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**Manx shearwater *Puffinus puffinus* evening rafting behaviour around colonies on
Skomer, Rum and Bardsey:**

**its spatial extent and implications for recommending seaward boundary extensions to
existing colony Special Protection Areas in the UK**

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1 Summary

The EU Birds Directive (79/409/EEC) provides a legislative framework for the protection, management and control of naturally occurring wild birds of EU Member States. As part of the implementation of the Birds Directive in the UK, JNCC is currently undertaking work to contribute to the identification of the most suitable areas for consideration as Special Protection Areas (SPAs) for birds in the marine environment. This work is being carried out on behalf of UK government and the nature conservation agencies (Natural England (NE), Scottish Natural Heritage (SNH), Countryside Council for Wales (CCW), and, in Northern Ireland, the Council for Nature Conservation and the Countryside (CNCC).

One strand of this work is the identification of seaward extensions to existing seabird breeding colony SPA boundaries, which are currently bound by the mean low water mark (mean low water springs in Scotland). This report presents recommendations in support of setting of site-specific seaward boundary extensions to three SPAs which have been designated for their internationally important concentrations of Manx shearwaters *Puffinus puffinus*, namely the Skomer and Skokholm SPA, Rum SPA, and Glannau Aberdaron and Ynys Enlli/Aberdaron Coast and Bardsey Island SPA. These SPAs include the UK's three largest Manx shearwater colonies, together hosting up to 90% of the world's population.

Any seaward boundary extension to an existing seabird colony SPA should include marine areas on which the existing interest feature (in this case, breeding Manx shearwaters), are ecologically dependent. Breeding Manx shearwaters regularly form aggregations at sea (called rafts), up to 10km from the colony shore in the evening, prior to coming ashore to feed the chick after night-fall. Although the function of rafting is not known for certain, it is clearly an important behaviour, given the number of birds that engage in it, and the fact that rafts are regularly formed around the colony. It is not possible to use conventional visual survey techniques to assess the locations of rafting birds (primarily because rafts are formed in the evening through to nightfall). This report describes work using radio-telemetry to locate key areas used regularly in the evening by rafting Manx shearwaters around the three breeding colonies of Skomer (south-west Wales), Rum (western Scotland) and Bardsey (west Wales).

Fieldwork was carried out between July and August, in 2003 (Skomer), 2004 (Rum) and 2005 (Bardsey), with radio-tags fitted to 30, 28 and 30 breeding adults at each colony respectively. Radio-tracking was carried out from early evening until birds returned to their colonies after nightfall, and locations of rafting birds were generated through analysis of radio-tracking data. Radio-tracking was found to be an appropriate and useful way of determining the spatial extent of Manx shearwater rafts, although there were some limitations to the data. The growth of chicks from tagged adults over the study period indicated that radio-tags did not significantly affect the adult's ability to adequately provision their chick on Bardsey or Skomer, but may have done to a small extent on Rum.

Based on kernel analysis of the rafting locations of tagged birds, we recommend a seaward boundary extension of 4km for Skomer and Skokholm SPA, 6km for Rum SPA and 9km for the Bardsey Island part of the Glannau Aberdaron and Ynys Enlli/Aberdaron Coast and Bardsey Island SPA. For any other SPA for which Manx shearwater is a designated feature, we recommend a seaward boundary extension of at least 4km, or possibly further if future investigation suggests so.

2 Introduction

2.1 Special Protection Areas in the marine environment

In 1979, the European Community adopted the Council Directive on the conservation of Wild Birds (79/409/EEC) (the Birds Directive), which relates to “the conservation of all species of naturally occurring birds in the wild state in the European territory of the Member States to which the treaty applies” (EEC, 1979). Article 4 of the Birds Directive provides for the establishment of special protection areas (SPAs) for those species of bird listed in Annex 1 (Article 4.1) and for regularly occurring migratory species (Article 4.2)

The Directive states that the protection requirements of these species should be met in “the geographical sea and land area” of Member States (EEC, 1979), but despite the fact that SPAs exist for many inland and coastal areas, most SPAs do not extend further than mean low water mark (or mean low water springs in Scotland). This gap in coverage is currently being addressed by the Joint Nature Conservation Committee (JNCC), by considering three potential types of marine SPA (Johnston *et al.* 2002):

- (1) Marine extensions to existing seabird colony SPAs (e.g. McSorley *et al.* 2003);
- (2) Inshore areas used by marine waterbirds (e.g. seaduck, divers and grebes) outwith the breeding season (e.g. Webb *et al.* 2005a, Webb *et al.* 2005b, Webb *et al.* 2006a, Webb *et al.* 2006b); and
- (3) Offshore areas used by wide-ranging seabirds, probably for feeding but possibly for other purposes.

This report presents data in support of the first strand of work, namely seaward extensions to existing breeding colony SPA boundaries. It builds on already completed work, recommending boundary extensions to northern fulmar *Fulmarus glacialis*, northern gannet *Morus bassanus*, common guillemot *Uria aalge*, razorbill *Alca torda*, and Atlantic puffin *Fratercula arctica* breeding colony SPAs (McSorley *et al.* 2003 and McSorley *et al.* in prep.). These generic seaward boundary extensions were recommended on the basis of data collected from boat-based surveys around a sample of colonies aimed at identifying the extent of the sea areas that were used for maintenance behaviours such as preening, bathing, and displaying. However, there are a number of species whose colony-based aggregations could not readily be identified by this method. One such species is the Manx shearwater, a wide-ranging, migratory seabird that breeds in the UK. During the breeding season, Manx shearwaters form aggregations (‘rafts’) at sea in the evening, prior to returning to their colonies once night has fallen. These rafts are formed between one and ten kilometres from the colony (Brooke 1990). This report describes work using radio-telemetry to locate key areas used regularly in the evening by rafting Manx shearwaters around the three largest breeding colonies in the UK, and on the basis of these data, makes recommendations for marine extensions to these existing terrestrial SPAs for this species.

2.2 The conservation status of the Manx shearwater in Great Britain and Ireland

The Manx shearwater is a pelagic seabird with approximately 88.7% of the biogeographic (world) population breeding in Great Britain (GB) and Ireland (Table 1). The remainder

breed in the Faroe Islands, Iceland, Portugal, Spain and France, with a very small number in Canada (in decreasing order of breeding population size; Mitchell *et al.* 2004). The four main breeding colonies in the UK, which together comprise 99% of the GB population, each exceed the 1% biogeographical threshold, thus qualifying as SPAs under Stage 1.2 of the SPA selection guidelines (Table 1 and Stroud *et al.* 2001). Nesting Manx shearwaters are especially vulnerable to mammalian predators, particularly the brown rat *Rattus norvegicus*, although avian predators such as gulls, in particular the great black-backed gull *Larus marinus*, and great skua *Stercorarius skua* may also impact on breeding populations (Brooke 1990; Newton *et al.* 2004).

Table 1. Manx shearwater population size estimates (Apparently Occupied Sites, AOS). All estimates are adapted from Mitchell *et al.* 2004 except Copeland Island, which is the ASSI cited population estimate, Ian Enlander (Environment Heritage Service (EHS), N. Ireland) *pers. comm.*

	Population Size (AOS)	95% CL	Percentage of biogeographic population
Biogeographic Great Britain	338,000 – 411,000		
Ireland	295,089	277,803-313,263	67.6-92.7% ²
SPAs			
Rum	37,178	27,269-60,804	6.6-18.0% ²
Skomer, Skokholm and Middleholm	120,000	107,000-134,000	26.0-39.6% ²
Aberdaron Coast and Bardsey Island	151,000	148,024-153,968	36.0-45.6% ²
St Kilda	16,183	16,183 (Upper CL only)	3.9-4.8% ³
Potential SPAs			
Copeland Island	4,803	3,371-5,687 ¹	0.8-1.7% ²
	4800	-	1.2-1.4% ³

¹CL for Hirta population (4581) only; ²based on the lower/upper CL expressed as a percentage of the highest/lowest value of the biogeographic population estimate; ³based on the actual estimate expressed as a percentage of the highest and lowest value of the biogeographic population estimate.

2.3 Breeding ecology of Manx shearwaters

Manx shearwaters are migratory, spending the winter in the south Atlantic, and returning to their breeding colonies in Britain and Ireland from late February (Brooke 1990). Each breeding pair excavates a burrow and underground nest chamber (or use burrows previously excavated by other shearwaters, puffins, or rabbits *Oryctolagus cuniculus*), in which a single egg is laid during May (Brooke 1990). Incubation is carried out by both parents with male shifts lasting on average 7.27 ± 2.02 days and female shifts lasting on average 5.83 ± 1.79 days (data from Skokholm in 1975 and 1976; Brooke 1990). Hatching occurs during late June to early July, when one of the parents attends the newly hatched chick continuously for approximately one week (Brooke 1990), after which time the parents return only at night to feed it. Most foraging trips last 1-4 days (average 1-2 days), although they can be occasionally longer (Gray & Hamer 2001). It is therefore likely that a chick will be fed most nights by at least one parent (one feed every 1.2 nights; Brooke 1990).

In common with other Procellariiformes (shearwaters, petrels, albatrosses), Manx shearwater chicks accumulate large fat reserves, often rendering them heavier than their parents. Fat accumulation by Procellariiformes probably acts as a buffer between the long foraging trips of the adults and chick starvation (Hamer & Hill 1997). In the 10 days prior to fledging (chicks fledge approximately 71 days after hatching, in early September), feeding frequency and meal mass decline steeply (Hamer & Hill 1997) causing the chick to lose weight to enable them to fledge.

2.4 Evening rafting behaviour of Manx shearwaters

Prior to dusk during the breeding season, adult shearwaters assemble in flocks or 'rafts' on the surface of the sea 1-10 km from the colony shore (Brooke 1990). When darkness falls, these 'rafting' birds, of up to 10,000 individuals, fly to their burrows to feed their chicks, regurgitating partly digested fish. Returning to the colony after nightfall in Procellariiformes is thought to be a predator avoidance strategy, and attendance at the colony may be reduced on moonlit nights, when predation risk is higher (e.g. Mougeot & Bretagnolle 2000). The function of evening rafting behaviour is not known for certain, but it is thought to be due to the fact that the birds forage at large distances from the colony and cannot precisely time their return to the colony to coincide with nightfall, so they assemble to wait until it is safe to land (Warham 1990). Rafts may also provide an arena for courtship behaviour and other social interactions, as well as maintenance behaviour such as preening and resting (Warham 1996). Rafts, which can include thousands of birds, are formed on most evenings during the breeding season, and likely include both breeding and non-breeding birds (Brooke 1990, Furness et al. 2000).

Relatively little research has been carried out on the use of the waters immediately adjacent to breeding colonies by Manx shearwaters. Brooke (1990), states that rafts form between 1-10km from the colony, but does not cite any evidence to support this. RSPB (2000) proposed a marine extension to existing breeding Manx shearwater colony SPAs of 15km, based on a precautionary approach to Brooke's 1-10km figure. The current research is the first to attempt to accurately quantify waters important for this evening rafting activity.

JNCC has carried out two boat surveys around the islands of Skomer and Skokholm in June 1990 and June 2001, which targeted a number of seabird species, including Manx shearwater (Stone *et al.* 1990 and McSorley *et al.* 2003). The first was designed to determine foraging ranges, with transects extending out to 45km from the colonies, while the second was to specifically look at colony-based aggregations, and only extended out to 5km. The boat surveys in 1990 found that early morning rafts of Manx shearwaters were formed 5-10km from the colonies, dispersing after 09:30. Over the five days of survey in 2001, only 19 Manx shearwaters were detected, with no rafts observed. Both surveys were conducted from early morning to mid afternoon, so neither coincided with the timing of the formation of evening rafts. Although rafts of Manx shearwaters can form offshore from colonies during the day, these diurnal aggregations, like those observed during 1990, are not considered in this report; identification of locations for consideration as SPAs for such aggregations of shearwaters will be addressed separately, through analysis of an extensive database containing data on diurnal aggregations of seabirds (the European Seabirds at Sea (ESAS) database).

Other data relating to colony-based Manx shearwater rafts are largely anecdotal, and no detailed studies have been done investigating the fine-scale distribution of rafting birds around colonies. There is currently a project being carried out using radio-tags on breeding

Manx shearwaters at Copeland Island to assess rafting distributions but data from that study are yet to be published (Ian Enlander, EHS, *pers. comm.*).

2.5 Aims and objectives

The work described in this report aimed to establish whether Manx shearwaters breeding in existing colony SPAs, make regular use of marine areas adjacent to their colonies, to form evening rafts. If this can be established, such areas could also be accorded protection under the Birds Directive, by inclusion of these areas within the existing SPA.

The specific objectives of this project were:

1. to determine whether breeding Manx shearwaters regularly use the waters adjacent to the study colonies in the evening;
2. to identify the locations of rafts on the water;
3. to determine any effects of burrow location and time of evening on raft location;
4. if (1) and (2) are positively established, to recommend possible seaward extensions to existing terrestrial breeding colony SPAs to encompass evening rafting distributions.

3 Methods

Individual breeding birds were tracked using radio-telemetry, to determine the location of rafting birds and to assess how regularly rafts were used. Other, more traditional, visual survey methods were not suitable for the following reasons: land-based counts have only limited coverage of the sea around colonies (up to approximately 2-3km from the shore), while boat-based or aircraft-based surveys may disturb rafting birds, possibly causing them to move location; most importantly, due to the timing of rafting behaviour (from evening until after dusk), such visual observations have limited use and are also greatly affected by the sea and weather conditions.

3.1 Study colonies and timing of visits

Ideally, the location of rafting birds should be investigated over several breeding seasons at all four SPAs supporting the species in the UK. This was not possible for this project due to financial, time and logistical constraints. Instead, the locations of rafting birds were investigated at three of the four SPAs, for one breeding season each. It was deemed unsafe (in terms of bird capture, and working during darkness) to carry out fieldwork within the forth SPA of St Kilda.

Fieldwork took place from May to August at the UK’s three largest Manx shearwater colonies namely, the islands of Skomer, Rum and Bardsey during 2003, 2004 and 2005 respectively. Colonies were visited two or three times during the season (Table 2). The first visit allowed the identification and marking of a sample of occupied burrows. This visit was timed to coincide with incubation, when there would be at least one adult in the burrow, and when vegetation was low enough that burrow entrances were easily located. The second visit coincided with chick-rearing, and was used to attach radio-tags and track the adults. The third visit (to Skomer only) was intended for a second round of tracking during the pre-fledging period. Manx shearwater breeding success between 2001-2005, averaged 0.56, 0.68 and 0.81 for Skomer, Rum and Bardsey respectively (JNCC Seabird Monitoring Programme).

Table 2. Timing of visits to Skomer, Rum and Bardsey during 2003, 2004 and 2005.

Colony	Year	1 st visit (incubation)	2 nd visit (chick-rearing)	3 rd visit (pre-fledging)
Skomer	2003	11-16 May	12-29 July	13-18 August
Rum	2004	18-22 May	12 July – 10 August	n/a
Bardsey	2005	7-12 May	30 July – 21 August	n/a

Skomer, a small island of 2.93km² (approximately 3 x 2km) comprising a relatively flat plateau that reaches 70m elevation in only a few locations (Figure 1). Skomer is bordered on all sides by 30-40m high cliffs, which host breeding northern fulmars, lesser black-backed gulls *Larus fuscus*, herring gulls *L. argentatus*, great black-backed gulls *L. marinus*, black-legged kittiwakes *Rissa tridactyla*, common guillemots, and razorbills. The relatively flat plateau is pockmarked by the burrows of Atlantic puffins, rabbits and Manx shearwaters. The highest point on the island is 79m at the Triangulation Point (S3, Figure 1). Skomer is a currently rat-free island.

In contrast to Skomer, Rum is a relatively large mountainous island of 105km² (approximately 13 x 14km), reaching 812m elevation at the peak of Askival in the south east (Figure 2). The Manx shearwater colony is located on areas called 'greens' where the grass has been enriched by shearwater faeces. The highest density areas are found on the upper slopes of Hallival, Askival and Trallval (Figure 2; Murray & Shrewry 2002). There is a large brown rat population on Rum and it is possibly as a result of rat predation that the colony is restricted to the highest, most inaccessible parts of the island. There are few other large concentrations of seabirds on the island, although there are several pairs of breeding red-throated diver *Gavia stellata*. Rum is also the location of a long term project on the wild populations of goats *Capra hircus*, and of red deer *Cervus elaphus* that occasionally supplement their diet with shearwater chicks possibly to boost their mineral intake (Furness 1988).

Bardsey (Ynys Enlli) is a small island of around 2km² (approximately 2.5km in length and, at its widest point, is just over 1km across) (Figure 3). The island is relatively low lying in the west (less than 10m), but on the eastern side, the peak of Mynydd Enlli, is 167m high. The island hosts breeding shags *Phalacrocorax aristotelis*, herring gulls, greater black-backed gulls, kittiwakes, guillemots and razorbills. Bardsey is currently a rat-free island.

On each island, study sites (parts of the colony where adults were tagged) were chosen on the basis of providing good geographical spread, having a high density of burrows, and being easily accessible. Four sites were chosen on Skomer; Pigstone, The Wick, behind the House, and The Neck (Figure 1). Two sites were chosen on Rum; Hallival and Askival (Figure 2). Five sites were chosen on Bardsey (Pen Cristin, Nant, Northwest Fields, Cristin and the South End (Figure 3). On Rum, although Trallval is one of the highest density areas, it was discounted as a study site on safety grounds.

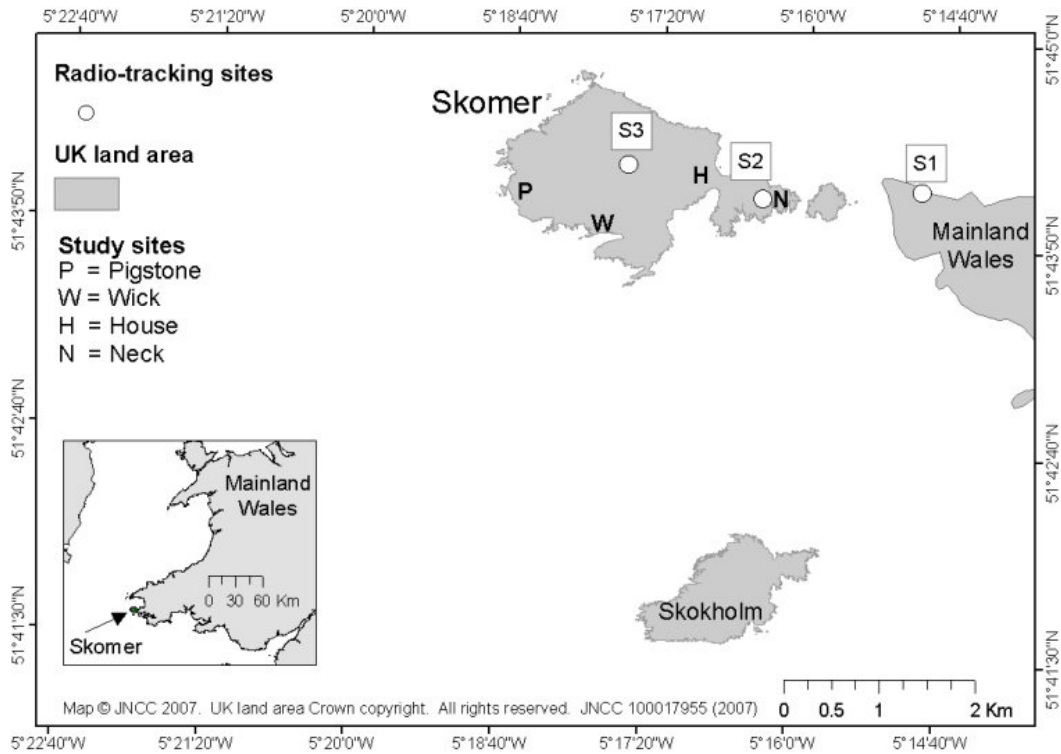


Figure 1. Map of Skomer, Pembrokeshire, showing study sites where adults were tagged, and radio tracking stations (S1-3). Map inset shows the location of Skomer in relation to mainland Wales.

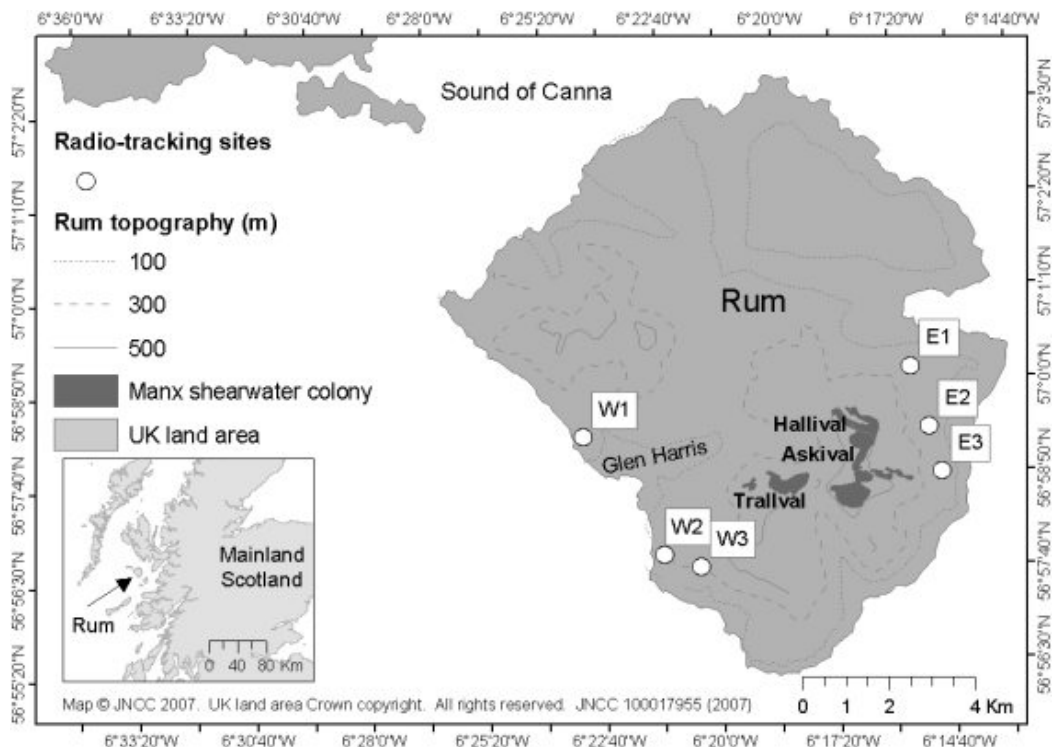


Figure 2. Map of Rum, Highland, showing study sites where adults were tagged and radio tracking stations in the East (E) and West (W). Map inset shows the location of Rum in relation to mainland Scotland.

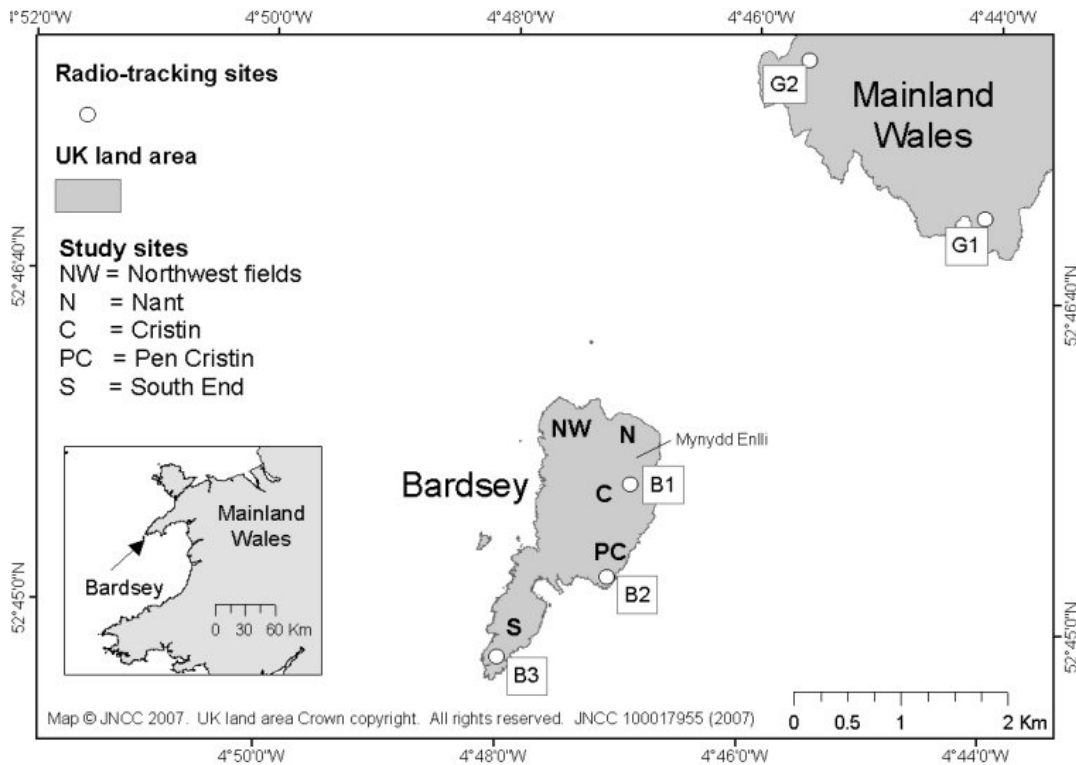


Figure 3. Map of Bardsey, Gwynedd, showing study sites, where adults were tagged, and radio-tracking stations on Bardsey (B1-3) and Gwynedd (G1 and 2). Map inset shows the location of Bardsey in relation to mainland Wales.

3.2 Capturing and processing study birds

3.2.1 Burrow selection and processing adults

During the first visit to each of the three colonies, burrows with a visible entrance were checked by hand for an egg and incubating adult. On Bardsey, further burrows were checked during the second visit on 3 August 2005. Adults were carefully removed by hand from accessible occupied nest chambers and where possible, their sex determined using cloacal inspection (females' cloacae are bluish, open and swollen after egg-laying (Gray & Hamer 2001)) to ensure that there was no gender bias in the group of tagged adults. In addition to cloacal inspection, birds were only considered male if there was an egg present, to avoid assigning the incorrect sex to a non-breeding female or a female that had not yet laid an egg. Birds were ringed, if not already (using BTO metal rings), weighed (using a Pesola balance) and the bill, head and bill, tarsus and wing length measured (using a wing rule and Diamax callipers). Accessible, occupied burrows were marked with a stake and their position recorded using a hand held Global Positioning System (GPS) receiver, to allow re-location later in the season.

3.2.2 Tag attachment

The sample of marked burrows was re-checked in July, during the chick-rearing period. Most burrows were checked during the evening, when adult attendance is higher. Adults were weighed and measured, and those that were suitable (see below) had a VHS radio-transmitter tag attached using a tail-mount following the method of Gray and Hamer (2001) (Figure 4).

Tags were attached to the two central tail feathers using either self-amalgamating tape (Gray and Hamer 2001, Skomer) or *Tesa* tape (Phillips *et al.* 2004, Rum and Bardsey). The tags used weighed 8.9g in the Skomer study and 4.4g in the Rum and Bardsey studies (Table 3). The heavier tags were used initially because of their longer life (2 months); however, as these tags fell off before this time elapsed it was decided that the smaller, shorter-lived tags (4 weeks) should be used on Rum and Bardsey. The process of weighing, measuring and attaching a tag took no longer than 10 minutes per bird and birds were immediately returned to their burrow after processing.



Figure 4. Radio tag attachment on Rum. Tag attachment was usually carried out at night; however, this adult was caught at the nest during the day, while weighing chicks in July (Photo © Tim Dunn).

Table 3. Specifications of radio tags used on Skomer, Rum and Bardsey. All tags were made by Biotrack Ltd. and had a 230mm primary whip-antenna extending along the length of the bird and a 140mm secondary (ground plane) antenna perpendicular to the primary antenna.

Site	Type	Weight	Dimensions (mm)	Range	Life (months)	Attachment method
Skomer	TW-3	8.9g	L32 x W16 x H13	>20km	2	Self amalgamating tape
Rum and Bardsey	TW-4	4.4g	L26 x W9 x H9	>20km	1	<i>Tesa</i> tape

Kenward (2001) recommends that tail-mounted tags weighing 2-3% of the birds' weight may be spread over two tail feathers (Figure 4). One tail feather would not be sufficient to hold the tag, while attachment to more than two tail feathers would impair ability to spread out the tail. Breeding adults weigh on average 424g (350-535g) in June (Cramp and Simmons 1977). On Skomer, if the tag (8.9g) weighed more than 2.5% of a bird's total weight we did not attach a tag, therefore only adults weighing more than 356g were tagged. On Rum and

Bardsey (where tags were 4.4g), adults weighing less than 350g were not tagged. Priority for tagging was accorded to the heaviest adults. In addition to this, only adults with chicks older than 5 days were considered for radio tag attachment, thereby reducing the likelihood of desertion by the adult (C. Gray *pers. obs.*). Chick age was estimated from wing lengths, using standard growth curves (Brooke 1990 for Skomer and Bardsey, Thompson 1987 for Rum). Where possible, tagged birds were caught at the end of the study and their tags carefully removed.

3.2.3 Assessing effects of tags

Attachment of devices to breeding birds can potentially have detrimental effects on the birds' flight and foraging performance, which may in turn affect chick provisioning, fledging success and ultimately chick or adult survival. Within the scope of this study, chick provisioning was considered the only performance parameter that it was practical to measure. Therefore, to determine whether there were any significant detrimental effects of tag attachment, chick growth rates were measured and compared between control chicks (where neither adult had a tag) and experimental chicks (where one adult had a tag). Control chicks were situated within the same study sites as the experimental chicks.

Chicks were weighed and measured in July at the time of tag attachment, and again in August at the end of the tracking period, and the growth rate (gd^{-1}) calculated for each chick. Two-tailed t-tests were carried out in S-Plus 2000 (© 1988-1999 MathSoft, Inc) to test for any significant differences in growth rates between the control and experimental groups of chicks on each colony. A significant difference between the weights on control and experimental chicks would indicate an effect of the tags on the parent's ability to supply the chick with sufficient food.

3.3 Data collection and analysis

3.3.1 Radio-tracking

Radio-tracking commenced immediately after tags were attached and was generally conducted between 17:00 and 00:00 hours (GMT). *Sika* receivers and five-bar rigid *Yagi* antennas were used to receive the signals from tags. All radio-tracking equipment was supplied by Biotrack Ltd. <http://www.biotrack.co.uk/>. The radio frequency of each tag was programmed into the *Sika* receiver before fieldwork took place; each receiver was fine tuned to each individual tag to maximise detectability and range of tags.

Radio-tracking was conducted from three locations on Skomer and mainland Pembrokeshire, six locations on Rum, and five locations on Bardsey and mainland Gwynedd (Figures 1, 2 and 3 respectively). Contact was maintained between observers via mobile phone and/or CB radio. Tracking locations were chosen that afforded: the best geographical spread of observation points; good radio/phone contact; a good line of sight to the sea; and sufficient elevation above sea level to be unaffected by wave height, yet as close to the coast as possible to minimise distance from rafts. To maximise detection of radio-tags on the water, observers were located as high above sea level as possible to ensure a good "line of sight" to the tagged birds; the detectable range of the tag is greatly reduced when the observer is at sea level (C. McSorley, *pers. obs.*). Tracking locations were not positioned on the mountain tops of Rum (because of the risk of exposure and extreme weather conditions at night e.g. lightning storms), at large distance from the sea, at large distance from the base (rendering them

difficult to access at night), and where magnetic rocks might have affected compass readings. Observers were located 50 - 80m above sea level (asl) on Skomer; 200m asl and 250m asl on East and West Rum respectively; and at 50m, 100m and 160 m asl on Bardsey. In addition, an observer was located at various locations along the Pembrokeshire coast, and at 100m asl (G1) or 150m asl (G2) on mainland Gwynedd (Figure 3).

On arrival at the tracking station observers scanned through all bird frequencies to determine which birds were within detectable range. A co-ordinator then compiled a schedule for tracking each of these birds in turn. Observers used synchronised watches to take simultaneous bearings to a specific individual at the end of a 3 minute interval, working their way through the schedule of study birds. This procedure was followed for periods of up to 30 minutes depending on how many birds were detectable.

Bearings were taken (to the nearest degree) from the direction providing the strongest signal by using a compass aligned with the direction of the observers' *Yagi* antenna. As well as bearings, each observer recorded the following for each signal: signal strength, whether the bird was moving, how confident they were in their bearing, whether they felt the signal was being affected by topography, and if there was any disturbance (e.g. a boat in the area). These notes were used in determining which bearings should be used for biangulation or triangulation and which should not be used (see below).

At the end of each tracking schedule observers scanned through all the tag frequencies for new arrivals that might have come within range since the last scan. The procedure (scanning and simultaneous taking of bearings) was repeated all evening until such time as the tagged birds had flown into the colony.

3.3.2 Estimating locations from bearings - biangulation and triangulation

Analyses were performed only on those birds that were thought to be rafting; data were checked prior to analyses and any bearings that were clearly incorrect, or were for birds that were flying or feeding, were removed. This was determined based on signal strength, notes taken by the observers and comparison of signal direction between stations. The location of each detectable bird was determined using biangulation (using two bearings) or triangulation (using three bearings), where the location of the tagged bird is at the crossing point of the two or three bearings taken from two or three different known locations. Biangulation was used in situations where only two observers were present, where a third signal was not detectable, or where little confidence was attached to one of the signals. Where all three observers were unsure of the bearings, no location was estimated.

Bird location was determined by *post-hoc* analysis of bearing data with LOASTM 3.0.2 (Location Of A Signal) software © 1998-2004 (Ecological Software SolutionsTM). Bearings were adjusted for magnetic north using the appropriate adjustment for each area. A maximum likelihood estimator was used for triangulation; this uses an iterative algorithm that tries to find the minimum angular error between the observed set of the bearings and the signal's estimated location. Thus, the maximum likelihood estimator generates the most likely estimate for the given three bearings.

3.3.3 Home range analyses

Home Range Analyses were used to identify the most important concentrations of rafting Manx shearwaters based on the estimated locations from radio-tracking. Home range analyses are a suite of methods that use location data to determine the area used by an individual or group of individuals. A home range may be described as an area repeatedly utilised by an animal and is a measure of space use by animals (Kenward 2001, Hemson *et al.* 2005). There are several methods for determining home range; the most commonly used being concave and convex polygons, ellipses, harmonic mean contouring, and kernel contouring (Kenward *et al.* 2003).

In recent years kernel contouring methods have been more widely used than the other methods (Herring & Collazo 2005; Adams *et al.* 2004; Reynolds 2004), as they “accommodate multiple centres of activity, do not rely on outlying points to anchor their corners and are less influenced by distant points” (Hemson *et al.* 2005). In this way they are useful for analysing data that may have several outlier locations (locations that are outwith the main aggregations that may be the product of inaccurate bearings, or are only very occasionally used). Although there is a potential problem in kernel contouring methods (see section 3.3.3.1), this method was used here as it is the most appropriate method for analysing these data.

3.3.3.1 Kernel contouring analyses

Kernel contouring analyses were employed to determine the location of the most important aggregations of rafting Manx shearwaters using the software package *Ranges6* v1.2199, Anatrack Ltd (Kenward *et al.* 2003). Because each bird generated few data, data from all birds were pooled (serial independence of observations is not required for kernel analyses, De Sola *et al.* 1999). Therefore individual home ranges were not generated; rather a “home range” for all individuals was calculated.

Ranges6 generates a matrix of location density from a scatter of actual locations using an estimator; in this case a kernel estimator was used. Kernel analysis requires a smoothing parameter (h). The reference smoothing parameter (h_{ref}) calculated by *Ranges6* tends to overestimate range areas so this can be multiplied by a fractional value, which can be calculated using Least Squares Cross Validation (LSCV) (Kenward *et al.* 2003). LSCV performs best with 30 or more locations (Kenward *et al.* 2003), however, there has been recent evidence suggesting that LSCV may sometimes fail to generate an appropriate smoothing parameter when applying it to real, unsimulated data (Hemson *et al.* 2005). This failure rate is highest for a sample size of more than 100 locations (61%) and is particularly common when there are a large number of identical locations or points are very close together; the example used in the Hemson *et al.* (2005) study was a lion's (*Leo panthera*) den that was used intensively at certain times of the day generating many locations that were very similar or the same. In our study, there was no central place (apart from the burrow) that would cause the locations to be very similar or identical. Once the birds had gone into the burrow the signal ceased so birds were not tracked at their burrows. LSCV did not fail for our kernel contour estimates (although see Section 4.7). Therefore, it is unlikely that the above problem applies to the data presented here.

Tracking resolution is affected by the accuracy of the tracking; with a 5-bar yagi antenna, Kenward *et al.* (2003) suggest a 1:20 rule where if the bird is located 2km away the

resolution will be 100m, or if the bird is 20km away, the tracking resolution will be 1km. Given that most locations were within 4km of the colony, tracking resolution in *Ranges6* was set to 200m. The number of matrix cells was set to 100.

Ranges6 calculates the densities within a grid of cells, ranks them, and then assigns isoline contours (termed cores here) around each 5% of the total estimated population. In this context, a kernel core is the area covered by the cumulative 5 percentiles of the total number of locations e.g. the area covered by 5%, then 10%, 15%, 20%, 25%, etc of the locations.

4 Results

4.1 Tag attachment and removal

Access was possible to the nest chambers of a total of 98 burrows on Skomer, 120 on Rum and 104 on Bardsey (Table 4). The number of adults tagged at each study site is shown in Table 4. Mean weights of tagged adults at the time of tag attachment were 424g (range = 360-485g) on Skomer, 420g (range = 375-505g) on Rum and 442g (range 400-510g) on Bardsey. There was no gender bias within the experimental (adult birds with tags) groups on each colony, as far as can be deduced from the birds of known gender (Table 4, $\chi^2_{\text{Skomer}} = 0.11$; $\chi^2_{\text{Rum}} = 0.10$; $\chi^2_{\text{Bardsey}} = 0.19$; $P > 0.05$, 1df for all).

Table 4. The number of marked burrows and tagged birds of each gender, for each study site within each colony

Colony	Site	Total no. of burrows marked	Tagged Birds			
			Males	Females	Unknown gender	Total
Skomer						
	Pigstone	14	5		2	7
	The Wick	35	3	5		8
	Behind house	23	1	3	4	8
	The Neck	26	2	4	1	7
	Total	98	11	12	7	30
Rum						
	Hallival	45	8	9	1	18
	Askival	75	5	3	2	10
	Total	120	13	12	3	28
Bardsey						
	Cristin	9	0	0	2	2
	Nant	32	3	4	4	11
	Pen Cristin	35	3	1	5	9
	NW Fields	21	0	2	3	5
	South	7	0	0	3	3
	Total	104	6	7	17	30

On Skomer, by the end of the second visit, six birds were still being detected, but none were detected during the third visit in August, so it is impossible to determine how long the tags stayed on after the 29 July. During the third visit, 20 of the tagged birds were recaptured and all had lost their tags. Eleven of these birds had all 12 tail feathers intact, indicating that the tag fell off naturally, leaving the tail feathers whole and unaffected. The other nine birds either had central tail feathers missing or broken, indicating that the tags were either pulled clear of the feathers by preening or that the tail feathers were broken or pulled out by the tag.

At the end of the study on Rum, it was possible to visit only part of the colony for three nights due to poor weather. Consequently, only three tagged adults were recaptured on Rum; two of these had not retained their tags, and the central two tail feathers were broken, while one bird retained its tag, although the tag battery power was depleted. This latter bird had retained its tag for 15 days; both the feathers and the tag were in good condition before and after tag removal so it is likely that the tag would have stayed on for longer.

At the end of the Bardsey study, 11 birds still had tags that were being detected. Seven of these were captured and their tags removed. The remaining four were not recaptured, either because they were not attending the chick at the time of visiting the burrow, or because there was not enough time before the end of the study to visit the burrow.

4.2 Effect of tags on chick growth

On Skomer, morphometric data for 63 chicks were measured on two days in July and of these, 53 were weighed and measured again over two days in August; four of the remaining nests had failed and six could not be relocated. On Rum, 51 chicks were weighed and measured on two days in July, and 49 of these were weighed and measured again over three days in August; the burrows of the two remaining chicks could not be relocated. On Bardsey, 65 chicks were weighed and measured between 31 July and 3 August 2005 and of these, 61 were weighed and measured again between 17 and 20 August; the burrows of the four remaining chicks could not be relocated. All experimental chicks at the three sites survived for the duration of the study, and were weighed and measured in July and again in August, except for one on Bardsey, whose burrow was too deep to access the nest chamber.

Figure 5 shows the mean growth rates (and standard deviations) for control and experimental chicks on Skomer, Rum and Bardsey. On Skomer, there was no significant difference in growth rates (gd^{-1}) between control and experimental chicks (mean growth rate $[\text{mgr}]_{\text{experimental}} = 7.78$, $\text{mgr}_{\text{control}} = 7.71$, $t = 0.107$, $df = 51$, $p = 0.919$). On Rum, there was a slight significant difference in growth rates between experimental and control birds ($\text{mgr}_{\text{experimental}} = 11.12$, $\text{mgr}_{\text{control}} = 12.67$, $t = 2.29$, $df = 47$, $p = 0.027$). On Bardsey, there was no significant difference in growth rates between control and experimental chicks ($\text{mgr}_{\text{experimental}} = 2.95$, $\text{mgr}_{\text{control}} = 2.60$, $t = 0.336$, $df = 51$, $p = 0.738$); the mean growth rate for the experimental group was actually slightly higher than for the control group. The chicks on Bardsey were older at the time of the study compared to Rum or Skomer, and their growth rates were much lower. Some chicks were beginning a period of mass recession (weight loss prior to fledging) and some experimental and control birds had negative growth rates. The chicks were older on Bardsey as fieldwork was performed later in the breeding season.

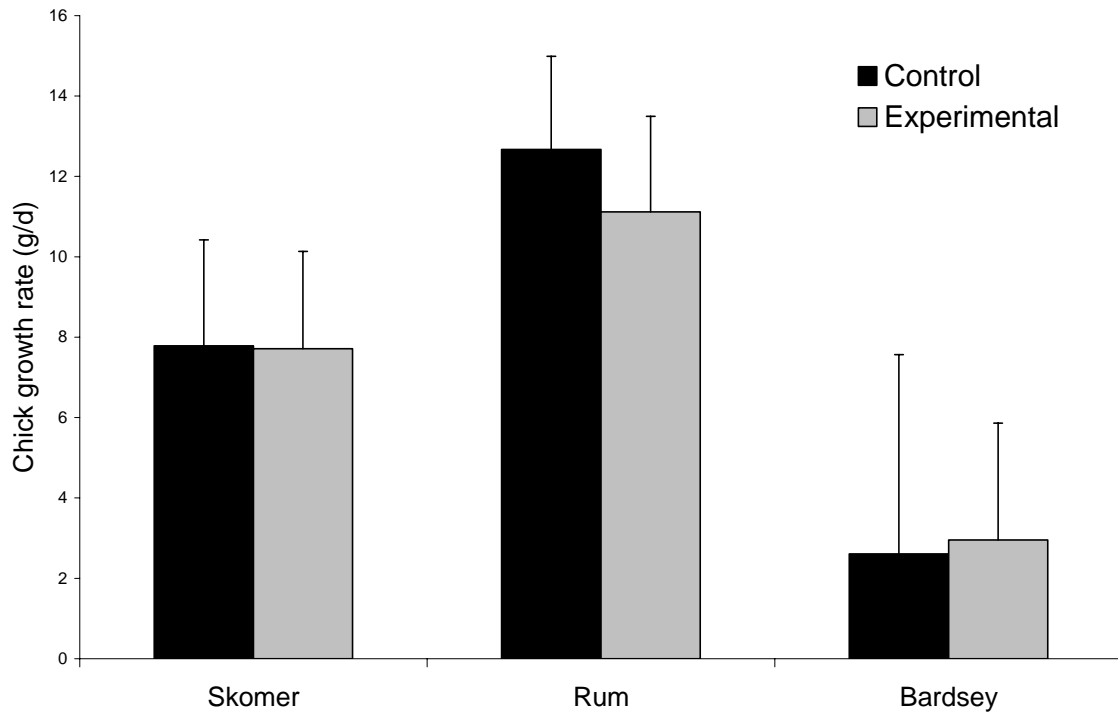


Figure 5. Mean growth rates (and standard deviations) for control and experimental chicks on Skomer, Rum and Bardsey.

4.3 Radio-tracking and analysis of bearings

Radio-tracking took place on 14 days between 15 and 29 July 2003 (Skomer), on 15 days between 15 July and 6 August 2004 (Rum) and on 18 days between 31 July and 19 August 2005 (Bardsey). Seven birds on Skomer and three on Rum were not detected again after being fitted with a tag. Of these, four (40%) were recaptured (all Skomer birds) and all had lost their tag, indicating that the birds went undetected because of tag loss rather than because they were not attending the colony. All other tagged birds were detected at least once during the study and of those, 67% were detected within the vicinity of the colony within two days of tag attachment. Tagged birds were sometimes detected rafting on several consecutive evenings; at Rum and Skomer five birds were detected rafting on at least two consecutive nights, and on Bardsey 12 birds were detected rafting on at least three consecutive nights. The length of time that tagged birds remained detectable by radio-tracking varied between colonies, with tagged birds being tracked for over a longer period on Bardsey (Figure 6).

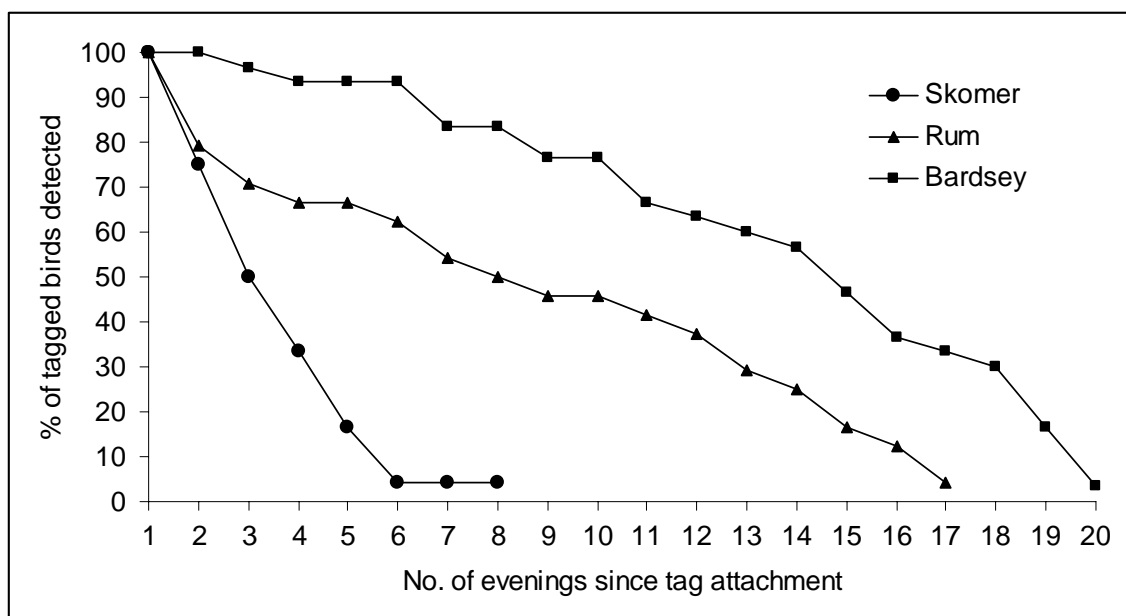


Figure 6. The percentage of tagged birds that remained detectable, for each evening following tag attachment (although not all tagged birds were detected each evening). Birds that were never detected are not included in the calculation.

Most tagged birds started rafting at about 19:30 hours (GMT), with the occasional bird arriving earlier on some evenings. The number of birds tracked per evening ranged from 3-12 (Skomer), 1-12 (Rum) and 3-19 (Bardsey). All birds that were detected on the water were included in the tracking schedule.

The relatively flat terrain on Skomer allowed observers at the highest point on the island (S3, Figure 1) to obtain almost 360° coverage. However, many bearings to the west of Skomer did not converge, probably due to large rocks at the west end of the island interfering with signals from tagged birds. In addition, observers were stationed on the highest points of the island, which fall in a line of east-west orientation (the only way observers could remain in contact because of poor mobile phone / CB radio reception and have good line of sight to the rafts), so convergence of bearings in these directions was often problematic. On Rum, the topography only allowed adequate signals from a limited stretch of water in front of the observers, with coverage only up to 180° possible. Thus, bearing data could only be collected for birds rafting to the west and the east of Rum. On Bardsey, the observer at the highest point on the island, Mynydd Enlli (Figure 3) was able to obtain 360° coverage. However, the topography of the island prevented good signal reception at Pen Cristin, thereby reducing sampling to the north, and similarly, there was limited sampling obtained to the west of Bardsey from poor reception on the mainland. Despite this, it was often possible to calculate locations using bearings from two observers (biangulation), as the mainland observer was able to get bearings when the Pen Cristin observer could not, and *vice versa*.

In total, 218, 290 and 539 bird locations were generated using the LOAS software for Skomer, Rum and Bardsey respectively. These data were further processed to remove any locations that appeared to be outliers (i.e. very far away for the signal strength received, and with low confidence in the bearings taken), or on land, leaving a total of 174, 264 and 385 locations for Skomer, Rum and Bardsey respectively. Of the 23 birds detected from Skomer, locations for 19 birds were estimated, of the 25 birds detected from Rum locations for 20

birds were estimated and of the 30 birds detected from Bardsey, locations for 30 birds were estimated.

All locations estimated are assumed to be of birds that were rafting, as data from flying or feeding birds had already been removed (see 3.3.2). When rafts were visible to observers (prior to nightfall), the bearings for tagged birds were often in the direction of visible rafts, indicating that tagged birds were rafting with other individuals and their rafting locations were representative. Tagged birds appeared to regularly participate in rafting behaviour, with 58%, 40% and 93% of birds from Skomer, Rum and Bardsey respectively recorded as participating in rafting at least twice during the study period (Table 5). These values are likely to be underestimates as it was possible for rafting birds to go undetected on any one evening (particularly on Rum, where signal coverage around the island was limited).

Table 5. The frequency with which tagged birds were detected rafting.

Frequency	No. of tagged birds (and %) that were located in rafts		
	Skomer	Rum	Bardsey
1	19 (100)	20 (100)	30 (100)
2	11 (58)	8 (40)	28 (93)
3	6 (32)	3 (15)	23 (77)
4	3 (16)	1 (5)	20 (67)
5	1 (5)	0	14 (47)
>5	0	0	10 (33)

4.4 Rafting behaviour

4.4.1 Effects of burrow location

To test whether burrow location influenced raft location at each of the islands, rafting birds from each tag site were classified according to whether they were located in rafts north-west, north-east, south-west or south-east of the island (for Skomer and Bardsey), or in rafts east or west of the island (for Rum) (Figures 7-9). There was a significant difference between the observed and expected frequencies in each category for each island (Skomer: $\chi^2 = 40.04$, $p \leq 0.001$, $df = 9$; Rum: $\chi^2 = 33.67$, $p \leq 0.001$, $df = 1$; Bardsey: $\chi^2 = 67.94$, $p \leq 0.001$, $df = 12$), inferring that burrow location does influence where the birds raft.

Overall, Skomer birds tended to raft most often to the north of the island. Birds breeding at the House (NE), Pigstone (W) and Wick (S) rafted most often to the north-west, while birds breeding at the Neck (E) were located more often to the north-east (although they often were located to the north-west as well). Birds breeding at the House, Neck and Pigstone were rarely, if at all, located in waters to the south. However, birds breeding at the Wick (the most southerly site) did use the waters to the south-west and, to a lesser extent the south-east. There was some, fairly limited, evidence that birds on Skomer used rafts located closest to their burrow, i.e. birds with burrows at the Wick (on the south of the island) were sometimes located in southerly waters; and birds with burrows at the Neck to the east of the island, were often located in easterly waters. However, this was not consistently the case, and sometimes birds from the Wick initially rafted to the north of the island, but relocated to the southerly waters later on in the evening.

It was surprising that there was a significant difference between the observed and expected frequencies in each category for Rum, given the close proximity of the two tagging sites.

Tagged individuals from both study sites rafted in both areas, however most of the westerly locations were from birds that bred at Askival (Figure 8). Birds rafting to the west of Rum may reach their nest site by flying directly east up the Glen Harris valley system (Figure 1) across land and round the back of the site possibly positioning themselves to fly east up this valley. However, there was also evidence that birds which rafted in the west gradually moved southwards before finally disappearing around to the east side of the island, presumably to reach their nests from the east. Thus it seems that on Rum, topography and access routes to the burrow, as well as burrow location, may influence raft locations, particularly just prior to birds returning to their colony.

On Bardsey, birds breeding in the east and south east of the island (Cristin and Pen Cristin) tended to be located in waters to the south-east. Birds breeding in the southwest of the island (South End), tended to use waters to the southwest and southeast of the island. Birds breeding in the northwest of the island (Northwest Fields) tended to use waters to the south-east, but also to the northwest; 37% of tagged birds located to the northwest of the island were from burrows in Northwest Fields. Birds from the northeast of the island (Nant) used water to the southeast and to the north east of the island. Thus, on Bardsey, there was evidence that birds tended to raft in waters closest to their burrow.

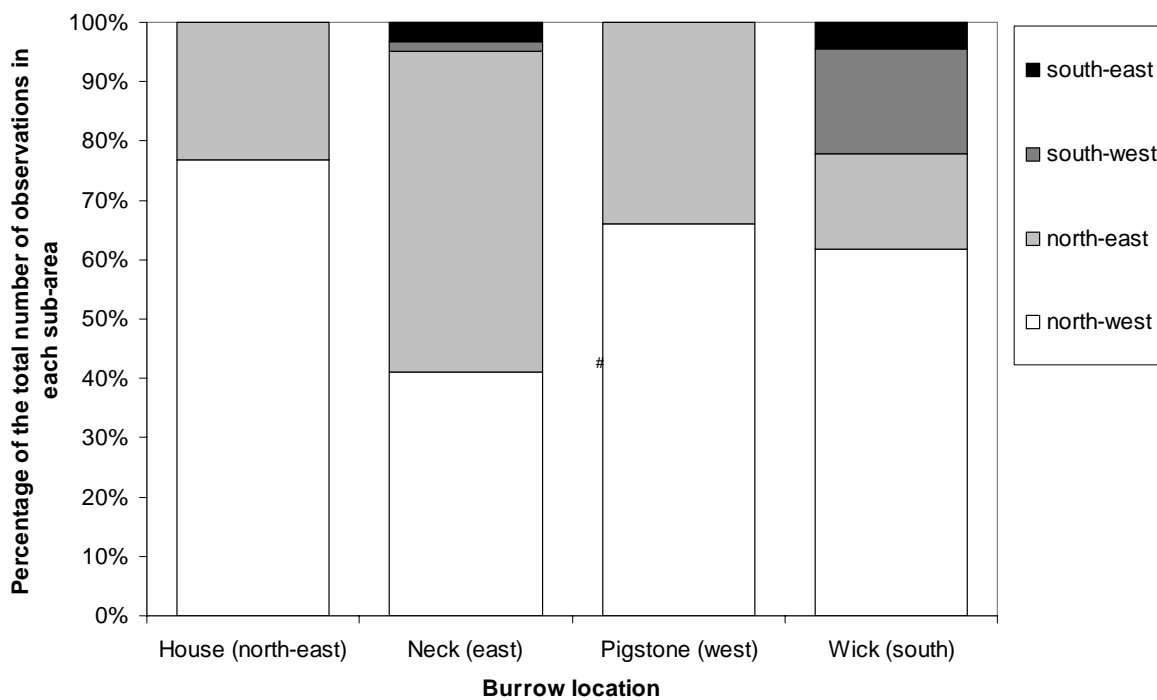


Figure 7. The percentage of the total number of locations of rafting Manx shearwaters around Skomer in four areas, in relation to their burrow location (House, Neck, Pigstone and Wick). Sub-areas were delineated by a grid of four cells centred on the mid-point of Skomer.

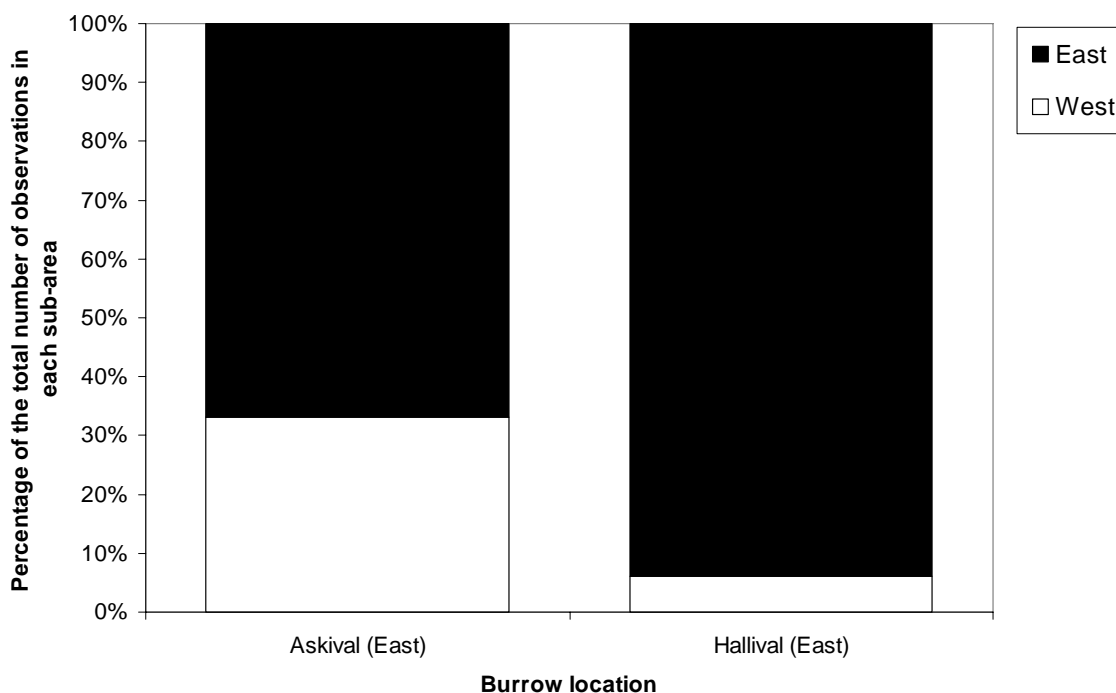


Figure 8. The percentage of the total number of locations of rafting Manx shearwaters around Rum in two areas (west and east of Rum) in relation to their burrow location (Hallival and Askival). Sub-areas were delineated by a grid of two cells centred on the mid-point of Rum, running north to south.

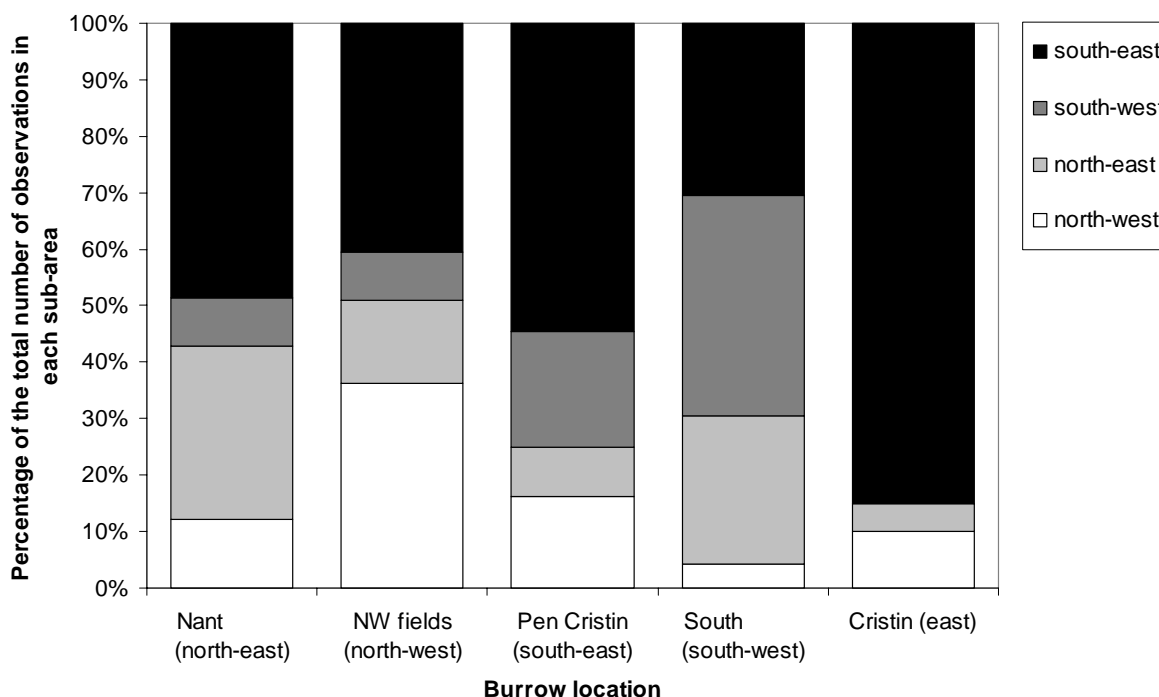


Figure 9. The percentage of total number of locations of rafting Manx shearwaters in four areas in relation to their burrow location (Nant, Northwest fields, Pen Cristin, South and Cristin). Sub-areas were delineated by a grid of four cells centred on the mid-point of Bardsey.

4.4.2 Time of evening

There were no locations generated earlier than 19:00 (GMT) on Skomer and Rum, as birds did not start rafting within range of the observers until at least 19:00 on Skomer and 19:30 on Rum. On Bardsey, where radio-tracking generally started 17:00-18:00 (the earliest time being 16:00), the earliest locations generated were at 16:45. On all three islands there was evidence that rafting birds moved significantly closer to the colony as the evening progressed (Spearman's Rank correlation: $r = -0.19$, $P < 0.01$, $n = 174$, Skomer; $r = -0.13$, $P < 0.05$, $n = 264$, Rum, $r = -0.32$, $P < 0.001$, $n = 385$, Bardsey). This was also the case when data from all three islands were combined ($r = -0.28$, $P = 0.001$, $n = 823$) (Figure 10).

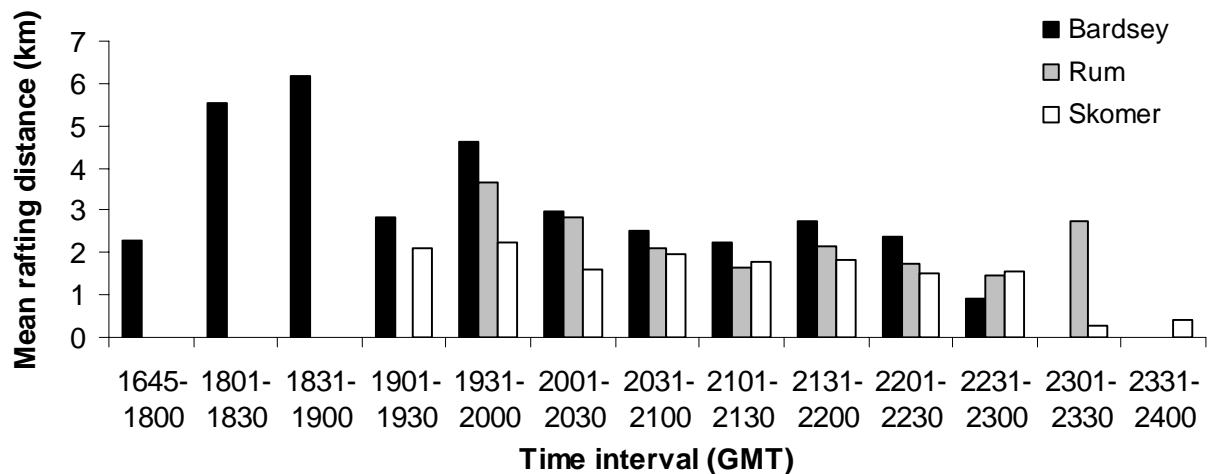


Figure 10. The mean rafting distance (km) of Manx shearwaters from their breeding islands, at different time intervals over the evening.

4.4.3 Time of season

There was no evidence that the rafting distances changed significantly over the course of the study period for Skomer or Bardsey (Spearman's Rank correlation: $r = -0.09$, $P = 0.22$, $n = 174$, Skomer; $r = 0.07$, $P = 0.18$, $n = 385$, Bardsey) (Figure 11). In contrast, there was a significant negative correlation for Rum (Spearman's Rank correlation: $r = -0.13$, $P < 0.05$, $n = 264$) (Figure 11). In contrast, there was a significant positive correlation between rafting distance from the colony and day of the season when data from all islands were combined (Spearman's Rank correlation: $r = 0.12$, $P < 0.01$, $n = 823$).

4.4.4 Moon phase and cloud cover

On all colonies, casual observations suggested that far fewer birds appeared to come into the colony on nights when the moon was full (or near full) and the sky was clear, than on cloudy nights: This was true both of non-study birds seen on the ground outside the burrows and of study birds recorded attending the nest. There were too few data to investigate whether birds entered the colony later on the brightest nights (little cloud cover and a full moon).

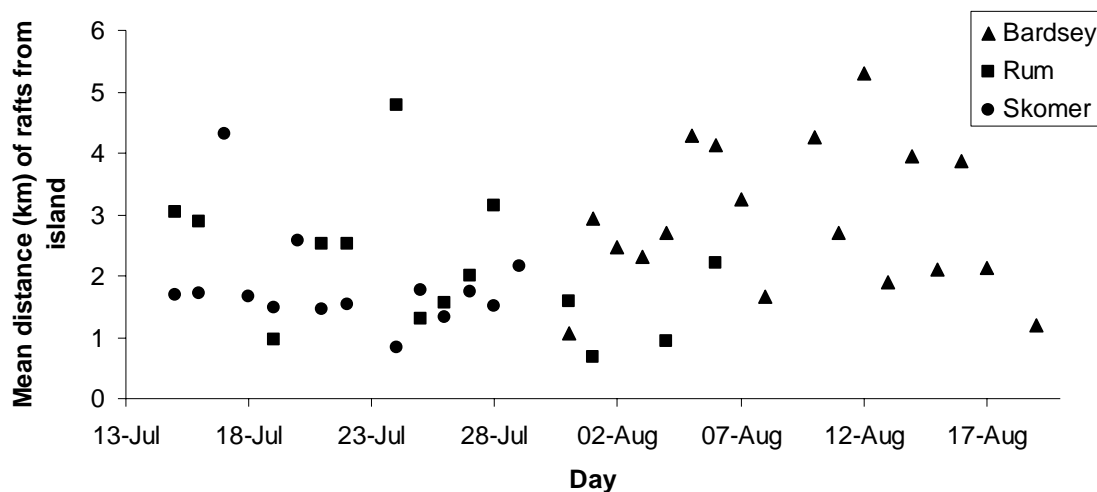


Figure 11. The relationship between mean distance (in km) of rafts from each island on each tracking date in the breeding season.

4.5 Error associated with bearings

The effect of having one observer (out of three) giving an inaccurate bearing was investigated by altering one of the original bearings by ± 1 and ± 5 degrees and calculating the distance of this new ‘inaccurate’ location from the original location. This was done using a randomly selected sample of 30 triangulated bearings from Rum. The mean distance between an altered location and the recorded location varied between 0.181-0.232km for a 1° change and between 0.543-0.706km for a 5° change (Table 6).

Table 6. The effect of altering one bearing out of three bearings by ± 1 and ± 5 degrees on the location generated by LOAS software. This is measured by the calculating the distance from the new location to the recorded location for a sample of 30 recorded locations from Rum. The table shows the mean and standard deviation of these distances.

Error in bearing	Distance (in km) of ‘inaccurate’ locations from the original locations			
	-1°	$+1^\circ$	-5°	$+5^\circ$
Mean	0.181	0.232	0.706	0.543
Standard deviation	0.612	0.895	1.872	1.164

4.6 Kernel analysis

For kernel analyses, Skomer and Rum data were split into two regions for the following reasons. On Skomer, birds were located successfully to the north and to the south of the island but there were fewer locations on the south side of the island. If the location data from the north and south sides of the island had been analysed together, the north side may have been accorded greater importance, as an artefact of sampling intensity. Therefore, data from the north and the south of Skomer were analysed separately. On Rum, tracking data were collected from two locations on the island, but sampling effort was much lower at the west site than the east. If these data had been analysed together the east side may have been artificially accorded greater importance. Again, data were treated separately for kernel

analysis. It was not necessary to split the data from Bardsey as there was an even spread of sampling effort and location data around the island.

The LSCV (Least Squares Cross Validation) method was used to select the most appropriate smoothing parameter within *Ranges6*. LSCV should be carried out when sample size is greater than 30 (Kenward *et al.* 2003). As there were only 17 locations at South Skomer, the LSCV method was not suitable, so the smoothing parameter calculated for the North Skomer data was used instead as recommended in Kenward *et al.* (2003). The smoothing parameter multipliers calculated using LSCV were 0.57 (Skomer North and South), 0.41 (Rum East), 0.29 (Rum West) and 0.19 (Bardsey).

4.6.1 Relationship between the kernel cores and the proportional area they cover

There are two measures of a species distribution that kernel analyses may generate; the first is home-range and the second is the core area. A home-range has been described by Kenward (2001) as “an area repeatedly traversed by an animal”. The core area is an area within the home-range that an individual will spend most of its time e.g. a nest site, or feeding hot-spot. Figure 12 shows the proportion of the total area covered by each cumulative five percentile kernel core for each island; this type of plot may be used to determine which kernel core to use to define a species’ ‘home-range’ (Vernes and Pope 2001; Kenward 2001; Kenward *et al.* 2003) or, in this case, the rafting range of Manx shearwaters. One hundred percent of the area is covered by the 100% kernel core, with the proportion of area decreasing with each decreasing cumulative 5 percentile core. For all islands, the greatest decrease in proportion of area occurred between the 100% and 95% kernel cores. This means that the outermost 5% kernel (i.e. the locations furthest away from the central kernel or aggregation) covers a greater area than each of the subsequent 5% kernels. Therefore, to describe the rafting range, we used 95% kernel cores so as not to include very large areas of sea that were not used to a significant degree by rafting birds; this is analogous with other studies using 95% cores to describe home-ranges (BirdLife International 2004; Herring & Collazo 2005; Hyrenbach *et al.* 2002).

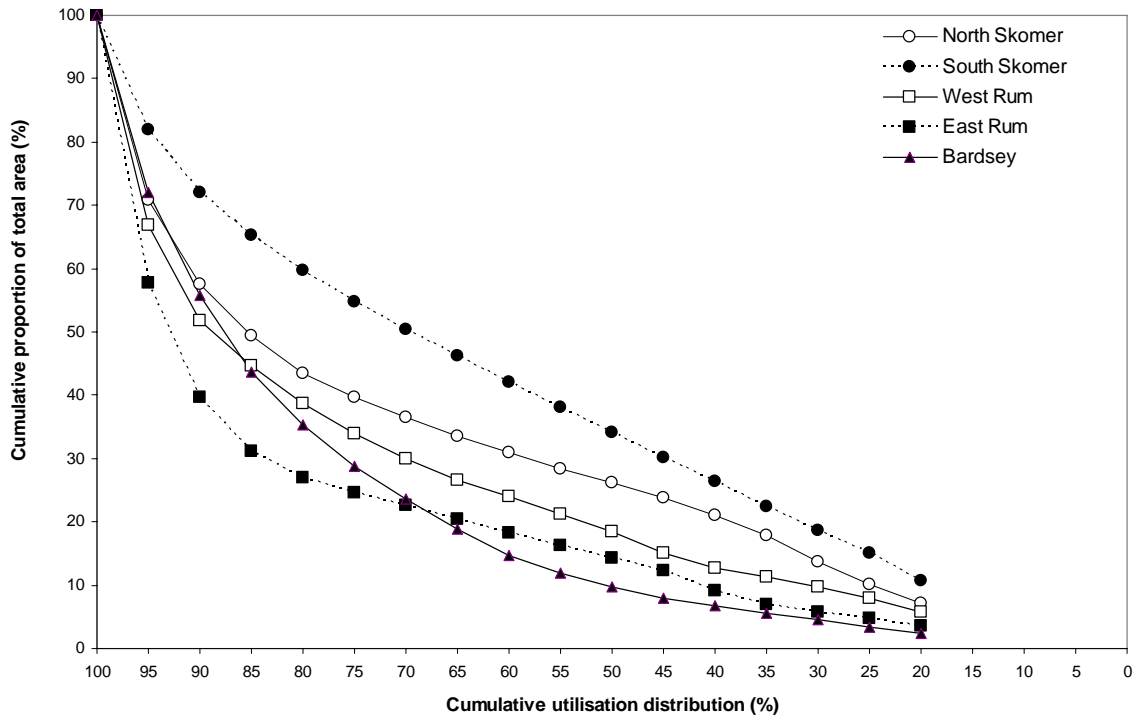


Figure 12. A utilisation plot showing the proportions of the total area (%) included by successive kernel cores, for each area analysed. 100% of the locations are held within 100% of the total area.

Figures 13, 14, and 15 show the 95% and 90% kernel cores generated using *Ranges6* for Skomer, Rum, and Bardsey, respectively, and indicate that there is little difference in geographical extent between the 95% cores and 90% cores. The maximum extent for the 95% cores (not including small ‘satellite’ aggregations containing only a few locations) is 4km for Skomer, 6km for Rum, and 9km for Bardsey. Although birds occur at greater distances, they are not within the aggregations identified by the kernel core analyses.

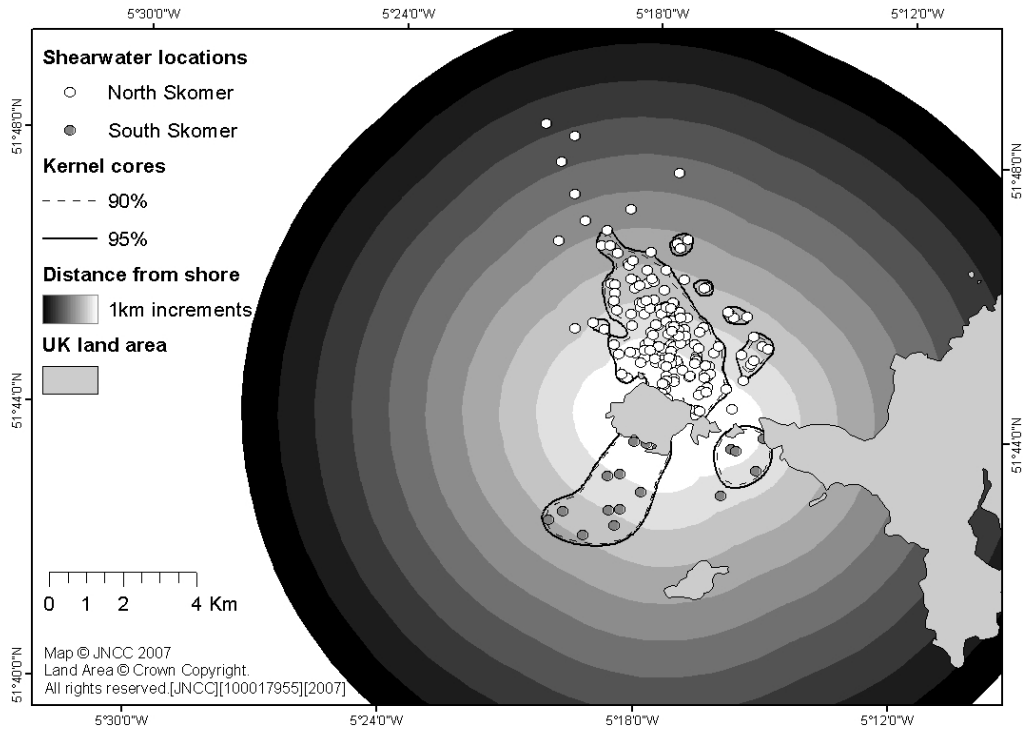


Figure 13. Locations of rafting Manx shearwaters off Skomer, and the 90 and 95% kernel cores generated from kernel analysis. Shading denotes distance from shore at 1km increments.

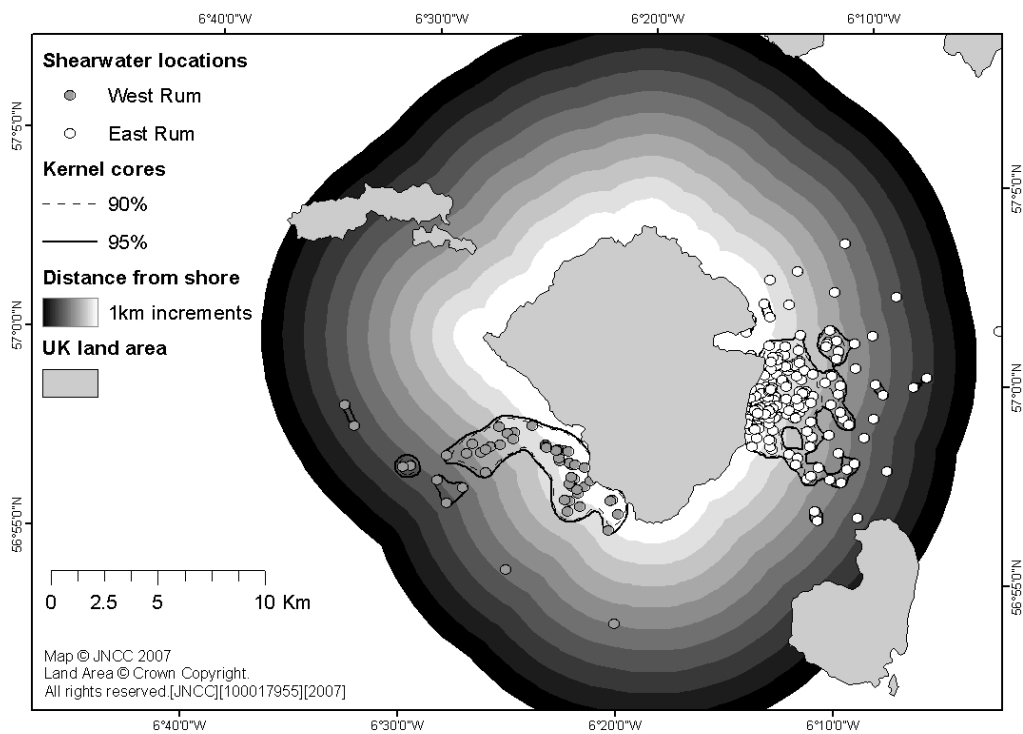


Figure 14. Locations of rafting Manx shearwaters off Rum and the 90 and 95% kernel cores generated from kernel analysis. Shading denotes distance from the shore at 1km increments.

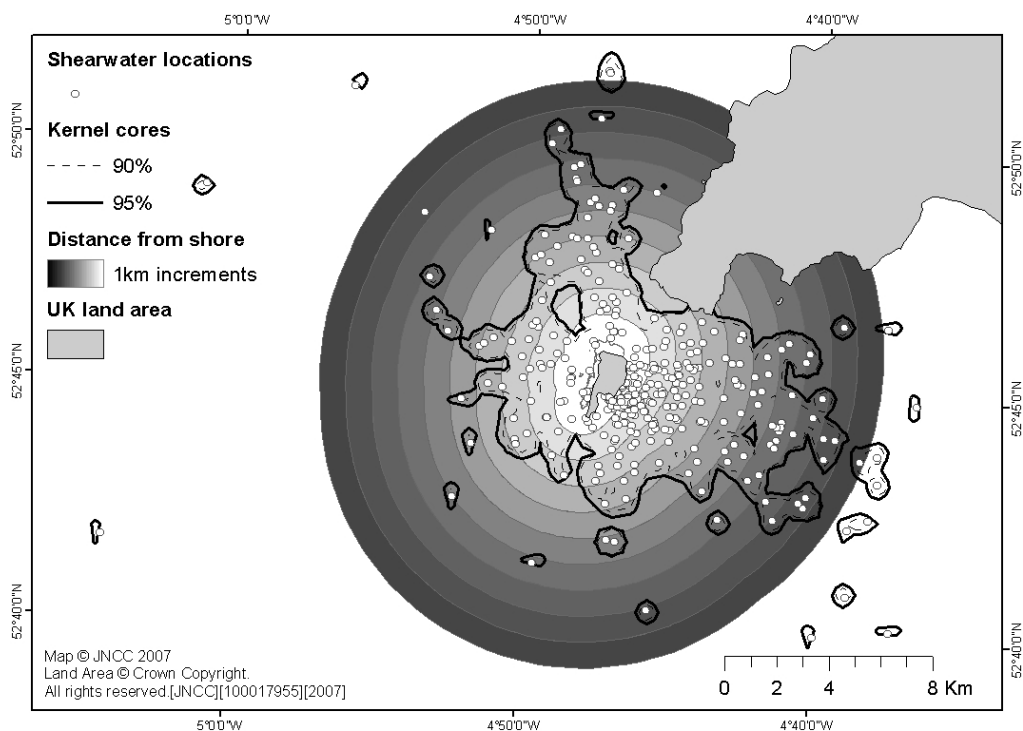


Figure 15. Results of kernel analyses of Bardsey bird location data showing the 90 and 95% kernel cores and observed locations. Shading denotes the distance from the shore at 1km increments.

4.7 Effects of sample size

The number of birds for which locations were estimated, and the total number of locations estimated, varied between colonies, with Bardsey having the highest and Skomer having the lowest sample sizes both for individuals and for locations (see Results 4.3). It was possible that by increasing sample size, there was an increased probability of estimating locations further offshore. The larger sample sizes for Rum and Bardsey may therefore have resulted in the kernel analysis indicating that rafts extended further offshore. To assess if this was the case, kernel analysis was repeated on a random sub-sample of individuals and of locations from Rum and Bardsey colonies, using sample sizes equivalent to those from Skomer (i.e. 19 individuals and 174 locations). As there were only 20 individuals used in Rum, random sub-sampling of individuals for this colony was not performed. The results from these repeated kernel analyses were assessed against the original results by comparing the average distances of locations from land, using a z-test. Maximum distances were also compared, although no statistical test was possible.

When kernel analysis was repeated on a random sub-sample of 174 locations for Bardsey, the LSCV routine failed to calculate the smoothing parameter multiplier. Thus, the multiplier calculated from the original data set was used instead (0.19). Similarly, the LSCV routine failed for West Rum, so a fixed multiplier of 0.29 was used, as calculated from the original data.

There was no significant difference in the mean distance of tagged bird locations from the colony between the original data and the random sub-sample of location data for either Bardsey or Rum (Bardsey: $z = 1.43$, $P > 0.05$; E Rum: $z = 0.05$, $P > 0.05$; W Rum: $z = 0.20$, $P > 0.05$). Similarly there was no difference in the mean distance of tagged birds from Bardsey,

between the original data set of 30 individuals, and a random sub-sample of location data from 19 individuals ($z = 0.25$, $P > 0.05$). The maximum distances that tagged birds were detected from the colony for each dataset did not change. The specific area included within the 90% and 95% kernel cores for each sub-set of data was not noticeably different from that using the original data set.

5 Discussion

This study shows that radio-tracking is an effective and appropriate method for collecting data on Manx shearwater evening rafting distribution around the colony, where traditional boat-based, land-based or aerial surveys are not possible. Rafting birds were successfully located by radio-tracking at all three colonies. However, tracking was limited by topography and weather conditions, especially on Rum, where lightning risk, high winds and rain were major limiting factors. The tags used on Rum and Bardsey remained attached for longer than those used on Skomer. Evidence from recaptured birds on Skomer suggested that many tags fell off, or were pulled off more easily. The *Tesa* tape used for attaching the tags on Rum and Bardsey, together with the fact that these tags were lighter, made a more secure attachment and resulted in data being collected over a longer period for each bird.

5.1 Rafting behaviour

Visual observations during the evening showed that Manx shearwater rafts were generally ephemeral with the birds settling on the sea and within a few minutes flying to a new location; Brooke (1990) states that the movement rate is higher in windy conditions. Tagged birds were sometimes located on several consecutive evenings. This is consistent with the work carried out by Gray and Hamer (2001), which showed that Manx shearwaters often make daily foraging trips, allowing them to sometimes return to the colony nightly.

Furness *et al.* (2000) assumed Cory's shearwaters *Calonectris diomedea* tended to raft opposite their breeding site, based on visual observations of birds coming ashore close to where they had been rafting. Brooke (1990) also thought that there was a possibility that Manx shearwaters came ashore adjacent to where they had been rafting. At all three islands in this study, there was a significant difference between the observed and expected frequencies in different categories of tagged bird locations according to burrow location, suggesting that burrow location may affect where birds raft. Evidence that birds tended to raft on waters adjacent to their burrow locations was strongest for birds at Bardsey, but fairly limited for birds on Skomer and Rum. However, there was no evidence to suggest that birds nesting close to each other rafted together. It is likely that the topography on Rum also played a role in determining rafting locations, especially towards the end of the evening, when birds may position themselves to allow easy access to a preferred flight path along valleys.

Brooke (1990) states that rafts of Manx shearwaters tend to approach the shore, once darkness falls. There was evidence that birds moved closer to the colony as the evening progressed for each of the three islands in this study.

There was anecdotal evidence that fewer Manx shearwaters return to their colonies on clear, moonlit nights; on Skomer, adult attendance at the burrow was lower on clear, bright nights than on cloudy, dark nights. On Rum, there was limited evidence that some birds returned to the colony earlier on cloudy nights than on moonlit nights, but this was not conclusive. Manx shearwaters are likely to be less conspicuous at the colony (either by lower attendance, or by changing their behaviour) on bright, moonlit nights because there is a higher risk of predation by visual hunting predators (Mougeot and Bretagnolle 2000).

5.2 Effect of radio-tags

In this study, adverse effects of radio-tagging were minimised by adopting the following procedures: (1) minimising handling time, (2) attaching tags during chick-rearing rather than incubation, (3) using tail-mounted rather than back-mounted tags, (4) using tags that were within recommended weight limits, and (5) removing tags at the end of the study where possible.

The whole process of catching, weighing, measuring, ringing, and attaching the tag took no longer than 10 minutes, thus minimising disturbance. Tags were attached during the chick-rearing period, when desertion is less likely than during incubation (Manx shearwaters, Gray & Hamer (2001); guillemots and razorbills, Wanless *et al.* (1988)). Tail-mounted tags were selected in preference to back-mounted tags for this study, as the latter would increase drag, and are more susceptible to being forced off the bird when it enters and leaves its burrow. Additionally, dead Manx shearwaters have been found stuck in their burrows, indicating there is little room for more bulk on the birds' bodies. Tail-mounted radio-tags have been used on a wide variety of seabirds, including: Manx shearwaters (Gray & Hamer 2001), black-legged kittiwakes (Ostrand *et al.* 1998), and Cory's shearwater (Furness *et al.* 2000). The tags used in this study were within the weight limits suggested by Kenward (2001). It has been shown that tail-mounted 2g transmitters (19 x 8 x 10 mm) do not adversely affect chick provisioning rate and quality in Manx shearwaters (Gray & Hamer 2001). The transmitters used here were more than double (Rum and Bardsey) or more than four times (Skomer) this weight, but this was deemed necessary because 2g transmitters do not provide sufficient range to allow detection of birds of at least 10 kilometres away from the colony shore. By the end of the study, almost all radio-tags had either fallen off naturally, had been pulled or preened off by the bird, or were removed by us, and it is thought that the remaining tags would not have stayed attached for a significant amount of time after the study (eventually being preened off or lost through moult after the breeding season).

There is some evidence that the growth rate of seabird chicks may be affected by the attachment of radio-tags to the parent birds (e.g. auks, Wanless *et al.* 1988; sooty shearwaters, Sohle *et al.* 2000). However, in this study, there was no significant difference in growth rates between control and experimental chicks on either Skomer or Bardsey, and only a slight significant difference found for chicks on Rum (experimental chicks grew slightly more slowly than control chicks).

5.3 Assumptions and limitations of the data

It was assumed that the estimated locations of tagged birds were representative of the raft locations for all breeding birds at each colony; this does seem likely, as observations before nightfall indicated that at least some signal bearings were in the direction of rafts that were visible i.e. tagged birds were rafting with other individuals. In addition, tags did not appear to affect the ability of the birds to provision their chick at Skomer and Bardsey, and only slightly for Rum, lending support to the assumption that tagged birds were behaving normally.

The study was limited to the chick rearing period to avoid desertion by handled birds, which is more likely during incubation. It is not known whether rafting behaviour changes between incubation and chick-rearing, and it is difficult to speculate about this, given that the function

of rafting behaviour is unclear. However, within our chick-rearing study period, there was no evidence that rafting distance changed significantly over time for Skomer or Bardsey, and only weak evidence that rafting distance decreased over time for Rum. Although there was a significant positive correlation when data from all islands were combined, it seems unlikely that this reflects a true relationship of rafting distance increasing over time. Rather it is more likely to be due to the data from the latter part of the study being limited to Bardsey, the island with the greatest rafting extent.

It was possible to collect only one season's data at each colony. It seems likely that the location of rafts is probably most influenced by small temporal scale effects such as tide, wind direction and sea state (which might influence the ease of remaining in the desired rafting location) and topographical features of the colony (which will govern access routes to the colony). It is possible that the former may vary as much within a season, as between seasons. In the absence of other data, the spatial extent of rafts determined for each colony in this study is the best estimate currently available.

On Skomer and Bardsey, birds were tagged from four and five areas respectively around the island, providing a good geographical spread of burrow locations. On Rum, tagging locations were limited due to the constraints of maintaining safe and practical working conditions; it was not possible to tag birds on Trallval. Because Trallval is further west than Askival or Hallival these birds may have rafted in more westerly or even northerly marine areas. Therefore, it is likely that the tagged birds on Skomer and Bardsey were a good representative sample of the total population, whereas on Rum, this may not have been the case.

The quantity and quality of data collected from tagged birds varied between the islands, with sample sizes being smallest for Skomer, and largest for Bardsey. It was not always possible to estimate locations for all instances where a signal was received from a tagged bird, and this was particularly a problem with data from Skomer and Rum. Generally, non-convergence of the signals was due to topographical interference and / or the location of the tracking stations. On Skomer, locations could not be estimated when birds rafted to the west of Pigstone (although it was clear that the birds did raft there), either because the bearings did not converge or because some observers could not detect the bird. Similarly, on Rum, birds have been observed rafting to the north during the breeding season (S. Morris, SNH, pers comm.). However, due to access difficulties, birds could not be tracked if they rafted the north or north-west of island, or off the southernmost point of the island. Thus, raft locations generated around Rum were confined to the east and west. Although it was not possible to generate bird locations around the whole of Skomer and Rum, it is assumed that the birds did indeed raft around the entire island, as suggested from visual observations and radio signals. Radio signal coverage was most extensive for Bardsey, and it was possible to generate bird locations around the entire island.

Data quality can be affected by the accuracy of bearings. Observers may take inaccurate bearings due to; tiredness; rain and cold making it more difficult for observers to work; high winds affecting the yagi antenna position; topography interfering with the signal; tag signal anomalies (decreased signal strength due to reduced battery power, drift in frequency or increase in frequency of 'bleeps'); and movement of the bird. Inaccuracy of bearings was minimised by taking two steps: (1) Prior to fieldwork, observers were trained in the use of radio-tracking equipment. A tag was placed in a known location, and each observer took a bearing to it, at set distances (up to a maximum of 25km line of sight). This training ensured

that observers were confident in assessing the location of the strongest signal and used consistent techniques, to collect bearing data. This was also done in the field when tags had been deployed on the shearwaters. (2) For each bearing, observers took notes describing the bearing and their confidence in them, making it possible to identify, and determine whether to exclude, a potentially inaccurate bearing. The effect of using an inaccurate bearing to estimate a location was assessed, and it was found that a bearing which was out by 1° or 5°, could alter the location by up to around 230m or 700m respectively. Given that rafting birds constantly change position over a greater scale than the bearing error, it is assumed that errors in bird locations of this magnitude are unlikely to change the overall conclusions reached from kernel analysis.

5.4 Seaward extensions to existing terrestrial Manx shearwater SPAs

5.4.1 Rationale for possible marine boundary extensions to SPAs

All existing UK Manx shearwater SPAs are terrestrial and comprise those sites that hold qualifying numbers under Stage 1.2 of the SPA guidelines, or that qualify through hosting a multi-species assemblage under Stage 1.3 of the guidelines (Stroud *et al.* 2001). These are Skokholm and Skomer SPA; Rum SPA; and Glannau Aberdaron and Ynys Enlli / Aberdaron Coast and Bardsey Island SPA, which qualify under Stage 1.2, and St Kilda SPA, which qualifies under Stage 1.3. The seaward boundaries of these sites currently extend to mean low water in Wales, or mean low water springs in Scotland. Any extension of these SPA boundaries into the marine environment should be focussed on areas on which birds from those SPA sites are ecologically dependent i.e. ensuring their survival and reproduction. Definition of extensions to these existing SPAs will pertain to an existing SPA qualifying interest feature, in this case, breeding Manx shearwaters although, as extensions, all qualifying species of the SPA will be represented in them if they are classified. Non-breeding and prospecting birds also visit breeding colonies during the breeding season (Furness *et al.* 2000) and presumably also raft adjacent to the colonies. Thus, any extension to SPAs into the waters adjacent to the colonies will, perforce, provide some protection to non-breeding birds.

The results of this study indicate that rafting behaviour was recorded at least twice, during the study, by 40-98% of tagged birds. Given that the results show minimum frequencies, it is reasonable to conclude that most tagged birds regularly engaged in rafting behaviour. Given the numbers of birds observed to be involved in rafting (tens of thousands in some cases; Brooke 1990), it is likely that most breeding birds attend rafts before coming ashore, on at least some occasions. Consequently the waters around colonies used for rafting would appear to be an essential resource for breeding Manx shearwaters, on which the species is ecologically dependent. It is therefore appropriate to recommend the consideration of the extension of existing Manx shearwater colony SPAs into the marine environment on the basis of these data.

5.4.2 Defining the extent of the interest feature

In this case, the marine component of the interest feature may be defined as the marine area that is important to Manx shearwaters for evening rafting prior to coming ashore to their burrow. These areas do not include marine foraging areas for Manx shearwaters; foraging areas are outside the remit of this report and will be assessed at a later date. The spatial extent

of any SPA marine extension needs to be determined, as well as whether site-by-site or generic extensions are most appropriate to the SPA suite. In this study, kernel analysis was used to assist in defining which marine areas were important for rafting Manx shearwaters in the evening.

Isoline contours (termed cores here) were assigned around each 5% of the total estimated population and in this context, a kernel core is the area covered by the cumulative 5% of the locations e.g. the area covered by 20%, then 25% of the locations. Rejection of the final 5% (95-100%) of locations is sensible, as inclusion of these locations within a possible seaward boundary extension would have included very large areas of sea that were not used to a significant degree by rafting birds. Kernel analysis indicated that there was little difference in the spatial extent of the 90% and 95% kernel cores. On this basis, and using a precautionary approach, the area enclosed by the 95% core was chosen to define the area of significant use by rafting birds, and hence the extent of the marine component of the interest feature, namely rafting Manx shearwaters adjacent to the colony in the evening.

Data were collected on birds breeding within part of the Skokholm and Skomer SPA (Skomer only) and the Glannau Aberdaron and Ynys Enlli / Aberdaron Coast and Bardsey Island SPA (Bardsey only). For the Skokholm and Skomer SPA, it is assumed that the extent of the rafts used by birds breeding on Skokholm and Middleholm are similar to those breeding on Skomer. Therefore a generic boundary extension is recommended for the whole Skokholm and Skomer SPA (inclusive of all three islands). The Glannau Aberdaron and Ynys Enlli/Aberdaron Coast and Bardsey Island SPA hosts breeding Manx shearwaters only on Bardsey Island. Therefore any seaward boundary should include an extension from this part of the SPA only.

5.4.3 The marine extent of the interest features for Skokholm and Skomer SPA, Rum SPA, and Glannau Aberdaron and Ynys Enlli / Aberdaron Coast and Bardsey Island SPA

The result of kernel analyses showed that there were some disjunct aggregations, or 'satellites' identified by the 95% kernel core at Rum and Bardsey. These satellites generally included only a few locations, thus the marine extents of the interest feature for Rum and Bardsey are defined using the main 95% kernel core but excluding these satellites.

The 95% kernel cores indicate that the marine extent of the interest feature for the SPAs under consideration here, are defined as 4 km from low mean water for the Skokholm and Skomer SPA, 6 km from low mean water (spring) for the Rum SPA, and 9 km from low mean water for the qualifying part of the Glannau Aberdaron and Ynys Enlli / Aberdaron Coast and Bardsey Island SPA (i.e. Bardsey Island).

The reason for the difference in the spatial extent of the interest features at these three SPAs is unknown, but it probably relates to several site-specific features. The colony on Rum is confined to the peaks of several high mountains, whereas the colonies on Skomer and Bardsey are distributed across these low lying islands. The topographical differences between the islands may have some influence on rafting birds (e.g. through providing shelter from adverse weather conditions). Other factors that may vary between the islands, and which might cause the difference in the spatial extent of rafts are oceanographic factors (such as tides and location of tidal races), disturbance on the water, proximity to foraging grounds and predation threat.

The spatial extent of rafts around Bardsey was determined using data collected during a later stage in chick-rearing and may account for the difference to some degree. Feeding frequency and meal mass is known to decline steeply in the 10 days prior to fledging (Hamer & Hill 1997) and some of the chicks in our Bardsey study were already undergoing mass recession. So it is conceivable that birds which do not intend to feed their chick as often or as much, might be less ‘tied’ to the colony and this might affect rafting behaviour e.g. rafting further out. However, there was no evidence that birds rafted significantly progressively further out over the course of the study period for Bardsey, or for the other islands, so it is thought unlikely that the greater maximum extent of rafts around Bardsey is due to data being collected during a later stage in chick rearing.

Another issue which might influence the spatial extent of the rafts is one of data quantity and quality. We tested to see if the difference in sample sizes might result in different spatial extents, by selecting a random sub-sample of data from Rum and Bardsey equivalent to the sample size on Skomer. We found no significant difference between the spatial extents of the original data and the random sub-sample of data, and feel it is unlikely that larger sample sizes on Rum and Bardsey resulted in larger estimated spatial extents to any great degree. However, it is possible that the difference in signal coverage quality between the islands may affect the results. For example, if signal coverage had been limited on Bardsey and locations could only be estimated to the north-west and south-west of the island, kernel analysis would have indicated a smaller spatial extent of rafts, as the greatest extent of rafts occurred to the north-east and south-east.

5.5 Recommendations for possible SPA seaward boundary extensions

The Skokholm and Skomer SPA has previously been recommended for a 1km seaward boundary extension through its qualifying numbers of breeding Atlantic puffins (*Fratercula arctica*) under Stage 1.2, and also for its seabird assemblage under Stage 1.3 including, amongst others, razorbill, common guillemot and Atlantic puffin (McSorley *et al.* 2003). The Rum SPA also has previously been recommended for a 1km seaward boundary extension through its seabird assemblage including, amongst others, common guillemot under Stage 1.3 (McSorley *et al.* 2003). Glannau Aberdaron and Ynys Enlli/Aberdaron Coast and Bardsey Island SPA has not previously been recommended for any seaward boundary extensions for other seabird species.

On the basis of the results of this study, it is recommended that:

1. Existing Manx shearwater colony SPAs be extended into the marine environment by a distance that includes 95% kernel cores as revealed by the kernel analyses in this report.
2. The Skokholm and Skomer SPA be extended by a total of 4km into the waters adjacent to the existing SPA.
3. Rum SPA be extended by a total of 6km into the waters adjacent to the existing SPA.

4. The Glannau Aberdaron and Ynys Enlli / Aberdaron Coast and Bardsey Island SPA be extended by a total of 9km into the waters adjacent to the Bardsey Island part of the SPA only.
5. On the basis that there seems relatively consistent ecological dependence on the waters around SPA breeding colonies, between years and between colonies, of at least 4km, it is recommended that the boundaries of all colony SPAs for which breeding Manx shearwater is a designated feature (including St Kilda) be extended by at least 4km, but possibly further if available information suggests it.

These recommended extensions should be measured from the high mean water mark, to include the intertidal area between the low mean water (or spring) mark and the high mean water mark within the extension.

The extent of the interest features and also possible extensions to the SPA boundaries for the Skokholm and Skomer SPA, Rum SPA, and the Bardsey Island part of the Glannau Aberdaron and Ynys Enlli / Aberdaron Coast and Bardsey Island SPA, are shown in Figures 16 to 18 respectively. The possible seaward boundaries have been determined using previously agreed principles, i.e. that they should be as simple as possible, and placed along parallels of latitude or meridians of longitude or as diagonal lines between two points where this provides a more easily identified or more practical boundary (Johnston *et al.* 2004). Land areas outwith the existing SPA should not be included within this seaward boundary extension. Final determination of the boundary rests with the relevant country nature conservation agencies and competent authorities. Appendix 1 provides a table of coordinates of the recommended seaward boundary extensions for Skokholm and Skomer SPA, Rum SPA and Glannau Aberdaron and Ynys Enlli / Aberdaron Coast and Bardsey Island SPA.

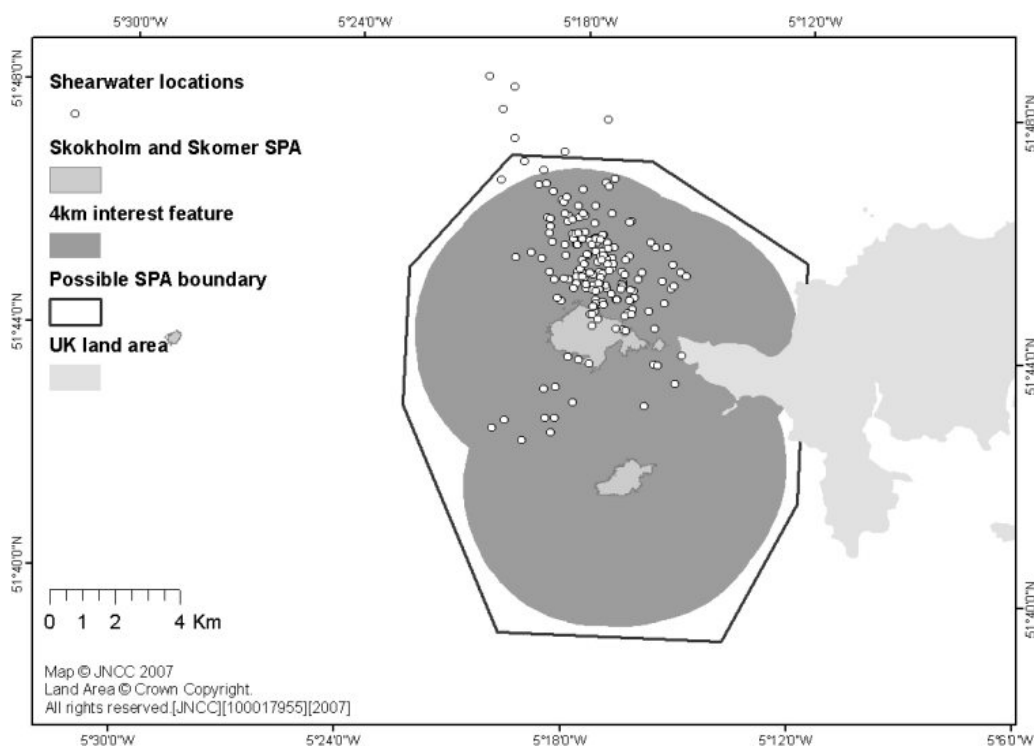


Figure 16. Map of the Skokholm and Skomer SPA showing the recommended extent of the marine component of the interest feature, and a possible SPA boundary.

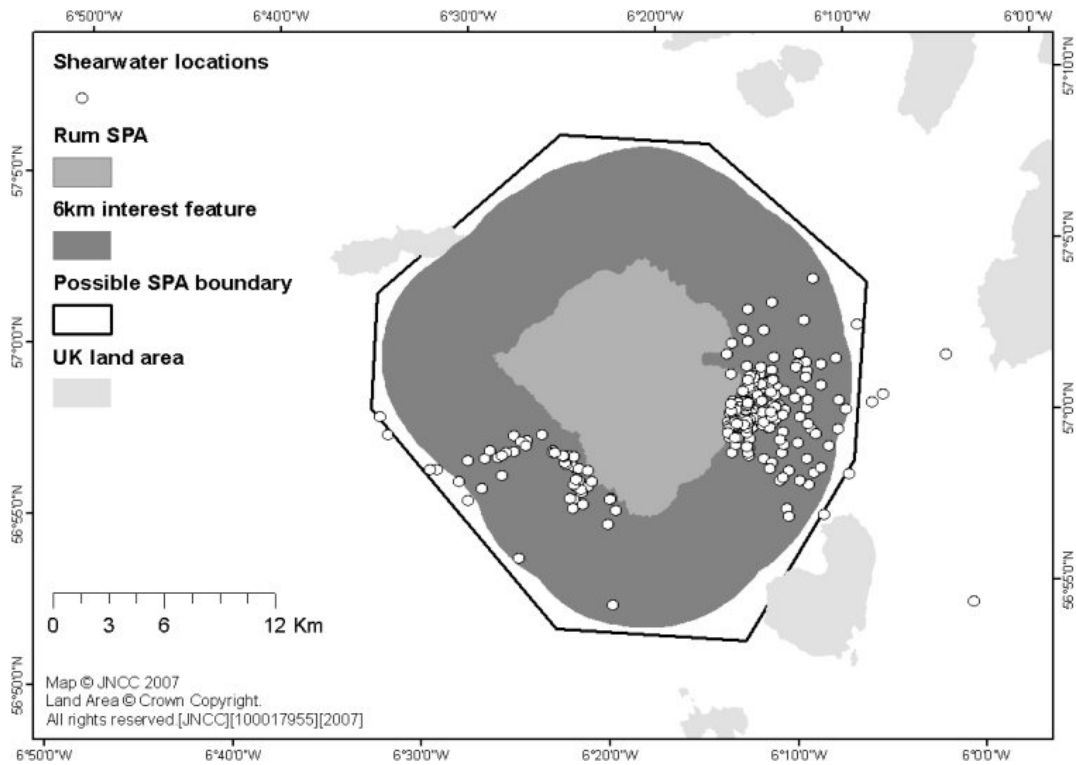


Figure 17. Map of the Rum SPA showing the recommended extent of the marine component of the interest feature, and a possible SPA boundary.

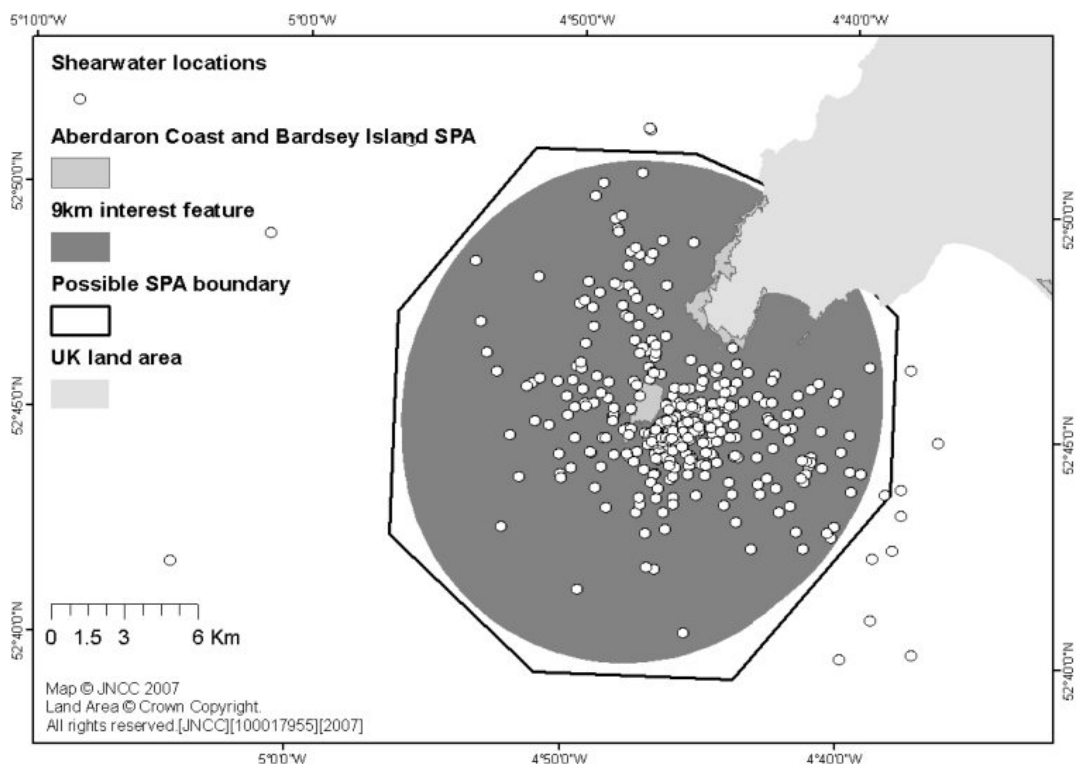


Figure 18. Map of the Glannau Aberdaron and Ynys Enlli / Aberdaron Coast and Bardsey Island SPA showing the recommended extent of the marine component of the interest feature, and a possible SPA boundary.

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8 Appendix 1

Table of possible SPA seaward boundary extension coordinates in degrees, minutes and decimal minutes (2 decimal places) of latitude and longitude.

	Longitude	Latitude		Longitude	Latitude		Longitude	Latitude
Skomer	-5°16.20'	51°47.10'	Rum	-6°33.96'	57°02.13'	Bardsey	-4°51.68'	52°51.16'
	-5°11.94'	51°45.52'		-6°24.73'	57°07.11'		-4°45.83'	52°51.16'
	-5°11.94'	51°41.56'		-6°16.77'	57°07.11'		-4°43.06'	52°50.47'
	-5°13.80'	51°39.24'		-6°7.87'	57°03.40'		-4°38.28'	52°47.71'
	-5°19.76'	51°39.24'		-6°7.87'	56°58.16'		-4°38.28'	52°43.76'
	-5°22.54'	51°42.92'		-6°13.07'	56°52.67'		-4°43.80'	52°39.54'
	-5°22.54'	51°45.18'		-6°23.22'	56°52.67'		-4°51.04'	52°39.54'
	-5°19.95'	51°47.10'		-6°33.96'	56°58.75'		-4°56.47'	52°42.47'
							-4°56.47'	52°47.42'