 literature.

Forager	Scientific name	Night-time coefficient
Dunlin	*Calidris alpina*	0.82
Ringed plover	*Charadrius hiaticula*	0.49*
Turnstone	*Arenaria interpres*	0.82
Knot	*Calidris canuta*	0.82
Redshank	*Tringa totanus*	0.95*
Grey plover	*Pluvialis squatarola*	1.00*
Black-tailed godwit	*Limosa limosa*	0.87*
Oystercatcher	*Haematopus ostralegus*	0.81*
Curlew	*Numenius arquata*	0.82
Shelduck	*Tadorna tadorna*	0.82

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1045   **Appendix F.** Bird size in relation to their favourite size-class preys.

Bird	Weight	Preferential preys
Dunlin, ringed plover	48 – 64 g	*P. ulvae*, *C. volutator*, *M. balthica* (3 – 6 mm), *H. diversicolor* (10 – 50 mm)
Grey plover, black-tailed godwit	240 – 310 g	*P. ulvae*, *C. volutator*, *M. balthica* (8 – 20 mm), *H. diversicolor* (>25 mm)
Oystercatcher, curlew	540 – 885 g	*M. balthica* (> 8mm), *H. diversicolor* (>50 mm), *C. maenas* (10 – 50 mm)
Shelduck	1051 g	Small preys or small size-classes of prey

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1047   **Appendix G.** Appendix References

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