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Quantifying the relative use of coastal waters by breeding terns: towards effective tools for planning & assessing the ornithological impact of offshore wind farms

Final report


© Martin Perrow

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Executive Summary

Introduction

The potential impact of the development of offshore wind farms (OWFs) upon seabird populations is a key issue within the current debate on sustainable energy provision. Terns, (*Sterna* spp. and *Sternula albifrons*), especially when on their breeding grounds, have emerged as sensitive receptors in many consented and planned OWF projects. To date, information on the interaction of terns with OWFs has remained scant due to a lack of understanding of the foraging ecology of terns especially at specific sites and the inability of standard assessment tools to define the relative use of specific areas by foraging terns

Aims & methods

The current project aimed to advance the use of a series of methodological and assessment tools, some of which were initially developed in the Greater Wash SEA area (funded by Centrica/AMEC) with others developed specifically in this project. In essence, this involved a move towards an individual-based approach.

Techniques included: 1) the development of visual tracking of foraging birds from colonies using a high-powered rigid-hulled inflatable boat (RIB – Fig. A), 2) use of both observation at colonies and boat-based colony transects immediately offshore of a colony to estimate flight bearing and passage rate of outbound and inbound birds, 3) development of individual-based simulation modelling to determine foraging patterns of birds derived from flight bearing and distance relationships, 4) detailed observation of type and rate of provisions delivered to chicks, 5) development of a energy balance model to predict the optimality of different provisioning strategies for both chicks and adults and how far adults could travel from colonies in energetic terms and 6) the use of data generated by visual tracking in collision risk modelling.

Figure A. Visual tracking of terns from a rigid-hulled inflatable boat was developed as an alternative to telemetry as a combination of low body weight and wide-ranging behaviour coupled with body immersion when foraging may make terns unsuitable for tagging.

Work was undertaken over two breeding seasons (2008 and 2009). In the curtailed 2008 season, work was undertaken at Blakeney Point in North Norfolk, part of the North Norfolk Coast SPA in which both Sandwich *Sterna sandvicensis* and Common Terns *S. hirundo* are designated as qualifying species. Both species feature as sensitive receptors in offshore wind farm developments in the Greater Wash encompassing North Norfolk and Lincolnshire, with Appropriate Assessment (AA) being triggered in a number of cases for Sandwich Tern. Comparative tracking of Sandwich Tern (*n*=26) the focus of previous studies, and, for the first time, Common Tern (*n*=25), was conducted.

In 2009, more extensive tracking throughout the breeding season was undertaken on Sandwich Tern (total *n*=194 with *n*=85 extensive tracks) at Cemlyn Bay, part of the Ynys Feurig, Cemlyn Bay and Skerries SPA on Anglesey in North Wales. A trial of tracking was also undertaken on a small number of Arctic Terns *S. paradisaea* (*n*=7) originating from the Skerries. Finally, in North East England, a relatively large number (*n*=107) of Common Terns were tracked from RSPB Saltholme on Teesside

Results & Discussion

Notwithstanding some potential limitations, especially in relation to quantifying the extent of larger scale movements, non-intrusive visual tracking provided unparalleled insights into the foraging distribution, behaviour and foraging activity of breeding terns at sea. Coupled with additional observations at colonies, a number of hitherto poorly described general themes of tern foraging ecology were revealed.

Contrary to previous dietary studies based on chick provisioning, both Sandwich and Common Terns were recorded feeding on invertebrates, with these invariably being consumed by the self-feeding adult at sea. Other very small items such as larval fish were also taken (Fig. B). Otherwise, provisions to chicks tended to be dominated by a small number of fish species, principally clupeids (Herring *Clupea harengus*/Sprat *Sprattus sprattus*) and sandeels (*Ammodytes* spp. and *Hyperoplus* – Fig. C) in line with many other seabird species breeding in the British Isles. Some local variation in the minor contribution of other species was also noted.

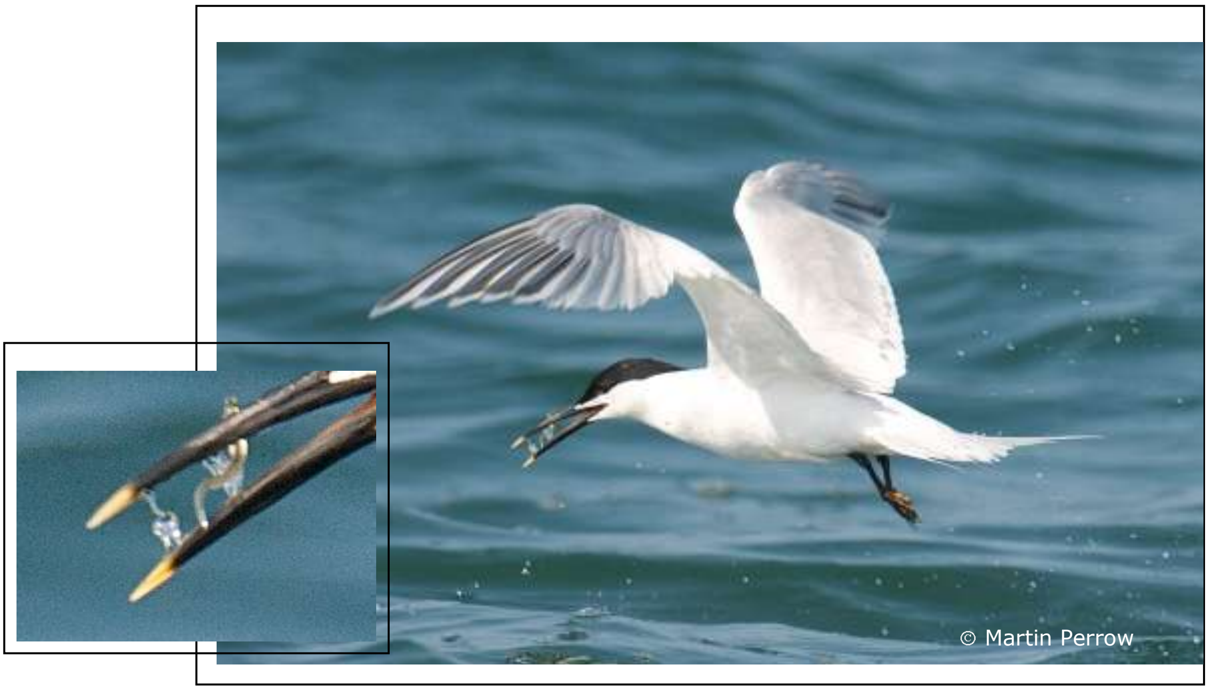

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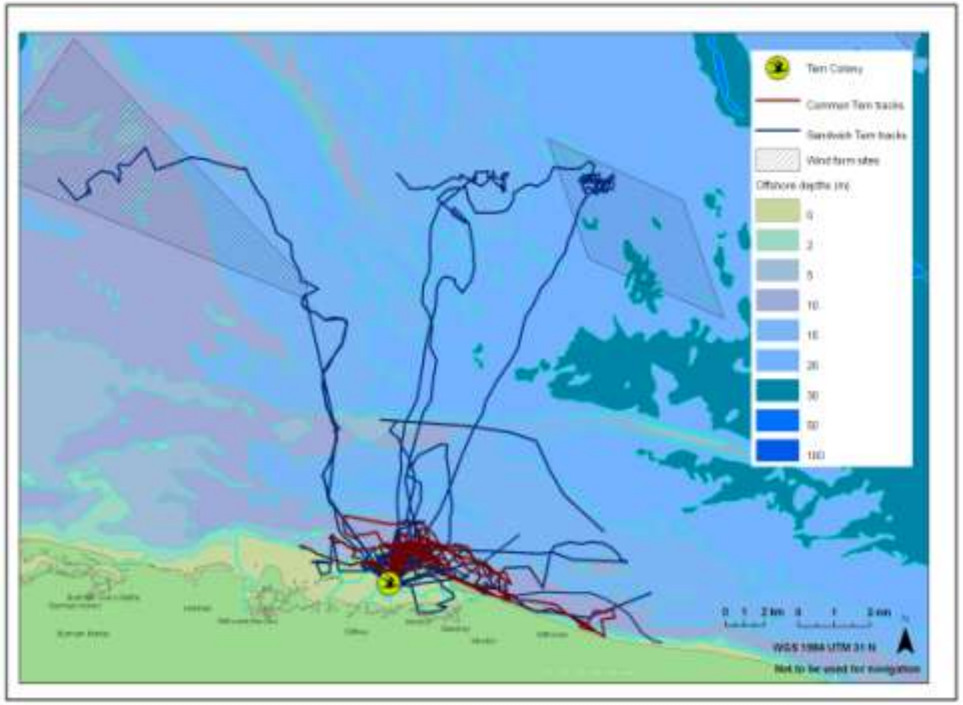
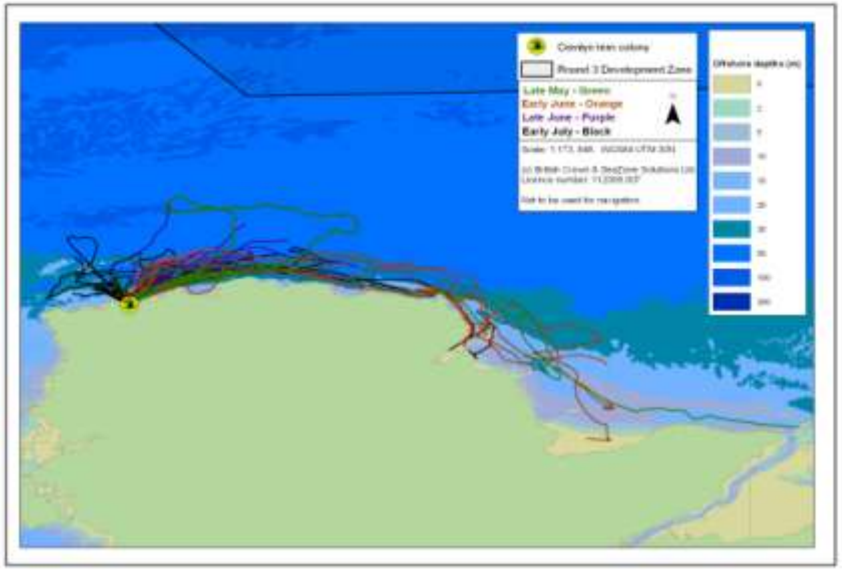
Figure B. Tracked Sandwich Tern from the Cemlyn Bay colony capturing a larval fish (inset).

Figure C. Tracked Common Tern at Teesside returning to the Saltholme colony with a large sandeel. Such large prey items were not recorded being taken by Common Terns from Blakeney Point, although they were typical prey of Sandwich Terns nesting close by.

A direct comparison of Sandwich and Common Terns at Blakeney Point in North Norfolk, revealed clear differences in foraging pattern and behaviour between the two species. Common Tern exploited a more diverse range of small prey items in inshore waters never travelling more than 2 km offshore but up to ~9 km from the colony parallel with the coast, whilst Sandwich Tern reached a maximum of 22 km (less than the previously recorded maxima of ~53 km) offshore whilst targeting larger prey (Fig. D). At Cemlyn Bay, where Sandwich Tern also shared breeding habitat with Common and Arctic Terns, it exhibited similar range to birds in North Norfolk, being tracked to 40 km from the colony, although never more than 8 km offshore (Fig. B). At Teesside, in complete contrast to the patterns in North Norfolk, Common Tern behaved much more like Sandwich Tern, travelling over 6 km from the inland colony at RSPB Saltholme before even reaching the estuary. At sea, the longest movements were up to nearly 10 km offshore and 14 km along the coast (Fig. D).

The observed patterns were tentatively suggestive of niche differentiation between sympatrically nesting terns. In the absence of breeding Sandwich Tern on Teesside individual Common Terns appeared to exploit the prey base that would otherwise be utilised by their larger congener (Fig. C). Whilst the mean prey delivery rate for Common Tern at Saltholme (0.52 feeds hr^{-1} ± 0.32 s.d.) was markedly lower than that recorded at Blakeney Point (1.54 feeds hr^{-1} ± 1.04 s.d.), the larger mean size of prey items including over >20 cm in length, meant that the estimated energy delivery rate was significantly higher (16.14 KJ hr^{-1} ± 13.07 s.d at Saltholme, 5.85 KJ hr^{-1} ± 4.54 s.d. at Blakeney Point). These findings highlight the extreme plasticity in foraging and provisioning strategy shown by Common Terns. The stark differences in prey selection between colonies indicate the danger in drawing generalised conclusions on tern foraging tactics from studies conducted at small numbers of sites, given the huge potential for spatial (local or regional) and temporal variation.





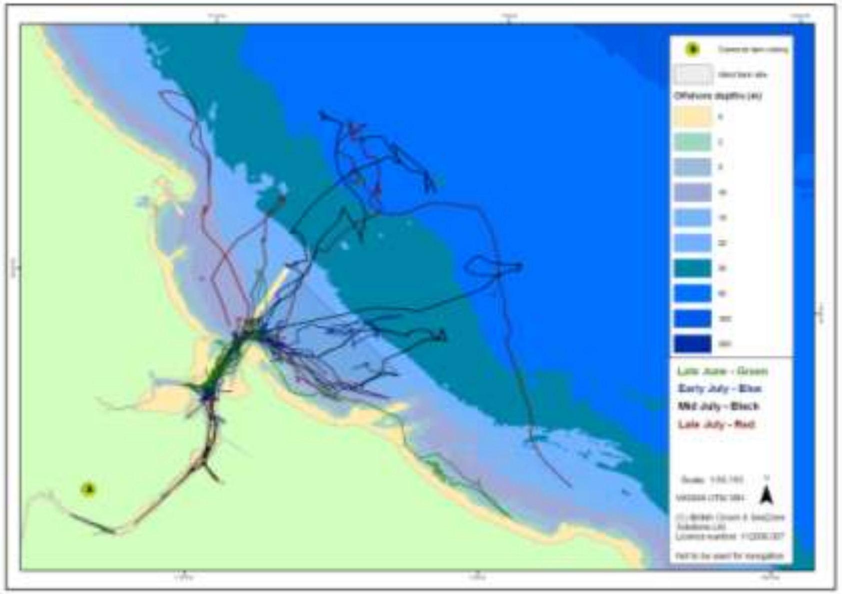


Figure D. Tracks of terns from colonies in relation to offshore wind farms: Sandwich and Common Terns from Blakeney Point in North Norfolk (above), Sandwich Terns from Cemlyn Bay on Anglesey (top right) and Common Terns from Saltholme on Teesside (below right).

Energy balance modelling was undertaken specifically on Sandwich Tern in both North Norfolk (using pooled data from 2006-2008) and Cemlyn Bay (using data gathered in 2009). Data on prey capture rates taken during tracking combined with energy content estimates derived from previous research, allowed the development of models that predicted the optimality of different provisioning strategies for both chicks and adults. These predictions correlated closely with observed patterns of prey size provisions (i.e. modes of 6 cm or 9 cm in length) made during colony observation, suggesting that Sandwich Tern provisioning behaviour could be meaningfully predicted using data gathered at sea during visual tracking. Model outputs suggested that variation in size selection strategy was related to the outcome of a trade-off between chick provisioning and adult energy balance. In simple terms, travelling further and for longer whilst accumulating energy, is to the advantage of self-feeding adults but to the potential disadvantage of a chick requiring a defined energy daily intake to grow at an optimal rate.

Fundamentally, the utility of the models was underpinned by the close relationship between prey item size and capture rate (Fig. E). In all prey species, patterns conformed strongly to the prediction that capture rate would decrease in relation to item size, such that larger prey items required longer foraging search times. The minimum size of item that an individual selected for provisioning could therefore be used to predict the likely time spent searching on each foraging bout. Given the generally linear nature of Sandwich Tern foraging flightpaths in North Norfolk, this search time could be used as a reliable predictor of the distance from shore likely to be reached on each foraging bout. As such, it was possible to model at-sea foraging range as a function of the minimum size selection threshold adopted by any given individual tern.

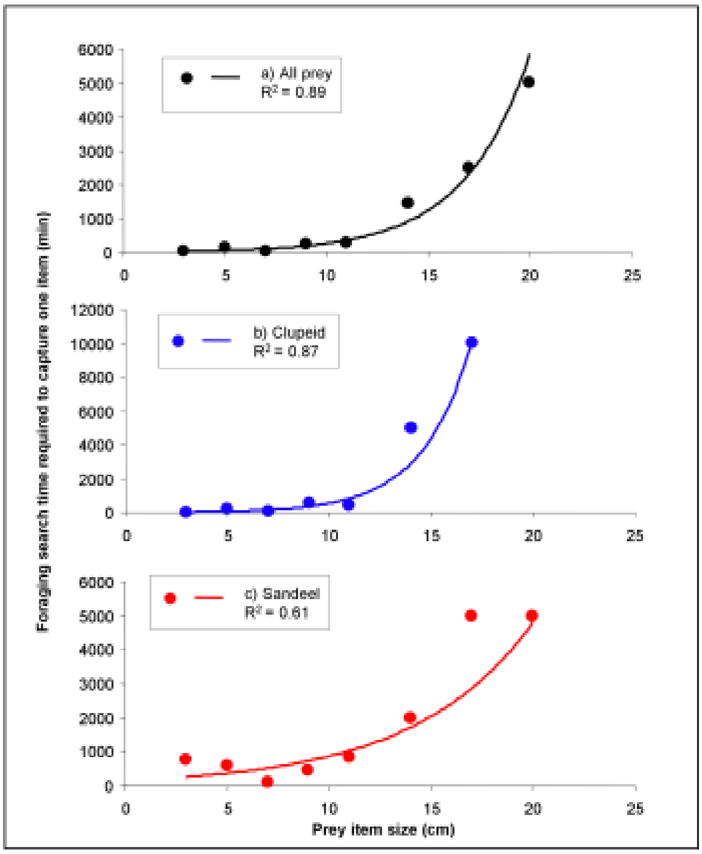


Figure E. Relationship between prey item size and capture rate per hour foraging for Sandwich Terns from North Norfolk colonies, for the principal prey types and all prey combined. Points represent midpoints of continuous size bins of varying width. Lines show exponential functions, together with their respective Pearson R^2 statistics. Capture rates were observed during 55.6 hours of tracking of Sandwich Terns at sea from North Norfolk colonies between 2006 and 2008 combining date from this and previous studies (Centrica Energy 2008, 2009).

The likely offshore foraging range of individuals adopting optimal thresholds was predicted to be 7–36 km, broadly matching the offshore distances recorded during visual tracking (Fig. F). Virtually all the OWFs in the Greater Wash fall within the upper limit of this range. Modelling also illustrated that at-sea foraging range was likely to be dependent on several factors, including prey abundance (of all prey sizes in proportion). A 25% reduction in prey abundance from 'normal levels' measured during model development reduced the distance that could be travelled by adult terns by around half to 9-19 km. With a reduction by 50%, adults could not maintain optimal chick growth rates at all, illustrating the sensitivity of breeding performance to prey abundance. Conversely, with a 50% increase in prey abundance, adults could range up to 74 km whilst still maintaining chick growth.

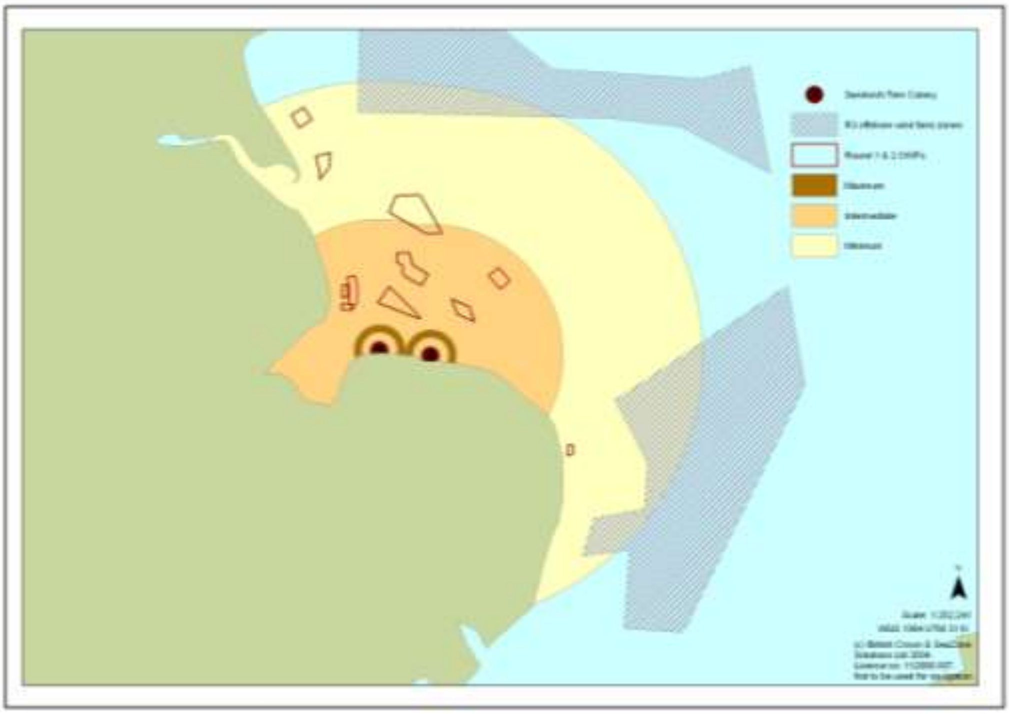


Figure F. Predicted foraging range of Sandwich Terns from the North Norfolk colonies at Scolt Head (west) and Blakeney Point (east) assuming the metabolic demands of adults and 90% of the minimum provisioning rate to chicks are met, at minimum, intermediate and maximum levels of kleptoparasitism.

Kleptoparasitism by Black-headed Gulls *Chroicocephalus ridibundus* on Sandwich Terns attempting to deliver prey to their chicks is prevalent at their shared colonies in North Norfolk (Fig. G). The relationship between kleptoparasite and victim is mediated by the relative disadvantage to the victim of selecting larger prey items to carry to chicks, given that kleptoparasites at the colony selectively target carriers of larger prey items.

Moreover, modelling of the attack rate, prey type and size and energy content of different prey supported the hypothesis that Black-headed Gulls in North Norfolk were able to differentiate between clupeids and sandeels, allowing them to optimise their kleptoparasitic strategy by always targeting items of equal energetic content with equal intensity. This was not the case at Cemlyn Bay where Black-headed Gulls and Sandwich Terns have only nested in sympatry for a few years. As a result, it was tempting to suggest that insufficient time has elapsed for learning and the development of individual 'specialist' kleptoparasites at this colony.

Assuming an prevailing 'intermediate' level of kleptoparasitism on Sandwich Terns within the colony, modelling demonstrated that the intensity of this food piracy also played a key role in determining the range of adult Sandwich Terns in the Greater Wash. At low levels of kleptoparasitism, the optimal trade-off between chick provisioning and adult energy balance could be achieved by adopting a relatively high size selection threshold, and consequently making fewer but longer foraging bouts. At high kleptoparasitism levels, the opposite was predicted, due in part to the increased risk of loss of large items, as well as the overall impact of prey loss on energy provisioning rates to chicks, meaning that adults would be required to trade-off their own energy balance in order to meet the minimum growth requirements of chicks. Adults were therefore predicted to adopt a lower minimum size selection threshold under a high intensity of kleptoparasitism, and thus make more frequent, but shorter (7-10 km) foraging trips.

Figure F. Black-headed Gull successfully stealing a clupeid from a Sandwich Tern returning to the colony at Blakeney Point in North Norfolk.

Modelling showed that Sandwich Tern was energetically capable of freely ranging across the entire area of the Greater Wash containing OWFs, unless prey abundance declined or the intensity of kleptoparasitism became too high. This was supported by evidence of long distance movements of individual birds (22 km offshore in this study and 53 km from previous studies). Whilst tracklines provide a guide to where birds may forage (i.e. two of the 26 Sandwich Terns tracked in this study ranged as far, and foraged within, two different OWF sites), the relative importance of different areas relative to OWFs could not be readily determined. This is a result of concern that a small sample size of birds tracked for long distances over long time periods (over 1.5 hours) cannot adequately represent large numbers of movements from a large colony. For example, passage rate observations estimated ~1.18 million flights were made from the 2,400 pairs of Sandwich Terns at the Blakeney colony in 2008.

The simulation modelling of foraging distribution developed in previous studies was therefore re-worked for data gathered in 2008 (Fig. H). In the model, each of n=15,000 individual simulated ‘birds’ was randomly allocated a flight direction from the range of possibilities observed during transect runs with the distance flown by each individual bird drawn from a leptokurtic bearing-specific statistical (Weibull) distribution. Bearing specific distance distributions were broadly guided by tracking data. Outputs of the model were ‘endpoints’, where the bird forages before returning to the colony (Fig. H) and ‘flyovers’ of birds passing through a particular OWF on their way to an endpoint at greater distance.

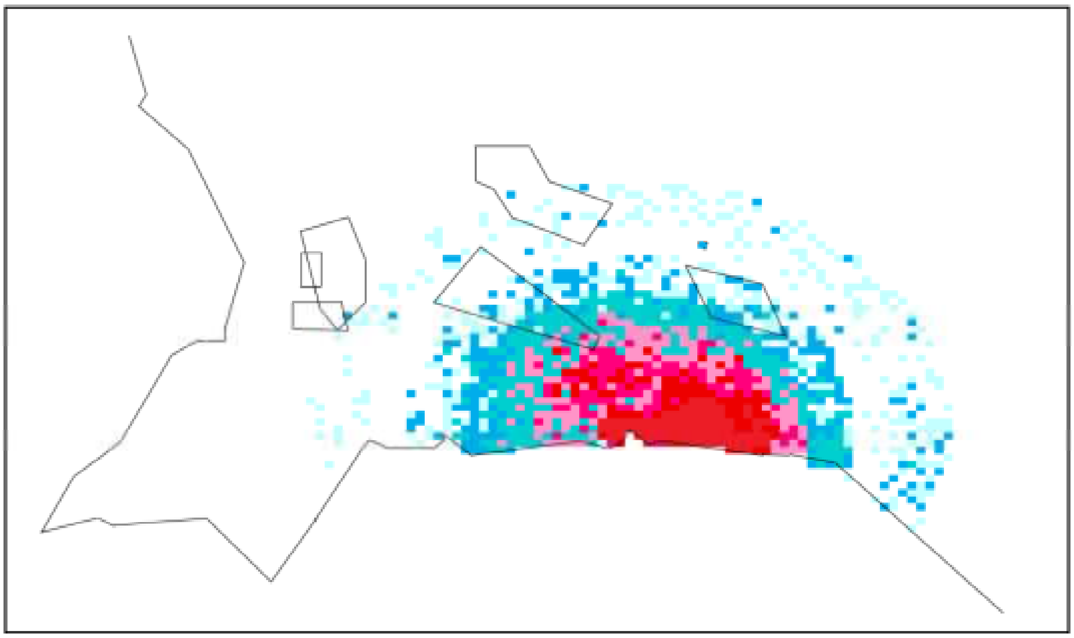


Figure H. Density map in 1km x 1km squares of 'end-point' foraging locations within the Greater Wash for Sandwich Terns originating from Blakeney Point in 2008, as derived from 15,000 simulated flights in the foraging model. Density increases through blue to green to pink and red. Polygons delimit proposed or completed wind farm sites within range of foraging terns on this occasion.

In 2008, the simulation model predicted relatively low usage of the OWFs by Sandwich Tern, with 2.8% of flights ending in foraging points in one site or another. Combined with predicted flyovers the total proportion of flights in which birds spent time in the sites was 3.4%, compared to 7.7% for tracked birds. Notably, modelling predicted 95% of simulated endpoints/flyovers would occur in the same two OWF sites (Docking Shoal and Sheringham Shoal) that were actually visited by tracked birds. Slightly lower usage predicted by the model compared to the use by tracked birds was thought likely to relate to the reduction in range observed in 2008 compared to previous years, which in turn may have been linked to tracking only being conducted later in the season.

Assuming an 'endpoint' represents a mean of 1 flight distance through an OWF (i.e. on average a foraging bird would reach half-way across a uniform site before returning) and a 'flyover' represents 2 flight distances (i.e. the bird crosses and returns on the same path) and knowing the actual flight distance across each OWF, the total length of all flights of all birds across an OWF over the course of the season was estimated. Combined with estimated annual collision mortality per km of flight for each OWF derived from previous collision risk modelling, data from the foraging model could be used to calculate collision risk. This was low at <6 birds per annum overall, invariably linked to the tendency towards shorter flights at the end of the season at Blakeney in 2008. Nevertheless, comparison with previous modelling data supported the view that the model may provide comparable estimates to that derived in boat-based surveys and could be of value in determining the relative risk of different OWFs for breeding birds.

A key factor in collision risk is the flight height of birds passing through OWFs. The proportion of time (49%) that tracked Sandwich Terns spent at >20 m flight height within the potential strike zone of turbines in the Greater Wash was considerably higher than that observed on boat-based surveys at any of the OWFs (up to 28%). The reason for this anomaly was difficult to reconcile particularly as Common Terns showed little evidence of a difference in flight height according to the different sampling methods (Figure G). Moreover, at Cemlyn, tracked Sandwich Terns spent a lower proportion of time at strike height (22%) more in line with boat-based surveys elsewhere, whilst Common Terns at Teeside spent twice the amount of time at strike risk height than they did in North Norfolk. These observations imply colony-specific patterns of behaviour, which in turn may depend on foraging strategy and type of prey. However, changes in behaviour near to the colony (e.g. perhaps avoiding kleptoparasites or predators), general behaviour (e.g. foraging or travelling) and wind speed and direction on the day of sampling, as well subtle bias between observers linked to the height of the survey platform, may all be at least partly responsible. Unless there is a convincing argument to adopt a specific flight height for a particular site during the assessment of wind farms, it is thought prudent to simply define a generic proportion of birds at risk height for use in collision risk modelling to allow direct comparison between sites.

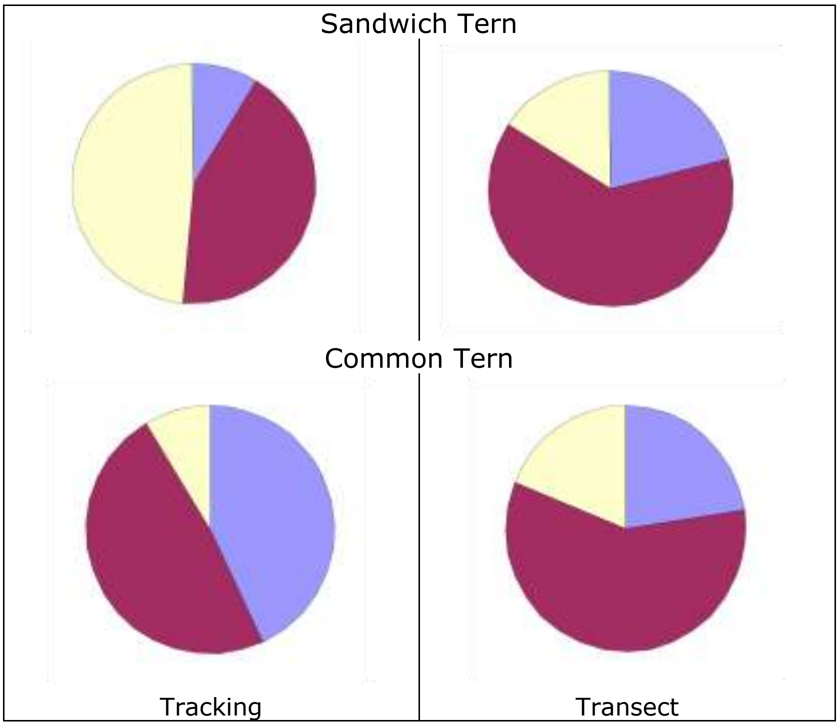


Figure G. Proportion of time Sandwich and Common Terns spent at different flight heights (<1m – blue, 1-20 - red and 20-120 m – beige) during tracking and as observed in boat-based transects near to the Blakeney colony in North Norfolk.

Conclusions & recommendations

The techniques developed in this study have considerable applicability at all stages of the planning and assessment process, both before and after the construction of offshore wind farms. Visual tracking for example, is a simple-to-undertake alternative to telemetry in particular circumstances, with scope to adapt to specific conditions (e.g. particular sea conditions or flight speed of different species) by use of different combinations of vessel type and size. As well as terns, the methodology is suitable for use on species such as gulls (Laridae) and skuas (*Stercorarius* sp.).

Taking into account the combination of tracking, modelling and records of birds from the aerial survey programme in the Greater Wash, a guide value for the range of Sandwich Terns is suggested to be 75 km, in line with previously suggested maxiumum values. Tracking of Common Terns at Teesside where birds ranged to 18 km from the colony also suggests the generally quoted values of the range of this species of up to 30 km or so are broadly correct. Experiences of tracking Arctic Terns from the Skerries where a single individual was tracked for 57 km at up to 29 km from the colony before being lost, suggested Arctic Terns range further than suspected. The maximum range for this species may prove to be closer to Sandwich Tern than Common Tern.

The general view from the literature that Sandwich Tern is more vulnerable to OWF development than Common Tern and Arctic Tern was not entirely supported by this study as a result of highly site-specific circumstances including the distance of the OWF(s) and the highly variable nature of foraging patterns of Common Tern in particular. Arctic Tern may also prove to similarly variable in this context. Nevertheless, tracking confirmed that breeding Sandwich and not Common Terns were vulnerable to OWF development in the Greater Wash as a result of foraging range and flight height characteristics. However, Arctic Terns from the Skerries and not Sandwich Terns from Cemlyn proved to be more likely to interact with the Round 3 Irish Sea zone, although whether they are at risk may depend on their flight height.

Recommendations for further work was structured around several themes including: 1) tracking of particular species at key sites, 2) determination of the response of terns to OWFs, 3) definition of avoidance rates and rates of mortality of terns at constructed sites, 4) development of PVA to predict longer term impacts upon particular species at particular sites, and 5) further understanding of the linkage between terns and their fish prey.

The key species at key sites were Arctic Terns from the Skerries, part of the Ynys Feurig, Cemlyn Bay and Skerries SPA on Anglesey in North Wales, in relation to the development of the Irish Sea Round 3 zone, and Common Terns from RSPB Saltholme in relation to the Teesside OWF which is due to be constructed in 2011. Understanding the impact of the Teesside OWF upon breeding Common Terns in terms of its effect on foraging conditions during noisy construction and on mortality through collision once it is built, may ultimately prove vital for the future of the Saltholme colony. A comparative approach of tracking and colony observations as was undertaken in this study, is recommended to be undertaken in 2011 (the year of construction), 2012 (operation) and perhaps beyond. The value and need for this work may be demonstrated by the use of bespoke PVA to determine the population impact of the level of mortality that is predicted from collision risk modelling generated from visual tracking data gathered in this study.

Effective risk assessment of any OWF is currently limited by a lack of detailed information of the response of any tern species to wind farms and definitive avoidance rates for any species. The available evidence suggests that avoidance may be lower than expected from flight manoeuvrability, as terns do not generally appear to deviate from turbines either as a result of a low perception of risk, but also because they may have limited field of forward once the head is inclined when searching for prey. Visual tracking of terns is recommended to determine the response of birds to turbines and, with sufficient sample size, actual avoidance. Monitoring before-and-after construction is especially useful as it is more likely to provide clear evidence of the nature of the response of the birds in a wider context.

The basis of the suggested approach is to collect and track individuals on course to cross any part of a site from a distance far enough away from the site (~ 1 km) to mean that birds have not already begun to respond to the presence of the OWF, and thence across and beyond the site. During tracking all behavioural aspects (flight height, flight speed, evasive action and any collision) would be recorded until they have left the site. Given enough effort, this relatively short-distance tracking has the chance of generating a large sample size of 100s or even 1000s of tracklines.

As a result of the importance of the issue, the paucity of information and the lengthy timescale to achieve a before-after comparison, it was also thought valuable to undertake post-construction monitoring at built sites. Sites known to experience considerable tern traffic include Scroby Sands of relevance to breeding Little (at Great Yarmouth North Denes) and Common Terns (at Breydon Water) and passage Sandwich Terns, and Lynn & Inner Dowsing (LID) for Common and Sandwich Terns on passage (with the additional prospect of some use by breeding Sandwich Terns).

Finally, it is recommended that an attempt be made to measure the abundance and distribution, both in spatial and temporal terms, of the fish prey of terns at selected colonies, following the intensive trial undertaken in the Greater Wash (see Centrica Energy 2009). This would aim to further understanding of the relative importance of different areas for terns, explain and verify patterns observed in any modelling and attempt to define the nature and extent of indirect (trophic) impacts of OWF development.

In reation to the latter, the study at Scroby Sands (Perrow *et al*. 2006, 2008) provided evidence of the potential for short and longer-term impacts of changes in abundance and distribution of fish prey linked to OWF construction, on the foraging range and patterns of Little Terns, with implications for a nearby SPA colony. The subsequent loss of the population in 2010 (six years after construction and four years after monitoring ceased) for unknown reasons reinforces the need for a specfic investigation of fish at the site using the methods developed previously (a custom built tow net for young-of-the-year fish). Should birds return to the colony the methods used to previously monitor the response of Little Terns to the OWF should also be repeated over the course of at least one breeding season.

Otherwise, there is clear value in illustrating the nature of the resource available to terns and how this is distributed in time and space including in relation to OWF development by monitoring before and after OWF construction. The Greater Wash, in which a number of sites are under development and which are predicted to impact upon Sandwich Tern to a greater or lesser extent, would seem to be an appropriate target for fisheries work. An approach of using acoustic fisheries surveys carried out using multibeam or swath echosounders to generate indices of fish abundance across wide areas that may also be matched to specific habitat variables, is suggested. Some sampling with suitable trawl gear would be required to confirm the type and size of fish present especially where these occur in dense patches (shoals) and to enable calibration of target strength in order to provide a measure of stock density.

Acronyms

AA	Appropriate Assessment
BERR	Department for Business, Enterprise and Regulatory Reform
BOU	British Ornithologists Union
BTO	British Trust for Ornithology
CCW	Countryside Council for Wales
DECC	Department of Energy and Climate Change
DTi	Department of Trade and Industry
EIA	Environmental Impact Assessment
ES	Environmental Statement
FEPA	Food and Environment Protection Act 1996
JNCC	Joint Nature Conservation Committee
NE	Natural England
NNR	National Nature Reserve
OWF	Offshore Wind Farm
PVA	Population Viability Analysis
RSPB	Royal Society for the Protection of Birds
SEA	Strategic Environmental Assessment
SNH	Scottish Natural Heritage
SPA	Special Protection Area
WWT	Wildfowl and Wetlands Trust

1. Introduction

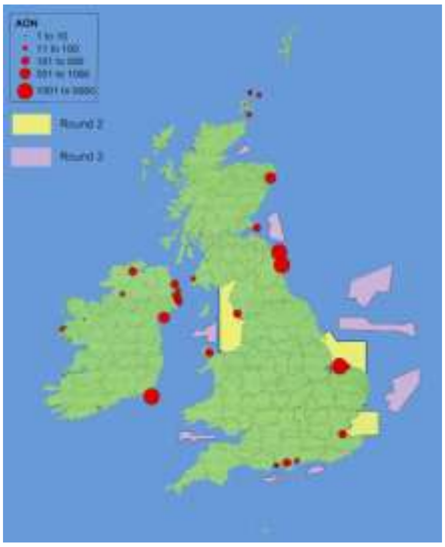
1.1 Overlap between terns and wind farms

Breeding terns contribute significantly to the international conservation importance of the UK's seabird colonies through their inclusion in 52 Special Protection Areas (SPAs) designated under the EU Birds Directive (see www.jncc.gov.uk). In order of abundance the five breeding species are Arctic Tern *Sterna paradisaea* (~53,000 pairs), Sandwich Tern *S. sandvicensis* (~11,000 pairs), Common Tern *S. hirundo* (~10,000 pairs), Little Tern *Sternula albifrons* (~1,900 pairs) and Roseate *Sterna dougallii* (52 pairs) (Mitchell *et al*. 2004). The latter two species are the rarest seabirds breeding in the British Isles and along with Sandwich Tern are of European Conservation Concern (SPEC) (BirdLife International 2004a). Within the UK, Roseate Terns are the only seabird on the 'red list' of birds of high conservation concern (BirdLife International *et al.* 2007, Eaton *et al*. 2009). Common Tern has recently joined Sandwich, Arctic and Little Terns on the amber list of species of medium conservation concern (Eaton *et al*. 2009).

The distribution of coastal colonies of all species, perhaps apart from Common Tern, which also breeds inland, is rather patchy (Fig.1). This is exemplified by Sandwich Terns, which breed in a few often large, disjunct colonies in the UK from Norfolk (~3,700 pairs) to Northumberland to the east coast of Scotland. There are further colonies in Ireland clustered particularly around the coasts of County Antrim and County Down, with a large colony (1,048 pairs) also in County Wexford, as well as some smaller colonies elsewhere (Mitchell *et al*. 2004, Fig. 1a). Coupled with the patchy distribution of offshore wind farms (OWFs) including operational, consented, proposed and future sites within the three development Rounds, there is varying potential for overlap between terns and OWFs. As a result of breeding in a handful of sites away from development zones there is very little potential for interaction between Roseate Terns and OWFs (Fig. 1b). Similarly, with breeding concentrated in the North and West of the UK there is relatively little potential for interaction between breeding Arctic Terns and OWFs, apart from perhaps the proposed Round 3 development zones in the Irish Sea, the Firth of Forth and possibly the Moray Firth (Fig. 1c), as well as sites in the recent round of development in Scottish Territorial Waters (not shown in Fig. 1). However, much of the large UK passage population (~159,000 ind. including juveniles but excluding birds from other countries) has the potential to pass through waters occupied by OWFs.

Colonies of Little Tern are widely scattered, but with a distinct concentration in South East England with potential for interaction with OWFs in Round 1 and in the Greater Wash and Thames Round 2 strategic areas (Fig. 1d). In fact, Little Terns have already been subject to intensive study in relation to an OWF, with the development of the Round 1 Scroby Sands OWF close (minimum of 2km) to the largest colony of Little Terns in the UK at North Denes, part of the Great Yarmouth North Denes SPA for the species. The colony regularly holds over 200 pairs, which is ~11% of the UK total, around 3.5% of the North & Western European population and 0.6% of the entire European population inclusive of the poorly defined but large populations in Russia and Turkey (BirdLife International 2004a). Radio tracking of individuals as part of impact assessment confirmed the limited range of foraging birds (~6km) (Perrow *et al.* 2006). This means that OWFs outside of the immediate coastal zone and away from colonies present little threat to Little Terns (Allcorn *et al.* 2004). A paucity of records of Little Terns from the offshore zone in passage periods (e.g. SCIRA Offshore Energy Ltd 2006, Centrica Energy 2007, 2008, 2009) also suggests much migration occurs in the coastal zone with any necessary transit across the open sea (e.g. the English Channel) being rather rapid.

The widespread distribution of Common Terns means there is considerable potential for interaction with both breeding colonies and passage migrants. For example, breeding colonies occur in all three Round 2 strategic areas comprised of The Greater Wash, North West coast (Solway Firth to Liverpool Bay) and Thames Estuary (Fig. 1e), with the largest colony on the



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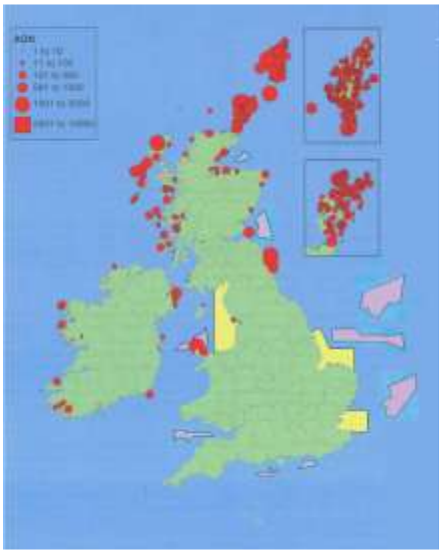
1b



1c

1d

1e

Figure 1a-e. Location and size of tern colonies in the UK (& all Ireland) as documented in Seabird 2000 (Mitchell *et al.* 2004) relative to the approximate location of the Rounds 2 and 3 of wind farm development.

Where:

1a Sandwich Tern (top left)

1b Roseate Tern (top right)

1c Arctic Tern (middle left)

1d Little Tern (middle right)

1e Common Tern (bottom left)

East Coast of England at Teeside (420 pairs in 2007 – David Braithwaite, site manager at RSPB Saltholme) within 3 km of the consented Round 1 Teeside development. A large post-breeding population also develops in UK waters, and in August 2008 up to 13,400 ind. roosted at Spurn Point (http://www.spurnbirdobservatory.co.uk/sightings/august08.html), Humberside. These birds apparently dispersed widely into coastal waters to feed before returning to roost (*pers obs*) promoting discussion of the likely impact of sites such as Humber Gateway (Round 2) and Westermost Rough (Round 1).

Sandwich Terns also form post-breeding aggregations with 5,100 ind, present at Gibraltar Point in Lincolnshire on 10th August 2008 (Nightingale & Dempsey 2008) near the constructed Round 1 Lynn & Inner Dowsing sites. Scroby Sands in Norfolk, the location of a further Round 1 site, may also accumulate hundreds of birds at this time (ECON 2008). However, the origin of many birds is difficult to determine, with Sandwich Terns from breeding colonies in Denmark and the Netherlands likely to cross the North Sea at this time, with the possibility of reciprocal transfer of birds from UK colonies (Wernham *et al.* 2002). In contrast, there is no doubt over the potential for interaction of birds from some breeding colonies and OWFs, with the most obvious being that between proposed Round 2 OWFs in the Greater Wash and the Scolt Head/Blakeney Point complex (two main colonies 20 km apart) within the North Norfolk Coast SPA. This colony complex is the largest in the UK averaging 3,741 pairs between 1986-2004. Sandwich Terns are a qualifying species of the North Norfolk Coast SPA, with the colony designated as containing 24.7% of the UK population (http://www.jncc.gov.uk/UKSPA). In fact, a higher proportion (~40%) is currently present, representing 5–6% of the European breeding population and 2.3-2.8% of the World population. Common, Little and Roseate Terns are also qualifying species within the North Norfolk Coast SPA, with the former two also designated within the adjoining Wash SPA. The two SPAs and adjacent inshore waters comprise the Wash Special Area of Conservation (SAC).

It was thus of no surprise that Sandwich Tern became the key sensitive receptor of impact assessment of the various proposed OWFs in the Greater Wash. An Appropriate Assessment (AA) was triggered following the submission of the Environmental Statement (ES) on Sheringham Shoal OWF (BERR 2007a) and further AA's are anticipated upon Docking Shoal, Race Bank and Dudgeon. Special measures continued after consent at Sheringham Shoal OWF with the FEPA (Food, Environment Protection Act 1985) license requiring a validation of the calculated collision risk for Sandwich and Common Terns (http://www.mfa.gov.uk/environment/energy/existing R2.htm). It is perhaps more surprising that other species of terns, such as Common Tern have not received more attention in relation to Teesside, Westermost Rough or Humber Gateway OWFs.

1.2 Risks of wind farms for terns

Terns are fast flying and highly manœuvrable implying that they would not be at particular risk from collision (Garthe & Hüppop 2004). However, work at Zeebrugge in Belgium (Everaert & Stienen 2006) showed that between 2001-2005 an average of 61 Common Terns, 16.8 Sandwich Terns and 6.8 Little Terns were killed annually by a line of turbines along the breakwater alongside the mixed colony which had set-up on the purpose-built peninsula created as mitigation for the extension of the nearby port. Peak numbers killed in any single year were 129 Common Terns, 54 Sandwich Terns and 10 Little Terns, with collision rate linked to colony size at least for the larger species. There was also evidence for sex-biased mortality with male Common Terns at particular risk as a result of their higher foraging frequency as the provisioning parent (Stienen *et al.* 2008).

It is now thought that terns, amongst other predatory species such as large gulls, (Northern) Gannet *Morus bassanus* and skuas (*Stercorarius sp.*) do not perceive particular risk from turbines, unlike groups such as waterfowl, waders and passerines (Centrica Energy 2007). The latter groups are at risk of predation from aerial avian predators and may conceivably apply this perception of potential risk as aversion to novel structures within their flight window. Considerable aversion to the presence of turbines is manifested as far-field avoidance from considerable distance of up to several kilometres (e.g. Desholm & Kahlert 2005). Such behaviour may contribute much to avoidance rates. The relatively unmanœuvrable Common Eider *Somateria mollissima* for example, avoided Nysted wind farm at a rate of 98-98.2% (Petersen *et al*. 2006). With far-field avoidance a variety of species of geese have been estimated to avoid land-based turbines at rates as high as 99.9% (Fearnley *et al*. 2006).

The position of the eyes in different groups of birds linked to functional differences and their relative position in the food chain has considerable influence on visual ability in birds. Species such as waterfowl with their eyes on the top of the head have excellent all round vision including above and behind them. In his presentation to the BOU (7th April 2010) Graham Martin of the University of Birmingham illustrated that many other birds, have only a very small proportion of the visual field dedicated to forward vision (2%) and even a small movement of the head in the vertical plane may mean that the birds concerned (including raptors, cranes and probably other predatory species including terns), are blind in the direction of forward flight. Aerial foragers such as some raptors (e.g. falcons, hawks and eagles) as seabirds such as terns, large gulls, skuas and Gannet that that are seeking to take prey below them (i.e. in the sea, on the ground or other birds in the air) look downward and thus tilt the head in the vertical plane to do so. Coupled with the fact that these species may expect to be foraging in largely open environments may mean that little avoidance behaviour is exhibited and collision with objects such as turbines may occur more frequently than expected.

There is little evidence of far-field avoidance by terns to date with the few studies of relevant OWFs commenting on the tendency of terns to fly straight through lines of turbines without undue deviation (Pettersson 2005, Petersen *et al*. 2006). Near-field avoidance may thus be essential for terns to avoid collision. However, even high manœuvrability may be insufficient to combat the extremely high tip-speeds of turbines coupled with the presence of disorienting vortices. Studies at Zeebrugge, where attempts have been made to determine avoidance rates from known rates of passage and collision, suggest that terns may have avoidance rates in the region of 98-99% that are similar to more unmanœuvrable species (Whitfield 2008).

With the general lack of avoidance of wind farms, the risk of collision compared to displacement and barrier effects may thus be more or less mutually exclusive threats, with collision seen to be more likely to generate a population-scale impact. However, terns may also be susceptible to indirect effects of OWFs including changes in the distribution and abundance of their prey as well as changes in the nature of bed features (e.g. sand bars) and current patterns instigated by structures in the water column. At Scroby Sands OWF there was strong circumstantial evidence of an effect of pile driving during construction upon Herring *Clupea harengus* leading to subsequent poor recruitment (Perrow *et al*. 2006). Prior to this, young-of-the-year (YOY) Herring was thought to be the mainstay of Little Tern breeding success at the nearby North Denes colony. As a result of birds needing to travel more widely in search of prey, the use of the OWF increased with a concomitant increase in collision risk (Perrow *et al*. 2008).

1.3 Limitations of standard assessment methods

Knowledge of the likely interaction between terns, especially breeding birds within colonies, and OWFs is vital to effectively plan and assess the impact of many OWFs. In particular, there is a clear need to understand the range of birds foraging from colonies and the relative use of OWFs compared to other coastal waters. Recognising this, the DTi (becoming BERR and now DECC) funded a pilot study to determine foraging distribution of terns at colonies in the Greater Wash (including Scolt Head, Holkham and Blakeney but also including Great Yarmouth and Winterton), North West (Hodbarrow, Ribble, Seaforth, Gronant and Cemlyn Bay) and Thames (Foulness/Maplin and Burntwick Island) Round 2 SEA areas (Allcorn *et al*. 2004). Selected colonies contained at least 1% of the national breeding population of Sandwich, Common or Little Terns. The project managed by the RSPB, WWT and JNCC used both aerial and boat-based survey methods.

Although the study was of some value in assessing the relative merits of the assessment methods and provided some insight into the distribution of the birds, a major limitation was the restricted survey area of only 15 km from colonies for aerial surveys and just 5 km for boat-based surveys. The later study of Perrow *et al.* (2006) on Little Terns using radio telemetry illustrated that, with hindsight, those boat-based surveys more or less encapsulated the likely range of Little Terns. However, the later aerial surveys in the Wash undertaken as part of the assessment of Round 2 wind farms implied that Sandwich Terns could reach 60 km or more (defined by the edge of the survey area) from colonies (DTi 2006, BERR 2007b) (Fig. 2). Moreover, neither boat-based or aerial surveys gathered detailed information on foraging patterns and distribution of important foraging areas as they effectively relied on chance encounters with fast-flying birds (10 to over 20 m sec^{-1}) along set transect lines. Importantly, interpreting the results of this study in an particular way appears to have generated false optimism in some scoping exercises that the larger terns were unlikely to be a significant issue for wind farms at >20 km from the coast.

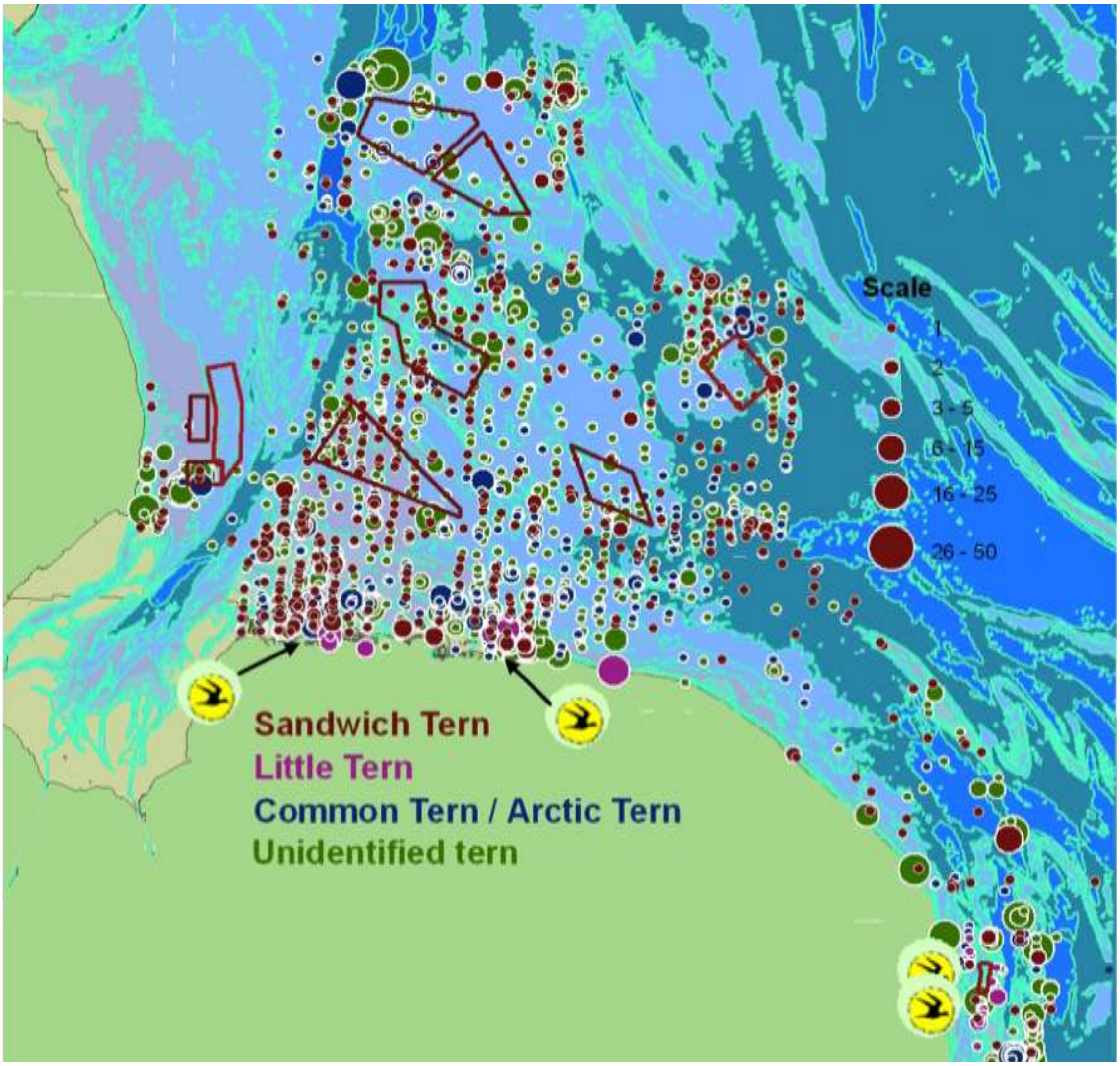


Figure 2. Records of all terns (*n*= 2315) in 15 aerial surveys of the Greater Wash carried out from November 2004–September 2006 by Wetland Advisory Service of Wildfowl & Wetlands Trust for DTI/BERR (DTI 2006, BERR 2007b). The different species/groups are shown by different colour codes with the location of the major colonies in North (Sandwich, Common, Little and Arctic Terns) and East Norfolk (Little and Common Terns) shown by flying bird symbols set in yellow. In North Norfolk, the Scolt Head (left) and Blakeney Point (right) colonies are some 20km apart.

The comprehensive aerial survey programme of the Greater Wash reinforced the basic limitation of aerial surveys with a large proportion (72%) of the 2,315 terns recorded defying species identification. The speed of the survey platform also prevented recording of basic behaviours such as foraging or even whether the birds were heading away from or to the colonies. Moreover, it was difficult to be sure of the origin of the birds recorded. For example, although it could be assumed that all Sandwich Terns present in the breeding season originated from the North Norfolk SPA this need not necessarily be the case as a result of the presence of an unknown proportion of non-breeders and failed breeders from other colonies. Nevertheless, the combined surveys are a valuable snapshot of tern distribution and the use of Jacob's Selectivity Index has provided some idea of the relative importance of different OWFs to terns (see Centrica Energy 2008, 2009). However, this approach is vulnerable to the influence of particular surveys in what is temporally patchy data. Moreover, only relatively few birds (<10%) from the known population in the colonies in north Norfolk were represented on any one survey occasion, which was perhaps exacerbated by the exclusion of the Wash estuary itself as a result of Ministry of Defence airspace restrictions.

Thus, whilst standard aerial and especially boat-based surveys are more or less essential in characterising the abundance and distribution of birds, including terns, within OWF sites/zones, it is important to accept that these methods each have limitations that may prevent more specific questions being answered, especially those linked to the relative importance of one area over another or the habitat use of birds of particular origin such as a protected colony. Part of the reason for this may simply be that the birds concerned may range over a much wider area that can be readily sampled. This is not to say however, that extensive boat-based surveys may not be useful, particularly where these also monitor habitat variables that may be used in models designed to explain bird distribution (e.g. Schwemmer *et al*. 2009).

Defining the relative importance of different areas is central to definition of protected areas such as marine SPAs, three types of which are currently being considered under the Marine Natura 2000 project (Johnston *et al*. 2002): 1) seaward extensions to existing breeding seabird colony SPAs, 2) inshore areas used by non-breeding birds e.g. seaduck, grebes and divers, and 3) aggregations of wide-ranging seabirds. Terns fit within categories 1) and 3) with the latter potentially including both breeding and passage birds. Designation of SPAs for foraging terns falls under the remit of the JNCC and their statutory partners (NE, CCW and SNH).

Progress in defining SPAs has been made in relation to a number of species using a variety of methods including the use of aerial survey data of the proposed Round 2 strategic areas to support the potential designation of further SPAs in the Thames estuary for Red-throated Diver *Gavia stellata* and for both Common Scoter *Melanitta nigra* and Red-throated Diver in Liverpool Bay (Webb *et al*. 2006). In recognition of the importance of inshore areas for active behaviours such as bathing, preening and displaying, boat-based surveys have also been successfully used to define seaward extensions of 1 km for (Common) Guillemots *Uria aalge*, Atlantic Puffin *Fratercula arctica* and Razorbill *Alca torda* and 2 km (for Gannet) from six colonies (McSorley *et al.* 2003). Unfortunately, analysis of even the extensive boat-based and aerial survey data (>3 million records) held on the European Seabirds at Sea team database has proved to be of extremely limited value for breeding terns (JNCC *pers comm*.) requiring an alternative approach. Individual telemetry has proved to be a way forward for some wide-ranging species such as Manx Shearwater *Puffinus puffinus* (Wilson *et al*. 2009).

Overall then, it was seen to be critical to advance the means of defining areas of importance for terns to not only plan and assess the impact of OWFs, but also underpin planning of designated areas. There is precedence of the latter 'piggy-backing' on the former (Webb *et al*. 2006) emphasising that the two objectives need not be mutually incompatible, as there is no obvious clear limitation why SPAs cannot include operational OWFs. Nevertheless, the role the OWF plays in the ability of the designated area to meet its legislative obligations must be clear, in that the OWF cannot negatively affect the integrity of the SPA.

1.4 Development of alternative assessment methods

Individual-based methods provide an obvious means of improving understanding of at-sea foraging distributions of seabirds. Recent advances in remote techniques such as radio and satellite telemetry and well as geographic positioning system (GPS) dataloggers have proved to be successful in elucidating the foraging movements of many seabirds at sea (e.g. Hamer *et al*. 2000, Daunt *et al*. 2002, BirdLife International 2004b, Perrow *et al*. 2006, Guilford *et al*. 2008, Wilson *et al*. 2009). Nonetheless, studies of individual foraging movements and at-sea behaviour can be logistically challenging (Wilson *et al*. 2002).

Radio telemetry proved to be highly successful on Little Terns (Perrow *et al.* 2006) and following these experiences a trial on Sandwich Terns from Scolt Head was undertaken by ECON Ltd. on behalf of Centrica Energy/AMEC in the Greater Wash in relation to their Docking Shoal and Race Bank projects (Centrica Energy 2008, 2009). Low retention of tags, probably linked to the rigours of foraging activity in this species, including plunge-diving from ≥20m or so above sea surface, meant this was not successful. Initial observations also showed that manual radio tracking was unlikely to be cost-effective as a result of lengthy time intervals between nest changeover (4-6 hours or more). This led to the trial of simply tracking birds leaving the colony using a rigid-hulled inflatable boat (RIB) capable of speeds of >35 knots (Centrica Energy 2008, 2009, Perrow *et al*. 2011). Tracked birds appear to ignore the following vessel and in suitable conditions individuals could be tracked for a complete foraging bout (perhaps up to 2 hours in length), providing an exact record of the route taken, the location of foraging areas and all foraging attempts and items consumed. The level of detail of this information surpassed anything that could be derived from standard survey methods and even remote techniques such as radio tracking (Perrow *et al*. 2011). The visual-tracking technique was then extended for use at both Scolt Head and Blakeney Point in different years (Centrica Eneregy 2008, 2009).

Flight direction and passage rate of Sandwich Terns from the colonies were described from transect surveys (also doubling as a safety vessel) from a relatively small vessel (~10 m in length) vessel moving parallel with the coast to the seaward side of the colony and covering all likely flight routes from the colony. During tracking, Sandwich Terns proved to travel along remarkably straight flight paths implying a predetermined foraging location. Using a set of ‘rules’ derived from surveys and tracking, including the likely angle of deviance from the initial route from the colony and maximum likely distance for a specific flight bearing, a species and colony-specific simulation model of foraging distribution was constructed. The number of simulated flight routes and foraging end-points could then be scaled to realistic values for the colony in the course of the breeding season, which proved to be in excess of a million individual flights for a colony of a few thousand pairs (Centrica Energy 2009).

Data was presented as a map of foraging end-points allowing the relative importance of different OWF areas (i.e. as %) to be readily assessed including within standard matrix-based analysis. The combined number of flights into an OWF culminating in a foraging end-point within the OWF and through the OWF *en-route* to an area further offshore were used in collision risk analysis as an alternative to estimates generated from boat-based assessments, which are typically limited to a small number of surveys ultimately dependent on a limited number of snapshots to estimate densities of flying birds. A further advantage of modelling derived from the individual-based approach in this case is that it deals only with birds originating from (and assumed to be breeding) at SPA colonies.

Patterns of foraging distribution may vary on a temporal (tidal state, day, season and year) and spatial (by colony and habitat distribution perhaps also linked to tidal state) basis according to many factors. Of these, prey abundance and state of development (incubation, chick rearing and fledging) are thought likely of most significance. This implies at the very least, gathering of colony-specific data to determine a colony-specific model.

Visual tracking was developed for Sandwich Terns and it was not clear whether other species such Common or Arctic Terns could also be tracked. In particular, it was unknown whether these species would show the same ambivalence to being followed by boat or if their flight patterns and foraging behaviour would lend themselves to tracking (e.g. if they flew too fast or used inaccessible habitats such as rough seas or extremely shallow harbours and bays).

1.5 Key values of an alternative approach

An alternative approach using a combination of individual-based tracking, a means of estimating passage rate to and from colonies (e.g. colony-transect surveys or perhaps direct observation of smaller colonies) and some individual-based modelling to further understanding of foraging patterns and decision-making was thought to offer a more targeted and cost-effective approach to data gathering for terns in relation to specific OWFs than the standard aerial/boat survey-based solution. Such an approach may be used for any number of sensitive species especially those that are likely to range over a wide area and perhaps encounter a number of OWFs. This would include Gannet, Fulmar, Manx Shearwater and perhaps even gulls such as Lesser Black-backed Gull and Kittiwake. Most of these larger species would be best tracked through the use of tags of one sort or another, although visual tracking could be useful for gulls in particular circumstances.

It could also be argued that the efficacy of this alternative approach is maximised once the key species and potential issues have been clearly identified through baseline data gathering using survey-based assessment. Expert judgement based on experience and insight into species ecology may however, allow similar conclusions regarding gthe nature of key species and issues to be reached more rapidly. Consequently, the alternative approach may be valuable at all stages of project development. For example, data may allow developers/regulators to assess risks in the early phases of development when displayed in a sensitivity-type assessment, such as that derived by Garthe & Hüppop (2004) in the German sectors of the North and Baltic Seas. Moreover, individual bird based data may be used to assess likely risks within zones, individual site ESs or AAs and even during the impact-assessment phase of a consented project. Thus, the approach may be of value in all Rounds of the offshore wind industry including Round 1 & 2 developments in need of a greater understanding of the impacts upon terns, assessment of likely impacts in Rounds 2 & 3, and as steering in the selection of sites within Round 3 zones.

Incidentally, individual-based methods, coupled with some more standard telemetry, have now been adopted by the JNCC to help define SPA extensions for breeding terns. This followed the recommendations of the Workshop on Marine SPAs for Terns Around the UK arranged by the JNCC ON December 17th 2008. Fieldwork on several tern species at a number of colonies around the UK was undertaken concurrently with this project in 2009.

2. Aims and objectives

This project was primarily concerned with translating the experiences of Sandwich Terns in the Greater Wash to other species and locations that may interact with wind farm developments in all Rounds of development (1, 2 and the recently proposed Round 3). It was run over two seasons, with the bulk of work concentrated in Season 2 (2009). In Season 1 (2008) further development of the techniques and limited further data gathering in the Greater Wash was undertaken to add to the current database on Sandwich Terns gathered on behalf of AMEC/Centrica (see Centrica Energy 2008, 2009). Fieldwork provided a second season of data at Blakeney Point (the first was gathered in 2007) as an equivalent to the two seasons of data previously gathered at Scolt Head (2006 and 2007). Moreover, a first-time specific attempt was made to track Common Terns from Blakeney Point, with a view to gathering data on this species at another site in Season 2.

Whilst previous data was concerned primarily with assessing the likely impact of Docking Shoal and Race Bank OWFs, building on this would generally aid impact assessment in this strategic area containing a number of developments. These include two sites (Lynn & Inner Dowsing often classed as one) that have recently been constructed, two that have been consented (Sheringham Shoal and Lincs), three that have been submitted (Docking Shoal, Race Bank and

Dudgeon), and another in the final stages of project development (Triton Knoll).

In Season 2, it was planned to introduce further localities into the project. Possibilities included: 1) North East England at Teesmouth where RSPB Saltholme has recently housed 420 pairs of Common Terns (>4% of the GB population) within ~7 km of the consented Round 1 Teeside OWF, 2) Ynys Feurig, Cemlyn Bay and the Skerries on Anglesey designated as supporting 1,290 pairs of Arctic Terns, 460 pairs of Sandwich Terns and 189 pairs of Common Terns (www.jncc.gov.uk) within possible range of the Round 3 site in the Irish Sea, 3) the North West of England in the current Round 2 strategic area perhaps with centres on the Hodbarrow Sandwich Tern colony (360 pairs) and the Ribble/Seaforth Common Tern colonies (269 pairs), 4) the Firth of Forth, designated supporting 334 pairs of Common and 440 pairs of Sandwich Tern (www.jncc.gov.uk) immediately inshore of the recently proposed Round 3 development area, 5) the Sands of Forvie Sandwich Tern colony (524 pairs) linked to proposed developments in Aberdeen Bay, and 6) the Thames Round 2 SEA area at the Foulness/Maplin colonies of Common Tern (74 pairs) and the Burntwick Island colony of Sandwich Tern (148 pairs).

Following submission of the interim report in May 2009 to COWRIE and thence to the project advisees, including members of the Futures Group and the Bird sub-group of COWRIE, the decision was taken to undertake further work on the Common Tern colony at RSPB Saltholme in relation to the Teesside OWF and the mixed colonies of terns dominated by Sandwich Tern at Cemlyn Bay. Selection was driven by a need to understand the potential impact of a large Round 3 zone in the case of the Irish Sea Zone which was within the prospective range of Sandwich Terns of Cemlyn Bay (assuming a similar scope to birds from North Norfolk) and the high level of concern (notably from the RSPB and the Teessmouth Bird Club) of the impacts of the consented Round 1 Teesside OWF upon a rapidly expanding and now nationally important colony of Common Tern. These birds also interact with the Teesmouth and Cleveland SPA, for which breeding Little Terns and passage Sandwich Terns are listed as qualifying speces. As the Saltholme colony is a recent phenomenon, Common Tern is currently not included in the designation. A further advantage of the selection of both sites was the opportunity to gather comparative data on Sandwich Tern relative to the situation in North Norfolk colonies and on Common Tern in the absence of sympatric species. Selection of Cemlyn Bay with the Skerries nearby also offered the opportunity to at least trial the tracking technique on Arctic Tern.

In both seasons, the underlying twin objectives of the project were to: 1) further understanding of the foraging ecology (including range and behaviour) of several tern species and 2) provide data that may be incorporated into foraging distribution modelling and also collision risk modelling where specific wind farm sites existed. Data gathering was to be undertaken towards the end of the breeding season (July) in Season 1 and throughout the breeding season of May to August in Season 2. The information to be gathered may be summarised as follows:

- Confirm foraging patterns and behaviour by aiming to track up to n=50 of any species at any colony in Season 1 and n=100 birds of any species in Season 2.
- Determine passage rate and flight direction of terns leaving and returning to the colonies (additional information to include type and size and prey transported).
- Record the type (to species wherever possible) and size (from bill length) of prey delivered to partners/chicks within the colonies.

Additional dedicated observation at colonies was required to assess of important prey types and a measure of prey abundance (through provisioning rate), which were likely to be important determinants of the foraging range and location of foraging terns. In other words, knowledge of these aspects would help explain the observed and modelled patterns.

This final report incorporates all information from both seasons (Season 1 & 2) of data gathering.

3. Methods

3.1 Study sites

3.1.1 Blakeney Point

Blakeney Point NNR forms part of the North Norfolk SPA in which both Sandwich Tern and Common Tern are qualifying species (www.jncc.gov.uk). Within the site, Sandwich and Common Tern exhibit a rather different nesting strategy. Sandwich Terns typically return to the area in late March, with birds often on eggs by late April/early May. It is thought that only one egg is generally laid (M. Rooney *pers comm*, pers obs.), seemingly less than in other colonies elsewhere (e.g. an average of 1.6 in the Netherlands - Steinen 2006). If the egg or chick is lost, re-nesting is not thought to occur. However, in some years, there is an further arrival of a variable number of birds sometimes as late as early June, that boosts the nesting population. The origin of these birds and the reasons behind their arrival remains unclear. Late additions tend to simply append themselves to the main colony, which is integrated within a large colony (1250 pairs in 2008 - E. Stubbings NT pers comm.) of Black-headed Gull *Chroicocephalus ridibundus*. Sandwich Tern actively selects embryonic dunes laying eggs directly on the sand within stands of dune grasses and the woody *Sueda vera* at high density (perhaps up to 10 pairs m^{-2}) (Fig. 3). Apart from presenting a line of stabbing bills to aerial attack, birds do not actively mob potential predators, a role fulfilled by the more aggressive Black-headed Gull.

Figure 3. Part of the high density Sandwich Tern colony in embryonic dune grasses amongst stands of woody *Suaeda vera* at Blakeney Point.

In contrast, Common Tern nests in smaller and far more widely spaced loose groups of up to 40-50 pairs on shingle and or sandy substrate above high-water. A number of locations around the site have been selected, most notably on the main beache past the gap leading to Far Point (after which public access to the rest of the Point is restricted during the breeding season), the beach near the watchtower (also fenced), and on Mid Point (inaccessible to the public with access also tidally restricted). Arriving later than Sandwich Tern in mid to late April, Common Tern does not generally nest until mid-May. Unlike Sandwich Tern Common Tern lays up to three eggs and also has a capacity to re-nest if a clutch of eggs is lost. Birds undertake active nest defence by fiercely mobbing potential predators.

Common Tern has a long history at Blakeney Point with breeding recorded as early as 1830. The largest numbers occurred much later between 1935 and 1940, and again from 1950 to 1952, when the site supported well over 2,000 pairs (Taylor *et al*. 1999). Although the UK population trend for Common Tern has not been quantified, comparison of census data from 1969-70 and 1985-87 indicates a change in the distribution of nesting Common Terns away from the coast in favour of inland breeding areas (http://www.jncc.gov.uk/pdf/UKSPA/UKSPA-A6-90.pdf). In keeping with this, the largest colony in Norfolk is now at Breydon Water (202 pairs in 2007 – NNNS 2008) on a series of artificial nesting platforms. Whilst birds from the colony still fly to the sea to forage (Perrow *et al*. 2008) the relative importance of the sea and inland waterways (rivers and lakes in the Norfolk Broads) as foraging areas remains unknown.

Sandwich Tern was suspected to be breeding in Norfolk as early as 1893, although the first official record was not until 1920 with a single breeding pair at Blakeney Point. By 1923 the species was also recorded nesting at Scolt Head (Brown & Grice 2005). Following an underlying increase to the 1970s in which several colony locations were intermittently used (Salthouse, Warham Greens, Scroby Sands and Stiffkey Binks), numbers of Sandwich Terns have remained broadly stable (~3,700 pairs) with the population distributed between Blakeney Point and Scolt Head. There is some suggestion of alternation between these sites every 3-4 years (NNNS 2007), with virtually the entire breeding population of the SPA at one or other colony in some years. For example, in the national censuses of 1969/70 (Operation Seafarer), 4,022 pairs were recorded at Scolt Head with 0 at Blakeney, with a similar result of 4,200 and 75 pairs respectively in Seabird 2000 (Mitchell *et al*. 2004). However, in the intervening period peak numbers of pairs at Blakeney reached 3,850 pairs in 1981 and 3,700 pairs in 1992. Likely factors contributing to colony switching include availability of prey at sea (Stienen *et al*. 2000), predation by Red Fox *Vulpes vulpes* and kleptoparasitism by Black-headed gulls (Stienen *et al*. 2001). These factors may all prove to interact, although how this may operate remains unclear at the present time.

Before the initiation of this project in 2008, there were thought to be >2,000 nesting pairs of Sandwich Tern mostly with young chicks and ~80 pairs of Common Tern incubating eggs. (D. Wood Head Warden *pers comm*., 10th June 2008), which made the project feasible. As is typical the single colony of Sandwich Tern comprised of an official final total of 2,400 pairs was located on Far Point. The season followed the expected pattern with the majority of pairs laying eggs in mid-May, hatching chicks in mid-June, with almost all chicks having fledged by mid-July. The peak fledgling count for 2008 was 1,529 (E. Stubbings NT, *pers comm*.). As is also typical, a smaller number of birds (~250 pairs) settled in early June, ultimately leading to the presence of fledgings into late July.

In 2008, Common Terns nested on Far Point and Mid-Point with the majority of the 103 pairs at the former. A total of 33 chicks fledged. The timing of colony development was slightly later than that of Sandwich Terns, with relatively large and mobile chicks observed in early July, which were near to fledging by the final set of observations on 12th July. Whilst 2008 represented an unusually wet and cool summer, there were no particularly severe storms or floods that have washed out nests in other years. There were also no significant predation events affecting either colony, although a number of Stoats *Mustela erminea* were caught and removed from Blakeney Point during the season (E. Stubbings, NT, *pers comm*.).

For the purposes of comparison between foraging Sandwich and Common Terns and within the constraints of the late letting of the contract coupled with the need for cost-efficiency, the work was intensively undertaken in two periods. The first was in early July (4-6th inclusive) and the other in mid-July (12-14th) in the late chick-rearing period for both species. The latter occasion was immediately prior to the fledging of the bulk of the Sandwich Tern chicks, with most Common Tern chicks fledging 1-2 weeks afterwards. Intense sampling periods allowed cost-efficient mobilisation from Morston (Blakeney Harbour) on day 1 on high water with a return in daylight, with a repeat of the effort on days 2 and 3 in each period.

Although effort over the 2009 season was primarily directed towards understanding tern movements at other sites around the UK, namely Teesside and Anglesey, a small amount of work was also carried out at Blakeney. This included three visits to the colony in June (1st June, and 14th-15th June) and July (7th-8th July), and a single day of passage rate determination from transects at sea (26th June). However, intense fog during the work at sea meant the data had to be excluded from analysis. No visual tracking was undertaken at Blakeney in this year.

3.1.2 Cemlyn Bay and the Skerries

Cemlyn Bay and the Skerries forms part of the Ynys Feurig, Cemlyn Bay and Skerries SPA on Anglesey (North Wales) designated as supporting 1,290 pairs of Arctic Terns, 460 pairs of Sandwich Terns and 189 pairs of Common Terns (www.jncc.gov.uk). In fact, the number of nesting terns is currently considerably higher, with up to 2,850 pairs of Arctic Terns nesting on the Skerries alone. This site is a series of rocky islets around a main island dominated by a lighthouse and helicopter-landing pad (Fig. 4) situated some 3.4 km from Carmel Head at the northwestern tip of Anglesey. The RSPB manage the site with a summer warden (Denise Shaw) and assistant living on the island throughout the breeding season. A small vessel delivers supplies from Holyhead.


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Figure 4. View of part of the Arctic Tern colony on the Skerries, an offshore island complex around 3 km from the northwestern tip of Anglesey.

The Skerries supports the largest breeding colony of Arctic Terns in Wales and represents by far the largest concentration of these birds for its latitude in the UK. The terns have bred here since before the turn of the 20th century, with 10,000 pairs recorded. However, the colony suffered major declines followed by subsequent rapid increases. The first of these occurred in the early 1900s when numbers fell to just 15-20 pairs in 1908 later recovering to 'several hundred' birds in 1935. Numbers declined again thereafter with no nesting birds between 1961 and 1979. Although this abandonment was attributed to rats, there is no evidence to support this anecdotal claim. Nesting resumed again in 1980 with wardening begun in 1987. The subsequent rise to a peak of 2,850 pairs contrasts with population trends at other major colonies, such as Orkney and Shetland, where numbers declined by 27% between 1985 and 1990. Despite the proximity of other breeding colonies on Anglesey (Cemlyn is approximately 6.3 km away) only a few Common Terns (~100 pairs) breed on the Skerries, whilst Sandwich Terns rarely occur. Roseate terns, including colour-ringed individuals, also frequent the island (*pers obs*) but breeding is rarely proven. The attraction of the site appears to be relatively predator-free space (although the Peregrine Falcons *Falco peregrinus* breeding at Carmel Head appear to commute regularly to the site to prey on adults and chicks) and what is thought to be profitable feeding patches in the tidal rips and races, which are a feature of the islands. The prevailing dynamic (confused) sea conditions, particularly for a km or two around the islands, afford the local nickname of 'The Scaries'.

Although several attempts were made to include the Skerries and its Arctic Terns in the programme of works in the area, landing was only possible on one occasion on 12th June 2009, during incubation. One team of observers trialled tracking terns leaving the island on foraging trips with a land-based telescope supported by counts of birds in different areas around the islands. A second team attempted the visual tracking of Arctic Terns using a RIB.

The tern colonies at Cemlyn Bay are in a strikingly different location on two low-lying artificial islands in a non-tidal lagoon behind a complete shingle spit across the Bay (Fig. 5). A small tidal stream flows around the lagoon to discharge into the sea at the western end of the Bay. The vegetation on the lagoons is a mixture of grasses and herbaceous goosefoot (*Chenopodium* sp.) and Sea Kale (*Crambe maritima*). Cemlyn is the only breeding site for Sandwich Terns in Wales and has recently grown from 53 pairs in 1984 to 1,024 pairs in 2009. The number of breeding pairs has fluctuated which appears to be relatively typical for a developing colony (Ratcliffe 2004 in Mitchell *et al*. 2004). Productivity has generally been low, largely as a result from predation from Grey Heron *Ardea cinerea* and Herring *Larus argentatus* and Great Black-backed *L. marinus* Gulls. Herons are thought to have been responsible for decimating the chick population in some years leading to almost total failure. Predation occurs mostly at night, which has led to innovative deterrents such as the use of lasers to frighten visiting birds.

For all species, nests are simply located amongst the vegetation with each species tending to form clusters of conspecifics, although coloniality appears to be most developed in Sandwich Terns. The larger island tends to be preferred by Sandwich Terns and attendant breeding Black-headed Gulls (up to 440 pairs). However, nesting also occurs on the smaller island. Likewise, both islands also support breeding Common and Arctic Terns, although the smaller island appears to contain a higher density of these species. Numbers of Common and Arctic Terns vary between years and both appear to have been relatively high in 2009 with 80 Common and 46 Artic Tern pairs producing and estimated 125 and 75 fledglings respectively. In 2009, whereas the productivity of Sandwich (0.41 chicks per pair) and Common Terns (0.32 chicks per pair) was similar, it was much higher for Arctic Tern (0.81 chicks per pair).

Studies were undertaken throughout the breeding season from 27th May to 7th August at Cemlyn in 8 periods over two or three successive days during which both tracking and colony observations were conducted simultaneously using a team of 3 or 4 people. The only restriction to the programme this was when poor weather prevented tracking. The colonies were observed using a telescope located on the shingle ridge at the top of the beach, which is also accessible to the general public. Counts of incoming and outgoing birds (see 3.2.2 below) were conducted from a similar location more or less midway the two islands. Tracking was conducted from a RIB collecting outgoing birds as they crossed the Bay.

Figure 5. Nesting terns on the larger of the two islands in the lagoon at Cemlyn Bay on Anglesey.

3.1.3 Saltholme on Teesside

The RSPB Saltholme reserve opened in early 2009 incorporating a large area (380 ha) of former brownfield and marshland with an established history of bird interest. The existing Saltholme Pools have been supplemented by further landscaped areas of open water, in which artificial islands of cockleshell have been installed. One such island in Paddy's Pool supports the bulk of the Common Terns nesting at Saltholme (Fig. 6). The Teesside area has a history of breeding Common Terns, with these formerly breeding at a number of locations around Teesside including Greatham Creek, Charltons Pond and Cowpen Marsh (Joynt *et al*. 2008). Following the creation of islands in the Bran Sands lagoon this species increased dramatically throughout the 1990s, and after it was announced in 2001 that these islands were to be removed to allow development, additional nesting areas were created near Greatham Creek, at Greenabella Marsh and in Saltholme Pools. The RSPB constructed a second island at Saltholme in Paddy's Pool in 2004. The entire population now appears to nest within the Saltholme reserve, with a peak of 420 pairs in 2007 representing one of the largest colonies in the UK. The numbers of nesting birds declined to 360 pairs in 2008 and to 300 pairs in 2009.

Although the island in Paddy's Pool is also used by Black-headed Gulls there is a mismatch in the timing of breeding between the two species with Common Terns tending to nest later, from the last week of May. The majority of tern chicks hatch around the third week of June, by which point many Black-headed Gull chicks have fledged. Fledging of Common Tern starts around the third week of July with the last birds fledging into August. Studies were undertaken from late incubation until fledging from 19th June to 23rd July in periods over two or three successive days. As at Cemlyn Bay, tracking and observations were undertaken simultaneously using a minimum of 4 (occasionally 5) people in two teams. Observations of prey provisioning and kleptoparasitic interactions were undertaken from the hide overlooking Paddy's Pool, with observations of flight paths and passage rate undertaken on the visitor path leading from the hide that allows a virtually unrestricted view over the pool and its surrounds.

Saltholme is unique in that adult terns traverse a complex of pools, marshland, roads and industrial areas bisected by a number of power lines before they reach Seal Sands and the estuary of the Tees at Teesmouth. Tracking was undertaken by waiting in the RIB at the head of the deepwater channel to the nuclear power station near Seal Sands for birds to emerge on a direct flight path from the colony (see 3.4.3 below).


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Figure 6. The artificial cockleshell island in Paddy's Pool at RSPB Saltholme used by nesting Common Terns.

3.2 Passage rate and flight direction from colonies

3.2.1 Blakeney Point

in 2008, passage rate and flight direction of terns were determined using the methods previously developed and documented by Centrica Energy (2008, 2009. In basic terms, this involves continuous observation of terns crossing in front of a vessel (a ~12m workboat with sufficiently low draught to allow approach to 300 m of shore) along a sufficiently long transect line covering all flight lines both species of terns may take to/from the colony (Fig. 7). The workboat was manned by two crew with observations conducted by one/two recorders.

Previous experience at Blakeney Point showed Sandwich Terns could take a direct route across land from/to the colony when travelling to/from the east, necessitating the extension of the transect line for some distance along the coast to the eastsoutheast. In previous surveys, it had also proved necessary to employ two separate transect routes to intercept birds flying broadly westwards, according to the state of the tide. The main route, used in all tidal states other than high water was 9.5 km in length and was designed to allow detection of virtually all terns leaving in any direction. To the west, this involved extending the route close to shore, whilst to the east it was designed to intercept any terns taking a direct route across land to and from coastal fishing grounds (Fig. 7).

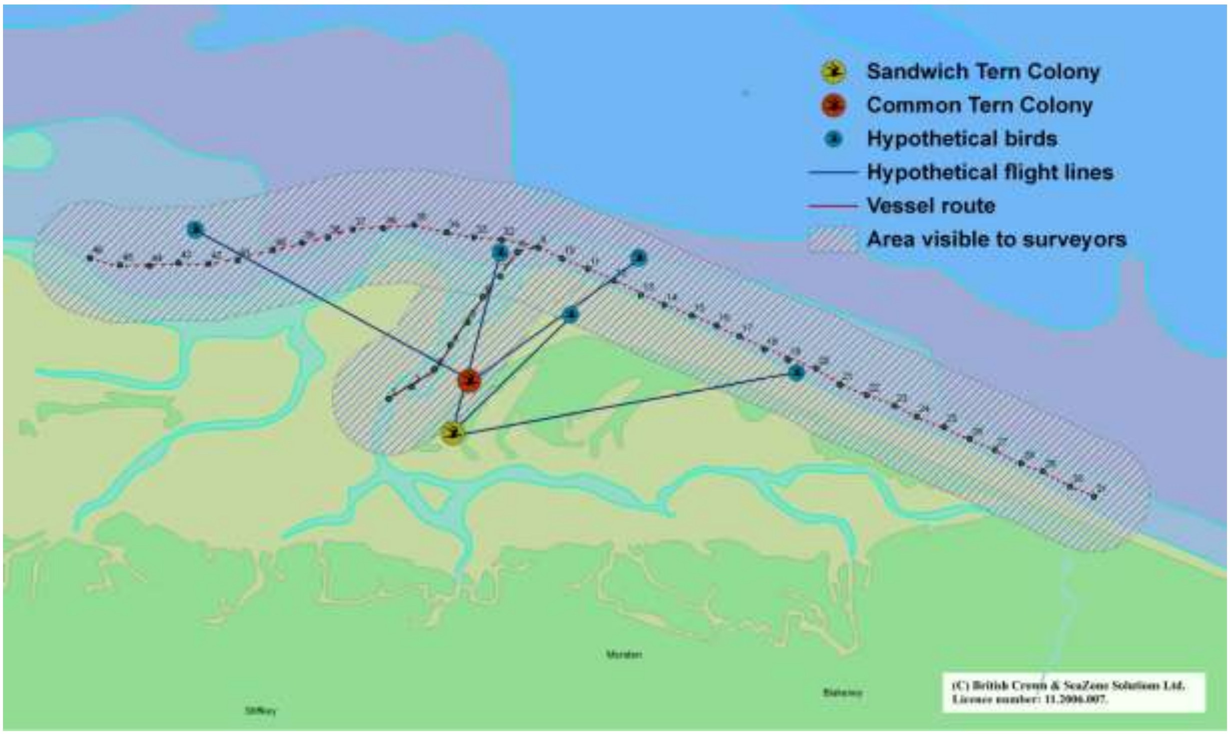

Figure 7. Vessel transect used to assess flight lines of foraging terns showing the minimal potential for birds leaving/returning on acute angles to the east or west going undetected. Numbered snapshot locations are shown.

Around high water, a shorter route (7.36 km) into the harbour mouth was effective, but as the harbour virtually dries down at low water, this route became inaccessible as the tide ebbed. In practice, this route was used on the first run of the day from the harbour to snapshot 31, and on the last run from snapshot 31 back to snapshot 1 (see Fig. 7). This allowed monitoring of the harbour area, which could be used intensively by foraging birds when sufficient water was present. On the runs to and from the harbour the area calculation shown below was adjusted accordingly.

Transects were undertaken simultaneously with tracking over all tidal states in daylight hours (06:00-20:40). The timing of high tide effectively determined how much time was available and how many runs over the transect route could be undertaken in each day. This varied between 5-8 for a total n=34 in 2008 (9 runs were achieved on the single occasion in 2009). Workers swapped tasks during the course of the day and undertook regular breaks to prevent fatigue and maintain data quality.

Recording methodology was similar to that adopted in standard boat-based surveys with continuous recording over 180^{O} (i.e. both sides of the vessel) in combination with specific modifications:

- Only terns were recorded.
- Birds were recorded as travelling 'in' or 'out' of the colony or as 'no clear direction', typically as birds were engaged in foraging behaviour searching for prey, or actively fishing (hovering, diving or handling prey).

- Flight bearing of each individual was estimated in 10^O divisions.
- Bearing and distance (in standard distance bands A-D with E out of transect) of each bird from the vessel were recorded in order to fix its location when first seen.
- Flight height was recorded in categories of 0 (on water), 0-1 m, >1-20 m, 20-120 m and >120 m, partly according to the height of turbines above water surface (>20 m).
- In addition to the continuous recording, instantaneous snapshots (*n*=31 for the high water route and *n*= 38 at other tidal states) over 180^O ahead of the vessel were taken at 250 m intervals with the number and behaviour of all terns recorded.

The methodology assumes that all terns crossing the transect line within 300 m in front of the surveyor (i.e. bands A-D) were seen and recorded, with birds passing beyond the 'detection range' of 300 m distance from the boat excluded from analysis. An estimation of the total passage rate R (per hour) was calculated by:

$$R = A/T * Lr /d$$

where A is the total number of counts in the survey, T is the total time of the survey, Lr is the length of the run (= 5 km), and d is the detection range (= 0.3 km).

A passage rate of birds outbound and inbound was determined for each run. The mean ±1SE time to undertake a run was 60 ± 1.82 mins, with variation caused by strong tidal currents related to engine output. Nevertheless, the run, adjusted for time, provided a useful unit of measurement, which could be readily related to the tidal cycle and time of day.

In addition to passage rate, the density of terns in flight (ind. km^{-2}) for each run on each sampling occasion was calculated from the number of birds in snapshots divided by the combined area of snapshots where each snapshot covers 0.18 km^2 (300 m x 2 [sides of the vessel] for a 180° scan). For the shorter, high water transect route the total area of snapshot was 5.58 km^2 increasing to 6.84 km^2 for the longer, main transect. Birds were stratified on the basis of behaviour, with birds classed as foraging, actively engaged in feeding activity (hovering, diving or capturing prey), in display, or simply in flight outbound or inbound (often carrying prey) from/to the colony. The density of terns was used as an indicator of overall activity levels.

Preliminary plots (not shown) of the passage rates hour by hour throughout each survey occasion showed that there were definite peaks and troughs in the data suggesting there were periods of little activity interspersed with periods when there was a marked increase in either the number of birds heading out to forage or the number returning with prey, suggesting some effect of environmental variables (see Dunn 1973, Stienen *et al*. 2000). The influence of environmental factors on both outbound and inbound mean passage rates and activity levels was therefore examined using a range of predictor variables including tidal period (measured as hours before or after high water), tide height (measured at nearby Cromer), wind speed (Beaufort scale), wind direction and time of day. Mean densities of all flying birds derived from snapshots carried out at 250 m intervals on each run were used as an expression of activity levels. These density values included birds that were actively foraging within the survey transect, as well as inbound and outbound birds. Observations were stratified according to the behaviour observed for each individual bird, including foraging, active fishing and display behaviour for separate analyses. The relative frequency of each behaviour class was analysed in relation to the same range of predictor variables. Whilst a thorough analysis proved possible for Sandwich Tern, the limited number of observations of Common Tern during survey runs (see 4.1.1 below) limited statistical power for elucidating relationships between passage or activity rates and environmental variables. The dataset for Common Tern was smaller partly because there were fewer birds, but may also relate to potential differences in foraging behaviour, discussed further in section 4.3 below.

For all analyses, relationships were explored statistically using General Linear Models (GLMs) with Gaussian error distribution and identity link function, programmed in R version 2.9. In cases where the frequency distribution of the response variable deviated from normality, normalising log transformations were carried out prior to analysis. Temporal variables such as time of day and tidal period were included in analyses as categorical variables (i.e. observations separated into discrete time periods) to account for the potential non-linearity of temporal patterns. Due to sample size limitations, the maximum number of predictor variables that could be explored in multivariate model selection was restricted. Consequently, the significance of each predictor was tested initially using univariate GLMs. The relative influence of each the three most significant variables was then assessed by comparing model goodness of fit across all combinations of those variables using Akaike's Information Criterion (AIC), with lower values indicating better fitting models (Burnham & Anderson 2002).

3.2.2 Cemlyn Bay

Counts of the passage movements of the three species of terns – Sandwich, Common and Arctic – to and from the Cemlyn Bay colony were undertaken over one hour on 21 occasions over nine dates and spanning all periods of the tidal cycle and diurnal period (from 08:30 – 20:00 hrs). One person conducted counts by either dictating to a data recorder or by using a series of hand-held clicker counters. Wherever possible (usually where a second data recorder was employed), the proportion of birds returning with prey and the nature of that prey was recorded. Size of prey was recorded relative to bill length of 5.43 cm for Sandwich Tern (Stienen *et al*. 2000), 4.0 cm for Common Tern and 3.5 cm for Arctic Tern (Cramp & Simmons 1985). The identity of prey was recorded in the most detail possible (i.e. to species wherever possible, but otherwise to genus, family or simply as fish or invertebrate where seen poorly). Identification of prey was aided greatly by periodic capture of a series of digital images taken by a high specification DSLR camera with a telephoto lens of up to 680 mm focal length.

The flight direction of birds either leaving or returning to the colony could not be readily determined partly as birds appear to generally fly on a curving course across the bay to and from the open sea, and thus a bearing taken at the colony may bear little resemblance to actual flight bearing. For Sandwich Terns, which were the subject of tracking, flight direction was taken from the bearing of tracked birds (*n*= 139) at around 1 km from the colony, once out of the bay. To increase the size of this dataset a further *n*= 55 birds were tracked for 1-2 km from the colony, typically in conditions when birds could not be followed for greater distances. Examples of unsuitable conditions included a wind direction that provided a tailwind increasing the speed of birds beyond the capability of the vessel or high sea state and wave height decreasing vessel speed below that of the speed of commuting birds. Such occasions were distributed throughout the tracking period.

Exploration of the environmental correlates of passage rate was only conducted for Sandwich Terns, which were the focus of tracking. Sample size was too small to permit multivariate statistical modelling and as a consequence, separate univariate exploratory GLM analyses of passage rate in relation to time of day and tidal state were conducted.

As it was only possible to land on the Skerries on one occasion (see 3.1.2 above), no systematic attempt was undertaken to record passage rate or flight direction of Arctic Terns from the colony. However, an attempt was made to trial appropriate methods and these may be used in any future work undertaken at the site.

3.2.3 Saltholme on Teesside

Similar methods of determining passage rate to that adopted at Cemlyn Bay were undertaken at Saltholme, with a total of 23 one hour time periods conducted over all states of tide in the period from 07:35 – 19:00 on 10 dates. However, in contrast to terns at Cemlyn, the flight bearing (to 10^0) of both outgoing and incoming Common Terns at Saltholme could be readily determined by a pair of observers positioned on the footpath near Paddy's Pool with a panoramic view of the surrounding area. Direct flight lines from and to the colony indicated that birds were travelling directly to and from foraging grounds. In the case of birds apparently taking a direct route to the estuary, tracking of some birds with a telescope revealed these to be undeterred from their chosen flight path by large roads carrying heavy traffic, power lines and buildings. In such cases, birds simply gained height to navigate over any possible obstacles.

Analysis of environmental correlates of passage rate was undertaken in the same manner as at Cemlyn, with separate univariate exploratory GLM analyses of passage rate in relation to time of day and tidal state.

3.3 Prey type and delivery rate

3.3.1 Blakeney Point

Immediately prior to the first observation and tracking period on 1st July 2008, two surveyors visited Blakeney Point to reconnoitre the positions of the colonies of both species and possible observation positions. The opportunity was also taken to conduct initial observations of the Sandwich Tern colony. In each tracking period, two of the surveyors returned to the Old Lifeboat Station as guests of the National Trust wardens. This allowed additional observations of birds in the Sandwich Tern colony as well as within the most easily accessible Common Tern colony on the beach near Far Point, in daylight hours before and after deployment of the RIB to/from shore and thence the workboat from its mooring in the harbour.

One or two observers undertook three and two visits to the Sandwich and Common Tern colonies respectively, each lasting 1.25–7.5 hours in duration. All observations were conducted using high-quality binoculars (Leica Duovid 10-15 x) or a telescope (Kowa 884 20-60x or 30x wide). For Common Terns nesting in a loose group, several discrete families (*n*=4-8) containing 1-3 chicks could be observed simultaneously. The number, type and size (relative to mean bill length of 4 cm) of prey consumed by one or other chick in the family group, was recorded. A provisioning rate (chick^{-1} hr^{-1}) was readily derived for each family group of known size. Total observation time (duration for each group x number of groups) was ~41 hrs.

Observations were conducted in a slightly different way for Sandwich Terns nesting in a dense colony. Here, the number, type, size (relative to mean bill length of 5.43 cm) and fate of prey (e.g. consumed by chick or adult or kleptoparasite) delivered to a group of chicks (*n*=13-28) and their attendant adults were observed in time blocks of 1-2 hours. On the first visit, the smaller chicks were relatively sedentary and up to 14 individuals could be observed at any one time. On the second and third occasions, the more developed chicks were highly mobile within the colony and it was not possible to follow individuals for anything other than a very short period of time. The number of chicks in view was thus recorded every 1-2 mins, with the resulting weighted mean value applied to the overall number of deliveries to derive an estimate of individual (per chick) provisioning rate. Total observation time was 58 hrs derived from the number of chicks on the first visit multiplied by the duration of the observations added to the group size x duration of observations on the second and third visits.

Similar observations were made in 2009 on Sandwich Terns, although in this instance birds were watched for 2-hour blocks on all occasions. On the first occasion (1st July), the young ranged in size from chicks estimated to be between 9-10 days old to much larger juveniles that were near to fledging, although by the second two occasions (14th and 15th July) all of the birds observed were fully fledged juveniles.

In addition, for Sandwich Terns only, timed observations of a succession of randomly selected returning adults were also made. For each returning adult the type and size of prey carried, fate of the prey (e.g. ultimately delivered to chick or partner, lost to gull or another tern, swallowed by adult or unknown), the number of attempts the adult made to deliver the prey and number and ferocity of any kleptoparasitising attacks by Black-headed gulls or other terns were all recorded. An event was classed as a kleptoparasitic attempt if any nearby gull showed deliberate movement towards the focal tern, causing evasive movement. Events that did not progress beyond these initial movements were classed as ‘type 1’ kleptoparasitism attempts. More extreme events, for example where a gull or gulls continued to chase the tern, forcing further evasive movements, were classed as 'type 2' events. For each focal observation, an attack intensity score was calculated by summing all recorded kleptoparasitism events during the observation bout, with type 1 events being awarded one point and 'type 2' events two points. In order to analyse the influence of prey type and size on the likelihood of kleptoparasitism, Generalised Linear Models (GLMs) with a binomial distribution and log link function were used. These models use a binary response variable whereby zero values denote observations where no kleptoparasitism attempts were recorded and values of one denote observations where at least one attempt was observed.

3.3.2 Cemlyn Bay

Observations on Sandwich Terns were conducted at Cemlyn for up to 12 hrs per day between the periods of 27th May and 9th July 2009 in a similar manner to that adopted at Blakeney Point, but with the observer(s) in the colony rotating tasks between observations of individual chicks, following delivering adults potentially subject to kleptoparasitism and estimating passage rate (see 3.2.2 above).

Time blocks for chick observations were 1-2 hours with up to 19 broods watched when chicks were relatively small. The relative length of the vegetation and the relative proximity of the colony restricting the field of view through a telescope even at lowest magnification limited the number of broods that could be watched at any one time. The relatively small size of the islands meant that older chicks (unless they were fully fledged) were largely sedentary compared to Blakeney, meaning this could also be watched more or less continuously. Kleptoparasitism events were recorded in the same way as at Blakeney, although it quickly became clear that the intensity of attacks was far less frequent at Cemlyn.

3.3.3 Saltholme on Teesside

Observations of Common Tern at Saltholme were undertaken in a more similar way to those upon Sandwich Tern at Blakeney and Cemlyn Bay rather than Common Tern at Blakeney, largely as a result of the coloniality of nesting birds in a restricted nesting space. For example, a larger number of broods (9-23) containing 1-3 chicks could be observed simultaneously. There was also a need to determine the rate and intensity of attempted kleptoparasitism of both adult provisioning adult Common Terns and their receiving chick(s), which was undertaken by Black-headed Gulls and especially by other Common Terns and their older chicks. Such behaviour was not recorded at Blakeney Point.

As at Cemlyn, the pair (or three on one occasion) of observers swapped tasks during the day, individually undertaking observations of broods over 2 hrs interspersed by shorter (0.5 – 1 hrs) bouts of timed delivery attempts (as conducted for Sandwich Terns at Blakeney Point) and 1 hr periods of passage rate observations when they needed to work as a pair (see 3.2.3 above). Observations were undertaken for 5- 8 hrs between 07:30 and 19:00 hrs, outside the normal opening hours of the reserve with full support from the RSPB.

3.4 Tracking foraging terns at sea

3.4.1 Blakeney Point

Previous work on Sandwich Tern had proved birds to be large enough to maintain continuous visual contact by eye (visual tracking) from aboard Alpha 1, a 6.3 m Humber Offshore Ocean Pro rigid-hulled inflatable boat (RIB) capable of reaching speeds of up to 35 knots carrying a driver, recorder and observer(s) (Centrica Energy 2008, 2009) (Fig. 8). The preferred distance for observations was 50-100 m from the bird during which all aspects of behaviour could be determined. This included changes of speed, flight height and subtle deviations in wing beat rate indicating when potential prey had been sighted (wing 'flicks'), as well as the process of diving and the identity and size of prey captured.


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Figure 8. Rigid-hulled inflatable boat (RIB) used to track Sandwich and Common Terns in 2008, with driver and recorder (the observer is taking the picture).

Tracking of both Sandwich and Common Terns was undertaken at Blakeney Point in 2008 (no further tracking was undertaken in 2009). No attempt had previously been made to track Common Tern using a RIB and notwithstanding subtle differences in foraging patterns compared to Sandwich Tern, this species proved to be equally amenable to be monitored by the technique. For ease of switching attention between species during tracking, the colony of Common Tern on the beach towards Far Point in close proximity to the single colony of Sandwich Tern was selected for study. On four of the five different tracking sessions, individuals of both Sandwich Tern (*n*=2-9) and Common Tern (*n*=1-18) were tracked, the only exception being the first occasion when only individuals of the more familiar Sandwich Tern were chosen.

The aim of tracking was to follow randomly selected individuals of either species leaving their respective colonies and to follow them throughout a complete bout until their return[1]. However, in practice this was often not possible, although the proportion of birds for which this was achieved was similar between the two species, with 62% of *n*=26 Sandwich Tern and 60% of the *n*=25 Common Tern. Reasons for losing birds were relatively similar to between species, with birds simply outflying the vessel, confusion and loss of birds in foraging aggregations, flight over shallow water/sandbars and loss of visibility in torrential rain all playing a part. Nonetheless, the main factors differed with 31% of Sandwich Terns lost after they outstripped the vessel (cf. 20% for Common Tern) perhaps due to the superior flight speed of the larger species, whilst 60% of Common Terns were lost within feeding groups (cf. 13% of Sandwich Tern), illustrating the tendency of this species to forage in large aggregations.

In all tracking at sea a number of variables were recorded at ~1 min intervals within the constraints of recording data from a rapidly moving vessel in variable conditions. The latter ranged from 1-4 Beaufort wind scale with variable directions in the quadrants from northwest to southeast. The variables recorded included:

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[1] on one occasion a bird was selected when the original bird had been lost and the vessel was a long way offshore.

- The location of the tracked bird on a hand-held GPS, thereby assuming the vessel passed an almost identical location a few seconds later than the bird.
- Flight speed determined directly from the speed of the vessel.
- Flight height in categories of in categories of 0 (on water), 0-1 m, >1-20 m, 20-120 m and >120 m, linked to height bands in boat-based surveys (see Centrica Energy 2008, 2009).

For individuals of both species that were either tracked for a complete bout or lost during tracking, bout duration (hrs), flight speed (km hr^{-1}), distance travelled (km), maximum distance from the colony (km), maximum distance offshore (km), and rate of foraging attempts (hr^{-1}) were calculated. An angle of deviance of flight was also estimated in which the bearing over the 5 fixes (mean distance of 4.08 km) from the colony was taken as the line of flight and compared against a bearing from the colony to the position furthest from this line of flight. All distance and bearing functions were derived from plots of tracklines using ArcGIS (v.9.2).

The proportion of fixes (time) birds spent in the vicinity of other terns and other species of birds (e.g. gulls and auks) and mammals (seals and cetaceans) was used as an expression of foraging association between conspecifics and within so-called multi-species foraging associations (MSFAs) (Camphuysen *et al*. 2004, Camphuysen 2005) respectively. Most individual Sandwich (85%) and Common Terns (86%) were recorded successfully foraging and the location, type and size were recorded, although a relatively high proportion of prey could not be specifically identified even to generic 'fish' or 'invertebrate' for either species (25% and 27% for Sandwich and Common Tern respectively). However, many birds were recorded foraging repeatedly using the same techniques on what appeared to be the same or similar items, although only a few items had been clearly identified. Consequently, missing items in such bouts were assigned as the same as the observed item(s) improving the level of identification to 61% and 35% for Sandwich and Common Tern respectively. The remaining items were assigned according to the proportions of particular fish and invertebrates captured by that individual. A mean length of each fish species and for a generic 'invertebrate' was then assigned from pooled records of identified items captured by all birds. Length-weight relationships were used to derive approximate biomass (g) of each item consumed. Relationships for clupeids and sandeels were taken from Stienen *et al*. (2000) with a relationship for invertebrates (fresh weight =0.000372445*length1.6969 N=386, r^2 =0.69) derived from a mixture of the sea slater (*Idotea* sp.) and shrimps (from small *Schistomysis spiritus* to large *Palaemon* sp.) sampled by Perrow *et al*. (2008).

With considerable variation in all variables even amongst birds with complete bouts (e.g. bout duration ranged from 1-70 mins for a distance of 1.6-77 km in Sandwich Terns), there were no statistically significant differences in variables between birds that were lost relative to those that were tracked (Mann-Whitney tests all p>0.13) and thus all data were pooled.

As well as tracking at sea, a number (*n*=17) of Common Tern and a single Sandwich Tern were tracked using a shore-based telescope (Kowa 884 20-60x). These observations were conducted as a result of an inability to launch the RIB (and thus also reach the workboat moored in the harbour) because of an insufficient depth of water at high tide on the first high water of day 1 (02:44 hrs) in the second period. Unexpected deterioration of the weather also meant that a launch on the second high water at 15:20 hrs could also not be performed. The position of the tracked bird was determined at regular intervals by estimation of bearing (using a compass on the telescope) and distance of the bird from the observer, with the latter aided by the relative position of a number of buoys in the navigable channel, which had previously been accurately geo-referenced.

The proportion of Common Tern tracked over a complete bout was similar to that conducted at sea (53% cf. 60%), with the single Sandwich Tern also recorded over a complete foraging bout. There were no statistically significant differences in any variables between Common Terns that were followed over the entire bout or lost during the bout. These data were therefore pooled and compared with those gathered during tracking at sea. With no differences in any variable, the datasets for both RIB-based and shored-based tracking were combined for Common Terns, with the single Sandwich Tern followed over a complete bout also added to the RIB-based data for the species. Total *n* was thus *n*=27 for Sandwich Terns and *n*=42 for Common Terns. Mann-Whitney tests were then used to test for inter-specific differences in any variables.

3.4.2 Cemlyn Bay and the Skerries

Tracking was undertaken in basically the same manner as undertaken at Blakeney Point, with Sandwich Terns selected and contacted within ~200 m of leaving the colony within Cemlyn Bay itself. However, on one occasion, it became clear that birds were also leaving across the headland to the west of the colony. Tracking a sample of these birds required the vessel to be positioned outside of the bay itself in a safe location to the west of the mainly submerged (apart from at low water) reef system.

Tracking was primarily[2] undertaken aboard *Liparis* an 8 m RIB fitted with a 150 HP engine with a maximum speed of 55 km hr^{-1} (~30 knots). The vessel was launched from Bull Bay some 11 km away to reach Cemlyn or from Holyhead to reach the Skerries (see below). The rocky, mostly deepwater (30 m may be present within a few metres of the cliffs) coastline was charcterised by heavy swell waves often relating to tidal state produced 'confused' seas in otherwise suitable conditions. A combination of the prevalence of more difficult conditions and relatively low speed of the vessel led to a low proportion of Sandwich Terns (13%) of the *n*=139 birds tracked (an additional *n*=55 were tracked over 1-2 km solely for the purposes of determining flight direction) being followed continuously for a complete bout. A further 4% were lost whilst flying back to the colony. A total of 77% were lost from view by flying faster than the vessel, with 13% confused with other birds. Of the remainder 2% of birds were lost in fog, 2% were lost flying over rocky areas, and 1% (2 birds) landed on beaches some distance from the colony in groups of other birds.

A return to the colony to track another bird each time the initial bird had been lost introduced the risk of inadequately describing something close to the full extent of the potential range of the birds foraging from the colony. As a result, where the initial bird had outstripped the vessel when in transit, a tactic of waiting for another on the same flight line was adopted. As most birds approved to undertake eastward movement along the coast from the colony, only a short time generally elapsed before another bird became available to track. A sample of 'composite' tracks (*n*=10) involving up to 8 birds per track was thus also derived. This illustrated that Sandwich Terns commuted up to 40 km from the colony, in tracked bouts of up to 57 km in length and up to 87 min duration. These values obviously still remain an underestimate of the scope of foraging terns from the colony. However, a high proportion of birds were recorded foraging which tends to suggest that a reasonable understanding of foraging range and tactics was likely to have been gained.

The trial of tracking Arctic Terns at the Skerries was undertaken over a single day (12th June) using the same methods as described for Sandwich and Common Terns at Blakeney and Sandwich Terns at Cemlyn. Whilst Arctic Terns also generally proved amenable to the technique, the notoriously difficult sea conditions around the Skerries added to the difficulties of tracking these birds with only 2 of the 7 birds tracked (29%) for an entire bout. However, of the others, 29% were lost with other birds, 13% flew too fast to follow, and 29% had to be left as there was a risk of the vessel running out of fuel. Nonethless, one of the latter two birds was tracked for the longest distance at 57 km reaching nearly 29 km from the colony. This bird was attracted to auks, especially Puffin *Fratercula arctica* presumably as a result of the potential for feeding auks to drive prey to the surface that may then promote multi-species foraging associations (Camphuysen 2005). However, Puffins proved to be more susceptible to disturbance by the vessel at close quarters than the tern, and typically flushed. Although forward planning to maintain greater distance as the tracked tern approached foraging auks was

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[2] a 7 m vessel was also used on the first tracking occasion

attempted where these could be seen, it seems likely that the foraging success of the tracked tern was lower than it might have been.

3.4.3 Teesside

Tracking was undertaken using Per Mare, an 8.4 m ex-Royal Navy RIB fitted with a wheelhouse and powered by a 225 hp Honda V6 outboard engine. The vessel was moored in Hartlepool Marina some 7 km to the north of Teesmouth. Hartlepool is tidally restricted although the lock system at the marina allows access up to 5 hrs either side of high water. On each occasion, the RIB accessed Teesmouth from the sea, informing the coastguard of its activities in what is an extremely busy shipping channel.

As outlined earlier (see 3.1.3 above) the RIB was positioned at the head of the deepwater channel to the nuclear power station near Seal Sands within the Teesmouth estuary to intercept Common Terns on a direct flight line from the colony. On several occasions, patrols were taken upstream to determine if birds were also using any other flight paths to access the river. This proved to be rare, with only 4 of the n=107 terns tracked being collected upriver of Seal Sands. Sampling flight lines from the colony (see 4.1.3 below) supported the view that Common Terns generally take a direct flight path to the estuary and not the river.

Tracking was undertaken as at the other sites, although it was complicated by the wheelhouse on Per Mare, which meant that the observer tracked the bird from the stern of the vessel relaying instructions to the skipper inside the wheelhouse, especially in relation to which bird was being tracked. This contributed to the loss of birds during tracking, which was also complicated by the position of the breakwater at South Gare as when heading broadly south birds tended to fly over this structure as well as and overland on a more acute angle to the coast. On such occasions, the vessel had to deviate around the breakwater, which typically took several minutes leading to the loss of the tracked bird. A bird encountered on the same flight line or adopting similar behaviour to the initial focal bird before it was lost was then followed, resulting in some composite tracks in a similar manner to Cemlyn. A number of terns were also lost by their use of a very shallow area of water in an embayment on the northern side of the breakwater where the vessel could not follow. Indeed, the vessel was obliged to spend virtually all of its time when in the estuary mouth within the dredged deepwater shipping channel, on account of the treacherously shallow waters with a variety of submerged obstructions outside of it. In these circumstances, the position of the bird was generated by taking the approximate distance (m) and compass bearing of the bird from the vessel at specified time intervals (1-2 min) for later adjustment in GIS.

As a result of a combination of physical factors such as birds outstripping the vessel (21%) or birds being lost heading out over South Gare (9%) coupled with the prospect of confusing birds in feeding aggregations (27%), a low proportion of Common Terns (19%) were followed for a complete bout.

3.5 Modelling approaches

3.5.1 Simulation of foraging movements

The first attempt to visually track Sandwich Terns at Scolt Head in 2006 (Centrica Energy 2008, 2009) showed that outbound birds (n = 37) travelled along remarkably straight flight paths from the colony with a mean (± SE) of 28.2 ± 9.7° flight deviation (see 3.4 below). Birds thus appeared to have preconceived knowledge of a suitable foraging location prior to leaving the colony. Initial flight direction was thus likely to be a good predictor of the general direction of the foraging bout, providing the opportunity to construct a foraging simulation model based on bearing specific distance distributions (probability density functions or PDFs). This was written in Visual Basic by Aulay Mackenzie at the University of Essex and used the relatively large dataset of the bearing of outbound birds recorded from transect surveys.
The same model was then applied to Scolt Head and Blakeney Point in 2007 using specifically

gathered data. Tracking from Blakeney Point in 2007 produced a similar dataset of *n*=45 birds whilst recording a higher flight deviation of 45.3 ± 16°. Data from the current study with *n*=26 provided a further increase in the angle of deviation of 53.5 ± 13.9° suggesting some change in the patterns of flight behaviour between years and perhaps also between colonies. Despite the potentially confounding effect of deviation in flight bearing on model output, in order to provide a comparative approach with previous results, the same model structure was adopted in the current study.

In the model, each of 15,000 simulated birds flying from the colony was randomly allocated a flight direction from the range of possibilities observed during transect runs. In previous modelling (see Centrica Energy 2008, 2009) the distance flown by each individual bird in the model was drawn from a direction-specific statistical distribution, the parameters of which were determined by broad reference to data from tracked birds. Sandwich Terns are capable of extreme range, as shown by previous aerial surveys where terns were recorded to 60 km, the edge of the survey area (DTi 2006). Birds were also physically tracked to 45 km in 2006 and 62 km (Blakeney) and 72 km (Scolt Head) in 2007. A continuous distribution is theoretically appropriate to capture rare long-distant movements, although the outcome of the model is not dependent on the detail of the extremes, as individuals in this category will have flown beyond any OWF considered. Conservatively, the model assumes that the distribution of distance travelled will be leptokurtic, that is, there will be fewer very long distant foraging trips than that which would arise from the same mean and variance in a Gaussian model.

Distribution of flight distance was thus derived from the Weibull function, of the form:

$$y = \frac{\alpha}{\beta^{\alpha}} x^{\alpha-1} e^{-\left(\frac{x}{\beta}\right)^{\alpha}}$$

where the cumulative density function is given by:

$$y = 1 - \exp\left[-\left(\frac{x}{\beta}\right)\right]^{\alpha}$$

In 2008 however, the range of Sandwich Terns was reduced compared to previous years, with a maximum of 27 km for a tracked bird (see 4.3 below) i.e. 38-60% of maximum values in previous years. Coupled with the relative lack of data to determine bearing-specific distance relationships, the same Weibull model was used for all flight bearings. The parameters of the distribution were $\alpha = 1.82$, $\beta = 12.45$ with $r^2 = 99.8\%$. The mean distance travelled according to this model was 10.45 km with 80% confidence limits (CL) =16.2 km and 95% CL of 23.1 km, with the overall values predicting some 90% of movements within 20 km (Fig. 9). This accords reasonably well with the mean maximum distance of 6.8 km of tracked birds (see 4.3 below).

The output of the model comprised 'end-point' foraging locations displayed in density maps on a grid of 1 km x 1 km representing around 81 % of the total estimated foraging flights at Blakeney Point in 2008. In other words 12,161 of the 15,000 simulated flights were recorded on the gridded map, the remainder falling in 'inshore' locations as a result of the sensitivity of the model to the error around flightline bearings. The proportion of 'birds' foraging in particular areas according to the model including the respective OWFs could then be readily compared with the real, but coarse distribution generated by tracking birds and that determined by aerial surveys (DTi 2006, BERR 2007b). Moreover, birds overflying any area including an OWF ('flyovers') on the way to another, more distant foraging end-point could also be determined.

At Blakeney Point in 2008, Common Terns showed a different pattern of foraging behaviour (see section 4.4.1 below) resulting in an extremely large angle of deviance from the initial bearing (89.27 ±16.25°), which was judged to undermine the basis of the existing model and no modelling of foraging distribution of Common Tern was undertaken. Similarly, no specific attempt to modify the existing foraging model was made for Sandwich Terns at Cemlyn Bay as tracking had showen that there was very little, if any, prospect of interaction with the Irish Sea Round 3 development zone in the Irish Sea (see section 4.4 below) as a result of a rather restricted pattern of movement often in an eastward direction along the coast.

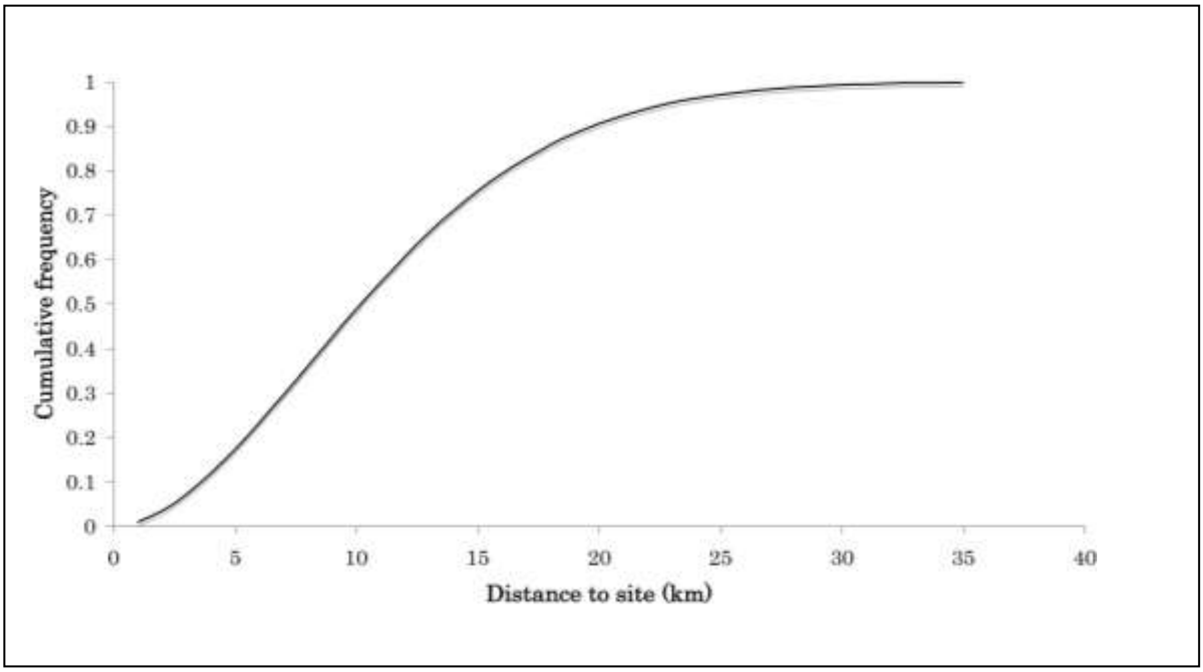

Figure 9. The Weibull distribution of the flight distance relationship applied to all flight bearings of Sandwich Terns outbound from the Blakeney Point colony in 2008.

The extremely limited tracking of Arctic Terns from the Skerries meant there was too little data to develop a meaningful model. However, the prospect of considerable range in a number of different directions, and with the potential for breeding birds in what is a relatively large colony to reach the Round 3 zone on foraging trips, suggests that modelling may be a useful tool should further work be undertaken at this colony. Should this occur, it remains possible that a function to incorporate the foraging behaviour pattern of the birds using fractal analysis of foraging track data could be meaningfully added to the existing model.

At Saltholme, although Common Tern adopted a different foraging pattern to birds at Blakeney Point, with scope to reach greater distance offshore (see section 4.4.4 below) and thus bearing a superficial resemblance to the patterns of Sandwich Terns, this was also interspersed by ‘wandering’ movements within the estuary and also occasionally within the river itself. Consequently, the model in its previous form could also not be meaningfully applied. Moreover, the relatively small size of the colony (300 pairs) and the relative proximity of the proposed OWF compared to the distance of foraging movements meant that there was already reasonable confidence in the gathered dataset to adequately evaluate the interaction between the OWF and breeding birds. The risk of collision, a key interaction, was assesed through application of collision risk modelling (see 3.5.3 below).

3.5.2 Foraging range from an energy balance approach

A key benefit of gathering data on the foraging ecology of target species is the enhanced ability to understand the behavioural factors that might fundamentally influence interactions with an OWF(s). In the case of terns, a key question is what influences the foraging ranges of breeding adults, and hence the extent to which they overlap with OWF developments. Direct measurement of foraging ranges accomplished by visual tracking, has helped illustrate the scope of movements. However, tracking has only been conducted within a relatively short period, and the extent of temporal variation in foraging range remains unknown. Furthermore, the difficulty of tracking terns for complete foraging bouts in some conditions, particularly at greater distances from shore (see 3.4 above) means that direct measurement from visual tracking is likely to underestimate offshore foraging range.

In order to improve our understanding of factors influencing tern foraging, data gathered over several years (i.e. incorporating the data in Centrica Energy 2008, 2009 gathered from 2006 and 2007) both during visual tracking and by observations in the colony were synthesised to develop a dynamic energetic model of foraging behaviour. The model was initially constructed using data from the North Norfolk Sandwich Tern colonies, which represents the most complete dataset on foraging ecology available, including relatively detailed information on prey capture rates at sea, prey species and size selection for provisioning, kleptoparasitism rates and foraging flight dynamics from a combination of observations in colonies and tracking foraging adults at sea.

Fundamentally, a breeding adult tern is likely to seek to maximise the rate of energy provision to chicks, whilst also meeting its own energetic needs. Energy provisioning has two underlying components: the rate at which items are fed to the chick, and the energy content of those items (minus any handling costs such as indigestible parts). Generally, larger high-energy prey items are likely to be scarcer and harder to find than smaller low-energy ones, meaning that the optimal provisioning strategy usually represents a trade-off between delivery rate and the size of items delivered. For Sandwich Terns, a further consideration might be the potential for loss of items through kleptoparasitism, particularly as kleptoparasites are known to target individuals carrying larger high-energy items (Stienen *et al*. 2001).

The trade-off between provisioning rate and prey size is of particular significance to this study as it is likely to be a strong determinant of foraging range. Tracking has revealed that foraging Sandwich Terns follow a relatively linear path after leaving the colony, generally taking them offshore (as opposed to searching back and forth in inshore waters - see 3.5.1 above). If foraging individuals choose to balance the trade-off in favour of capturing large high-energy items, they might need to search for long periods before finding such an item, potentially resulting in long distance offshore movements. If the trade-off were balanced in favour of provisioning more frequently with smaller items, individual foraging bouts would likely be much shorter and reach lower distances from shore.

Tracking of Sandwich Terns has indicated that many foraging bouts last upwards of two hours and can reach distances of >60 km from shore (Centrica Energy 2009) although most foraging trips tended to be much shorter (mean distance reached from shore per tracked bout = 6.1 km ± 9.3 s.d.). This broad variation in bout length implies that Sandwich Terns might adopt multiple provisioning strategies, potentially searching for large high-energy items or targeting small items that allow them to maximise the rate at which provisioning can occur.

In order to begin to quantify the optimal provisioning strategy ofSandwich Tern, the range and respective energy content of prey items taken by adults at sea was examined and estimated. The energy content of sandeels and clupeids the principal prey types was determined using published length-energy regression curves from Wanless *et al*. (2005):

Equation 1: Sandeels: Energy (KJ) = $0.0081 \times L^{3.427}$

Equation 2: Clupeids: Energy (KJ) = $0.0096 \times L^{3.845}$

where L is the length of the item in centimetres.

Tracking showed that foraging adults consumed some invertebrates most of which could not be identified specifically, apart from some Brown Shrimp *Crangon crangon*. Energy content of a generic shrimp-like invertebrate was estimated from the published length-energy regression for Northern Shrimp *Pandalus borealis* (from Lawson *et al*. 1998):

Equation 3: Invertebrates: Energy (KJ) $=10^{1.6537} \times \log(L)^{-3.4837}$

From data gathered by visual tracking, size- and species-specific capture rates of each of these classes of prey by Sandwich Tern in North Norfolk were determined. On the basis of all prey items observed being ingested during 55.6 hours of direct observation of Sandwich Terns at sea, the mean rate of energy intake for foraging individuals in the region was then estimated. It should be noted that some observed items were not identified specifically (usually very small items, identified as either fish species or unknown) and as a result these items were assigned to either clupeid, sandeel or invertebrate on the basis of the relative proportion of each group within the sample of identified items on that occasion. Items caught and carried back to the colony were not included in energy intake calculations. Overall, the mean rate of energy intake was estimated to be 99.6 KJ hr^{-1}.

Using this value, it was then possible to calculate an energy budget for a foraging adult tern by estimating the energy usage in flight and at other times. Previous studies have shown that energy usage during flight exceeds the basal metabolic rate by a factor of around 4.77 (Brenninkmeijer *et al.* 2002). Several previous studies have also reported direct measurements of basal metabolic rate in Sandwich Tern (Ellis 1984, Brenninkmeijer *et al*. 2002), with values showing significant variation in relation to latitude, as occurs in most species (e.g. shorebirds - Kersten *et al.* 1998). Brenninkmeijer *et al.* (2002) provided a regression curve based on these values to predict basal metabolic rate for Sandwich Terns any given latitude. From this regression, we estimated the basal metabolic rate of Sandwich Terns in North Norfolk to be 9.32 KJ hr^{-1}, a value very similar to that estimated at the nearby Waddensee (Brenninkmeijer *et al.* 2002). This gave an estimated mean energy consumption rate during flight of 44.43 KJ hr^{-1}.

From these estimated rates of energy intake and use during foraging flight, it was then possible to construct a model to predict energetic gains of different foraging strategies based on the capture rates of particular species and size of prey by tracked Sandwich Terns. A fundamental assumption of the model is that adult Sandwich Terns attempt to capture any appropriately sized prey item that becomes available during foraging and do not show size selectivity, at least within the size range of prey items that can be taken (approximately 0-30 cm length for clupeids and sandeels). The model allows for subsequent selection decisions as to whether an item will be ingested or carried back to the colony. Following this assumption, the observed capture rate can be used as a direct indicator of the availability of each prey species and size class.

As the energetic properties and abundances of sandeels and clupeids differ, separate models were constructed to examine foraging tactics in relation to these prey types. Although it is not clear whether Sandwich Terns differentiate between prey species, significant differences in the relationship between size and energetic content between the two prey types means that the relationship between size, capture rate and energy balance can be modelled most meaningfully by considering them separately. These models were also combined to generate a model for all prey types assuming no selectivity of any particular prey type.

As the energetic content of both prey species increases dramatically at higher sizes (particularly for clupeids, see equations above), small differences in the rate at which larger size classes are captured could significantly influence the energetic productivity of foraging. More importantly, the size of prey that adults select to bring back to young will be a strong determinant of how long a foraging trip is likely to last, and hence how far offshore the individual may travel. In order to explore this relationship, capture rates for each prey type (and all prey combined) as a function of prey item size, were modelled using capture rates calculated for discrete size classes. In each case, relationships were best explained using exponential functions, which were then used to estimate the minimum search time required for a foraging adult to capture an item of a given size (or greater) for each prey species.

Such equations allowed prediction of the typical search time that would be required to locate an item of a given minimum size. In turn this allowed examination of the implications of variation in prey item size selection strategies by Sandwich Terns. During breeding, it is likely that each individual adult Sandwich Tern will adopt a minimum size selection threshold for provisioning, (i.e. a minimum size before an item to be carried back to the colony). Individuals adopting a high minimum size threshold will search for longer periods in order to locate a prey item exceeding their threshold size, relative to individuals adopting lower threshold levels.

Evidence from visual tracking suggests that fish prey are broadly distributed within offshore waters around the North Norfolk colonies, and that prey items of any size can be located at any distance from the colony. Capture likelihood for larger prey items is therefore unlikely to be dependent on distance reached from the colony, but on the time spent foraging (and hence the size-specific capture rate). An individual adopting a high size selection threshold will therefore generally need to search for a long time period in order to capture an item of their minimum required size, as predicted by the above equations. However, this will not always be the case due to the likelihood that during any given bout items exceeding the minimum size threshold might be captured in much shorter time periods. In order to account for this, estimated search times were weighted by the probability distribution of capture likelihoods for items of each size class across discrete search time periods, derived from observed capture rates. These probability distributions were used to generate a weighted mean search time for each minimum size selection threshold considered (ranging from 2 cm to 18 cm for each prey type). In order to test the robustness of the resulting search time models, model predictions were compared against observed search times for each size class, as determined from observed capture rates during tracking.

Having established a robust model to predict the typical search time required to capture an item of a minimum given size, it was then possible to examine how prey size selection by adults might influence foraging range. A model derived from the above information was then used to predict the distance from shore that an individual Sandwich Tern might be expected to reach on a typical foraging trip if adopting a given minimum size selection threshold (and hence search time) for provisioning. From the typical search times and hence flight distances required to locate prey items of a minimum given size, a time budget was constructed to estimate the number of daily provisioning events for different prey size selection strategies. In addition to search time, each foraging bout involved transit time to carry the item back to the colony, which was determined according to the mean flight speed (measured from tracking at 32.6 km hr^{-1}) and the predicted distance reached from the shore for a given search time. In addition, a hand-over time of 5 mins for each provisioning attempt was assumed (based on colony observations and allowing for a brief rest period). Summing these timings, the total duration of a foraging bout, and hence the number of foraging trips that can be undertaken were estimated assuming constant provisioning activity by one parent for 14 hours per day (the approximate daylight period during the chick rearing).

Using estimates of the energetic content of prey items in relation to item size it was possible to predict the energy that could be returned to the brood for each foraging bout in relation to the minimum size selected for provisioning by adults. Predicted energy returns per bout can be combined with the number of provisioning attempts possible per day for each size selection strategy to predict the level of energy likely to be provisioned to chicks in a single day. This provided the basis of the optimal provisioning strategy.

Basic outputs were relatively simplistic in that they did not take into account a number of other factors that might influence the optimality of provisioning strategies. One factor of particular importance was the energetic requirement of adults during provisioning. During each provisioning event, adults must spend a period of time carrying the prey item to the chick, during which no self-feeding can occur. Each bout will also involve a hand-over period when the chick must be located and the prey delivered. As such, provisioning activity involves significant periods of time when adults must maintain energetic flight, but are unable to feed and therefore have the potential to go into energy deficit. In order to account for this, the energy balance of provisioning adults was modelled by calculating the energy expended by an individual during each foraging bout, based on the predicted search time, return transit distance and hand-over time, and hence time spent in active flight (assuming a mean flight speed of 32.6 km hr^{-1}). Transit distance was estimated from a linear function relating search time to distance reached from colony using data from complete tracked bouts.

Various factors might influence how far foraging terns travel from the colony over time, including prey abundance and distribution, levels of competition (density dependence) and the influence of obligate kleptoparasites such as Black-headed Gull on chick provisioning rates. Given that the population of terns in North Norfolk has remained relatively constant over the last 30 years in particular with a mean (± SE) of 3,550 ± 116.3 thus implying that the level of competition (unless prey abundance changes) has remained relatively constant, there was little impetus to specifically explore density dependence in this case. In contrast, variation in prey abundance over time has a fundamental influence on the breeding productivity of most seabirds (Becker *et al.* 2007, McLeay *et al.* 2008, Crawford 2009), and can be a strong determinant of foraging strategy during brood provisioning (Suryan *et al.* 2000, 2002). Moreover, Sandwich Tern is known to lose prey to kleptoparasites at relatively high rates (Stienen *et al*. 2001, Steinen 2006). It is well documented that the likelihood of kleptoparasitic loss increases in relation to the size of item being carried, introducing the possibility of a significant influence of kleptoparasitism on the relationship between prey size selection strategy and the actual energy delivered to the brood. The influence of prey availability and kleptoparasitism were thus seen as the more important aspects to consider in the modelling exercise.

Rates of prey loss were determined from 56 hrs of observations at North Norfolk colonies between 2006-2009. This showed differences between the two principal prey types, which required consideration. Different intensities of kleptoparasitim were modelled according to the potential maximum and minimum thresholds suggested by observations. To explain, a high proportion of attacks by kleptoparasites involved terns being driven outside the viewable area, preventing observers from determining the final outcome of the attack. Thus, the actual observed rate of loss may be seen as a minimum value, with the corresponding maximum rate assuming that all individuals lost from view went on to lose their prey item during the attack. The true rate of loss is likely to lie somewhere between these maximum and minimum rates.

Using power curves based on these relationships, three kleptoparasitism scenarios were modelled: maximum (assuming all unknown outcomes were losses), minimum (including only observed losses) and intermediate levels (taken as the midpoint of the minimum and maximum power curves for each species). Size-specific kleptoparasitic loss rates were applied to each capture probability distribution for each size selection threshold to predict weighted mean energy returns per bout after the effects of kleptoparasitic loss. Models were then used to predict the daily energy provision rate for chicks under different size selection and kleptoparasitism scenarios.

For prey availability, the mean prey capture rates recorded during visual tracking from 2006-2009 were seen to be a proxy measure of relative prey abundance (or more accurately, the availability of prey to terns). The magnitude of long-term variation in the abundance (or availability) of prey within the Greater Wash off the North Norfolk coast remains poorly understood, but the energetic model provides a means of estimating the likely effects of prey abundance variation on Sandwich Tern foraging strategy.

The parameter of greatest interest in relation to this project is the at-sea foraging range of adults during provisioning, which can be predicted using estimates of the search time required to locate a prey item of a given minimum size (see above). Search times are dependent on the capture rate and hence prey abundance, of each prey size class. In order to examine the implications of prey abundance variation, the model was re-run for a series of scenarios involving proportionate changes to the mean capture rate (+50%, +25%, -25% and -50%, affecting all size classes equally) and hence equivalent changes to weighted search times. Estimates of brood provisioning rates were then generated for each scenario based on minimum size selection thresholds, which could then be used to predict the typical distance from shore reached under each scenario.

Finally, in order to determine if there was any broad variation in individual foraging strategy between colonies, which may mean Sandwich Tern is likely to be at risk of interaction with OWFs at simlar distance offshore in some colonies but not others, the data gathered at Cemlyn Bay during 2009 was also subject to modelling.

3.5.3 Collision risk

Modelling collision risk and evaluating its effect on background mortality is seen as a vital component of the assessment of the likely impact of an OWF (as it is on land). It is important to view the output of any modelling as a guide, rather than an accurate prediction of the number of collisions, partly as the level of likely mortality depends heavily on the rate of avoidance of different bird species. The standard 'Band' collision risk model (Band *et al*. 2000) developed at SNH has been reviewed and is thought to be fundamentally sound (Chamberlain *et al*. 2005) of the model. This model has subsequently been subject to a small number of adjustments to increase the accuracy of the output and its use in an offshore situation (Centrica Energy 2008, 2009).

Modelling is theoretically straightforward given key parameters of the placement, dimensions and operation of the wind turbines and the movements, abundance and behaviour (especially flight height and flight speed) of the birds. The model calculates the number of birds that may be killed in two broad steps: 1) calculation of the number of birds flying through the area of the proposed wind farm and, 2) calculation of the probability that a bird in the wind farm will pass through a rotor and be hit by a rotor blade. Step 1 is calculated from survey results, the layout of the wind farm and the size and operation of the wind turbines whereas Step 2 is a product of the chance of a bird being hit by a blade (the collision risk) and the bird's avoidance rate. The process involves calculation of a collision risk factor somewhere between 5 and 20%. The influence of this on the final number of predicted collisions is relatively small compared to some other factors, most notably the avoidance rate. In other words, the final outcome is relatively insensitive to most of the detail within the model itself.

There is a difference between collision risk modelling for onshore compared to offshore wind farms, stemming from differences in survey methodology. For a site on land the calculations begin with bird numbers or flight lengths observed from fixed points in vantage point surveys. For boat-based surveys offshore, calculations begin with bird density derived from bird numbers observed in each calendar month, which is a typical survey unit.

In the latter case, a key but precautionary assumption is that density is constantly maintained (ie as one bird leaves the site, another replaces it). With known bird flight speed an hourly passage rate may be derived. Knowing the number of daylight hours per month (Forsythe *et al*. 1995), a monthly passage rate is then derived from the hourly passage rate multiplied by the number of daylight hours in the case of diurnally active terns (Stienen *et al*. 2000, Garthe & Hüppop 2004). The number of monthly passages is corrected to include only the proportion of that species seen at indicative rotor height (i.e. >20 m above sea surface) and to incorporate seasonality in the operation of wind turbines. This allows for the fact that at wind speeds below about 4 ms^{-1} (the cut-in speed) rotor blades are stationary and birds are not at risk. To calculate the chance that a bird flying through the wind farm will pass through a rotor, random flight paths are generally assumed (i.e. no preferred flight direction) unless these are known. The average number of rotor passages for each flight through the wind farm may then be obtained by applying the wind farm layout (incorporating the average distance across the site, which may be derived using a monte carlo simulation) and the number of wind turbines.

Monthly mortality is calculated based on the number of monthly passages multiplied by the number of rotor passages per transit and by the collision risk factor. Annual mortality is simply derived from the sum of the monthly estimates. An appropriate avoidance rate is then applied, which is not well known for terns. Back-calculation from data provided by Everaert & Stienen (2006) for the Zeebrugge wind farm on a breakwater near a large mixed tern colony (ie terns almost invariably had to cross a line of turbines to reach the open sea) suggested an avoidance rate of 99.6% for Sandwich Tern and 98% for Common Tern. Using more data from the study of Everaert & Stienen (2006), Whitfield (2008) subsequently suggested an arguably more realistic value of 99% for Sandwich Tern. However, NE and JNCC, the regulatory authorities, prefer a precautionary vaue of 98% for all terns.

In this project, results from the simulation model were put through the collision risk modelling process outlined above according to the methods of Folkerts (2008). In principle, endpoints are likely to cross less of the site than flyovers, with the latter crossing the site twice (2FL), once on the way out and once on the way back. Assuming a random distribution of individuals reaching endpoints suggests that on average an individual would cross half the site to feed and then the same half as it returned, to achieve the equivalent of one flight crossing (1FL). A total distance travelled by Sandwich Terns across each site in the course of the season may be derived from the the proportion of total estimated flights resulting in endpoints and flyovers to the different sites combined with the average distance travelled in each of those flight types. Folkerts (2008) calculated average flight lengths across the Docking Shoal and Race Bank relative to their position from both Scolt Head and Blakeney Point colonies. At Blakeney, this was 6.61 km for Docking and 5.54 km for Race. An equivalent length of 2.76 km for Sheringham was derived from potential flightlines from Blakeney at 5° intervals.

For Common Terns at Teesside, a predicted passage rate across the OWF was derived from the mean hourly passage rate of birds to and from the colony as recorded during observations. The mean monthly passage rate was then multiplied by the number of daylight hours on each day in each month of occupancy (from mid-May to mid-August for 86 days in total) to derive a total number of flights during the season. The proportion of birds with complete tracks (i.e. followed from the time they entered Teesmouth to the time they left, usually with a prey item) that crossed the wind farm was assumed to be representative of the potential passage rate across the site. As it was higher than the proportion of tracked birds with complete tracks (35% from *n*= 7 of 20), this was likely to represent a worst-case scenario.

Modelling was then undertaken in the manner described above using the neccessary parameters of Common Tern (Table 1) and of the prospective wind farm (Table 2). The proportion of birds at rotor height (11.8%) was derived specifically for the birds from this colony.

Table 1. Morphological and behavioural parameters of Common Tern used in collision risk modelling at Teesside, with Sandwich Tern modelled in North Norfolk for comparison. Values are taken from the general literature (http://www.rspb.org.uk[1], http://www.hornsrev.dk[2]).

Species	Bird length (m)[1]	Wingspan (m)[1]	Flight speed (m sec^{-1})[2]	% at rotor height
Common Tern	0.33	0.88	10.8	11.8
Sandwich Tern	0.39	1.00	10.5	44.0

Table 2. Wind turbine parameters used in the calculation of the collision risk factor. As the actual size, type and make of turbines to be installed at Teesside was not available, representative parameters for previouslty installed offshore turbines are shown.

Size of wind turbine (MW)	Number of turbines	Number of blades	Pitch (degrees)	Diameter (m)	Maximum chord (m)	Rotational speed (rpm)
3.6 MW	30	3	10	90	3.4	15.9

4. RESULTS

4.1 Flight direction, activity patterns and passage rates

4.1.1 General patterns

Blakeney Point

A total of 4,166 (88% of records) Sandwich Terns, 375 Common Terns (8%) and 188 Little terns (4%) were recorded from the transect line (see 3.2.1 above and Fig. 7) in broad agreement with their abundance in breeding colonies at Blakeney Point (92%, 4% and 4% respectively). It was generally not possible to ascertain whether individual Little Terns were inbound or outbound according to their flight bearing, as there are a number of small Little Tern colonies at various locations along Blakeney Point. Most birds were seen as individuals, although groups of up to 26 birds were observed. Similar proportions of Sandwich (29.6%) and Common Terns (22.1%) were recorded as outbound (total *n*=1235 and *n*=83 respectively) with lower proportions (20.4% and 10.1% respectively) inbound (total *n*=851 and *n*=38 respectively). Of the returning Sandwich Terns, 53.5% were carrying fish, compared to 39% of Common Terns.

Calculated passage rates for Sandwich Terns reached >2,000 birds hr^{-1} outbound and >3,000 ind. hr^{-1} inbound (Table 3). The far less numerous Common Tern provided far lower passage rates with maxima of 233 and 149 ind. hr^{-1} outbound and inbound respectively. No Common Terns were recorded in runs on some sampling occasions. Densities of the two species also ranged considerably, with maxima of up to 15 ind. km^2 for Sandwich Tern and 3.8 ind. km^{-2} for Common Tern. Compared to their abundance in the breeding colonies, Common Terns were therefore proportionally far more numerous in the inshore waters close to the colony than Sandwich Terns. Moreover, a greater proportion of Common Terns were recorded as foraging/actively fishing (84%) compared to Sandwich Terns (57%).

Table 3. Outbound and inbound passage rates (ind. hr^{-1}) and density estimates (ind km^{-2}) for both Sandwich and Common Terns derived from continuous recording and instantaneous snapshots respectively, during runs (*n*=34) of the colony transect lines. Mean (±1SE), maximum (max) and minimum (min) values are shown. In the year of study the number of pairs of Sandwich and Common Terns nesting at Blakeney Point was 2400 and 103 respectively i.e. a ratio of 23:1.

Species	Passage rate (number of ind.)						Density (ind. km^2)		
	Outbound			Inbound					
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Sandwich Tern	1061 ± 88.4	2335	343	759 ± 108.3	3030	111	6.72 ± 0.53	15.23	1.46
Common Tern	69.59 ± 12.6	233	0	31 ± 7.6	149	0	0.77 ± 0.16	3.80	0.00

As a general rule, although all bearings in the direction of the open sea were represented, Sandwich Terns tended to favour an easterly/eastsoutheasterly bearing along Blakeney Point on outbound passage (Fig. 10). However, there was a tendency to return from the northeast suggesting that birds had sought to exploit inshore prey initially and then moved further offshore before returning. An alternative explanation is that returning birds take the most direct route from easterly inshore foraging grounds, flying over land where they were not readily recorded by colony transects.

Outbound Common Terns showed less bias towards an easterly flightline, with a greater tendency to fly inshore into Blakeney Harbour as well as due west parallel to the coastline. Returning Common Terns showed a very similar pattern to Sandwich Terns, and in the absence of offshore foraging in this species (see below) it is likely that birds readily flew overland to reach the colony.

Individuals of both species exhibited a tendency to return to the colony at ≤1 m flight height (Fig. 11), with this being especially noticeable for Common Terns. In contrast, individual of both species mostly left the colony at a height of between 1-20 m, with proportionally more Sandwich Terns >20 m. Using all records, the flight height distribution was very similar between the species, with the majority of birds between 1-20 m. Only a few Sandwich Terns (0.33%) were recorded at heights of >120 m, typically in display. Common Terns were never observed at this height.

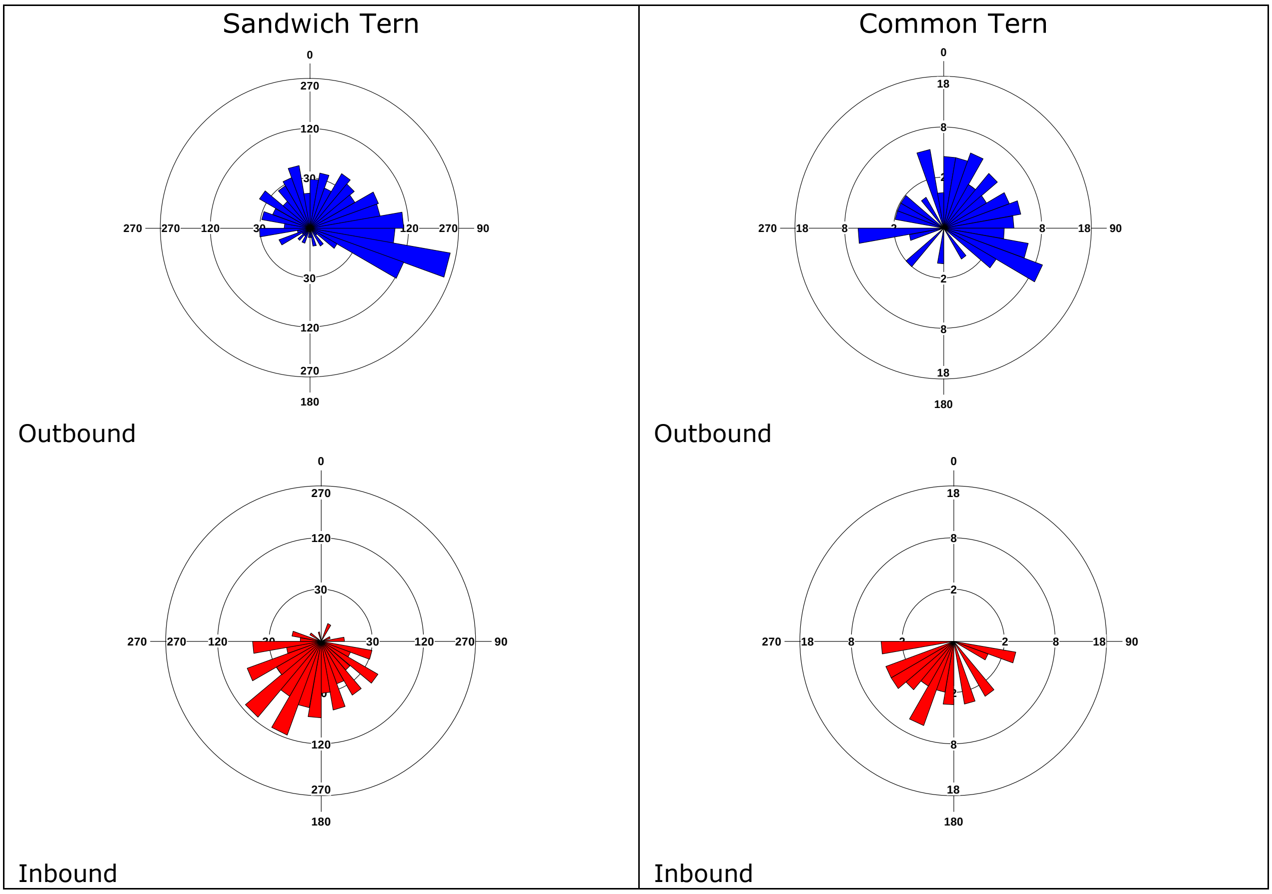

Figure 10. Flight bearings of Sandwich Terns (left) and Common Terns (right) outbound (blue) and inbound (red) from/to their respective colonies at Blakeney Point located at the centre of each rose.

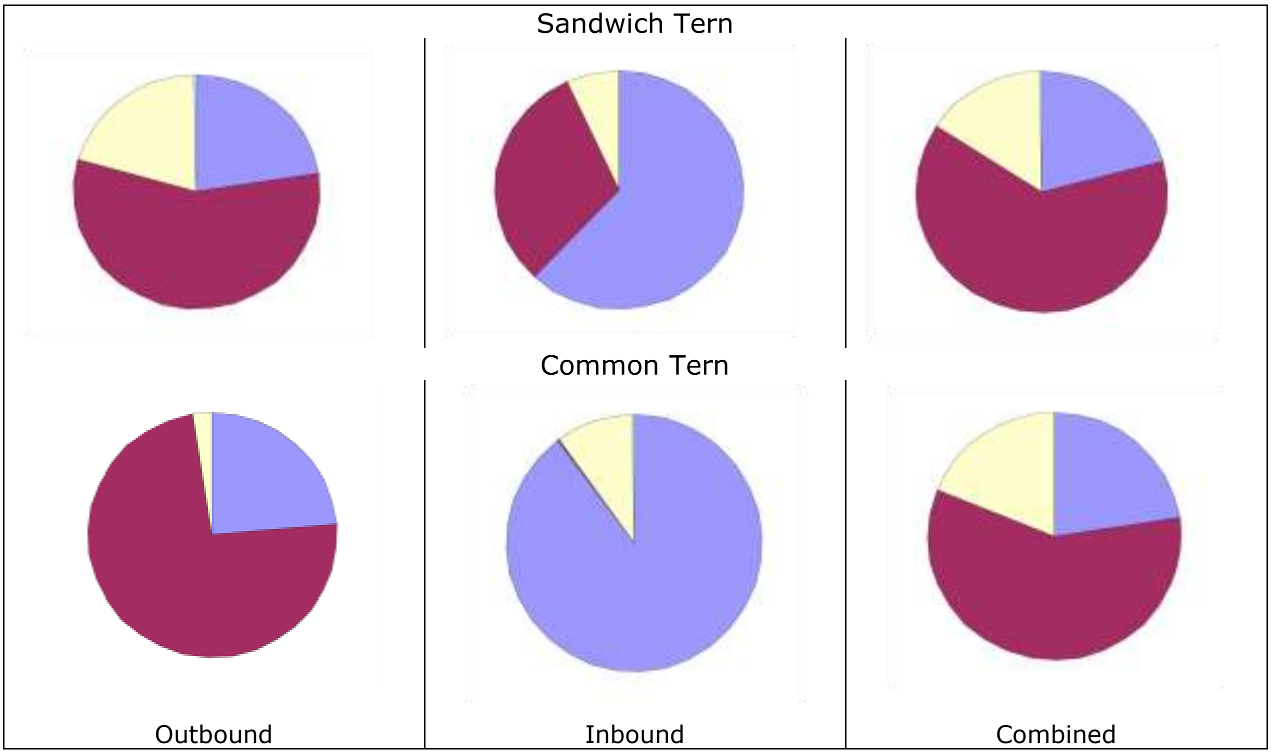

Figure 11. Distribution of flight height categories (blue = <1m, red = 1m-20m and beige = 21-120m) of Sandwich (*n*=4778) and Common Terns (*n*=1354) inbound, outbound and combined observed on all transect line runs at Blakeney Point. The combined total includes *n* =263 birds with no clear direction.

Cemlyn Bay

In total, 22,444 outbound and 22,188 inbound Sandwich Tern flights were recorded, with a mean outbound passage rate of 1,069 individuals hr^{-1} (± 163 s.e.) and corresponding mean inbound passage rate of 1,056 individuals hr^{-1} (± 159 s.e.). The high degree of congruence between inbound and outbound passage rates suggests that the numbers of terns involved were recorded accurately during observation periods (or at least with a similar error). The ease of viewing and relatively narrow movement vector between the colony and the sea were thought to be important in this respect. The outward direction of flight was determined from tracked birds and is outlined below (see 4.4.2 below).

Saltholme on Teesside

A total of 4,807 outbound and 6,179 inbound Common Tern flights were recorded during observations. The discrepancy between inbound and outbound flights (less obvious when rates are considered – see below) was thought to relate to the tendency for some outbound individuals to immediately gain height after leaving the breeding island, making them slightly more difficult to detect than individuals at lower heights, thereby resulting in a small proportion of undetected outbound individuals. Inbound terns on the other hand, invariably returned to the colony at lower heights and were therefore easier to detect.

Outbound passage rates varied from 119 individuals hr^{-1} to 360 individuals hr^{-1}, with a mean of 209 individuals hr^{-1} (± 56.5 s.d., *n*=23 hour-long observation periods). This compares with a corresponding range of 161 to 414 individuals hr^{-1} for inbound flights, with a mean of 269 individuals hr^{-1} (± 60.2 s.d.). Given that the colony was estimated to number 300 breeding Common Tern pairs, these mean passage rates imply that typical foraging bouts last between 1 hr 7 min and 1 hr 26 min, assuming only one parent is provisioning at any given time (see 4.2.4 for a more detailed discussion of provisioning rates and foraging bout lengths).

Both inbound and outbound Common Terns showed a strongly uni-directional pattern of movement, with some 77% of all outbound flights and 81% of all inbound flights following a bearing between 20° and 40° directly to/from Seal Sands estuary, some 3.5 km to the north and northeast of the colony (Fig. 12). For both outbound and inbound terns, directions in the range of 0° to 120° accounted for more than 99% of all flights, indicating that virtually all foraging occurred in areas to the east of the colony in the direction of the sea. Given that freshwater habitats were available in all directions surrounding the colony, this strongly suggests that very little foraging occurs in freshwater habitats during chick rearing. This hypothesis was supported by anecdotal observation of the relative lack of foraging terns over freshwater habitats within the general area of the reserve

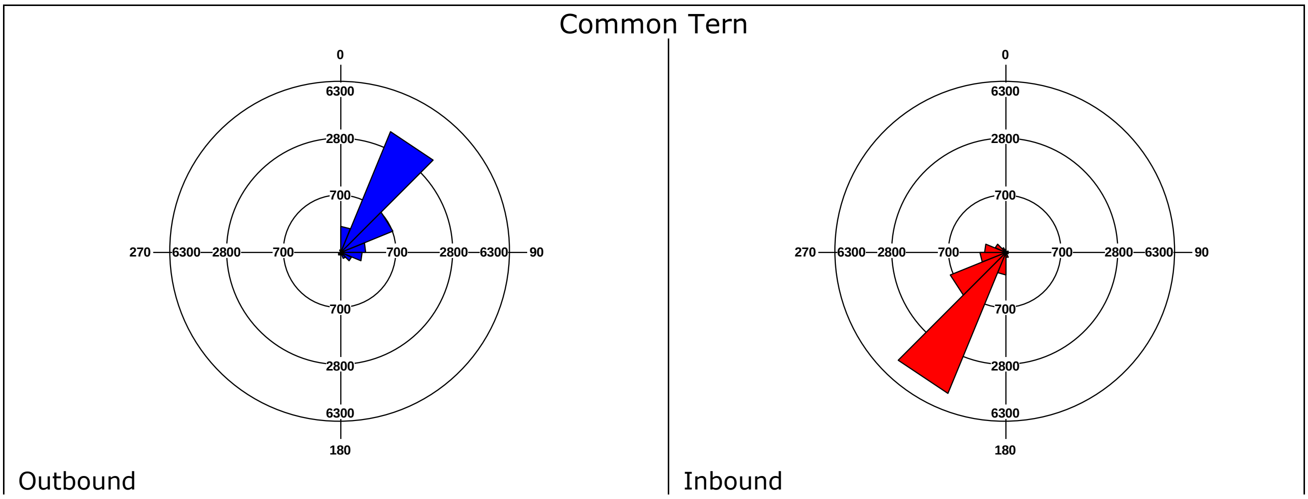

Figure 12. Flight bearings of outbound (blue) and inbound (red) Common Terns from/to the Saltholme colony located at the centre of each rose.

4.1.2 Environmental factors influencing tern activity

Blakeney Point

Statistical models revealed that there were no significant relationships between any of the environmental factors (including time of day, tide state, tide height and wind direction or strength) and hourly passage rates of either outbound or inbound Sandwich Terns. Similarly, there were no significant relationships between environmental variables and snapshot densities of foraging, actively fishing or displaying birds. However, overall snapshot density of all Sandwich Terns on each survey run was weakly, but significantly, related with time of day (GLM ANOVA $F_{7,33}$=2.32, P=0.056, time included as fixed categorical variable). Whilst birds were present within the survey area throughout the daylight period, there was some evidence of a peak in density shortly after dawn and a secondary and potentially more significant peak in the evening (Fig. 13). Increased urgency in foraging directly before and after darkness seems likely to be a response to compensate for any energy deficit incurred by both adults and chicks during darkness hours when foraging does not occur.

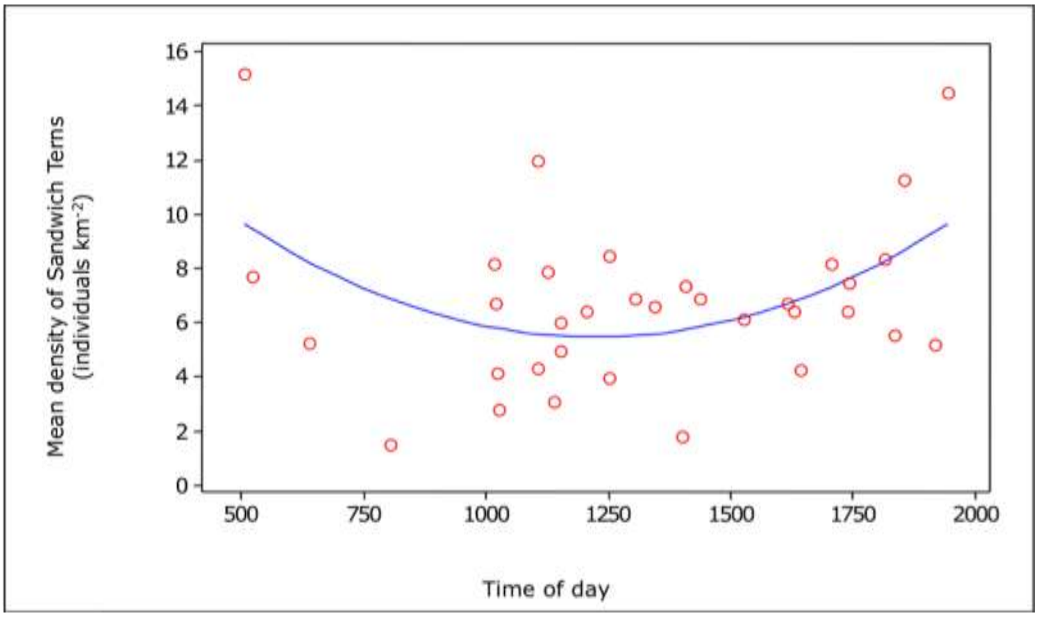

Figure 13. Relationship between time of day and the mean (±1SE) snapshot density of Sandwich Terns recorded in during each survey run at Blakeney Point in 2008. Time relates to that at the start of each survey run.

In addition, there was also a significant relationship between Sandwich Tern density and tidal period (Fig. 14). When analysed as a categorical variable to account for the non-linearity of the relationship, the effect of tidal state was highly significant (GLM ANOVA $F_{3,33}$=4.61, p=0.009), with mean snapshot densities being highest around high tide (GLM coefficient 0.135 ± 0.06) with low, flowing and ebbing tides having similar densities of birds. Multivariate model selection using AIC revealed that tidal state had much stronger explanatory power than any of the other variables considered, with a selection probability of 0.96 (compared to a value of 0.05 for time of day).

For Common Tern, there were no significant relationships between outbound or inbound passage rate and any environmental predictor variables. But as for Sandwich Tern, mean snapshot density of Common Tern was found to be significantly related to tidal state (GLM ANOVA $F_{3,33}$=3.21, p=0.003), with highest densities around high tide (GLM coefficient 0.327). Unlike Sandwich Tern, densities were lowest on the ebbing tide, and similar at low water and on the flooding tide (Fig. 15).

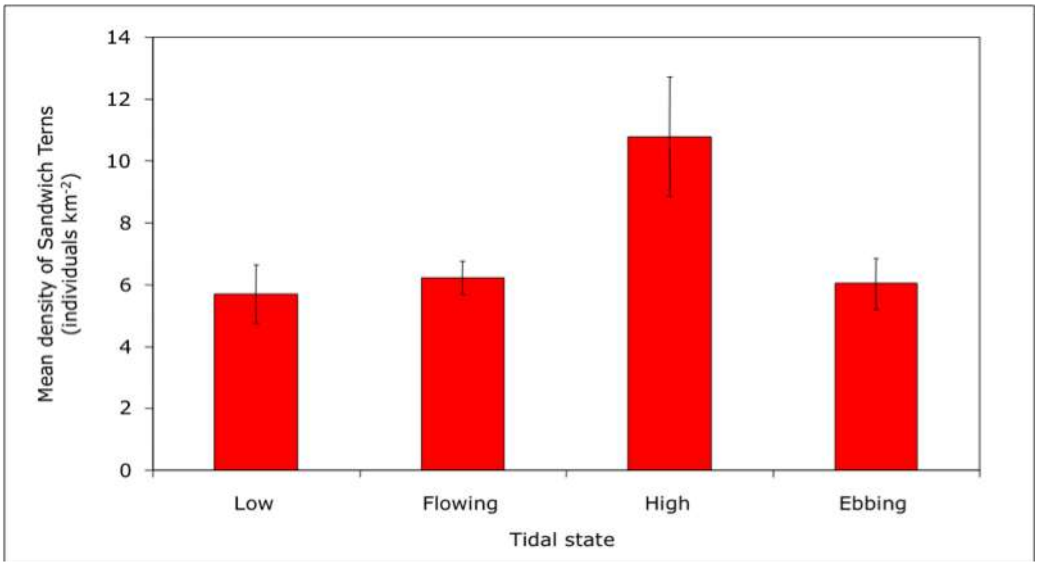

Figure 14. Relationship between tidal state and the mean (±1SE) snapshot density of Sandwich Terns during each survey run at Blakeney Point in 2008. Tidal state categories reflect three-hour periods centred on high or low water, with intervening periods representing ebbing or flowing stages.

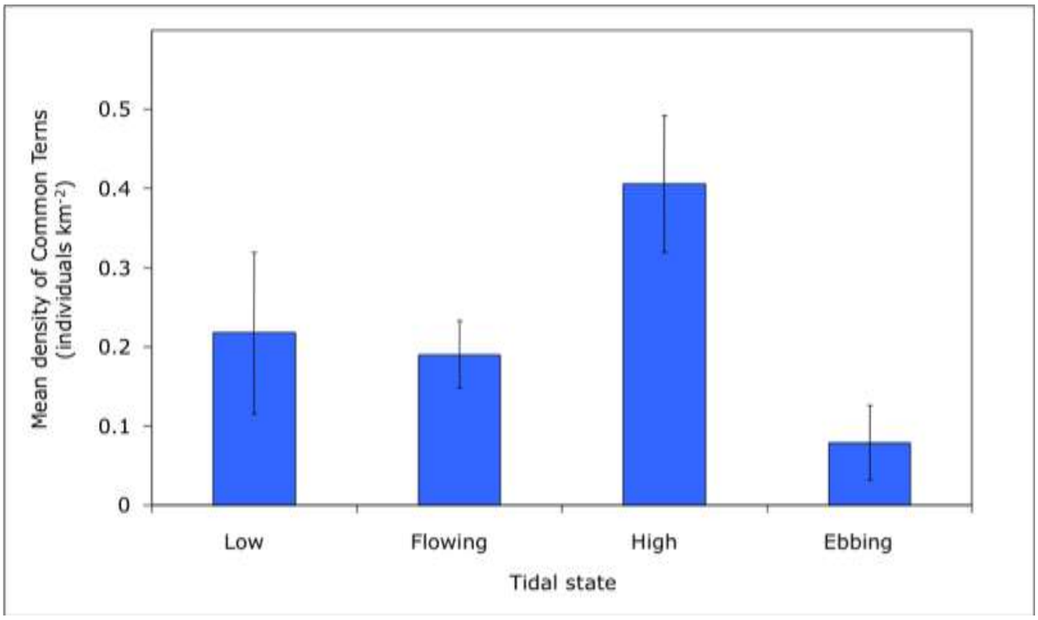

Figure 15. Relationship between tidal state and the mean (±1SE) snapshot density of Common Terns during each survey run at Blakeney Point in 2008. Tidal state categories reflect three-hour periods centred on high or low water, with intervening periods representing ebbing or flowing stages.

There was also a significant relationship between mean snapshot density of Common Tern and wind direction (GLM ANOVA $F_{4,33}$=2.83, P=0.046), with highest densities with winds from the northwest and west and lowest with winds from the southwest to southeast (Fig. 16). Multivariate model selection indicated strong support for the significance of both tide state and wind direction on Common Tern densities, with AIC selection probabilities of 0.98 and 0.97 respectively, compared to 0.11 for time of day.

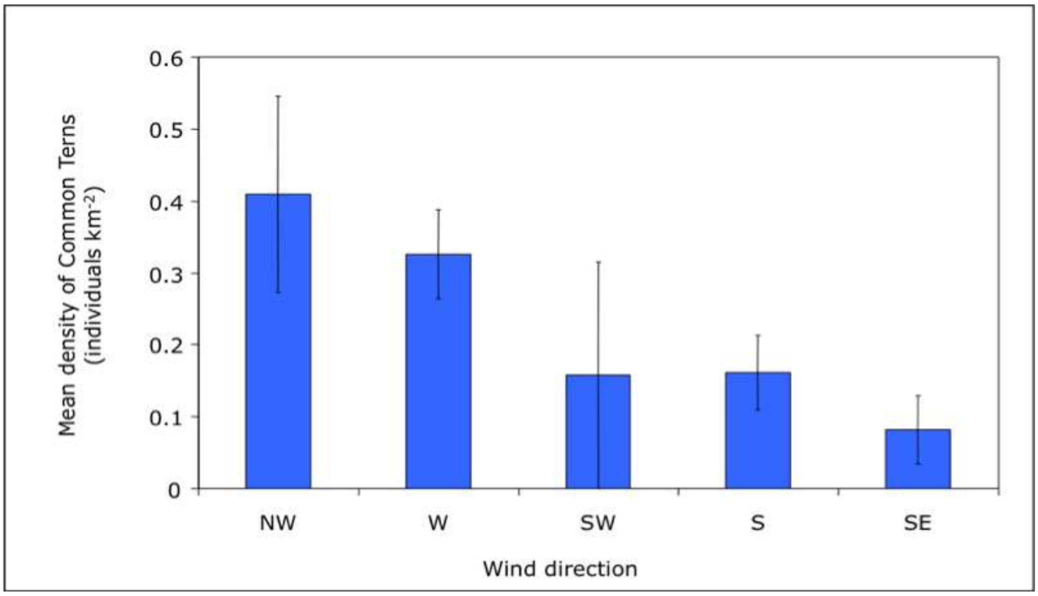

Figure 16. The relationship between wind direction and the mean (±1SE) snapshot density of Common Terns during each survey run at Blakeney Point in 2008.

Cemlyn Bay

As was also observed at Blakeney Point, outbound passage rates of Sandwich Tern at Cemlyn showed a slight diurnal pattern, with outbound passages peaking during the early and late parts of the daylight period, particularly during the late evening (Fig. 17), although the relationship was not statistically significant (GLM ANOVA F5,20=1.164, P=0.259).

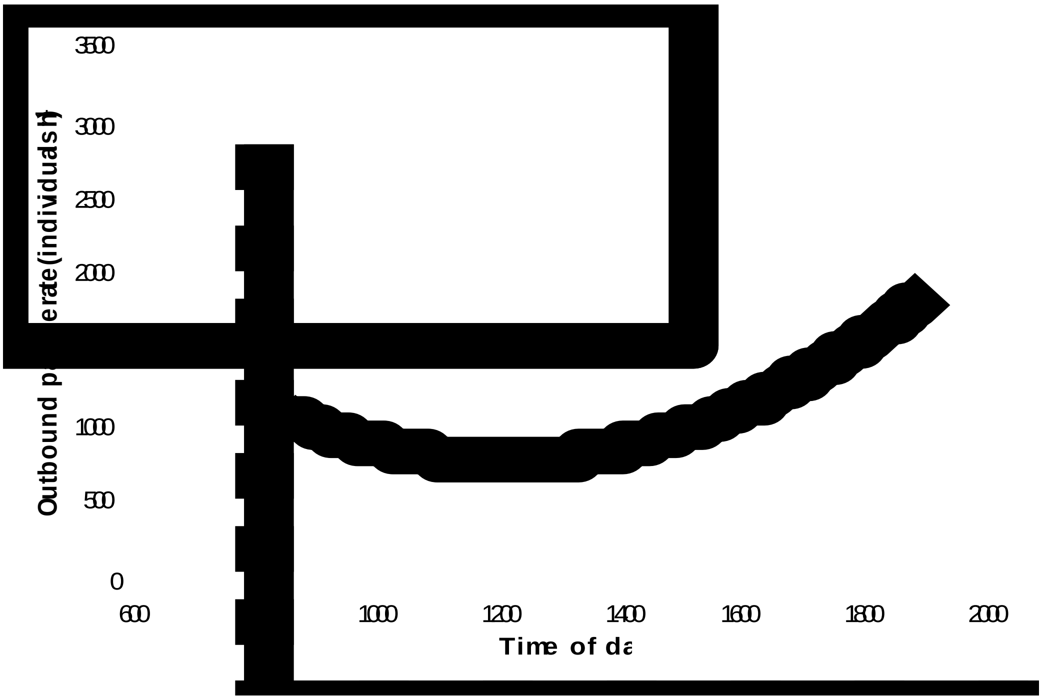

Figure 17. Relationship between outbound passage rate of Sandwich Terns and time of day at Cemlyn Bay.

Passage rate did not show a significant pattern of activity in relation to tidal state as although outbound passage rates peaked at low tide at Cemlyn (Figure 18), passage rates were broadly similar at other tidal states (GLM ANOVA $F_{3,20}$=0.563, P=0.670). This pattern differs markedly from that observed for Sandwich Terns at Blakeney, where passage rates peaked at high tide.

Combined with the lack of significant relationships with either wind speed or wind direction it was concluded that passage rates of Sandwich Terns at Cemlyn were not strongly related to any of the environmental factors considered, suggesting that provisioning activity generally occurred at relatively similar levels in all conditions covered by the surveys.

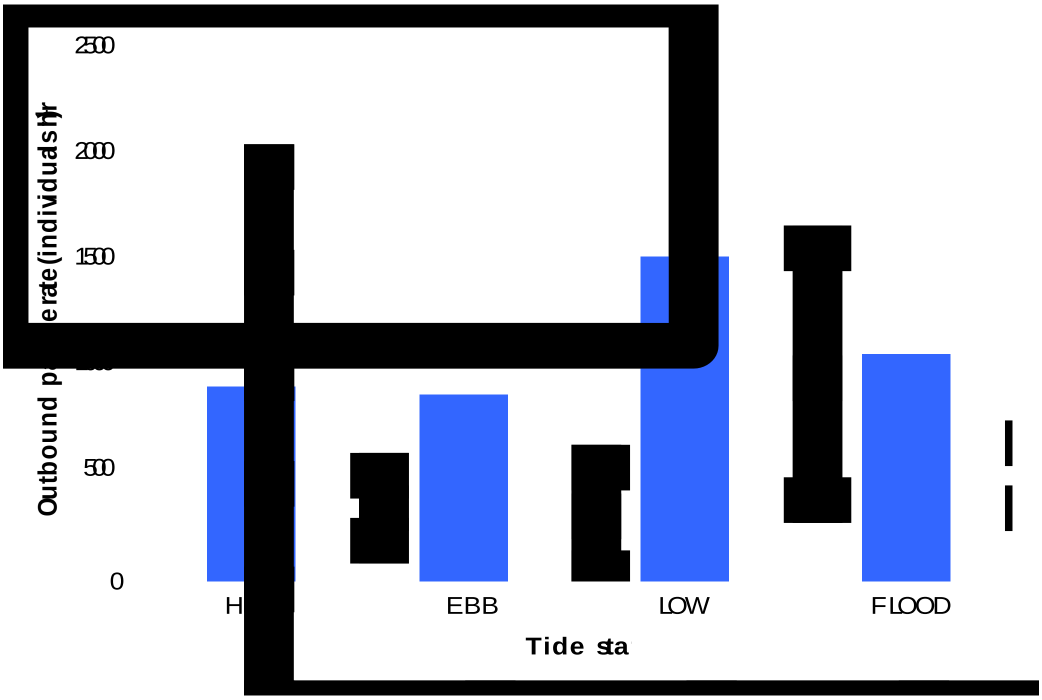

Figure 18. Relationship between outbound passage rate of Sandwich Terns and tidal state at Cemlyn Bay. Tidal state categories reflect three-hour periods centred on high or low water, with intervening periods representing ebbing or flowing stages.

Saltholme on Teesside

Unlike Sandwich Tern at other colonies and like Common Terns at Blakeney Point, Common Terns at Teesside showed little to no evidence of a pattern of diurnal variation in activity (Fig. 19) expressed as a non-statistically significant relationship (GLM ANOVA $F_{4,22}$=-0.856, P=0.403, with time considered as a fixed categorical effect). The slight magnitude of difference in passage rates across the daylight period reinforced that notion that foraging activity occurred with similarly high intensity throughout the day.

Common Tern passage rates were however significantly related to the tidal cycle (GLM ANOVA $F_{3,22}$=7.178, P<0.01), with highest outbound passage rates noted during periods when the tide was low or flooding, with lowest rates on ebbing tides (Fig. 20). The pattern of reduced outbound activity during ebb mirrors that observed for Sandwich Terns at Blakeney Point (see above). There was no evidence of any relationship between passage rates and wind direction or strength, although the range of conditions covered by surveys was relatively narrow (wind directions from northeast to southwest and wind speeds of Beaufort 1-4).

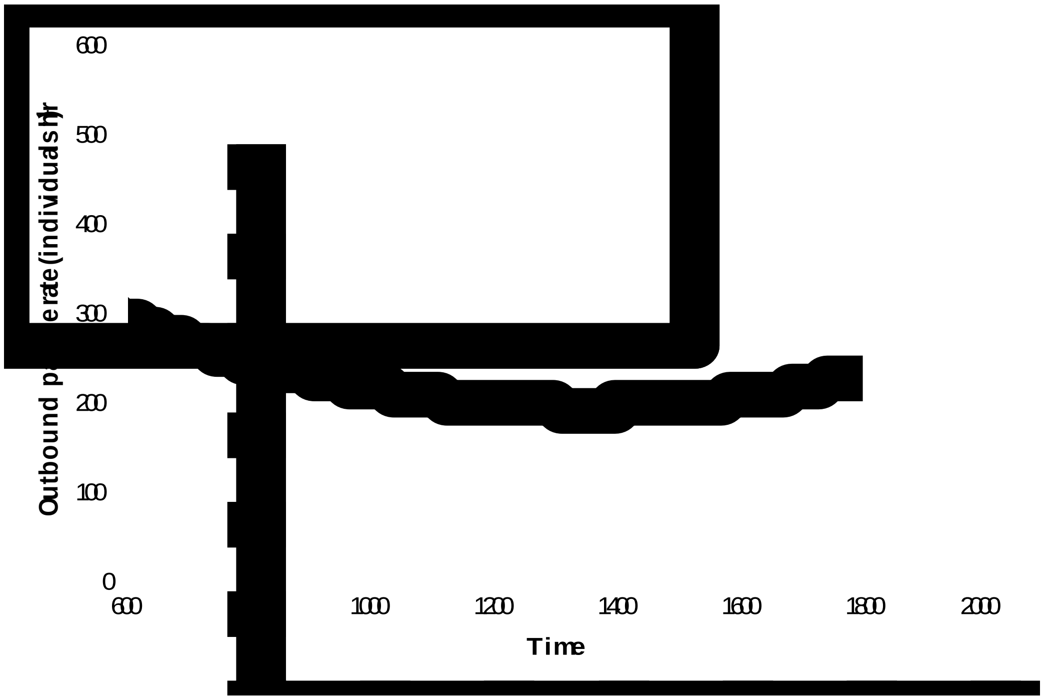

Figure 19. Relationship between outbound passage rate of Common Terns and time of day at Saltholme.

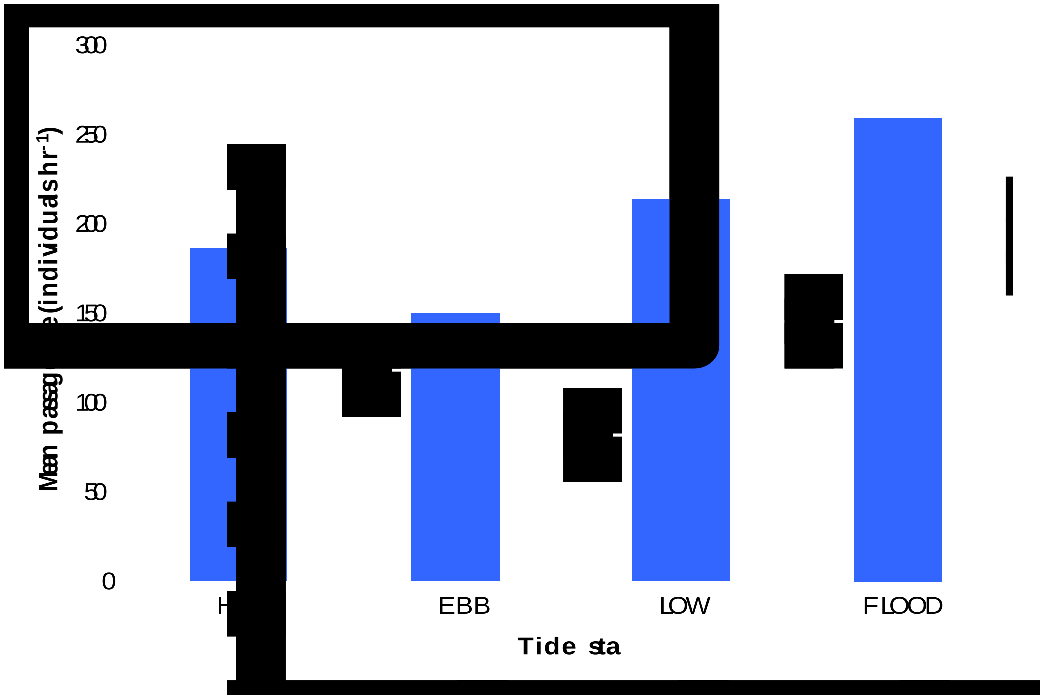

Figure 20. Relationship between outbound passage rates of Common Terns and tidal state at Saltholme. Tidal state categories reflect three-hour periods centred on high or low water, with intervening periods representing ebbing or flowing stages.

4.2 Prey type and delivery rate

4.2.1 Sandwich and Common Terns at Blakeney Point

Observations in 2008 provided comparative data on the nature of provisions delivered to Sandwich and Common Tern chicks. The former were fed with a high proportion of clupeids (52% of 33 observed items) supplemented by a relatively high proportion of sandeels (27%), with relatively fewer fish of other species (18%)(Fig. 21). Common Tern chicks were also fed a relatively high proportion of clupeids (59% of 97 observed items) (Fig. 22 & 23), but with a relatively large proportion of other fish species that were not specifically identified (21%). Sandeels only formed a small fraction of chick diet (6%).

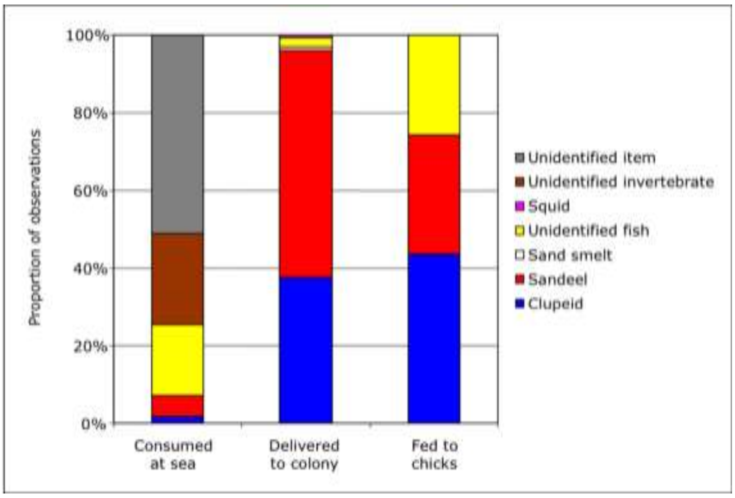

Figure 21. Composition (% of items observed) of prey consumed/captured at sea (*n*=55), delivered to the colony (*n*=199) and presented/fed to chicks (*n*=33) by Sandwich Terns at Blakeney Point. The items captured at sea includes a fraction of initially unidentified prey items that were subsequently assigned to prey group where birds were repeatedly foraging on what appeared to be the same items.

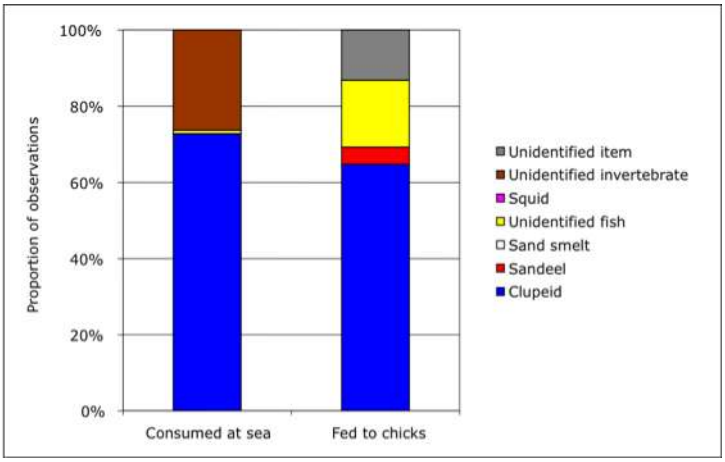

Figure 22. Composition (% of items observed) of prey consumed/captured at sea (*n*=369) and presented/fed to chicks (*n*=97) by Common Terns at Blakeney Point. The items captured at sea includes a large fraction of initially unidentified prey items that were subsequently assigned to prey group where birds were repeatedly foraging on what appeared to be the same items.

Figure 23. Common Tern presenting two small (~4 cm) clupeids (a single item is more usual) to its chicks in the colony. Clupeids of this size comprised the majority of chick provisions.

Figure 24. Sandwich Tern presenting a large (~11 cm) clupeid to a chick. Note the attacking Black-headed Gull in the background attempting to steal the prey item.

There were apparent differences in the nature of chick diet of both species relative to the composition of prey captured by adults. Captured invertebrates were invariably consumed at sea and were thus not taken back to chicks by either tern species (Figs. 21 and 22). (This is borne out by the larger dataset for Sandwich Tern presented below). The mean ± 1SE lengths of items consumed (3.54 ± 1.99) and carried (6.66 ± 0.35) by Sandwich Tern indicate that there may be some difference in the size of prey items captured at sea and actually presented to chicks, although the high variation in the length of prey items consumed means that the difference was not statistically significant.

The size range of prey items presented to chicks also differed between the two species (Figs. 23-25). The majority of prey items provisioned by Common Tern were below 5 cm in length, whereas Sandwich Tern presented a wider range of prey sizes including some above 10 cm in length. It should be noted, however, that the size ranges presented to chicks appeared to be more similar than that taken or carried by adults at sea, where the mean size of items captured by Sandwich Tern was twice that captured by Common Tern (> 8 cm cf >4 cm), especially when this is combined with items delivered to the colony (Fig. 26). Whilst this discrepancy may relate to the relatively small sample size of items actually presented to chicks within the colony, the impact of selective kleptoparasitism of the largest items also makes a genuine difference possible (see 4.1.1 below).

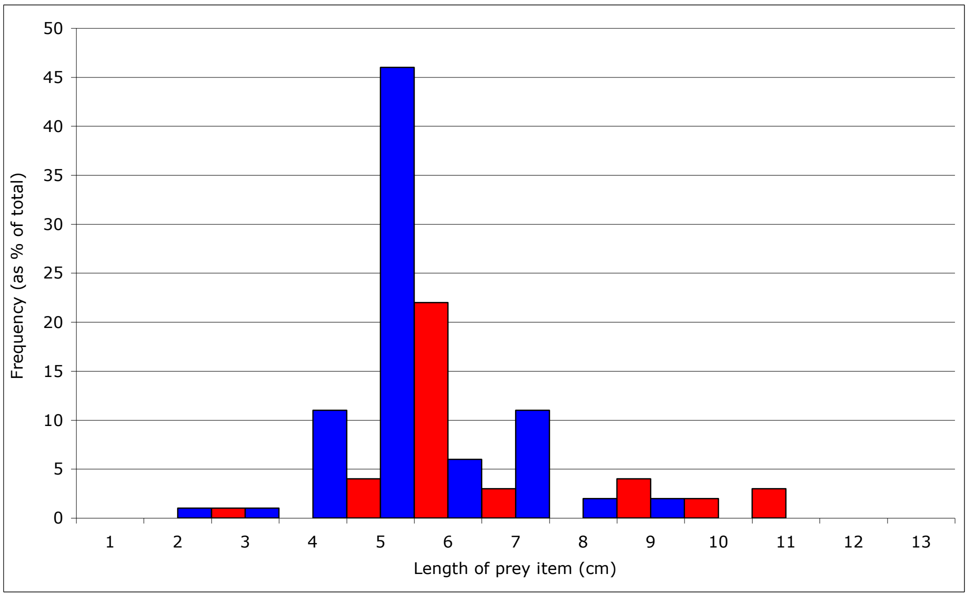

Figure 25. Length frequency distribution (%) of prey presented to Sandwich (red) and Common Tern (blue) chicks by provisioning adults (*n*=33, 97 respectively).

Sandwich and Common Terns differed significantly in the rate at which prey items were delivered to individual chicks with Common Terns delivering at a much higher mean rate of 1.53 ± 0.21 feeds hr^{-1}, in comparison to 0.35 ± 0.07 feeds hr^{-1} for Sandwich Tern (Fig. 27). However, the average size of prey item was significantly larger for Sandwich Tern (Mann-Whitney W=28955, $p<0.001$) in terms of prey length (Sandwich Tern mean ± 1S.E. = 85.3mm ± 2.86, Common Tern mean ± 1S.E. = 44.1mm ± 2.45). Nevertheless, despite the larger average size of items brought by Sandwich Terns, the estimated hourly rate of biomass delivery was significantly higher for Common Tern (Mann-Whitney W=597, $P<0.001$), with a mean of 1.54 ± 0.21 g hr^{-1} in comparison to 0.37 ± 0.12 g hr^{-1} for Sandwich Tern. It therefore appears that the Sandwich Tern's specialism towards larger fish prey did not provide any advantage in terms of chick provisioning in comparison to the more generalist Common Tern, at least during the period in which observations were made.

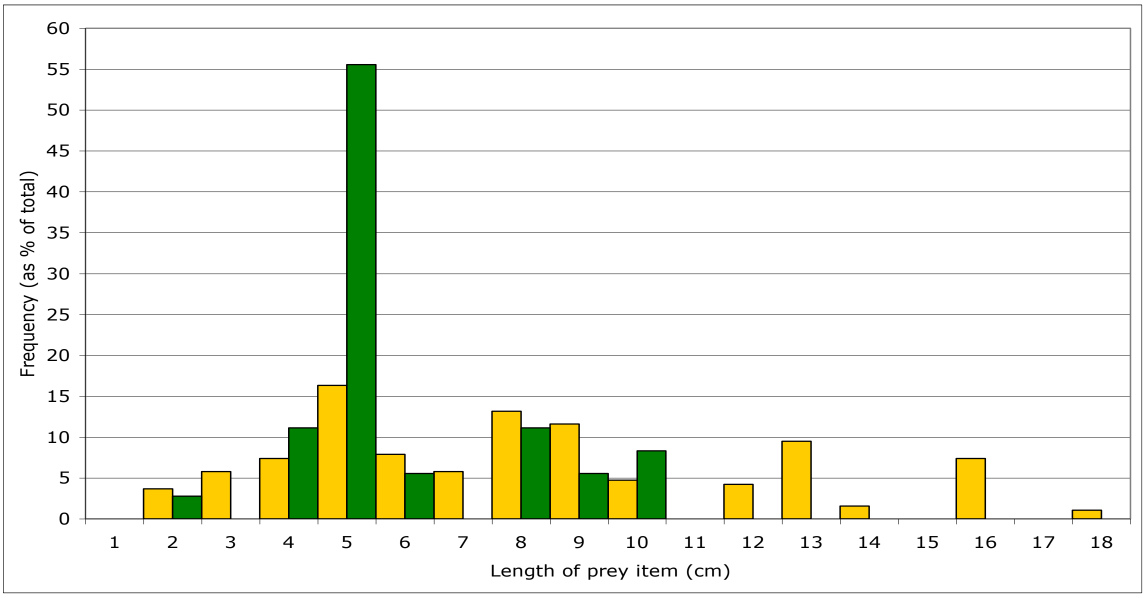

Figure 26. Length frequency distribution (%) of fish prey delivered to the colony by Sandwich Terns (yellow) and successfully presented to Sandwich Tern chicks (green) (*n*=190,33 respectively).

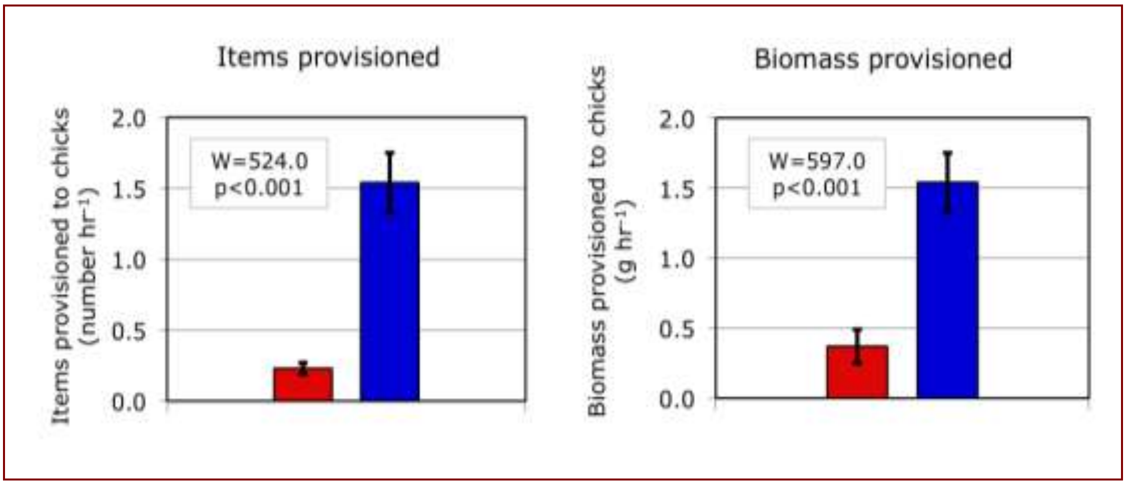

Figure 27. Comparison of chick provisioning rate expressed as number and biomass of items for Sandwich (red) and Common (blue) Terns.

4.2.2 Sandwich Tern diet and chick provisions in North Norfolk

The much larger dataset available for Sandwich Terns from both Blakeney Point and Scolt Head from 2006-2009 (see also Centrica Energy 2008, 2009) for captures at sea (*n* = 1089) and presented to chicks (*n* = 827) reinforced the conclusion from 2008 that clupeids and sandeels dominate chick diet, but also indicated the two groups were of approximately equal prevalence in terms of the number of items brought to colonies (Fig. 28). At sea however, clupeids appeared to be caught at much higher frequency than sandeels, although a relatively high proportion of fish prey items observed at sea were not identified specifically, providing the possibility that the true proportions of each prey type may have been masked. Invertebrate prey again featured in the diet of adults, but these items were never observed being brought back to the colony.

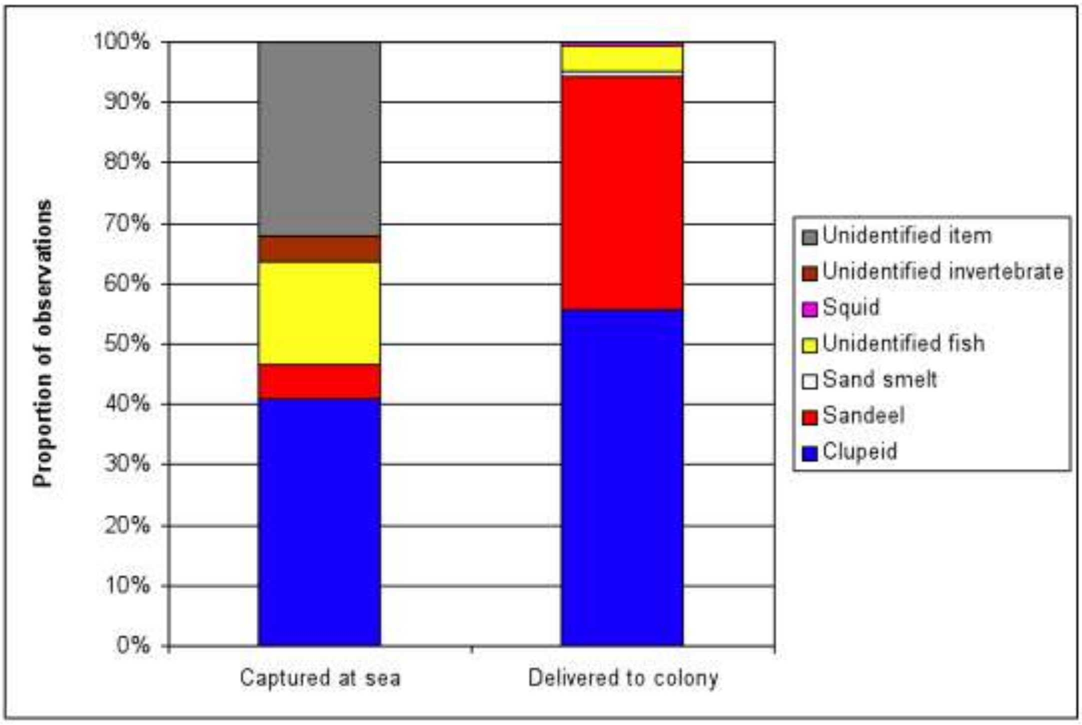

Figure 28. Diet composition (% of all observed items) of Sandwich Terns in North Norfolk, for adults foraging at sea (left, based on visual tracking data, *n*=1,089 items) and Sandwich Tern chicks (right, based on observations of adults bringing items into colonies, *n*=827 items).

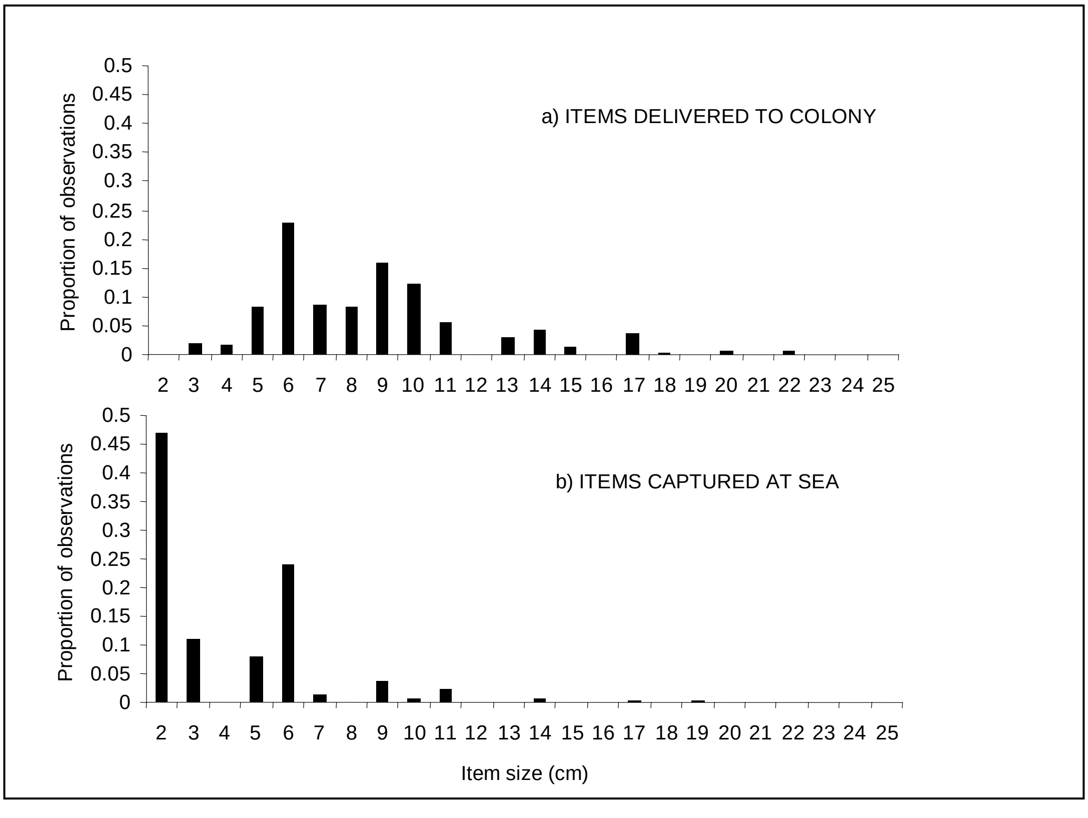

Figure 29. Size distribution of prey items (all species) caught by Sandwich Terns at North Norfolk colonies in 2006-2009. Items brought into colony (a) are derived from observations within colonies of birds carrying items to chicks (*n*=1,089 items), whilst items caught at sea (b) are derived from visual tracking data (*n*=827 items).

The difference between the composition of items delivered to chicks and those captured at sea reflects a degree of selectivity in provisioning by adults, with adults feeding on a wider range of prey items and choosing to deliver only a narrow range of items, namely clupeids and sandeels. The nature of this selectivity was illustrated by considering the size of items taken at sea in relation to those delivered to colonies (Fig. 29), with the former strongly dominated by very small items (mean length over all prey types = 3.75 cm ± 1.98 s.d.). Items brought back to the colony showed a relatively even distribution around a much higher mean length (8.11 cm ± 3.62 s.d.) with relatively few very small items (<5 cm).

Considering each of the principal prey types in isolation, it is clear that the overall pattern for all prey is mirrored by that of clupeids in that the relatively high proportion of very small items (< 3 cm) captured at sea were not carried back to the colony (Fig. 30). The size distributions of clupeids caught at sea is indicative of a large number of young-of-the-year (YOY) fish whilst clupeids delivered to the colony appeared to be fish of at least one year of age or older. Conversely, for sandeels, the size distributions captured at sea and brought to colonies were relatively similar (Fig. 31), although a slight bias towards smaller items being caught at sea than those delivered to the colony remained. This suggests that YOY sandeels did not feature significantly in Sandwich Tern diet, although this could also relate to difficulties in specifically identifying very small sandeels (<5 cm) during visual tracking (indeed, a relatively high proportion of very small items were left unidentified during visual tracking). However, it is also possible that small sandeels were genuinely less abundant or available to terns as prey relative to larger size classes. The fact that this pattern was observed from data gathered over three seasons tends to suggest this is not simply a pattern generated from inter-annual fluctuation in recruitment of sandeels.

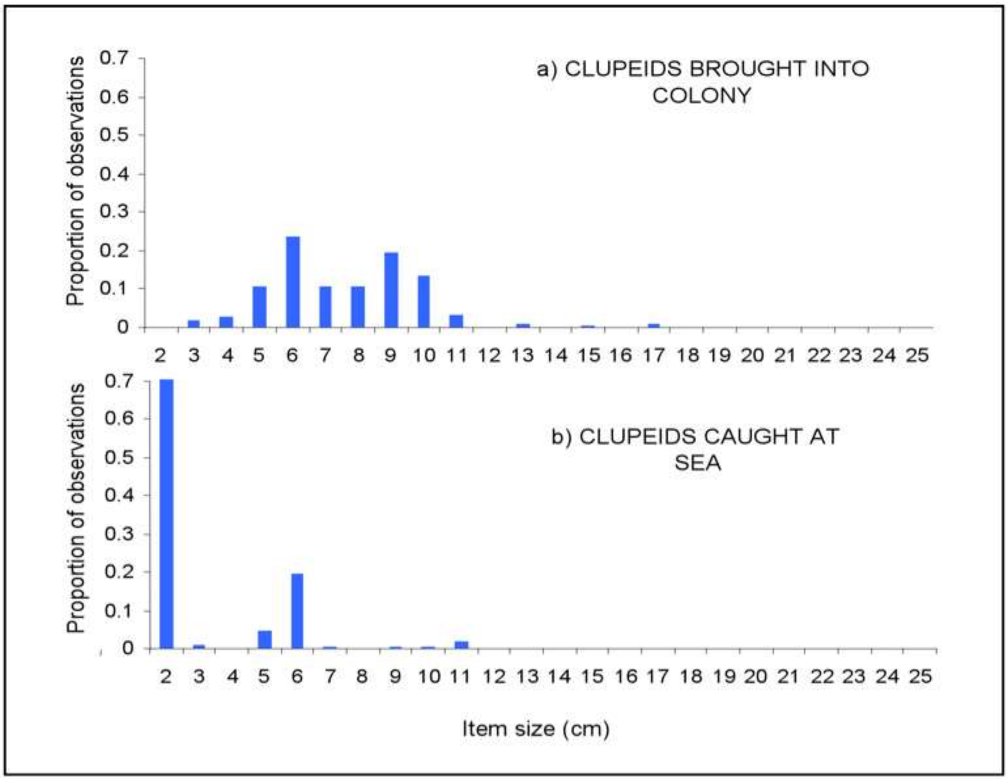

Figure 30. Size distribution of clupeids captured by Sandwich Terns from the North Norfolk colonies in 2006-2009. Items brought into colony (a) are derived from observations within colonies of birds carrying items to chicks (*n*=459 items), whilst items caught at sea (b) are derived from visual tracking data (*n*=446 items).

Overall, differences in the size distributions of prey delivered to colonies and prey items captured at sea provided clear evidence of size selectivity by adult Sandwich Terns. Smaller items (<5 cm), particularly clupeids but also invertebrates, sandeels and possibly other fish species, were frequently caught and consumed by adults at sea but were not generally carried back to the colony. The low relative energy content of these small items seems likely to have made them less worthwhile as provisions.

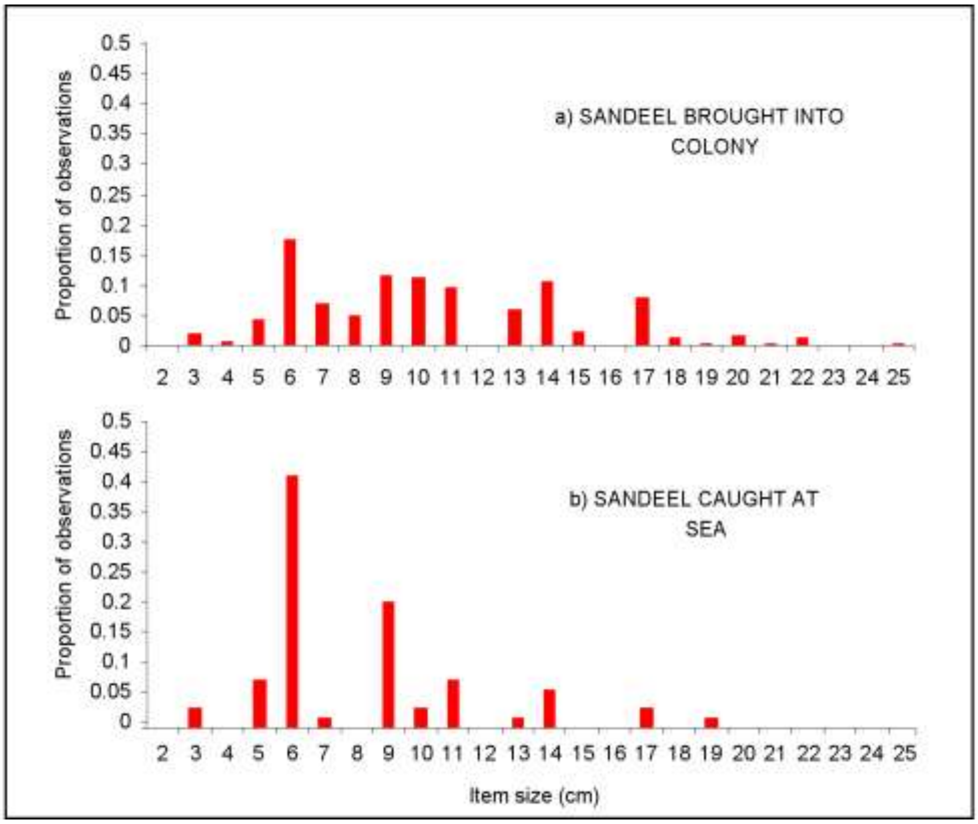

Figure 31. Size distribution of sandeels captured by Sandwich Terns from the North Norfolk colonies in 2006-2009. Items brought into colony (a) are derived from observations within colonies of birds carrying items to chicks (*n*=321 items), whilst items caught at sea (b) are derived from visual tracking data (*n*=62 items).

4.2.3 Sandwich Tern at Cemlyn Bay

As was the case in North Norfolk, Sandwich Terns breeding at Cemlyn Bay showed a relatively narrow dietary spectrum during the breeding season, predominately comprised of clupeids and sandeels. Again, the diet of adults determined from visual tracking differed significantly from that of chicks determined during colony observations with respect to both the variety of prey taken and the relative size of prey items (Fig. 32).

Chick provisions were strongly biased towards sandeels and clupeids, together with smaller numbers of two other fish groups/species not recorded in North Norfolk, namely gadoids (cod and their allies) and rockling, probably Three-bearded Rockling *Gaidropsarus vulgaris*. These contributed 5.8% and 1.4% of observed items by number respectively (Fig. 32). At sea, sandeels and clupeids made up a much lower proportion of items ingested by adults, although many more items of these prey types were likely to be included within the relatively high proportion of unidentified fish (21.9%). Also prevalent within the sample of items ingested offshore were small larval fish (generally < 3 cm in length), which could not be identified to species. Invertebrates of similar size were also taken, as also noted in North Norfolk. These very small items were never recorded being brought back to the colony.

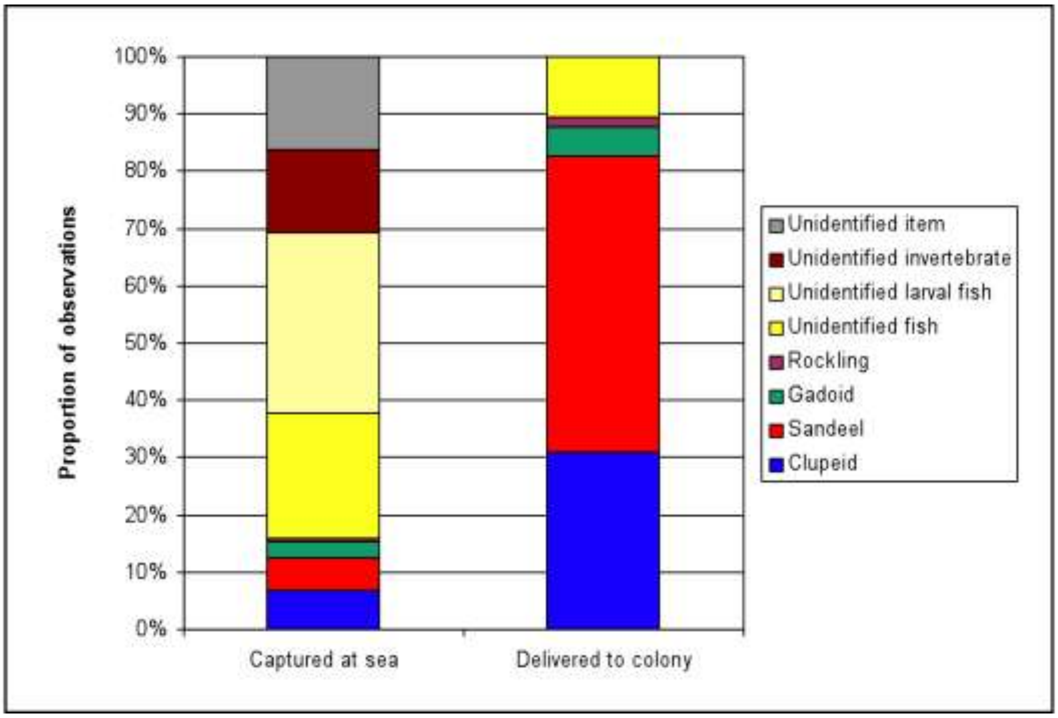

Figure 32. Diet composition (% of all observed items) of Sandwich Tern from Cemlyn Bay, for adults foraging at sea (left, based on visual tracking data, *n*=617 items) and Sandwich Tern chicks (right, based on observations of adults bringing items into colonies, *n*=478 items).

The size distribution of prey brought to the colony as chick provisions by Sandwich Terns at Cemlyn Bay was markedly similar to that observed in North Norfolk (Fig. 33). At both sites, the relative proportions of clupeids and sandeels of different sizes were very similar, as was the overall size distribution, being dominated by items between 5 cm and 12 cm in length. Although overall prey size distributions did not differ markedly between sites, some differences were apparent. For example, there was some evidence of a higher preponderance of small items returned by Cemlyn Sandwich Terns, with 18.1% of all items being less than 5 cm in length, compared to 11.9% for Blakeney Point. In addition, fewer very large items appear to be brought back by Sandwich Terns at Cemlyn, with 7.1% of all items > 12 cm in length, compared to 14.3% for Blakeney Point. This difference seems to relate largely to the relative paucity of large sandeels being brought to the colony at Cemlyn, with only 6.3% of sandeels exceeding 12 cm in length compared to the 31.5% above of this size and above in North Norfolk. The size range of gadoids (mean length of 10.1 cm ± 2.9 s.d.) and rockling (8.3 cm ± 3.9 s.d.) was broadly similar to that of clupeids and sandeels.

Amongst fish prey, the energetic content of individual items is not linearly proportional to their size, as larger items carry disproportionately higher energetic content. This is particularly true for clupeids due to their greater body depth and consequently higher biomass than sandeels of equivalent body length. Only the energetic content of the dominant clupeids and sandeels was calculated, as the energetic content of the other items at Cemlyn in particular, could not be estimated accurately. Clupeids accounted for a significantly higher proportion of overall energy delivered than sandeels, particularly in the case of Cemlyn Bay (Fig. 34). Indeed, clupeids accounted for an estimated 74.4% of the energy delivered during colony observations at Cemlyn Bay (excluding contributions from other prey species), which compares to an equivalent value of 58.6% at North Norfolk colonies. As might be expected given the size distribution of prey delivered at each site (Fig. 33), large sandeels made a greater contribution to overall energy delivery at Blakeney and made only a small contribution at Cemlyn, where small sandeels appeared to be more important both in terms of the number delivered (Fig. 33) and their proportionate energy contribution (Fig. 34).

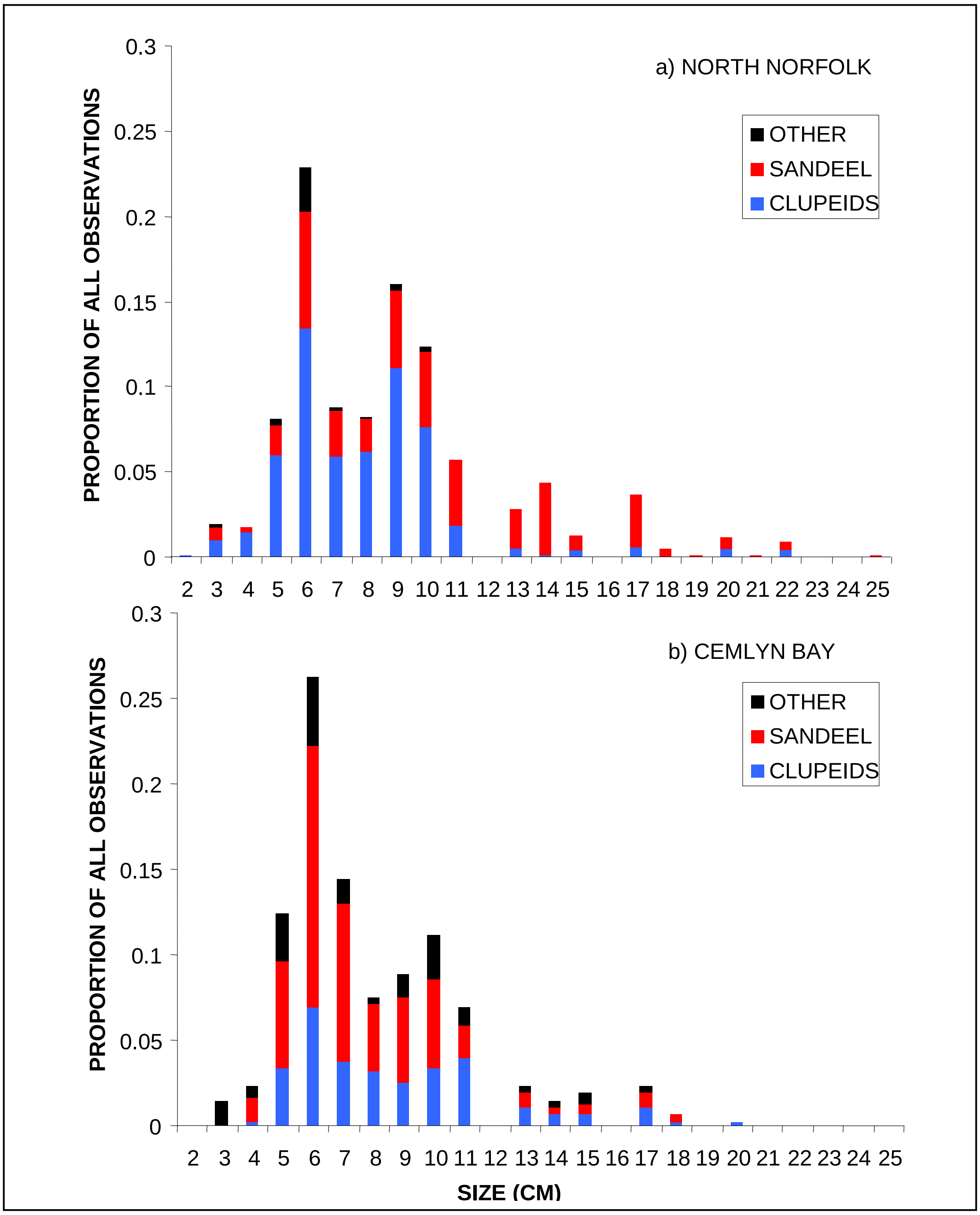

Figure 33. Size distributions of prey items brought back to colonies by Sandwich Terns in (a) North Norfolk and (b) Cemlyn Bay, Anglesey, showing relative proportions of sandeels, clupeids and other prey species (including unidentified items) for each size class.

The mean provisioning rate for Sandwich Terns at Cemlyn Bay in 2009 was 0.75 feeds chick^{-1} hr^{-1} (± 0.11 s.d.), which was more than double the mean provisioning rate recorded across North Norfolk colonies in 2007-2009 (0.33 ± 0.19 s.d.) and statistically significant (Mann Whitney W=4, P>0.001). The mean estimated rate of energy provision in North Norfolk was 9.19 KJ hr^{-1}, which equated to 128.62 KJ day^{-1} assuming 14 hours of provisioning activity each day. At Cemlyn, the equivalent rates were much higher at 14.28 KJ hr^{-1} and 198.98 KJ day^{-1} than those for Norfolk. It should also be noted that for both sites, the estimated mean rate of energy delivery was well below a published estimate of the minimum level required to maintain growth in Sandwich Tern chicks (247 KJ day^{-1} - Drent *et al*. 1992), hinting at some form of underestimation in brood provisioning observations in this study.

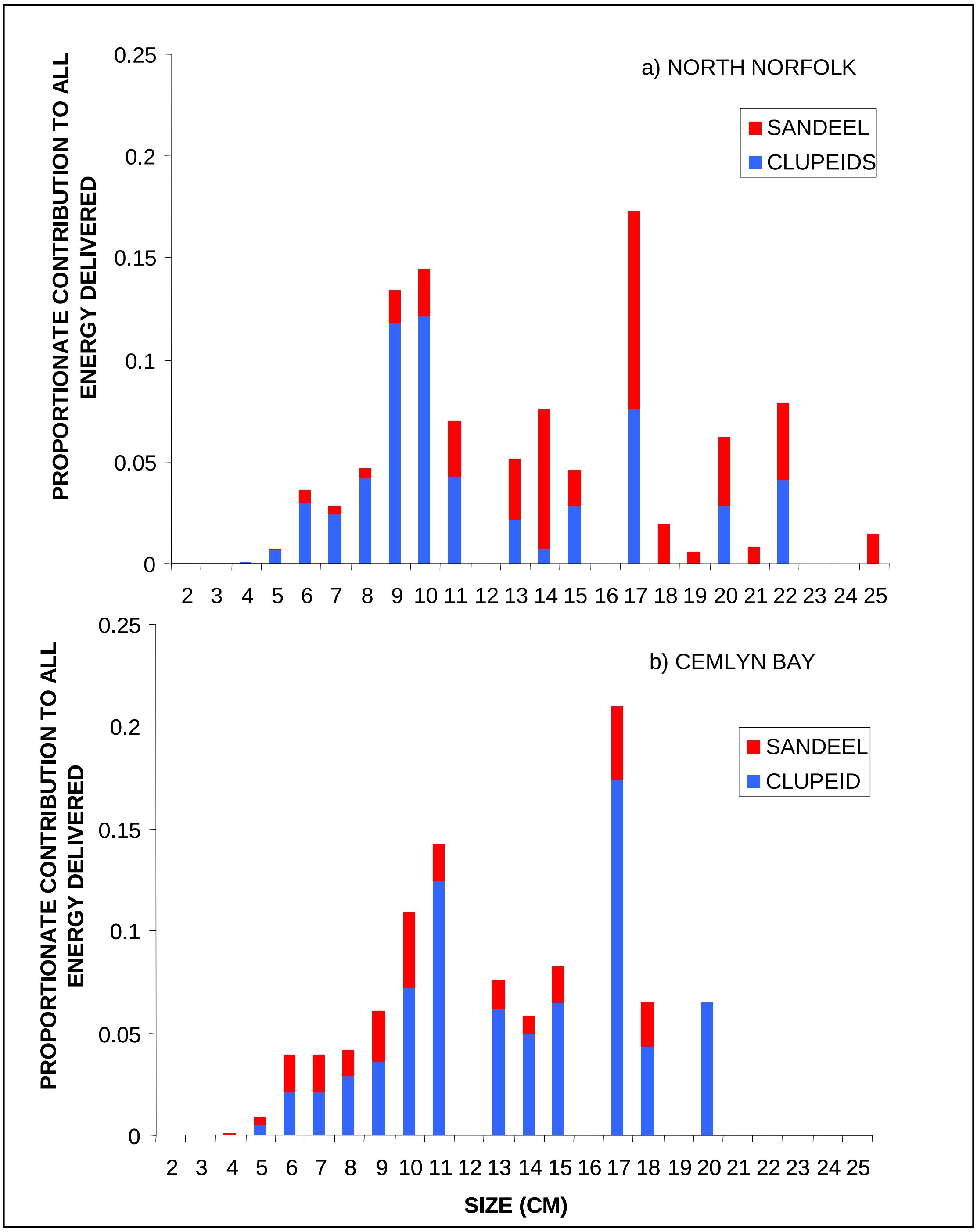

Figure 34. Proportionate contributions of each prey species and size class to total energy provisioning by Sandwich Terns at colonies in (a) North Norfolk and (b) Cemlyn Bay, Anglesey, derived from observations of adults returning to colonies carrying prey items. Energetic content of each item was estimated using species-specific length-weight regressions.

4.2.4 Common Tern at Saltholme

Observations at Saltholme provided an opportunity to examine Common Tern prey selection in the absence of breeding Sandwich Tern to contrast with the situation in North Norfolk (see 4.2.1 above). At Saltholme, chick provisions were dominated by clupeids, mainly thought to be Sprat *Sprattus sprattus*, with sandeels, gadoids and sticklebacks, probably Three-spined Stickleback *Gasterosteus aculeatus*. Notably, the size distribution of prey brought to the colony at Saltholme differed considerably from that observed at Blakeney Point, being dominated by larger clupeids and especially sandeels and also gadoids (Fig. 35). In this respect, Common Terns at Saltholme were similar to Sandwich Terns at Cemlyn Bay and especially Blakeney Point (Fig. 33).

Whereas the mean prey delivery rate for Common Tern at Saltholme (0.52 feeds hr^{-1} ± 0.32 s.d.) was markedly lower than that recorded at Blakeney Point (1.54 feeds hr^{-1} ± 1.04 s.d.), the larger mean size of prey items meant that the estimated energy delivery rate was considerably higher at 16.14 KJ hr^{-1} (± 13.07 s.d) at Saltholme compared to 5.85 KJ hr^{-1} (± 4.54 s.d.) at Blakeney Point.

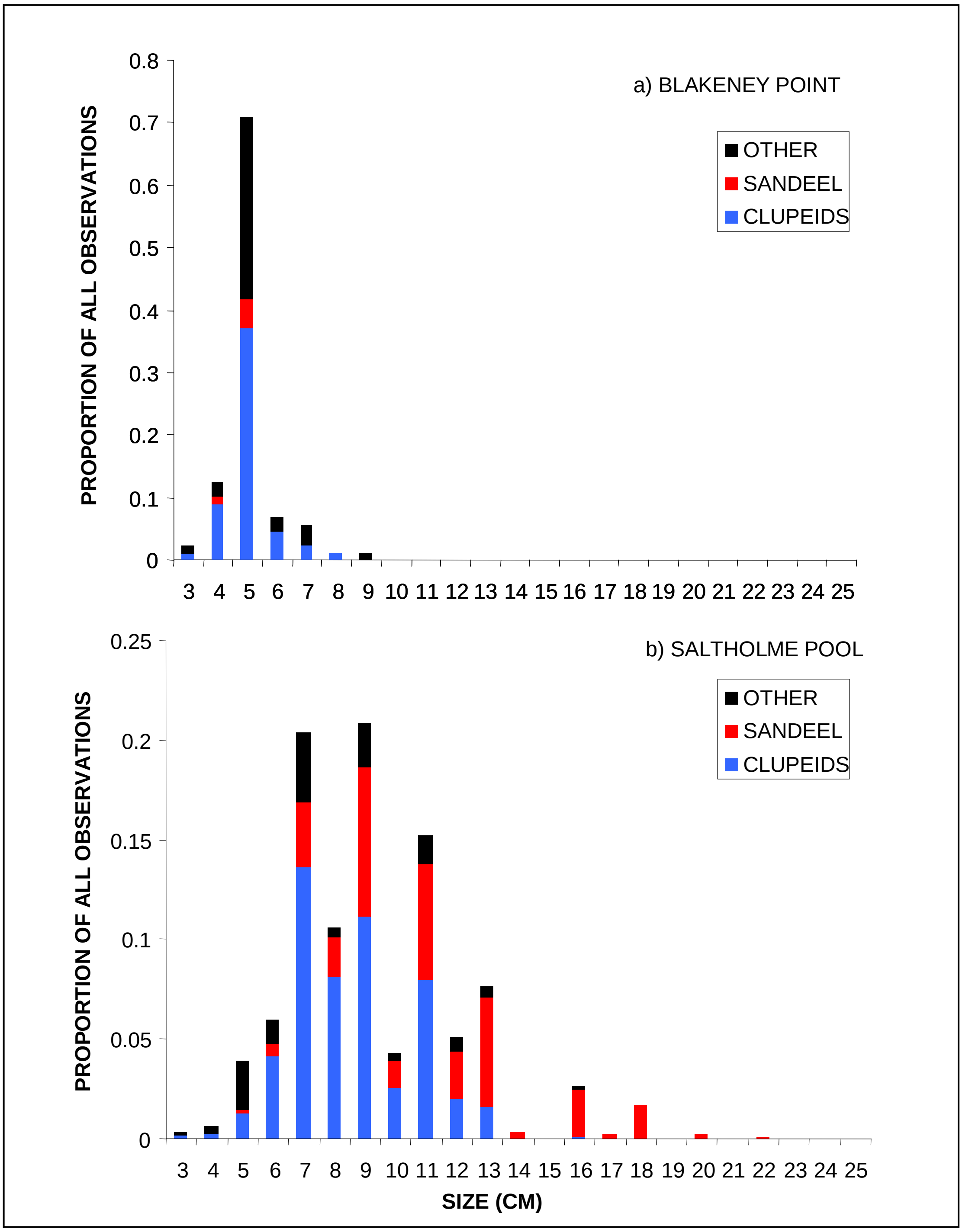

Figure 35. Size distributions of prey items brought back to colonies by Common Terns at (a) Blakeney Point and (b) Saltholme, showing the relative proportions of sandeels, clupeids and other prey species (including unidentified items) for each size class.

4.3 Patterns of kleptoparasitism

4.3.1 Sandwich Tern at Blakeney Point and Cemlyn Bay

Studies conducted at Blakeney Point from 2007-2009 inclusive (i.e. including data in Centrica Energy 2008, 2009) and at Cemlyn Bay in 2009 allowed a detailed comparison of how kleptoparasitism varies between sites. At Blakeney Point, kleptoparasitic attacks occurred with relatively high frequency, with some 28.4% of all observed prey-carrying adults (*n*=191) being subjected to at least one kleptoparasitic attempt by Black-headed Gulls. At Cemlyn, the overall rate of attack was much lower, with 8.8% of all observed individuals receiving at least one attack (*n*=478). This difference was manifested in the rates at which prey items were lost to kleptoparasites (Fig. 36).

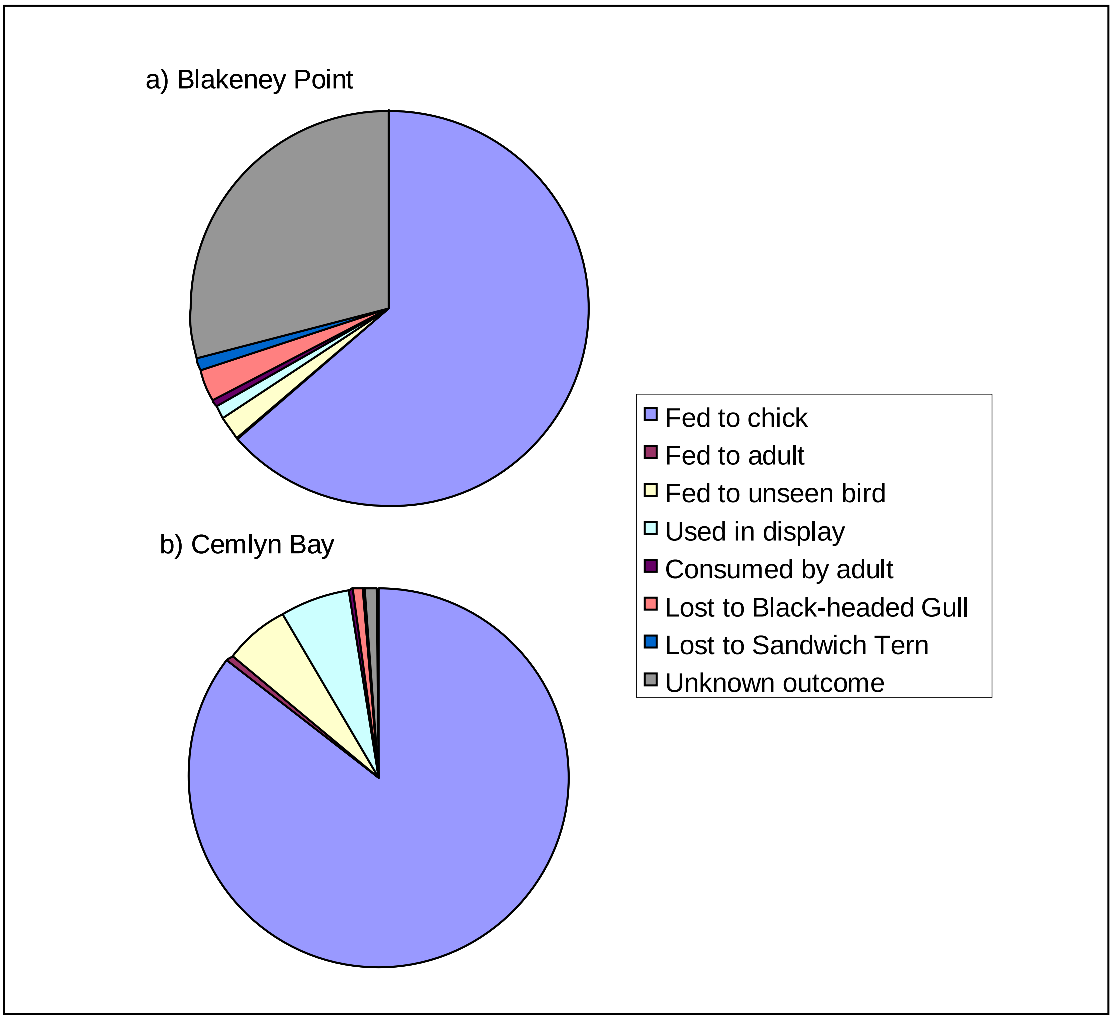

Figure 36. Outcomes, by proportion, of provisioning attempts by Sandwich Terns carrying prey items into colonies at (a) Blakeney Point and (b) Cemlyn Bay.

At Blakeney Point, 2.7% of all prey items observed being brought into the colony were seen to be lost to Black-headed Gulls, compared to only 0.6% at Cemlyn. A feature of kleptoparasitic attacks at Blakeney Point was the high frequency with which adult terns carrying prey items were chased outside the area of the colony by pursuing kleptoparasites (Fig. 37). In addition, a large proportion of returning adults made multiple passes (up to 24 were recorded) over the small area where the chick was located with occasional attempts to land followed by evasive flights at the first sign of attention from would-be robbers, presumably to avoid the rapid escalation of violent attack from multiple gulls (Fig. 38).

Figure 37. Black-headed gulls in pursuit of a Sandwich Tern attempting to deliver a large sandeel to a chick in the colony.

Figure 38. Successful kleptoparasitism by a Black-headed Gull upon a Sandwich Tern with a large sandeel. The tern was brought down in the process and pinned to the ground by several attacking gulls (inset).

Departing birds occasionally flew several hundred metres or more from the colony, often to the sea where the prey was dipped in the water (~6% of all deliveries) presumably to rehydrate it (after being air-dried during transport often over considerable distance – see 4.4 below), potentially making it easier for the chick to swallow and thereby reducing the prospect of it being stolen from its gullet by an attacking gull. Observations of the same individual were made for over 6 mins, with the chance of it being lost from view every time it left the colony. As a consequence the proportion of events with unknown outcomes at Blakeney Point was relatively high (29.1%) compared to Cemlyn (1.1%) where most delivery attempts could be followed to their conclusion. Given that most of 'unknown outcomes' involved birds being strongly pursued by kleptoparasites, it is likely that in reality, a high proportion of these events ended in prey items being lost. As such, the estimated prey loss rate to kleptoparasites at Blakeney is likely to be considerably higher than the 2.7% rate observed directly, within the range of 2.7 – 31.8%. Conversely, at Cemlyn there was considerable confidence that the rate of prey loss to kleptoparasites was indeed low, within the range of 0.6 -1.7%.

Previous studies have shown that kleptoparasitic attacks by Black-headed gulls on Sandwich Terns do not occur at random, but are targeted towards individuals carrying larger prey items (Stienen *et al*. 2001). This is not surprising given the higher energy content of large items, as well as the greater relative ease a larger item may be seized in mid-air by an attacking gull. This pattern was detected at both Blakeney Point and Cemlyn Bay, and in both cases there were slight differences in the relationship between the likelihood of attack and size of prey item size between clupeids and sandeels, the two principal prey types. That kleptoparasites would target terns carrying clupeids and sandeels with differing intensity may be explained by the significant difference in energy density between the two prey types, with clupeids being the higher. Indeed, clupeids had the highest energy values of a range of fishes and invertebrates in the northwest Atlantic measured by Lawson *et al*. (1998). According to the length to energy content regressions published by Wanless *et al*. (2005) biomass and energy content, of clupeids increases at a significantly higher rate with increasing body length than that of sandeels, such that large clupeids contain significantly more energy content than sandeels of equivalent size. As such, kleptoparasites might be expected to target terns carrying clupeids with higher intensity than those carrying sandeels of equivalent size.

At Blakeney Point, this prediction was largely born out by observed patterns of kleptoparasitic attempts. Binary GLMs predicting the likelihood of kleptoparasitic attack (i.e. with binary response variables denoting 0 for no attempt, 1 for at least one attempt) showed there was a significant effect of prey type (Z=2.029, P=0.042), with coefficients indicating that attack likelihood was higher for terns carrying clupeid prey than those with sandeels. There was also a highly significant relationship with prey size (Z=4.125, P<0.0001), with attack likelihood increasing significantly at larger prey sizes. Separate models constructed for terns carrying clupeids and sandeels (Fig. 39) showed that for items of small size (<8 cm), rates of kleptoparasitic attack were slightly higher for sandeels than for clupeids, but this pattern was reversed at larger sizes, with terns carrying large clupeids being subjected to a much higher likelihood of kleptoparasitic attack. In contrast, at Cemlyn Bay, there was little evidence of a difference in the rate of kleptoparasitic attack between terns carrying clupeids and those carrying sandeels. Although prey size remained a strong predictor of attack likelihood in binary GLMs (Z=6.456, P<0.0001), prey type was not found to have a significant effect (Z=-1.030, P=0.303). In separate models for terns carrying each prey type, the predicted relationship between prey size and attack likelihood was very similar in both cases (Fig. 39).

If kleptoparasitising Black-headed Gulls are able to differentiate between clupeids and sandeels they should target terns carrying large clupeids more intensely than those carrying large sandeels as a result of the significant difference in energetic content between items of equivalent size. Whilst this appears to be the case at Blakeney Point, there is no evidence of such a pattern at Cemlyn Bay. Taking this hypothesis further, if Black-headed Gulls were truly able to differentiate between the two prey types, the likelihood of kleptoparasitic attack would be similar for items of equivalent energetic value, regardless of the prey type involved. In order to test this, the energetic value of all prey items was estimated using length-weight regressions to model attack likelihood as a function of energy content for each prey type. At Blakeney Point, models for clupeids and sandeels both produced very similar results (Fig. 40). However, at Cemlyn Black-headed Gulls attacked terns carrying sandeels at a much higher rate than would seem to be optimal given their relatively low energetic content (Fig. 40). This is suggestive of an inability to differentiate clupeid and sandeel prey by Black-headed Gulls at this site.

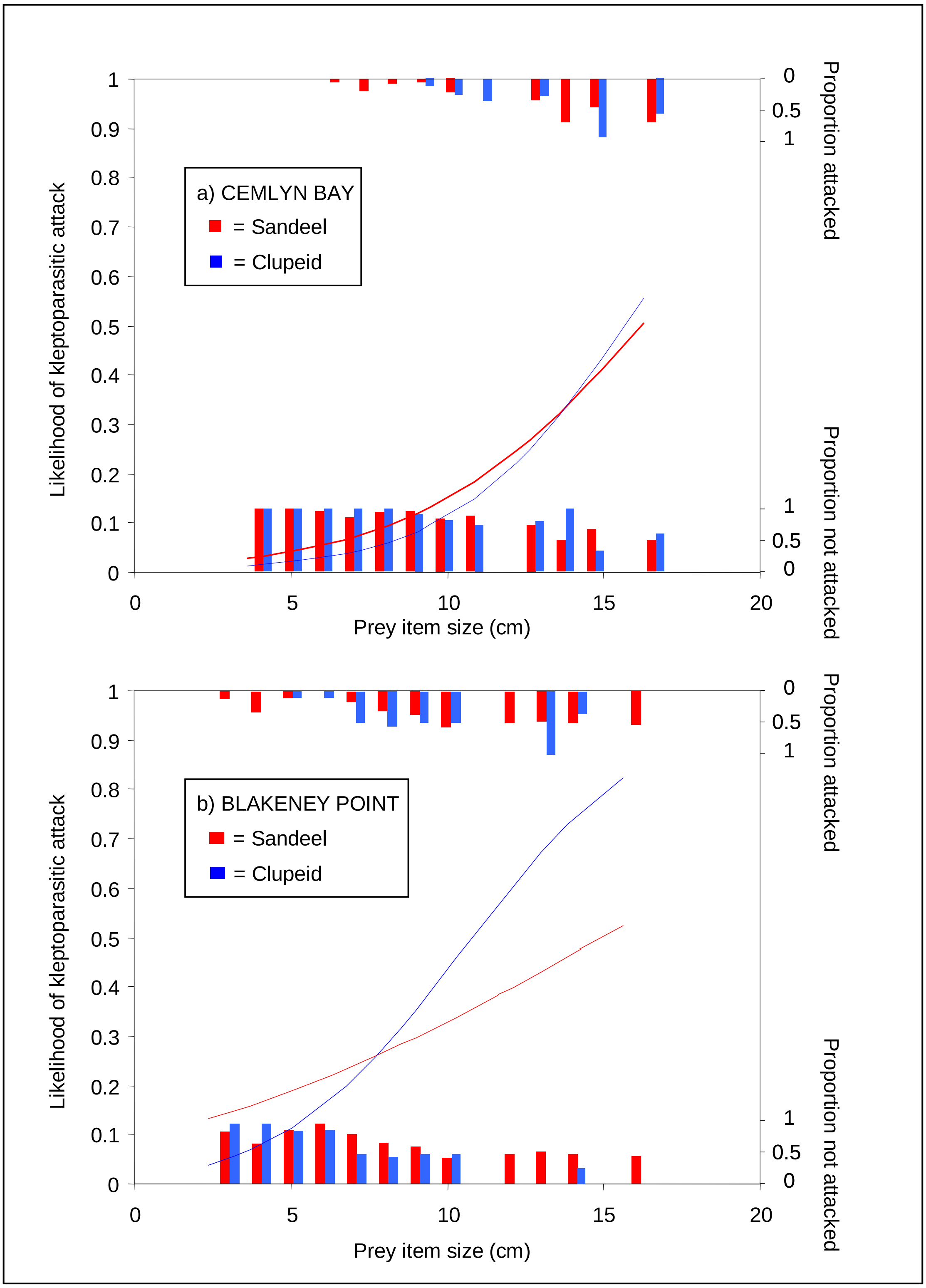

Figure 39. Relationships between the sizes of different prey items carried into colonies and the likelihood of attracting a kleptoparasitic attack from Black-headed gulls at (a) Cemlyn Bay and (b) Blakeney Point. Lines show predicted values from univariate binomial GLM's constructed using data for each site and prey type separately. Bars show the proportions of individuals that attracted a kleptoparasitic attack (upper bars, inverted) and those that did not (lower bars) for each prey item size class.

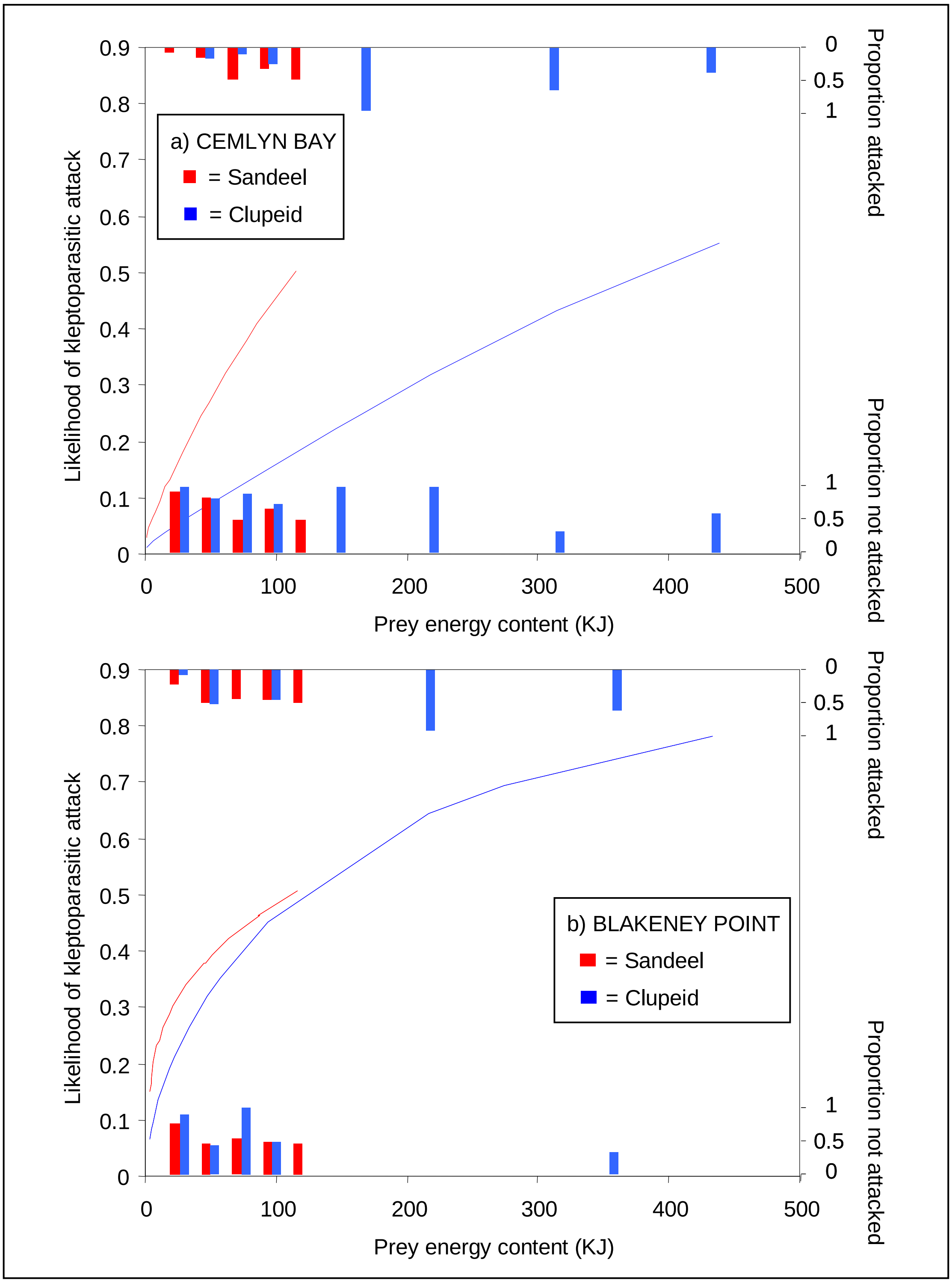

Figure 40. Relationships between the energy content of prey items and the likelihood of attracting a kleptoparasitic attack from Black-headed Gulls at (a) Cemlyn Bay and (b) Blakeney Point. Lines show predicted values from univariate binomial GLM's constructed using data for each site and prey type separately. Bars show the proportion of observed individuals attracting a kleptoparasitic attack (upper bars, inverted) and those that did not (lower bars) for each prey item size class.

4.3.2 Common Tern at Saltholme and Blakeney Point

Unlike Sandwich Tern, Common Tern is not known for routinely breeding in mixed colonies with Black-headed Gulls, although it is common for some mixing to occur. At Blakeney Point, for example, breeding Common Terns tend to settle over a more dispersed area and are less concentrated around the main area occupied by Black-headed Gulls, resulting in a lower degree of overlap. This, coupled with the smaller size of prey items typically taken by Common Terns at this site (see 4.2.1, Fig. 35), potentially making them less attractive to kleptoparasites, may also contribute to a lack of kleptoparasitic activity.

At Saltholme Pool in 2009, the main Common Tern colony was occupied by a small number of breeding Black-headed Gulls (<50 pairs). Again, despite the close proximity of breeding Black-headed Gulls presence, no losses of prey to kleptoparasitic gulls were recorded amongst the 211 delivery attempts (Fig. 41). Nevertheless, only 65.8% of observed delivery attempts successfully resulted in the feeding of chicks. A relatively high proportion (17.6%) involved events where the outcome was unknown, usually due to observed individuals moving to parts of the colony that were not visible. Kleptoparasitism by other Common Terns was also relatively important, accounting for 5.2% of observed prey items. A high proportion of these losses (45.5%) involved Common Tern chicks stealing prey items at the moment of hand-over from an adult to another chick. Particularly during the latter part of the season, large numbers of chicks gathered together in close proximity within the colony, and many individuals would contest each prey item that was delivered. It should be noted however that as many pairs raised two or more chicks, some apparent kleptoparasitic losses could have involved theft by a member of the same brood, therefore not representing 'true' losses to the provisioning adults.

Of the remaining kleptoparasitic losses, most cases involved prey items being stolen in mid-air by other adult Common Terns (36.4%), whilst the remainder (18.2%) involved prey items being stolen by adult Common Terns on the ground, generally at the moment of hand-over to the intended chick.

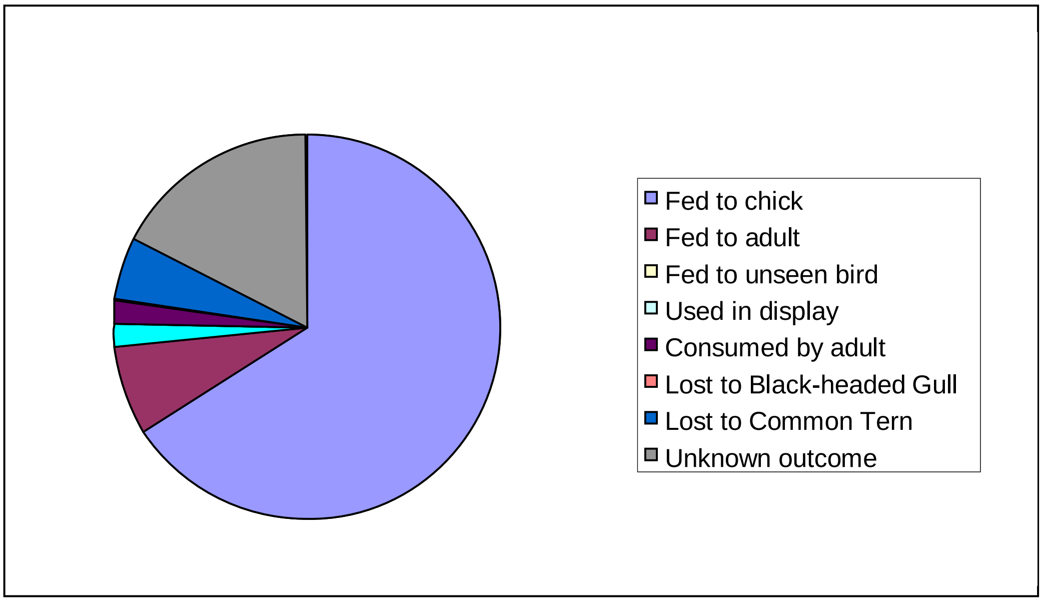

Figure 41. Outcomes, by proportion, of provisioning attempts by Common Terns carrying prey items (n=211) into the Saltholme colony in 2009.

The maximum potential level of kleptoparasitic loss of Common Tern at Saltholme may be estimated by adding the known losses (5.2%) to all unknown outcomes (17.6%), giving a value of 22.8%. The true mean rate of loss is therefore likely to lie somewhere in the range of 5.2 – 22.8%. This is of a similar magnitude to that estimated for Sandwich Terns at Blakeney Point (2.7 – 31.8%) and much higher than that observed for Sandwich Terns at Cemlyn Bay (0.6 - 1.7%), where Black-headed Gulls were the principal kleptoparasites.

4.4 Tracking foraging terns at sea

4.4.1 Sandwich and Common Terns at Blakeney Point

Plots of all location fixes and polylines of all tracked Sandwich and Common Terns illustrated some of the differences in the spatial use of inshore waters by the two species around the Blakeney Point colony and in relation to operational, consented and proposed OWFs in the Greater Wash (Figs. 42-44). Only for Sandwich Terns were either the maximum distance from shore (23.7 km) and the maximum distance from the colony (26.88 km) recorded sufficient to reach any of the OWFs. Those OWFs potentially reached by Sandwich Terns tracked in 2008 were Docking Shoal (minimum distance of 15 km from the colony) and Sheringham Shoal (19 km). As predicted by their recorded range, individual Sandwich Terns were physically tracked within the limits of both the proposed Docking Shoal and the consented Sheringham Shoal OWFs (Figs 43 & 44). It is important to note that whilst all other potential sites fell outside the range described from the latter part of the season in 2008, in other years of more extensive tracking, Sandwich Terns proved to be capable of reaching all OWF sites in the Greater Wash (see 5.2.3 below).

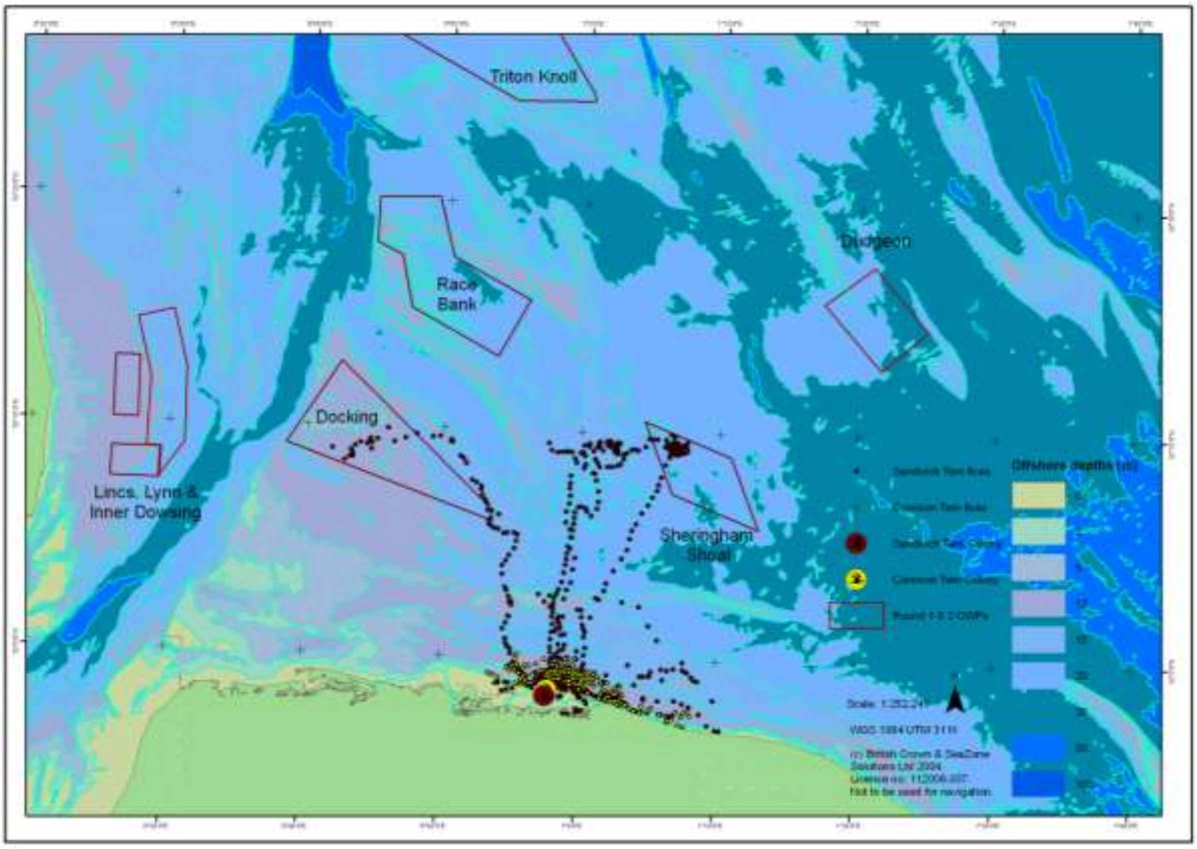

Figure 42. Fix locations of all Sandwich (dark red) and Common (yellow) Tern tracked from Blakeney Point in 2008 in relation to their respective colonies and the locations of all proposed, consented and constructed OWFs in the Greater Wash SEA area.

In contrast, no Common Tern was recorded within an OWF and would have to at least double the maximum distance travelled of 10.57 km from the colony to reach one. This seemed highly unlikely given that Common Terns were not observed beyond 2.07 km from shore (i.e. 14% of the distance required) (Fig. 44). As a result, or perhaps partly responsible for the observed pattern, Common Terns were not observed over waters deeper than 10 m (Fig. 44) whilst Sandwich Terns were observed actively and successfully foraging in waters of up to 18 m deep (Fig. 43). Whlst accepting the potential for inter-annual differences in foraging patterns, the relative lack of individual variation and restriction of Common Tern to inshore waters at this locality suggested that this was unlikely to change significantly within and between years.

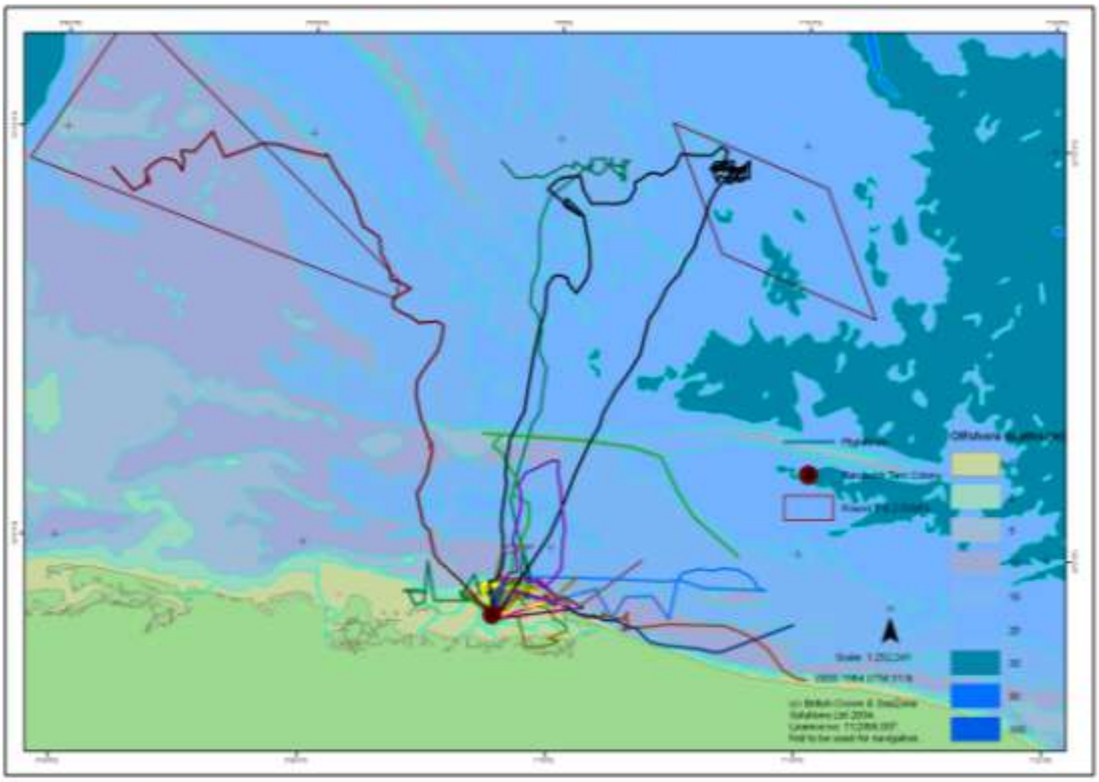

Figure 43. Flightlines of all Sandwich Terns (*n*=26) from Blakeney Point plotted from fixes taken during visual tracking at sea and from land, in relation to the proposed and consented OWFs in the Greater Wash.

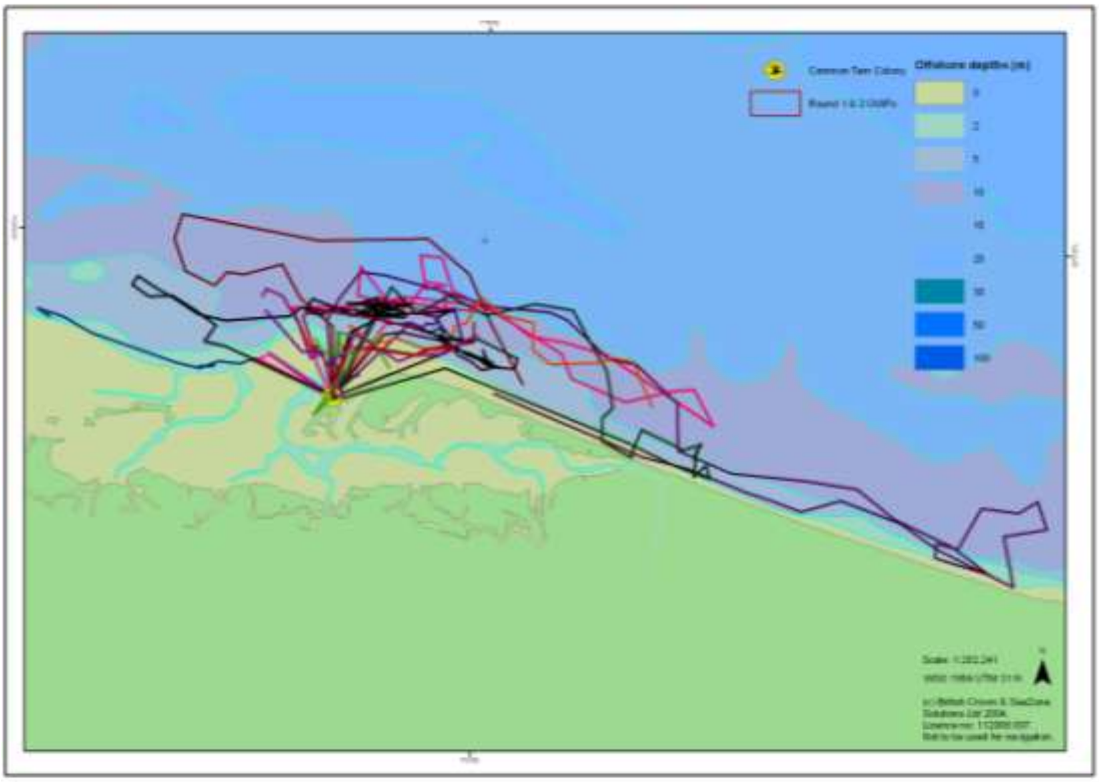

Figure 44. Flightlines of all Common Terns (*n*=42) from Blakeney Point plotted from fixes taken during visual tracking at sea and from land, in relation to the proposed and consented OWFs in the Greater Wash. (Note the reduction in map scale from Sandwich Tern in Fig. 43 above).

However whilst Sandwich Tern had the capacity to reach at least some of the Round 2 sites, many individuals (61%) were observed foraging <2 km offshore in the same areas as Common Tern, which meant that there was no significant difference in the maximum distance offshore reached by each species when directly compared in 2008 (Fig. 45). Nonetheless, Sandwich Tern travelled significantly further within foraging bouts (mean ± 1SE =19.22 ± 4.51 km) compared to Common Tern (mean ± 1SE = 5.16 km ± 4.14 km), reaching areas significantly further from the colony (Fig. 45). With no significant difference in flight speed between the two species (mean of 16.26 m sec^{-1} in Sandwich Tern and 10.71 m sec^{-1} in Common Tern), Sandwich Tern achieved greater distances through significantly longer foraging bouts of up to 99 mins compared to a maximum of 77 mins in Common Tern (Fig. 45).

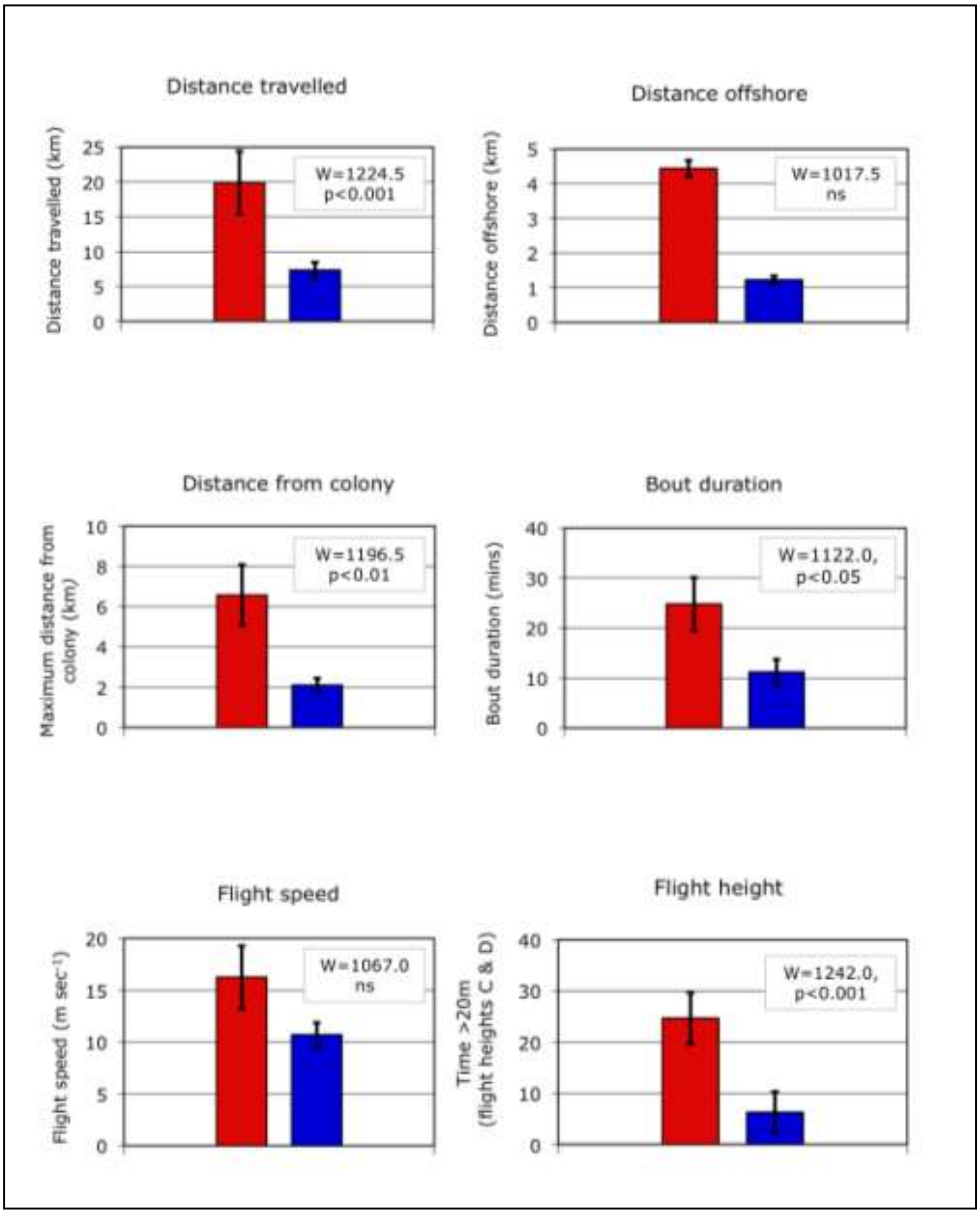

Figure 45. Comparison of flight attributes of foraging Sandwich (red) and Common (blue) Terns tracked from Blakeney Point.

A further feature of Sandwich Tern tracklines, particularly those extending offshore, was the low angle of deviance of flights (mean ± 1SE = 51.46 ± 13.88) suggesting individuals were heading for specific foraging locations when they left the colony (Fig. 43). The simulation model exploited the trait of travelling more or less directly to foraging areas (see 4.5 below). Individual Common Terns on the other hand tended to orientate parallel to the coast and patrol or quarter back and forth, before perhaps moving on to a different locality (Fig. 44). The angle of deviance of flight was thus high (mean ± 1SE = 89.27 ± 16.25 overall) and could not be exploited in modelling.

Both species appeared to use other terns and other species to identify potential foraging areas with approximately one in two Sandwich (56%) and Common Tern (57%) joining other birds within the first five fixes from the colony. As well as heading to aggregations of feeding terns, Common Terns were tracked heading towards Razorbills *Alca torda* on six occasions, whilst Sandwich Terns headed towards Bottle-nosed Dolphins *Tursiops truncatus* on two occasions, seals on three occasions and Gannets on five occasions. Both species showed a tendency to form foraging aggregations with conspecifics, other terns, gulls and auks and marine mammals. Some 30% of Sandwich Tern location fixes were spent in the vicinity of other Sandwich Terns. Common Terns spent a similar percentage of time foraging in groups, with 9% foraging with other Common Terns. There was however no consistent difference in the patterns of association for conspecifics compared to other species in either Sandwich or Common Tern (Fig. 46). Large multi-species foraging aggregations (MSFA's) only formed in inshore waters near the colony (Fig. 47), most likely linked to the concentration of fish around sandbars in relation to a falling and to a lesser extent, a rising tide. On one occasion 320 terns, of which the majority were Common, were recorded in association with ~120 Black-headed Gulls around a pool left on a drying bank where a shoal of small fish had become trapped. Small aggregations also occurred during the low water slack period, although never in the equivalent high water period.

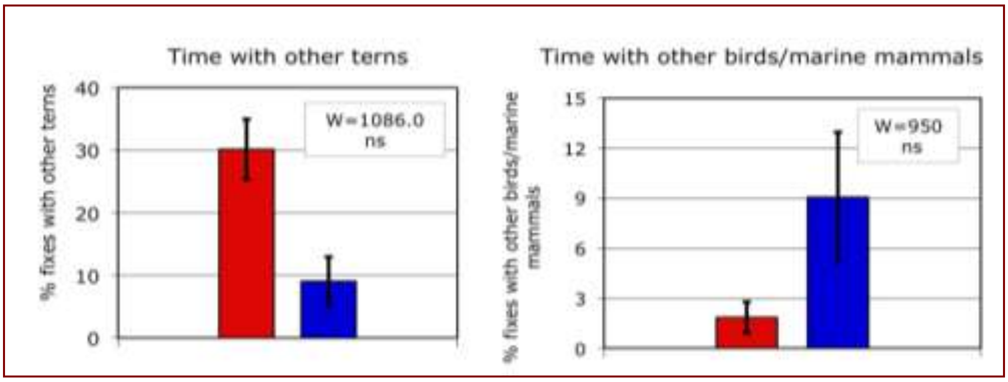

Figure 46. Social interactions of tracked Sandwich (red) and Common (blue) Terns expressed as the proportion of location fixes in the presence of other terns (including those of another species) (left) and other species of bird and marine mammals including both cetaceans and pinnipeds (right).

When foraging, Sandwich Tern spent significantly more time at greater flight height than Common Tern, with 49% of fixes >20m compared to 6.7% for Common Tern (Fig. 45). For Sandwich Tern this produced a markedly different distribution of flight heights compared to that observed in colony transects (Fig. 48), which also varied according amongst inbound and outbound birds (see Fig. 11 above). Differences in flight height alluded to differences in foraging behaviour between the two species with Sandwich Terns habitually feeding through plunge-diving (94%) compared to Common Terns making most attempts through surface feeding (47%) in which items are snatched from the surface, supported by plunge diving (Fig. 49).

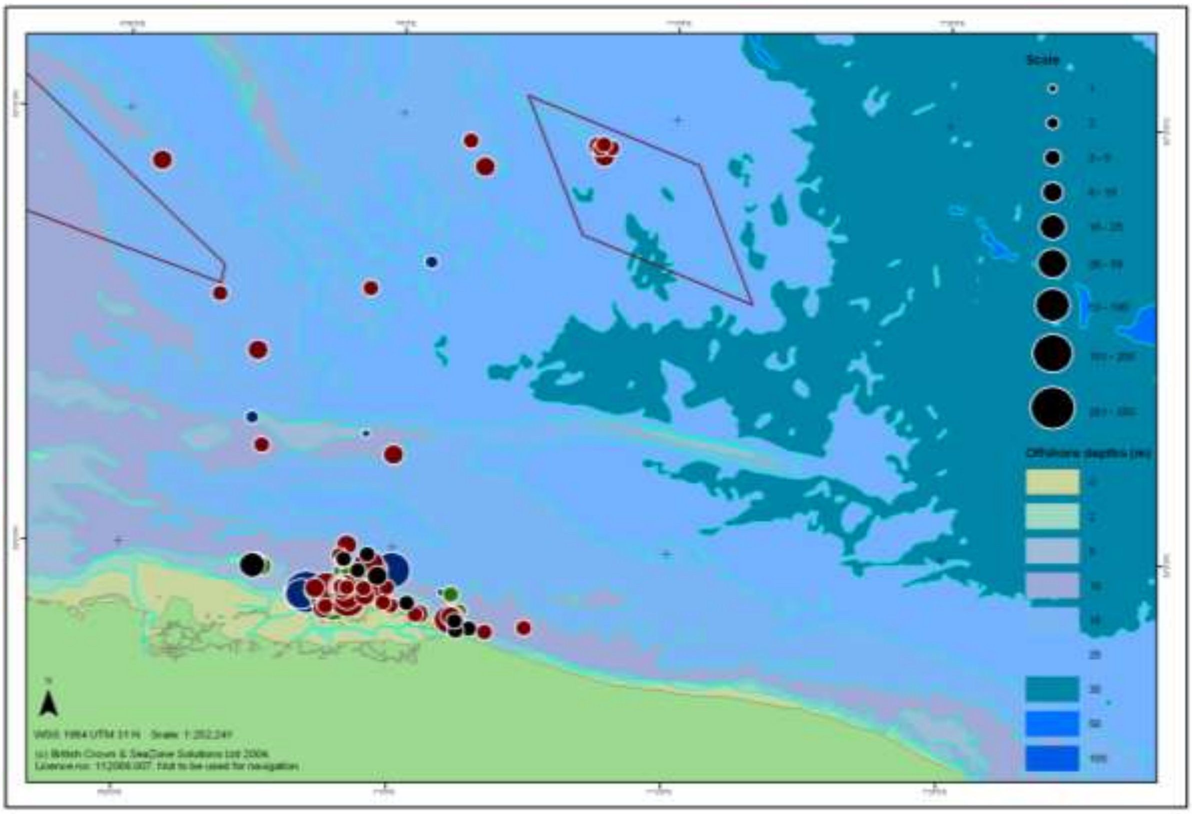

Figure 47. Locations of foraging aggregations of Sandwich Tern (red), Common Tern (black), mixed terns (green) and multi-species foraging aggregations including with other seabirds, cetaceans and seals (blue) in relation to proposed and consented OWFs in the Greater Wash.

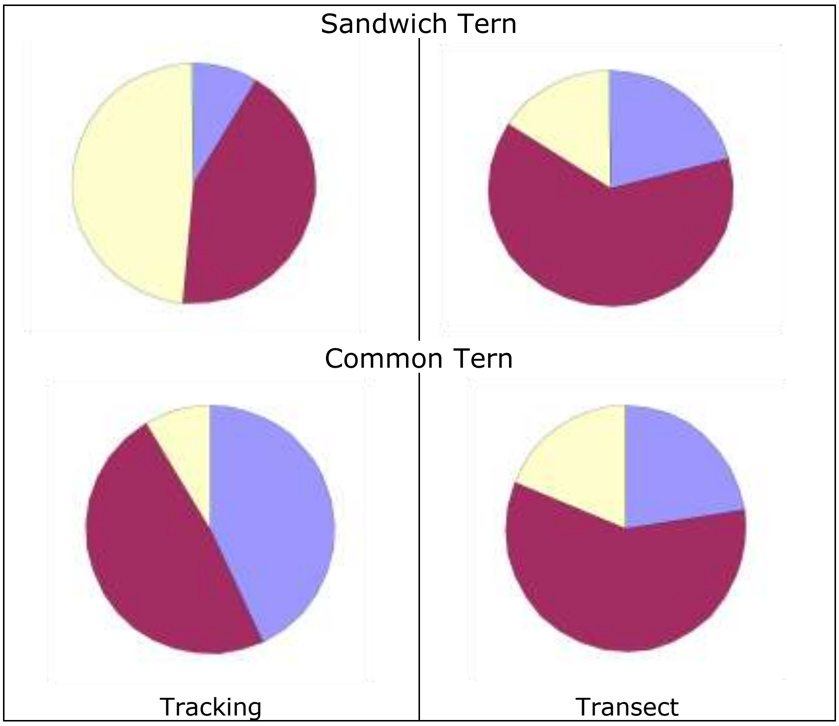

Figure 48. Distribution of flight height categories (blue = <1 m, red = 1 m-20 m and beige = 21-120 m) of tracked Sandwich (*n*=611 fixes from 26 individuals) and Common Terns (*n*=245 fixes from 42 individuals) compared to records of individuals (*n*=4778 and *n*=1354 respectively) observed on all transect line runs.

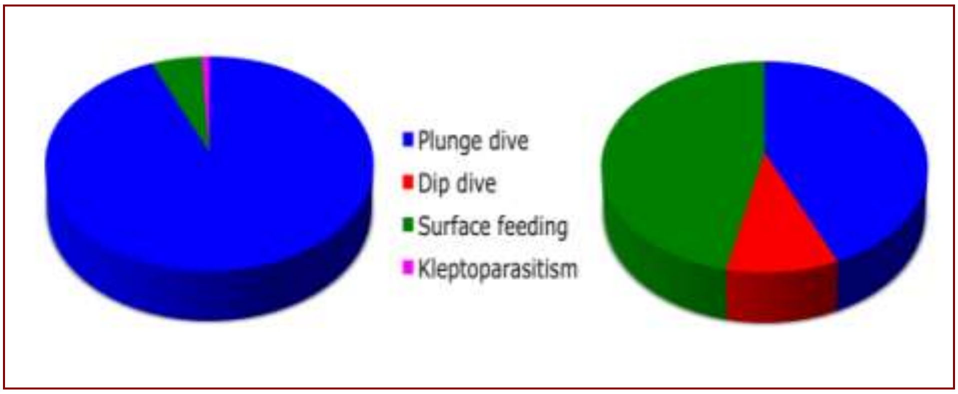

Figure 49. Feeding techniques employed by tracked Sandwich Terns (left) and Common Terns (right).

As a result of plunge diving, Sandwich Tern was observed to disappear below the surface, whereas Common Tern never completely immersed both body and wings. Only a small proportion of attempts by both species were clearly unsuccessful, as suggested by the lack of prey handling behaviours and immediate re-adjustment of body position sometimes to make another attempt at the same item. Otherwise, it was assumed that the attempt was successful and the prey was small and rapidly swallowed. In accordance with the greater prey handling and recovery time associated with plunge diving in Sandwich Terns, the frequency of foraging attempts was significantly higher in Common Terns at a mean rate (±1SE) of 67.16 ± 7.06 attempts per hour compared to 21.37 ± 11.14 in Sandwich Terns (Fig. 50). Significant differences were apparent despite considerable individual variation with some individuals of both species making no attempts to feed with others making a large number of attempts (maxima of 180 in Sandwich Tern and 255 in Common Tern). Sandwich Tern captured significantly longer prey, irrespective of its composition (see 4.4 below) suggesting larger prey were accessed by deeper diving into the water column. As a result of the capture of larger prey, the rate of biomass capture including prey transported back to the colony and the rate of biomass ingested at sea was not different between the two species (Fig. 50).

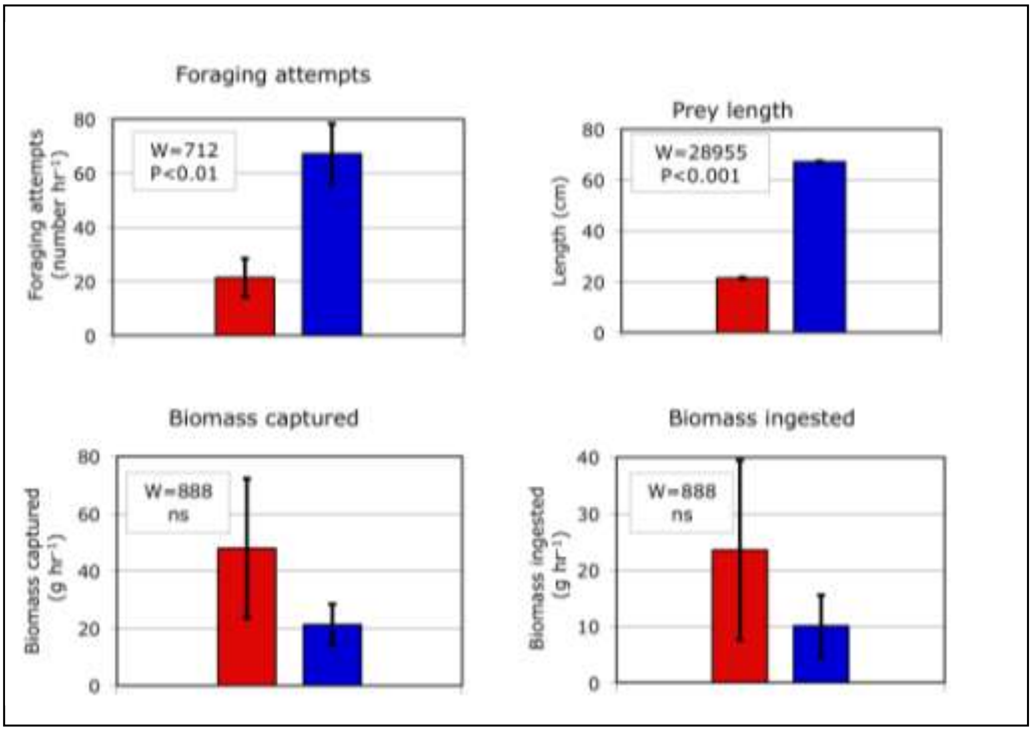

Figure 50. Rate of foraging attempts, total length of prey captured and rate of biomass captured and ingested by tracked Sandwich (red) and Common (blue) terns.

The considerable range in feeding rate amongst individuals of both species was testament to the temporal and spatial patchiness of prey items. Multiple feeding attempts at the same/similar location were a feature of Common Tern feeding activity whereas Sandwich Terns tended to capture single prey at each location before moving on, especially when foraging at greater distance from shore (Fig. 51).

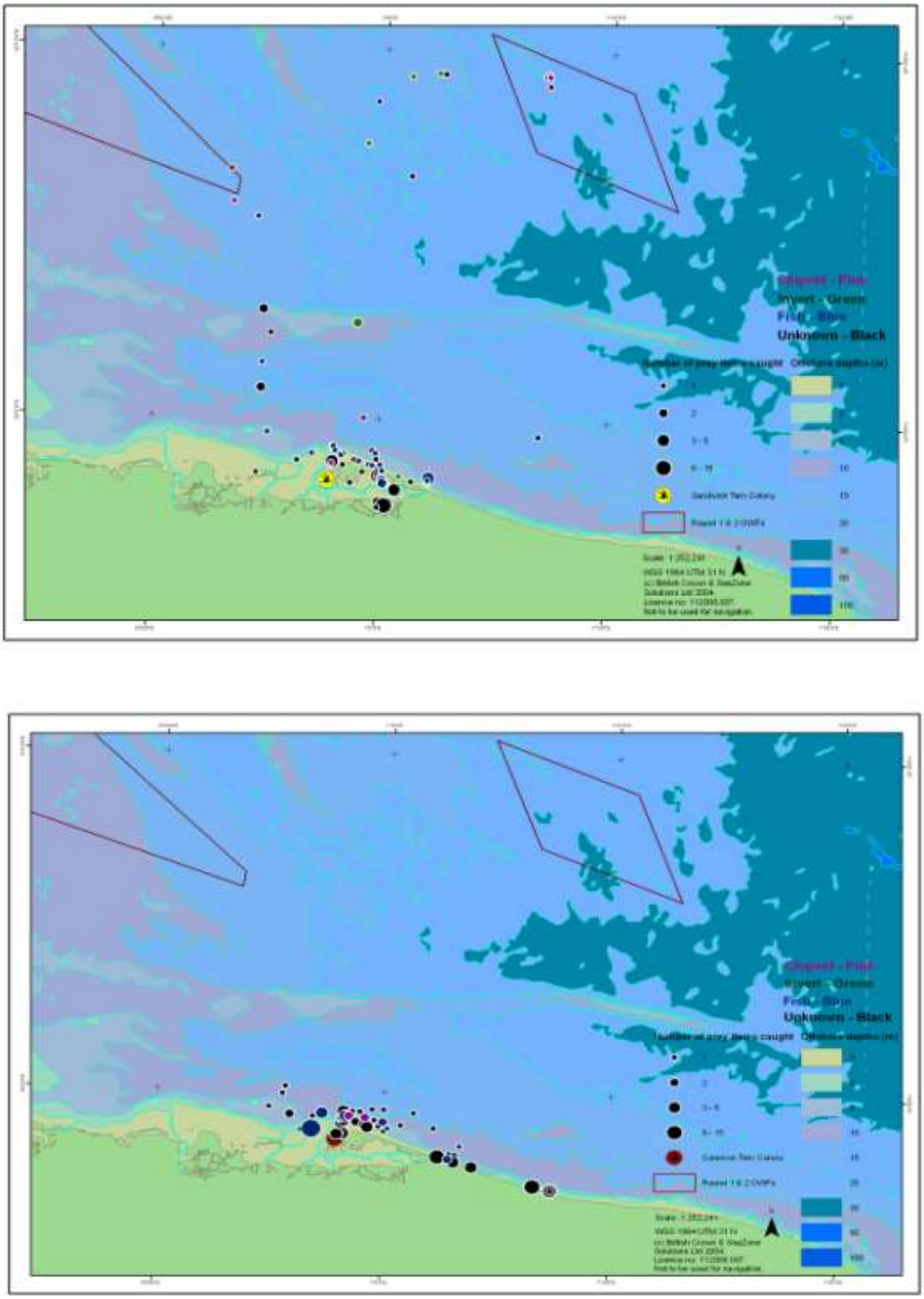

Figure 51. Distribution and number of different prey items captured by tracked Sandwich Terns (total *n*=103 above) and Common Terns (total *n*=342 below) in relation to proposed and consented OWFs in the Greater Wash.

In some foraging bouts individuals of either species made no attempt to feed themselves, but simply returned to the colony with the first captured prey item. Even so, in the case of Sandwich Tern, there was some evidence of selection of larger items to be carried back to the colony with no item smaller than 5.4 cm transported, whilst the majority of items captured were of <4 cm although the very small sample size precluded meaningful statistical comparison, as was also the case for Common Tern.

Whilst both tern species were observed feeding on shoaling small clupeids (known collectively as 'whitebait') including YOY at <30 mm body length, other small fish (often difficult to indentify) and invertebrates, only Sandwich Tern was observed foraging on sandeels at sea (Fig. 52) (although some were observed being presented to chicks by Common Tern – see above). Some of the sandeels caught by Sandwich Terns were relatively large at up to around 13.6 cm (i.e. 3 bill lengths) in contrast to the other fish and prey items taken by Sandwich Terns (maximum of 7.2 cm), and all fish caught by Common Terns (all ≤1 bill length or ~4.0 cm). Given that larger fish including both sandeels and clupeids were caught in both inshore and more offshore locations (see Fig. 51) the limited dive depth of Common Tern when foraging was thought to be responsible for the lack of larger fish its diet.

Figure 52. Tracked Sandwich Tern emerging from a plunge-dive with a small (~6cm) sandeel.

4.4.2 Sandwich Tern at Cemlyn Bay

A total of *n*=194 individual birds were tracked from Cemlyn Bay. However, *n*=55 birds of these were tracked only over 1-2 km with the intention of determining flight directions. Of the *n*=139 remaining individuals, *n*=64 (45%) were amalgamated into *n*=10 composite birds, whereby once a bird was lost, another exhibiting the same fight attributes was selected from close to the point the first bird was lost. Thus, *n*=85 bird tracks were available for analysis, although *n*= 139 was used when describing the proportion of birds lost for different reasons.

Sandwich Terns tended to strongly select an easterly initial flight direction from the colony (Fig. 53). Being as a relatively large proportion (72%) of birds were tracked over a greater distance than 1-2 km it is not surprising that this easterly trend is mirrored in the tracklines including all birds (*n*=194) (Fig. 54). This is, however, also influenced by the inclusion of composite 'leap-frog' tracklines. Without this, a reduced foraging range would have been recorded primarily because a very high proportion of birds could not be tracked for a complete bout (87%). In the majority of these cases (77% of lost birds), the tracked bird outflew the tracking vessel as a result of insufficient speed relative to sea conditions. Confusion of the tracked bird with others within foraging aggregations (13%) accounted for much of the remainder. The tendency to lose birds curtailed the limit of a number of parameters of tracks of Sandwich Terns at Cemlyn compared to Blakeney Point, including bout duration, distance travelled and distance from the colony (Table 4). In the event, the maximum track length was 57 km, with another bird reaching 33 km from the colony. Such figures are somewhat longer than than the mean ± SE track-length of 7.7 ± 1.4 km. The true maximum range of birds from the colony thus remains unknown and it is conceivable that birds may enter the Menai Strait or even reach the coast of North Wales on foraging trips.

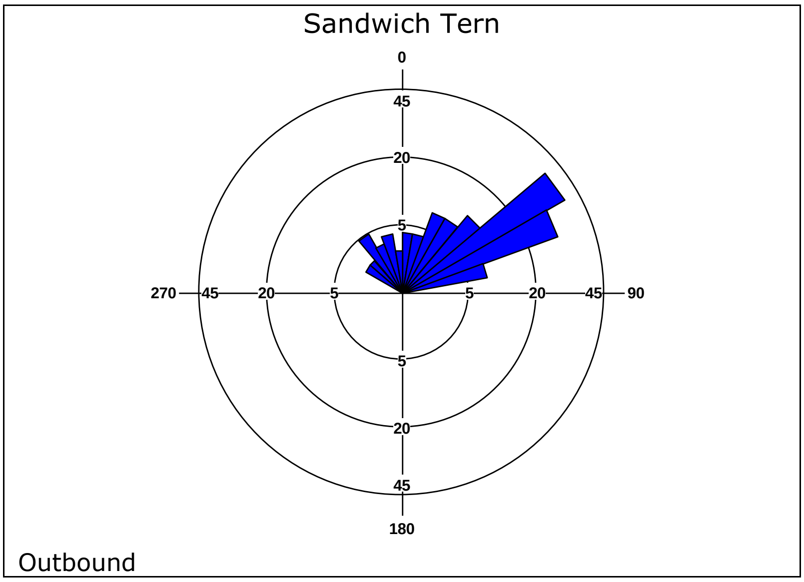

Figure 53. Outward flight bearings of Sandwich Terns from Cemlyn Bay located at the centre of the rose.

A striking feature of the tracklines obtained was their limitation to the coastal strip with no track reaching more than 7.6 km offshore. This produced a generally different pattern of linear tracklines compared to the fan-like pattern at Blakeney Point (compare Figs. 43 and 54). However, the relatively small number of longer offshore tracklines at Blakeney meant that there was no significant difference between the distances reached offshore by Sandwich Terns at the two different colonies (Table 4). Nevertheless, partly as a result of the greater distance offshore of the Round 3 zone in the Irish Sea compared to OWFs in the Wash, the possibility of the foraging range of breeding Sandwich Terns from Cemlyn overlapping with an OWF appeared to be remote (Fig. 54).

Plotting the location of all foraging attempts revealed clusters in what seemed to be preferred foraging areas (Fig. 55). These included the area around Middle Mouse, Point Lynus, Dulas Bay, Traeth Dulas and Red Wharf Bay. These areas incorporate rather different habitat types. Whereas Middle Mouse is an isolated rock 820 m offshore, Point Lynus is an area of turbulent seas around a rocky outcrop with deep water (up to 50m) only 200 m from the shore. In contrast, Dulas Bay, Traeth Dulas and Red Wharf Bay are shallow (<5 m) embayments often associated with streams discharging into the sea producing extensive areas of finer bed substrate. These areas are likely to be the origin of the sandeels captured by terns at a variety of locations (Fig. 55).

Basic flight parameters such as recorded flight speed and flight height were similar between birds from Cemlyn and Blakeney suggesting birds foraged in a similar way (Table 5) despite the abbreviation of bouts at Cemlyn. However, birds from Blakeney appeared to spend a higher proportion of time at >20 m flight height compared to tracked birds from Cemlyn (49% cf. 23% respectively). The number of foraging attempts per hour of birds from Blakeney was also slightly higher overall (20 vs. 12), but as a result of smaller mean prey length (4.0 cf. 7.4 cm) the overall energy intake was slightly higher at Cemlyn (103.3 KJ hr^{-1} cf. 99.6 KJ hr^{-1}).

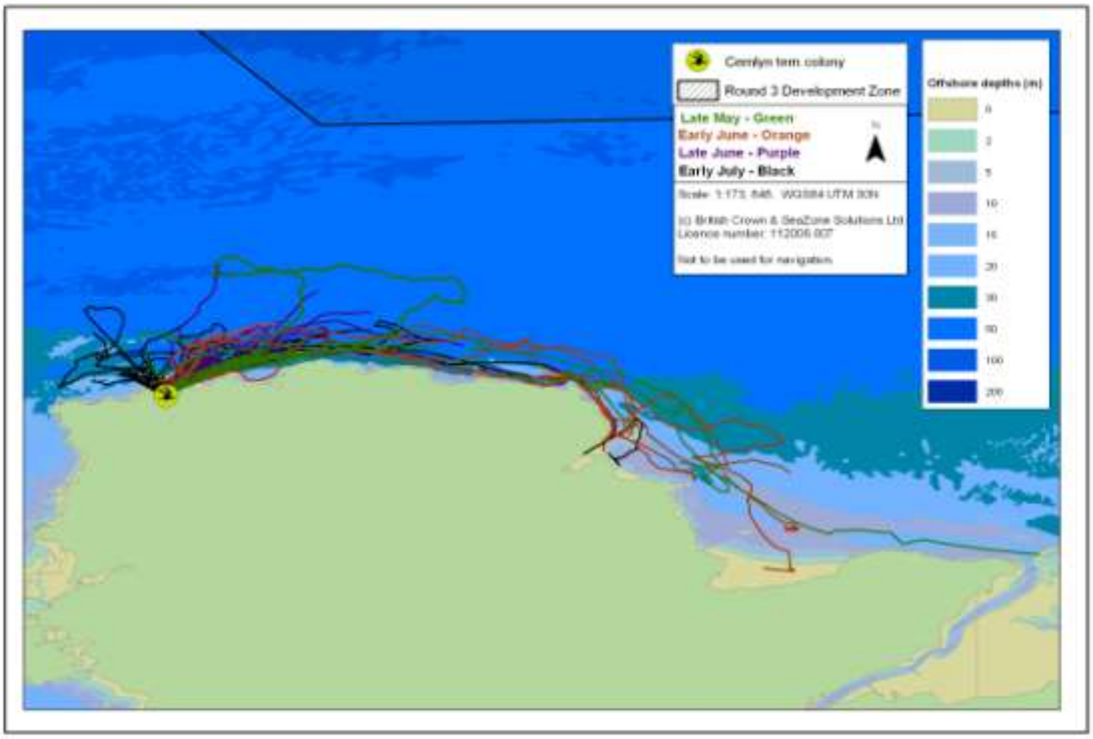

Figure 54. Flightlines of all Sandwich Terns (*n*=194) from the Cemlyn Bay colony plotted from fixes taken during visual tracking at sea in relation to the proposed Round 3 OWF zone in the Irish Sea.

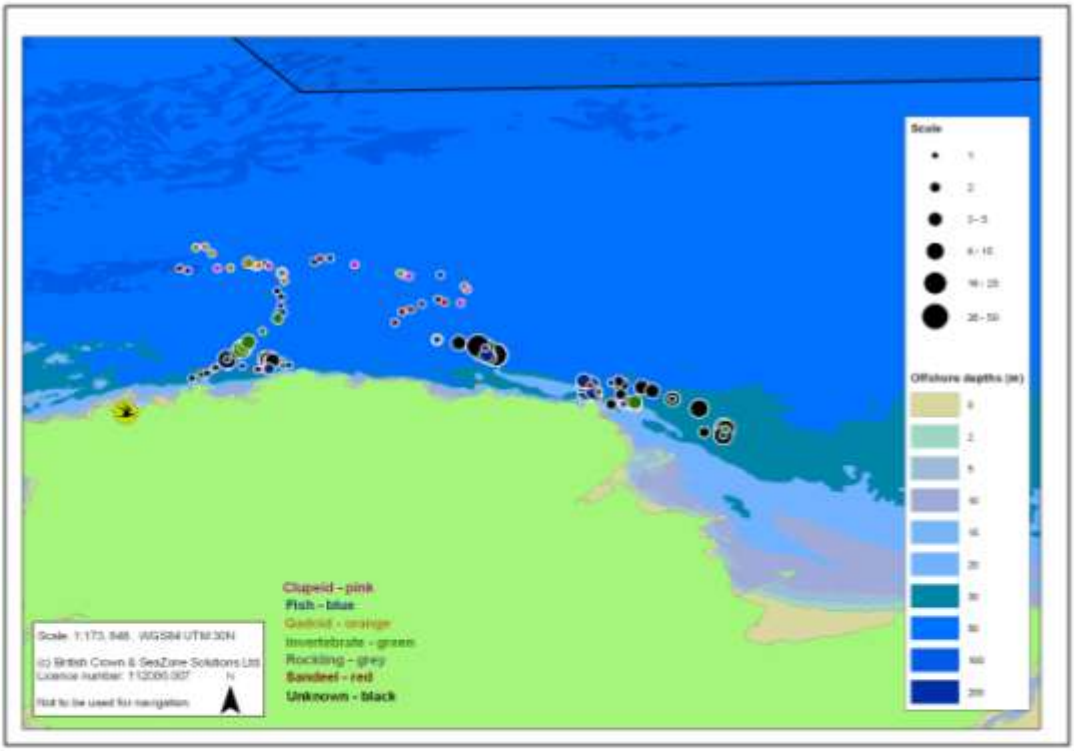

Figure 55. Distribution and number of different prey items (total *n* = 332) captured by tracked Sandwich Terns from the Cemlyn Bay colony.

Clupeids and sandeels comprised the bulk of identified prey items captured by terns from both colonies but in different proportions, with the former taken more frequently at Blakeney and the latter taken more often at Cemyn. A number other fish prey including gadoids and rockling was included in the diet of birds at Cemlyn (see also 4.2.3). The slightly higher rate of capture of unidentified, typically small, fish at Blakeney was more or less substituted by similar–sized invertebrates in the waters of Anglesey. The fraction of unidentified items was also higher amongst birds from Cemlyn (Table 4).

Table 4. Comparison of the mean (± SE) values of the various aspects and parameters within foraging bouts of Sandwich Terns tracked from Blakeney Point in 2008 (*n*=26) and Cemlyn Bay in 2009 (*n*=85 apart from *n*=139 in relation to proportion of complete bouts).

Aspect	Parameter	Blakeney Point	Cemlyn Bay
Bout	Proportion (%) complete	63	12
	Duration (min)	24.8 ± 5.3	10.0 ± 1.1
Distance	Distance travelled (km)	15.4 ± 3.6	7.6 ± 0.8
	Maximum distance from colony (km)	6.6 ± 1.5	15.8 ± 0.2
	Maximum distance offshore (km)	4.4 ±1.4	1.8 ± 0.1
Flight	Speed (km hr^{-1})	39.0 ± 4.6	34.0 ± 0.3
	Height (% >20 m)	48.6	22.8
Interaction	Time with other terns (%)	34.1	19.5
	Time with other species (%)	3.1	8.7
Foraging	Foraging attempts (n hr^{-1})	21.4 ± 7.2	11.5 ± 2.0
	Total energy intake per hour (kJ hr^{-1})	96.6	103.3
Prey type	Clupeid (n hr^{-1})	8.08	5.12
	Sandeel (n hr^{-1})	1.16	8.52
	Gadoid (n hr^{-1})	0.00	0.83
	Rockling (n hr^{-1})	0.00	0.28
	Unidentified fish (n hr^{-1})	3.35	1.73
	Invertebrate (n hr^{-1})	0.61	1.39
	Unidentified (n hr^{-1})	6.32	11.88
	Other items (n hr^{-1})	0.04	0.03

4.4.3 Arctic Tern at the Skerries

The seven Arctic Terns tracked from the Skerries on one occasion during the incubation period showed rather variable patterns of ranging behaviour (Fig. 56). One bird showed a Sandwich-tern like pattern of flying considerable distance from the colony on a direct course for much of the time. It did however, continually orientate towards auks, particularly Puffins, which could not necessarily be seen before they flushed from the vessel. This seems likely to have influenced the foraging success of the tracked tern. The wide-ranging bird invariably skewed the mean values for distances reached from the colony, but nonetheless confirmed that Arctic Terns may have a propensity to undertake foraging bouts of considerable distance and duration. In Anglesey, this led to the potential for breeding Arctic Terns to interact with the Round 3 Irish Sea zone. The tendency towards longer movements than other species at other colonies was not the primary reason for the relatively low proportion of birds tracked, which was influenced by having to leave two of the seven birds tracked as a result of fuel and time constraints.

Other tracked Arctic Terns showed Common-Tern like wandering movements nearer the colony, surface-dipping to collect small items, particularly associated with the tidal rip currents that are a feature of the waters surrounding the Skerries. The prevalence for small items is reflected in the very high rate of foraging attempts, but low total prey length captured per unit time compared to Common Terns at Blakeney and Saltholme (Table 5) as well as Sandwich Terns (Table 4). Whilst this could simply be linked to the availability of different types of prey in the waters surrounding different colonies, the difference in prey type between Arctic Terns and Sandwich Terns from nearby Cemlyn, which are likely to have a similar suite of available prey species is marked (Table 4). Invertebrates thus appear to be of particular importance to foraging adult Arctic Terns. Whether invertebrates feature significantly in provisions to chicks remains unknown.

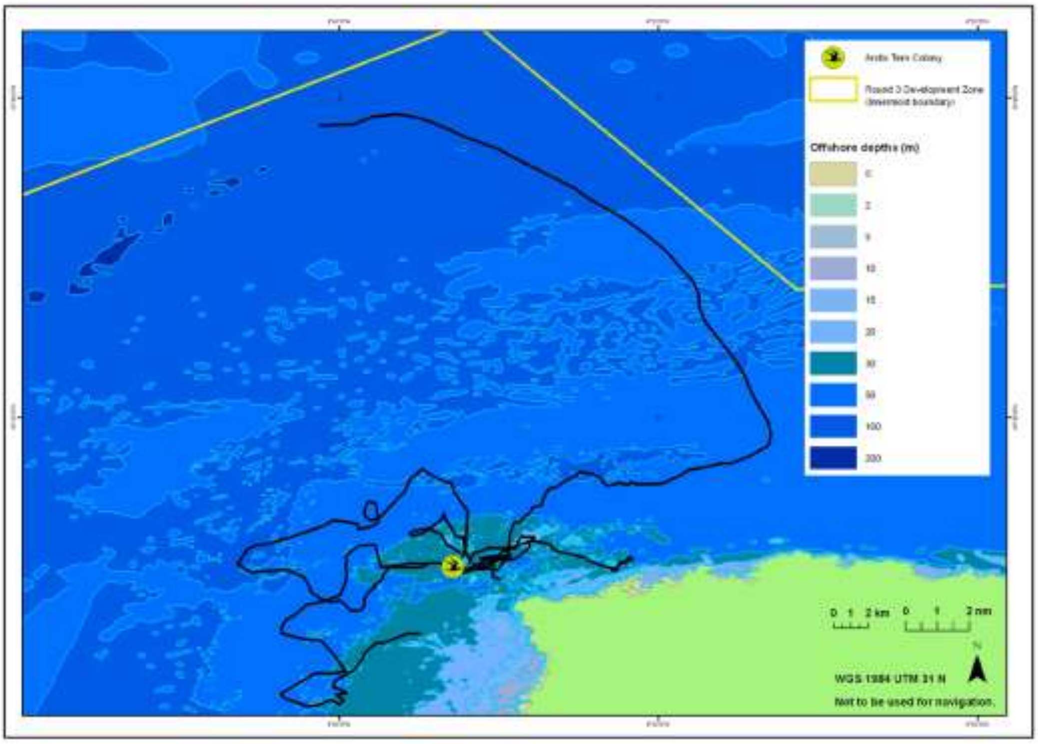

Figure 56. Flightlines of all Arctic Terns (*n*=7) from the Skerries plotted from fixes taken during visual tracking at sea, in relation to the proposed Round 3 OWF zone in the Irish Sea.

4.4.4 Common Tern at Saltholme

Common Terns from Saltholme exhibited a clear preference to head directly for the Tees estuary and the sea (see 4.1.1 above). Tracked birds reinforced the apparent preference for maritime habitats by rarely attempting to forage in the river upstream of the main dock area (Fig. 57). Although much foraging activity was recorded within the Tees estuary itself, just less than 1 in 2 birds (46 %) ranged further into the open sea, effectively heading in all directions to produce a radiating fan-like pattern (Fig. 57). In fact, this may even underestimate the relative importance of the open sea as a foraging ground as a high proportion (76%) of the *n*=107 birds tracked were lost before heading back to the colony, during which time they may have gone to sea. This was on account of the restrictions of following birds in shallow waters in the estuary, which then led to confusion with other birds (28%) and the tendency of birds to take a direct route over the breakwater when heading to the south of the estuary (8.5%).

The physical geography of the area with extensive shallow areas that could not be accessed without a risk of encountering underwater obstructions, and the generally high vessel traffic are thought to have made an important contribution to the low proportion of tracked birds (Table 5). After all, there was little to suggest that some feature of the flight characteristics was responsible, with flight speed being somewhat slower (44%) than that exhibited by birds at

Blakeney. This appears to have been manifested as a considerable increase (131%) in the proportion of birds at flight height >20 m. Moreover, sea conditions were also generally good, particularly in the protected environment of the estuary itself.

Table 5. Comparison of the mean (± SE) values of the various aspects and parameters within foraging bouts of Common Terns tracked from Blakeney Point in 2008 (*n*=42) and Saltholme in 2009 (*n*=107) and the small number (*n*=7) of Arctic Terns tracked from the Skerries in 2009.

Aspect	Parameter	Common Tern		Arctic Tern
		Blakeney Point	Saltholme	Skerries
Bout	Proportion (%) complete	64.0	15.4	28.6
	Duration (min)	14.9 ± 4.1	13.1 ± 1.4	45.3 ± 9.9
Distance	Distance travelled (km)	6.6 ± 1.8	4.0 ± 0.5	24.5 ± 7.4
	Maximum distance from colony (km)	2.2 ± 0.4	8.1 ± 0.3	8.1 ± 3.2
	Maximum distance offshore (km)	1.0 ± 0.1	1.9 ± 0.2	8.5 ± 3.5
Flight	Speed (km hr^{-1})	35.2 ± 6.1	19.6 ± 1.1	28.0 ± 3.7
	Height (% >20 m)	6.7	11.8	0
Interaction	Time with other terns (%)	31.1	28.3	43.3
	Time with other species (%)	5.3	5.2	2.5
Foraging	Foraging attempts (n hr^{-1})	48.9 ± 9.1	39.12 ± 5.0	130.6 ± 33.3
	Mean prey length captured (cm)	2.5 ± 0.2	3.9 ± 0.2	2.5 ± 0.2
Prey type	Clupeid (n hr^{-1})	1.0	1.1	0
	Sandeel (n hr^{-1})	0	0.7	0
	Gadoid (n hr^{-1})	0	0	0
	Unidentified fish (n hr^{-1})	2.7	1.1	1.0
	Invertebrate (n hr^{-1})	2.4	0.8	0.6
	Unidentified (n hr^{-1})	4.4	7.3	133.2

The pattern of foraging tracks was radically different from that produced at Blakeney Point with Common Tern at Saltholme ranging nearly four times further from the colony and 90% further offshore on average (Table 5). Although the planned Teesside OWF at its closest is only just over 1 km of the coast, it is some 9 km from the colony. If placed in the Greater Wash the OWF would seemingly be beyond the typical range of Common Terns. This is not the case at Teesside where 19% of all tracks crossed some part of the OWF. If only complete tracks (*n*=16) are considered then this proportion increased further to 25%. Part of the reason for the greater bout range may be linked to the differences in respective foraging conditions for the birds in the waters of the Wash and Teesmouth. Clupeids were the mainstay of identified items captured at both colonies, but judging from a much higher foraging rate as well as higher mean prey size (Table 5), the foraging conditions at Teesside were particularly rich. In a similar manner to Sandwich Terns, this may have allowed Common Terns to reach greater distance from the colony whilst self-feeding and to still maintain chick growth rate.

At sea, Common Terns from Saltholme spent time in the company of post- or non-breeding auks particularly later in the season (black and red lines in Fig. 57), seemingly benefitting from feeding parties of these birds driving prey to the surface where they were also captured by species such as Kittiwake. Such behaviour was never observed in the Wash, where there are no nearby auk colonies and passage of auks tends to occur after the breeding season of terns has been completed. These associations accounted for the presence of clusters of captured prey items further offshore and over deeper (30-50 m) waters (Fig. 58).

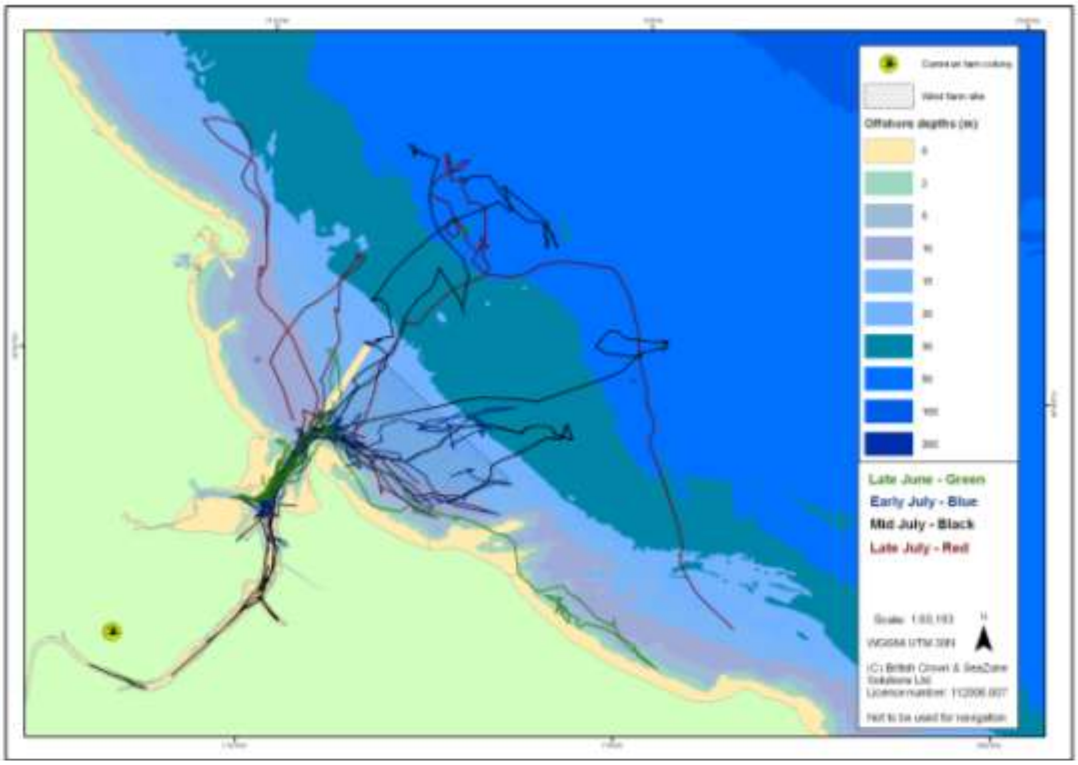

Figure 57. Flightlines of all Common Terns (*n*=107) from Salthome plotted from fixes taken during visual tracking, in relation to the consented Teesside OWF.

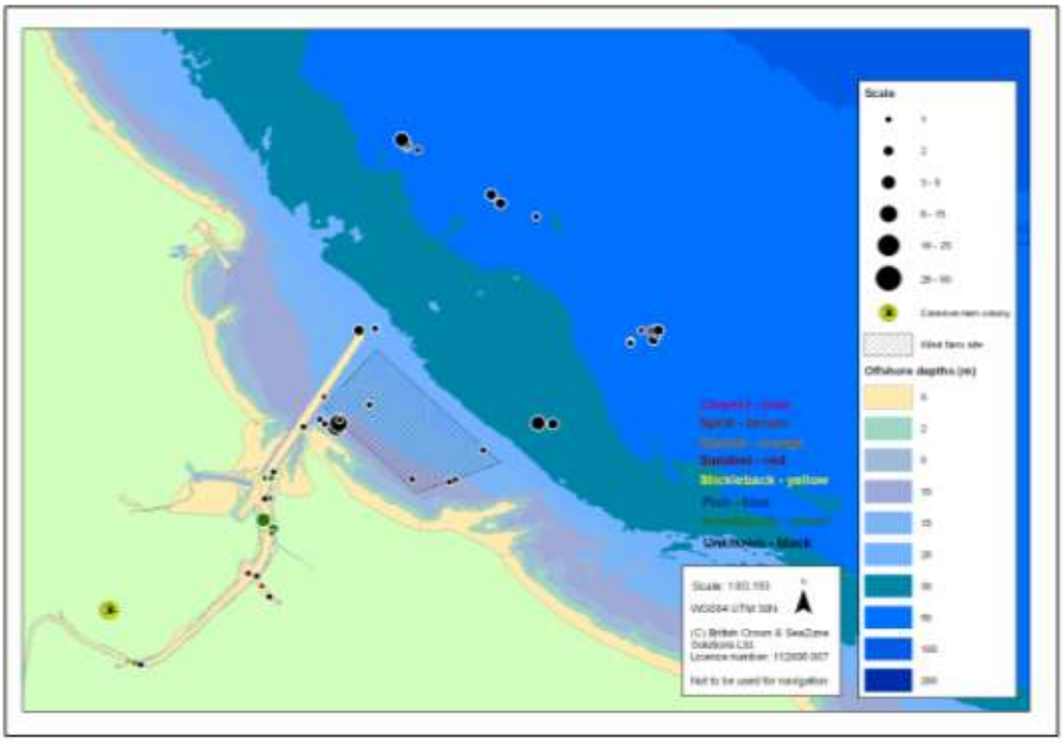

Figure 58. Distribution and number of different prey items (total *n* = 98) captured by tracked Common Terns from Saltholme.

4.5 Simulation of Sandwich Tern foraging from Blakeney Point

The foraging simulation model was successful in generating a set of predictions for the spatial distribution of activity exhibited by Sandwich Terns foraging from Blakeney Point in 2008 as densities of foraging endpoints expressed on a regional scale (Fig. 59). Modelling predicted that the highest densities of foraging endpoints fell within close proximity to the colony, with a significant drop-off in densities at distances greater than 20 km. As such, the number of foraging endpoints falling within proposed offshore wind farm sites was relatively low (Fig. 59, Table 6).

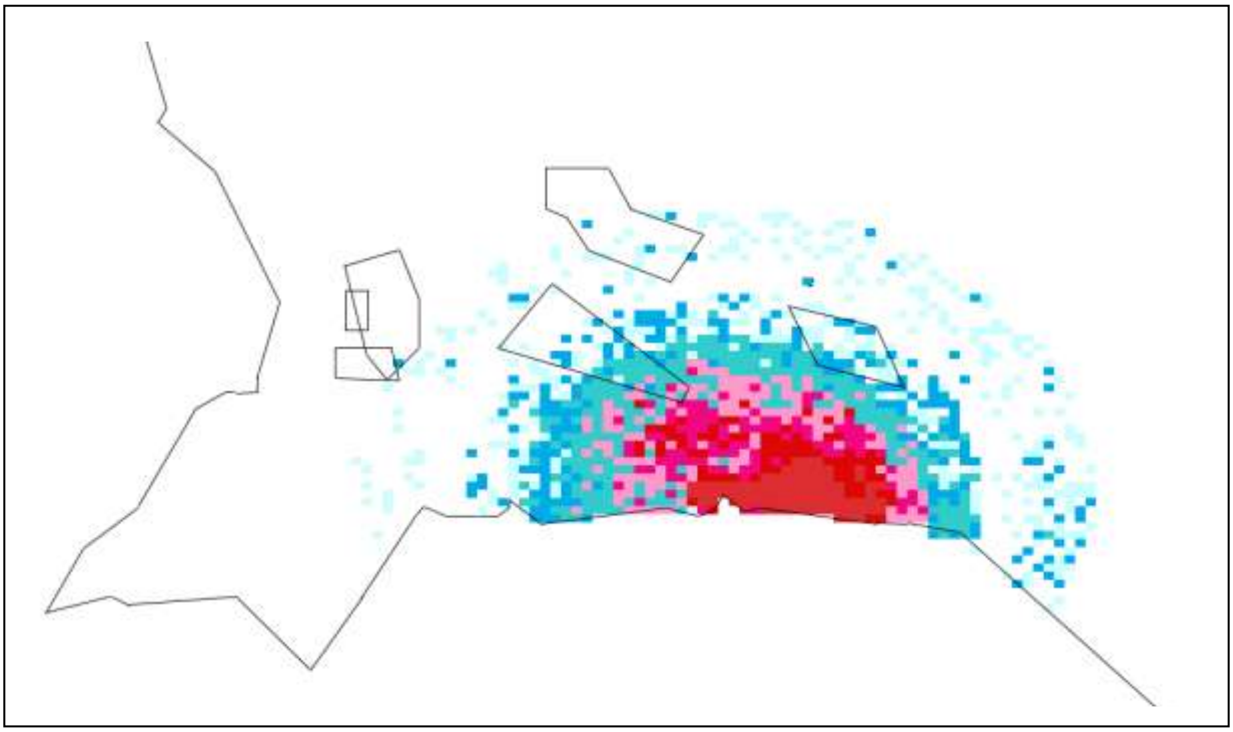

Figure 59. Density map in 1km x 1km squares of 'end-point' foraging locations for Sandwich Terns from Blakeney Point in 2008, derived from the foraging simulation model (15,000 simulated flights). Density increases through blue to green to pink and red. Polygons delimit proposed or completed wind farm sites for which precise locations are known (i.e. Dudgeon and Triton Knoll, sites generally beyond the reach of foraging birds predicted by the model in this circumstance, are excluded).

In total, over all the OWFs either in planning or consented, 2.8% of foraging endpoints was predicted to fall within OWF site areas. In addition, 0.56% of other foraging flights were predicted to pass through at least one of the sites. The extent of overlap between Sandwich Tern foraging activities and OWFs was therefore predicted to be minimal on the basis of the 2008 surveys. However, it should be noted that the information feeding into the model was from the latter part of the season, when foraging distances appear to be shorter relative to earlier stages of the season (Centrica Energy 2009) and are unlikely to represent the breeding season as a whole.

A total distance travelled by Sandwich Terns across each site in the course of the season was calculated from the proportion of total estimated flights resulting in endpoints and flyovers in/over the different sites, combined with the average distance travelled in each of those flight types. For the Blakeney colony in 2008 this was estimated to be 177,055 km for Docking, 47,549 km for Sheringham and 11,113 km for Race Bank. From standard collision risk modelling, Folkerts (2008) derived an annual mortality per kilometre through Docking Shoal and Race Bank, which with layouts with 3.6MW turbines were 2.39×10^{-3} and 2.29×10^{-3}

respectively. For the broad purposes of comparison here and assuming a similar risk (even though this may not be supported by the collision risk modelling undertaken to date – SCIRA Offshore Energy Ltd 2006) a mid-value of 2.34×10^{-3} was used.

Table 6. Numbers and proportions of 'end-point' foraging locations and 'flyovers' (birds *en-route* to more distant endpoints) occurring within the site+buffers of all proposed/consented OWFs within the Greater Wash using known locations, derived from the foraging simulation model for Blakeney Point in 2008. Total *n*=15,000 simulated flights with *n*=12,161 foraging end-points with a flight bearing error of 20^0.

	Foraging endpoints		Flyovers	
OWF site	Number	% of total	Number	% of total
Docking Shoal	242	1.99	17	0.14
Sheringham Shoal	83	0.68	48	0.39
Race Bank	13	0.11	4	0.03
Lincs	2	0.02	0	0.00
Lynn & Inner Dowsing	0	0.00	0	0.00

Suggested annual mortality was thus 423, 113 and 26 at 0% avoidance from Docking, Sheringham and Race Bank respectively. An appropriate avoidance rate of 99% avoidance (see Whitfield 2008) suggests just 4.2, 1.1 and <1 individuals would be killed at these sites respectively. It must again be stressed that these are not suggested to be realistic values in this case as the data from Blakeney Point in 2008 was limited to the end of the season and flights in the earlier part of the season are likely to be much longer, thereby encompassing OWFs further from shore.

4.6 Sandwich Tern foraging range from an energy balance approach

4.6.1 Determination of optimal provisioning strategies

The capture rate during tracking of clupeids and sandeels (including only items identified with certainty) as well as all prey combined, expressed as the time required to locate one item of a given size during foraging is shown in Fig. 60. The principal difference in rate between the two main prey types was at small size (<5 cm or less than one bill length), at which clupeids were more frequent and hence required shorter search times. At larger sizes over 12 cm, this pattern was reversed, with capture rates for sandeels being significantly higher than those of clupeids.

As the energetic content of both prey species increases dramatically at higher sizes (particularly for clupeids, see above), small differences in the rate at which larger size classes are captured could significantly influence the energetic productivity of foraging. More importantly, the size of prey that adults select to bring back to chicks will be a strong determinant of how long a foraging trip is likely to last, and hence how far offshore the individual may travel. In order to explore this relationship, capture rates for each prey type (and all prey combined) were modelled as a function of prey item size using capture rates calculated for discrete size classes. In each case, relationships were best explained using exponential functions, which were then used to estimate the minimum search time required for a foraging adult to capture an item of a given size (or greater) for each prey species.

The following predictive equations linking prey item size with search time were generated:

Equation 4 Clupeids: Search time (min) for size x = (1 / 7.2361 exp(-0.4183x) x 60

Equation 5 Sandeels: Search time (min) for size x = (1 / 0.3836 exp(-0.1712x) x 60

Equation 6 All prey: Search time (min) for size x = (1 / 5.0862 exp(-0.3103x) x 60

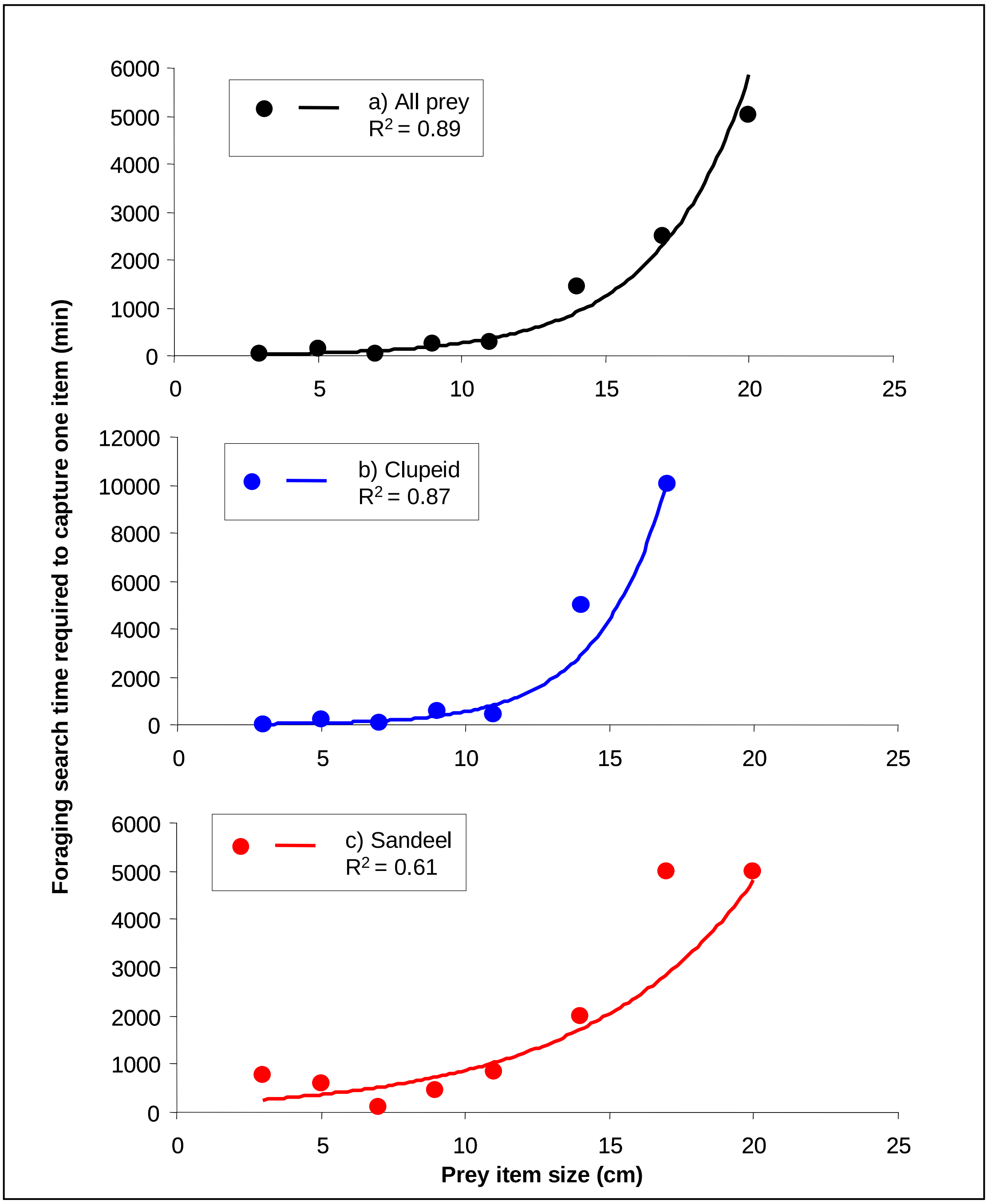

Figure 60. Relationship between prey item size and capture rate per hour foraging for Sandwich Terns from North Norfolk colonies, showing a) all prey combined and the two principal prey types, b) clupeids and c) sandeels. Points represent midpoints of continuous size bins of varying width. Lines show exponential functions, together with their respective Pearson R^2 statistics. Capture rates were observed during 55.6 hours of tracking of Sandwich Terns at sea from North Norfolk colonies in 2006-08.

In order to test the robustness of the resulting search time models, model predictions were compared against observed search times for each size class, as determined from observed capture rates during tracking (Fig. 61). In each case, model predictions were strongly correlated with observed values (all prey Pearson $R^2 = 0.99$; clupeids Pearson $R^2 = 0.95$; sandeel Pearson $R^2 = 0.87$), indicating a high degree of confidence in model performance, particularly in the case of the overall model for all prey types.

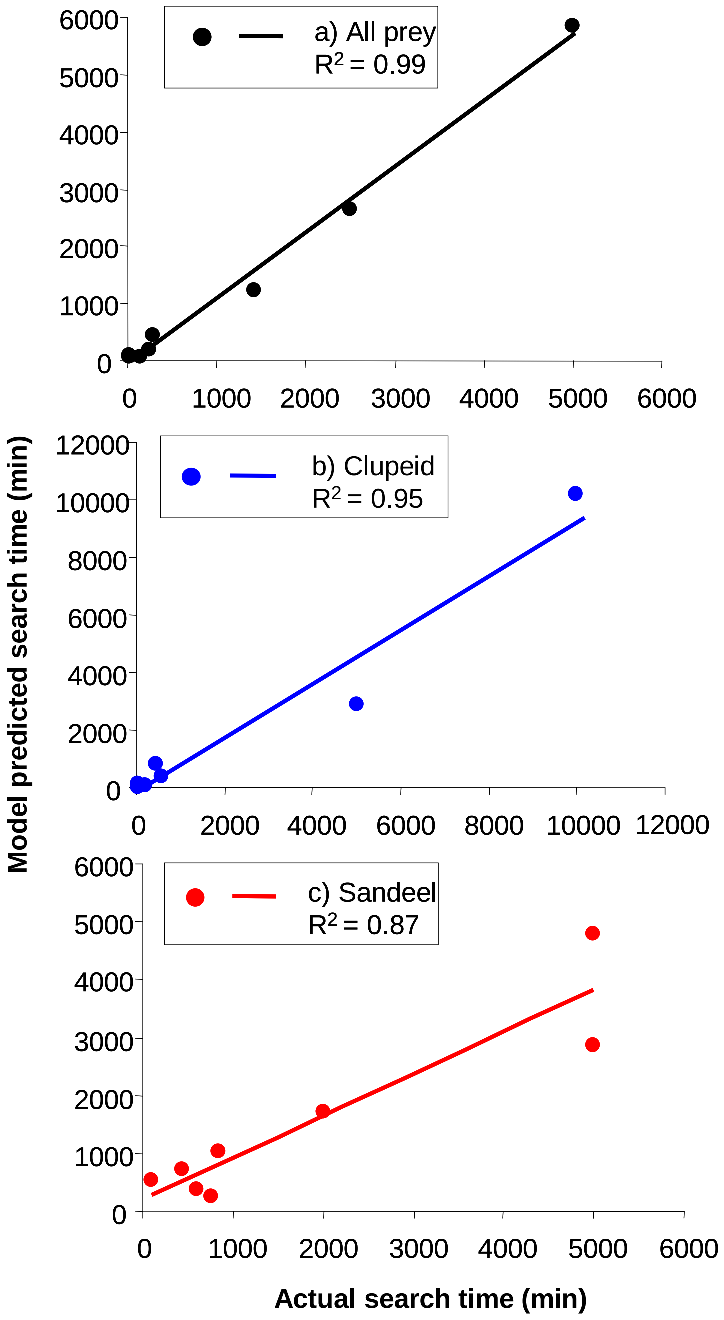

Figure 61. Correlations between modelled predicted search times and actual search times determined from size specific capture rates observed during tracking, for prey items of varying size caught by Sandwich Terns from North Norfolk colonies in 2006-08.

Search time was related to distance reached from shore from complete foraging bouts determined by tracking at North Norfolk colonies (Fig. 62). Distance from shore tended to increase proportionately with search time, as might be expected given the generally linear nature of Sandwich Tern foraging flights. The relationship between search time and distance from shore was therefore taken from a linear correlation of these variables, and was assumed to be similar for both prey species:

Equation 7 Distance from shore (km) = 0.2382 t - 1.1201

where t is the search time in minutes.

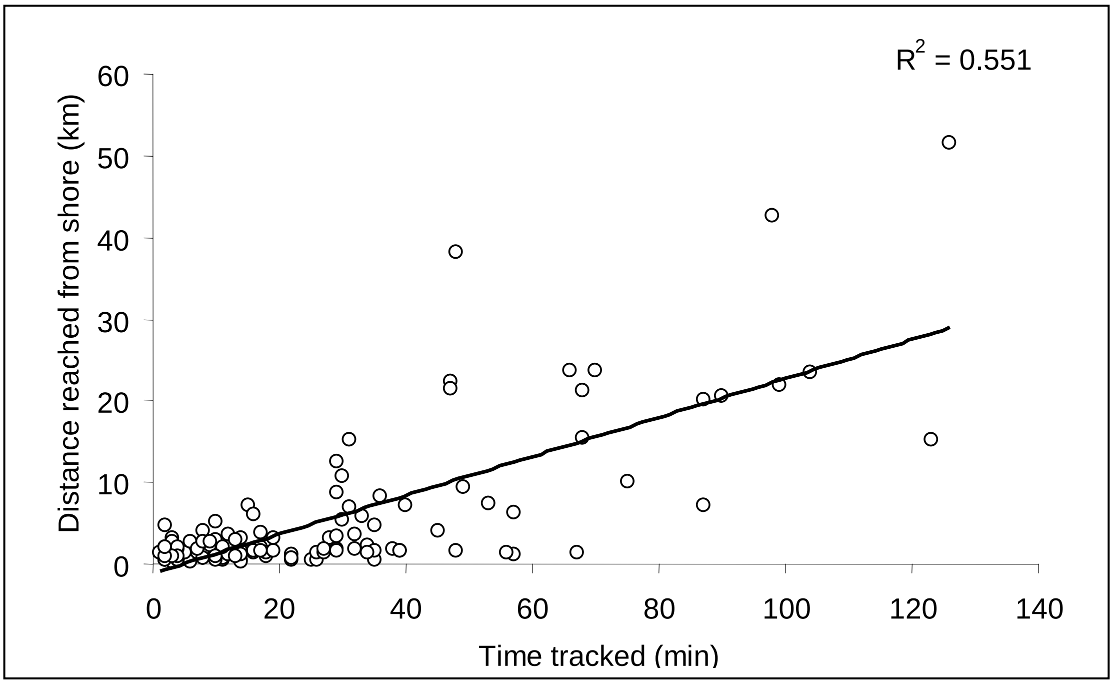

Figure 62. The relationship between tracking time (prior to the tracked individual returning to the colony) and the distance reached from shore by tracked individual Sandwich Terns from North Norfolk colonies in 2006-08.

The distance from shore that Sandwich Terns might be expected to reach on typical foraging trips if they adopt a given minimum size selection threshold (and hence search time) for provisioning is shown in Fig. 63 for each prey species, as well as for all prey combined. As it is unlikely that individual Sandwich Terns target one prey species exclusively (all evidence suggests that pairs provision chicks with both sandeels and clupeids), the relationship for all prey combined is likely to be the most meaningful in this case.

Having determined typical search times (and hence flight distances) required to locate prey items of a minimum given size, a time budget was constructed to estimate the number of provisioning events that might be possible in a single day for different prey size selections strategies. In addition to search time, each foraging bout incorporated transit time to carry the item back to the colony, determined according to the mean flight speed (measured from tracking at 32.6 km hr^{-1}) and the predicted distance reached from the shore for a given search time (see Eq. 7 above). Prey hand-over time was also included and assumed to be 5 minutes for each provisioning attempt (based on colony observations and allowing for a brief rest period). Summing these timings, the total duration of a foraging bout and hence the number of foraging trips that can be undertaken, assuming constant provisioning activity by one parent for 14 hours per day (the approximate daylight period during the chick rearing) was estimated. Predicted daily provisioning rates for the two prey types and all prey combined are shown in Fig. 64.

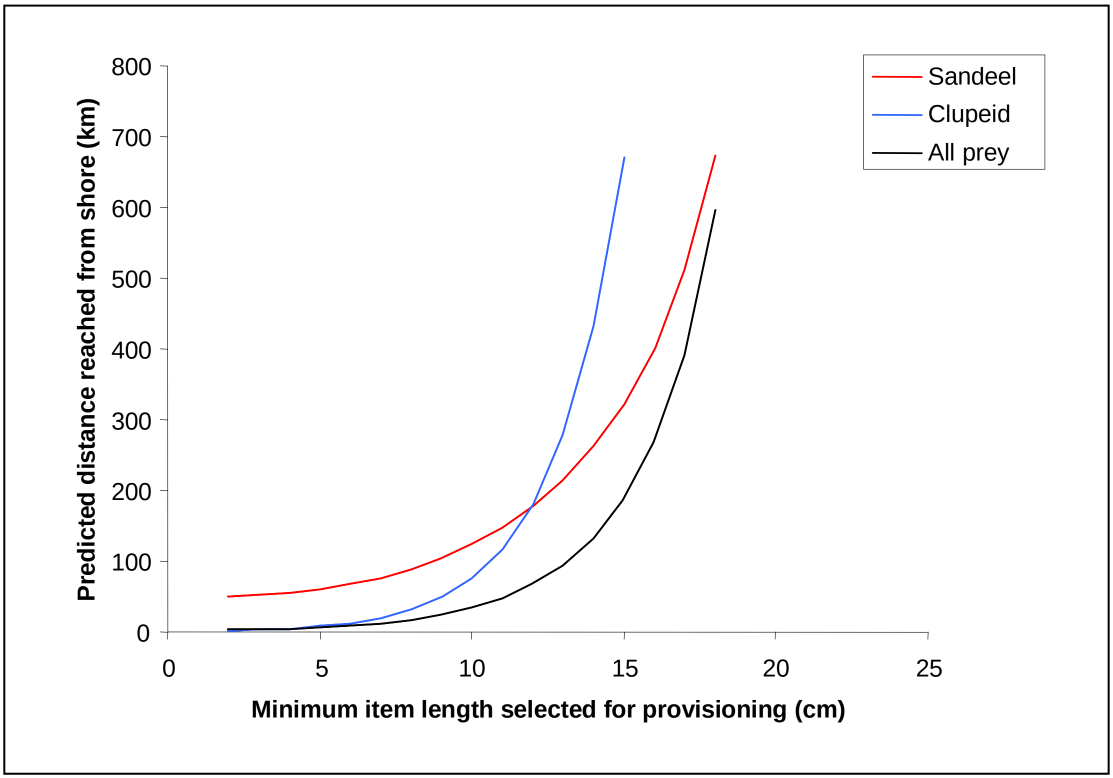

Figure 63. Model predictions of the distance reached from shore on a typical foraging bout depending on the minimum size of item selected for provisioning. Lines show hypothetical relationships for individuals feeding on a single prey species (coloured lines) as well as both prey types (black line).

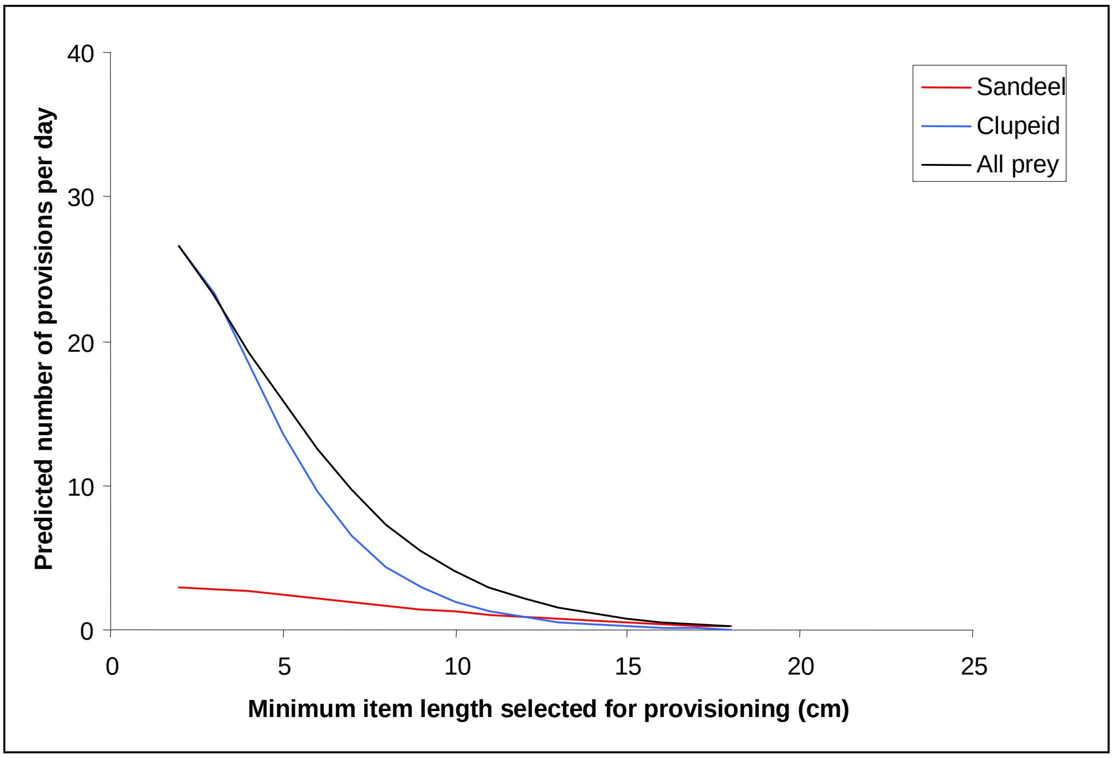

Figure 64. The number of provisions predicted to be possible for a Sandwich Tern in a 14 hour day if a single parent is provisioning at any given time, based on size-selection models for clupeids (blue line), sandeels (red line) and all prey types combined (black line).

If adults selected only items larger than 10 cm for provisioning, the number of provisioning events likely to be possible in a single day would be very small (<10 in all cases - Fig. 64). However, given the significant increase in the energetic content of larger items, the energy delivered to chicks will not be directly proportional to the number of provisioning events. Using estimates of the energetic content of prey items in relation to item size (see Eq.s 1 & 2), it is possible to predict the energy that could be returned to the brood for each foraging bout in relation to the minimum size selected for provisioning by adults. In order to determine the mean energy return per bout for each size selection level, it is necessary to account for the possibility that terns might capture prey items larger than their minimum size threshold during any given foraging bout. Whilst the likelihood of capturing prey of different sizes is dependent on the capture rate (see Fig. 60 above), on any given foraging bout a larger item might be encountered by chance after a relatively short search time. Consequently, individuals with low size selection thresholds, and consequently short search times per foraging bout, will still capture large prey items on occasion. The mean energy return for a given foraging bout is therefore dependent on the capture probability distribution for prey items of varying size given a particular search time. This probability distribution is derived from the size-specific capture rates predicted by Eq.s 4, 5 and 6. In order to determine the mean energy return per bout, the energy from each item available above the minimum threshold (up to the maximum observed prey item size) was weighted by the likelihood of capture in each case, given the threshold search time. Several examples of such probability distributions are shown in Fig. 65, for individuals with minimum size selection thresholds of 5, 7 and 9 cm for all prey types.

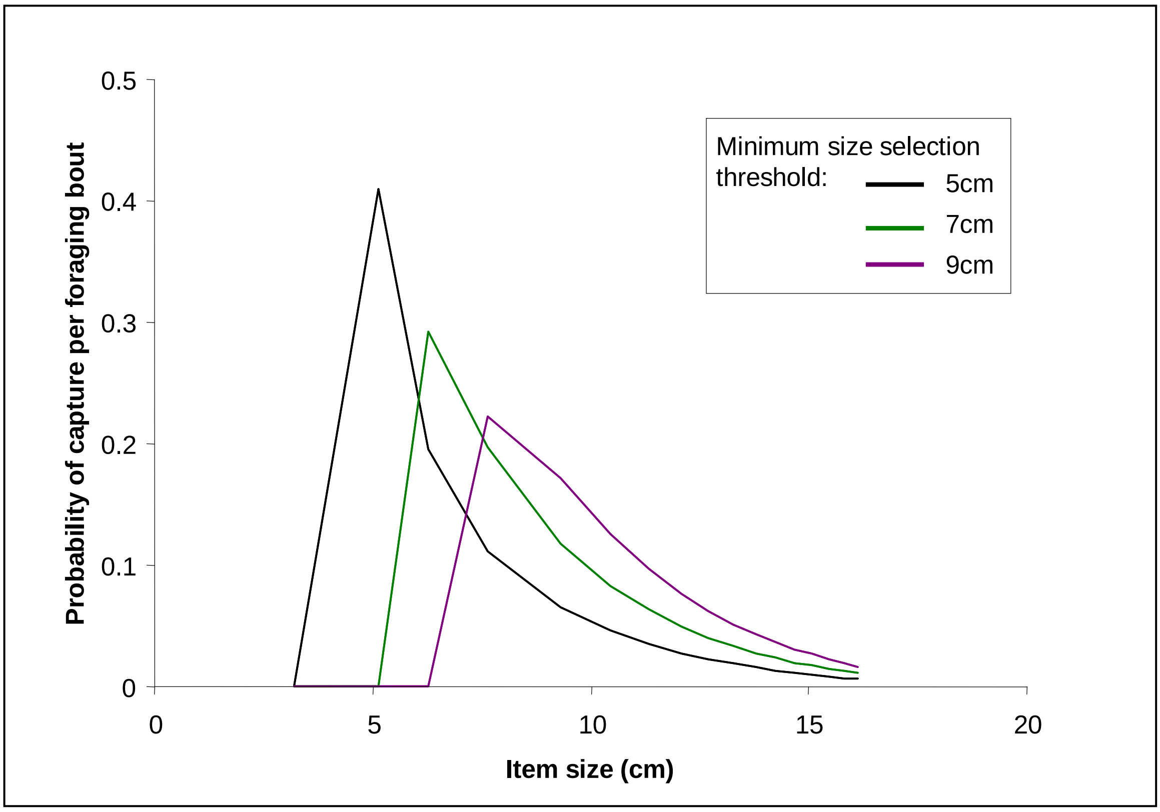

Figure 65. Probability distributions showing capture likelihood for prey items of varying size (including all prey types), based on search times determined by the minimum size selection threshold. Three size selection threshold scenarios are shown (5 cm, 7 cm and 9 cm, which equate to weighted search times of 36 min, 62 min and 114 min respectively).

Predicted energy returns per bout can be combined with the number of provisioning attempts possible per day for each size selection strategy, allowing a prediction of the amount of energy likely to be provisioned to chicks in a single day (Fig. 66). In this, it is assumed that a single parent attempts to provision throughout the 14 hour daily activity period. It is clear that when all prey types are targeted, energy delivery to the brood per day is maximised by having a relatively low size selection threshold (c. 6 cm) and hence delivering predominantly small items

(Fig. 66), despite their low relative energy content.

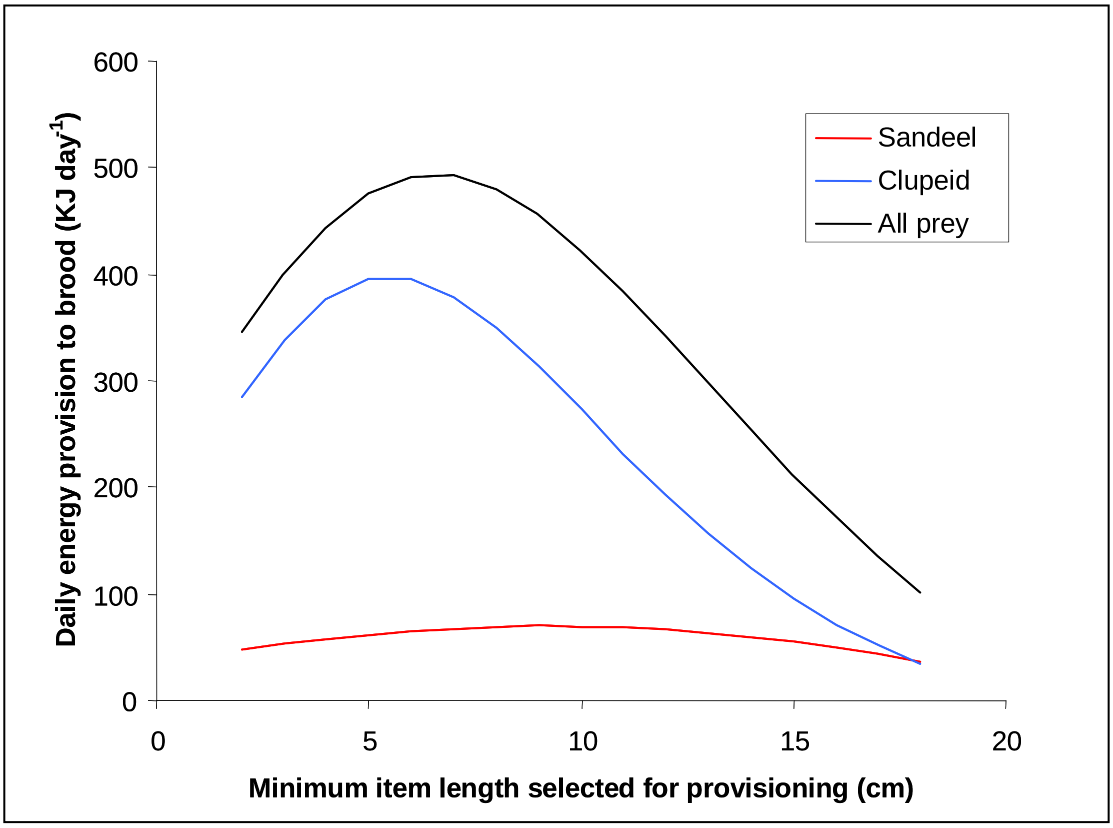

Figure 66. Predicted maximum daily energy provision rates for Sandwich Tern broods in a 14 hour day if a single parent is provisioning at any given time, based on size-selection models for clupeids (blue line), sandeels (red line) and all prey types combined (black line).

4.6.2 Incorporation of parental costs

The basic model predictions described above are relatively simplistic in that they do not take into account a number of other factors that might influence the optimality of provisioning strategies. One factor of particular importance is the energetic requirement of adults during provisioning. The energy balance of provisioning adults was modelled by calculating the energy expended by an individual during each foraging bout, based on the predicted search time, return transit distance and hand-over time, and hence time spent in active flight (assuming a mean flight speed of 32.6 km hr^{-1}). Transit distance was estimated from a linear function relating search time to distance reached from colony using data from complete tracked bouts, giving the following equation:

Equation 8 Transit distance (km) = 0.1407 x s - 0.3038

where s is the weighted search time predicted for each minimum size selection threshold.

The model also included energy lost each day during the hours of darkness, assuming that all individuals maintain basal metabolic rate during this period (see Brenninkmeijer *et al*. 2002). Predicted daily energetic losses were then balanced by the energy gained by adults during each search period (when self-feeding can occur), according to the observed rate of energy gain through prey consumption during foraging (see 4.6.1 above). This allowed determination of the net daily energy gain or loss for adult Sandwich Terns for a range of minimum size selection strategies (Fig. 67).

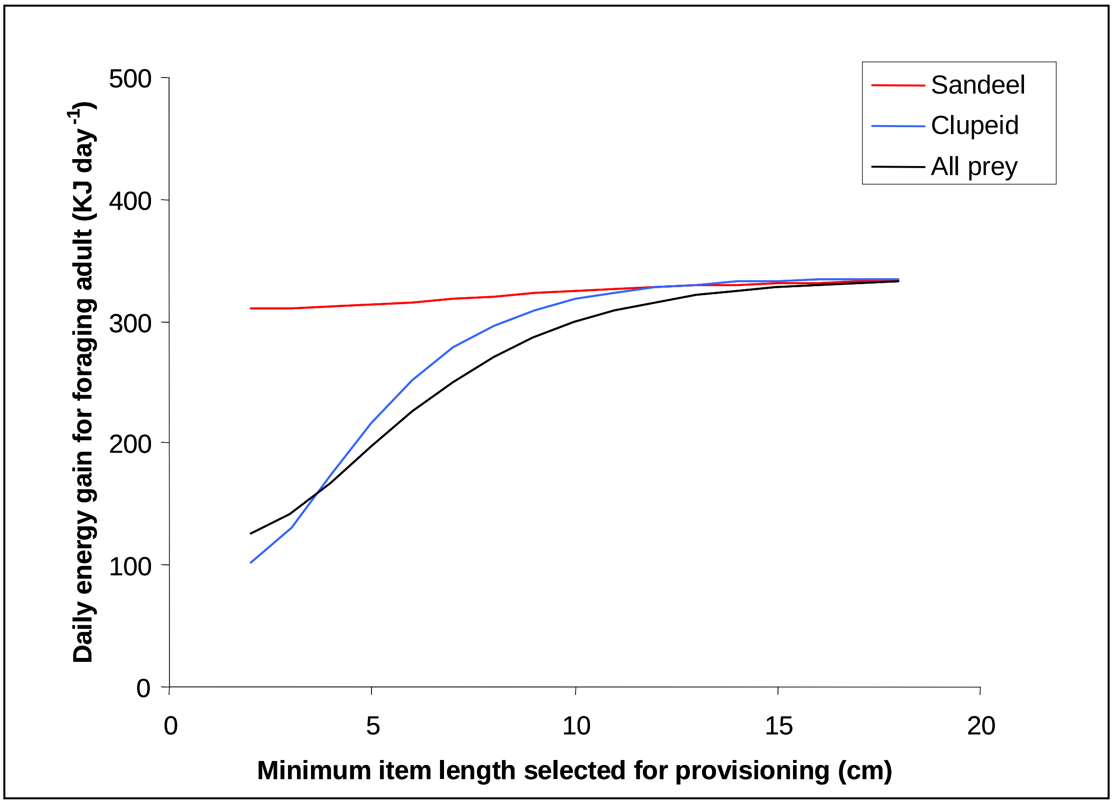

Figure 67. Predicted net daily energy gains for adults whilst provisioning chicks assuming an 18 hr daily period of activity, in relation to the minimum size of prey item selected for provisioning.

Given that the rate of energy intake during foraging (96.6 KJ hr^{-1}) is considerably higher than that expended during foraging flight (44.4 KJ hr^{-1}), the rate of energy gain increases in relation to the time spent foraging, which in turn increases at higher minimum size selection thresholds (as larger items require longer foraging search times). If adults exclusively targeted either clupeids or sandeels to provision chicks, their own daily energy gains would generally be higher than if they utilised both prey species, particularly in the case of sandeels (Fig. 67). This results from the capture rate being lower when targeting just one prey type, leading to higher foraging search times and therefore increased energy gain for the adult. As previously stated, Sandwich Terns are unlikely to select only one prey type during foraging, making the model prediction for all prey types more meaningful (the black line in Fig. 67). The net daily energy gain for adults declines significantly at minimum size selection thresholds below 10 cm. This undoubtedly reflects the high number of provisioning attempts that can be made when selecting such small items (see Fig. 64 above), resulting in adults spending relatively less time foraging. The net daily rate of energy gain reaches an asymptote above ~10 cm (Fig. 67) as a result of the extremely small number of provisioning attempts that can be made when targeting prey items of this size (Fig. 64), meaning that there is relatively little difference in the time spent foraging and in transit when targeting these large items.

4.6.3 Impact of kleptoparasitism

Observed rates of prey loss through kleptoparasitism at North Norfolk colonies in 2006-09 differed slightly between the two principal prey types (Fig. 68) irrespective of whether maximum (all individuals lost from view lost their prey item during the attack) or minimum (occasions when individuals were seen to lose their prey item) rate losses are used. (The true rate of loss is likely to lie somewhere between these maximum and minimum rates). Rates of loss for clupeids exceeded those for sandeels of equivalent length, particularly at larger sizes, in accordance with their higher relative energy content (see Eq.s 1& 2).

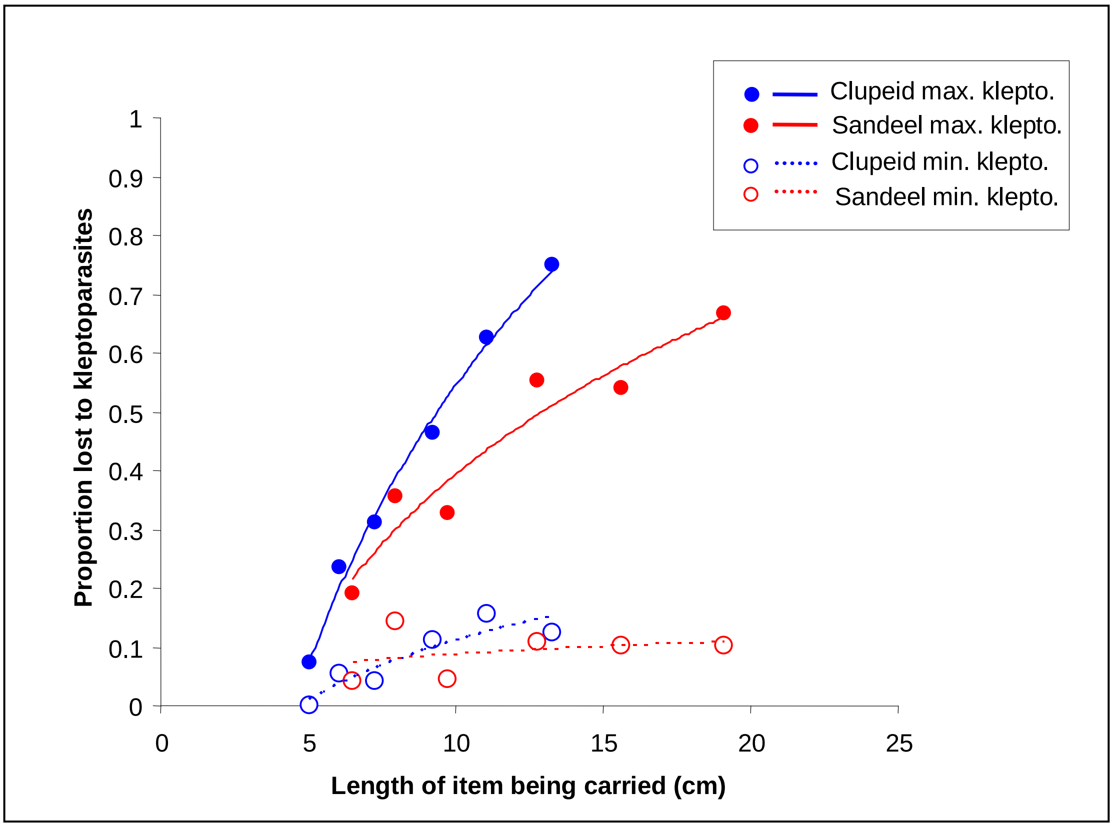

Figure 68. Observed rates of prey loss to kleptoparasites for Sandwich Terns during 56 hrs of observations at North Norfolk colonies in 2006-2009. Maximum kleptoparasitism rates (squares) assume that all individuals driven outside the colony by kleptoparasites subsequently lost their prey item, whilst minimum rates include only direct observations of prey item loss.

The results of the power curve modelling predictions of daily energy provision rate for chicks under different size selection and different kleptoparasitism levels (minimum, intermediate and maximum) are shown in Fig. 69. The overall pattern of optimality was broadly similar across all three kleptoparasitism levels, with brood provisioning rates always peaking at relatively low size selection thresholds (c. 6 cm). However, kleptoparasitism had a significant influence on the quantity of energy that could be provisioned at any given size selection threshold, with lower size selection thresholds resulting in lower overall rates of energy loss due to the increased likelihood of kleptoparasitism of large items (compare Fig. 69 with Fig. 66 above).

The model could also be used to predict daily energy provisioning rates in relation to distances reached from shore on each bout across the three levels of kleptoparasitism (Fig. 70). Given that selection of relatively small items was optimal under all kleptoparasitism scenarios, making shorter foraging trips and therefore staying closer to shore (<25 km, Fig. 70) would optimise rates of energy provision. The level of energy provision for any given foraging distance did, however, show significant variation across the kleptoparasitism levels. This variation has the potential to influence outcome of any trade-off between brood provisioning and adult energy balance.

The energy balance for adults remained unchanged across kleptoparasitism levels as a result of the number of provisioning events that could be attempted in a day also remaining unchanged in relation to kleptoparasitism (note that any energetic costs to adults associated with evading kleptoparasites are not incorporated in the present model). However, the extent to which adults trade-off their own energetic requirements in favour of brood provisioning is likely to be dependent on the energetic requirements of chicks, and how easily these can be met in any given kleptoparasitism scenario. (Although energetic requirements of chicks would be expected to change during development this was assumed to be at a constant average level for the purposes of the current model).

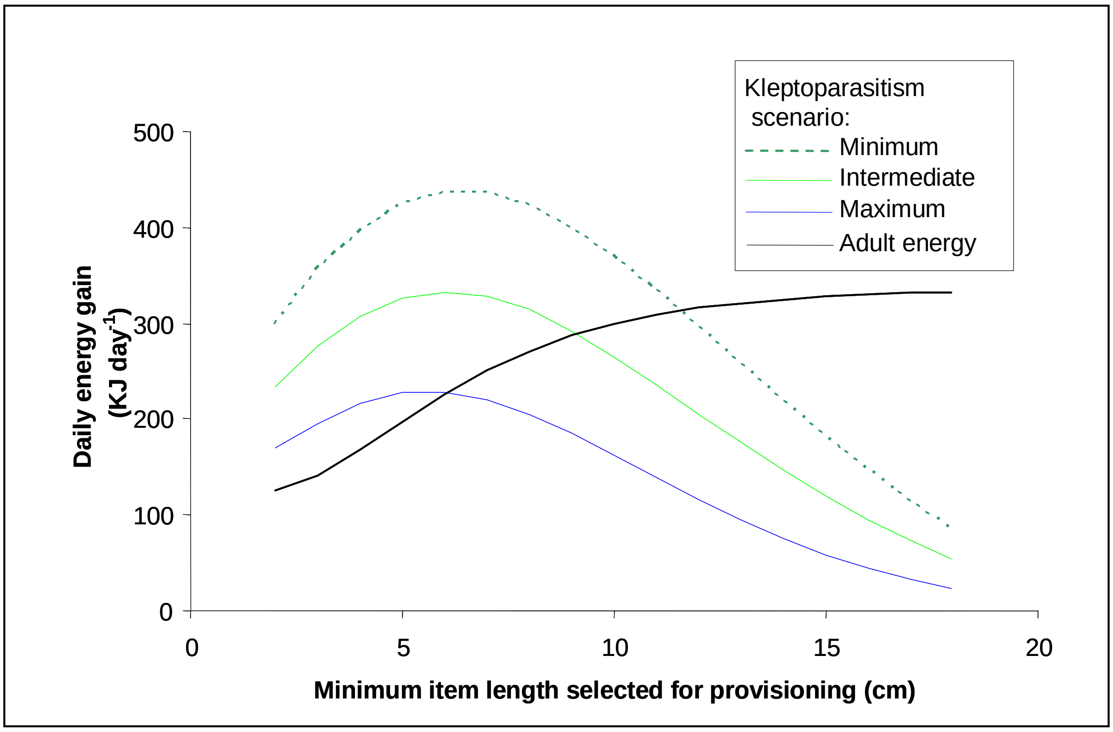

Figure 69. Model predictions of daily energy provisioning rates for Sandwich Tern broods (coloured lines) at estimated minimum, maximum and intermediate levels of kleptoparasitism within North Norfolk colonies in 2006-09, in relation to minimum size selection thresholds. Net daily energy gains for adults are also shown (black line). Each scenario assumes that all available prey types are targeted.

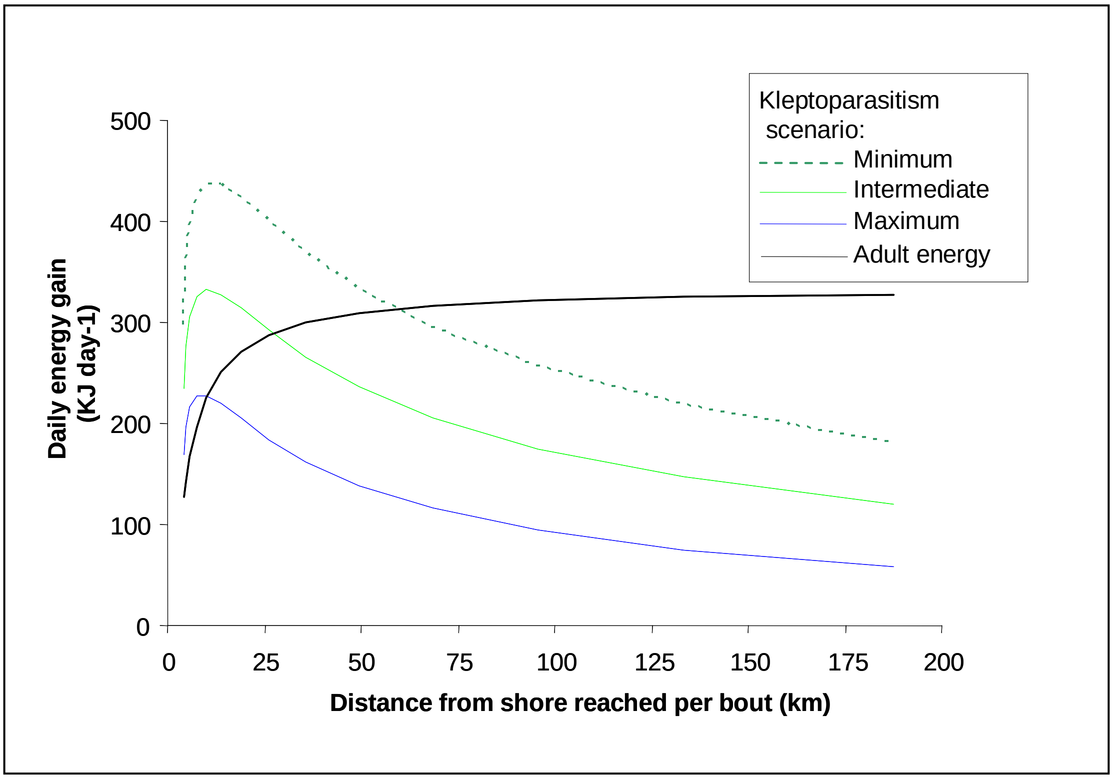

Figure 70. Model predictions of daily brood provisioning rates for Sandwich Tern broods at minimum, maximum and intermediate levels of kleptoparasitism observed within North Norfolk colonies in 2006-09, in relation to the distance reached from shore by adults on each foraging bout. Net daily energy gains for adults are also shown (black line). Each scenario assumes that all available prey types are targeted.

For Sandwich Tern chicks, previous studies of development have shown that at peak growth rates, individual chicks require up to 385 KJ day^{-1}, with the provisioning rate required to maintain minimum growth estimated to be 247 KJ day^{-1} (Drent *et al*. 1992). Under the maximum kleptoparasitism scenario, the energy-provisioning rate required to maintain peak chick growth (385 KJ day^{-1}) could not be met at any size selection threshold. Indeed, the maximum brood provisioning rate attainable was estimated to be 231 KJ day^{-1}, based on adults adopting a minimum size selection threshold of 5.8 cm (Fig. 69) and therefore travelling short distances from shore on each bout (9.7 km in Fig. 70). Importantly, adults adopting this strategy would make significantly lower daily energetic gains than could be attained at higher minimum size selection thresholds (Figs 69 & 70).

Under the minimum kleptoparasitism scenario, the brood provisioning rate required to maintain maximum chick growth (385 KJ day^{-1}) may be attained at a range of size selection thresholds, the highest being 9.4 cm (Fig. 69). At this level, the energy balance of adults is also close to being optimised suggesting that at lower kleptoparasitism levels, adults might be able to balance the trade-off further in favour of their own energetic needs (i.e. adopting a higher size selection threshold) without having any significant impact on the rate of energy provisioning for their chicks. Adults adopting such a strategy would reach significantly greater distances offshore than would be optimal under the high kleptoparasitism scenario. For example, individuals with a minimum size selection threshold of 9.4 cm would be expected to reach a mean distance of 28.1 km from shore on each bout (Fig. 70).

Model validity was tested through comparison of the actual distribution of prey sizes brought into North Norfolk colonies using data collected during kleptoparasitism observations representing an independent dataset (i.e. not used in the development of the model) with the provisioned prey sizes predicted by the model derived from various size selection threshold levels (Fig. 71). Clearly, the actual provisioning prey size distribution does not closely match any of the model predictions, showing a much broader spread of prey sizes than is predicted for any modelled size selection threshold level. This is perhaps not surprising given that all individuals within the population would be unlikely to share an identical prey size selection threshold. In fact, the observed prey size distribution shows some evidence of bimodality, with two significant peaks at 6 cm and 9 cm (Fig. 71). This raised the possibility of the adoption of two size selection strategies within the population (not necessarily simultaneously, as the observed prey size distribution is drawn from several years).

Consequently a further model of predicted prey size distribution in which size selection thresholds of 6 cm and 9 cm were adopted by half of the tern population was constructed. A comparison of this model prediction with the observed pattern is shown in Fig. 72. The close match between these distributions provides tentative support of the hypothesis that two provisioning strategies were adopted within the population, with some individuals adopting a low minimum size selection threshold (c. 6 cm) and others a higher threshold (c. 9 cm). It is interesting to note that the upper threshold corresponds closely to the value predicted to represent the optimal trade-off between adult fitness and brood provisioning at minimal kleptoparasitism levels (see Fig. 66 above), whilst the lower value is closer to the optimal level predicted at maximum kleptoparasitism levels. This suggests that the apparent bimodality in prey size distribution could theoretically represent a response to variation in the intensity of kleptoparasitism over time.

An alternative hypothesis might be that observed bimodality results from terns applying different size selection strategies to the two principal prey types (sandeels and clupeids). Whilst the observed prey size distributions do indeed differ between these prey types, model predictions based on combined size selection thresholds at 6 cm and 9 cm provide relatively close matches in both cases (Fig. 73). The most significant discrepancy relates to the lower frequency of large clupeids (>12 cm) in the observed data than is predicted by the model. It is tempting to speculate that this might reflect a degree of avoidance of these items by Sandwich Terns, associated with the extremely high risk of loss to kleptoparasites for these items.

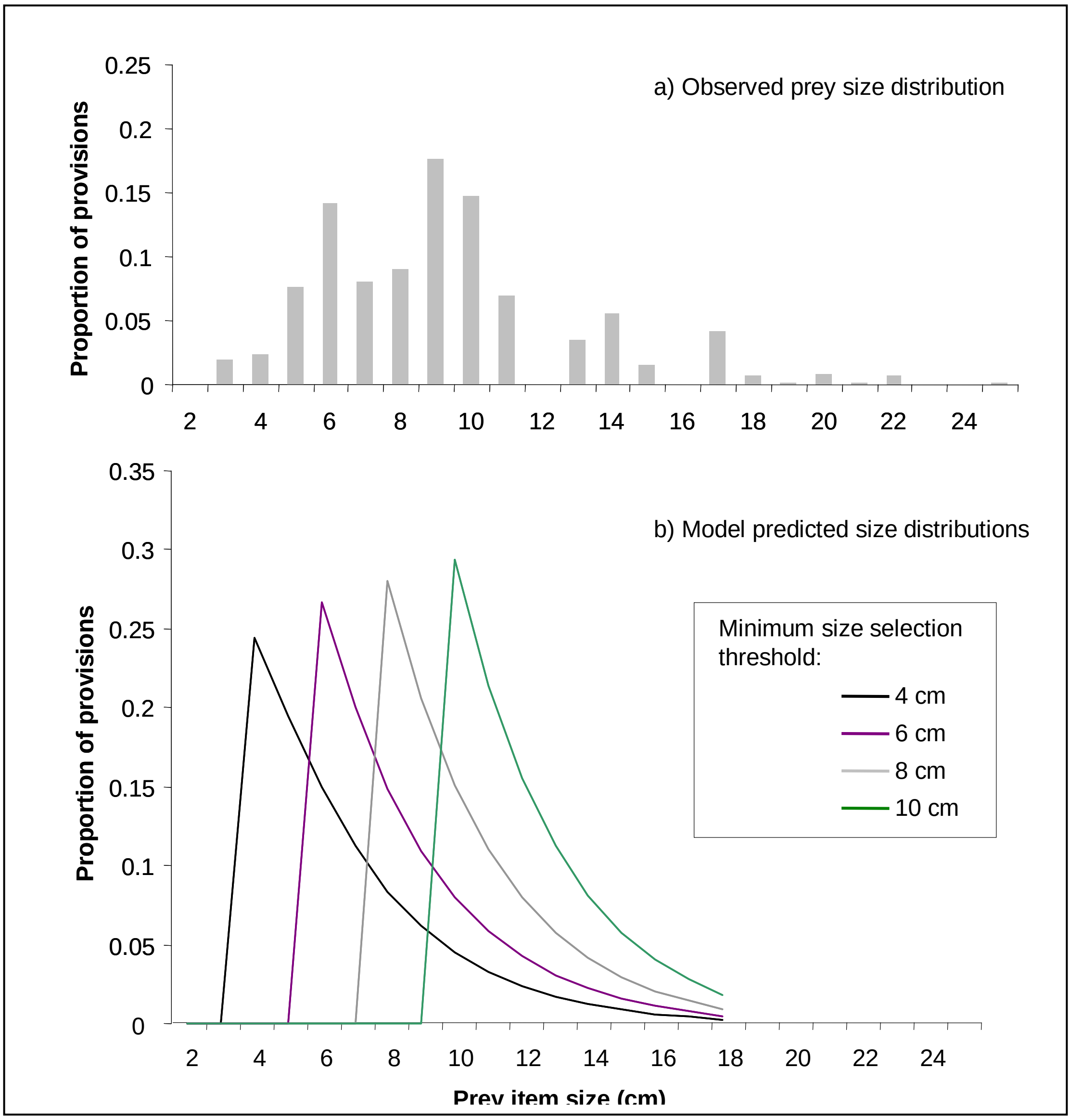

Figure 71. Observed (a) and predicted (b) size distributions of prey items brought to chicks by Sandwich Terns in North Norfolk colonies in 2006-09. Model predictions are derived for a range of minimum size selection thresholds, and are based on size-specific capture rates associated with predicted search times for each scenario. Observed frequencies are derived from observations of prey items being carried into colonies.

Given the relative congruence between model predictions and observed prey sizes being brought into the colony, it seems likely that in reality Sandwich Terns adopt minimum size selection strategies within the range of 5 cm to 10 cm for all prey. These values encompass the range of size selection strategies that are predicted by the model to fulfil the minimum energy requirements of both chicks and adults, within the limits of the range of kleptoparasitism scenarios considered. Based on these values, the model suggests that Sandwich Tern foraging trips will typically reach distances in the range of 7.4 km to 35.8 km from shore. It should be noted that these predictions represent mean distances rather than maxima; in reality, considerable variation is likely to exist both above and below the predicted mean, although this variance cannot be estimated using the model.

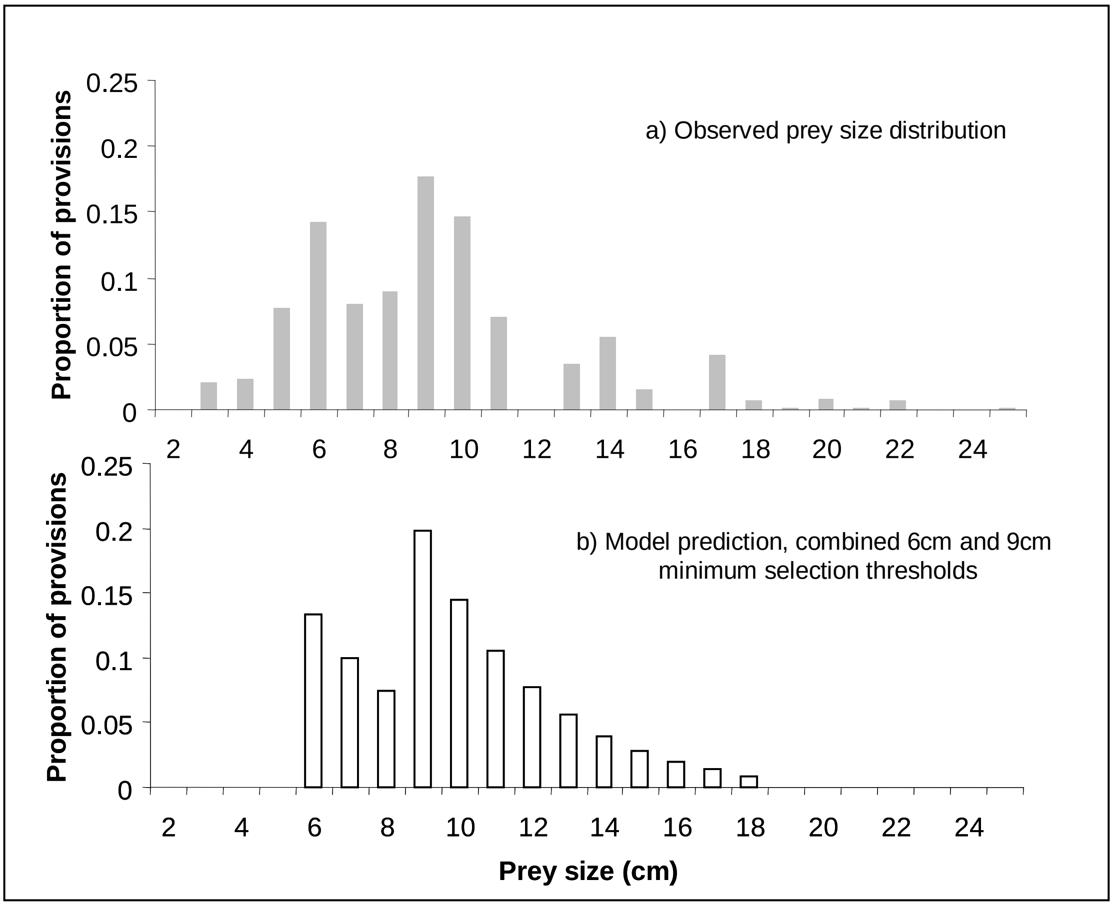

Figure 72. Observed (a) and predicted (b) size distributions of prey items brought to chicks by Sandwich Terns in North Norfolk colonies in 2006-09. Model predictions are derived by combining 6 cm and 9 cm minimum size selection thresholds, assuming each threshold is used by half the population. Observed frequencies are derived from observations of prey items being carried into colonies.

The performance of the model was further tested through comparison of predicted provisioning rates with those recorded during colony observations. Taking the model scenario that best predicted the observed prey distribution (dual size selection thresholds of 6 cm and 9 cm), the model predicts a provisioning rate of 0.57 feeds hr^{-1} under the minimum kleptoparasitism scenario, 0.43 feeds hr^{-1} at intermediate kleptoparasitism levels and 0.29 feeds hr^{-1} under the maximum kleptoparasitism scenario. The observed rate therefore falls within the range of values predicted between intermediate and maximum kleptoparasitism levels. Model predictions of daily energy provision under this strategy were 418 KJ day^{-1} at minimum kleptoparasitism levels, 312 KJ day^{-1} at intermediate levels and 206 KJ day^{-1} at maximum levels.

The model therefore fitted well with the published estimate of the minimum (247 KJ day^{-1}) and maximum (385 KJ day^{-1}) energy requirement for growth of Sandwich Tern chicks. However, at North Norfolk colonies, the mean provisioning rate observed in 2006-09 was 0.33 feeds hr^{-1} (±0.19 s.d.), whilst the estimated mean energy delivery rate was 9.19 KJ hr^{-1}, equating to 128.62 KJ day^{-1} assuming 14 hours of provisioning activity. Whilst it is possible that energy provisioning rates were underestimated during colony observations, the extensive dataset of Stienen *et al*. (2001) at the large colony at Griend in the Netherlands, where individuals also suffered high rates of kleptoparasitism showed similar results. Here, adults supplied on average, ~100 KJ day^{-1} to newborns to a peak of ~350 KJ day^{-1} immediately prior to chick fledging. However, the discrepancy between the energy delivered by adults and consumed by the chick increased during the season, and with considerable variation in the energy consumed by each chick. Thus, on average, chicks received <200 KJ day^{-1} in the last two weeks before fledging. Although Stienen & Brenninkmeijer (2002) showed growth influenced prospects of survival of chicks, poor growth leading to low fledging mass could be overcome soon after fledging.

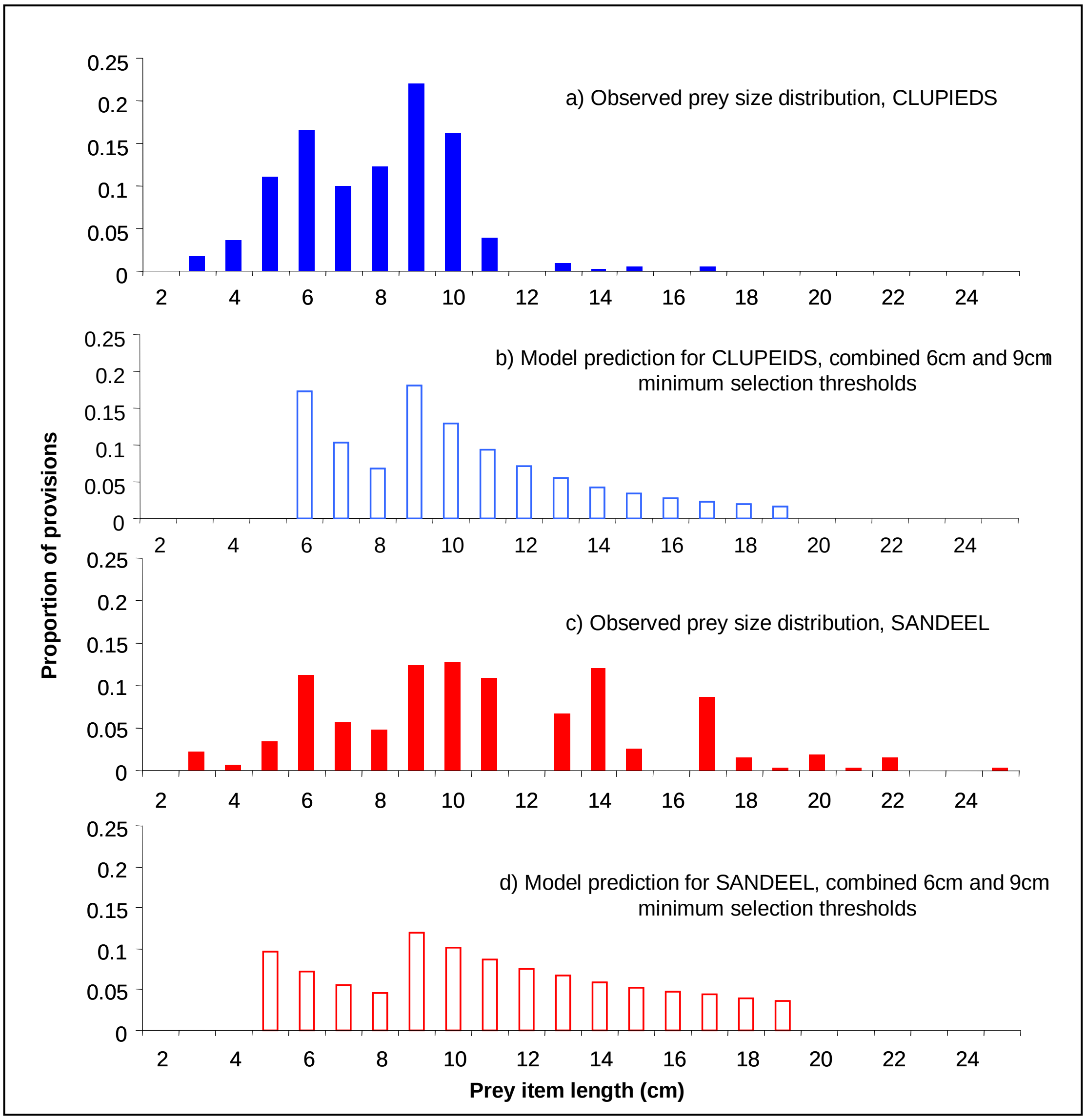

Figure 73. Observed and predicted size distributions of clupeid (a & b) and sandeel (c & d) brought to chicks by Sandwich Terns in North Norfolk colonies in 2006-09. Model predictions are derived by combining 6 cm and 9 cm minimum size selection thresholds, assuming each threshold is used by half the population. Observed frequencies are derived from observations of prey items being carried into colonies.

A further indicator of model performance was a comparison of predicted hourly passage rates from the Blakeney Point colony with those estimated from boat-based transect surveys. In 2007-08, the mean outbound passage rate recorded was 1,061 individuals hr^{-1} (± 88.4 s.e.). The best model (i.e. assuming dual size selection strategies of 6 cm and 9 cm) predicts that on average, provisioning adults will make 9.01 foraging bouts per day, or 0.64 bouts per hour. Taking the mean population size of the Blakeney colony in 2007-08 (1,665 pairs), this gives a predicted mean outbound passage rate of 1,070 individuals hr^{-1}, assuming provisioning is carried out by only one parent at any given time. The extremely close congruence between predicted and observed values adds further confidence in the performance of the model.

Perhaps the most important implication of this modelling exercise is that the intensity of kleptoparasitism within colonies by Black-headed Gulls could have a significant influence on the foraging strategy of Sandwich Terns. If kleptoparasitism levels are low, it may be beneficial for Sandwich Terns to target larger items and hence make longer foraging trips, potentially taking them large distances from shore and therefore increasing the likelihood of contact with OWFs.

Conversely, at maximum kleptoparasitism levels, the model predicts that Sandwich Terns should adopt a lower size selection threshold, and as a consequence, make shorter foraging trips closer to shore.

4.6.4 Predicting responses to changes in prey abundance

The prey capture rates used in the modelling exercise represent mean rates covering the period in which visual tracking was conducted (2006-09), reflecting a proxy measure of relative prey abundance, or more accurately availability of prey to terns. The magnitude of long-term variation in the abundance (or availability) of prey within the Greater Wash remains poorly understood, but the energetic model provides a means of estimating the likely effects of prey abundance variation on Sandwich Tern provisioning behaviour.

The parameter of greatest interest is the at-sea foraging range of adults during provisioning, which can be predicted using estimates of the search time required to locate a prey item of a given minimum size (see above). These search times are dependent on the capture rate, and hence prey abundance, of each prey size class. In order to examine the implications of prey abundance variation, the model was re-run for a series of scenarios involving proportionate changes to the mean capture rate of +50%, +25%, -25% and -50% (affecting all size classes of prey equally) and hence equivalent changes to weighted search times. Estimates of brood provisioning rates were then generated for each scenario based on minimum size selection thresholds, which could then be used to predict the typical distance from shore reached under each scenario. The results of this modelling exercise are shown in Fig. 74.

The pattern of optimality in brood provisioning in relation to distance from shore was similar across all scenarios, with maximised provisioning rates when foraging trips reached distances of < 25 km from shore. The relative impact of kleptoparasitism on optimality patterns also remained unchanged. However, the level of energy that could be provisioned for any given distance varies significantly between the four scenarios. The most important implication of this variation is that the energetic requirements for chick growth (385 KJ day^{-1} for peak growth; 247 KJ day^{-1} for minimum growth) can be met for a wider range of strategies (and hence offshore distances) when prey abundance increases. Consequently, with a 50% increase in prey abundance, adults were predicted to be able meet the maximum growth rate requirement of chicks when reaching distances of up to 72 km from shore under the minimum kleptoparasitism scenario, allowing them to maximise their own daily energy balance. The model therefore tentatively suggested that Sandwich Terns might reach offshore waters more frequently if prey abundance was to increase, assuming proportionate kleptoparasitism levels did not change.

As prey abundance decreased, the model predicted that minimum energetic requirements of chicks could be met for a narrower range of strategies, reducing the capacity for adults to trade-off chick provisioning rates in favour of their own energetic balance. With a 50% reduction in prey abundance, minimum chick growth requirements could only be met when foraging trips were relatively short (c. 18-22 km) under the minimum kleptoparasitism scenario, whilst at higher levels of kleptoparasitism minimum chick growth requirements were not met at all. As such, reductions in prey abundance were likely to result in adults taking relatively shorter foraging trips in order to optimise provisioning rate to chicks, regardless of the kleptoparasitism scenario. If prey abundance was reduced by 50%, the model predicts that breeding might become unviable unless kleptoparasitism levels were minimal.

It should be noted that the above analyses consider scenarios in which changes to prey abundance impact all prey size classes in proportion. In reality, changes in fish abundance are unlikely to closely follow such a simple pattern, as the factors influencing survival and productivity tend to differ between size and age classes. As such, fish populations are often strongly age- or size- structured, such that certain cohorts may be particularly abundant at any given time.

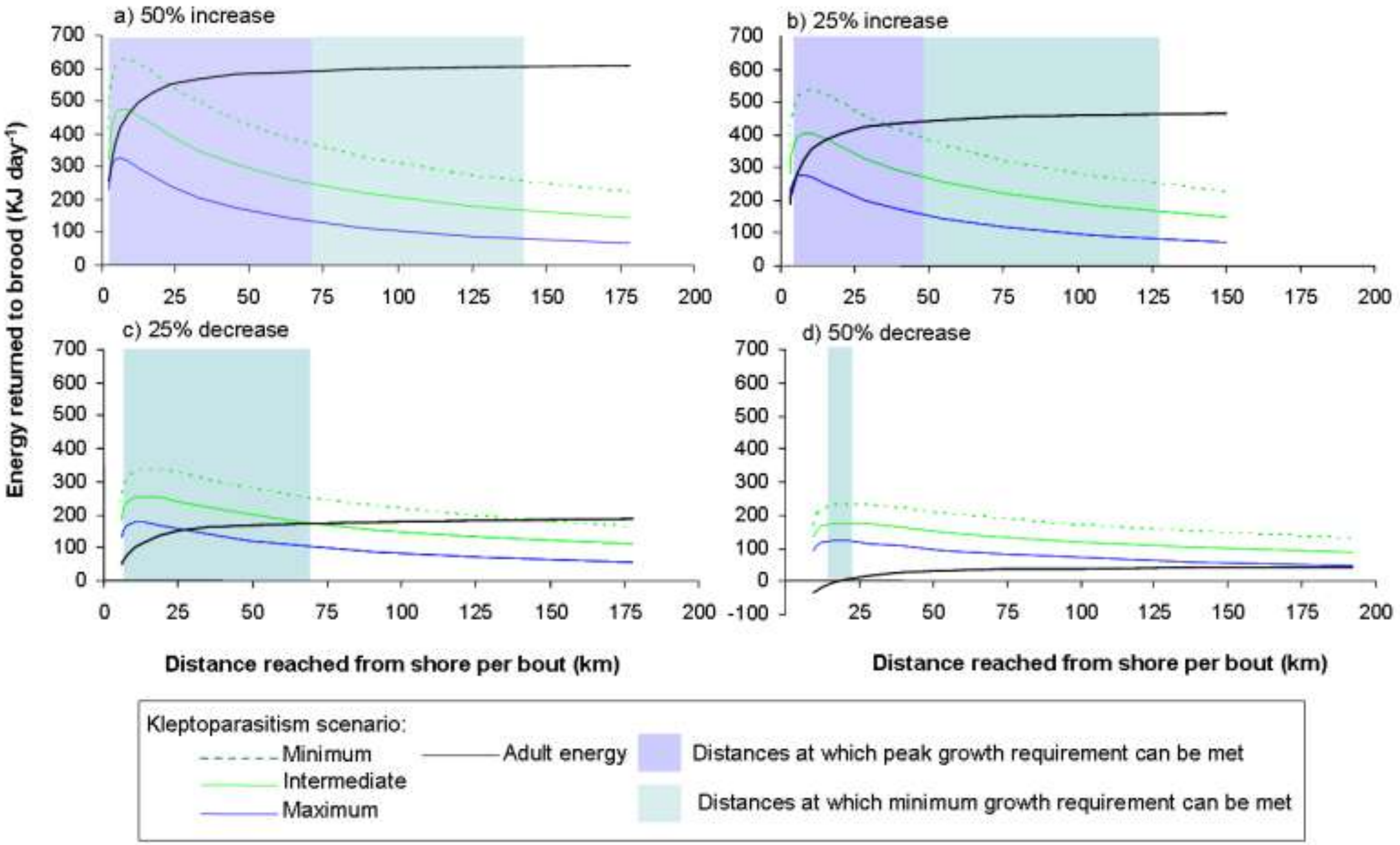

Figure 74. Model predictions of the relationship between brood provisioning rates and typical distances reached from shore during single foraging bouts for a range of scenarios (a-d) involving changes in prey abundance (and hence capture rate, affecting all prey size classes proportionately). Shading indicates the range of distances over which the daily energy requirements for maximum (dark blue) and minimum (light blue) chick growth can be met under the minimum kleptoparasitism scenario.

4.6.5 Comparison between colonies

Although data were only available for a single year from Cemlyn Bay, a relatively strong dataset was generated during 27 hours of tracking Sandwich Terns at sea, as well as 64 hours of colony observations. As such, it was possible to parameterise the same energetic model using data collected at Cemlyn in order to assess the similarity of the two regions in terms of foraging and chick provisioning.

Overall, the size-specific prey capture rates recorded during tracking were relatively similar between the two regions (Fig. 75 cf Fig. 60), with capture rates and hence search times increasing significantly in relation to item size in both regions. However, unlike in North Norfolk, capture rates at Cemlyn Bay did not increase exponentially at small prey sizes, as indicated by the slight increases in search time for the smallest size class (<3 cm, Fig. 75). Consequently, for both clupeids and sandeels (and all prey types combined), capture rates were highest for items in the range of 3-5 cm (Fig. 75).

As observed search times for very small items were longer than those of larger items, it was appropriate to exclude the smallest size class when modelling the relationship between search time and minimum size selection in order to avoid nonsensical outputs (i.e. searching for longer in order to capture a smaller item). Consequently, exponential functions were fitted to search times for all size classes above 3 cm, resulting in the following equations:

Equation 9 Clupeids: Search time (min) for size $x = 12.602 \times \exp(0.3957x)$

Equation 10 Sandeels: Search time (min) for size $x = 32.139 \times \exp(0.2891x)$

Equation 11 All prey: Search time (min) for size $x = 11.604 \times \exp(0.3179x)$

As in the case of North Norfolk models, these predicted search times were then weighted by size-specific capture probability distributions to give a weighted mean search time required to capture a prey item of a given size. The linear relationship between search time and distance reached from colony using tracking data from Cemlyn to estimate the return transit distance (and hence time, given the mean flight speed) associated with each given mean search time, was then modelled using the following equation:

Equation 12 Distance from colony (km) = $0.352\ t + 1.415$

where t is the weighted search time in minutes.

It is notable that Sandwich Terns from Cemlyn were predicted to reach higher distances from the colony per given unit of search time in comparison to those at Blakeney Point, in agreement with the observed higher rate of movement away from colonies during tracking to reach more distant foraging areas (see 4.4.2 above).

Using the above equations, the daily brood provisioning rates that would be possible for a range of minimum size selection thresholds were predicted. The same basic assumptions that were applied in North Norfolk (i.e. one parent provisioning during 14 hours of activity per day with a hand-over time of five minutes per bout) were used. The predicted number of provisioning attempts that could be made in a day for each size selection threshold is shown in Fig. 76. It is notable that the maximum provisioning rate possible of 17.7 provisions day^{-1}, targeting all prey is considerably lower than the maximum of 26.5 provisions day^{-1} predicted for birds in North Norfolk colonies (see Fig. 66 above).

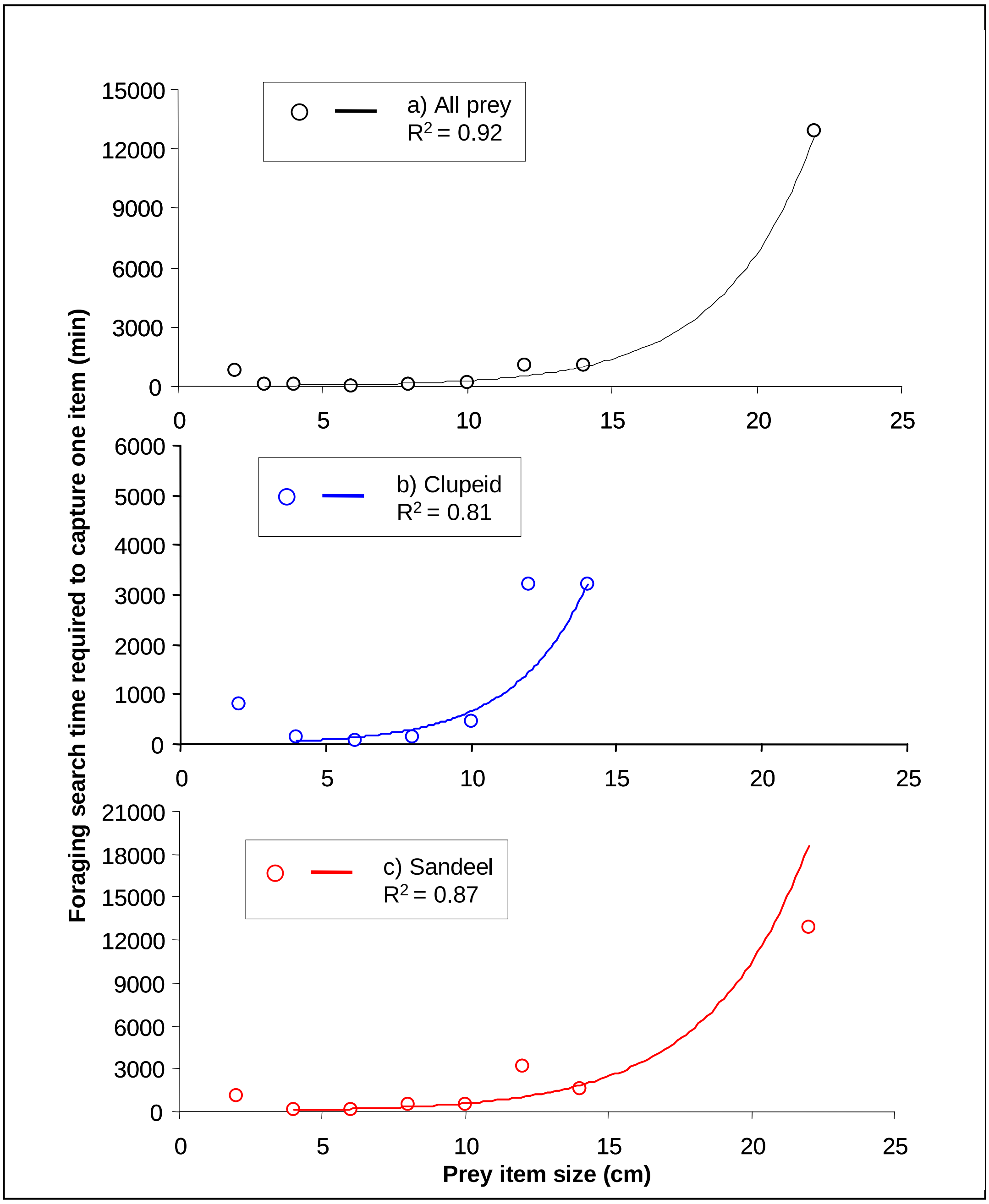

Figure 75. Relationship between prey item size and capture rate, expressed as the foraging search time needed to capture a single item, for Sandwich Terns at Cemlyn Bay showing a) all prey combined and the two principal prey types, b) clupeids and c) sandeels. Capture rates were observed during 26.8 hours of tracking from Cemlyn Bay in 2009. Smallest size category is excluded.

Predicted maximum daily energy provisioning rates for a range of size selection thresholds at Cemlyn are shown in Fig. 77. Mirroring the pattern predicted for North Norfolk (see Fig. 66 above), energetic returns for chicks at Cemlyn are maximised if adults adopt a relatively low minimum size selection threshold (c. 6 cm) when targeting all prey types. It is notable that the maximum daily provisioning rate predicted to be attainable at Cemlyn (370 KJ day^{-1}) is significantly lower than the equivalent value predicted for North Norfolk colonies (493 KJ day^{-1}). The relative contributions of clupeids and sandeels to energy provisioning are relatively similar between the two regions, although sandeels are predicted to have a slightly higher contribution by proportion at Cemlyn (compare Figs 77 & 66).

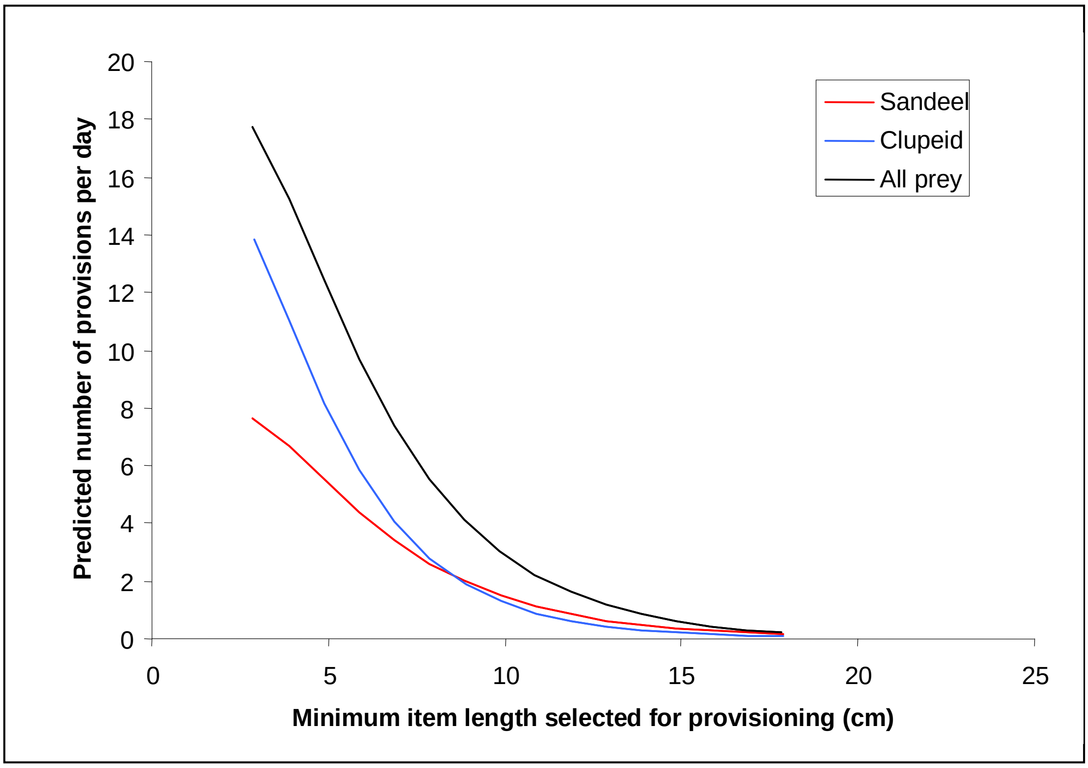

Figure 76. The number of provisions predicted to be possible for Sandwich Terns at Cemlyn Bay in a 14 hour day if a single parent is provisioning at any given time, based on size-selection models for Clupeids (blue line), Sandeels (red line) and all prey types combined (black line).

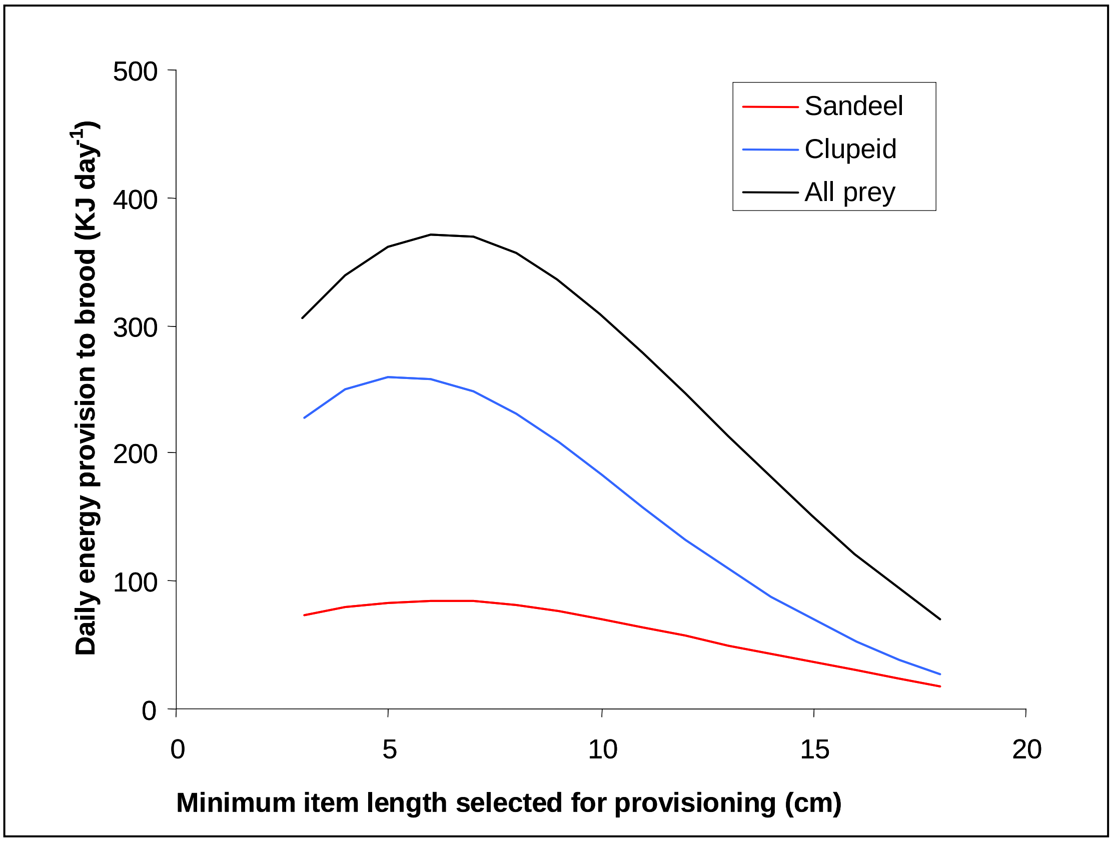

Figure 77. Predicted maximum daily energy provision rates for Sandwich Tern broods at Cemlyn Bay in a 14 hour day if a single parent is provisioning at any given time, based on size-selection models for clupeids (blue line), sandeels (red line) and all prey types combined (black line).

As for North Norfolk (see 4.6.1 above), the energy balance of adults during provisioning could also be incorporated for Cemlyn by estimating the rate of energy intake during foraging flight, balanced against all energetic costs associated with provisioning. Energy intake was estimated using the method described for the North Norfolk model giving a value of 91.7 KJ hr^{-1}, slightly lower than the value estimated for North Norfolk of 96.6 KJ hr^{-1}. Assuming a rate of energy loss of 44.4 KJ hr^{-1} during flight, this gives a net gain of 47.3 KJ hr^{-1} at Cemlyn, some 9.1% lower than the equivalent rate estimated for North Norfolk. This lower rate of energy gain, together with the larger transit distances per unit search time at Cemlyn (and hence reduced time foraging per provisioning bout) resulted in the predicted adult energy balance being considerably lower for any given size selection threshold than in North Norfolk (cf Fig. 78 with Fig. 67). Whlst adult energy gains were again maximised at higher size selection thresholds adults were predicted to enter energy deficit at size selection thresholds below 6 cm (targeting all prey). As such, Sandwich Terns at Cemlyn Bay appear to face a similar, if more severe, trade-off to that of terns in North Norfolk, balancing the rate at which energy can be provisioned to chicks against their own energetic requirements.

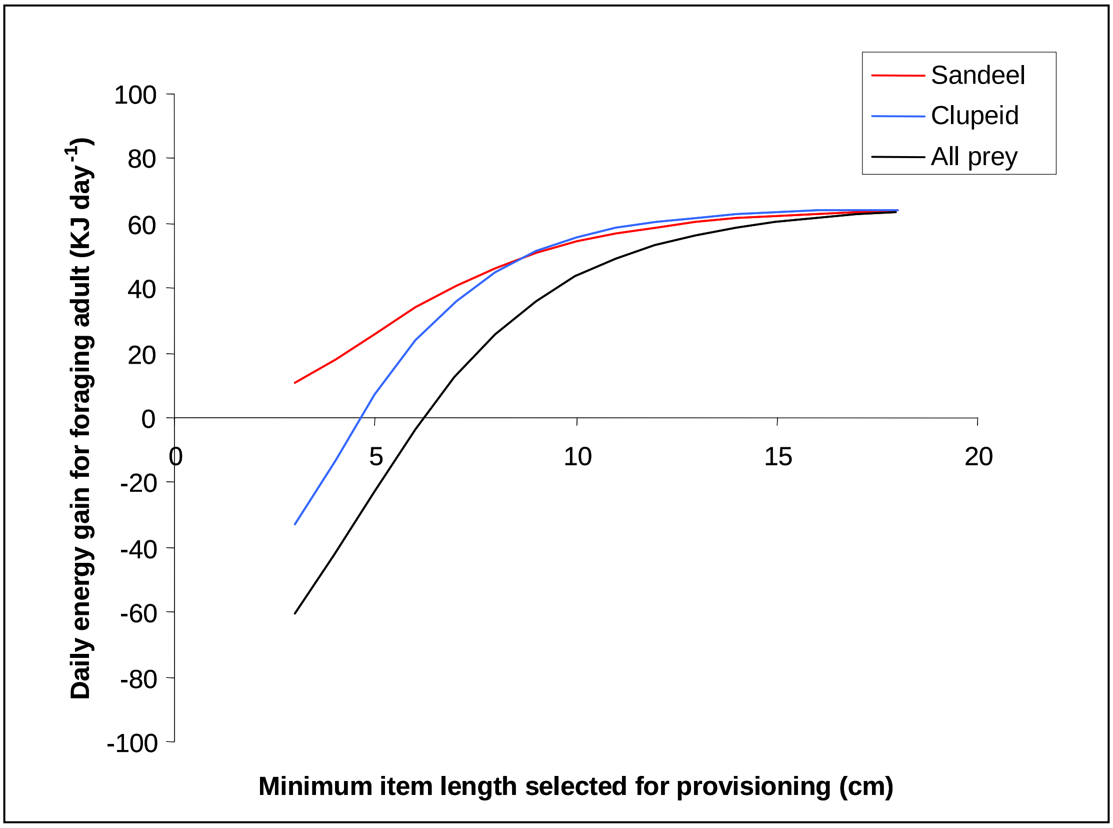

Figure 78. Predicted net daily energy gains for adults whilst provisioning chicks assuming an 18hr daily period of activity, in relation to the minimum size of prey item selected for provisioning.

Rates of kleptoparasitic prey loss were significantly lower at Cemlyn Bay than those observed within North Norfolk colonies (see 4.3.1 above), with estimation of prey loss rate being made with much higher precision at Cemlyn compared to Blakeney Point due to the very low proportion of observed events with unknown outcomes (1.1% at Cemlyn, compared with 29.1% in North Norfolk). Following the approach used for North Norfolk models, a maximum kleptoparasitism scenario was modelled at Cemlyn Bay assuming all unknown-outcome events ended in prey loss, together with a minimum kleptoparasitism scenario based solely on the observed rate of prey loss. Predicted daily energy returns to broods under these scenarios (assuming all prey types are targeted) for a range of minimum size selection thresholds, together with the associated energy budget for adults, are shown in Fig. 79. As expected given the low level of uncertainty in kleptoparasitic prey loss rates, there is little difference between the minimum and maximum kleptoparasitism scenarios, with both showing a peak in energy provision rate to broods at a minimum size selection threshold of 6 cm. This threshold also corresponds with the point at which the predicted adult energy budget becomes positive as at size selection thresholds lower than 6 cm, adults are predicted to enter energy deficit (Fig. 78).

The maximum daily brood provisioning rate is predicted to be between 338 KJ day^{-1} (maximum kleptoparasitism) and 349 KJ day^{-1} (minimum kleptoparasitism), based on a size selection threshold of 6 cm (Fig. 79). In either case, this falls short of the energy required to maintain maximum chick growth rates (385 KJ day^{-1}), although it does exceed the minimum level required to support growth (247 KJ day^{-1}). This minimum provisioning level could be attained at size selection thresholds up to 10.6 cm (under either kleptoparasitism scenario), at which point energetic gains to adults would be approaching optimal levels.

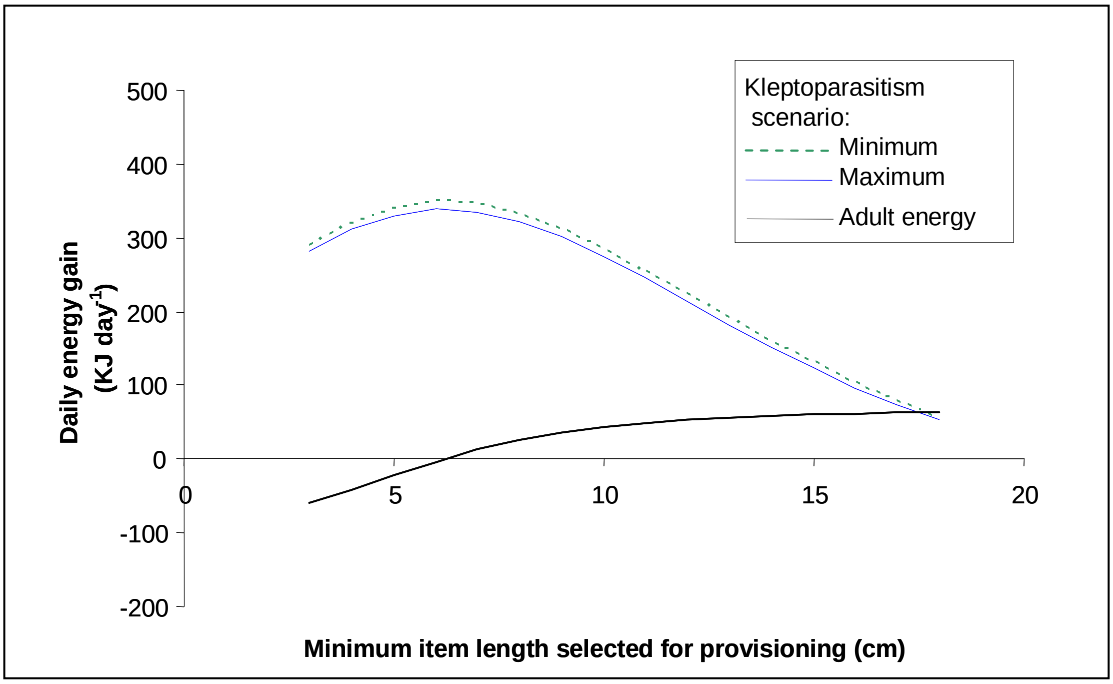

Figure 79. Model predictions of daily energy provisioning rates for Sandwich Tern broods (coloured lines) at estimated minimum and maximum levels of kleptoparasitism at Cemlyn Bay in 2009, in relation to minimum size selection thresholds. Net daily energy gains for adults are also shown (black line). Each scenario assumes that all available prey types are targeted.

Visual tracking revealed that typical Sandwich Tern foraging patterns differ between Cemlyn Bay and North Norfolk colonies with respect to the linearity of foraging flight paths. In North Norfolk, foraging flights tended to be strongly linear (see 3.5.1 above) although this pattern was less pronounced in 2008. The relationship between distance travelled and distance reached from the colony allowed search times to be used to predict the distance from shore reached per bout for any given prey size selection strategy. At Cemlyn, however, foraging flight paths tended to be more curvilinear, with most foraging activity occurring in relatively close proximity to land (Fig. 54). Consequently, search times could not be meaningfully used to predict distance from shore for terns at Cemlyn. However, search time was a good predictor of distance reached from colony during a bout (see Equation 12 above), allowing this parameter to be modelled in relation to predicted energy returns (Fig. 80).

Under both kleptoparasitism scenarios, brood provisioning rate peaked at a minimum size selection threshold of prey of 6 cm. At this threshold, typical foraging bouts were predicted to reach distances of 18.4 km from the colony (Fig. 80). At the highest selection threshold for which minimum energy requirements could be met (10.6 cm), foraging bouts were predicted to reach distances of 66.6 km from the colony. The daily energy gain of adults was predicted to increase significantly at higher size-selection thresholds, such that the optimal trade-off between chick provisioning and adult energy balance was likely to involve a size-selection strategy within the range of 6-11 cm.

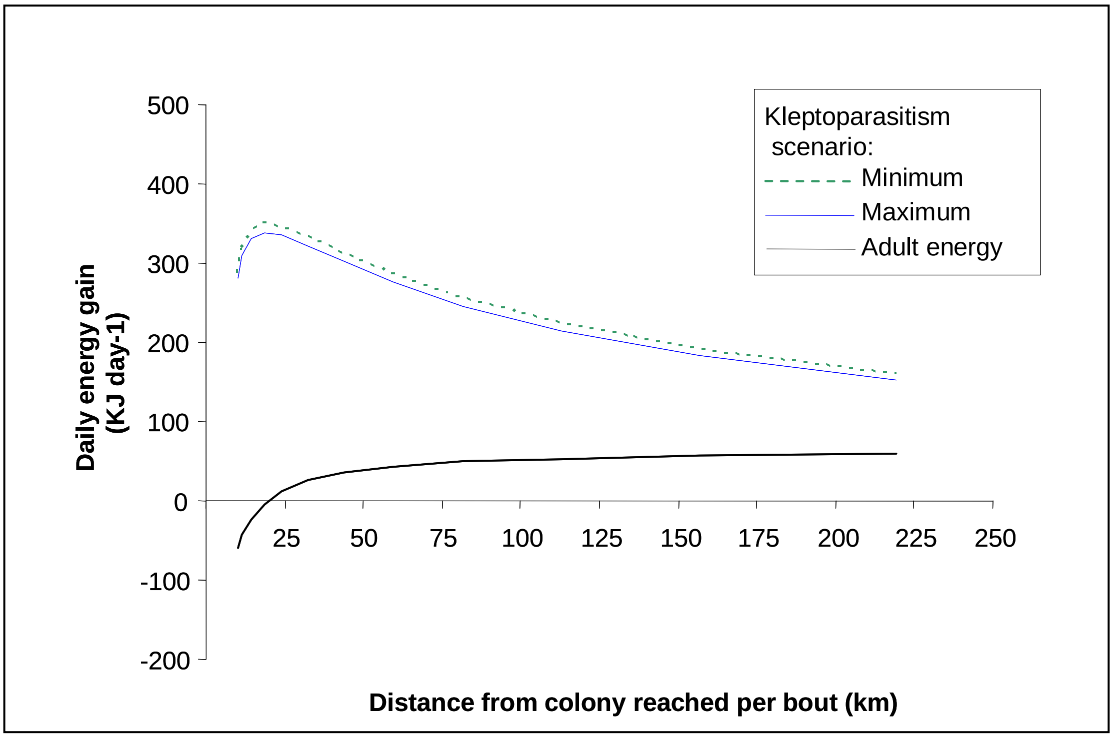

Figure 80. Model predictions of daily brood provisioning rates for Sandwich Tern broods at minimum and maximum levels of kleptoparasitism observed at Cemlyn Bay in 2009, in relation to the distance reached from the colony by adults on each foraging bout. Net daily energy gains for adults are also shown (dashed line). Each scenario assumes that all available prey types are targeted.

To test this model prediction, the observed prey size distribution of items being brought into the colony at Cemlyn was compared with the predicted size distributions for various selection threshold levels within the optimal range (i.e. 6 cm to 11 cm). Observed and predicted prey size distributions showed strongest congruence for a minimum size selection threshold of 6 cm (Fig. 81). This strongly suggests that Sandwich Terns at Cemlyn adopted a strategy to optimise the rate of energy delivery to broods, potentially at the expense of their own energy budget, given that daily energetic gains are predicted to be close to zero for this strategy. It is possible that this cost was mediated by provisioning being carried out by more than one parent at any given time at this colony.

The hourly provisioning rate predicted by the model on the basis of a 6 cm selection threshold strategy with one parent provisioning was 0.69 feeds hr^{-1}, which compared favourably with the value of 0.75 feeds hr^{-1} (± 0.11) observed in reality during colony observations and over twice that observed in North Norfolk (0.33 feeds hr^{-1}). This tentatively supports the idea that dual parental provisioning might have occurred at certain times at Cemlyn.

It is also interesting to note the relative absence of bimodality in the observed prey distribution at Cemlyn, unlike that recorded in North Norfolk (Fig. 72). In turn, given the low rate of kleptoparasitism and the relative lack of variation in size-selection observed at Cemlyn, this is tentatively supportive of the hypothesis that the adoption of the alternative of multiple size-selection threshold strategies in North Norfolk colonies might represent a response to variation in kleptoparasitism intensity.

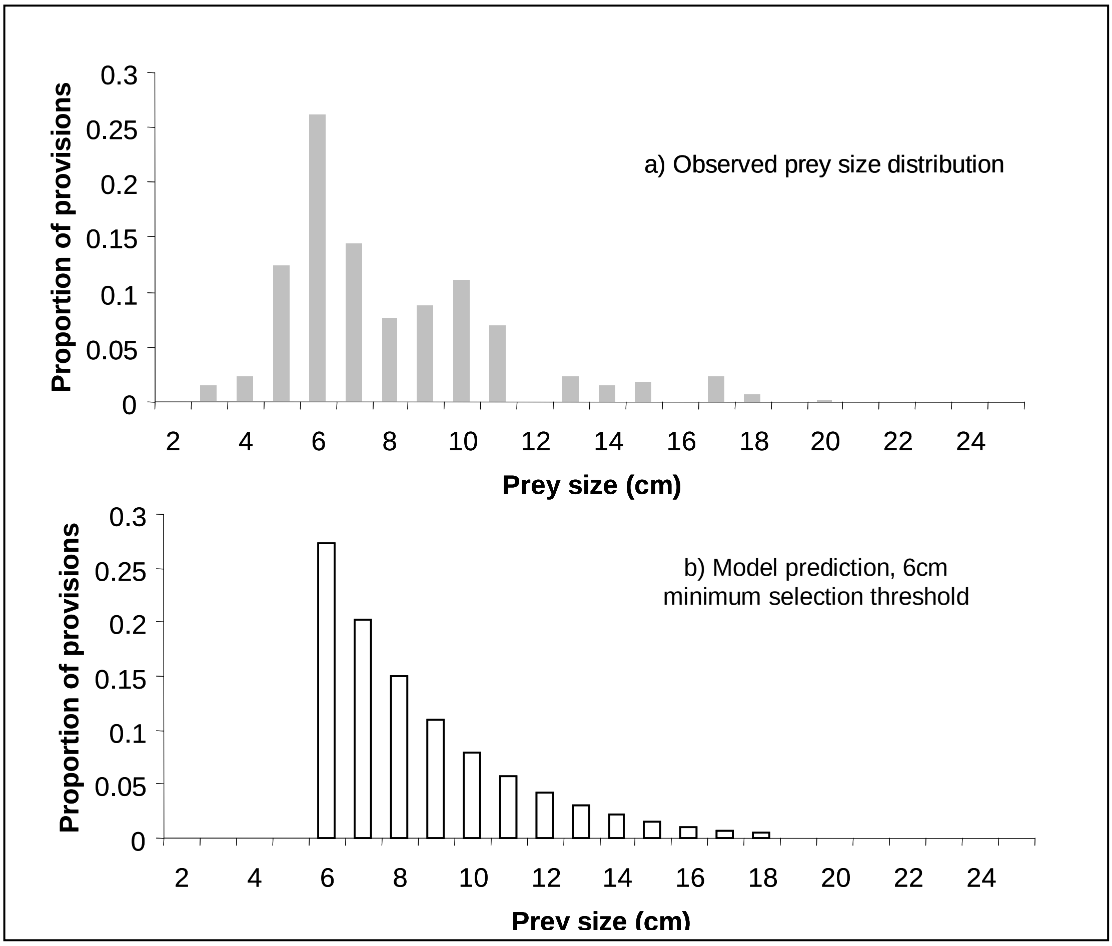

Figure 81. Observed (a) and predicted (b) size distributions of prey items brought to chicks by Sandwich Terns at Cemlyn Bay in 2009. Model predictions are derived from a 6 cm minimum size selection threshold. Observed frequencies are derived from observations of prey items being carried into colonies.

4.7 Collision risk of Common Terns from Saltholme

The collision risk factor for Common Terns at Saltholme was relatively low at 8.9%. According to the results of tracking, the passage rate of terns across the site increased markedly during the season by more than doubling from 50,160 passages in May to 106,904 passages at peak in July at the peak energy requirements of chicks prior to fledging. The relatively low proportion (12%) of birds flying at potential risk height of >20 m coupled with the relatively low proportion of predicted passages through rotors (influenced by the layout of the site with relatively few turbines) were important factors in the calculated collision risk (Table 7).

Using a 98% avoidance rate calculated 'backwards' from the passage rate and collision fatality figures of Everaert & Stienen (2006) collected at the coastal wind farm at Zeebrugge, suggests the loss of 17 breeding birds a year during the period of colony occupation (Table 7). This equates to 2.8 % of the population of birds in 2009. Assuming an adult survival rate of 0.93[3], such mortality equates to a 28% increase over and above the background mortality experienced by breeding adults annually and 164% additional mortality to that experienced by adults whilst at the colony in the breeding season (i.e. ~3 months).

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[3] Published figures vary from 0.88 (Garthe & Hüppop 2004) to 0.93 (from the studies of Peter Becker *et al*. cited in BWPi 2004)

Table 7. Estimated collision mortality (individuals) of breeding Common Terns from the Saltholme colony at the Teesside OWF at a range of avoidance rates. The mortality at the 98% avoidance rate suggested by the data of Everaert & Stienen (2006) is highlighted in bold.

OWF site	Rates of avoidance (%)			
	0	95	**98**	99
Teesside	825	41	**17**	8

5. Discussion

5.1 Foraging strategies of Sandwich and Common Terns

5.1.1 Diet

Like many seabird species breeding in the British Isles, the dietary spectrum of tern species may be relatively narrow dominated by a small number of fish species during the breeding season (e.g. Monaghan *et al*. 1989, Uttley *et al*. 1989, Phalan 2000, Stienen *et al*. 2000, Perrow *et al*. 2006, Stienen 2006). Sandwich Tern in particular is reported to be a specialist upon a restricted range of relatively large shoaling clupeids and sandeels (sandlance) (Stienen *et al*. 2000). The Waddensee studied by Stienen *et al*. (2000) is structurally similar to the Greater Wash, being dominated by shallow waters containing sandbanks, which is assumed to partly account for the similarities in diet of Sandwich Terns in the Netherlands and in North Norfolk observed in this study.

Nevertheless, a mixture of clupeids and sandeels in these areas may contain at least four or five species - Herring and Sprat amongst the clupeids and Great Sandeel *Hyperoplus lanceolatus*, Lesser Sandeel *Ammodytes marinus* and perhaps Small Sandeel *A. tobianus* - that differ considerably in their ecology. Different stocks of Herring for example spawn at different times in the North Sea, in both inshore and offshore locations (Coull *et al*. 1998). Juveniles and adults may thus be present in inshore waters in different locations. Sprat on the other hand, tend to spawn offshore, with passive drift of juveniles and active migration of older age classes into inshore waters later in the summer months. Amongst the sandeels, although both main species (Great and Lesser Sandeel) are thought to reside in burrows in sandy substrate at night, they are both actively shoaling species by day. Sandeels have clear differences in diet, with the smaller sandeel species feed on zooplankton whereas Great Sandeel progresses to eating small fish, including other sandeels, when it reaches 10-15 cm in length (www.fishbase.org).

Moreover, although clupeids and sandeels still dominated the diet of Sandwich Terns at the Cemlyn Bay colony in North Wales, a number of other, perhaps more surprising species were taken. These included rockling, probably Three-bearded Rockling (Fig. 82) as well as gadoids. The general association of the former with rocky habitats close to shore illustrates the potential of different foraging strategies for Sandwich Terns.

Common Tern is already widely considered to be a generalist able to utilise a wide variety of aquatic habitats and exploit a range of different prey types (Brown & Grice 2005). In line with this, the differences between Common Terns in North Norfolk and Teesside were striking. At the former, small clupeids (~4 cm) were the dominant item presented to chicks. Although clupeids (probably Sprat) were still the most important item at Teesside, larger items of a range of species including gadoids, perhaps mostly Poor-cod *Trisopterus minutus* (Fig. 83) were more prevalent. Whilst the mean prey delivery rate for Common Terns at Saltholme (0.52 feeds hr^{-1} ± 0.32 s.d.) was markedly lower than that recorded at Blakeney Point (1.54 feeds hr^{-1} ± 1.04 s.d.), the larger mean size of prey items meant that the estimated energy delivery rate was significantly higher at Saltholme (16.14 KJ hr^{-1} ± 13.07 s.d) than at Blakeney Point (5.85 KJ hr^{-1} ± 4.54 s.d.).

Figure 82. Sandwich Tern returning to the Cemlyn Bay colony carrying what appears to be a Three-bearded Rockling *Gaidropsarus vulgaris*

Figure 83. Common Tern returning to the Saltholme colony carrying what appears to be a Poor-cod *Trisopterus minutus*

Differences in the range of prey exploited, together with observed differences in offshore foraging patterns between Common and Sandwich Terns at Blakeney indicated some niche differentiation between the two species, with Common Terns exploiting a more diverse range of small prey items in inshore waters, whilst Sandwich Terns also took larger fish prey in offshore waters. However, in the absence of sympatric Sandwich Terns at Teeside, Common Terns are tentatively suggested to have had the opportunity to exploit a more offshore environment with the potential to encounter a wider range of prey species i.e. subject to competitive release. As a result, the size range of prey presented to chicks, with modal prey size of 6-9 cm but with fish to >20 cm in length was remarkably similar between Sandwich Tern at Blakeney and Common Tern at Saltholme (cf Figs 33 & 35).

The potential for niche separation even within a narrow dietary spectrum has been suggested previously in sympatric tern species. In the study by Rock *et al*. (2007a) prey provisioned to sympatrically nesting Common and Arctic Terns overlapped significantly, with both species feeding mostly on hake (*Urophycis* sp.) and sand lance (*Ammodytes* sp.) (i.e. one of the sandeel genera represented in the Wash). But despite what appeared to be limited availability of prey species, Arctic Terns delivered proportionally more hake and less sand lance than Common Terns and the sand lance they delivered were smaller on average than those delivered by Common Terns. Foraging habitat segregation by the two species was suggested, inroducing the potential for this to change in different situations.

Moreover, diet has generally been described by observations of prey delivered to chicks (e.g. Stienen *et al*. 2000, Stienen 2006, Rock *et al*. 2007ab). But as outlined by Shealer (1998), adults may consume smaller prey than presented to chicks or mates. Studies using pellet analysis such as that of Granadeiro *et al*. (2002) on Common Terns breeding on the Azores, support this view, as a result of the relative frequency of small prey even including invertebrates (11.3% of pellets).

In the current study, the potential to closely observe birds feeding at sea provided further insight into the nature of the prey resource for terns. At Blakeney Point for example a relatively high proportion (20-26% by number) of items consumed by self-feeding adult Sandwich Terns and Common Terns were invertebrates, supporting the view from pellet analysis. This pattern was also not restricted to North Norfolk, with a 2.3 fold higher rate of feeding upon invertebrates seen amongst Sandwich Terns from Cemlyn (Table 5). Invertebrates taken from all sites included species such as Brown Shrimp amongst smaller shrimps and probably sea slaters (*Idotea* spp.) Apart from occasional Squid *Loligo vulgaris* such prey were never seen presented to chicks. This is in line with the much higher calorific of lipid-rich fish compared to chitinous invertebrates (Massias & Becker 1990). Adult terns of various species thus appear to actively and strongly select particular prey for transportation back to the colony, with invertebrates being consumed immediately. Unfortunately, too few data were available to conclusively demonstrate selection of particular size classes of fish prey.

Overall, what is apparently important to terns provisioning chicks may belie the nature of the prey base for all components of the population. This, in conjunction with considerable plasticity in foraging and provisioning strategy of several, if not all tern species, and given the huge potential for spatial (local or regional) and temporal variation in patterns, it is dangerous to draw generalised conclusions on tern foraging tactics from studies conducted at small numbers of sites.

5.1.2 Foraging techniques

Despite the considerable potential for overlap in diet between terns and the potential for different species to vary tactics according to the specific details of the environment, there does appear to be some basic differences in the foraging abilities of Sandwich and Common Terns at least. For example, Sandwich Tern habitually plunge dives from considerable height (up to ~20 m) probably in order to capture relatively large prey items. This in turn accounts for the relatively high proportion of time that Sandwich Tern spent at considerable flight height (with 49% of time of tracked birds at >20 m at Blakeney although this was reduced to 23% at

Cemlyn). In contrast, tracked Common Terns from Blakeney and Teesside respectively spent 8% and 12% of their time at >20 m. When in an area that seemed to offer the prospect of prey, Sandwich Terns tended to slowly circle at height (perhaps up to 40 m), perhaps adjusting to appropriate height when potential prey were sighted and hovering briefly before plunge-diving. Birds frequently adjusted body and wing position during diving although the head remained locked onto the target. The additional height presumably offers greater potential to see prey at greater depth in the water column and also offers the prospect of generating sufficient speed to break the surface. As a result, Sandwich Terns were observed to disappear below the surface in this study. Borodulina (1960) and Dunn (1972) report birds may reach 2 m depth below the surface, although whether they unfold their wings and swim in the manner of gannets and boobies (*Morus* and *Sula* spp.) or even akin to surface diving shearwaters (e.g. Cory's Shearwater *Calonectris diomedea*) is unknown.

In contrast, although frequently practising plunge diving, no Common Tern was ever seen to completely immerse. At Blakeney, some 43% of records of Common Tern were at a flight height <1 m (compared to 9% for Sandwich Tern), and although this incorporates all behaviours, a technique peculiar to Common Tern of rapid hovering for several seconds above a small area, perhaps waiting for prey to come into dipping range, was employed at this height. Such behaviour may be a particular adaptation to capture of inverebrates and small clupeids near Blakeney Point as it was not seen at Teesside, although birds foraging over pools left by the outgoing tide did show ‘stepped’ hovering with the final phase close to the surface. Overall at Teesside however, birds typically foraged in the range of 1-20 m with only 6% of records at <1 m.

Both species cued into the activity of other species including foraging auks, cetaceans and other terns. However, whilst joining groups of foraging birds attacking shoals of fish, Sandwich Terns typically foraged in isolation and when in visual contact with other foraging individuals were often heard to call. As this then often led to physical displacement and chasing, calling appeared to be a warning to maintain distance rather than an advertisement. This suggests the success of foraging birds may be hampered by the presence of other diving individuals, with prey retreating to even greater depth. That is unless, prey become concentrated near the surface as a result of the sub-surface activities of foraging auks or cetaceans. These latter species are seen as ‘drivers’ with terns as ‘facilitators’ of multi-species foraging associations, a role also taken by Black-legged Kittiwake *Rissa tridactyla* in other localities (Camphuysen 2005). Larger gulls, classified as ‘scrounger-type’ species, frequently seek to kleptoparasitise others in this situation. Although no tracked birds were seen to lose prey to gulls, a small proportion of Sandwich Terns were successfully kleptoparasitised by other Sandwich Terns. This may account for the aggressive tendencies for one foraging bird to another as documented above.

The inability of Common Tern to penetrate far below the surface suggests greater reliance on foraging auks to drive prey and particularly larger prey to the surface. There are no breeding auks in either North Norfolk or Teesside, although the waters of both areas support numbers of auks outside their breeding season. The relative proximity of Teesside to important colonies at Bempton Cliffs/Flamborough Head with the additional prospect of links to colonies further north around the Farne Islands and into Scotland, meant that parties of Guillemots became a feature of the waters around Teesside from the end of June, with numbers increasing throughout July. The relatively late-breeding Common Terns at Saltholme were thus able to exploit foraging opportunities provided by these birds. In July, some 3% of time was spent in associations with auks. The tendency for foraging auks to attract other species appeared to be of particular disadvantage to Common Terns. As soon as larger numbers of gulls became attracted to an aggregation, it appeared that Common Terns abandoned it.

Vulnerability to attack may also partly account for the tendency of both tern species at all colonies to transport prey back to the colony at a flight height of <1 m. At this height, both species may be less conspicuous to potential kleptoparasites including skuas, especially Arctic Skua *Stercorarius parasiticus*, later in the season. Numbers of skuas are known to attend the North Norfolk colonies from July onwards focussing on returning Sandwich Terns in particular. At Blakeney Point however, Common Tern did not appear vulnerable to kleptoparasitism with no attacks observed at sea or in the colony. At Saltholme, kleptoparasitism was mostly restricted to attacks on chicks by other chicks in the colony. Consequently, the fact that Common Terns routinely transported prey back to the colony at <1 m above sea surface also points to some aerodynamic advantage at travelling at this height.

5.1.3 Factors influencing foraging patterns

At Blakeney Point, sampling a transect line immediately offshore of the colony provided the opportunity to test the relationships between both passage rate and density near the colony and environmental factors influencing activity. Whilst there was only a weak relationship with the outbound passage of Sandwich Tern with time of day, the relationship with density was stronger, with peak activity immediately after dawn and and a secondary and potentially more significant peak in the evening. A similar, but less significant pattern for passage rate was observed at Cemlyn Bay. The observed patterns correspond with the demands of chicks requiring feeds immediately before and after the nocturnal period of inactivity (Dunn 1972 and Frank 1992; discussed in Stienen *et al*. 2000). Being visual predators, Sandwich Terns do not generally forage at night, and as such adults also have an urgent requirement for food around dawn when energy levels are lowest. Similarly, a high intake of food is required before dusk in order to maximise stored energy before the period of darkness.

Studies of other species have also suggested that diel patterns in foraging activity may reflect changes in the availability of prey (Piersma *et al*. 1988, Richner 1995). Steinen *et al*. (2000) argued that this was likely to be the case for Sandwich Terns breeding on the island of Griend in the Netherlands, where the most important prey type at that colony, clupeids such as Herring moved closer to the water surface at dawn and dusk, making them more available to foraging terns. Such a phenomenon is also likely to occur in North Norfolk where clupeid fish are also of key importance as prey.

Tidal state was the strongest predictor of mean Sandwich Tern snapshot density along the colony transect out of all the environmental variables considered. This finding broadly concurs with other studies of Sandwich Tern foraging activity, particularly those of Steinen *et al*. (2000), who showed that rates of food provision to chicks peaked in the periods before and during high tide. Other studies have shown that Sandwich Terns tend to vary their foraging tactics in relation to the tide cycle, for example targeting different areas during different periods of water depth (Essen *et al*. 1998, in Steinen *et al*. 2000). In general, a flooding tide was thought likely to concentrate shoaling fish in inshore waters, potentially bringing them into shallow areas where they are more likely to be available to foraging terns.

Given the relative strength of the relationship with the mean snapshot density, it is perhaps surprising that there was no significant relationship between tidal state and rates of passage to and from the colony. This discrepancy could be related to the fact that tidal conditions close to the colony may be relatively irrelevant for birds leaving the area to forage in areas some distance away, resulting in a potentially significant time delay between leaving the colony and arriving in the eventual foraging destination. The discrepancy might also be explained by differences in the relative influence of tidal state on prey availability in inshore and offshore waters, with a greatest effect in shallow inshore waters surveyed by the transect line. As such, the high densities of terns recorded during in the survey area during the high tide period might reflect a greater number of terns feeding close inshore. The fact that was no significant relationship between densities of foraging terns and tidal state casts some doubt on this hypothesis, although it should be noted that stratifying data by behaviour caused a severe reduction in sample size and subsequent statistical power.

Despite the problems of passage rate at the colony reflecting activity at some distance from the colony, there was some evidence of an effect of tidal state at Cemlyn. However, greater passage was observed at low rather than high water. This may be linked to the rather different environmental conditions along the deepwater generally rocky coast of Anglesey with relativey few large sandy bays. Here, low water may make prey associated with the coast such as rockling and gadoids, as well as sandeels in bays, more available to birds. Even at low water, a considerable depth of water was still available. In contrast, low water in the Wash may lead to extremely shallow water or even exposure of sandbanks. Fish occupying shallow waters at other tidal states would conceivably have to seek refuge in deeper water at low tide.

In accordance with the detailed studies of Becker *et al*. (1993) and Schwemmer *et al*. (2009) in the Waddensee, tidal patterns may be important in determining Common Tern foraging activity. Both tide and wind were important at Blakeney in determining activity close to the colony where much foraging occurs. The significant increase of activity around high water could be linked to movement of potential prey both closer to shore and higher in the water column. Under these conditions prey may also associate with particular habitat features such as the extensive sandbanks and bars associated with the harbour mouth and to the east along the coast towards Wells-next-the-sea. Wind direction was of importance for Common Tern, with northwesterly and westerly winds from the wider Greater Wash increasing tern activity. Along with easterlies and winds with a northerly component, such wind direction is likely to cause swell and turbulence than the other wind directions recorded in the study, including southwesterly, southerly and southeasterlies. The latter almost regardless of strength, are negated by the presence of the landmass in North Norfolk. Wind-driven turbulence is thought likely to bring small prey items closer to the surface in the reach of Common Tern (Schwemmer *et al*. 2009). The larger prey targeted by Sandwich Tern that may typically be distributed lower in the water column may be relatively immune to low levels of turbulence, which may explaining the lack of a relationship between wind direction and activity rates of Sandwich Tern.

In contrast, Common Tern passage at Saltholme was highest during periods when the tide was low or flooding (Fig. 20). This may be related to the apparent tendency for prey fish to become trapped in pools and embayments (especially Bran Sands) within the Teesside estuary, which regularly accumulated large numbers of terns. Alternatively, a flooding tide could have lead to movement of fish, such as shoaling clupeids into the estuary. At Saltholme, there was no evidence of any relationship between passage rate and wind direction or strength, although the range of conditions covered by surveys was relatively narrow (wind directions from northeast to southwest and wind speeds of Beaufort 1-4). In addition, the estuary is relatively protected from most wind directions and even relatively strong easterly winds only seemed to significantly affect the outer parts of the estuary.

There was no effect of wind direction or strength or other variables such as tidal state on the inbound or outbound passage rates of Sandwich Terns at either Blakeney Point or Cemlyn Bay. This study agrees with that of Dunn (1972) and Taylor (1983) who also found no negative effect of wind strength on provisioning rate. But as pointed out by Stienen *et al*. (2000), the effect of wind does not start to become apparent until after values of 8 m sec^{-1} (Beaufort force 5) and then is only seriously affected at extreme values upwards of 14 m sec^{-1}. The latter is equivalent to Beaufort force 7 ‘when the sea heaps up and white foam from breaking waves begins to be blown in streaks’. Such near gale-force winds appear to be rarely recorded in the breeding season of the terns, although storms may lead to the death of tern chicks, as was the case in 2004, when around 1,000 well-grown Sandwich Tern chicks perished. It is unclear whether this event was a result of exposure or starvation as a result of provisioning adult birds being unable to forage, or a combination of both. Such events appear to be a rare although important stochastic effect on tern breeding success. Consultation of >100 years of data in North Norfolk suggests such serious events occur with a periodicity of one event around every decade in the North Norfolk Sandwich Tern population (Perrow *et al*. *unpubl data*).

Overall, there was rather less support than perhaps expected for the findings of Stienen *et al*. (2000), who documented highly significant effects of time of day, tidal state and particularly wind strength on chick provisioning rate for Sandwich Terns. Stienen *et al*. (2000) also showed the type of prey delivered varied according to environmental conditions, with more clupeids at dawn and dusk corresponding to their diurnal pattern of activity and height in the water column, whilst sandeels predominated around midday. An important difference between Stienen *et al*. (2000) and the current study is that former is a truly extensive dataset gathered over 7 years that means even a weak effect may become apparent. The key variable measured was also different with provisioning rate measured by Stienen *et al*. and passage rates and activity measured in this study.

In general terms, perhaps the take-home message should be that although environmental variables may be important, especially at the extreme end of their range, the role of different factors is likely to vary amongst species and particulary in relation to locality and the specific prey base and conditions encountered. Otherwise, the overriding pattern may be that the demands of growing chicks effectively forces adults to forage throughout daylight hours in more or less all weather conditions and tidal states.

5.1.4 Chick provisioning and kleptoparasitism

Returning to the colony carrying provisions intended for chicks (and perhaps partners), Sandwich Terns run the gauntlet of kleptoparasitising Black-headed Gulls in a similar manner to that documented for a range of seabird species such as boobies, shags, gulls and auks parasitised by frigatebirds, skuas and even some petrels and pelicans (Gaston 2004). Terns may both be pirate and victim (Oswald *et al*. 2005, Shealer *et al*. 2005, Stienen 2006). The benefits to the food pirate are clear and neatly demonstrated by the superior reproductive success of kleptoparasitising Roseate Terns (stealing from other Roseate Terns) compared to non-kleptoparasitising ('honest') individuals (Shealer *et al*. 2005).

With such benefits it is not surprising that a number of species may attempt food piracy upon a vulnerable species, such as the five species (excluding conspecifics) attacking Sandwich Terns at l'Albufera de Valencia in Eastern Spain (Dies & Dies 2005). Here, mainly Black-headed and Slender-billed Gulls (*Chroicocephalus genei*) generated similar attack (24%) and rob (5.5%) rates upon Sandwich Terns as were seen at Blakeney Point. A further similarity was the corresponding increase in the time taken to deliver prey to chicks as the size of the prey increased. In the intensive and relatively long-term study of Sandwich Terns and Black-headed Gulls at Griend in the Netherlands, Stienen *et al*. (2001) showed that gulls robbed 18% of the *n*=16,650 items returned to the colony.

Under the extreme regime of kleptoparasitism by Black-headed Gulls at Griend, the intensity of this behaviour was dependent on the size of prey item alone (Stienen *et al*. 2001). In contrast, in the current study at Blakeney Point, analyses suggested that there was a significant difference in the way kleptoparasitic Black-headed Gulls targeted Sandwich Terns depending on the type as well as the size of prey they carried. Given that clupeids have greater biomass and energy value per unit length and are thus higher-quality prey items than sandeels, it might be expected that Black-headed Gulls would target 'clupeid-carriers' more vigorously than 'sandeel-carriers'. However, for terns carrying small items, a kleptoparasitic response was more likely to occur when carrying a sandeel than a clupeid, although the opposite was indeed true for items larger than about 8 cm in length, where clupeid-carriers had a higher likelihood of attack. For clupeid-carriers, the intensity of attack was also likely to be higher when carrying larger items. Overall, the highest rates of kleptoparasitism were observed for large clupeids and the lowest rates for small clupeids, with sandeel-carriers experiencing intermediate rates. Part of the explanation for this pattern may be that Black-headed Gulls are less able to differentiate prey types when the item being carried is small. The shape of sandeels causing them to droop and flex in the bill when being carried, may also make them appear larger than they really are.

At Cemlyn Bay, the proportion of terns attacked (8.8%) and robbed (<1.7%) was much lower. Models predicting kleptoparasitic attack likelihood as a function of prey energy content also yielded markedly different results, with the likelihood of attack being broadly similar between prey types for items of equivalent size. It is tempting to speculate that inter-regional differences relate to the timespan over which mixed breeding between Sandwich Terns and Black-headed Gulls has occurred in each area. In North Norfolk, Sandwich Terns have been established breeders for more than 80 years, whilst at Cemlyn Bay the Sandwich Tern colony developed relatively recently (established in 1984), with 2009 being the first year in which large numbers of Black-headed Gulls bred within the colony. Given that sandeels and clupeids are unlikely to be available to Black-headed Gulls as prey items by any means other than kleptoparasitism, a lack of exposure may mean that individual Black-headed Gulls may have not yet learnt to target Sandwich Terns carrying such prey, and even if they do they have not developed any ability to differentiate between these prey types. In North Norfolk, the long period of co-existence between Sandwich Terns and Black-headed Gulls has perhaps facilitated the development of an ability to differentiate these prey items, allowing the kleptoparasitic strategy to become more optimal. Curiously, there is also little evidence that Black-headed Gulls differentiate between Herring and sandeels at Griend (Stienen *et al*. 2001) where the interactions between gulls and terns have been studied in detail since the mid 1960s (Stienen 2006).

Overall, the fact that Sandwich Tern chick diet at Blakeney was dominated by small clupeids compared to the prey delivered to the colony suggested that the frequency and intensity of kleptoparasitic attacks by Black-headed Gulls was sufficient to structure chick diet. Given that clupeids of any size are likely to be more energetically productive than sandeels of equivalent size, small clupeids could theoretically represent the most productive prey type for chick rearing. However, this would be dependent on the rate at which these items can be provided, as well as the extent to which the cost of bringing, and then losing, larger items to gulls was balanced by their enhanced energetic content. Steinen *et al*. (2000) indicate that provisioning expressed as biomass delivered per day increases with chick age, reaching nearly 70 g chick^{-1} day^{-1} at peak. The mean (±1SE) delivery rate (g) in this study of 0.61 g hr^{-1} (± 0.18) supplying 8.5 g chick^{-1} day^{-1} was a fraction (<15%) of the maximum reported in Stienen *et al*. (2000). Although methodological differences and the fact that observations may account for some of the difference with short observation periods reducing the likelihood of detecting the delivery of rare, large items or periods of more intense activity, these seemed unlikely to offer anything like a full explanation.

In principle, in order to meet the shortfall, adult Sandwich Terns either have to deliver some large fish in the course of each day or increase the rate of provisioning small clupeids. Otherwise, the ability of chicks to grow and ultimately fledge appears to be compromised, despite the ability of Sandwich Tern chicks to modify growth rate and the length of the development period to compensate for food shortage (Stienen & Brenninkmeijer 2002). In the case of provisioning small clupeids, the >6.5-fold increase in provisioning rate required appears to be far beyond the scope of even both parents foraging, assuming a like-for-like increase in the ability of each parent.

However, the need for full-time guarding of the chick from gulls and the aggressive attentions of other tern parents should the chick wander from the area of the nest, means that only one parent may forage at a time. Much of the foraging duty appears to fall to male terns (Cramp & Simmons 1985). Only when the chick reaches a large size, when it may join a crèche with other youngsters sometimes outside of the boundaries of the nesting colony, may it be that both parents are released from guard duty and switch to full-time foraging to feed their chick.

It thus seems that provisions of larger fish must be attempted. Clupeids delivered to the colony ranged from just under 3 cm to 16 cm at 0.07-36 g with sandeels ranging from 2.5 cm up to ~20 cm at 0.07-20 g. Provisioning the equivalent of just four 15 g meals per day (i.e. <one every 4 hours) represented by moderate-sized clupeids or larger sandeels would readily meet the estimated shortfall. However, this may prove to be difficult to achieve and not without cost. The energy balance approach using data generated from the observations of foraging birds during visual tracking clearly indicated the fine balance between provisioning chicks and providing sufficient energy to meet the metabolic demands of the provisioning adult.

The intake rate of 24 g hr^{-1} of breeding self-feeding Sandwich Terns in North Norfolk was far below the intake rate of 60 g hr^{-1} achieved by Sandwich Terns in their wintering grounds (Brenninkmeijer *et al*. 2002). The latter was thought to be about three times the basal metabolic rate (BMR) suggesting an easy living for Sandwich Terns in their wintering quarters. Conversely, this illustrates that breeding Sandwich Terns in North Norfolk may only be just above their BMR and thus even operate on something of a metabolic knife-edge.
The modelling exercise provided considerable insight into the overall effects of kleptoparasitism

upon the foraging decisions of Sandwich Terns and the trade-off between chicks and adults. Modelling stemmed from the basic premise that kleptoparasites selectively target carriers of large prey items thereby providing a relative disadvantage of selecting larger prey items at sea under threat of kleptoparasitism. At low levels of kleptoparasitism, the model predicted optimal trade-off between chick provisioning and adult energy balance could be achieved by adopting a relatively high size selection threshold, and consequently making fewer, longer foraging bouts. At high kleptoparasitism levels, the opposite outcome was predicted to arise, due in part to the increased risk of loss of large items, as well as the overall impact of prey loss on energy provisioning rates to chicks, meaning that adults would be required to trade-off their own energy balance in order to meet the minimum growth requirements of chicks. Adults were therefore predicted to adopt a lower minimum size selection threshold under high kleptoparasitism intensity and make shorter but more frequent foraging trips.

The size distribution of prey items observed being brought into colonies in North Norfolk conformed closely to that predicted by the model based on two separate minimum size selection thresholds being adopted by the population (associated with variation in kleptoparasitism intensity). It is likely that within any tern population, there will be considerable individual variation in size selectivity for provisioning, with multiple strategies being adopted across the population at any given time, either in response to kleptoparasitism risk or other factors. Nevertheless, the close congruence between model predictions and independent data on prey selection for provisioning from colony observations suggested that a high proportion of the population adopts one or other of these predicted size selection strategies (6 cm and 9 cm). This suggests that in order to meet the minimum energy requirements of growing chicks under the maximum kleptoparasitism scenario, adults would need to trade-off their own energetic gains in favour of obtaining the maximum possible provisioning rate.

The intensity of kleptoparasitism is likely to vary in relation to environmental conditions, such as being higher during periods of high wind speeds and at high tide (Stienen *et al*. 2001), although it is not clear whether terns would respond to such short-term fluctuations in kleptoparasitism by shifting their size selection strategy. Variation in kleptoparasitism levels is also likely to occur over longer time periods, associated with fluctuations in the relative abundance of Black-headed Gulls within colonies. If Black-headed Gull numbers were to decline within North Norfolk colonies and Sandwich Terns were to respond optimally, they might be expected to reach offshore waters more frequently over a long timescale. Although local populations of the principal kleptoparasite, Black-headed Gull, are not presently thought to be declining, breeding numbers do appear to fluctuate considerably and the potential exists for kleptoparasitism levels to change in future. Such changes could have a significant indirect influence on the impacts of OWFs on Sandwich Terns via a change in foraging range (see 5.2.1 below).

As a result of the structuring force of kleptoparasitism upon provisioning adults, the diet of Sandwich Tern chicks was essentially the same as that of those of Common Terns irrespective of the prey targeted at sea or even what was captured and subsequently delivered to the colony. Moreover, the similar biomass provisioning rate to individual Sandwich and Common Tern chicks belies the fact that Common Tern broods averaged 1.8 chicks compared to the single chick of Sandwich Tern, meaning individual families of the former received twice as much prey (in grams). The aggressive nature of Common Tern and the relative scarcity of sympatrically nesting gulls means that the presence of just a few adults in the colony appears to be a sufficient deterrent for would-be predators. This suggests greater flexibility for Common Tern parents compared to Sandwich Tern in North Norfolk, which on occasion may be manifested as both parents foraging to provision chicks, although much provisioning again appears to be achieved by the male alone (Steinen *et al*. 2008).

The high proportion of unidentified items meant that it was difficult to determine the exact nature of adult Common Tern diet at sea. Nevertheless, as this was partly determined by the extremely small size of many items, this suggested a prevalence of invertebrates rather than fish. Certainly, a different proportion of invertebrates were present in the identified fraction of both items taken at sea (20%) and that presented to chicks (0%). Again, it appears that the items of higher calorific content were selected for transport, even though the selection pressure for this may not be as intense for Common Terns foraging in inshore waters close to the colony compared to Sandwich Terns foraging further offshore (see 5.3 below).

5.1.5 Individual and population implications

On an individual basis, modelling demonstrated peaks in the abundance of a particular size-class of fish prey could have a significant influence on the optimality of size selection strategies. Unfortunately, in the absence of detailed information on the nature of prey abundance variation in the Greater Wash, the impacts of cohort-specific abundance variation could not be meaningfully modelled in this study. To do this, further work examining prey abundance variation is required. Nevertheless, it was clear from the model that should prey availability reduce the model predicts that minimum energetic requirements of chicks could only be met for a narrower range of strategies, reducing the capacity for adults to trade-off chick provisioning rates in favour of their own energetic balance. If prey abundance was reduced by 50% from the levels at which data was derived in the years of this study, the model predicts that breeding might become unviable unless levels of kleptoparasitism were at a minimum.

Whilst a 50% reduction in prey levels might be regarded as a relatively large change, it nonetheless illustrates that there is relatively little spare capacity in the current environment for individual Sandwich Terns, which may conceivably have relatively rapid consequences for the population as a whole. Further supportive evidence of a general limitation of resources is the tendency for Sandwich Tern to lay just one egg in North Norfolk (M. Rooney NE *pers comm.*, *pers obs*)[4], compared to the average of 1.6 at Griend in the Netherlands. Although the chance of survival of the second chick is much reduced, 2% of Sandwich Terns do manage to raise a second chick at Griend (Stienen 2006). This does not seem to occur at all in North Norfolk.

At a population scale, the relative stability of the population in recent years also suggests the carrying capacity of the environment to support Sandwich Terns has been reached following their colonisation of the area in 1920 at Blakeney Point (Taylor *et al*. 1999). Following the frst use of Scolt Head in 1923 and a range of other smaller sites, the population grew rapidly to >1,000 pairs by 1929. Relatively stability was then acheived for the following 20 years, with numbers peaking at around 2,000 breeding pairs. From 1962 onwards, a second significant period of growth occurred, with numbers building to 4,057 pairs in 1970. The second phase of increase may be related to the collapse of the population in the Nertherlands from 46,000 pairs in the 1950's to just 875 pairs by 1965, which was attributed to organochlorine pollution in the Rhine (Mitchell *et al*. 2004). The population has remained broadly stable at 3,700 pairs subsequently, dipping to a recent low of 2,400 pairs at Blakeney Point in 2008 but increasing to 3,100 pairs again in 2009. At both Blakeney and Scolt the birds have been historically protected through the routine control of ground predators and the limitation of human disturbance.

The relative stability of the population despite reasonable breeding success producing on average 0.68 chick pair^{-1} year^{-1} could mean that despite the apparent limitations of the environment the North Norfolk population operates as something of a source of recruits to other populations in the North Sea. However, the population at the larger scale is still well below previous levels according to BirdLife International (2004a), with Sandwich Tern maintaining a 'Depleted' status and thus of conservation concern. The work of Stienen (2006) suggests that the recovery of the North Sea metapopulation of Sandwich Tern has effectively been held in check by a limitation of prey, although further work is required to substantiate this idea.

Although less is currently known of the population dynamics of Common Tern, it appears to be in general decline, abandoning the coast in favour of breeding in freshwater habitats (Taylor *et al*. 1999). Although there is no specific evidence, the factor thought most likely to be driving these patterns is the abundance and distribution of fish.

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[4] although the very occasional observation of two small chicks in this study suggests two egg clutches are occasionally laid

Unfortunately, very little is yet known of the factors influencing the abundance and distribution of key fish species such as clupeids and sandeels in the Wash, or indeed in any of the waters around of the other colonies studied. This is mainly as little basic targeted research has even been attempted. An exception is the work on behalf of Centrica Energy (2009), which supported the view of the inshore movement of seemingly large shoals of clupeids, mainly Sprat, later in the season. Such spatial patterns of movement and aggregation may be influenced by a variety of factors including substrate, bathymetry, tidal patterns and climate. Temporal fluctuations in abundance may be related to sea temperature variation and tidal patterns in line with the North Atlantic Oscillation. Shifts in any of these parameters could initate changes in the abundance and distribution and phytoplankton, zooplankton and ultimately fish. Such 'bottom-up' trophic changes could then conceivably generate effects on individual tern foraging patterns, breeding success and ultimately the dynamics of the population.

The development of OWFs has a potentially important role in these processes where they overlap spatially with important areas for fish. Construction noise, principally as a result of pile driving may disturb or even kill fish perhaps even with longer-term consequences for recruitment of fish populations and indirect effects on seabirds including terns (see Perrow *et al*. 2006, 2008). Operation of OWFs on the other hand may have little impact, perhaps even offering alternative habitats and protected areas if commercial fishing does not take place within them. Clearly, understanding fish will ultimately be central to understanding the interaction between terns and OWFs. Even in the absence of such knowledge at this stage, there is much to be gained from the study of the terns themselves.

5.2 Vulnerability of Sandwich and Common Terns to wind farms

5.2.1 Possible sensitivity

Garthe & Hüppop (2004) derived a species sensitivity index (SSI) for 26 seabird species in relation to offshore wind farm development that included a range of parameters on the population size, conservation status, habitat use flexibility, sensitivity to disturbance and behavioural parameters such as flight height characteristics. Some parameters were based on actual data with others generated from opinion of 15 respected seabird experts using the Delphi technique. Amongst the four tern species assessed - Arctic, Black *Chlidonias niger*, Common and Sandwich – it was Sandwich Tern that was classed as the more sensitive and was particularly sensitive overall, ranking 4th behind Red-throated *Gavia stellata* and Black-throated *G. arctica* Divers and Velvet Scoter *Melanitta fusca*. Factors that made a particuar contribution to this ranking included high European threat and conservation status, relatively low biogeographical population size and relatively higher flight altitude than the other terns. Mainly as a function of its larger population size and low threat status Common Tern was seen as relatively insensitive ranking 15th. Arctic Tern was of even lower sensitivity at 17th on account of even lower flight height (with median values apparently <5 m).

Whilst the SSI index provides some broad idea of the likely sensitivity of the species it is a general tool that cannot take into account factors associated with specific OWFs. For example, although general conservation and population status is taken into account, in EIA, the sensitivity of a species is heavily influenced by the proximity of any designated area in which the species is included as a qualifying species, or to a lesser extent as a species contributing to an assemblage criterion. In fact, the tendency for terns to form sizeable colonies that each make a relatively high individual contribution to overall population size, as well as often being associated with generally valuable marine habitats, means that terns contribute to the value of a large number of designated areas (e.g. 52 SPAs – see 1.1 above). In other words, the presence of OWFs near tern colonies typically means that the individual species will often be classed as of 'Very High' sensitivity according to the matrix analysis of Percival *et al*. (1999).

The magnitude of any effect will then intuitively rely on the use of the prospective wind farm area by breeding birds, both in absolute terms in relation to collision risk and perhaps more in relative terms for disturbance/displacement. In turn, the distance of the OWF from the colony relative to the foraging range of breeding birds at any colony is likely to directly affect the intensity of use of the OWF. Foraging range, flight height of the species relative to the turbines and the rate of avoidance (Chamberlain *et al*. 2006) constitute key components of prospective collision risk determined by collision risk modelling (Band 2000, Chamberlain *et al*. 2005).

The magnitude of other potential effects of OWFs upon birds including any indirect effects upon prey influencing foraging patterns are less readily determined if the nature and distribution of the prey resource is not well known. However, should this be available in terms of the distance of alternative foraging grounds from the colony, the energy balance approach used in this report may make a useful contribution to understanding potential impacts upon chick provisioning and breeding performance.

The discussion below incorporates ecological features of Sandwich and Common Terns (with some additional observations upon Arctic Terns, in the different colonies studied) with a view to assessing the relative vulnerability of tern species to OWF development in different areas, thereby providing a broad comparison with the results of the SSI analysis.

5.2.2 Theoretical foraging range

Considerable variation in the prospective foraging range of tern species is reported in the literature. For example, Sandwich Terns are reported to forage from within a few kilometres of the colony to ~67 km, Common Terns from 3-10 km to a maximum of 37 km and Arctic Terns from <3 km to a maximum of 20 km (Cramp & Simmons 1985). Part of this variation may be explained by the relative lack of specific studies in which terns are proven to originate from a particular colony through techniques such as radio telemetry. Otherwise, observations of birds at sea may simply imply origin from a particular colony (e.g. Fasola & Bogliani 1990).

However, for any tern colony the relative proportion of breeders to non-breeders remains unknown and it seemed plausible that an increasing proportion of birds at greater distance from the colony may relate to non-breeding individuals. In the Greater Wash, this may also explain the occurrence of some Common Terns at considerable distance from the colonies, although records in July or perhaps even June may also relate to the considerable passage population of Common Terns through the Wash perhaps starting with early-returning failed breeders.

As illustrated in Fig. 2, the aerial surveys of the Greater Wash captured some Sandwich Terns at the edge of the outer edge of the survey (~60 km) in the breeding season suggesting this was within range of birds from the North Norfolk colonies. Despite reservations of the origin of these birds, the fact that Cramp *et al*. (1974) described the presentation of some tagged trout to chicks by Sandwich Terns at the Sands of Forvie colony some 70 km away from the release site of the trout in a freshwater system, provided clear evidence that Sandwich Terns may indeed range to considerable distance from the colony in specific circumstances. The question then remains if this sort of range could be generally achieved by birds provisioning chicks as a common trait amongst seabirds (and probably other predatory species) is for the range of adults to reduce as the reproductive cycle advances from the incubation to chick provisioning phase (Ojowski *et al*. 2001). In simple terms, the non-incubating adult has the capacity to range over large distance and over relatively long periods when freed from the constraints of responsibility associated with the nest.

The energy balance modelling conducted in this study illustrates that for Sandwich Terns and almost certainly all terns, there is a clear trade-off between provisioning chicks and adult energy balance, which is further complicated by the size selection threshold at which prey is returned to the colony. Fundamentally, the utility of the models developed for Sandwich Tern was underpinned by the close relationships between prey item size and capture rate, distance travelled and capture rate, and distance travelled and the distance reached offshore. In simple terms, the more time spent foraging, the greater distance offshore from the colony reached and the larger the fish likely to be available for transport to the colony. Whereas a different approach to modelling would be required for species such as Common Terns in North Norfolk, where the distance reached offshore was likely to be a poor indicator of time spent foraging, for Sandwich Terns, where good information was also available in relation to energy intake and expenditure, it was readily demonstrated that adults increased energy intake the further they travelled as a result of continuing to feed as they did so. Foraging on a range of prey including invertebrates (i.e. prey that are not presented to chicks) as they are encountered also appeared to be a fundamental part of adult foraging strategy.

The trade-off with chick provisioning means that adults must have sufficient time and thus travel distance available to encounter sufficient prey to meet their own metabolic demands. 'Normal' circumstances were assumed to be represented by the data gathered during the current study as at least chick recruitment to the population appeared to be within the typical range with a range of 0.5-0.81 chicks pr^{-1} yr^{-1} i.e. a mean of 0.65 compared to the overall mean [± 1SD] of 0.68 ± 0.31. Under a standard prey selection scenario of 6 cm and intermediate levels of kleptosparasitism (see 3.5.2 above), the model predicted that the metabolic demands of adults and 100% of the provisioning rate required to maintain minimum chick growth (247 KJ day^{-1}) could be met by adults ranging up to 38 km from the colony from a minimum value of 4 km (Fig. 84). Such a range encompasses the majority of the Round 1 & 2 sites in the Greater Wash.

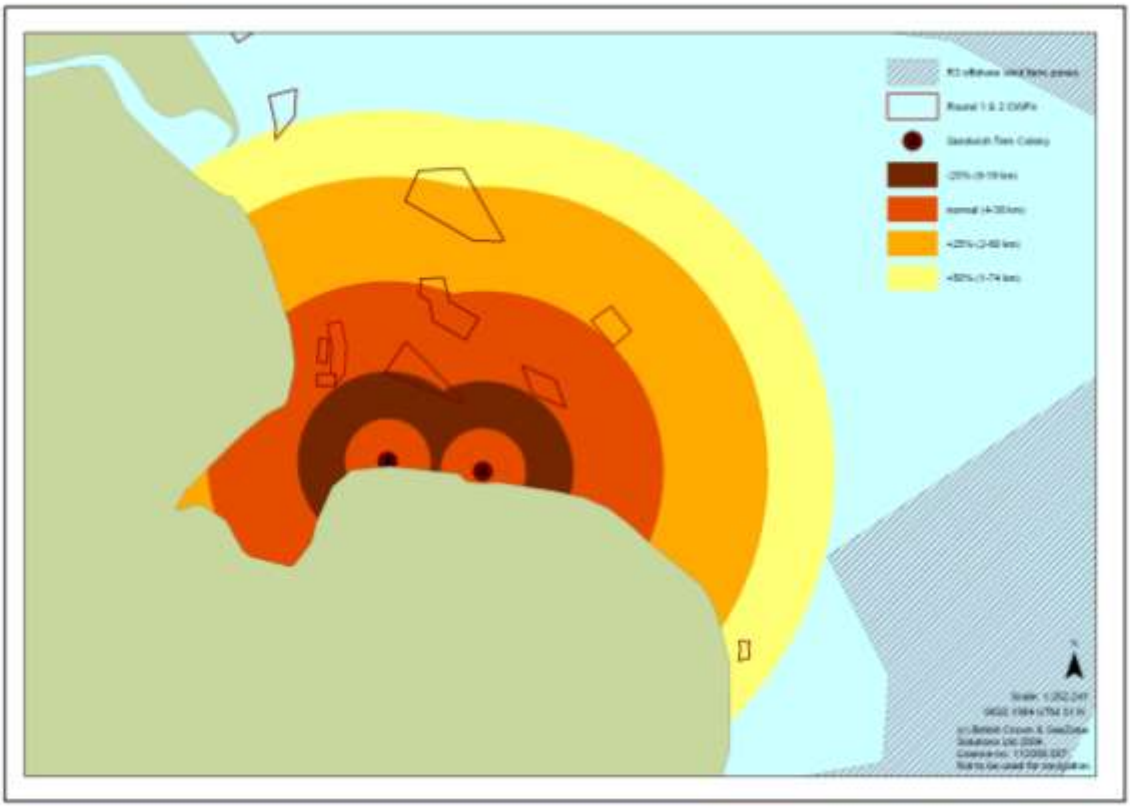

Figure 84. Foraging range of Sandwich Terns from the North Norfolk colonies at Scolt Head (west) and Blakeney Point (east) predicted from the energy balance model assuming the metabolic demands of adults and minimum growth rate of chicks are met, at different levels of prey abundance. The 'normal' scenario relates to conditions encountered in 2006-2008, with other stepwise scenarios of +50%, +25% and -25% variation in prey abundance. At conditions of -50% of 'normal' conditions the metabolic demands of chicks cannot be met.

Should prey become abundant, adults may adopt a larger size-selection threshold for chick provisions which then allows adults to spend sufficient time foraging. Thus, with a 25% increase in prey abundance, all sites may at least be reached although not entirely encompassed. This is achieved at a prey increase in the order of 50% with the Round 1 Scroby Sands OWF outside of the Greater Wash in East Norfolk also within range (Fig. 84). This is not to say that adults *would* range to these limits, just that they *can* from an energetic perspective. These upper limits of 60-74 km show remarkably close agreement with the observations of Sandwich Terns at the edge of the aerial survey area (Fig. 2) and what appears to be upper limit of the range suggested by Cramp *et al*. (1974).

When prey is less available to chicks either as a direct result of what is in the environment or as a result of the attentions of kleptoparasiting Black-headed Gulls, adult Sandwich Terns have to adapt their strategy accordingly. Under the minimum kleptoparasitism scenario in North Norfolk, the brood provisioning rate required to maintain minimum chick growth was attained at a range of size selection thresholds, the highest being 9.4 cm (Fig. 69). At this level, the energy balance of adults was also close to being optimal suggesting that at lower kleptoparasitism levels, adults might be able to balance the trade-off further in favour of their own energetic needs (i.e. adopting a higher size selection threshold) without having any significant impact on the rate of energy provisioning to their chicks. Adults adopting such a strategy would reach significantly greater distances offshore than would be optimal under the high kleptoparasitism scenario; for example, individuals with a minimum size selection threshold of 9.4 cm would be expected to reach a mean distance of >28 km from shore on each bout.

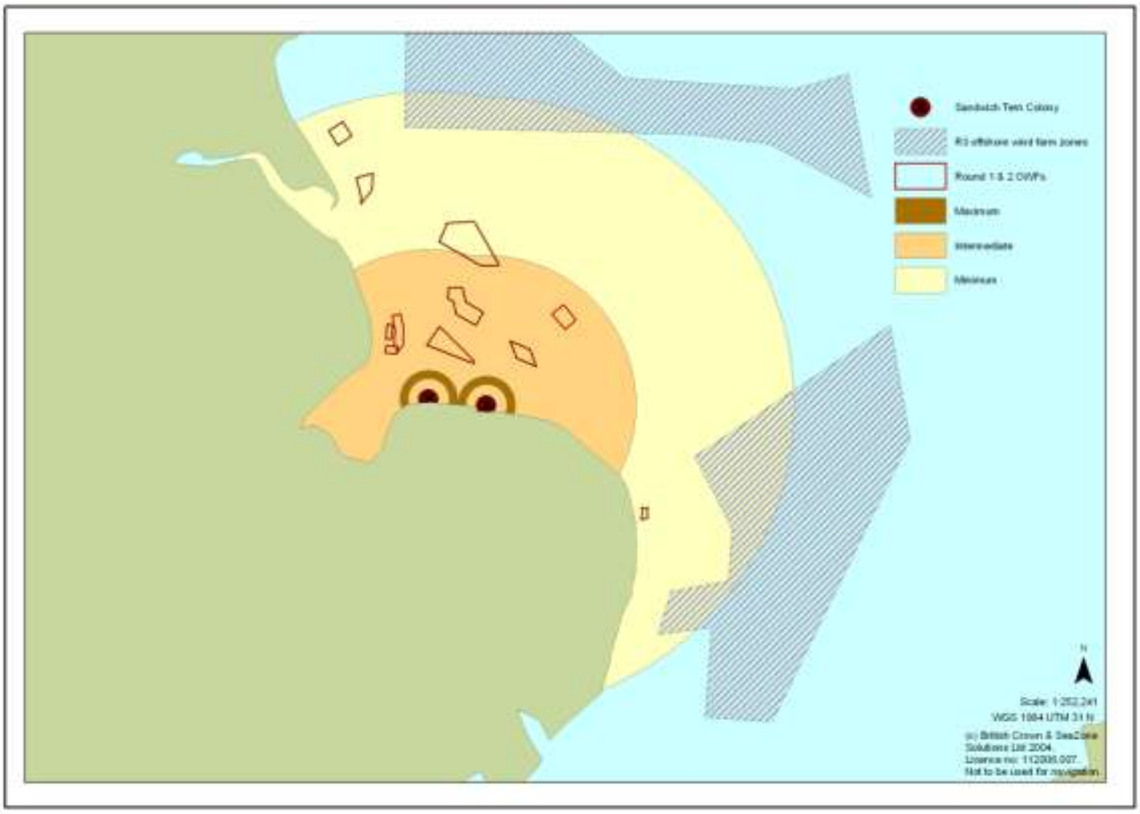

Figure 85. Foraging range of Sandwich Terns from the North Norfolk colonies at Scolt Head (west) and Blakeney Point (east) predicted from the energy balance model assuming the metabolic demands of adults are met, coupled with 90% of the minimum provisioning rate to chicks at different levels of kleptoparasitism: minimum, intermediate and maximum, where intermediate probably represents the prevailing condition in North Norfolk.

Releasing Sandwich Terns from kleptoparasitism therefore changes the potential (theoretical) foraging range. As maximum (100%) energy provisioning to maintain even the minimum rate of growth of chicks could not be maintained under all scenarios, a 90% chick growth scenario was used to illustrate the impact of kleptoparasitism on potential foraging range (Fig. 85). At minimum levels of kleptoparasitism and the ability to range a long way to capture large items to meet metabolic demands and growth rates of chicks, the potential range increased substantially to >100 km. At this range, even the Round 3 zones at Hornsea and Norfolk as well as the Round 1 site at Scroby Sands fell within the prospective range of foraging breeding adults (Fig.

85). At intermediate levels of kleptoparasitm, the model predicted that adults could reach up to 52 km (i.e. broadly comparable to the 38 km predicted for a 100% provisioning rate scenario), with this declining to a narrow range of 7-10 km under maximum rates of kleptoparasitism. This assumes the minimum size selection threshold of ~6 cm is adopted.

As well as prey abundance and the availability of prey to chicks as limited by kleptoparasitism, the potential for chick growth may also structure the foraging range of adults. Chicks have the capacity to vary growth rate during development and still fledge, which appears to be an adaptation to variable prey conditions (Stienen & Brenninkmeijer 2002). In theory, growth may still be maintained at the energy provision rate of 247 KJ day^{-1} (Drent *et al*. 1992) i.e. 64% of the optimal value of 385 KJ day^{-1}. In practice, Stienen *et al*. (2001) illustrate that the actual provisions received by chicks may be lower than this at ~200 KJ day^{-1}. At a value of 75% of optimal energy provisions (i.e. 289 KJ day^{-1}), the potential range of adults increased to 75 km, whilst at 50% of optimal energy provision (i.e. 193 KJ day^{-1}) it extended to 140 km encompassing all previously mentioned OWF sites and zones and even just overlapping with some sites in the Thames estuary (Fig. 86). The adults themselves were not predicted to experience reduced body condition apart from perhaps in times of extreme prey shortage, as they are able to self-feed whilst travelling. Rather, it illustrates, that, as under the kleptoparasitism scenario, in ‘poor’ years where adults initially attempt to provision chicks despite limitations in prey availability before this ultimately leads to chick starvation, the range of birds from the North Norfolk population could conceivably encompass many wind farms, perhaps increasing the prospect of collision.

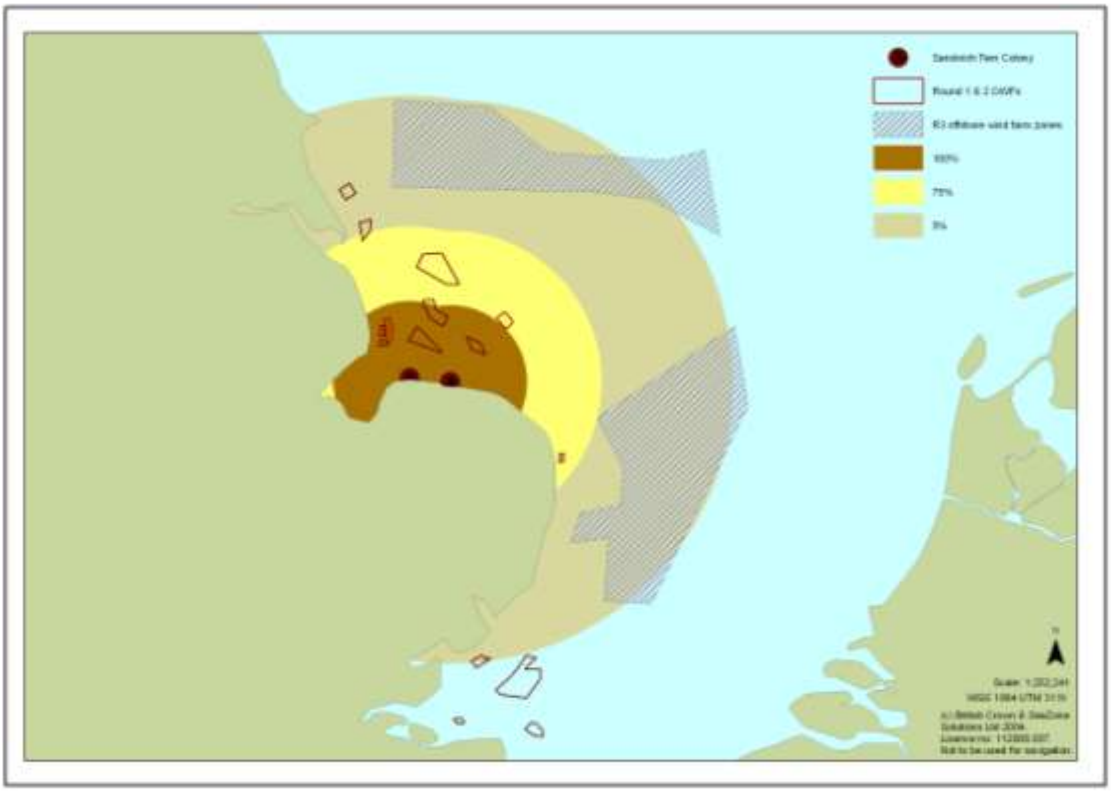

Figure 86. Foraging range of Sandwich Terns from the North Norfolk colonies at Scolt Head (west) and Blakeney Point (east) predicted from the energy balance model assuming the metabolic demands of adults are met but at decreasing provisioning rate to chicks from 100% (all) to 75% and 50% of optimal values.

5.2.3 Actual foraging range

Despite potential for considerable variation under specific conditions it was of note that there was relatively little difference in the maximum range exhibited by Sandwich Terns from Cemlyn Bay and colonies in North Norfolk at 33 km and 27 km respectively. If previous data gathered on Sandwich Terns from North Norfolk colonies is also incorporated, the recorded range doubles to 54 km (Centrica Energy 2009, Perrow *et al*. 2011, Fig. 87). It is likely that Sandwich Terns from Cemlyn at least match this range, given that the overwhelming majority of birds (88%) could not be followed for a complete bout. Overall, in conjunction with the theoretical possibilities described above (5.2.2), a general value of ~75 km is suggested as a guide to broadly define the range of Sandwich Terns. This is in line with the maximum value of 70km (mean of 14.7 km) suggested by the foraging radii approach adopted by BirdLife International (Ben Lascelles *pers comm*.) and reported in the planning document for Round 3 by the RSPB (Langston 2010).

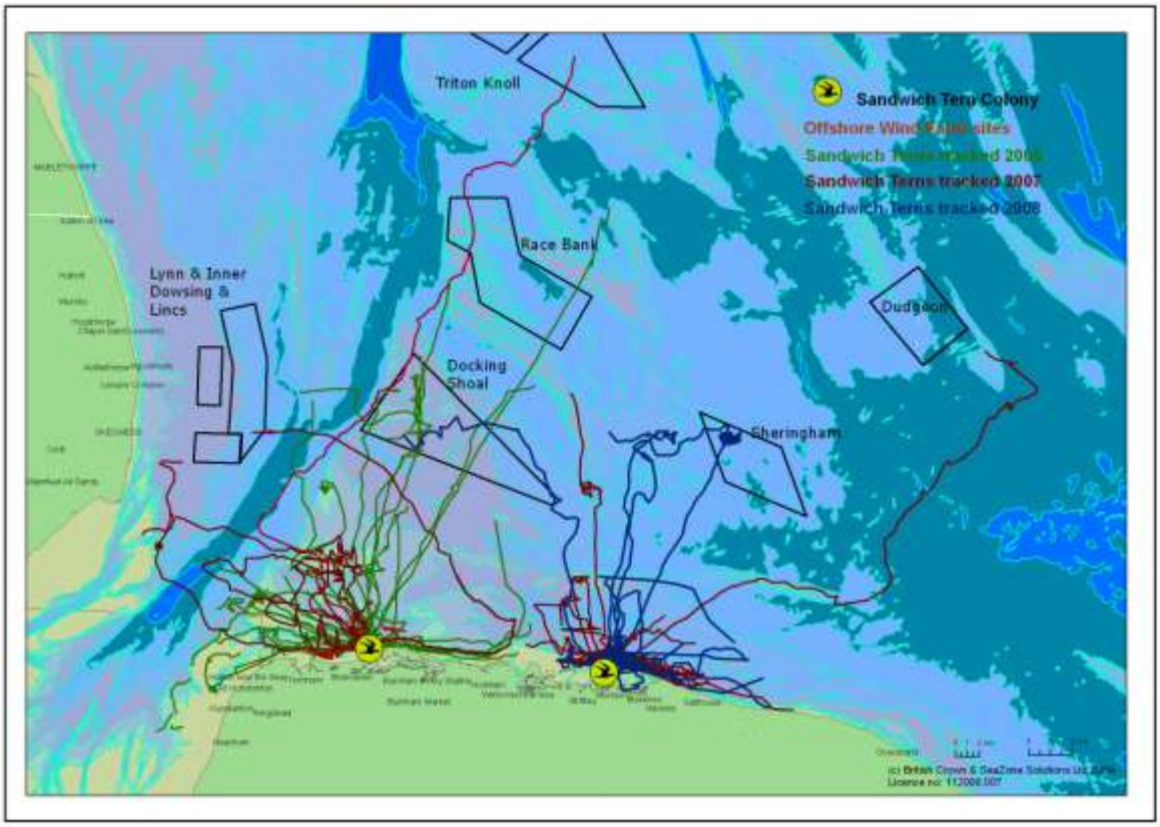

Figure 87. Tracklines of all Sandwich Terns (*n*=145) tracked from both Scolt Head in 2006 and 2007 (Centrica Energy 2008, 2009) and Blakeney Point 2007 (Centrica Energy 2009) and 2008 (current study) in relation to proposed and consented OWFs in the Greater Wash.

Retrospectively, aerial data seems to have broadly represented the range of Sandwich Terns in The Greater Wash (Fig. 2) and perhaps even at other colonies. However, whilst a figure of ~75 km and a foraging radii approach may help scope the potential for OWFs to overlap with the foraging range of Sandwich Terns, this may prove to be highly precautionary as the shape of the range is likely to be structured by available foraging habitat. This was clearly illustrated by the data from Cemlyn Bay. Here, a foraging radii approach would have suggested considerable overlap between foraging Sandwich Terns and the Round 3 zone offshore, whereas in fact there is very little evidence that this is likely, with virtually all movement of birds focussed on the coastal strip and shallow waters of large bays and perhaps even the estuarine waters of the Menai Strait itself. Such habitats appeared to offer the prospect of sandeel prey. Rather than Sandwich Terns reaching the Round 3 zone, there is greater potential for Arctic Terns from the Skerries to at least reach the southern part of the zone. However, the current dataset is extremely limited and more work will be required to confirm that this is the case as well as how frequently and when this occurs

The available evidence from different Sandwich Tern colonies, in combination with energy balance modelling reinforced the view that Sandwich Tern is adapted for long distance commuting from colonies, typically occupying the specialist 'long distance' foraging niche. This is despite the considerable differences in the nature of the habitat near the different colonies sampled as well as variation in other important factors such as the rate of kleptoparasitism. Howevever, in all cases sampled to date, Sandwich Tern was nesting sympatrically with other terns. The more 'generalist' Common Tern (Brown & Grice 2005) appeared to occupy the short distance or inshore niche when sympatric with a large colony of Sandwich Terns in North Norfolk, but strikingly illustrated the capacity for longer distance foraging in the absence of Sandwich Terns at Saltholme. Whether there is cause and effect in the presence of other tern species or whether other factors such as the type of prey available are fundamentally responsible for the observed patterns, cannot be separated at this stage.

Nevertheless, the immediate and obvious implication of the foraging patterns observed is that breeding Common Tern are highly unlikely to forage with any frequency at any of the areas occupied by proposed or existing wind farms in the Greater Wash. Boat-based surveys have recorded Common Tern within OWF sites in the period in which colonies are occupied by breeding birds, although some of these records may involve non-breeding birds or failed breeders. Moreover, the majority of records for any individual site were at the end or after the breeding period (Table 8) when birds disperse from colonies before ultimately commencing migration to their wintering grounds, mainly in West and Southern Africa. Common Tern is a widespread and common breeder throughout Northern Europe and even the passage population originating from colonies along the East Coast of the UK potentially passing along the western seaboard of the North Sea has been calculated to be in the region of 19,500 ind. (Centrica Energy 2009). Indeed, 13,400 ind. were recorded in August at Spurn Point in Humberside in 2008 (see 1. above). In 2009, a peak population of >40,000 birds was reached at a similar time (www.spurnbirdobservatory.co.uk/sightings/august09), illustrating that many birds from the Continental population cross the North Sea during the dispersal period, a fact also indicated by ring recoveries of birds from Northern Europe at this time (Wernham *et al*. 2002). Such is the complexity of dispersal patterns after breeding that adults and their dependent young may remain locally, move to other UK waters or even move to the coasts around Continental Europe. This means that at least some birds recorded in OWF sites outside the breeding period may have originated from North Norfolk colonies, although the proportion of birds involved may be very small.

At Teesside, breeding birds routinely reached the OWF when foraging from the colony. Admittedly, the OWF begins at only 1 km from shore, but the Common Terns from Saltholme have had to cross at least 6.5 km of a varied landscape of industrial land and fresh and brackish wetlands as well as navigating roads and power lines to even reach the Tees estuary. The distance travelled for a tern to reach the wind farm is thus at least 8.5 km and up to 12 km to cross the OWF, which is not far short of the equivalent of terns in North Norfolk reaching Sheringham Shoal OWF. This sort of foraging range is in keeping with the observations of Becker *et al*. (1993), who recorded flight distances of ~30 km for radio-tracked birds in the Waddensee, although the mean range of completely tracked bouts was only 6.3 ± 2.4 km. In a similar vein to Sandwich Tern, the maximum and mean foraging ranges of 37 km and 8.7 km suggested by the literature adopted in the BirdLife foraging radii approach and reported in Langston (2010), appears to be broadly realistic of the scope of Common Terns at colonies sampled to date. It is of note that birds tracked by the JNCC from the colony at Leith Docks in the Firth of Forth in Scotland appear to show a similar range (L. Wilson *pers comm*.). At Teesside at least, locally breeding Common Tern has the potential to interact with the wind farm on a regular basis on the basis of its foraging range alone. As already noted in the Greater Wash (see above), there is also considerable potential for birds on passage from a range of colonies to also interact with the site.

Table 8. Maximum density (ind. km^{-2}) of Sandwich and Common Terns recorded in each month during boat-based surveys of the consented and/or submitted Round 2 OWF sites in the Greater Wash SEA[5]. The number of years of survey is generally two (three in the case of Docking Shoal), with between 1-3 surveys in each month. All months in which at least some individuals were recorded at any site are included, with the period of potential colony occupation shaded for each species.

Species	Month	Site[1]				
		Docking Shoal[2]	Sheringham Shoal[3]	Race Bank[4]	Dudgeon[5]	Lincs[6]
Sandwich Tern	March	0.00	0.00	0.02	0.00	0.00
	April	0.33	0.09	1.58	2.15	0.00
	May	1.43	0.78	1.16	1.82	0.00
	June	1.98	0.69	0.95	1.67	0.30
	July	0.84	0.49	2.66	0.17	0.26
	August	0.64	0.52	0.59	0.00	0.82
	September	5.40	0.42	0.02	0.00	0.21
	October	0.00	0.00	0.00	0.00	0.04
Common Tern	March	0.00	0.00	0.00	0.00	0.00
	April	0.07	0.00	0.00	0.00	0.00
	May	0.13	0.07	0.02	0.00	0.00
	June	0.07	0.07	0.00	0.00	0.00
	July	0.11	0.08	0.00	0.00	0.39
	August	0.25	0.05	0.13	0.52	0.22
	September	0.27	0.03	0.02	0.09	0.00
	October	0.00	0.00	0.00	0.00	0.04

[1]Sites are arranged in order of mean distance from each of the main colonies of Sandwich Tern on the North Norfolk coast at Blakeney Point and Scolt Head, which also support Common Tern. Common Tern also breeds at a number of smaller colonies at varying distances from each OWF. Data for individual sites provided by [2]Centrica Energy 2008, [3]SCIRA Offshore Energy 2006, [4]Centrica Energy 2009, [5]Dudgeon Offshore Wind 2009, 2010, [6]Centrica Energy 2007.

Sandwich Terns breeding in North Norfolk were more than capable of reaching all the OWFs in the Greater Wash on a regular basis in the breeding season during their search for larger prey in offshore areas over both deeper water and the shallow waters over the offshore sandbanks prevalent in the Greater Wash. As indicated above, at 22 km, the maximum distance from shore reached by Sandwich Terns in this study was far lower than the ~53 km recorded previously (Centrica 2009). Part of the difference may stem from the relatively limited amount of tracking in the current study. However, the timing of tracking may also have played a role with greater ranging behaviour earlier in the season during incubation or in early chick development. Especially in incubation, adults may wander widely when self-feeding and may conceivably develop a broad 'map' of suitable foraging areas that may be exploited later in the season. This may be particularly true for habitat specialist sandeels, which are dependent on sandbanks as refuge habitat during the hours of darkness. Even if sandeels range by day, they may be relatively more predictable to locate than truly pelagic clupeids. Nonetheless, clupeids may show preferences for areas where their zooplankton prey become concentrated, perhaps by tidal currents around upwellings created by rapid changes in bathymetry created by different substrates such as around large sandbanks such as Docking Shoal or Race Bank and outcrops of harder substrate such as Cromer Knoll. Importantly, previous studies have suggested that clupeids move inshore later in the season, which may reduce the range that Sandwich Terns have to travel to locate suitable prey (Centrica Energy 2009). This in turn means that the proportion of sandeels in chick diet declines in favour of clupeids as the season progresses (Centrica Energy 2009). In the Netherlands at least, the proportion of Herring in the diet is thought to underpin breeding success (Stienen 2006), and so the availability of clupeids including Herring appears to be of vital importance.

Boat-based surveys universally recorded higher densities of Sandwich relative to Common Terns during the breeding period from April to August for Sandwich Tern and from May to August for Common Tern in North Norfolk (Table 8). This is not unexpected given that breeding Sandwich

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[5] surveys from another OWF site, Triton Knoll, have not yet been been submitted into the planning system and are not available for inclusion here

Terns generally outnumber Commons by at least 5.7:1 (Centrica Energy 2008). In line with the patterns generated here and in previous studies (Centrica Energy 2008, 2009), the sites that collected the highest densities of Sandwich Terns in boat-based surveys are those that are closest to the colonies including Docking Shoal (Table 8). However, there are some anomolies in the observed patterns.

First, low densities have been recorded at Lincs and LID OWFs. This is in agreement with previous tracking data from Scolt Head (in 2006), the closest colony to these sites that showed birds appeared to be reluctant to cross the deepwater channel of Lynn Deeps, presumably as this offered little foraging opportunity (Centrica Energy 2008). A similar lack of terns (many were not identified to species but presumably were mostly Sandwich Terns according to the numbers present in colonies) was observed in aerial surveys in the breeding season (DTi 2006 – Fig. 2). The second anomaly was the relatively low density of Sandwich Terns recorded by boat-based surveys at Sheringham Shoal, when tracking amd modelling implied that birds from Blakeney Point would routinely reach the site. Notably, SCIRA (2006) recorded greater densities of terns (up to 1.43 ind. km^{-2}) in the adjacent but more easterly control, and it was speculated that most terns on flights from colonies missed the site as they headed for foraging grounds such as Dudgeon Shoal further offshore. However, the relative lack of birds may simply be an effect of inter-annual variation in the selection of foraging grounds, given that the distribution of shoaling clupeids shoals may vary on an annual, seasonal or even daily basis. Capturing such variation in boat-based surveys tracking over only a few days of effort is clearly problematic. Finally, it is of note that that only 1,250 and 1,650 pairs (i.e. 34% and 45% of the mean total) were present at Blakeney in 2004 and 2005 when Sheringham Shoal was surveyed. In contrast, from 2007-2009, virtually the entire, population was based at Blakeney Point (1800 and 2400 pairs respectively).

The latter point introduces the notion that the relative position of the two major colonies of Sandwich Terns some 20 km apart influences the relative ease with which Sandwich Terns access particular foraging areas, the frequency at which different OWFs may be encountered and thus which OWF(s) pose greater risk of collision (Fig. 87). In the current study at Blakeney Point, Sandwich Terns favoured the easterly quadrant when leaving to forage from the colony, with a tendency to avoid the westerly quadrant. This suggests birds were likely to encounter Sheringham Shoal OWF or even Dudgeon at much greater distance. In previous studies at Scolt Head lying to the west of Blakeney, undertaken on behalf of Centrica Energy (2008, 2009), flightlines of Sandwich Terns were focussed on northerly and westerly movements, with birds traversing Docking Shoal and reaching the more distant Race Bank OWF, as well as inshore areas towards the inner section of the Wash (Fig. 87). Considering all tracking data to date there is an impression that if both colonies were occupied, birds from each would tend to occupy more or less mutually exclusive ranges (Fig. 87). Even when only one colony is occupied, as in 2008, the pattern still appears to hold true, although there may be a tendency for increased overlap, suggested by some tracked birds reaching the easterly part of Docking Shoal (see Figs 42 and 43). The relative risk of a particular OWF is thus likely to change in relation to the occupation of a particular colony or colonies in any one year.

The low overlap in ranges of birds from different colonies even when one colony is unoccupied even when this is well within range of foraging birds from the other colony, seems likely to be linked to the profitability of foraging in particular areas. This introduces the intruiging possibility that Sandwich Terns judge which colony location is likely to offer the best foraging conditions in any particular year thereby underpining the switching in colony location of Sandwich Terns in North Norfolk (see 3.1.1 above). Whilst the location of sandeels may be relatively predictable, the distribution of clupeids at some time later in the season when it becomes critical for breeding success is intuitively much more difficult to determine. Possible cues that could be used by terns include patterns of tidal currents or the location of phytoplankton blooms in early season. These may then determine the location of the zooplankton prey of fish and thus the fish themselves later in the season. It is also not clear whether tidal currents shift in a predictable fashion, as would perhaps be expected from changes in the North Atlantic Oscillation (NAO). Stienen (2006) has recently shown that breeding success of Sandwich Terns is closely linked with the NAO in colonies in the Netherlands. Here, a positive NAO tends to lead to increased availability of young herring. No such trend of breeding success is apparent in Eastern England, although there is no separation of birds from the Farne Islands from those in North Norfolk in Stienen's analysis. Moreover, any effect may be much more subtle, with shifts between colonies in close proximity at least partly compensating for any changes in the NAO.

5.2.4 Flight behaviour of Sandwich and Common Terns

The current study provides further insight into the flight behaviour of both Sandwich and Common Tern, particularly in relation to the influence of activity patterns upon flight height and the prospects of collision at OWFs. However, care must be taken in interpreting general patterns from observations conducted over relatively few days without the full range of wind directions and strengths that are likely to influence flight height. Nonetheless, some patterns are thought likely to hold true in many circumstances.

In North Norfolk, inbound individuals of both species, typically carrying prey for presentation for chicks were generally recorded near sea surface at <1 m. This may have a role of reducing the visibility of individuals to would-be kleptoparasites, but as only Sandwich Tern appears to be particularly vulnerable to this behaviour, this seems likely to only influence the behaviour of this species. The alternative explanation of an aerodynamic benefit from reduced wind resistance near the sea surface, particularly into a facing wind thus seems to offer a more general explanation of this behaviour. Birds are likely however to return to the colonies at much greater height in the presence of strong offshore winds to increase flight speed back to the colony.

Outbound individuals of both species tended to fly at greater height. For Sandwich Terns in particular, which tend to attack prey from height, this appears to maximise foraging opportunity through the prospect of searching for prey immediately on leaving the colony. For Common Tern, the combination of inbound and outbound individuals and those engaged in other activities observed in transects near the colony produced similar proportions of birds in different flight heights compared to tracked birds. This was however, rather different for Sandwich Tern, with 16% >20 m in colony transects compared to 49% for tracked birds. Despite the bias towards relatively few individuals, the observations of tracked birds were taken to be more representative of behaviour at sea.

When at sea in the Greater Wash, even if Common Terns reached OWFs they would seem to be barely at risk from turbine strike as a result of spending 7% of time at >20 m. This accords with the overall mean value of ~8% from observations from boat-based surveys at the different OWF sites (Table 9). In some circumstances, even where Common Terns were recorded within the site the absence individuals within the strike zone meant that collision risk modelling could not be undertaken. Data from Teesside, where Common Terns foraged in a different manner, with some birds flying a considerable distance offshore, suggested a higher proportion (12%) of birds at potential risk height. This is similar to the highest values (to 15.5%) recorded at some sites in the Greater Wash (Table 9).

Table 9. Proportion (%) of Sandwich and Common Terns recorded in the strike zone (20-120m) at the different Round 2 OWFs in the Greater Wash compared to records (*n*=611 fixes for Sandwich Tern and *n*=245 fixes for Common Tern) from tracked birds in the current study.

Species		Site[1]				
	Current study	Docking Shoal[2]	Sheringham Shoal[3]	Race Bank[4]	Dudgeon[5]	Lincs[6]
Sandwich Tern	48	28.1	13.3	27.04	15.45	14.8
Common Tern	7	7.9	15.5	2.02	1.72	14.8

[1]Sites are arranged in order of mean distance from each of the main colonies of Sandwich Tern on the North Norfolk coast at Blakeney Point and Scolt Head, which also support Common Tern. Common Tern also breeds at a number of smaller colonies at varying distances from each OWF. Data for individual sites provided by [2]Centrica Energy 2008, [3]SCIRA Offshore Energy 2006, [4]Centrica Energy 2009, [5]Dudgeon Offshore Wind 2009, 2010, [6]Centrica Energy 2007.

The proportion of time (49%) that tracked Sandwich Terns spent at >20 m flight height within the potential strike zone of turbines in the Wash was considerably higher than that observed on boat-based surveys at any of the OWFs in the planning system in the Wash (Table 9). It was also considerably lower amongst tracked birds from Cemlyn (23%). It is difficult to reconcile these differences. Both boat-based surveys and tracking tend to provide a considerable proportion of records from relatively few days, usually in relatively good weather conditions, providing the potential for bias. There may also be some differences between observers particularly in relation to different platforms at which flight heights are estimated. Boat-based survey vessels offer platforms in excess of 5 m eye-height and comparison with structures of known height aboard the vessel, whereas observations from a RIB are virtually at sea surface, although with the advantage of generally being in close proximity to the bird and offering the possibility of estimating flight height from multiples of wingspan (~1 m). It is also clear that Sandwich Tern spends a high proportion of time around 20 m which may lead to consistent under- or over-recording relative to this flight height. There is also the possibility of tracked birds displaying some avoidance of the RIB by flying at greater height than would be typical. This does seem unlikely given that birds seemed to undertake normal behaviours including active fishing in the presence of the RIB and observers and that at any sign of any behaviour that could be construed as a response to the vessel, a greater distance was placed between vessel and bird.

On balance, perhaps the key difference that suggests tracked birds in this study are more likely to provide a more representative reflection of flight height in relation to risk in OWFs is that it was conducted on birds engaged in foraging. Observations suggest that in the presence of prey, Sandwich Terns may slowly circle at considerable height, even plunge-diving from >20 m. In the generally brief encounters in standard boat-based surveys birds are relatively rarely recorded actively foraging or actively fishing (9% actively foraging, 0.8% of which were carrying fish, Centrica 2008b). This does not mean to say that birds are not foraging whilst in general flight, but that this may be more difficult to determine.

Moreover, the radical difference in the proportion of birds at different heights in different sites (e.g. 13% at Sheringham Shoal vs 27-28% at Docking Shoal and Race Bank) should not necessarily be taken as some sort of definition of the use of the site (e.g. a ‘foraging site’ or a ‘commuting site’) and that birds will always be recorded undertaking these behaviours. The temporal and spatial patchiness of prey, especially clupeids, may mean patterns vary considerably from year to year. It may be more appropriate to define a generic proportion of birds in strike height, unless there is good data to suggest otherwise, with this value being somewhat higher than currently suggested by many boat-based survey assessments.

A relatively high proportion of birds at strike height in the absence of turbines may, of course, not be maintained in the presence of turbines, thereby reducing the risk of collision (see 5.3.4 below). However, given that very few constructed sites have overlapped with breeding terns (with the obvious exception of Scroby Sands in relation to Little Tern – Perrow *et al*. 2006), there is little data available to judge whether or not terns ameliorate their flight behaviour in the presence of turbines. Some insight into this question is provided by the work of Everaert & Stienen (2006) at Zeebrugge, where a mixed colony of Sandwich, Common and Little terns nesting on a peninsula is separated from the sea by a breakwater supporting turbines. Although this is a very different situation from an OWF with birds virtually forced to fly through the line of turbines to reach the sea, it does provide something of an extreme worst-case scenario. Here, in the two years of study between 87-92% of Sandwich Terns and 72-93% Common Terns left the colony and crossed the line of turbines below turbine blade height (<16 m).

Whilst it is difficult to translate this directly to the different height bands used in OWF assessments, for both species at least it appears that this is slightly lower than the transect data from North Norfolk in this study, which is most representative of birds in close proximity to the colony. In this, 84% of Sandwich Terns flew lower than 20 m. Assuming an equal distribiution of birds from 0-20 m, suggests that 67% of Sandwich Terns flew at 16 m or less. For Common Terns, the equivalent value would be 65%. Individuals of both species may thus show some tendency to fly at subtly lower height in the presence of turbines. Moreover, in other words less Sandwich Terns were seen at height relative to the proportion at sea and more

Common Terns were seen at height closer to the colony than when encountered at sea. The tendency of Common Tern to fly at greater height near the colonies, especially for the purposes of display, was noted by Everaert & Stienen (2006) as a factor leading to higher collision risk for Common rather than Sandwich Tern. Moreover, male birds are much more likely to be killed than females, linked both to their flight behaviour and a propensity towards display behaviours at height near the colony, and the tendency for males to spend more time foraging to provision the brood and their mate (Stienen *et al*. 2008). Whether or not terns showed some subtle avoidance behaviour reducing collision mortality, this was still considerable with 109 and 129 Common Terns killed in 2004 and 2005 respectively (Everaert & Stienen 2006). Mortality of the considerably more numerous Sandwich Terns (mean of 3,302 pairs cf. mean of 1,654 pairs of Common Tern) was lower at 54 and 30 individuals respectively.

Overall then, there is little evidence to suggest that when close to their colonies, terns significantly modify their flight behaviour according to the presence of turbines and the risk of mortality they carry. A similar conclusion was reached in a more offshore situation by Pettersson (2005) at the Yttre Stengrunden OWF in Sweden, where both Common and Arctic Terns passed through the site without deviation. The fact that these were birds on passage migration, where the risk of mortality would be predicted to far outweigh the negligible energetic cost of a minor deviation to a long migration route (Pettersson 2005), further illustrates a lack of perception of the risk involved. It is thus difficult to decribe terns as anything other than potentially vulnerable to collision. However, it is clear that much work is required to validate this viewpoint, both through observation of the response to turbines as well as derivation of avoidance and collision rates.

5.2.5 Collision risk

Despite the uncertainty regarding the response of terns to the presence of turbines, worthwhile insights can still be drawn on potential impacts as a result of improved understanding of likely passage rates by breeding terns though OWF space provided by the simulation model. By drawing several information strands together in a readily interpretable output, the simulation model is seen to provide significant enhancement in this respect (Fig. 10). This was however only undertaken for Sandwich Tern in North Norfolk in the current project (see 6. below) primarily because both Sandwich Tern from Cemlyn Bay and Common Tern in North Norfolk did either not forage at sufficient distance offshore to overlap with any OWF or did not show sufficiently direct flightpaths from colonies to make the destination predictable. Further, whilst Arctic Tern from the Skerries showed the potential to interact with the Round 3 zone in the Irish Sea, too little data was gathered in the trial tracking in 2009 for this to be modelled. Further tracking and model development in relation to Arctic Terns remains a possibility for future work (see 6. below). In contrast to other sites and species, the collision risk of Common Tern at Teesside could be calculated directly from the passage rate of birds across the site (see 5.2.5). The development of a model to predict the use of the OWF site may also have been hampered by the variation in flight path and the lack of an obvious destination in many cases.

Sandwich Tern in North Norfolk

For Sandwich Terns in North Norfolk, on the basis of information used to parameterise the model in 2008, it was apparent that OWFs[6] did not occupy the key foraging areas for Sandwich Tern, with just 2.8% of flights ending in foraging points in one site or another. Combined with predicted flyovers the total proportion of flights in which birds spent some time in the sites was 3.4%. This was slightly less than the 7.7% of tracked birds that were recorded in any site. It is of note that the same two OWF sites actually visited by tracked birds were suggested by the model to be the most likely to be selected, with these accounting for 95% of simulated endpoints/flyovers within an OWF.

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[6] modelling could not be applied to data from Dudgeon, which was only submitted into the planning system in 2010 after modelling was completed

Previous work highlights that patterns of foraging activity are seasonally variable, with a broader distribution of foraging locations extending further offshore earlier in the season during incubation and the early stages of chick development (Centrica Energy 2008, 2009). It is anticipated that if early-season data were available for 2008, a similar pattern would have arisen, generating more overlap between OWF locations and Sandwich Tern foraging patterns Nevertheless, it was still considered to be useful to demonstrate the value of the model in determining not only the relative importance of OWFs as foraging areas, but also how the outputs may also be used to guide collision risk modelling.

In broad terms, using the information gleaned across all monitoring effort, it was possible to estimate the total number of foraging flights made by the entire Sandwich Tern colony at Blakeney Point during the breeding season of 2008. Making the coarse assumption that the average hourly outbound passage rate recorded during colony transects was an accurate representation of daylight activity throughout the entire season (mid May to late July), it was estimated that some 1.18 million foraging flights were made overall. The foraging model estimated the proportion of these flights that have a foraging endpoint or flyover in each OWF (Table 2), suggesting for example, that 25,134 flights would cross at least part of Docking Shoal, with 12,272 for Sheringham Shoal and 1,652 for Race Bank OWFs. In principle, endpoints are likely to cross less of the site than flyovers, with, on average, the latter crossing the site twice (2FL), once on the way out and once on the way back. Assuming a random distribution of individuals reaching endpoints suggests that on average, an individual would cross half the site to feed and then the same half as it returned, to achieve the equivalent of one flight crossing (1FL). Folkerts (2008) calculated average flight lengths across the Docking Shoal and Race Bank relative to their position from both Scolt Head and Blakeney Point colonies. From Blakeney Point, this was 6.61 km for Docking and 5.54 km for Race Bank. An equivalent for Sheringham on 5^o flightlines from Blakeney was calculated to be 2.76 km.

A total distance travelled by Sandwich Terns across each site in the course of the season was then derived from the proportion of total estimated flights resulting in endpoints and flyovers to the different sites, combined with the average distance travelled in each of those flight types. For the Blakeney colony in 2008 this was estimated to be 177,055 km for Docking, 47,549 km for Sheringham and 11,113 km for Race Bank. From standard collision risk modelling, Folkerts (2008) derived an annual mortality per kilometre through Docking Shoal and Race Bank, which with layouts with 3.6 MW turbines were 2.39×10^{-3} and 2.29×10^{-3} respectively. For the broad purposes of comparison here and assuming a similar risk (even though this may not be supported by the collision risk modelling undertaken to date – SCIRA Offshore Energy 2006) a mid-value of 2.34×10^{-3} was used. Overall, this suggested an annual mortality of 423, 113 and 26 at 0% avoidance from Docking, Sheringham and Race Bank respectively. An appropriate avoidance rate of 99% avoidance (see Whitfield 2008) suggests mortality of 4.2, 1.1 and <1 individuals at these sites respectively. It must again be stressed that these are not suggested to be realistic values as the data from Blakeney Point in 2008 was limited to the end of the season and flights in the earlier part of the season are likely to be much longer, thereby encompassing OWFs further from shore.

Nonetheless, the process does show that by focussing on the individuals from breeding colonies, predicted collision mortality may be far lower than that derived from boat-based surveys encompassing birds in all seasons (Table 10). In fact, Folkerts (2008) demonstrated that collision estimates from the simulation model broadly followed those expected from boat-based surveys if only values from the breeding season were applied. In an example of Docking Shoal and Race Bank, 41.7% and 18.1% of the respective annual mortality was predicted by the foraging model using data from both Scolt (2006) and Blakeney (2007) colonies, compared to boat-based surveys. For Docking Shoal at least, this appeared to be broadly realistic as some 53% of passages were recorded outside the breeding season. In this case, the outputs from the simulation model rather closely resembled that derived from boat-based surveys, despite their rather different basis. In boat-based surveys, collision risk is derived by mean monthly density values where density is linked to passage rate through knowledge of flight speed and assuming a constant maintenance of density. Even with survey programmes over two (exceptionally three years) the number of surveys for each month is low leading to some vulnerability to abnormally low or high values on individual surveys. Poorly-timed (or conducted) surveys resulting in unnaturally low numbers of birds may grossly underestimate collision risk, whereas the chance encounter of large numbers of birds, for example on passage, may lead to overestimation of collision risk.

Table 10. Number of Sandwich Terns estimated to collide per annum with the worst-case turbine configuration assuming a 99% avoidance rate at the different OWFs in the Greater Wash, in comparison with that derived from the simulation model in 2006, 2007 & 2008. A combined colony figure simulating occupancy of both colonies is derived from a combination of data from Scolt Head 2006 and Blakeney Point 2007.

Assessment method	Site[1]					
	Docking Shoal[2]	Sheringham Shoal[3]	Race Bank[4]	Dudgeon[5]	Lincs[6]	Lynn & Inner Dowsing[7]
Boat-based survey	120[2]	12[3]	91[4]	38[5]	0[7]	0.01[8]
Foraging model Scolt Head, 2006	42[2]		12			
Foraging model Blakeney 2007	3[4]		0.4[4]			
Foraging model Blakeney 2008	4.2	1.1	0.3			
Foraging model (combined)	45		12.4			

[1] Sites are arranged in order of mean distance from each of the main colonies of Sandwich Tern on the North Norfolk coast at Blakeney Point and Scolt Head, which also support Common Tern. Common Tern also breeds at a number of smaller colonies at varying distances from each OWF. Data for individual sites provided by [2]Centrica Energy 2008, [3]SCIRA Offshore Energy 2006, [4]Centrica Energy 2009, [5]Centrica Energy 2007, [6]Dudgeon Offshore Wind 2009, 2010 and [7]Gill *et al.* 2002. [7]Collision modelling not undertaken as Sandwich Tern was not classified as a sensitive receptor at this site.[8]Collision modelling was undertaken for 'terns' as a generic group, although it is anticipated that the majority of these birds would be Sandwich Tern.

Moreover, whether or not birds outside the breeding season should be incorporated requires careful consideration. For example, Sandwich Terns encountered outside the breeding season in the Greater Wash may still relate to the SPA colonies in North Norfolk. But equally, these may be from other colonies not just in the UK but even from other North Sea coast colonies as there is some evidence of post-breeding dispersal of adult birds and their attendant juvenile offspring crossing the North Sea to Dutch and Danish waters and vice-versa (Wernham *et al*. 2002). To date, assessment has generally tried to attribute birds to particular locations often in relation to SPAs rather than simply refer to all individuals being likely to originate from SPA populations, wherever that may be. In fact, for several species of seabird, including terns, breeding populations are largely contained within SPAs.

Pooling data from all years suggests which breeding colony is occupied determines which OWF is likely to receive a greater proportion of flights and thus may broadly describe the relative risk of each OWF to breeding birds (Table 11). As outlined in 5.2.2 above, occupancy of Scolt Head suggests a relatively high proportion of flights through Docking Shoal with a far smaller proportion to the more northerly Race Bank, with some flights reaching the westerly OWFs of Lincs and LID. From Blakeney Point, Sheringham Shoal was predicted to become the most used site, although the proportion varied between years in accordance with the size of the dataset. In general terms, when Blakeney Point and not Scolt Head was the dominant colony, Docking Shoal appeared to reduce considerably in importance as a destination of flights. Very few flights were then predicted to reach Race Bank.

In conclusion, provided sufficient data is available to determine passage rates from the colony and there is sufficient confidence in the model output, which may be assessed through comparison with tracked birds, the simulation model appears to provide a sound basis for assessment and is seen as a useful adjunct to more standard collision risk modelling by specifically representing breeding birds. The basis of the model does, however, require species and site-specific information.

Table 11. The proportion (%) of Sandwich Tern flights expressed as foraging end points, flyovers and overall in each of the Greater Wash OWF sites as calculated from the simulation model applied to different colonies in different years. The 'combined colony' is a construct that assumes the colony is equally split between the two sites. Centrica Energy (2009) provided data for Scolt Head in 2006 and 2007, Blakeney Point (2007), and the combined colony.

Site[1] and year	Measure	Docking Shoal	Sheringham Shoal	Race Bank	Lincs	Lynn & Inner Dowsing
Scolt 2006	End point	5.09	0.85	2.87	2.21	0.67
	Flyover	26.03	3.14	4.80	1.85	1.00
	Overall	31.11	3.99	7.68	4.06	1.68
Scolt 2007	End point	2.74	0.91	1.49	0.96	0.08
	Flyover	34.36	3.15	1.75	0.87	0.23
	Overall	17.10	4.07	3.15	1.83	0.31
Blakeney 2007	End point	1.71	3.42	0.14	0.00	0.00
	Flyover	0.06	7.48	0.09	0.00	0.00
	Overall	1.78	11.24	0.24	0.00	0.00
Blakeney 2008	End point	1.99	0.68	0.11	0.02	0.00
	Flyover	0.14	0.39	0.03	0.00	0.00
	Overall	2.13	1.07	0.14	0.02	0.00
Combined colony	End point	3.25	2.25	1.39	1.01	0.31
	Flyover	11.90	5.69	2.24	0.84	0.46
	Overall	15.15	7.93	3.63	1.85	0.76

[1] Sites are broadly arranged in order of mean distance from each of the main colonies of Sandwich Tern on the North Norfolk coast at Blakeney Point and Scolt Head.

Common Tern on Teesside

Visual tracking of Common Terns originating from RSPB Saltholme provided what appeared to be sound basis for predicting collision risk associated with the Round 1 Teesside OWF. Little information appears to have been available on this issue to date. A similar approach had previously been adopted using radio telemetry data on Little Terns in relation to the Scroby Sands OWF immediately offshore of the Great Yarmouth North Denes SPA for the species. The predicted loss of 17 birds per annum at 98% avoidance constituted 2.8% of the 2009 population of ~300 pairs (Perrow *et al*. 2008)

Detailed studies of Common Tern on the North Sea coast in Germany suggest adult mortality rates as low as 7% (Nisbet 1978). At this rate, in the three months Common Terns tend to occupy the Saltholme colony, only 11 birds would be expected to die from natural causes. The predicted mortality from the Teesside OWF of 17 birds (at 98% avoidance) thus represents a 164% increase over and above background mortality during colony occupancy. Even if there is no attempt to partition the data between the months of occupancy and simply relate OWF mortality directly to the annual loss of 7% of the adult population (i.e. 42 birds), predicted mortality from the OWF is still clearly relatively high at 41% over and above annual background mortality.

In a discussion of collision mortality at Zeebrugge and what this meant for the populations of terns, Everaert and Stienen (2006) outlined that increases of between 0.5 – 1.0% additive mortality may significantly threaten population viability, with some models suggesting that population declines could occur with mortality increases of around 0.1% in long lived species. In the case of Common Tern at Teesside, 'additive mortality' from collision would be 2.8% of the population per annum. This immediately suggests that the population would be unable to sustain the level of mortality predicted from the Teesside OWF.

However, the outcome of increased mortality may be difficult to predict in any given scenario for various reasons. For example, in cases where breeding population size is limited by density dependent factors (e.g. competition for food and space) the population structure at any given time may include a surplus of non-breeding individuals. In such cases, increased mortality among breeding adults might allow a greater proportion of these 'surplus' individuals to breed, buffering the potential negative effect on population size and productivity. The use of population viability analaysis (PVA) is thus seen as a useful tool to understand the relative importance of collision risk mortality compared to other factors (Maclean *et al*. 2007). However, the quality of population data varies considerably between species and opinion may be divided on whether modelling of species where information is scant, is valuable or not.

A variety of commercial PVA packages are available to undertake PVA. Those using an individual-based (e.g. VORTEX - rather than a matrix-based approach are seen to be more valuable given the well-documented value of models based on individuals and individual behaviour (e.g. Sutherland 1996, Grimm 1999, Brook *et al*. 2000). Commercial software does however adopt a 'black-box' approach providing an output with extremely limited scope to understand how this was generated and how different parameters may interact. For this reason, it has been argued that a custom-built (bespoke) model in any given situation is likely to offer a greater depth of sophistication and understanding of important parameters (Mackenzie *et al*. 2009).

There is clear value in adopting PVA on the Common Tern population at Saltholme, perhaps coupled with further tracking work to verify the patterns observed and outcomes predicted from 2009 data. At this stage, with the considerable mortality predicted, it is difficult to see how the impact of the proposed OWF can be anything other than significant for the locally breeding population of Common Tern.

6. Concluding summary

6.1 Overview

The potential impact of OWF development on seabird populations is a key issue within the current debate on sustainable energy provision. In order to make meaningful predictions about the impacts of wind farm development and operation, a detailed understanding of the distribution, behaviour and ecology of affected species is a prerequisite. Terns are seen as sensitive receptors at a number of sites and zones around the UK.

The current project built on the extensive dataset detailing the foraging distribution and ecology of Sandwich Terns in the North Norfolk Coast SPA (see Centrica Energy 2008, 2009) before shifting focus to another SPA containing this species at Cemlyn Bay, Anglesey, as well as other species including Common Tern in North Norfolk and at RSPB Saltholme and undertaking a preliminary trial on Arctic Terns at the Skerries, a small offshore island group off the coast of North Wales.

During this project, further advances have been made toward making robust predictions about the impact of OWF development in a number of areas including the Round 1 Teesside OWF, the Greater Wash Round 2 development zone and the Round 3 Irish Sea Zone. The techniques developed in this study have considerable applicability at all stages of the planning and assessment process both before and after the construction of offshore wind farms. As well as being of value in the study of terns, the principles behind the techniques used may be applied to a variety of other seabirds. Specific details of the techniques developed are outlined in the sections below.

6.2 Visual tracking

The current project has seen the advancement of both empirical and analytical methods that are demonstrably effective in generating answers to key ecological questions linked to the impacts of OWFs. Foremost amongst the advances made is the continued development of the visual tracking methodology, allowing researchers to document the activity patterns of individual terns from the moment they leave the colony until the moment they return. This non-intrusive method has provided unparalleled insights into the foraging distribution of breeding terns, as well as their actual behaviour and foraging activity.

At Blakeney in 2008, a direct comparison of Sandwich and Common Terns revealed clear differences in foraging patterns and behaviours between the two species at this site. Common Tern specialised on small prey items such as young clupeids, selecting the latter as the dominant provision for chicks. A relatively high feeding rate was maintained with birds foraging at low flight heights (often <1 m above sea surface), using surface feeding in particular. Sandwich Tern exhibited a significantly lower feeding rate compared to Common Tern by using plunge diving from height and spending the majority of time during foraging bouts at >20 m above sea surface.

Sandwich Terns from Cemlyn Bay performed in a relatively similar manner to birds at Blakeney. Some differences in foraging rate were balanced by the size of items taken ultimately meaning that energy intake was similar. At both sites, invertebrates and larval fish (masked in the fraction of unidentified fish) were consumed at high frequency. Clupeids were captured more frequently in the Greater Wash off the North Norfolk Coast supplemented by sandeels, as suggested in the literature. Surprisingly, sandeels were the more numerous fish prey taken at Cemlyn, despite this being a rocky, deepwater coastline. Tracks and foraging activity of the birds suggested sandeels were likely to originate from the extensive coastal bays to the east of the colony.

Visual tracking showed that Common Tern to have considerable plasticity in foraging patterns with birds at Teesside behaving in a similar manner to Sandwich Terns by ranging to considerable distance (maximum of 17 km) from the colony and some way offshore (maximum of 10 km) whilst foraging over deep water (30-50 m). The capture and delivery of fish >20 cm in length to the colony, was comparable to that undertaken by Sandwich Terns at Blakeney Point and in contrast to Common Terns from the same colony. These patterns tentatively suggested niche differentation between sympatrically breeding terns and alternatively, competitive release for a species in isolation, such as Common Terns on Teesside.

Notwithstanding its potential limitations, especially in relation to quantifying the extent of larger scale movements (see Perrow *et al*. 2011 for further analysis of the factors influencing the efficacy of the method) visual tracking is a simple to undertake alternative to telemetry in particular circumstances. Although some authors report good results from telemetry amongst the small and medium-sized terns (<260g) (e.g. Perrow *et al*. 2006 - Little Tern, Becker *et al*. 1993 - Common Tern, Rock *et al*. 2007a - Common and Arctic Terns, Rock *et al*. 2007b - Roseate Tern *S. dougallii*), others report a range of problems (e.g. Massey *et al*. 1988 - Least Tern *Sternula antillarum*, Perrow *et al*. 2006 - Little Tern, M. Bolton *pers. comm*. - Roseate Tern, M. Lewis *pers. comm*. - Common Tern). Moreover, very few studies have unequivocally demonstrated that capture and subsequent attachment of devices had no effect on adult terns especially into the longer term (but see Klassen *et al*. 1992, Becker *et al*. 2001). Tagging thus carries a mostly undefined risk of an adverse effect on individual fitness that is shared amongst a small number of individuals. Even if the effect upon individual fitness resulting from visual tracking is also unknown, this is intuitively smaller as this is restricted to a single foraging bout in the worst-case.

Visual tracking may be readily adapted to specific circumstances (e.g. particular sea conditions or birds travelling at particular speeds) by use of different combinations of vessel type and size (RIBS are available up to 12 m length or so) and means of propulsion (outboard vs. inboard, single vs. twin engines) and engine size (upwards from a minimum of 150 HP). As well as terns there is also considerable scope for the extension of the methodology to other species such as small to large gulls (Laridae) and skuas (*Stercorarius* sp.).

In this study, visual tracking was used in its simplest form of generating a series of flight tracks to define the likely overlap between breeding terns and a particular OWF. In the cases investigated it was clear that breeding Sandwich Terns had considerable potential to overlap with OWF sites in the Greater Wash, but not with the Round 3 zone in the Irish Sea, although

Arctic Terns had the potential to do so. Conversely, breeding Common Terns did not show any potential to overlap with sites in the Wash, but overlapped considerably with the OWF at Teesside, partly as this site is close to shore and terns commute some distance (6.5 km) to reach the sea from their inland colony at RSPB Saltholme. The use of tracking may thus prove effective in scoping the potential for interaction at the inception of a project and may be used in conjunction with standard survey methods such as boat and aerial surveys in the site characterisation phase. Where there is a single-species (or few similar species) focus to such monitoring, visual tracking may even be used as a stand-alone approach to monitoring in preference to telemetry.

As birds may be particularly readily tracked over relatively short distances (Perrow *et al*. 2011), visual tracking may be particularly useful in relation to the study of impacts of specific OWFs to establish the behavioural response of terns to turbines and even avoidance rates. With sufficient sample size, rates of collision may then be quantified. Such an approach is currently being developed at Sheringham Shoal, one of the OWF sites in the Wash, prior to its construction. As current limited evidence suggests that terns do not tend to deviate from OWFs unlike other groups (Pettersson 2005, Petersen *et al*. 2006), the rate at which terns avoid collision may prove to be relatively low (Chamberlain *et al*. 2006).

Furthermore, a number of workers have recently demonstrated the value of tracking data combined with some form of relatively sophisticated bird:habitat association modelling to define areas used by foraging seabirds (e.g. Skov *et al*. 2007, Louzao *et al*. 2009). This builds on the similar approach used for boat-based transect data (Louzao *et al*. 2009, Schwemmer 2009). Visual tracking potentially provides a suitable means of establishing important foraging areas for terns around existing SPA colonies to meet obligations under the EC Birds Directive. Indeed, the JNCC have recently adopted visual tracking in an attempt to do just this at a number of colonies including Cemlyn Bay, Leith Docks, the Farne Islands and Coquet Island.

Clearly, the value of such an approach relies heavily on the strength of the relationship between some parameter of bird activity such as feeding records and specific habitat variables. At Cemlyn, the fact that Sandwich Terns were concentrated in a coastal strip suggests such an approach may be valuable. Otherwise, a bird:habitat modelling approach may be limited by the wealth of apparently suitable habitat available. In the Greater Wash for example, unless birds were closely coupled with specific variables such as changes in bathymetry leading to surface turbulence which could also be accurately described at high resolution (see Schwemmer 2009), an individual-based approach based on relatively simple parameters such as flight bearing and distance such as that adopted in this study would likely prove to be more profitable.

6.3 Colony observations

Observations at the colonies were undertaken simulataneously with visual tracking to confirm the nature of chick provisions and provisioning rate, and in the case of Sandwich Terns, the rate of kleptoparasitism from Black-headed Gulls. This data generally enhanced understanding of foraging patterns and behaviour. Observation of flight direction and passage rates using both observers at the colony (Cemlyn Bay and Salthome) and on a vessel just offshore of the colony (Blakeney Point) were also undertaken to underpin the various modelling approaches, as well as to provide insight into the influence of different environmental variables on tern foraging behaviour.

Species and colony-specific variation in passage rate (inbound and outbound) and activity patterns showed there was no fixed pattern for foraging terns. Variation in the activity patterns of different prey in different locations was thought likely to be important in this respect. For example, high water appeared to be important for both Sandwich and Common Tern activity in North Norfolk. Wind direction was also important for Common Terns in this case, with a combination of high water and wind directions that favoured swell and turbulence potentially bringing small prey to the surface close to shore. This appeared to be of no importance for Sandwich Tern foraging at greater distance offshore. At Teesside, the pattern was effectively reversed with an increase in passage rate of Common Tern at low water or on flooding tides. This appeared to relate to prey becoming trapped in pools as well as the movement of fish into the estuary on a flooding tide. Similarly, Sandwich Tern passage from the colony increased at low water at Cemlyn, which may have been related to the increased exposure of prey in the shallower coastal bays of this otherwise deep-water environment.

Overall, for Sandwich Terns in particular, there was a general suggestion from the often relatively weak relationships that adults sought to attempt to provision chicks irrespective of the state of the tide or time or day, perhaps varying selection of prey type or size at sea to compensate for differences in activity patterns of their prey.

6.4 Modelling approaches

Different modelling approaches were developed from the data gathered during visual tracking and colony observations to ultimately help quantify the use of coastal waters by terns and define the potential impacts of some specific sites around the UK. This included an energy balance model for Sandwich Terns to further understand the drivers behind foraging ecology of terns, including how far birds could travel from colonies. A previously developed simulation model of foraging distribution was applied to data gathered in this study on Sandwich Tern at Blakeney Point. A demonstration of how the model could be adapted to generate data that may be used in collision risk modelling of breeding birds (e.g. from important colonies) in isolation was also conducted. Finally, a worked example of how data gathered during visual tracking (on Common Terns at Saltholme) could be used in collision risk modelling was also provided.

6.4.1 Energy balance modelling

The energy balance modelling undertaken illustrated the value of data gathered during visual tracking to understand the dynamics of foraging strategy during breeding, and hence the factors that might influence at-sea foraging range. Data collected during tracking on prey capture rates combined with energy content estimates derived from previous research, allowed the development of meaningful models to predict the optimality of different provisioning strategies for both chicks and adults. These predictions correlated closely with observed patterns of prey size selection.

Fundamentally, the utility of the models was underpinned by the close relationship between prey item size and capture rate. In all cases, prey species conformed strongly to the prediction that capture rate would decrease in relation to item size, such that larger prey items required longer foraging search times. The minimum size of item that an individual selected for provisioning could therefore be used to predict the likely time spent searching on each foraging bout (weighted by capture probability distributions for all prey items exceeding that minimum threshold size). Given the generally linear nature of Sandwich Tern foraging flightpaths in North Norfolk, search time was used to predict the distance from shore likely to be reached on each foraging bout. As such, it was possible to meaningfully model at-sea foraging range as a function of the minimum size selection threshold adopted by any given tern.

Arguably the most important outcome of the modelling exercise was the prediction that at-sea foraging range might be partially dependent on the intensity of kleptoparasitism within the colony by Black-headed Gulls. This relationship is mediated by the relative disadvantage of selecting larger prey items under threat of kleptoparasitism, given that kleptoparasites selectively target carriers of large prey items. The model predicts that at low levels of kleptoparasitism, the optimal trade-off between chick provisioning and adult energy balance could be achieved by adopting a relatively high size selection threshold, and consequently making fewer, longer foraging bouts. At high kleptoparasitism levels, the opposite outcome was predicted to arise, due in part to the increased risk of loss of large items, as well as the overall impact of prey loss on energy provisioning rates to chicks, meaning that adults would be required to trade-off their own energy balance in order to meet the minimum growth requirements of chicks. In this case, adults were predicted to adopt a lower minimum size selection threshold and consequently make shorter, but more frequent foraging trips.

The size distribution of prey items observed being brought into colonies in North Norfolk conformed closely to that predicted by the model based on two separate minimum size selection thresholds (6 cm and 9 cm) being adopted by the population. It is likely that within any Sandwich Tern population, there would be considerable individual variation in size selectivity for provisioning, with multiple strategies being adopted across the population at any given time, either in response to kleptoparasitism risk or other factors.

When the model was used to predict the likely offshore foraging range of individuals adopting these optimal thresholds, the predicted values (4-38 km with intermediate level of kleptoparasitism) broadly matched the offshore distances recorded during visual tracking. Under more extreme scenarios the model suggested that the upper limit of Sandwich Tern foraging in North Norfolk is between 60-74 km. This bears a close resemblance to that suggested from aerial surveys, but is ~2-fold higher than the range suggested by outputs of the foraging radii approach generated from the literature. Overall, 75 km is suggested as a suitable guide to define the potential foraging range of Sandwich Tern from breeding colonies.

Model outputs strongly suggested that variation in size selection strategy was likely to be related to the outcome of a trade-off between chick provisioning and adult energy balance. In particular, this trade-off is likely to be influenced by kleptoparasitism intensity, as discussed above. However, various other factors could also influence the outcome of this trade-off, including the fitness or experience of the provisioning adult, environmental conditions (weather) and changes in the abundance, availability or spatial distribution of prey.

6.4.2 Simulation foraging modelling

The simulation model based on flight bearing-foraging distance relationships generated in previous studies of Sandwich Terns in North Norfolk was populated with data specifically generated in 2008 in this study. This provided outputs that mirrored tracking of individual birds and broadly agreed with previously described patterns (see Centrica Energy 2008, 2009), notwithstanding that only the late-season period was covered when the distance travelled by foraging birds may be reduced. Compressed activity nearer the colony may have reduced potential error in the model output as a result of greater deviance from the initial course than had been previously recorded for Sandwich Terns.

Outputs from the model suggested that two OWFs (Sheringham Shoal and Docking Shoal) would fall within range of birds from Blakeney Point in 2008, mirroring the results of tracking. This again illustrated the validity of the approach and suggested a variety of uses of the approach such as highlighting the relative importance of habitat lost as a result of OWF development or conversely, defining important areas for terns including offshore SPAs. A worked example of the use of the model in defining collision risk for breeding birds relative to other portions of the wider population, showed that this may be substantially lower than that provided by boat-based survey data.

The sort of simulation modelling conducted in this report may conceivably be readily adapted to other situations and other species. In particular, some form of fractal analysis of tracking data could be used to establish a series of modelling rules to be followed by individual simulated birds. This would enable modelling of terns, such as Common and Arctic Terns that seemingly tend to adopt more of a 'random-walk' foraging approach, adapting to circumstances as they arrive. Such a pattern may be more typical of shorter-range foraging, compared to the more direct, long-range movements of Sandwich Tern in particular circumstances.

6.4.3 Collision risk modelling

Standard collision risk modelling (Band 2000, Band *et al*. 2007) was readily applied to tracking data for which an estimated passage rate across the area of interest could be generated. The results of modelling performed on Common Terns at Teesside suggested that at 98% avoidance, it appeared likely that the relatively small local breeding population (300 pairs in 2009) would be unable to sustain the predicted losses. PVA could be used to more definitively outline the nature of the response of the population over the longer term.

6.5 Recommendations for further work

There are a number of themes that would benefit from further work including: 1) tracking of particular species at key sites, 2) determination of the response of terns to OWFs, 3) definition of avoidance rates and rates of mortality of terns at constructed sites, 4) development of PVA to predict longer term impacts upon particular species at particular sites, and 5) further understanding of the linkage between terns and their fish prey. Brief scopes of work are outlined below in relation to more specific recommendations upon particular sites and species.

Repeating the scope of works already undertaken in this study, namely visual tracking supported by colony observations is recommended in relation to development of particular OWFs. A clear candidate for this would be tracking of Arctic Terns from the Skerries, part of the Ynys Feurig, Cemlyn Bay and Skerries SPA on Anglesey in North Wales, in relation to the development of the Irish Sea Round 3 zone. The current study demonstrated that Arctic Terns are amenable to tracking and that birds from the 2,000 pairs strong colony have the potential to reach the zone. The relative importance of waters at some distance from the colony compared to the tidal rips and races that are a feature of the islands remains unknown however. Tracking in the manner outlined throughout the breeding season (May to July inclusive), coupled with observations of provisioning within the colony and the use of a second vessel following a transect route circumnavigating the island to estimate passage rate and activity patterns (this cannot be effectively achieved by observations on the island) is recommended.

A second specific use of visual tracking and colony observations would be to repeat the work previously undertaken (in 2009) on Common Terns at Teesside in 2011 and 2012 (and perhaps beyond), both during the construction phase of the Teesside OWF and into its subsequent operation. It is thought vital for the future of the RSPB Saltholme colony to understand the impact of the Teesside OWF upon breeding Common Terns, not only in terms of collision mortality (see below) but also the impact upon foraging patterns and ultimately breeding success during construction and in operation of the site. Prior to initiating further tracking at Teesside there is clear value in undertaking bespoke PVA to determine the population impact of the level of mortality that is predicted from collision risk modelling generated from visual tracking data gathered to date. Use of the bespoke approach undertaken for the North Norfolk Sandwich Tern population (Mackenzie *et al*. 2009) is recommended.

Effective risk assessment of the Teesside OWF and indeed any OWF is currently limited by a lack of detailed information of the response of terns to wind farms and definitive avoidance rates for any species. Visual tracking of terns is recommended to determine the response of birds to turbines and, with sufficient sample size, actual avoidance. Monitoring before-and-after construction is especially useful as it is more likely to provide clear evidence of the nature of the response of the birds in a wider context. Such an approach is currently being adopted for Sandwich Tern at the Sheringham Shoal OWF in the Greater Wash. Here, birds are not being tracked from distant colonies, but simply from a relatively short distance (1-2 km) away from the OWF site, although the distance involved is designed to be far enough away to mean that birds have not already begun to respond to the presence of the OWF by changing flight direction or flight height. Birds on a course to cross any part of the site are tracked with all behavioural aspects recorded until they have left the site. This relatively short-distance tracking has the chance of generating a large sample size of 100s or even 1000s of tracklines given enough effort. In order to generate sufficient sample size at Teesside, it may be necessary to supplement tracking of birds as they enter the estuary (as adopted in 2009) with further short-distance tracking across the OWF site.

Given the importance of the issue, the paucity of information and the lengthy timescale to achieve a before-after comparison, it is also valuable to undertake post-construction monitoring at built sites. Sites that experience considerable tern traffic include Scroby Sands of relevance to breeding Little (at Great Yarmouth North Denes) and Common Terns (at Breydon Water) and passage Sandwich Terns, and Lynn & Inner Dowsing (LID) for Common and Sandwich Terns on passage (with the additional prospect of some use by breeding Sandwich Terns). Again, it is recommended that short-distance tracking using RIBs be used to generate the most detailed information. At each site, careful timing of sampling is essential to maximise data collection. In the case of these two sites, both may benefit from sampling in April to collect birds on spring passage, with greater effort at Scroby between May and late June in the main breeding period of Little and Common Terns followed by more intensive effort at LID from July onwards as all tern species disperse from colonies in North Norfolk. It thus seems plausible that these two sites could be combined within one programme of work, perhaps using the same team and vessel transporting between North and East Norfolk.

Finally, it is recommended that an attempt be made to measure the abundance and distribution, both in spatial and temporal terms, of the fish prey of terns at selected colonies, following the intensive trial undertaken in the Greater Wash (see Centrica Energy 2009). Such work would be valuable for two reasons. The first would be to further understanding of the relative importance of different areas for terns and explain and verify patterns observed in modelling. The second, perhaps more pressing need for this work, would be to define the nature and extent of indirect or trophic impacts of OWF development.

In relation to the latter, whilst an impact upon fish is frequently anticipated, there is generally little to no linkage between birds and their fish prey during EIA. This is partly because any fisheries monitoring is often not targeted at prey of importance to birds such as shoaling clupeids or sandeels despite the fact that the former is deemed to be particularly sensitive to construction noise. Previous work in the Greater Wash by Centrica Energy (2009) attempted to monitor the relative abundance of such prey in different parts of the Wash by undertaking multiple short trawls using two types of net, a commercial trawl and a smaller, custom-built trawl. This was broadly successful in illustrating differences between different areas of the Wash and most importantly that shoaling clupeids, particularly Sprat, may undertake large inshore movements towards the end of the tern breeding season, which had considerable implication for foraging patterns and probably breeding success of terns.

However, sampling in the manner outlined suffers from the problem of low coverage at relatively high expense. Consequently, an approach of using acoustic fisheries surveys carried out using multibeam or swath echosounders to generate indices of fish abundance across wide areas that may also be matched to specific habitat variables, is suggested. Some sampling with suitable trawl gear would be required to confirm the type and size of fish present especially where these occur in dense patches (shoals) and to enable calibration of target strength in order to provide a measure of stock density. The Greater Wash, in which a number of sites are under development, would seem to be the most appropriate target for further fisheries work.

As well as illustrating the nature of the resource available to birds and how this is distributed in time and space, monitoring before and after OWF construction would aim to illustrate the importance of indirect effects. At present, only the study at Scroby Sands provides some indication of how changes in fish abundance and distribution tentatively linked to construction of the OWF, may impact on the foraging patterns (range and feeding rate) and diet of provisioning terns. In this case, this was Little Terns at the Great Yarmouth North Denes SPA (Perrow *et al*. 2006, 2008). Decline in the food resource was linked to discernible impacts at a colony level. In the absence of continued monitoring at this site, it is unknown whether the abandonment of the colony in 2010 for the first time in its 25-year history, was linked to possible ongoing issues in the recruitment of prey fish or other factors. A repeat of the specific sampling programme in 2011 some seven years after construction and five years after the termination of the specific sampling programme would be desirable. In this case, the same methods developed at the site would be best utilised, including use of the tow net developed specifically to sample the young fish taken by Little terns, specific work on the ranging behaviour of Little terns through radio telemetry and observations of foraging rates (also undertaken from shore) and provisioning rate to chicks in the colony.

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