Ecological Modelling 342 (2016) 60–81

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

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

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ARTICLE INFO

Article history:
Received 21 April 2016
Received in revised form 24 August 2016
Accepted 20 September 2016

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

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.

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 (>100m^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 10 km (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 com-

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http://dx.doi.org/10.1016/j.ecolmodel.2016.09.017
0304-3800/

munity 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 hydrodynamic model, these investigations explore how to predict which low-trophic level species (i.e. benthic invertebrate) are most likely to be affected by a direct local thermal discharge over an intertidal mudflat and how best to estimate the cascading, secondary consequences for their main avian predators further up the food chain. We answer these questions in two steps: first, by using an empirical understanding of benthic invertebrate physiology and ecology coupled with the outputs of a validated hydrodynamic model to assess the potential consequences of a local temperature increase on the benthic community; second, by using an understanding of bird physiology and behaviour in individual-based model to predict the knock-on consequences for the birds of changes in their invertebrate prey.

2. Method

2.1. Study site and context

The Severn Estuary (UK) is one of the largest estuaries in Europe and has the third largest tidal range in the world. It encompasses several sites supporting bird populations that are of national or international importance. Although the estuary is thought of as species-poor, prey items are found at very high densities across wide areas of intertidal mudflats and sandbanks (Boyden and Little, 1973; Mettam et al., 1994; Warwick and Somerfield, 2010; Warwick et al., 1991) which support considerable numbers of wading birds during the winter (Burton et al., 2010). The largest of these areas is Bridgwater Bay, which is composed of two main intertidal mudflats, Stert and Berrow flats respectively on the south and the north side of the River Parret (Fig. 1). Adjacent to the bay, Hinkley Point (HP) is the location of two existing nuclear power stations (HPA – no longer operating and HPB – operational) and permission has recently been granted for a third (HPC), the operation of which could have impacts on the local marine fauna and flora, including the wading bird and their preys.

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

The benthic invertebrate species *Corophium volutator*, *Hediste diversicolor*, *Macoma balthica* and *Peringia (Hydrobia) ulvae* are among the key biological features of the intertidal mudflats (Boyden and Little, 1973; Warwick et al., 1991). These species are known to form a component of shorebird diets (Goss-Custard et al., 2006; Langston et al., 2007) and the birds have been observed to actively utilise the mudflats to obtain the majority of their diet from the mudflat infauna (Burton et al., 2010; Clark and Prys-Jones, 1994). The trophic link between the birds and their infaunal prey means that any NNB activities potentially affecting the mudflat habitat may have direct implications for the benthic prey and knock-on secondary consequences for the bird populations at higher trophic levels.

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

The putative effect of a temperature increase on benthic taxa was first assessed by a literature review. Two elements were specifically sought: (i) the area of distribution where the species has been recorded and (ii) any specific physiological features tested *via* (e.g.) field or lab experiment or monitoring studies (Table 1). Only *M. balthica* showed evidence of temperature sensitivity. The clam is a cold-water species with a latititunal distribution along the eastern Atlantic ranging from the Arctic Pechora Sea to the Gironde estuary (Hummel et al., 1997) and various laboratory experiments, long-term monitoring and correlative studies have provided evidence to suggest that *M. balthica* might be sensitive to increasing seawater temperature (e.g. Honkoop and Van Der Meer, 1998; Honkoop et al., 1998; Philippart et al., 2003). The species is also thought to currently be experiencing a range contraction in western Europe primarily due to warming temperature in the southern limit of its distribution (Bachelet et al., 1990; Beukema et al., 2009; Jansen et al., 2007).

2.2.2. Thermal sensitivity of M. balthica

Growth of *M. balthica* is thought to cease at 15 °C (De Wilde, 1975), in the Wadden sea its main growth period has been observed to be between the time of first spawning in early spring and the time at which mean seawater temperatures reaches the 15 °C threshold. At other places however, populations have shown dual growing seasons during both spring and autumn, when food availability is sufficient to support a second growth in the latter part of the year (Beukema and Desprez, 1986). Nevertheless, the single annual growing season in spring and early summer appears to be the rule in western Europe, while the dual growing season exceptions are thought to be restricted to the southern limit of distribution (south of ~50°N) (Beukema and Desprez, 1986). With the assumption that the Severn Estuary populations follow the single growing season rule, future thermal effluents in the study area are expected to bring forward the 15 °C threshold, with an overall shortening of *M. balthica*'s only annual growth period and retarding biomass gain. As *M. balthica* is assumed to exhibit a linear growth (Beukema and De Bruin, 1977; Beukema and Desprez, 1986), an estimate of thermally-induced reduction of the growth period can therefore be used to predict resulting effects on biomass accrual using linear modelling (Fig. 2).

2.3. The individual-based model

2.3.1. Rationale

The selection of an appropriate model for investigating the trophic interactions between the birds and their infaunal preys requires consideration of aspects of the birds' ecology. Mortality and reproductive rate of the birds are the two most important demographic factors to assess (Stillman et al., 2010; Stillman and Goss-Custard, 2010). Individual-based models (IBM) are considered to be appropriate tools for such tasks since they consider important aspects of species interaction such as interference and competition and incorporation of individual variations (Stillman et al., 2010 Stillman and Goss-Custard, 2010).

MORPH is a flexible IBM platform designed to be used with a wide range of species and environmental issues (freely available at: http://individualecology.bournemouth.ac.uk/index.html). The tool is described in detail in Stillman (2008). Briefly, the basic principles of MORPH are as follows: Time progresses in discrete, fixed duration time-steps, the birds arrive on site on their species-specific arrival day, they remain at the same location during a time-step, either on a feeding patch or travelling between patches but cannot move between time-steps. They alter their location and the food they consume in order to maximise their perceive fitness and