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Forecasting future drowning of coastal waterbird habitats reveals a major conservation concern

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ABSTRACT

Climate change-induced rising sea levels are expected to affect coastal habitats worldwide, and the associated coastal squeeze in protected coastal areas might significantly alter availability of coastal habitats. This study combines coastal bathymetry and elevation models to develop a continuous topographic model covering coastal areas on a large geographical scale, and predicts the areal change in five habitats important to numerous breeding and migrating birds. Our model indicates considerable declines in coastal habitats as a result of coastal squeeze, and reveals major conservation concerns regarding future preservation of essential waterbird habitats. In our study area this will directly influence seven species of herbivorous waterbirds occurring at internationally important numbers, and a total of 41 species of coastal birds protected under the EU Birds Directive, many of which are currently designated as having an unfavourable conservation status. Declines in coastal habitats will also affect invertebrates and fish, and through effects on food webs have an even wider ecological implication. These findings highlight the need of focused coastal management, and illustrate the cost of uncritically protecting human agricultural interests while preventing natural dynamics of the coastal zone. Our analysis indicate that pulling down existing sea walls will reduce the loss by 37–65% dependent on habitat type, but that complete compensation is unlikely in our study area due to local topography. Managed retreat of coastlines might be an efficient solution to counteract the effects of coastal squeeze, but the time and interests associated with implementation of such mitigation measures imply that the time for action is now.

1. Introduction

Across the globe coastal habitats are the most important foraging, staging and breeding areas to millions of waterbirds (Bellrose, 1980; Delany et al., 2009; Morrison and Ross, 1989; Scott and Rose, 1996). The simultaneous presence of good quality forage, relatively undisturbed roosting sites and suitable nesting areas sustain countless avian populations worldwide, relying on these habitats throughout their annual cycle (Delany et al., 2009; Liordos, 2010; Lovvorn and Baldwin, 1996). The high association with these areas across many families (e.g. Anatidae, Charadiidae, Laridae, Podicipedidae, Rallidae, Scolopacidae) emphasise the major importance of coastal habitats, and underline how the land/water boundary creates ideal conditions for both breeding, staging and migrating birds.

To coastal birds foraging areas can be divided into five major habitat types: Deeper waters, shallow waters, mudflats, salt marshes, and near-coastal agricultural land. Different waterbird species are associated with one (and often more) of these habitat types, relying on specific physical properties to pave the way for both high nutrient forage (sea grasses, worms, mussels, salt marsh halophytes, cereal grains etc.) and roosting areas with low frequencies of disturbance (sandbanks, sea surface, rocky shores etc.). The use of shallow waters relates to the presence of macrophyte communities requiring light, low nutrient concentrations, a clear water column and certain salt concentrations (Bach, 1993; Nelson and Waaland, 1997). Mudflat foraging involve algae, sea grasses, crustaceans, bivalves and annelids, and the existence of mudflats rely on tidal movements and alternating flooding and exposure regimes at the water's edge (Dyer et al., 2000). Salt marshes are exploited for their halophytes, grasses and associated invertebrates, and the persistence of salt marshes depend on the interplay between irrigation, salt intrusion, sedimentation and proper management (Buttenschøn, 2007; Doody, 2008). Preservation of these habitats relies heavily on the integration between land and sea, and is founded on the relatively unhindered transport of matter across the land/water boundary. Near-coastal arable land on the other hand, is characterised by little or no influence from the neighbouring sea, and efficient crop production is dependent on the exclusion of these coastal processes (Ondrasek et al., 2011). Consequently,

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coastal defence is accelerating in many developing lowland areas with no remedy to secure important coastal habitats, and current land use practices increasingly threaten to disrupt the land–water interaction in modern landscapes (Rowley et al., 2007; Sterr, 2008).

Establishment of dikes, dunes, ditches and elevated field boundaries to prevent sea water intrusion to agricultural land might only have limited effects on the coastal dynamics of waterbird habitats in a static landscape. When sea level rises however, as currently projected in scenarios of future climate change and associated global warming, the persistence of coastal habitats is dependent on an inward displacement caused by gradual influence of terrestrial areas by the open sea. When this inland development is interrupted by sea walls safeguarding agricultural areas, the loss of coastal habitats from the ocean side is uncompensated on the terrestrial side, potentially causing declines in both shallow waters, mudflats and salt marshes. This expected loss of coastal habitats is frequently referred to as "coastal squeeze" (Doody, 2004; FitzGerald et al., 2008; Hughes, 2004).

The effects of coastal squeeze on near-shore habitat loss and potential impacts on waterbirds have so far only been studied for a few habitat/species associations. Shaughnessy et al. (2012) used bathymetry models to look at loss of *Zostera* sea grass habitats along the Pacific coast of North America and its potential impacts on a single flyway-population of black-bellied brent goose *Branta bernicla nigricans*, and in a previous study we used terrestrial digital elevation models to address saltmarsh habitat loss for three rare breeding wader species and one wintering goose population in Denmark (Clausen et al., 2013b).

In this study we combine elements of these previous studies into a much wider application, with the aim to predict climate change-induced coastal squeeze impacts on the distribution of five coastal waterbird habitats. We do this by developing what we believe is the first combined application of bathymetry and elevation data into a continuous land–water topographic map. This allow us to explore future climate change-related changes in habitat availability in the Limfjord area in Denmark on the whole range of waterbirds that are dependent on this area, from diving benthi- and pescivores to saltmarsh and agricultural land feeding herbivorous ducks, geese and swans.

Specifically, we aim to (1) Define the vertical distribution of five coastal habitats (deeper waters, shallow waters, mudflats, salt marshes and near-coastal agricultural land) in relation to sea level, (2) Investigate the proportional change in availability of each habitat associated with rising sea levels and coastal squeeze, (3) Clarify the potential to compensate future habitat loss by pulling down current seawalls and assure complete reintegration with the sea and (4) Discuss how this might affect coastal waterbirds in future coastal landscapes, including many species of strong conservation concern.

2. Methods

2.1. Study area

Changing habitat availability was modelled for a large (1500 km^2) brackish lagoon, the Limfjord (Lat: 56°41′N, Long: 8°52′E) and its surroundings in northern Jutland, Denmark (Fig. 1). The study area is comprised of a mosaic landscape including deeper offshore areas, shallow bays, extensive mudflats, saltmarshes and agricultural fields, and embraces some of the nationally most important *Zostera* beds, salt marshes and wet meadows in Denmark. The range of the tidal amplitude is limited to only 10–20 cm, and the effect of fluctuations in water level on availability of aquatic habitats is therefore regulated mainly by local wind patterns (Clausen, 2000; Wiles et al., 2006). The Limfjord has long been recognised as an internationally important staging area and nationally important breeding area for several species of waterfowl and a few waders throughout the annual cycle (Joensen, 1974; Laursen et al., 1997; Meltofte, 1997; Grell, 1998, Appendix A). The importance of the lagoon and its immediate surroundings as waterbird habitat is reflected through its extensive protection under EU legislation. This includes 15 Special Protection Areas (SPAs) under the EU Birds Directive, which have been designated for 41 species of birds associated with coastal habitats, and with a total of 146 designations (65 for breeding birds and 81 for staging and/or wintering birds, as some species are listed for several of the 15 SPAs; Appendix A). Most of these SPAs and a few other areas within the Limfjord have also been designated as Special Areas of Conservation (SACs) under the EU Habitats Directive, with the aim to promote conservation and protection of e.g. saltmarsh and mudflat habitats, natterjack toad *Bufo calamita* and harbour seal *Phoca vitulina* populations in the lagoon.

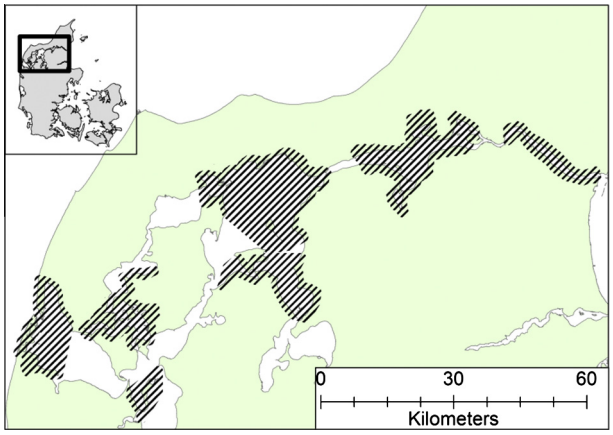

Fig. 1. Study area showing coastal areas (hatched) in the Danish Limfjord covered by the analysis of habitat availability. Areas were chosen because of their importance to the light-bellied brent goose *Branta bernicla hrota*.

2.2. Focal species

The coastal habitats dealt with in this study support a large number of waterfowl, waders, terns, grebes and coots, many of which can be expected to experience altered habitat availability due to climate change. The Limfjord in particular is an internationally important staging area to seven species of passing or wintering herbivorous waterbirds, supporting substantial numbers of light-bellied brent geese *Branta bernicla hrota* (95.7–100.0% of total flyway population), whooper swans *Cygnus cygnus* (6.0–8.5% of total flyway population), bewick's swans *Cygnus columbianus bewickii* (2.0–8.8% of total flyway population), northern pintails *Anas acuta* (3.5–4.2% of total flyway population), e*urasian* wigeons *Anas Penelope* (1.5–3.5% of total flyway population), mute swans *Cygnus olor* (1.6–2.1% of total flyway population) and common coots *Fulica atra* (0.8% of total flyway population, Appendix A). Recognising the importance of this area to herbivorous waterbirds, this group and associated habitats were used as the focus of the current study. All seven species feed on submerged macrophytes, algal beds and halophyte plants in the fjord and its surrounding areas, supplemented with different proportions of agricultural habitat use. Whenever ecological knowledge was necessary to aid the identification and outline of relevant herbivorous waterbird habitats (e.g. vertical reach in aquatic areas) we used the well-studied population of East Atlantic light-bellied brent geese to guide decisions. We chose this species because it has the highest conservation concern of the seven internationally important species involved, its ecology has been thoroughly studied, and it has an intermediate