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Evaluating the coastal environment for marine birds

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Abstract. The marine environment is being increasingly exploited by fisheries and the oil and gas industry. Conservationists urgently need the ability to identify the processes that determine patterns of abundance of marine species. We describe a preliminary Geographic Information System (GIS) in which spatial data on environmental variables (seabird colony locations, sea depth and seabed sediments) are integrated with realistic energy constraints faced by marine birds during the breeding season. A simple foraging model predicts the spatial variation in the quality of given locations as potential feeding sites under different feeding conditions and stages of the breeding cycle. We show how the approach can be used to help managers identify key marine areas and assess the impacts of environmental change or damage.

Keywords: Firth of Forth; Firth of Tay; *Phalacrocorax*; Sandeel; Seabed; Seabird; Sediment; Shag; Telemetry.

Introduction

With the increasing exploitation of Scottish waters both for fisheries and oil and gas production, the pressure on marine communities has intensified. From a conservation point of view the need to identify the factors and processes that determine patterns of abundance in marine species has never been more critical. In this paper we use a Geographical Information System (GIS) to integrate the results of recent studies on seabird feeding behaviour, collected using radio telemetry techniques, with spatial information on three environmental variables: namely, distance from the breeding colony, water depth and seabed sediments. In any given area this approach allows us to investigate how environmental characteristics potentially influence the feeding performance of marine species under varying levels of prey availability (Wanless et al. 1998).

The species we selected as a model was the European shag, *Phalacrocorax aristotelis*, which is an important avian predator in the inshore marine community. It is endemic to the northeast Atlantic and Mediterranean and more than 20% of the world population breeds in Britain and Ireland (Lloyd et al. 1991). The shag is a foot-propelled pursuit diver, that relies heavily on the lesser sandeel *Ammodytes marinus* as a food supply (Harris & Wanless 1991). It is predominantly a benthic feeder (Wanless et al. 1991a; but see Grémillet et al. 1998). In a recent paper we have described the development of this integrated approach in detail (Wanless et al. 1998), our aim here is to demonstrate the potential of the technique as a management tool in coastal systems. Specifically we show how it can be used to: (1) help delineate marine Special Protected Areas (SPAs) (2) assess the potential impact of an oil spill; and (3) estimate the effects of a reduction in food availability, such as might be brought about by overfishing.

Study area

To demonstrate the GIS approach we selected a study area that encompassed the Firths of Forth and Tay in Southeast Scotland (Fig. 1), an area which holds important concentrations of shags. The main breeding location is on the Isle of May, with smaller colonies on many of other islands in the Firth of Forth (Joint Nature Conservation Committee/Seabird Group Seabird Colony Register). From a management point of view the area is of particular interest because of its proximity to both the major sandeel fishing grounds centred on the Wee Bankie (ca. 30 km east of the Isle of May) and the high level of tanker traffic en route to and from the refinery at Grangemouth further up the Forth estuary. Information on the bathymetry and seabed sediments for the area was obtained from British Geological Survey maps (Anon. 1986). These data, together with those on the sizes and locations of seabird breeding colonies, were digitized and stored in a GIS. The bathymetry (bands of 0 - 10, 11 - 20, 21 - 30 m etc.) and sediment type polygons (Fig. 2) were intersected and then superimposed on a 1 km × 1 km grid of the area to produce small (< 1 km^2) polygons of known depth, sediment type and location. The physical environment of the area was relatively complex with a variety of sediment types and water depths generally being < 60 m.

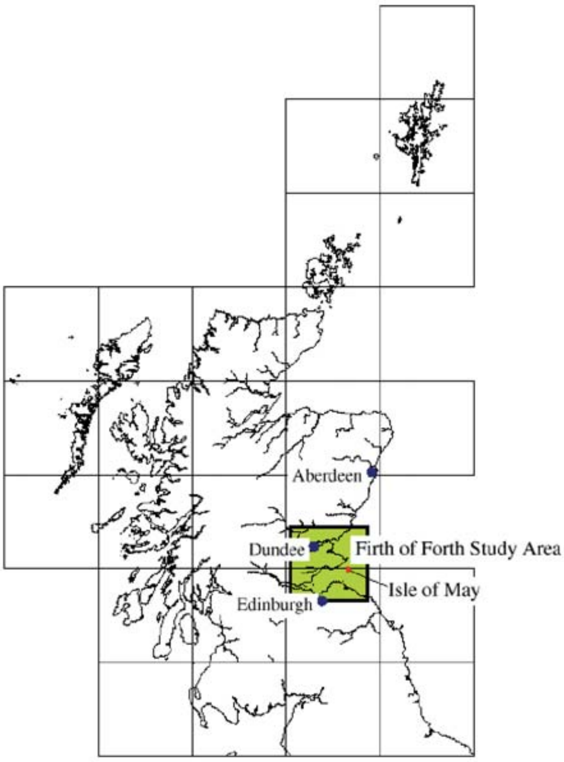

Fig. 1. The location of the Firth of Forth study area on the east coast of Scotland.

The foraging model

Full details of the model are given in Wanless et al. (1998). Unlike many marine birds the plumage of shags is not fully waterproof, and after feeding they must return to the coast to dry their feathers. In the nesting season this requires breeding adults to return to the colony to attend the eggs or chicks. Thus a fundamental environmental constraint is the distance of a feeding location from a breeding colony and hence the time costs incurred by a bird in flying to and from the feeding area. The average flight speed of a shag is 13.2 $m.sec^{-1}$ (Pennycuick 1987). Birds typically make one feeding trip per day during incubation, whilst during chick rearing the modal number is three per day (Wanless & Harris 1992). One adult is always present at the nest, and nest duties are shared fairly equally, so each bird has only a maximum of half the daylight hours for foraging (ca. 7 to 8 h each in summer at this latitude).

The second basic constraint is depth of water at each potential feeding location. We used the bathymetry data in the GIS together with an equation relating diving efficiency – the proportion of the total dive cycle spent foraging on the seabed during the 'bottom' phase of each dive (bottom-time) – and dive depth (Wanless et al. 1997) to estimate the predicted diving efficiency of a shag for any given polygon in the study area. Results from the model indicated that most of the area was potentially suitable feeding habitat for shags. Because diving efficiency declined with depth and depth changes with distance from the coast, polygons with the highest diving efficiency were located close inshore, while offshore areas tended to have relatively low efficiencies.

The third stage of the model development was to incorporate information on the likely distribution of potential food for shags. This was based on the observation that shags feed predominantly on lesser sandeels (Harris & Wanless 1991) and that the most important factor influencing the distribution of these fish is the seabed substrate: sandeels are more likely to be found in sandy sediments (Reay 1986). Accordingly, we used GIS to select out areas where the seabed sediments were classified as sand or gravelly sand, as a first approximation to potentially suitable feeding areas for shags. Suitable habitat was defined as having a sand to mud ratio of greater than 9 : 1, containing less than 30% gravel, and having particle sizes varying from 625 μm-2 μm (Anon. 1994). The Firths of Forth and Tay contain large areas of sandy sediments and there was no evidence that such sediments were associated with any particular depth bands. Predicted diving efficiencies within potentially suitable feeding habitats were highest in the inner Firth of Forth and around the entrance to the Tay estuary.

Total daily energy requirements of shags were estimated from the basal metabolic rate (BMR = 739 $kJ.d^{-1}$; Bryant & Furness 1995) and a field metabolic rate equivalent to 3 × BMR during incubation and 4 × BMR for an adult provisioning a brood of three chicks at the time of their peak energy demand. Peak daily metabolized energy for a chick was estimated from equations given in Weathers (1992). Assimilation efficiency was set at 0.85 (Dunn 1975) and the energy density of one group sandeels was taken to be 6.7 $kJ.d^{-1}$ (Hislop et al. 1991). Thus during incubation we estimated that a shag had an average daily requirement of 389 g of sandeels and an adult provisioning three chicks required 920 $g.d^{-1}$. To estimate the time needed to meet these energy demands we also needed information on typical feeding rates of shags. Such data are difficult to obtain but results from recent work on the Isle of May suggest that, on average, an adult shag feeding on one group (fish hatched in the previous calendar year, typically more than 10 cm in length) sandeels over a sandy substrate obtains 0.2 $g.sec^{-1}$ of bottom-time foraging (max 0.6 g sec^{-1} foraging, Wanless et al. 1998).

Having described the energetic and environmental parameters used to estimate the daily feeding times of a marine bird, we now demonstrate how such an approach can provide a useful tool for coastal zone management.

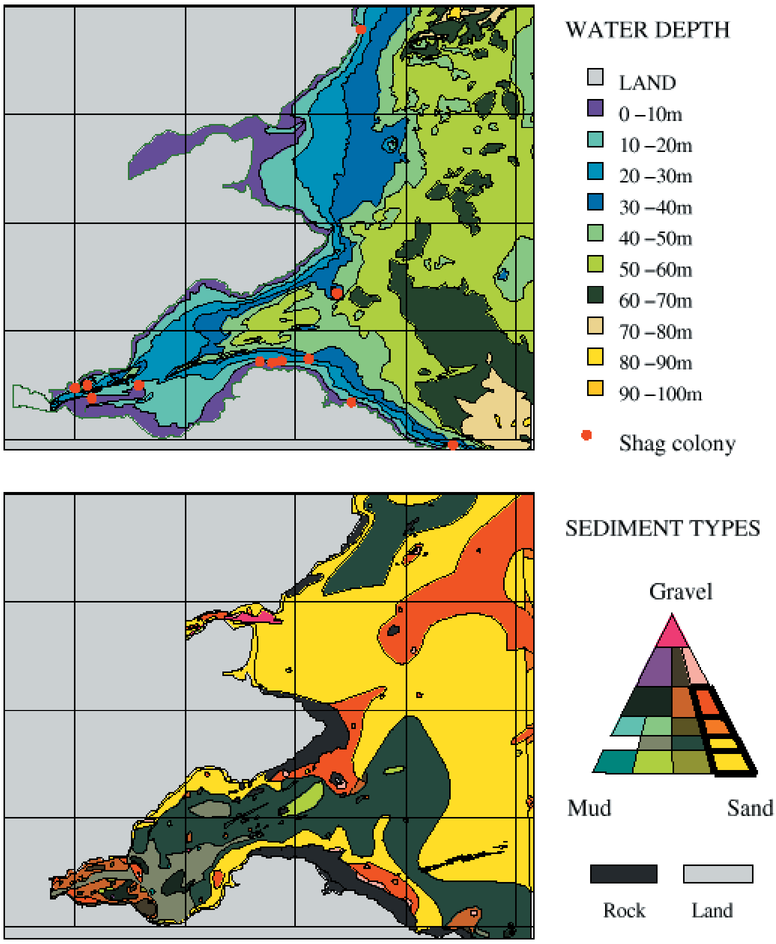

Fig. 2. Sea depths and seabed sediment types in the Firth of Forth. Data reproduced with permission of the British Geological Survey and the UK Hydrographic Office. In the key for the sediment types, the apex of the triangle represents gravel, the left hand side of the base mud, and the right hand side of the base sand: the thick black border at the bottom right of the triangle denotes those sediments considered suitable for sandeels.

We consider three management aspects: (1) the identification of sea areas important to marine birds at particular colonies; (2) possible indirect effects of oil pollution; (3) potential consequences of reduced stocks of prey species.

Identification of sea areas of importance to marine birds

With the introduction of the EC Habitats and Species Directive there is an increasing requirement for the UK to give legal protection to marine wildlife and marine habitats. The EC Directive calls for the establishment of a European network of protected areas to be made up of Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) (as defined in the Wild Birds Directive). In the context of identifying key marine areas, information on the distribution of seabirds at sea can be used to identify areas that appear to be consistently important (Carter et al. 1993; Skov et al. 1995). However, the use of a GIS-based modelling approach can not only indicate which sea areas are likely to be important but can also be used to explore the consequences of changing patterns of human activity and management on marine species. Fig. 3a shows the spatial pattern of predicted daily feeding times for shags breeding on the Isle of May, a National Nature Reserve (NNR), firstly during incubation and secondly during chick rearing under average feeding conditions. An SPA centred on the Isle of May would clearly be inappropriate for shags: most of the favourable (< 3h) foraging areas are inshore of the island while almost all the sea further off-shore is either unsuitable feeding habitat or has an estimated foraging time of more than 8h. Assessment of the extent and location of suitable feeding habitat is also greatly altered by the stage of the nesting cycle. Fig. 3a contrasts the low-demands of the incubation period with the higher demands of chick rearing. The extensive areas requiring less than 3 h feeding during incubation disappear completely during chick rearing, when no area has a predicted feeding time of less than 5 h.

The system can also be used to contrast the importance of sea areas with regard to a single colony (protect the nature reserve) compared with their importance to

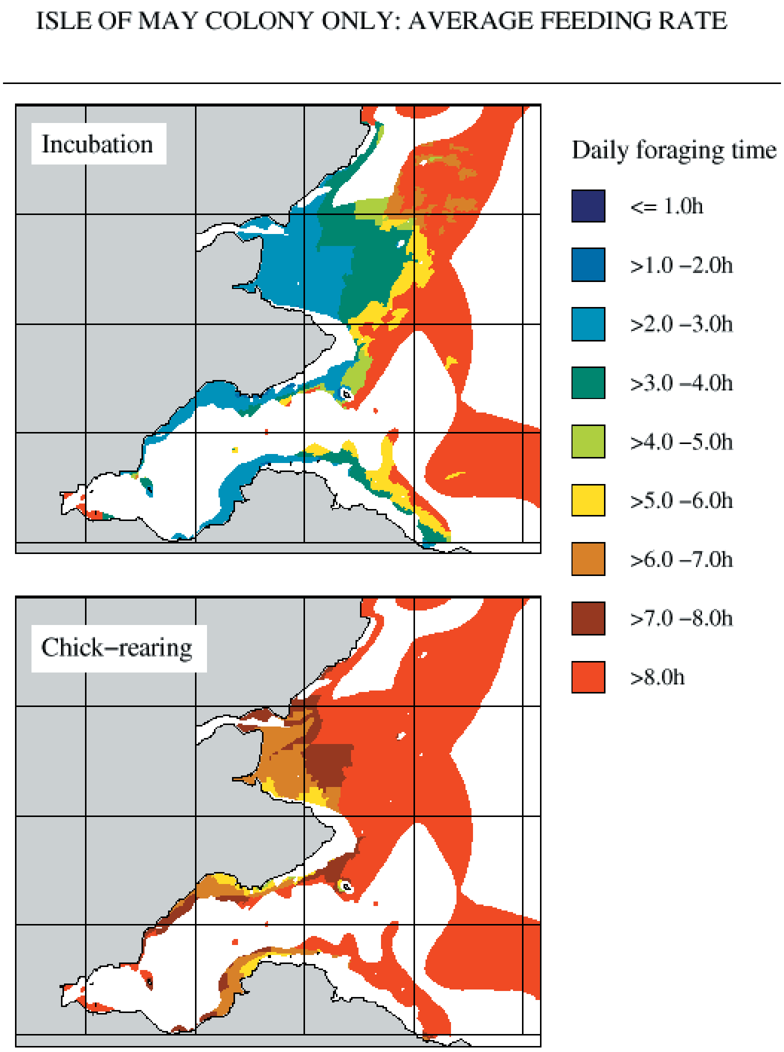

Fig. 3a. Estimated total daily feeding times for shags, *Phalacrocorax aristotelis*, breeding only on the Isle of May to feed anywhere in the area shown. The feeding costs are given in hourly bands from 1 to 8 and above 8, and shaded. The time calculations assume an average prey-capture rate of 0.2 g of fish per sec foraging time on the bottom, and are given for two phases of the breeding cycle: incubation (top) and chick-rearing (bottom).

shags at all the colonies in a region (protect the regional seabird community). The energetic calculations of Fig. 3a are based on flight costs to the Isle of May NNR only, although there are some other shag colonies in the Firth of Forth. Fig. 3b uses flight distance energetic data from each sea-polygon to the nearest colony. The shores of the Firth of Tay and the northern shore of the Forth do not have shag colonies (due to a lack of suitable cliffs), so the main changes in this region are along the southern shore of the Firth of Forth and in Largo Bay on its northern shore. Here, during chick rearing, appreciable areas that would require 6 to > 8 h feeding trips by shags from the Isle of May can be exploited in only 3 to 6 h by shags from other colonies. In other circumstances, where colonies were more widely distributed, the effects could be more extreme.

Indirect effects of a notional oil spill

We envisage a notional accident where an oil-spill occurs near Fife Ness (the eastern promontory between the Firths of Forth and Tay), and is moved along the northern shore of the Firth of Forth by wind and currents (Fig. 4). We assume that dispersed oil affecting the seabed and its fauna makes the 'slick zone' appreciably less suitable for shags to feed in during the chick rearing season: we emphasize that this is an illustrative example only. Current information on the likely effects of oil on coastal marine fish do show toxic and pathological effects, but are rather unclear about effects on fish densities (e.g. Anon. 1993). The inset of Fig. 4 shows the affected slick zone and its daily foraging time cost bands for feeding shags, while Table 1 lists the areas of the various time-cost bands affected, and their proportions of the total areas of those same time-cost

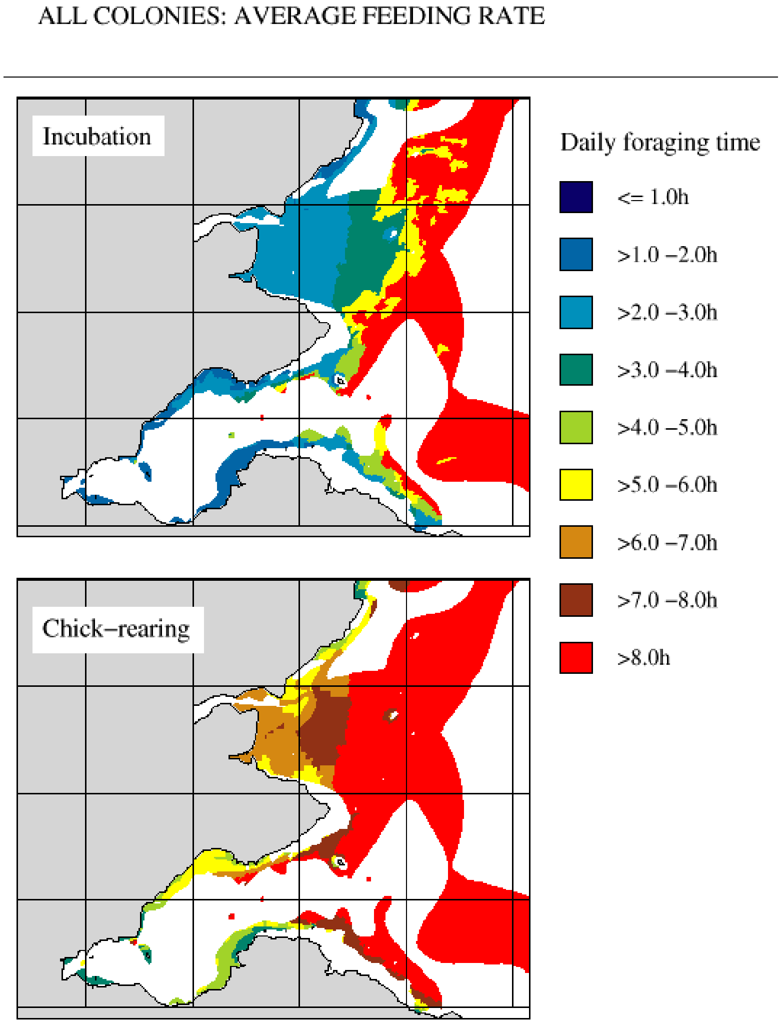

Fig. 3b. As for **a**, but with the travel costs to and from each part of the sea area now referred to the nearest shag colony, which is not always the Isle of May.

bands available to shags on the Isle of May, which is the nearest colony. Thus a simple program in the GIS system allows an actual, or potential slick's impact area to be assessed in relation to its likely impact on the chick-rearing of nearby colonies. In circumstances where shags from several colonies might concentrate in a small area (sand over shallow water) the effects of a small oil spill in the 'wrong' area could be dramatic and widespread, and such GIS approaches could identify such important areas in advance.

Notional effects of reduced food supply

During the shag breeding season sandeels migrate inshore from the deeper waters of the North Sea into shallower regions that are more profitable for shags to exploit (Wright 1996). Natural variation in the numbers and timing of these movements will presumably result in widely differing prey-capture rates for shags breeding at the Isle of May both within and between years. Following Wanless et al. (1998) we illustrate the effects of a plausible range of feeding rates on predicted daily feeding times. The top map in Fig. 5 corresponds to a prey capture rate of 0.1 $g.sec^{-1}$ (mass of prey captured per second of bottom-time spent foraging), typical of conditions for a year of poor food supply; the bottom map represents favourable conditions, for a prey capture rate of 0.6 $g.sec^{-1}$. These may be compared to the average conditions for chick rearing, which are illustrated as the lower map of Fig. 3b. The contrast between the situations of Fig. 5 is dramatic. At the high capture rate around half the area can be successfully exploited for under five hours total foraging effort per bird per day: at the low capture rate nowhere can be exploited successfully for less than six

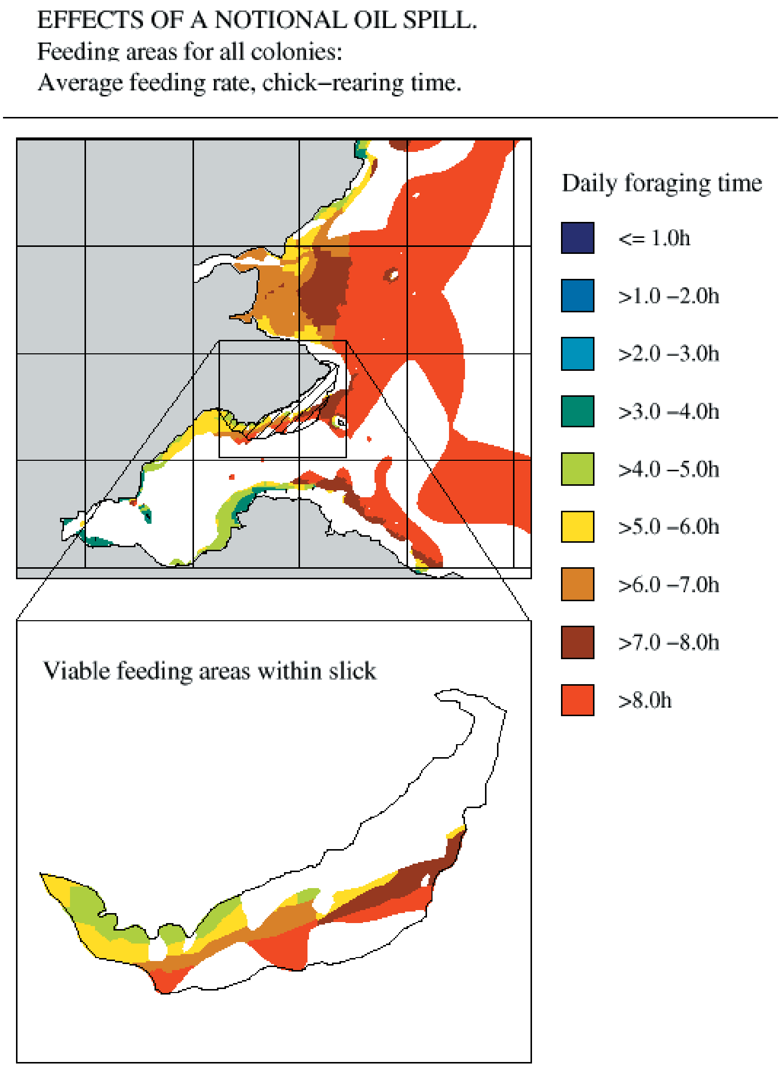

Fig. 4. Effects of a notional oil-spill on feeding areas available to shags. The top map represents feeding costs (for all colonies, see Fig. 3b), for average prey-capture rates during chick rearing, and shows the location effects of the notional oil-slick. The inset shows details of the feeding zones within the notional slick area. See Table 1 for the areas involved when the Isle of May is the nearest colony.

hours per day, and over 90% of the area readily exploited (< 5 h) at the high feeding rate has become unexploitable (requiring > 8 h).

These results should be considered in the context of the recent commercial exploitation of sandeels on the Wee Bankie (Anon. 1995), and the possibility that overfishing could reduce the capture rates of shags below those used here, perhaps resulting in much of the Firth of Forth becoming much less suitable as a feeding habitat able to support shags rearing a normal sized brood.

Table 1. Different foraging efficiency (time costs) bands for shags, *Phalacrocorax aristotelis*, showing the total areas in those bands available to shags breeding at the Isle of May, the total areas lost to a notional oil slick (see Fig. 4) and the percentage of area in the time band lost. Areas (ha) with respect to Isle of May shags.

Areas (ha) with respect to Isle of May shags			
Time class	Total May area	Slick area	% May area lost
< 1	0	0	0
> 1 - 2	0	0	0
> 2 - 3	54	0	0
> 3 - 4	3 040	0	0
> 4 - 5	7 299	811	11
> 5 - 6	11 189	959	8
> 6 - 7	17 870	607	3
> 7 - 8	17 820	614	3
> 8	127 569	819	1

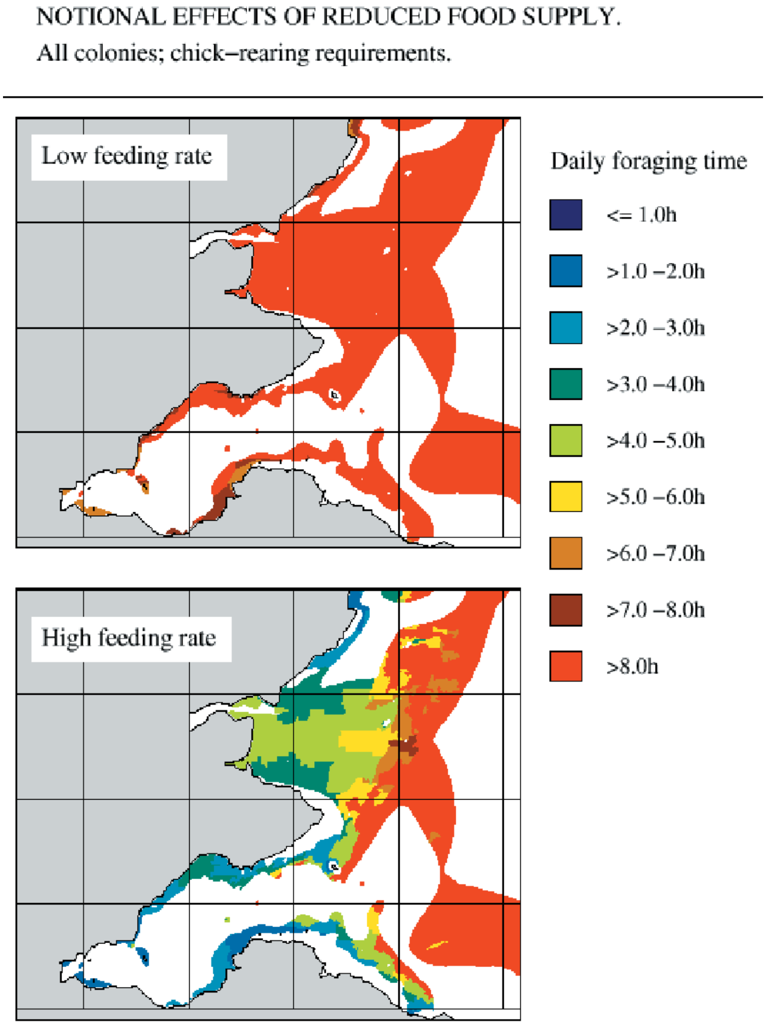

Fig. 5. Notional effects of reduced food supply. Estimated total daily foraging times for breeding shags during the peak energy demands of chick-rearing. The top map assumes a prey capture rate of 0.1 $g.sec^{-1}$ of fish foraging time on the bottom, the bottom a capture rate of 0.6 $g.sec^{-1}$. See Fig. 3b (lower) for average rate of 0.2 $g.sec^{-1}$.

Discussion

Surveys 'at sea' of fish and seabirds are difficult, expensive and often confined to small areas. Our contribution illustrates how crucial ecological data on feeding behaviour can be integrated with simple but extensive GIS data on the marine environment to predict those areas most likely to be important for supporting shag populations. We discussed elsewhere (Wanless et al. 1998) how these predictions could be checked against seabird survey data, and the problems introduced by census counts that include non-breeding shags that are not confined to colonies but can return elsewhere on the coast after feeding.

We have used the shag to illustrate this approach, as its bottom-feeding habits facilitate estimating the constraints on its feeding. However, collaborative work in progress as part of a European Union funded study of the effects of large industrial fisheries on non-target species aims to examine in detail the feeding behaviour of mid-water and surface feeding seabirds, particularly the common guillemot (*Uria aalge*) and black-legged kittiwake (*Rissa tridactyla*), as well as the spatio-temporal distribution (including the diurnal vertical distribution in the water-column) of the fish shoals on which they feed. Given such data, similar simple models may allow us to identify other areas of the sea likely to be of particular importance to other top avian predators.

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