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This report presents the results of marine and freshwater scientific work carried out for Marine Scotland under external commission.

Investigations into the interactions between harbour seals (*Phoca vitulina*) and vessels in the inner Moray Firth.

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Executive Summary

Shipping activity has increased greatly over the past 50 years, leading to growing concerns about potential harmful effects of increased shipping noise on marine mammals and the potential for physical injury due to collisions.

When originally commissioned, this project was designed to investigate the interactions between seals and vessels operating in the inner Moray Firth as part of a study into the cause of a particular type of mortality in harbour seals (*Phoca vitulina*), characterised by distinctive spiral lacerations. Such stranded carcasses are often referred to as corkscrew seals. Results of investigations of the wounds and associated pathological features of these, together with the spatial and temporal patterns of occurrence, had led to the conclusion that collisions with ducted propellers were the most likely cause of these wounds. These types of propulsion systems are widely used on tug boats and other work-vessels. Activity by both types of vessel was expected to increase in the inner Moray Firth during planned construction work associated with port developments.

In late 2014, observations of grey seal *(Halichoerus grypus*) predation on conspecifics which produced similar wounds provided a plausible alternative explanation of the likely cause of spiral lacerations. At that time there was insufficient evidence to rule out interactions with vessels as a possible cause of some of these mortalities, so the requirement to investigate the temporal and spatial overlap between seals and vessels remained.

A telemetry based study of the swimming behaviour of harbour seals was carried out in the Moray Firth to (1) allow a comparison of seal movements and vessel movements and (2) compare the densities of seals and shipping traffic to identify areas with high spatial overlap. A secondary aim was to provide data on seal movements between haulout areas, to identify connectivity between seal haulout sites in the Dornoch Firth Special Area of Conservation (SAC) and the potential construction site at Ardersier in the inner Moray Firth.

During the two year study in 2014 and 2015, 37 Ultra High Frequency (UHF)/GPS tags were deployed on harbour seals at two different sites at Ardersier and in the Dornoch Firth. Locations from the animals were interpolated to produce regularised locations at three minute intervals. Each location was assigned a status of 'hauled out' (when the animal was on land), or on a 'trip' (when the animal was at-sea). Each trip was associated with a specific departure and destination haulout site. Trips to and from each haulout site were then combined by smoothing all locations to produce a usage surface that was weighted by the population estimate derived from the number of seals counted at that haulout site during annual aerial surveys. All haulout sites were combined to produce estimated mean and associated 95% confidence interval usage maps on a 0.5 km x 0.5 km grid in the Moray Firth.

These maps were compared with shipping activity using Automated Information System (AIS) vessel tracking data from MarineTraffic.com. AIS data provided information on vessel movements within the Moray Firth over the same period as the seal tracking study, for all vessels using an operating AIS transmitter. An estimated mean shipping usage map was developed in a similar manner to the seal usage map. The maps were combined by multiplying seal density by ship density for each grid cell to provide a total number of minutes of seal/vessel co-occurrence per year in the inner Moray Firth. Annual co-occurrence is therefore the sum, over a year, of the

number of times individual seal-ship combinations occur in a 0.5 km by 0.5 km grid cell multiplied by the time step, in this case five minutes.

An annual total of 130,395 minutes of seal-vessel co-occurrence was estimated for the study area. Although this value appears high, the study area encompasses 10,137 km^2 and areas with a high number of co-occurrences were localised. Only four grid cells (1 km^2) displayed co-occurrence values above 2,500 minutes per annum and these were in narrow channels through which seals travel to access their haulout sites. Offshore sites showed comparatively low co-occurrence rates even in areas with high levels of shipping traffic.

In comparison with previous estimates of seal-shipping spatial overlap throughout the UK, the estimates for the Moray Firth appear low. Although the co- occurrence maps do not show clear evidence of avoidance behaviour, areas of high seal and high shipping usage are not coincident.

There does not appear to be any obvious relationship between incidences of strandings of spiral lacerated (corkscrew) seals and areas where seal-shipping overlap is high.

These results are not conclusive, but it is clear that the number and location of corkscrew seal strandings within the Moray Firth are not proportional to the estimates of seal-shipping overlap. A previous analysis of seal shipping interactions around the UK coast also indicated that areas where high incidences of corkscrew strandings were located did not generally coincide with intense seal-shipping co-occurrence (Jones *et al.,* 2015b). Some areas where corkscrew seal strandings were recorded had low or zero estimates of seal-ship co-occurrence.

Further analyses including data from other seal telemetry studies should be carried out to further test these conclusions. However, this study has provided a useful method for identifying areas of high co-occurrence and provides a method for highlighting areas of importance when considering the degree to which seals interact with shipping at a broad spatial scale.

Observations of movements of individual seals and vessels did not show any apparent responses; seals did not appear to react to close passing vessels; they neither moved towards nor away from them. A single seal was observed swimming directly to a vessel at anchor and remaining in close proximity (<80 metres) for 4 hours. The majority of seal-vessel close-passes occurred in the localised areas of high co-occurrence identified in the seal/ship density mapping exercise and appeared to be largely a result of a funnelling effect.

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1 Introduction

1.1 Background

In recent years, increasing levels of anthropogenic activity in the marine environment have led to concerns about their potential detrimental effects on the marine environment (Tougaard *et al.*, 2008; Lynch *et al.*, 2009; Erbe *et al.*, 2012) and on marine mammals in particular (e.g. Wilson *et al*., 2007; Van der Hoop *et al*., 2013; Hastie *et al*., 2015). Shipping activity has increased significantly over the past 50 years with the world fleet of motorized vessels (exceeding 100 gross tonnes) expanding from ~200 million to 558 million gross tonnes (Endresen *et al.*, 2007). Shipping activity has been cited as a major concern for some marine mammal species due to acute impacts such as physical damage from collisions with fast moving vessels, as well as chronic effects associated with the concomitant increase in shipping noise.

1.2 Collisions

Injury due to collisions with fast moving vessels is regarded as a serious risk for large cetaceans and sirenians (Beck *et al.*, 1982; Laist *et al.*, 2001; Panigada *et al.*, 2006; Williams and O'Hara, 2010) and in certain locations the frequency of collisions between vessels and marine mammals can become a direct and immediate conservation threat, e.g. the risk of vessel strikes to Florida manatees (*Trichechus manatus*) (Beck *et al.*, 1982; Lightsey *et al.*, 2006). Collisions with vessels are thought to pose a lower, but still important risk to small cetaceans (Evans *et al.*, 2011). By comparison, the role of direct collisions in pinniped mortality is poorly understood. Trauma ascribed to collisions with vessels have been identified in a small proportion of both live stranded (Goldstein *et al.*, 1999) and dead stranded seals in the USA (Swails, 2005). However, in these studies less than 2% of all necropsied seal deaths were identified as resulting from vessel collisions.

1.3 Sound

The potential effects of shipping noise on cetaceans have been widely reported (Solan *et al.*, 2016) and are a concern in some locations for acoustically sensitive species (e.g. Kastak *et al*., 2005; Merchant *et al.,* 2014). Phocid seals have sensitive hearing over a range from a few hundred Hz to around 60 kHz (Kastak and Schusterman, 1998). Low frequency noise from shipping is likely to be audible to both grey and harbour seals at relatively long ranges and has the potential to mask their vocalisations (the amount by which the audibility threshold for one sound is raised by the presence of another (Moore, 1982)). However, little is known about the effects of disturbance from shipping on the distribution, movements or behaviour of pinnipeds. Vessel activity is known to disturb seals from terrestrial haulout sites (Jansen *et al.*, 2015; Paterson *et al.*, 2016) but there appears to be no published information on the at-sea distributions of seals in relation to vessel activity.

1.4 Objectives

When originally commissioned, this project was designed to investigate interactions between seals and vessels operating in the inner Moray Firth, which were associated with a proposed re-development of the port facility at Ardersier. At the time, there was a concern that vessels operating close to haulout sites at Ardersier posed a specific risk to harbour seals. A particular type of mortality characterised by the presence of distinctive spiral lacerations rotating around the body have been recorded at a wide range of sites around the North Atlantic (Thompson *et al.*, 2010; Bexton *et al.*, 2012). Such stranded carcasses are often referred to as corkscrew seals (Bexton *et al.*, 2012; Brownlow *et al.,* 2016). Results of investigations into these wounds and associated pathological features, together with the spatial and temporal patterns of occurrence (Thompson *et al.*, 2010; Bexton *et al.*, 2012; Onoufriou *et al.*, 2014), led to the conclusion that collisions with ducted propellers were the most likely cause.

Topographically the Ardersier port development site is similar to Blakeney in Norfolk where it was thought that similar increases in vessel activity had been responsible for a spate of harbour seal mortalities. This led to concerns that the use of vessels with large ducted propellers, in an area not previously exposed to such vessels, and close to a large seal haulout site might lead to similar mortality events. This project was commissioned to investigate direct interactions between seals and shipping.

The primary aim of the project was to collect fine-scale movement data of seals and vessels associated with the port re-development to investigate reactions of individual seals to vessel activity and identify collision events. This would provide a sensitive monitoring programme to identify harmful interactions in near real-time and through identifying behaviour patterns of seals and vessels, assess the risk of interactions. A response plan was developed to instigate mitigation measures when seal-ship collisions were identified. However, the identification of grey seal predation as a more likely cause of the spiral lacerations rather than ducted propellers on vessels and delays in the Ardersier port development significantly altered the objectives of the study.

In December 2014, a series of observations from the Isle of May showed an adult male grey seal capturing, killing and cannibalising weaned grey seal pups (Bishop *et al.*, 2016). Detailed pathological examination of the resulting carcasses (Brownlow *et al.,* 2016) showed spiral lesions akin to those seen on typical corkscrew seals which had previously been attributed to propeller interactions. Together with observations in Germany of predation by male grey seals producing similar injuries to harbour seals (van Neer *et al.*, 2015) these observations provided a plausible alternative explanation for the spiral injuries to seals. Observations made in Germany prior to the first observed events in the UK (van Neer *et al.*, 2015), as well as additional events at the same and other UK sites in the months immediately after the initial observation, confirmed that such attacks are widespread around the UK and North Sea coasts and often produce these characteristic spiral lesions, leading to significant doubt about the association between these injuries and ducted propellers (Brownlow *et al.,* 2016). Investigations into the occurrence of spiral injuries and the extent and importance of grey seal predation on seals are continuing. Since there is not sufficient evidence to completely rule out interactions with ships as a possible cause of some of these mortalities, some aspects of the proposed seal-ship interaction study continued.

There were also considerable delays to the Ardersier Port re-development, with no clear indication of when work was likely to start. As a result, the project was re-focused as a more general study of interactions between seals and shipping. Consequently, the emphasis on seal movements relative to the expected intense vessel activity at the Ardersier site was changed to produce a more general study of harbour seal movements in relation to broad-scale vessel distribution within the Moray Firth.

Under the revised project scope, the seal tracking programme had two aims:

(1) To collect data on the movements of harbour seals to allow comparison with vessel movements and identify areas of spatiotemporal co-occurrence in the Moray Firth;

(2) To collect data on seal movements between regions to identify connectivity between the haulout sites in the Dornoch Firth Special Area of Conservation (SAC) and the potential construction site at Ardersier.

1.5 Data sources

1.5.1 Vessel traffic - Automated Identification Systems (AIS)

Characteristics of shipping traffic were extracted from AIS data provided by a commercial web-based AIS data archiving company (Marine Traffic, http://www.marinetraffic.com/). The International Maritime Organisation (IMO) requires all vessels 300 gross tonnes and above, and passenger vessels regardless of size, to carry an operating AIS transmitter (IMO, 1980). Vessels such as fishing boats, pleasure craft and pilot vessels are also included sporadically, although they are likely to be underrepresented. These data provide a relatively high temporal resolution track for each vessel equipped with an AIS transmitter. The transmitted data also contains a range of information at each location fix, including the operational status of the vessel, its heading and speed over the ground and in most cases, a list of physical characteristics of the vessel such as draft, gross-tonnage and length.

Online AIS services allow real-time assessment of vessel traffic, but a comprehensive, fully quality-assured database of the high resolution AIS data was required to provide a reliable usage estimate of shipping traffic within the Moray Firth. The full data set was also required to allow assessment of co-occurrences of individual ships and seals. Marine Traffic provided data detailing every ship's AIS record within the study area over the same sampling period as that covered by the seal telemetry data (described below) at a maximum temporal resolution of one record every 2 minutes.

1.5.2 Seal movement – Ultra High Frequency/Global Positioning System (UHF/GPS) telemetry

High resolution seal movement data were required to accurately describe the at-sea distribution of seals and to provide reliable descriptions of the movements of individuals in relation to vessels. Standard archival tags, previously used to study seal movements (e.g. Sharples *et al*., 2012; Russell *et al*., 2014; Hastie *et al.,* 2015) can produce high resolution data for all trips that return to a haulout site. However, any lethal encounter with a vessel would not be recorded as data are only retrieved during subsequent haul out events. A near-real time tracking system capable of relaying data from seals at sea was deemed to be an essential aspect of the study design.

No suitable telemetry system was available commercially to address this requirement and an attempt in 2012 to adapt satellite relay data logger tags that use the Argos satellite system for data transmission (Argos, 2011) was not successful. As part of a previous study requiring real-time tracking of seals from a small vessel, a collaboration was established with a commercial telemetry developer (Pathtrack Ltd) to design and build a telemetry system that combined the capacity to provide near real-time at-sea positioning of animals with data storage and periodic transmission to archival base stations on shore (Gordon *et al*., 2015; Hastie *et al*., In *Review*).

The UHF/GPS tags recorded location data when an animal surfaced. These data were processed by the tag using a Fastloc algorithm and then transmitted by UHF telemetry (in the 869.4-869.7 MHz frequency band) during the next surfacing (each surfacing transmitted the previous surfacing's location). Data were also stored on the tags so that they could be downloaded by UHF to fixed base stations once animals had hauled out ashore and were within line of sight of a base station. The tags were capable of storing up to 250,000 locations.

The base stations were fully autonomous, being powered from internal batteries charged by solar panels. When seals hauled out within range (line of sight) of a base station, stored data were transferred from the tags. When the base station signalled that data had been successfully transferred, the data pointer in the tag would be advanced to a new section of memory so the data were not deleted from the tags. Data were downloaded from the base stations periodically, either by connecting them to a laptop using a USB cable or by wireless transfer through a hand held mobile wireless receiver. The combination of two way communications between the tags and the base stations and multiple methods for retrieving data from base stations and tags resulted in a system that was flexible and adaptable. A complete database of all the telemetry data was assembled once all the tags had detached during the annual moult.

1.5.3 Harbour seal counts

Data on the number of seals for each discrete haulout were obtained from the SMRU aerial survey database. Aerial surveys of the harbour seal haulout sites in the Moray Firth are conducted annually during the moult in early August. Seals are counted from photographs taken from fixed-wing aircraft using oblique photography with a digital SLR camera with an image-stabilising lens. All seals along a specified coastline are counted and coordinates are recorded to an accuracy of +/- 50 m. Surveys take place within 2 h of low tide when low tide is between 12:00 and 18:00 h (Thompson *et al*., 2005). Survey data spans the period from 1997 to 2013 (SCOS, 2015). Counts from 2013 were used throughout this study.

2 Methods

2.1 Study area

Figure 1 shows the inner Moray Firth study area. It also highlights the sites referred to throughout this report. Seals were tagged at Ardersier and in the Dornoch Firth. The Ardersier tagging site is a sheltered, mainland sand beach adjacent to a disused service port in the narrow, western end of the inner Moray Firth (57.59185° N; 4.036346°W). The beach usually has a large haulout of both grey and harbour seals and groups of seals can occur anywhere along its 2.3 km length. The capture sites in the Dornoch Firth were sand bars in the main channel (57.838702°N; 4.047408°W), within a designated SAC for harbour seals. The 2013 aerial survey counted 199 harbour seals at Ardersier and 143 harbour seals within the Dornoch Firth SAC (SCOS, 2015).

2.2 Seal telemetry data

A total of 37 harbour seals were fitted with UHF/GPS tags (Pathtrack Ltd.) over a two year period; 12 at Ardersier in March 2014; 12 at Ardersier and 10 at Dornoch in March 2015. Three additional tags deployed in 2015 were fitted to seals upon their release after being held temporarily at the SMRU captive facility. In total, 31 tags produced and transmitted data successfully (Table 1).

Seals were caught using either tangle nets or seine nets adjacent to the haulout sites. Once caught, seals were anesthetised with intravenous Zoletil100® (Virbac, France) at a dose rate of 0.5 mg kg^{-1} and a tag was glued to the fur at the base of the skull using Loctite® 422 (Loctite, UK) instant adhesive. Tags began operating upon contact with seawater and were programmed to record a location every 3 minutes. This maximised the probability of capturing a location for every inter-dive surfacing while preserving sufficient battery life until the tag naturally fell off during the moult in late summer. Once tags were continually dry for 15 minutes they entered a 'haulout mode' and switched to a lower sampling rate of one location every 60 minutes. The inter-location time intervals are presented in Figure 2. The mean inter-location interval was 4.4 minutes.

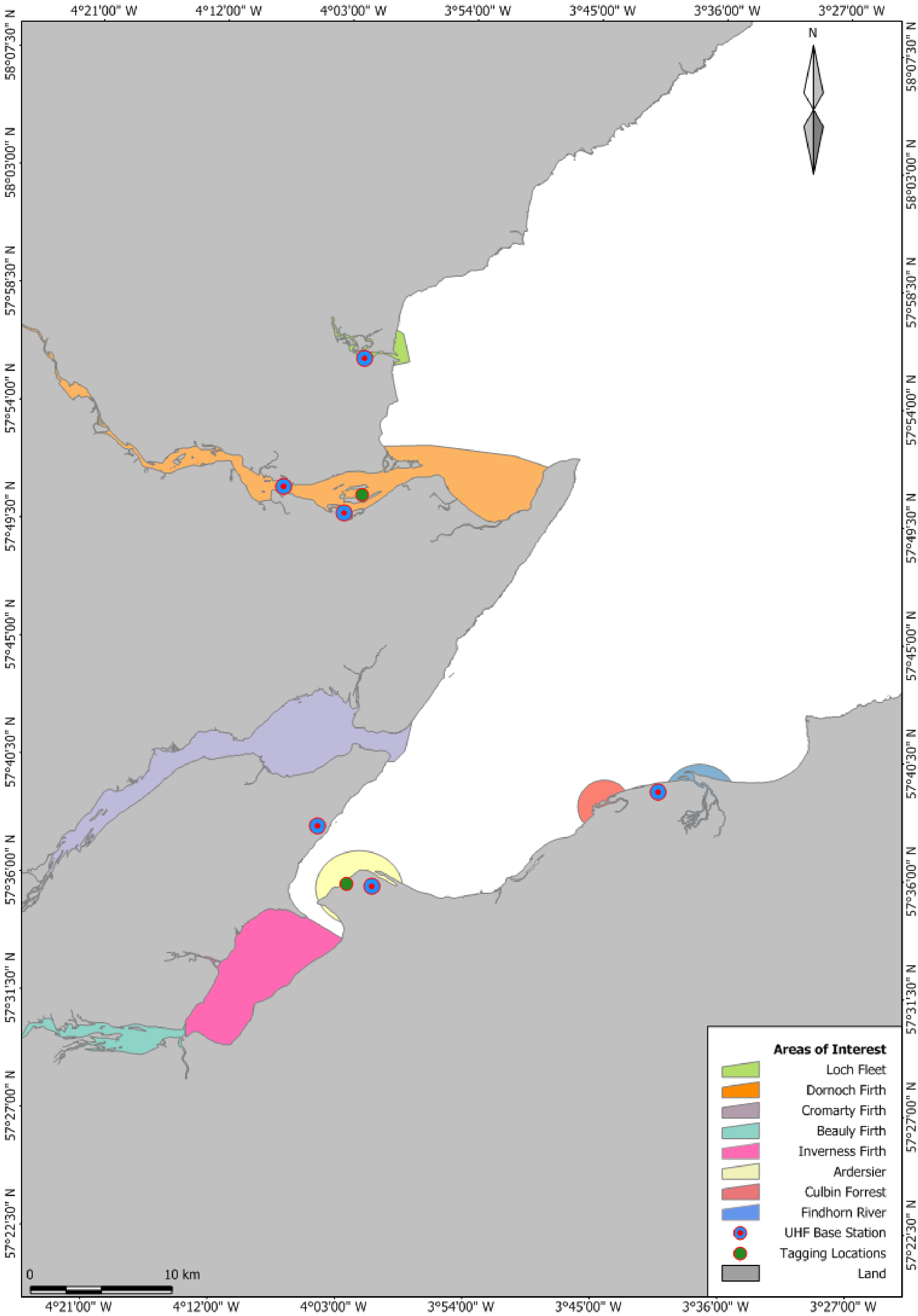

Figure 1: Moray Firth study area, tagging locations and UHF base station locations.

Table 1. Capture details and total tag duration for each individual seal. Tags that produced no data are highlighted in bold.

Tag ID	Year	Tagging Site	Sex	Mass at Capture (Kg)	Tag Duration (Days)
65170	2014	Ardersier	M	74.8	57.9
65180	2014	Ardersier	M	77.8	92.3
65181	2014	Ardersier	M	83.6	59.9
65184	2014	Ardersier	M	81.8	39.4
65185	2014	Ardersier	M	88.8	73.2
65186	2014	Ardersier	F	90.2	35.9
65187	2014	Ardersier	M	60.6	39.1
65189	2014	Ardersier	M	56	0.3
65190	2014	Ardersier	M	51.8	50.4
65192	**2015**	**Ardersier**	**F**	**70.1**	**-**
65194	2014	Ardersier	M	90.6	67.8
65196	2014	Ardersier	F	74.2	66
65198	2014	Ardersier	F	82	45.5
65145	2015	Ardersier	M	77.3	61.5
65202	2015	Ardersier	M	57.2	156.7
65203	**2015**	**Ardersier**	**M**	**85.4**	**-**
65204	2015	Ardersier	M	87.2	97.5
65206	2015	Ardersier	F	82.7	96.6
65207	2015	Ardersier	M	89.7	131.8
65208	**2015**	**Dornoch Firth**	**F**	**104.9**	**-**
65209	2015	Ardersier	M	79.1	145.8
65212	2015	Ardersier	M	87.1	98.3
65213	2015	Ardersier	F	94.3	91
65214	2015	Ardersier	F	79.7	89.7
65216	**2015**	**Ardersier**	**F**	**89.9**	**-**
65217	2015	Ardersier	M	85.1	111
65219	2015	Ardersier	F	80.3	98.2
65220	2015	Ardersier	M	87.7	114.2
65226	2015	Dornoch Firth	M	90.3	37.9
65232	**2015**	**Dornoch Firth**	**M**	**85.9**	**-**
65233	2015	Dornoch Firth	M	65.5	131.9
65234	2015	Dornoch Firth	M	88.5	38.6
65241	2015	Dornoch Firth	F	93.9	3.4
65249	2015	Dornoch Firth	F	80.3	3.9
65255	2015	Dornoch Firth	M	62.7	84.1
65258	2015	Dornoch Firth	F	72.7	20.9
65259	**2015**	**Dornoch Firth**	**F**	**82.9**	**-**

Archiving UHF receiver base stations were erected at six locations around the Moray Firth (Figure 1). These stations provided coverage of haulout sites that held 76% of the total number of seals counted during the most recent aerial surveys of the inner Moray Firth. Archival data from hauled out seals and real-time data from seals at-sea were logged continuously when in range and downloaded from the base stations at approximately weekly intervals.

2.3 Seal usage maps

Usage maps were produced based on the methodology of Jones *et al.* (2015a). A study area was delineated using the spatial extent of the seal telemetry data. Location data from the seals were cleaned to remove erroneous locations using thresholds of residual error (<200) and the number of satellites (>4) as per Russell *et al.* (2011). Additionally, speed over the ground was calculated between pairs of locations and the second location was removed when the estimated speed over the ground was greater than 3 ms^{-1} (a conservative estimate, given a constant transit speed above this was unlikely). Tracks of individual animals were linearly interpolated to produce one location at each 3-minute interval, which replicated the tag sampling rate (Figure 2); at a resolution of 0.5 km x 0.5 km grid cells, a location every 3 minutes ensured that a seal would be unlikely to transit across more than one grid cell along a transit line without being recorded, assuming a maximum transit speed of 2.5 ms^{-1}.

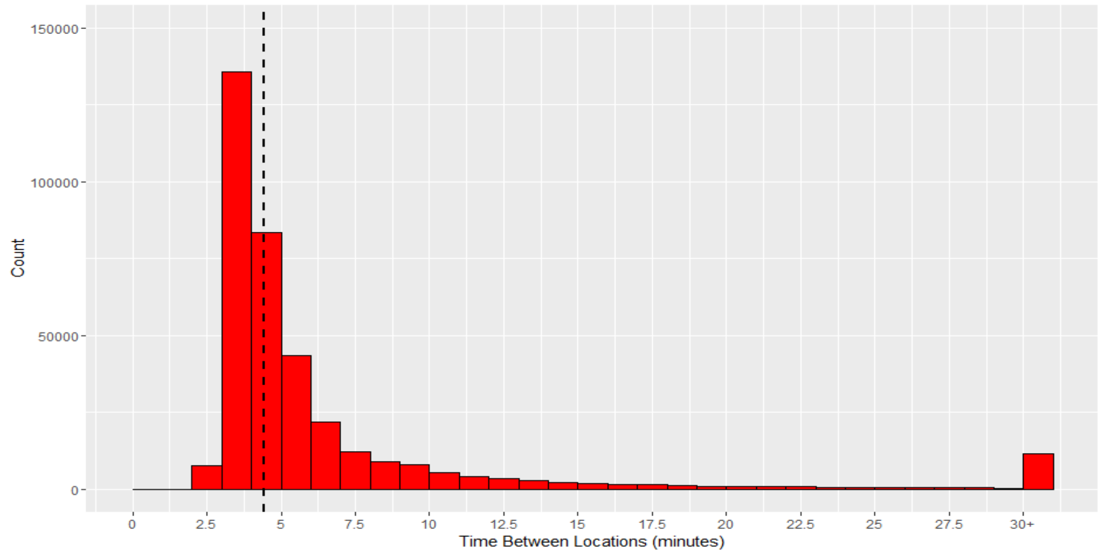

Figure 2: Histogram showing the time (in minutes) between each pair of cleaned locations. The mean inter-location interval is identified by the dashed line.

Occasionally, some tags did not record location information for a period ranging from a few hours up to several days, due to a software error. Periods where location information was not recorded were removed to avoid the biased estimation of usage in particular areas, e.g. to avoid estimating high usage due to apparently slow swimming along straight line “tracks” joining points separated by gaps of many hours.

To scale the usage maps to population level, aerial survey counts and locations arising from the telemetry data were required to be spatially explicitly linked.

Individual haulout sites could be identified through the aerial survey data and by locations at which telemetered animals had hauled out. In all instances, telemetry haulout sites matched aerial survey haulout sites (at the 0.5 km x 0.5 km scale of the analysis). However, in some locations seals were counted in aerial surveys at sites with no associated telemetry haul out events. Individual haulout sites were therefore clustered, based on visual inspection of their close proximity to each other (Figure 3), so that all aerial survey counts could be linked to telemetry data through haulout site cluster locations.

Continuous spatial surfaces to represent the proportion of time animals spent in different areas were derived by kernel-smoothing the at-sea telemetry data. The 'ks' package in R version 3.2.3 (Duong, 2016; R Core Team, 2015) was used to estimate the spatial bandwidth of the 2D kernel applied to each animal/haulout cluster map. In some instances, only a small number of locations were associated with an individual at a haulout site and bandwidth could not be estimated. In these cases, bandwidth for the individual rather than the specific animal/haulout site combination was used.

To quantify within haulout site uncertainty, linear models were built to estimate variance. All haulout sites with more than 7 animals associated with them were used based on sensitivity analyses conducted by Jones *et al*. (2015a). Kernel smoothed density estimates were bootstrapped 1000 times for each haulout site cluster to produce estimated means and variances. Each kernel smoothed map was normalised then reweighted based on the amount of data each animal contributed to the analysis (termed Information Content Weighting). Maps from each haulout site were aggregated, normalised and then scaled according to the number of animals observed at that site in the surveys, also accounting for the mean proportion of time animals spent at-sea. Confidence intervals for the usage maps were estimated based on variance of onshore counts and variation between spatial usage by individuals using a single haulout site (Jones *et al*. 2015a; supplementary information).

Seals in Loch Fleet were not included in these analyses. Only one tagged seal was observed to haulout in Loch Fleet and its movements were not considered representative enough to provide an accurate estimate of usage by seals from that sub-population. Anecdotal evidence from telemetry studies using animals tagged at Loch Fleet suggests that their movements would not substantially affect the usage in the areas covered by the tagged seals in this study. Furthermore, high shipping densities do not appear to coincide with the at-sea usage of the one animal observed to haul out at Loch Fleet. Excluding this animal and the aerial survey data from Loch Fleet will have little effect on the estimated levels of co-occurrence in the inner Moray Firth; although it will lead to underestimation for the north of the Moray Firth. A large data set from 25 harbour seals tagged at Loch Fleet, by Aberdeen University was been collected over the same time period. Therefore rather than using the one animal here to represent the Loch Fleet seal usage these data should be incorporated at a later stage in a wider analysis.

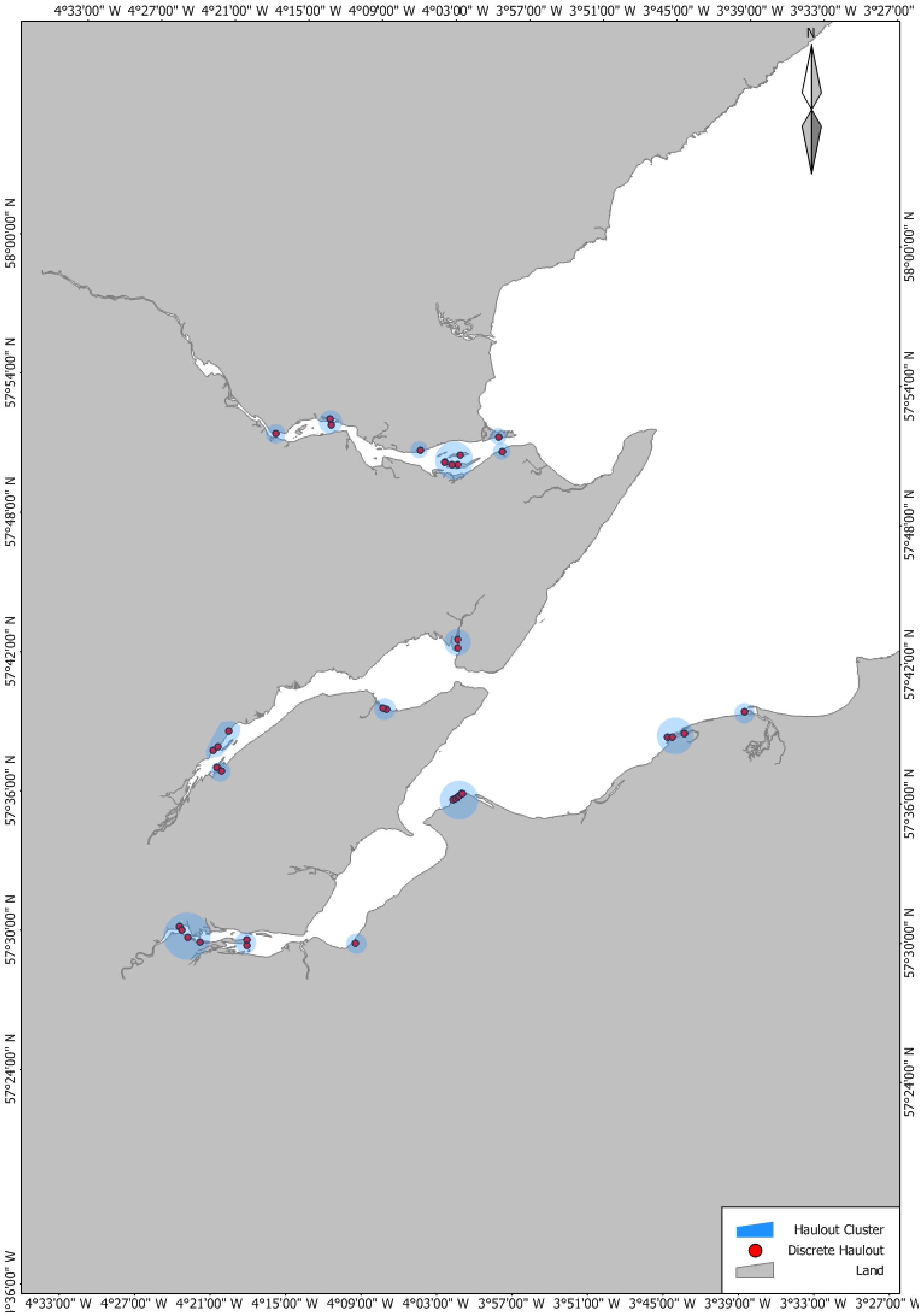

Figure 3: Haulout clusters for the inner Moray Firth. Discrete haulout sites without an overlaid blue haulout site cluster shape were treated as separate haulout clusters. For geographic area identification refer to Figure 1.

2.4 AIS vessel tracking data and seal-shipping co-occurrence[1]

AIS data describing shipping traffic in the Moray Firth between 11th March and 18th August in 2014 and 2015, were obtained from a commercial AIS company (Marine Traffic). This provided contemporaneous data to the seal telemetry data. AIS data defined 31 unique vessel types which were grouped into nine vessel categories of similar size and speed (Table 2). Vessels exhibiting ambiguous vessel type identifiers were grouped under 'Unspecified'. It was assumed that all shipping traffic was represented due to the AIS regulations applied to vessels 300 gross tonnes and over.

AIS data were filtered to exclude all vessels travelling at less than 0.2 knots. Every vessel location provided an associated logged speed (speed through the water), thus the filter would still include any vessel stationary on dynamic positioning (identified as a potential source for detrimental interaction with a seal). The highest temporal sampling rate for AIS transmitters was set to one location every 2 minutes, although the time between transmitted locations was often longer than this. To ensure seal and ship usage maps could be combined accurately, AIS data were linearly interpolated to 3 minute intervals so that seal and vessel movement data had the same effort associated with them. Both AIS and seal telemetry location data were gathered via GPS with a very high locational accuracy so location uncertainty was assumed to be negligible.

Ship usage maps were produced for each vessel group by overlaying locations from each vessel on the same 0.5 km x 0.5 km grid map created for the seal maps. The total number of locations within each grid cell was calculated for 2014 and 2015 and the mean of these values was taken as the estimated density. These values represented the ship usage over 160 days and the estimates were then scaled up by 365.25/160 to represent annual shipping usage in the inner Moray Firth. Shipping is assumed to have low temporal stochasticity and therefore simple multiplicative scaling up to annual usage is justified.

Mean annual number of minutes of harbour seal-shipping co-occurrence was calculated by first multiplying the number of vessel locations within a grid cell by seal usage for that grid cell. A co-occurrence was then defined as the simultaneous occupancy of a grid cell by a specific seal-vessel combination. Multiple co-occurrences of specific seal-vessel combinations were possible if both occurred more than once within that cell. This assumes that for vessels travelling at a speed slow enough to remain in a grid cell for more than one regularised location (i.e. travelling slower than 5.3 knots), multiple co-occurrences can occur between seal-vessel pairs. As the data used to estimate initial co-occurrence per grid-cell were interpolated to 5-minute intervals, the co-occurrence value was then multiplied by 5 to produce the estimated, annual number of minutes of co-occurrence of seals and vessels in each cell.

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[1] The term co-occurrence is used here to represent instances where individual seal and ship pairs coincided within a defined area. This is analogous to an encounter, but co-occurrence is used here to avoid potential confusion with use of the term encounters in Collision Risk Models.

Table 2. Total number of unique vessels in each vessel grouping and their constituents.

Vessel Type	Grouping	Number of Unique Vessels	Total Number of Grouped Vessels
Tug	1	73	73
Tanker	2	79	558
Tanker - Hazard A (Major)		9	
Tanker - Hazard B		7	
Tanker - Hazard C (Minor)		7	
Tanker - Hazard D (Recognizable)		3	
Cargo		424	
Cargo - Hazard A (Major)		27	
Cargo - Hazard C (Minor)		2	
Fishing	3	276	287
Dredger		11	
Pilot Vessel	4	2	324
Port Tender		2	
Sailing Vessel		224	
Local Vessel		6	
Pleasure Craft		90	
Dive Vessel	5	14	14
Search and Rescue	6	30	38
High Speed Craft		7	
Law Enforcement		1	
Military Ops	7	15	15
Passenger	8	62	62
Unspecified	9	172	172

2.5 Individual seal-ship movements

To quantify interactions between seals and ships, the distances between individual seals and the closest vessel were calculated. For computational efficiency, both the ship and seal locations were interpolated to the same 15 minute intervals. Distance between each seal and each ship were calculated at each time step. For each seal the distance to the closest vessel was retained. On each occasion when a seal ship distance was less than 0.1 km, the tracks of both the ship and seal over the preceding and following 12 hour periods were inspected visually. The direction of movement of the seal relative to the ship's track was used to visually identify any potential attraction or avoidance behaviour.

3 Results

3.1 Seal telemetry data

In total, 2241 seal days of data were collected. The amount of data was heavily skewed toward Ardersier tagged animals because very little data was collected by the receiving station in the Dornoch Firth (Figure 4). The base stations covering the Dornoch Firth were relocated twice and on each occasion the reception range was tested and appeared to provide adequate coverage. Finally, a series of manual data logging sessions were carried out in July and August. No seals were detected in the Dornoch Firth during these sessions.

There are three possible reasons for the lack of data from tags in the Dornoch Firth:

1. The tags malfunctioned and/or were scheduled incorrectly prior to attachment and therefore could not function as desired. However, the base station was functioning as it received and successfully logged data from other transmitters. All tags were programmed in an identical fashion so this seems an unlikely explanation.
2. Heavily used haulout sites which were out of range of the base stations were used and the seals did not surface within line-of-sight of a base station while in transit to and from these sites. As demonstrated above, the positioning of the base stations meant that 76% of seals hauled out during aerial surveys would have been covered.
3. Seals left the area prior to transmitting locations and did not return to within line-of-sight of a base station for the remainder of the tag's lifespan.

At present it is not possible to confirm which of these scenarios occurred.

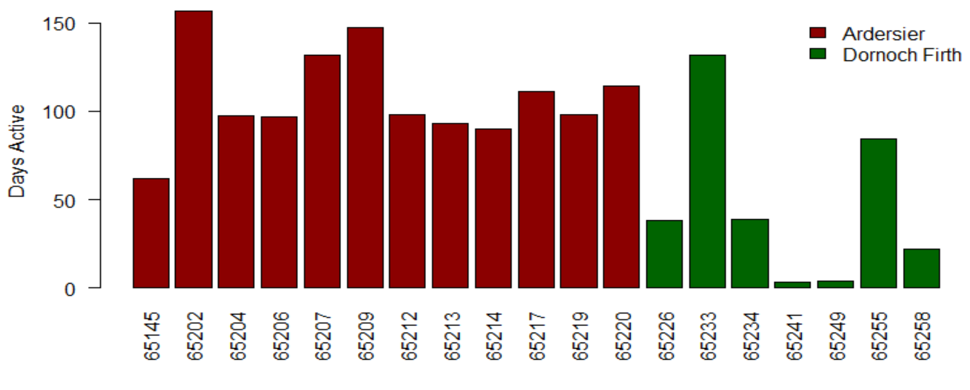

Figure 4: Total number data transmission days for each study animal in 2015.

Animals tagged at Ardersier showed varying degrees of site fidelity with haulout sites restricted to the southern coast of the Moray Firth, Loch Fleet, the Beauly Firth and the Cromarty Firth (Figures 5 and 6). Seal Tag ID 65147 was the only Ardersier-tagged animal observed to enter the Dornoch Firth during the study period although it did not haul out there. All animals tagged at Ardersier used the most easterly haulout sites near Culbin Forest and the mouth of the Findhorn River in addition to the tagging site. Furthest trip distance from the tagging site was 139.64 km (Tag ID 65204). Three male animals (Tag IDs 65220, 65212 and 65217) travelled further than 50 km from the tagging site. The longest observed trip was also by Tag ID 65204 and lasted 17 days. No animals from 2015 tagged sample entered Loch Fleet, however, one animal entered and hauled out there in 2014.

Seven of the 10 animals tagged at Dornoch produced data. Of these, five showed site fidelity to the tagging site; however, Tag IDs 65233 and 65255 showed movement between the two tagging sites (Figure 7 and Figure 8a). Four seals remained within a 25 km radius of the tagging site, although two of them (Tag IDs 65249 and 65241) only transmitted for 5.1 and 3.4 days respectively and are not reliable indicators of free-ranging behaviour. The furthest trip distance from the Dornoch tagging site was 100.9 km. A further two individuals were seen to travel further than 50 km from the tagging site: Seal Tag IDs 65226 and 65233 both of whom were male.

A total of 11 discrete haulout sites were used by tagged seals during the study period (Figure 9). Apart from Loch Fleet, all of these haulout sites were used by at least two tagged seals, suggesting a high degree of interchange between sites. In terms of directly observed movements between the harbour seal populations in the Dornoch Firth SAC and the potential construction site at Ardersier, only two seals used haulout sites in both areas. Both were tagged in the Dornoch Firth, i.e. two out of ten seals tagged in the SAC moved to the proposed construction site (Figure 8a). Conversely none of the seals tagged at Ardersier in 2014 or 2015 used haulout sites within the SAC. One seal in the 2014 Ardersier sample moved to Loch Fleet, a site adjacent to the SAC (Figure 8b) and made repeated foraging trips from and returning to, Loch Fleet for the rest of the tracking period.

The two seals that used both the Ardersier and Dornoch SAC haulout sites moved repeatedly between them. The tracking record for Tag ID 65233 lasted 131 days and included 166 individual trips, 7 of which resulted in transitions between Ardersier and Dornoch. The tracking record for Tag ID 65255 lasted 84 days and included 183 individual trips, 5 of which resulted in transitions between Ardersier and Dornoch. These two seals therefore alternated between the SAC and Ardersier approximately once every 18 days.

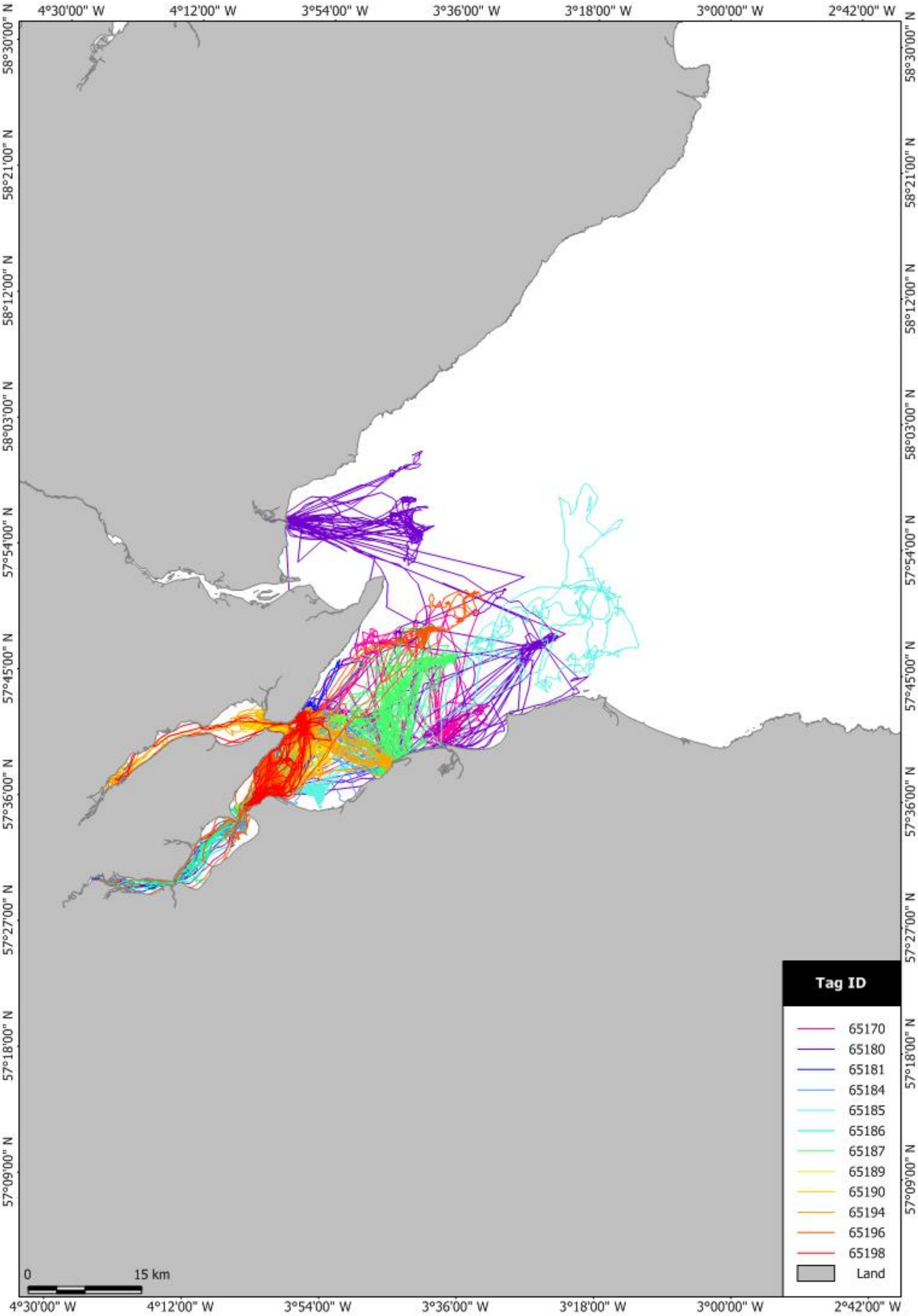

Figure 5: Telemetry tracks from individual seals tagged at Ardersier in 2014. For geographic area identification refer to Figure 1.

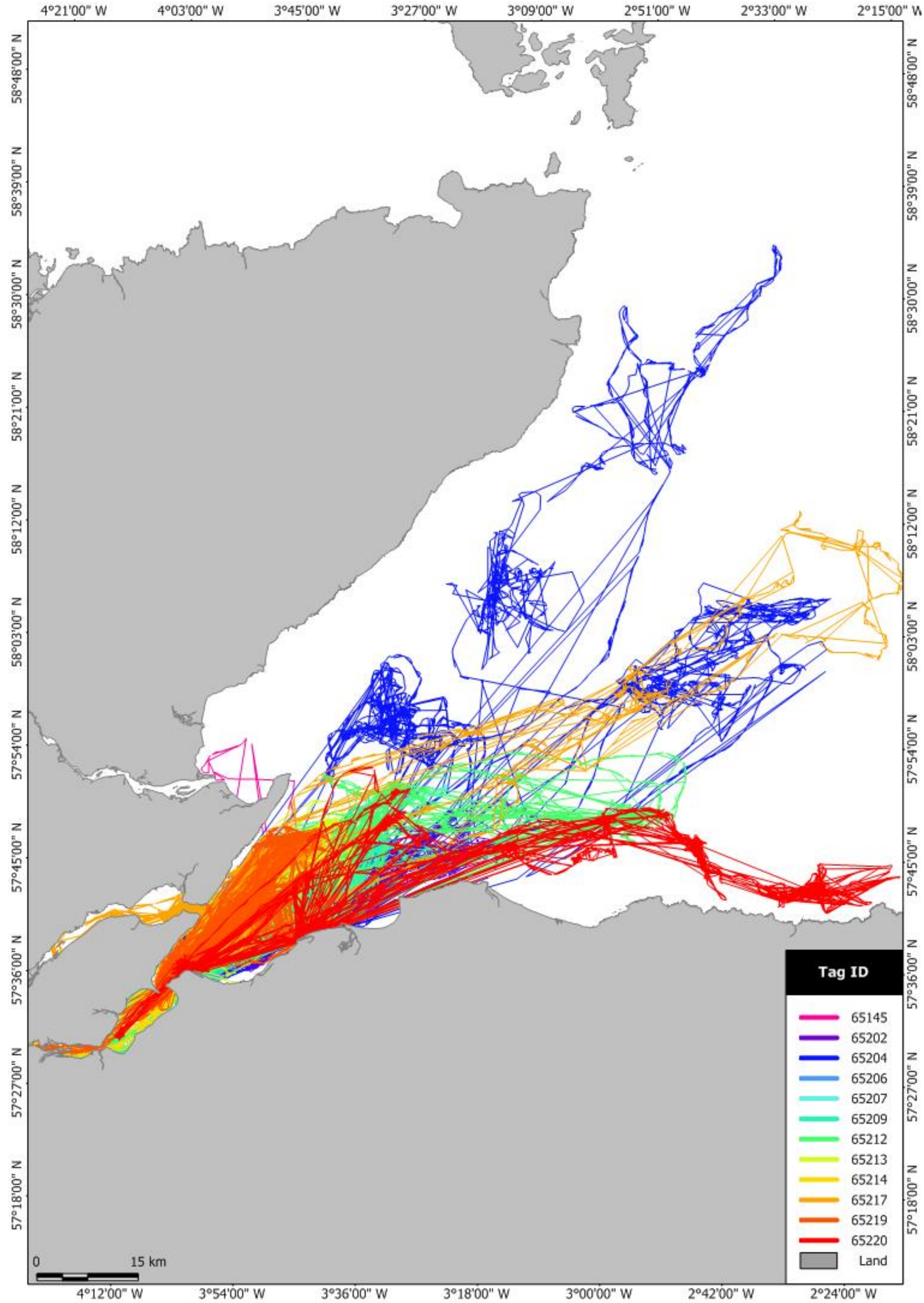

Figure 6: Telemetry tracks from the individual seals tagged at Ardersier in 2015. For geographic area identification refer to Figure 1.

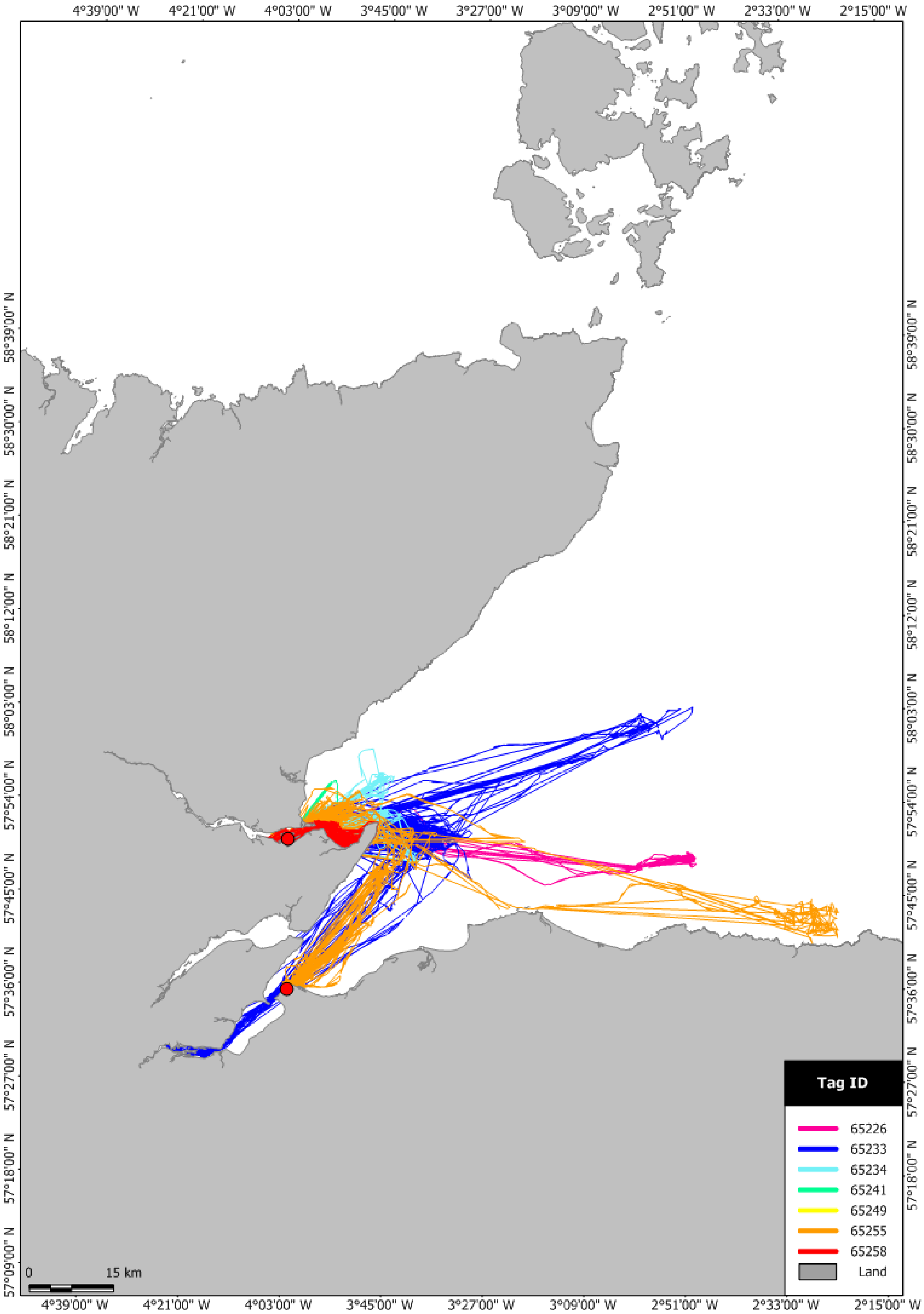

Figure 7: Telemetry tracks from those individual seals tagged in the Dornoch Firth in 2015 that provided data. For geographic area identification refer to Figure 1.

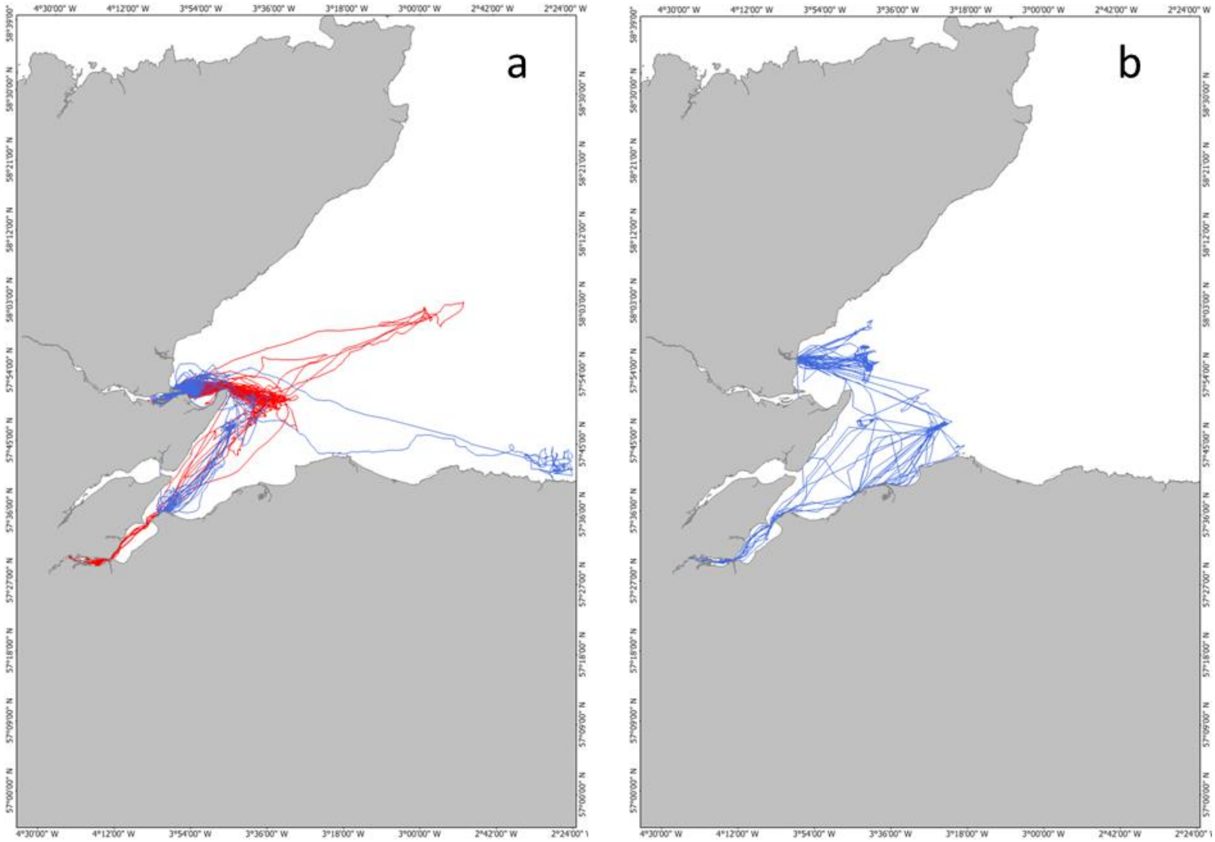

Figure 8: Tracks of (a) two seals tagged in the Dornoch Firth SAC in 2015 that moved to and used haulout sites at Ardersier and (b) one seal in 2014 that moved to and used haulout sites in Loch Fleet, adjacent to the SAC. For geographic area identification refer to Figure 1.

3.2 Seal usage

Figure 10 shows the estimated usage based on the movement patterns of the telemetry tagged seals in this study. The usage estimate for each cell is equivalent to the number of seals expected to be in it at any time. Figure 10 shows relatively high usage by seals near haulout sites in the inner Beauly and Cromarty Firths, Ardersier, Culbin Forest, Findhorn and the mouth of the Dornoch Firth (Figure 10). Additionally, high usage sites were identified 11.5 km north of the Culbin Forest haulout and in the outer Cromarty Firth. Sites further offshore were only used by three seals and to a lesser degree than the inshore sites so are represented by relatively low usage estimates. Upper and lower 95% confidence intervals for the usage surface are presented in Figures 11 and 12.

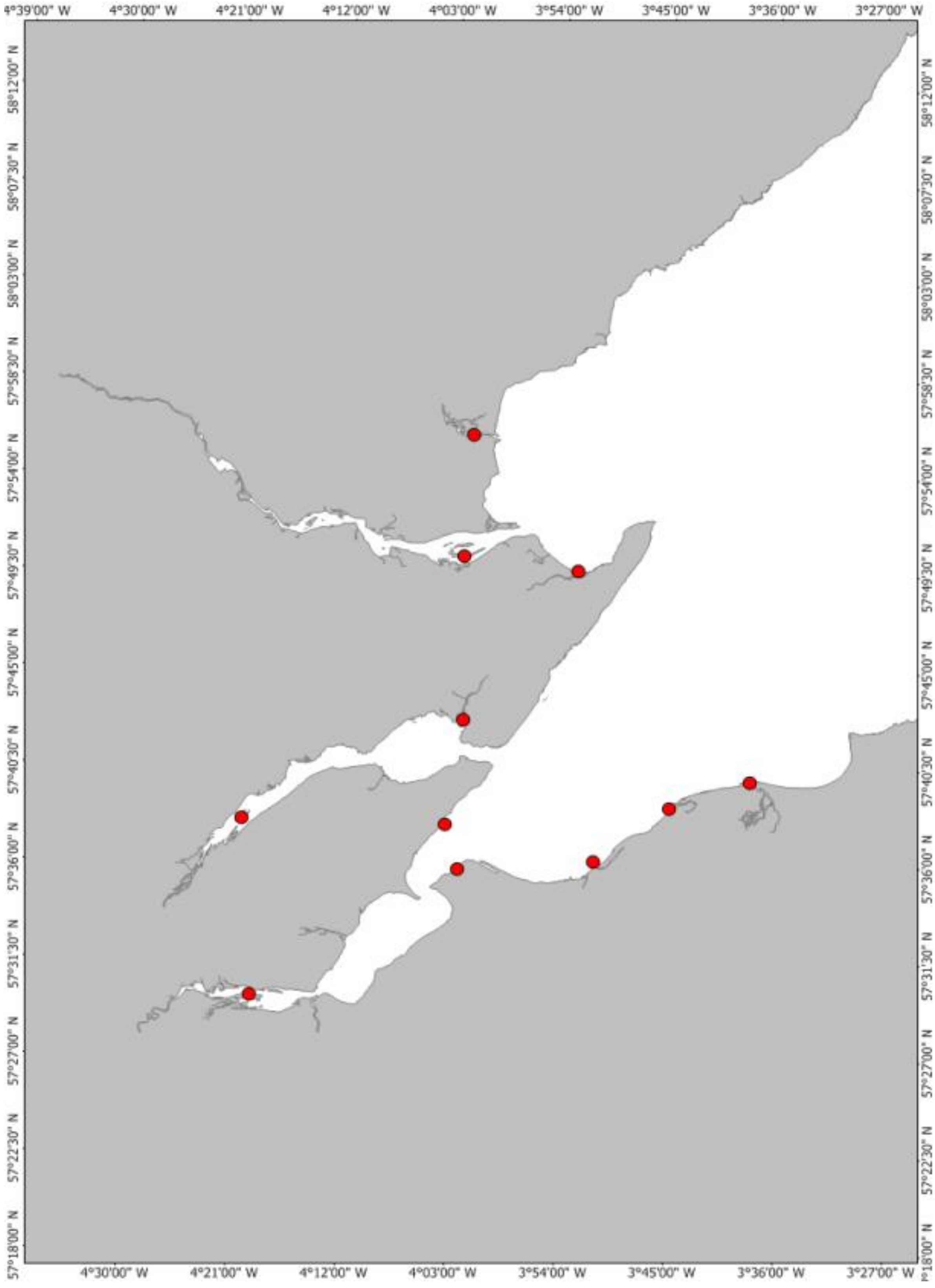

Figure 9: The 11 haulout sites used by tagged seals over the two year study period. For geographic area identification refer to Figure 1.

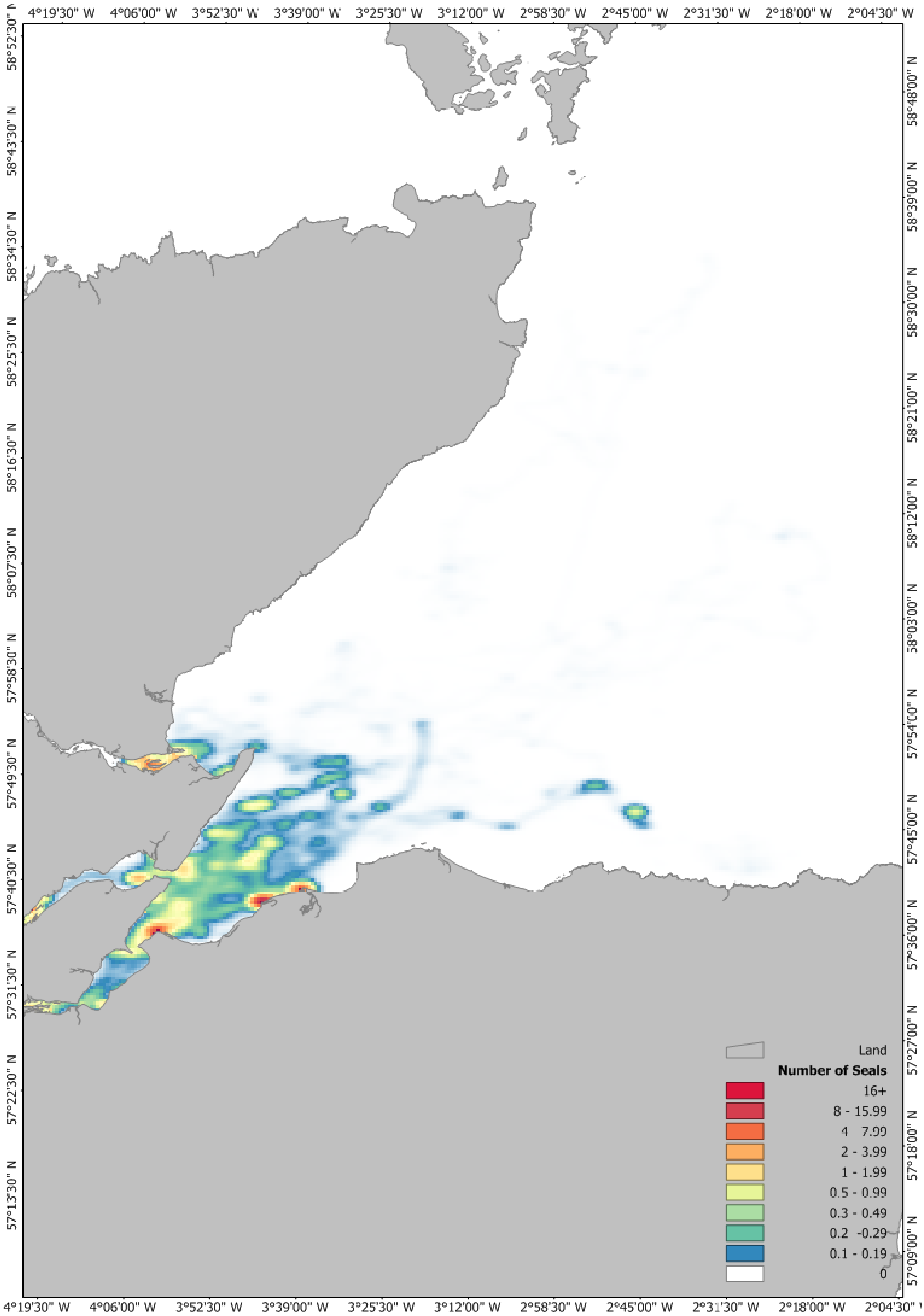

Figure 10: Estimated harbour seal usage in the inner Moray Firth. Seals using the Loch Fleet haulout sites were not included in this analysis (for details see main text section 3.3). For geographic area identification refer to Figure 1.

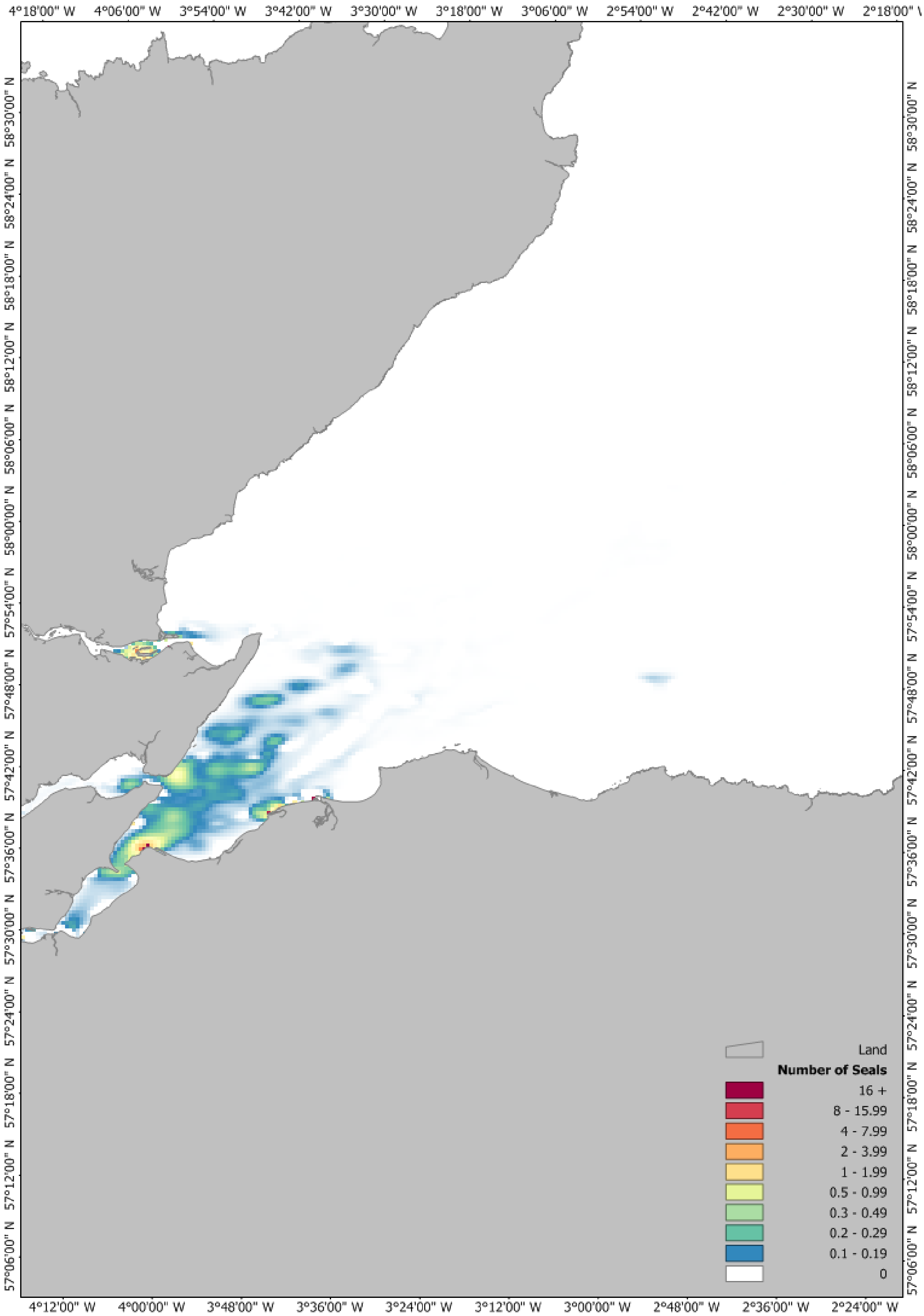

Figure 11: Lower 95% confidence interval for the estimated harbour seal usage in the inner Moray Firth. For geographic area identification refer to Figure 1.

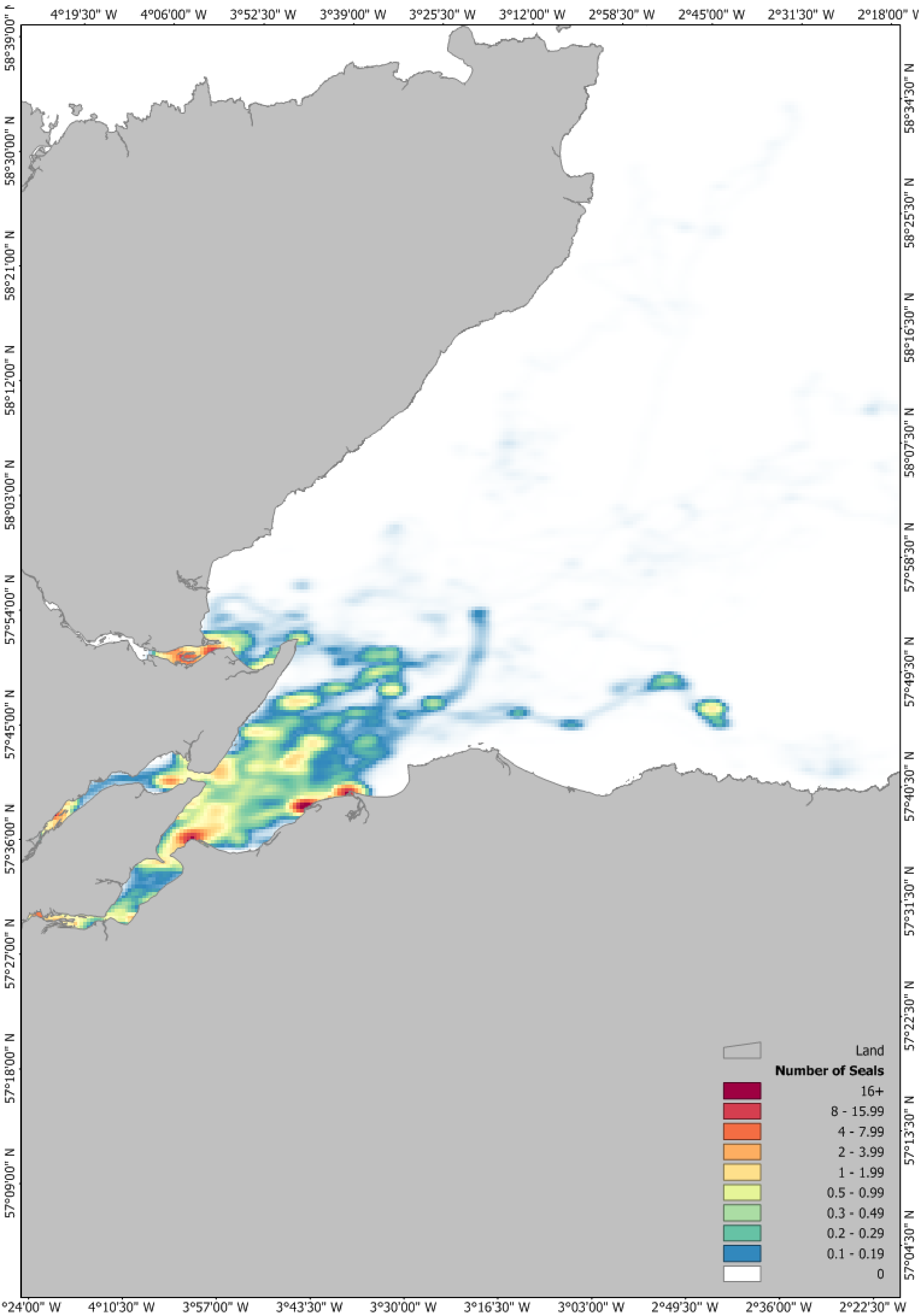

Figure 12: Upper 95% confidence interval for the estimated harbour seal usage in the inner Moray Firth. For geographic area identification refer to Figure 1.

3.3 Seal-shipping co-occurrences

A simple comparison of the tracks of individual seals with the raw AIS ship track data for the same period shows that some seals repeatedly used discrete, small areas close to areas of relatively high shipping activity (Figure 13a and Figure 13b). These areas are characterised by acute turning angles and slow speed over ground in the seal data, indicative of area restricted searching. This suggests that seals are not exhibiting overt avoidance of areas associated with high levels of shipping activity in the Moray Firth (Figure 13).

Seal-shipping co-occurrences in the Moray Firth were concentrated in shipping lanes with the majority occurring in the southern regions neighbouring the Inverness and Cromarty Firths (Figure 14). These shipping lanes can be seen as the areas of highest usage in Figure 13 and are characteristically narrow bands, peaking in usage in the narrow channels of the Cromarty and Inverness Firths. Confidence intervals were not produced as it was assumed that all vessel traffic was represented in the data with no temporal stochasticity. The area showing the highest number of offshore co-occurrences was located approximately 6.5 km north-east from the mouth of the Findhorn River.

The most intense areas of seal-shipping co-occurrence occurred close to the coast with only four 0.5 km x 0.5 km grid cells producing values over 2500 minutes of co-occurrence per year, at the entrance to the Cromarty Firth and within 500 metres of the haulout at Ardersier (Figure 14). Other areas of relatively high seal-shipping co-occurrence were located close to the tagging site at Ardersier and the outer Beauly Firth. A pronounced pattern of relatively high seal-vessel co-occurrence can be seen through both the Cromarty Firth and the Inverness Firth.

The total amount of time of seal-shipping co-occurrence per year was estimated to be 130,395 minutes (90.5 days). This results in an average of 0.13 days of co-occurrence per seal, using the 2013 aerial survey count of 696 individuals. No offshore areas produced co-occurrence above 1500 minutes per year and the AIS data showed no shipping in the Dornoch Firth or Loch Fleet.

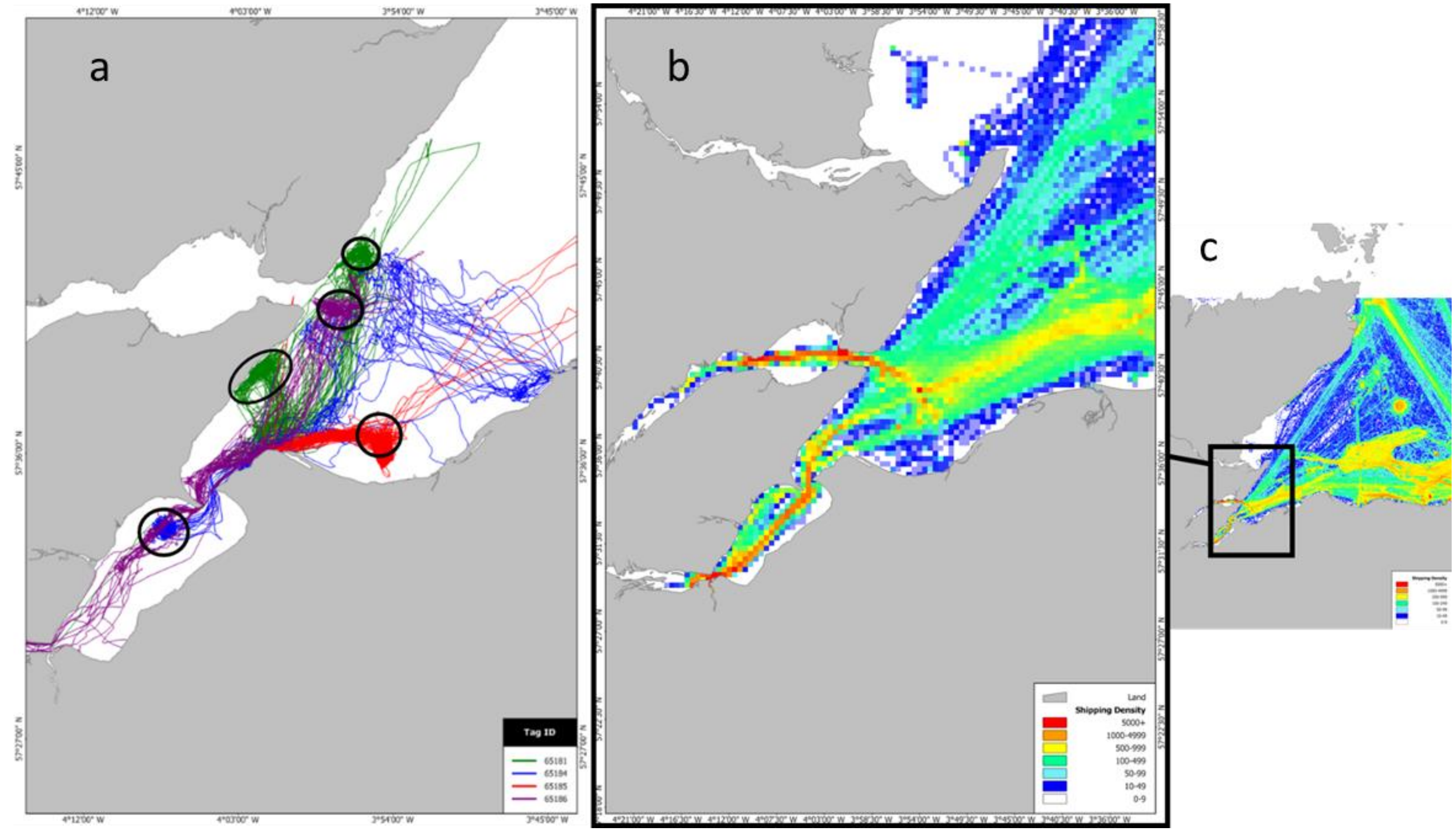

Figure 13: (a) Tracks of four harbour seals tagged at Ardersier in 2015. These seals continued to use small discrete foraging areas (circled in (a)) close to areas of relatively intense shipping activity (b). (c) Shipping traffic in the Moray Firth over the study period.

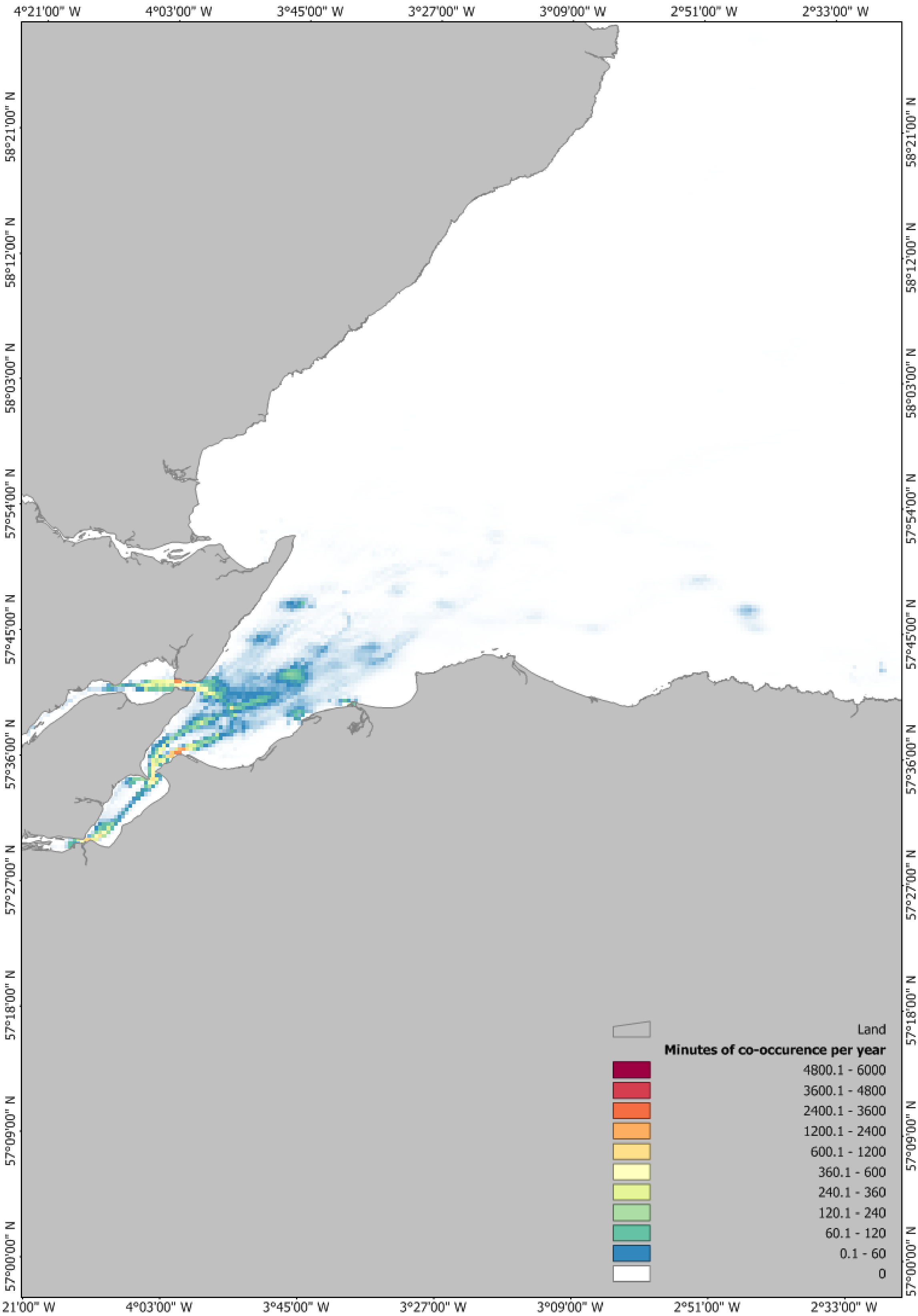

Figure 14: Mean annual number of minutes of harbour seal-shipping co-occurrence in the inner Moray Firth.

3.4 Individual seal-ship movements

Individual seal tracks based on GPS location fixes and individual vessel tracks based on raw AIS data were regularised to produce location estimates at 15 minute intervals. For each seal location, the distance to the closest vessel was calculated (Figure 15). The mean distance between seals and the nearest vessel was 13 km. Approximately 18% of the total at sea, activity in the seal telemetry record occurred within 5km of a vessel and approximately 1.7% occurred within 1 km (Figure 15).

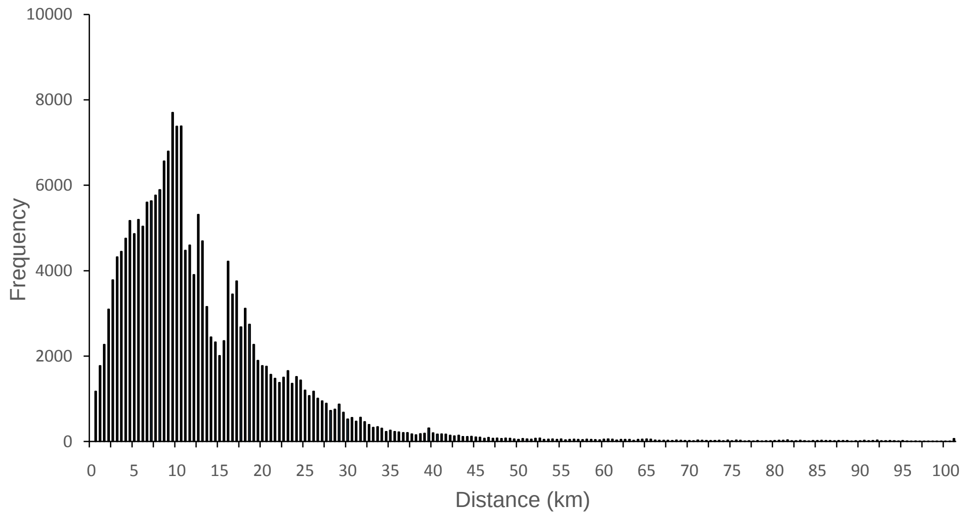

Figure 15: Distance to the nearest vessel of each seal telemetry location interpolated to 15 minute intervals.

Seventy-eight seal locations produced seal-ship distances of less than 0.1 km. All but one of these close passes were recorded in the areas identified as sites of intense seal-shipping co-occurrence in section 4.3 (e.g. Figures 16, 17 and 18). None of these instances involved apparent directed swimming towards the vessels in question but rather vessels either transited past a seal already occupying an area (Figure 18) or the seal and the vessel transited passed each other on different bearings (Figure 17). Seal-vessel proximity was never less than 0.1 km for more than 15 minutes (one time step in the interpolated data) for a moving vessel.

The activity of seal Tag ID 65255 (Figure 19) is unique in this data set in that it swam directly to and remained in close proximity with a tanker, at anchor off the coast near Banff. The seal remained within 80 metres of the vessel for ~4 hours, with only one brief transit away (>200 metres), returning almost immediately to the vessel. There was a gap of 79 minutes in the data, between 19:53 and 21:12, during which the seal swam 2.09 km towards the vessel. This was the only occasion when a seal was observed swimming directly towards, or remaining in close association with (less than 0.1 km) a vessel. It also represented the closest seal-ship interaction: <0.01 km. The seal continued to transmit data for a further 73 days after this event. The movements did not indicate that the close proximity event had compromised the animal in any way. This individual also appeared to swim along a route regularly used by fishing vessels near Macduff. However, it was not associated with any vessels in the AIS data during these transits (Figure 19).

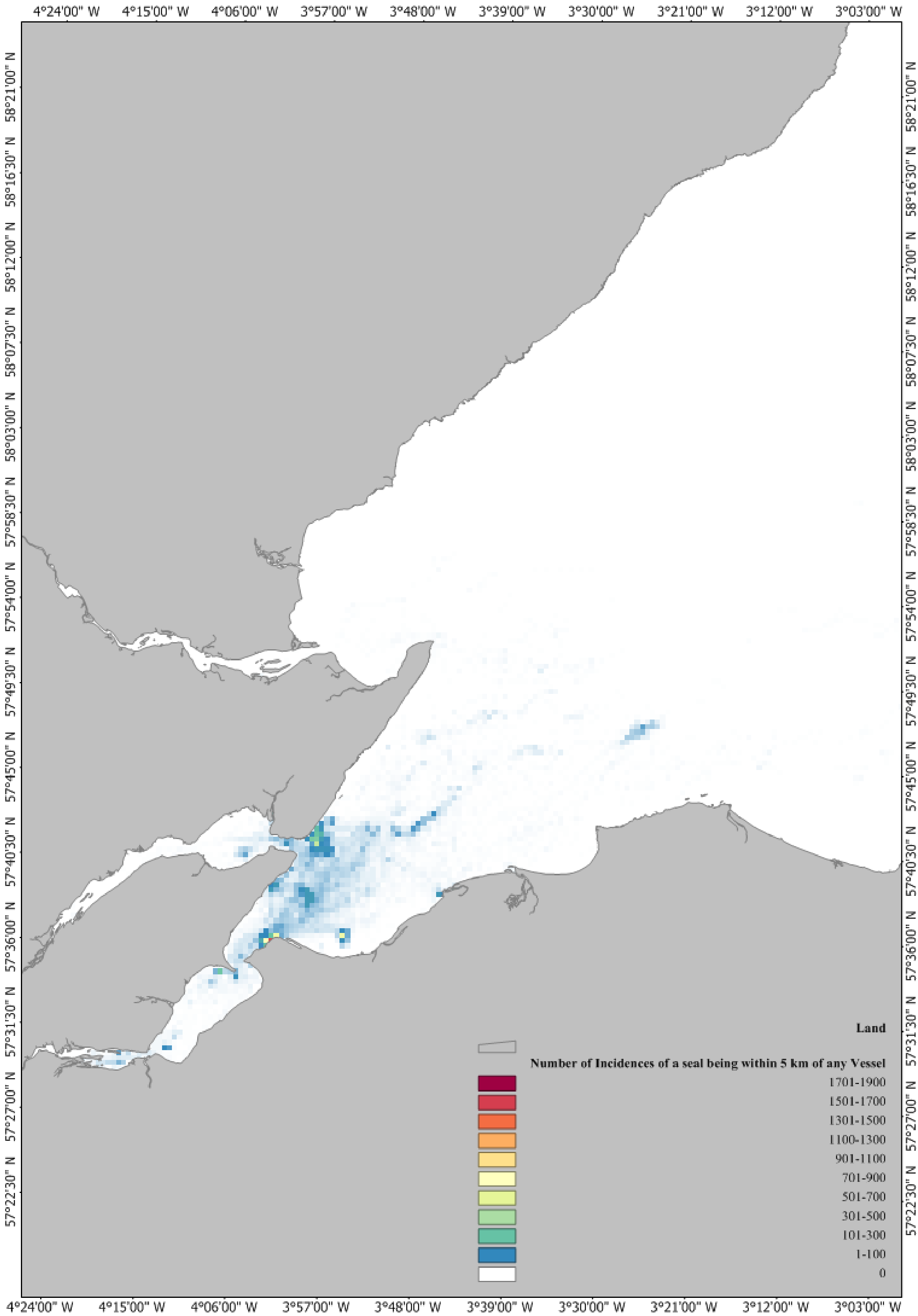

Figure 16: Number of 15 minute interpolated locations within 5 km of any vessel traffic for every 0.5 km by 0.5 km grid cell.

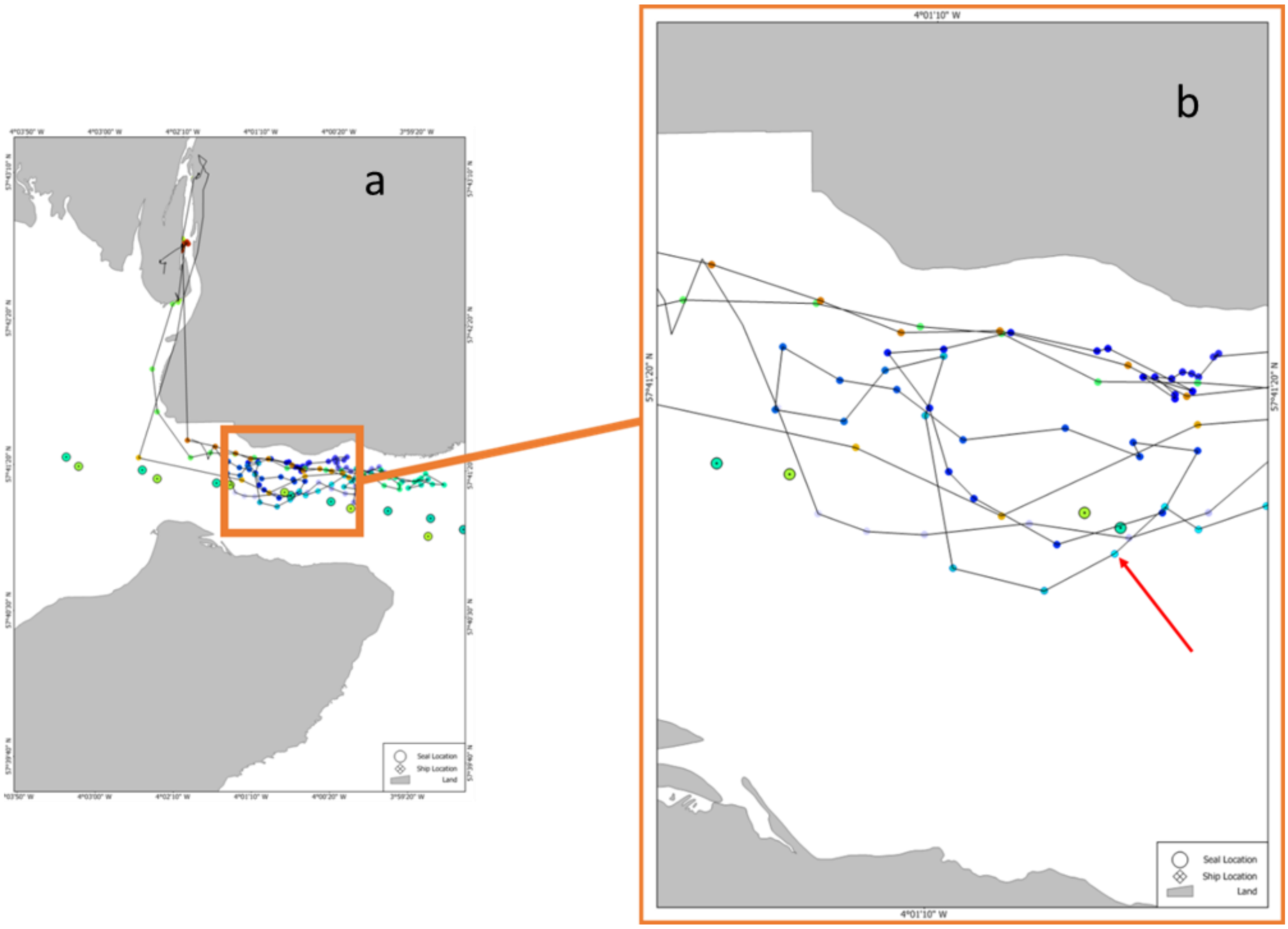

Figure 17: (a) Movements of seal 65190 in relation to a tug boat on 30/05/2014. (b) Enlarged view of the mouth of the Cromarty Firth where the closest seal-vessel pass was observed. Closest pass is indicated by the red arrow. Times of seal locations are colour coded from blue to red. Ship locations are coloured to show unique vessel IDs.

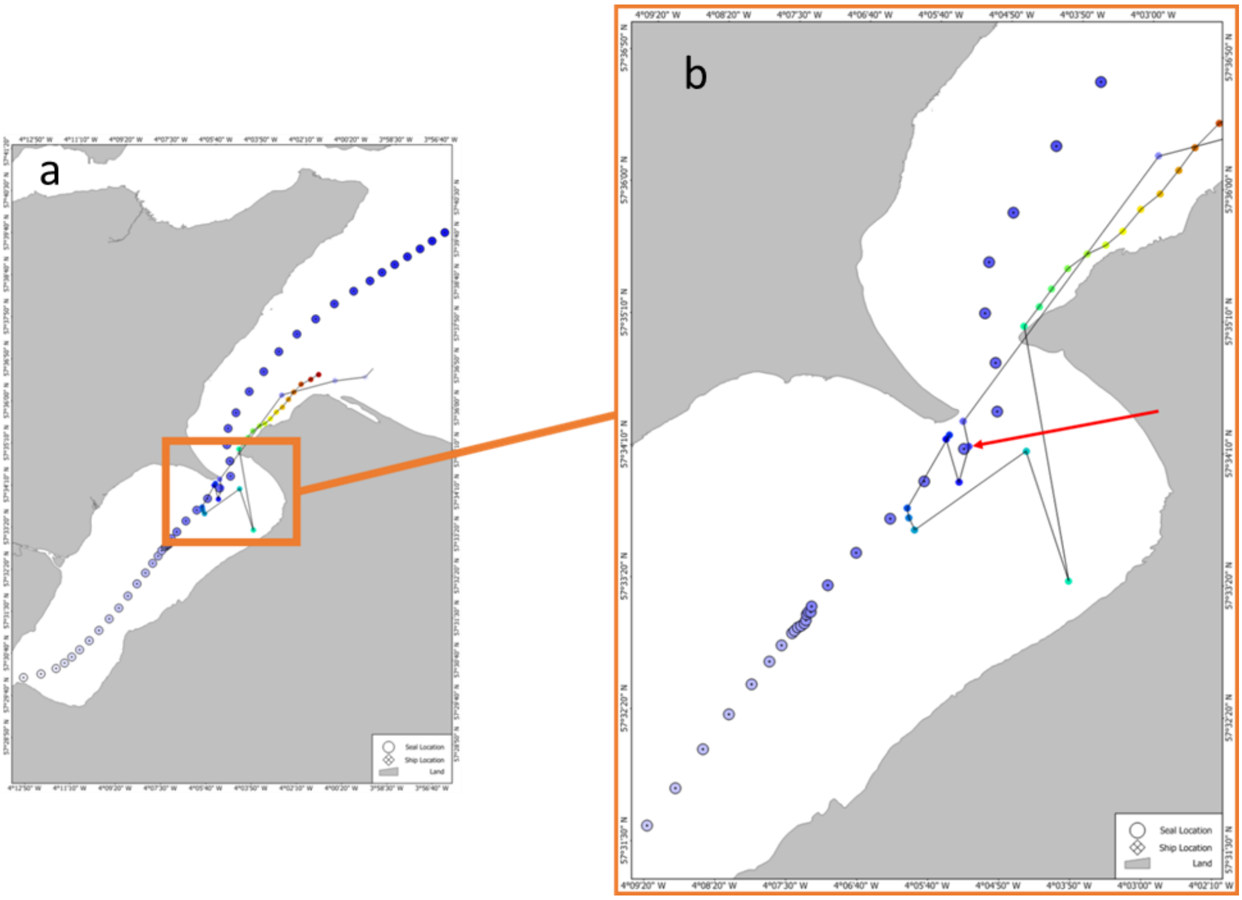

Figure 18: (a) Movements of seal 65214 in relation to a cargo vessel on 30/04/2015. (b) Enlarged view of the outer Inverness Firth and inner Moray Firth where the closest seal-vessel pass was observed. Closest pass is indicated by the red arrow. Times of seal and ship locations are colour coded from blue to red. Seal and ship location colours are identically scaled.

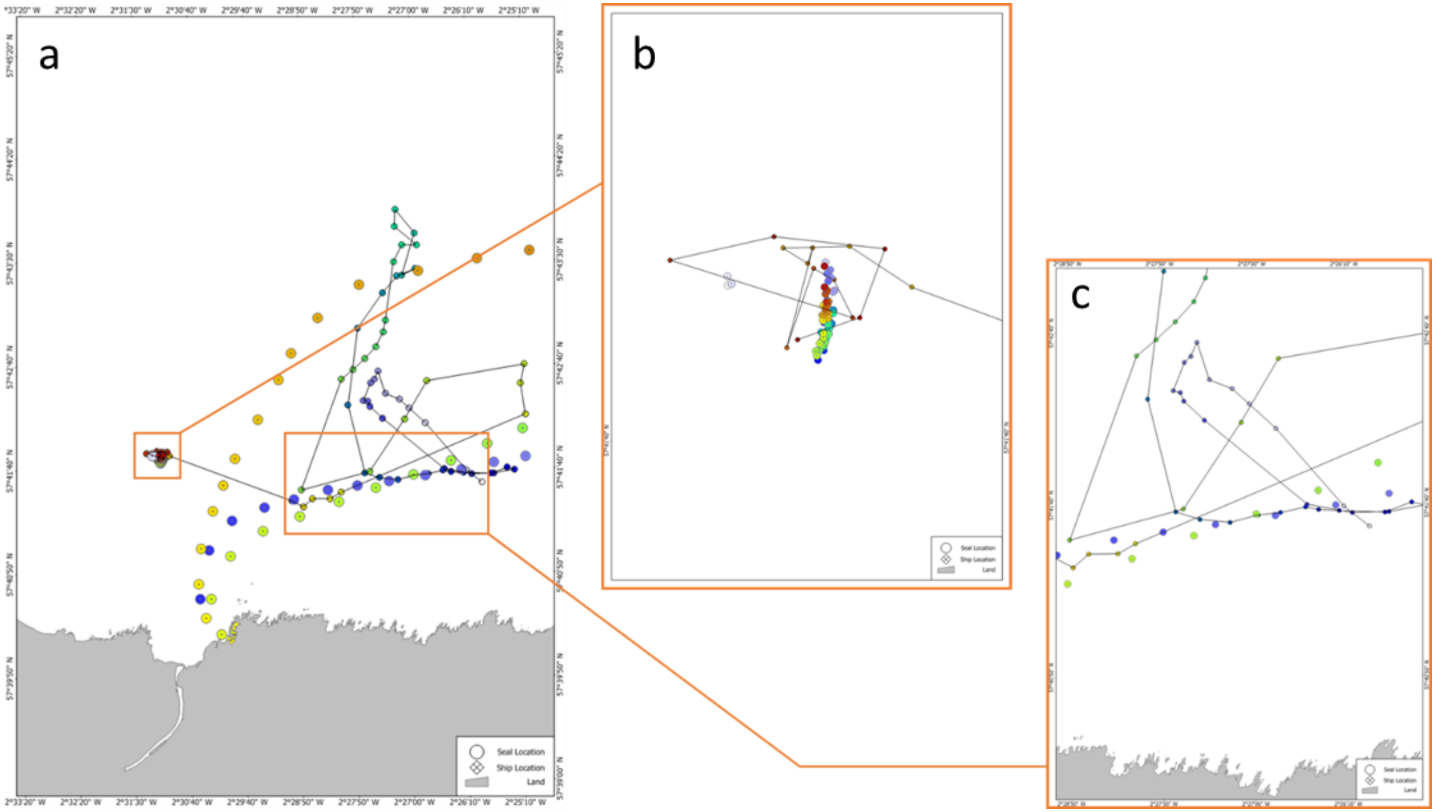

Figure 19: (a) Movements of seal 65255 in relation to shipping traffic on 23/03/2015 and 24/03/2015. (b) Enlarged view of the area 3.3 km north of mouth of the River Deveron (Banff) where the closest seal-vessel pass was observed. (c) Enlarged view of the area occupied by two fishing vessels, prior to the seals arrival. Times of seal locations are colour coded from blue to red. Ship locations are coloured to show unique vessel IDs.

4 Discussion

This study has detailed how fine-scale movement data for seals and ships was used to produce usage maps and estimate spatial co-occurrence. The usage maps provide an estimated rate at which harbour seals occupy the same 0.5 km by 0.5 km grid cell as vessels, assuming the movements of sampled individuals were representative of the local population. This is a useful tool for assessing the potential for interactions between seals (or any marine animal which can be tracked at an appropriately high resolution) and dynamic anthropogenic activity.

4.1 Implications

The usage maps appear to show that high co-occurrence was associated with a funnelling effect. The two most prominent areas of co-occurrence were at the entrance to the Cromarty Firth and the inner Moray Firth leading into the Inverness Firth. These are relatively long, narrow stretches of water. As vessel routes enter narrow areas close to seal haulout sites they inevitably overlap with transit routes of seals between haulout sites and foraging sites. This is not to suggest that seals are attracted to or are attempting to avoid vessels simply that they will necessarily occupy the same areas as ships during trips between their haulout sites and foraging sites.

Calculating the closest distance between contemporaneous locations of seals and vessels provided further evidence of the funnelling effect; almost all closest distances were located at the mouth of the Cromarty Firth or within 1 km of the coast at Ardersier. It appears that the predominant cause of seals being in close proximity to ships is that seals and vessels independently occupy the same area for a short period of time rather than as a result of directed travel by seals towards or away from vessels. When vessels were transiting through areas seals were already occupying, there were no apparent changes in the seals' behaviour (i.e. occupancy and turning angles) before or after the vessel had passed. The lack of overt signs of directed swimming towards vessels suggest that seals are not being attracted to shipping activity.

The shortest distance between a seal and a vessel was calculated as less than 10 metres and only 3 instances resulted in passes at less than 20 metres from a vessel. This is a small number of close approaches in a data set that represents 2241 days of seal activity in an area with regular shipping traffic.

Onoufriou *et al*. (2014) suggested that seals would only interact with ships' propellers if they were actively approaching slowly manoeuvring vessels. The absence of apparent directed swimming towards vessels and the few instances of close approaches in the extensive telemetry data set suggests that seals in the Moray Firth are unlikely to be interacting with propellers in this manner.

These values should be treated with caution, especially when dealing with low-margins for error as in the case of passes of less than 0.1 km, as GPS locations can have an associated error of up to 50 metres. The error in estimating distances between 2 GPS locations therefore has a potential compound error of up to 0.1 km.

The activity of seal Tag ID 65255 (Figure 19) was unique in this data set in that it swam up to and remained in close proximity to a particular ship for an extended period of four hours. The 78 minute gap in the track record prior to arrival at the ship means that it is not known if the seal swam directly to the vessel. However, the data suggest that once the seal became aware of the vessel it was attracted to it. This result may be important in the context of how static marine structures can act as refuge or foraging grounds. Harbour seals have recently been shown to be attracted to anthropogenic structures such as wind farms and pipelines (Russell *et al*. 2014).

The same individual appeared to swim along a track used by two fishing vessels. Neither vessel was present at the same time as the seal. The absence AIS data from some fishing vessels means that it is not known whether this was coincidence or the seal was following an unrecorded vessel. Inclusion of data from other sources such as the Vessel Monitoring Systems (VMS) could provide valuable additional insights into seal/vessel and seal/fishing activity interactions.

4.2 Association with corkscrew seal mortalities.

Areas of intense seal-ship co-occurrence in this study did not closely correspond with strandings reports of seals with spiral lesions. Previously, Jones *et al*. (2015b) used harbour seals and ship usage maps around the UK in 2011 and 2012 and overlaid these with corkscrew seal stranding locations. They noted that inshore waters of east Scotland, where the largest number of strandings occurred, were not associated with the highest encounter probabilities. Figure 20 (extracted from Jones *et al.,* 2015b) demonstrates the apparent absence of such coincidence on a national scale. Similarly, the most intense areas of co-occurrence in the fine-scale usage maps for the Moray Firth do not coincide with areas of high strandings reports. The potential for carcasses to drift was not taken into account and seals could potentially drift a significant distance after death. However, two confirmed corkscrew seal carcasses in 2015 were reported inside the mouth of the Dornoch Firth, approximately 8 km from the closest grid cell with any seal-shipping co-occurrences associated with them. Furthermore, two corkscrew carcasses were reported in 2014 in the Beauly Firth in an area with no recorded shipping activity and approximately 6.5 km from the closest grid cell with any seal-shipping co-occurrences. These carcasses are difficult to attribute to shipping interactions given their locations.

4.3 Caveats

4.3.1 AIS data

AIS data provided locations at a resolution of 2 minute intervals for every vessel 300 tonnes and over and all passenger vessels in the Moray Firth over the study period. Additionally a proportion of fishing vessels, pleasure craft, military vessels and pilot vessels that voluntarily carry AIS transmitters were also included in the analysis. While it is not possible to quantify the number of vessels not represented, it seems likely that fishing vessel density is underestimated as they represent a small proportion of the AIS data. The addition of all fishing vessels should be considered for future analyses.

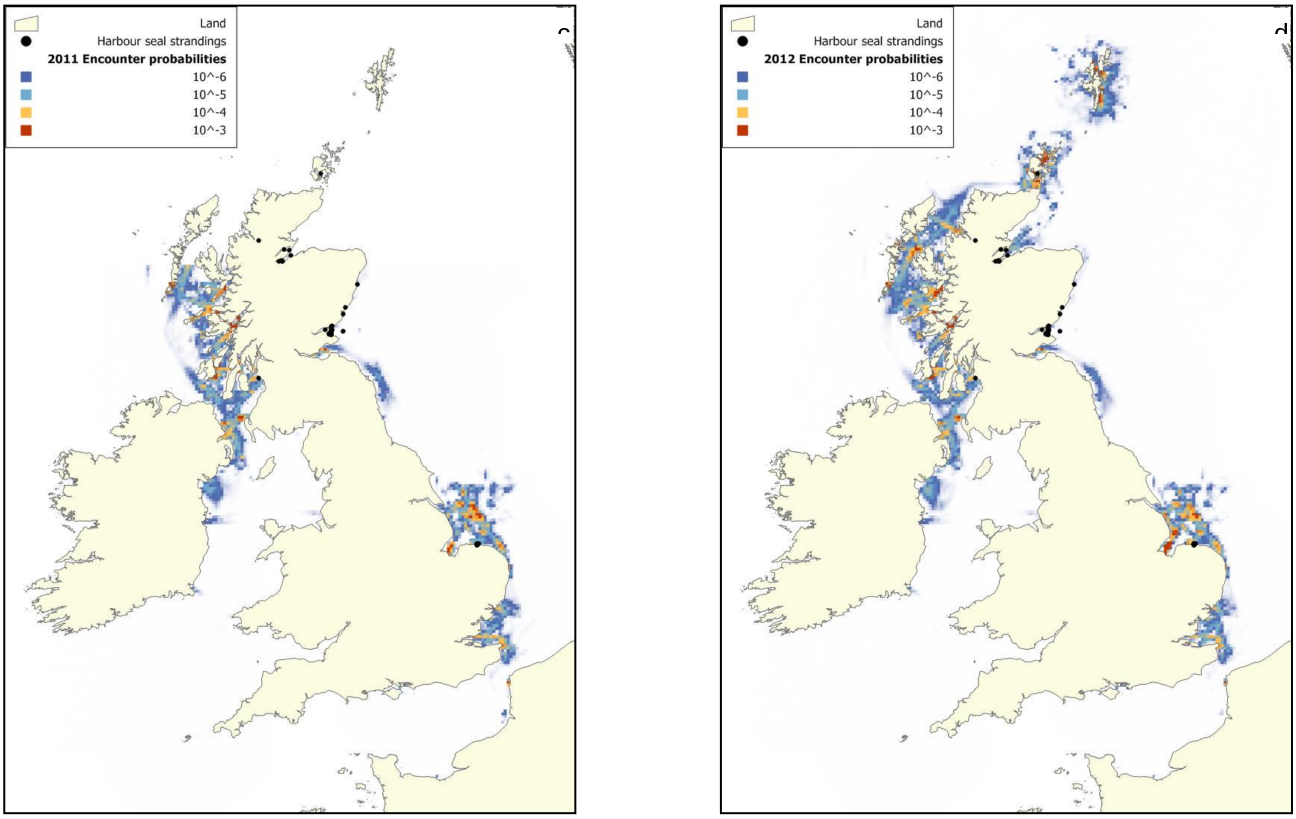

Figure 20: Relative encounter probabilities between harbour seals and shipping traffic in (left) 2011 and (right) 2012; at 5 km x 5 km resolution. Areas of high encounter probabilities are indicated in red and lower encounter probabilities are in blue. From Jones *et al.* (2015b).

4.3.2 Telemetry data

Haulout sites with smaller numbers of animals have higher uncertainty associated with them. Within haulout site uncertainty was estimated, which accounted for low sample size at a haulout site to some degree. However, usage within the Dornoch Firth may not be considered representative as only seven of the ten animals tagged in the Dornoch Firth transmitted location data and only five of these transmitted for more than 10 days. Fortunately, two discrete haulout site clusters were used by all seven animals so the mean usage could be more reliably estimated (i.e. confidence intervals around the mean were relatively small). However, usage in these areas and their associated at-sea co-occurrence estimates must be treated with caution. No usage could be estimated for the inner Dornoch Firth as none of the most westerly haulout sites were used and no seals visited the area. In this case null maps (as developed by Jones *et al.* (2015a)) were not produced. However, in this instance, it did not affect the co-occurrence results given the absence of shipping traffic in the inner Dornoch Firth. Similarly, only one animal used haulout sites in Loch Fleet so the usage by seals from that site and associated at-sea co-occurrence estimates were not calculated. Low levels of shipping in areas used by the one individual suggests that this exclusion will have had little impact on the co-occurrence map, but inclusion of telemetry data from parallel studies in Loch Fleet would resolve this issue.

4.3.3 Assumption of temporal homogeneity

Movement data for seals and ships in 2014 and 2015 were collected during the spring and summer months. This may not be representative of seal distribution in the Moray Firth at other times of the year. Harbour seals have been known to travel large distances (Sharples *et al.*, 2012) and the sampling period may not have been sufficient to adequately detect these behaviours. Therefore scaling to population levels and assuming the estimated co-occurrence rates are annually representative may be an oversimplification. This is further compounded by the fact that the aerial survey data, from which the kernel density estimates were scaled, are taken only during the summer months. While this is relevant to the telemetry data being used, the usage maps presented here should be interpreted as being representative of the spring/summer usage of harbour seals in the Moray Firth and may not be representative of year-round distribution.

5 Conclusions and future work

Given the relatively localised distribution of co-occurrence of seals and shipping in the inner Moray Firth it is unlikely that direct seal-shipping encounters are a major concern in this area. Funnelling effects mean that entrances to shipping channels containing seal haulout sites are areas of intense seal-shipping co-occurrence. The absence of coincident clusters of corkscrew seal carcass strandings in these areas given the high levels of potential for interaction is an important observation and requires further investigation.

Examination of relative movements of individual seals and vessels did not show any apparent responses. Seals did not appear to react to close passing vessels; they neither moved towards nor away from them. A single seal was observed to swim directly to a vessel at anchor and remain in close proximity (<80 metres) for 4 hours. This was the only observation indicating any form of reaction to a vessel and the vessel was stationary throughout.

The majority of seal-vessel close-passes, including all 78 instances where seals and ships were within 0.1 km of each other, occurred in the localised areas of high co-occurrence identified in the seal/ship density mapping exercise. Again, these instances appeared to be a result of a funnelling effect where seals and ships coincidentally passed through the same constrained areas.

Future work should include incorporation of additional telemetry data from parallel studies of harbour seal movements from the haulout sites in Loch Fleet. This should improve the coverage in the northern section of the Moray Firth.

Including movement data from fishing vessels would also improve the utility of the mapping exercise. Data from Vessel Monitoring Systems (VMS) could be incorporated in this framework to improve understating of interactions between seals and fishing activity.

6 Acknowledgements

We would like to thank the Forestry Commission and Port of Ardersier Ltd. for site access to Culbin Forest and Ardersier respectively which allowed data to be regularly collected and tagging work to be undertaken. Thanks also go to everyone involved in field work and data collection, specifically Mr. Simon Moss and Mr. Matthew Bivins, the Lighthouse Field Station at the University of Aberdeen, specifically Ms. Rebecca Hewitt, for their help with data collection and continued advice on local AIS use and the Moray Firth seal population, and Dr. Debbie Russell for her statistical advice and programming assistance.

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