Marine Mammal Scientific Support Research Programme MMSS/002/15

Marine Renewable Energy MRE1

Annual Report

Marine Mammals and Tidal Energy

Sea Mammal Research Unit
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Editorial Trail			
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Executive Summary

The work presented under the Marine Renewable Energy (MRE) theme falls in to three tasks;

MRE 1.1 – Fine scale marine mammal behaviour around tidal energy devices.

MRE 1.2 – Harbour seal movement modelling.

MRE 1.3 – Estimating collision risk using available information.

Since MRE 1.1 will not start until year 2 of the project, and the deliverables for MRE1.3 have been amalgamated into the Marine Scotland project CR/2014/12 (which will report separately), this annual report presents on the progress for MRE 1.2 only.

MRE1.2

- Progress is reported on the development of an Inter-Haulout Transition Rate Model to explore and characterise harbour seal population movements in the area of Orkney and the Pentland Firth.
- Data from 41 tagged seals were collated and processed. A method was developed to accurately position haulout bouts within the tracks from these tagged animals. This was particularly necessary for the Argos tags as they provide less accurate position track data than GPS/GSM tags.
- A method was also developed to cluster the large number of individual haulout sites into a smaller number of haulout site clusters. This process reduced the amount of computation time required to run the model.
- At a given haulout site, the probability of a simulated seal being associated with any one of the 41 individual haulout transition matrices generated from the tagging data will be proportional to the amount of time that the tagged animal spent at that site.
- The simulations within in this model have not yet been completed. However, all the methodological developments have been completed.
- The structure of a proposed harbour seal Individual Based Model (IBM) is presented with the aim of ultimately demonstrating proof of concept of the IBM approach. The model is based on individuals alternating between foraging at sea and hauling out ashore, based on their individual states (internal properties such as body condition). Movement models based on both memory and exploration are being developed and will be incorporated. Shortest sea-route algorithms have been developed to assist in simulating the memory-based movement of seals to specific targets.
- Whilst the major simulations within this model have not yet been optimised, illustrative movement simulations have been completed. The ultimate challenge is thus to produce a model of appropriate complexity whose predictions (emergent properties) fit well with independent tagging data. The methodology for model validation and parameter estimation is under development after which proof of concept can be demonstrated.

Contents

1 MRE1.1 - Fine scale marine mammal behaviour around tidal energy devices

1.1 Introduction

Concerns about the impacts of tidal energy on marine mammals derive primarily from the potential for injury or mortality as a result of direct interactions (collisions) between animals and moving rotors of tidal devices. However, the true risks posed by these devices remain uncertain due to a paucity of information on a) how marine mammals behave in close proximity to operating tidal turbines, b) how marine mammals use tidally energetic areas proposed for development and c) the individual consequences of turbine impact.

This work package comprises three linked tasks. Together, these will be used to derive parameters required to both populate improved collision risk models and to directly measure interactions on instrumented turbines.

1.2 Progress

Activity will start on the tasks in this work package in year 2 of the project.

2 MRE1.2 - Harbour seal movement modelling

2.1 Introduction

Quantifying movement patterns in harbour seals is necessary to predict and manage anthropogenic risk. Specifically, it enables predictions of how disturbance at one haulout site will predict the effect at another site. In a previous study[1] the inter-haulout movements of harbour seals captured and tagged near the Sound of Islay were quantified in an empirical transition matrix model. This study extends that work under three task deliverables:

1. The model will be extended to the Pentland Firth where both wave and tidal energy generation schemes are proposed.
2. Environmental and temporal covariates will be examined to test whether the model may be generalised in terms of inter-haulout distance. The model will also incorporate improvement in the way that transition matrices are assigned to simulated seals. Also the haulout sites will be clustered to avoid computationally difficult simulation of a large number of fragmented haulout sites.
3. The structure of an Individual Based Model (IBM) of harbour seal movement will be presented. This will provide proof of concept of whether such a model is feasible. The advantage of the IBM approach is that it should be of appropriate complexity and sufficiently tuned with data to provide a biologically defensible and robust predictors of environmental change on harbour seals movements.

This report summarises the work carried out under project MRE 1.2: Harbour seal movement modelling during 2015/16. Section 2.2 deals with deliverables 1 and 2. Section 2.3 deals with deliverable 3.

Two modelling approaches are presented. The first is Inter-Haulout Transition Rate Modelling (IHTRM). Telemetry data from tagged harbour seals are used to create inter-haulout movement transition matrices which attempt to reflect the local harbour seal *population* movements. The second approach is an Individual Based Model (IBM). IBMs attempt to build movement behaviour from biological first principles – using a set of individual behaviour rules. Given that these rules can be sufficiently guided and tuned by data, IBMs offer a modelling strategy that has the potential to present robust and biologically plausible scenarios to explore the effect of environmental change on seal movements.

[1] Marine Mammal Scientific Support Research Programme MMSS/001/11.

2.2 Inter-Haulout Transition Rate Modelling

2.2.1 Introduction

The work on Inter-Haulout Transition Rate Modelling (IHTRM) is currently ongoing. The computer intensive simulations are not yet complete and the results presented here should be considered as preliminary.

Extensive data processing has been carried out and the methodological developments have been completed and these are presented in this section.

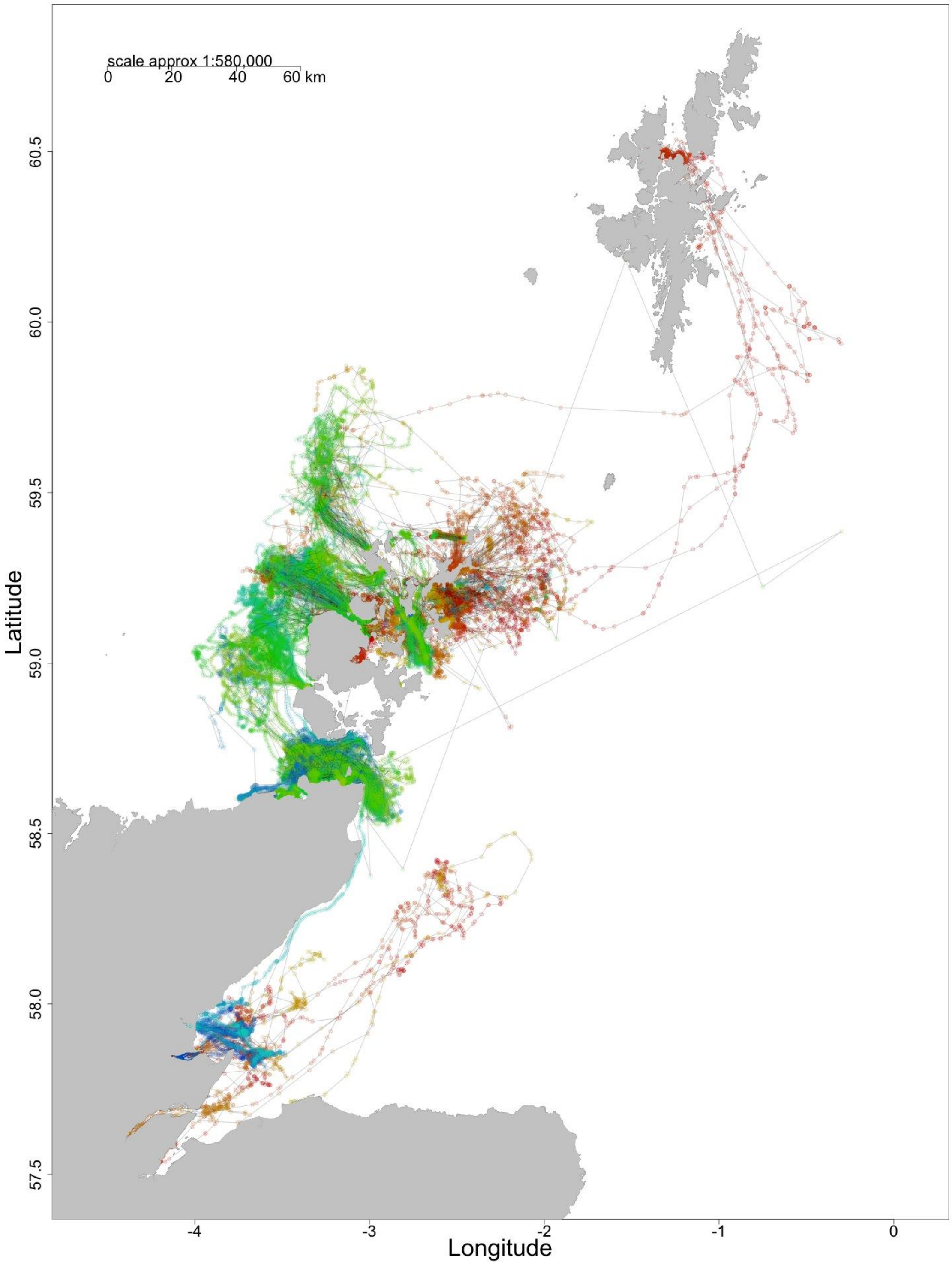

Figure 1. Tracks from 41 harbour seal tags: 19 ARGOS and 22 GPS. Each ARGOS track is coloured from red to orange (beginning to end) and each GPS from blue to green, to show the progression of each animal.

2.2.2 Methods

2.2.2.1 Data collection

An area of interest encompassing the Pentland Firth and Orkney Islands was defined (4.1° W to 1.8° E and 58.6° N to 59.9°N, see Figure 1). Telemetry data was compiled for tagged seals using this area (n=46[2]). Because this study focuses on seal movements among haulout sites, only animals with 10 or more haulout events were kept for the analysis (n=41). In total, 22 GPS/GSM tags (2011:13, 2012:6, 2015:3) and 19 ARGOS tags (2003:5, 2004:4, 2007:1, 2012:9) were included (Table 1).

Table 1. Details of the 41 harbour seals included in this study. Longitude (Lon) and Latitude (Lat) indicate the approximate location of capture and tagging.

Tag ID	Type	Lon	Lat	Year	Start	End	Sex	Mass
pv1-ali-03	ARGOS	-2.55	59.2	2003	02/10	06/04	F	87.0
pv1-bo-03	ARGOS	-2.55	59.2	2003	02/10	03/04	F	83.5
pv1-cat-03	ARGOS	-2.55	59.2	2003	02/10	06/05	F	66.0
pv1-dot-03	ARGOS	-2.55	59.2	2003	02/10	01/07	F	85.0
pv1-erin-03	ARGOS	-3.02	59.1	2003	02/10	15/03	F	82.5
pv6-pat-04	ARGOS	-2.60	59.1	2004	15/03	08/07	F	83.0
pv6-queenie-04	ARGOS	-3.02	59.1	2004	16/03	23/06	F	93.5
pv6-sally-04	ARGOS	-3.12	59.1	2004	18/03	31/05	F	78.0
pv9-dory-04	ARGOS	-4.01	57.8	2004	17/10	09/03	F	60.0
pv12a-181-07	ARGOS	-4.40	57.9	2007	01/03	13/06	F	61.0
pv24-112-11	GPS	-3.16	58.6	2011	24/09	09/03	M	92.8
pv24-148-11	GPS	-3.16	58.6	2011	24/09	14/02	M	76.2
pv24-150-11	GPS	-3.16	58.6	2011	26/09	17/01	F	86.6
pv24-151-11	GPS	-3.16	58.6	2011	25/09	06/12	M	84.8
pv24-153-11	GPS	-3.16	58.6	2011	26/09	25/01	F	72.0
pv24-165-11	GPS	-3.16	58.6	2011	30/03	17/05	M	90.6
pv24-394-11	GPS	-3.16	58.6	2011	30/03	26/06	M	49.6
pv24-541-11	GPS	-3.16	58.6	2011	30/03	10/08	M	96.8
pv24-580-11	GPS	-3.16	58.6	2011	29/03	01/07	F	89.0
pv24-590-11	GPS	-3.16	58.6	2011	30/03	09/06	M	49.8
pv24-598-11	GPS	-3.16	58.6	2011	29/03	17/07	F	84.6
pv24-622-11	GPS	-3.16	58.6	2011	31/03	15/06	M	91.4
pv24-x625-11	GPS	-3.16	58.6	2011	31/03	23/06	M	98.6
pv44-003-12	ARGOS	-2.77	59.1	2012	18/06	29/07	F	92.8
pv44-004-12	ARGOS	-2.77	59.1	2012	14/06	25/07	F	100.0
pv44-005-12	ARGOS	-3.12	59.1	2012	19/06	09/08	M	107.0
pv44-007-12	ARGOS	-2.77	59.1	2012	16/06	26/07	F	67.8
pv44-011-12	ARGOS	-3.12	59.1	2012	19/06	09/08	M	106.0
pv44-014-12	ARGOS	-3.12	59.1	2012	19/06	02/08	M	112.4
pv44-017-12	ARGOS	-2.77	59.1	2012	18/06	29/07	M	99.0
pv44-018-12	ARGOS	-2.77	59.1	2012	18/06	14/07	M	110.0
pv44-020-12	ARGOS	-2.77	59.1	2012	16/06	18/07	F	80.2
pv47-392-12	GPS	-3.12	59.1	2012	11/10	29/01	M	NA
pv47-427-12	GPS	-3.12	59.1	2012	10/10	27/10	M	NA
pv47-539-12	GPS	-2.77	59.1	2012	09/10	01/03	M	NA
pv47-583-12	GPS	-3.12	59.1	2012	10/10	17/01	M	NA
pv47-585-12	GPS	-2.77	59.1	2012	09/10	09/03	M	NA
pv47-588-12	GPS	-3.12	59.1	2012	11/10	12/01	M	NA
pv59-05-15	GPS	-4.07	57.9	2015	25/02	26/06	F	89.7
pv59-07-15	GPS	-4.07	57.9	2015	27/02	18/07	F	73.1
pv59-12-15	GPS	-4.07	57.9	2015	26/02	04/07	F	94.0

[2] It has recently been discovered that a small number of seals tracks were erroneously excluded in this data compilation process. The data shown in Figure 1 and Table 1 will be revised accordingly in the Final Report. However it is unlikely that the general results presented here will be substantially affected.

2.2.2.2 GPS data filtering

2.2.2.2.1 GPS tracks

GPS locations were filtered using their ‘residuals’ values and the number of satellites to exclude locations of lower quality. Locations with residuals > 25 or < 5 satellites were excluded. Each location was assigned a 95% C.I., the distance between the given location and the true location of the animal. This distance was modelled (using a Gamma distribution) as a function of the number of satellites, using a large published dataset on GPS error (Dujon 2014). Start and end dates were also trimmed by visual inspection to exclude inappropriate locations (e.g. locations after tag failure/detachment). The median usable lifespan of the tags was 87 days (range: 16 days to 176 days).

2.2.2.2.2 GPS haulouts

Using the track data, each time-stamped haulout was assigned a location. If there were any valid GPS locations during a haulout, the maximum likelihood coordinates were used for the haulout. If there were none, the GPS locations immediately preceding and immediately following the haulout were used to interpolate (linearly) the haulout location. These locations were then ‘snapped’ to the nearest coastline. The distance between the estimated and snapped location was termed the ‘snap distance’.

2.2.2.3 ARGOS data filtering

2.2.2.3.1 ARGOS tracks

ARGOS locations have much larger errors than GPS locations and were therefore filtered using several steps. A list of locations determined to be invalid by visual examination were first excluded. A Speed-Distance-Angle filter was then applied to exclude outliers, seen as ‘spikes’, from the tracks (Freitas *et al.*, 2008). A maximum speed of 5m/s, threshold angles of 5/10 degrees and distances of 5/10km were used. The remaining locations were then Kalman filtered (Jones *et al.*, 2015) using a lon-lat covariance matrix that was fitted to the GPS tracks above.

Because the Kalman filter did not take the coastline into account, some locations were over land. Two filters were therefore performed for these landlocked locations; (i) they were ‘snapped’ to the nearest coastline, (ii) the shortest path at sea between the locations at sea immediately preceding and following the landlocked location was calculated, and the landlocked location was then interpolated along this path. The shortest sea route was calculated using the R package ‘gdistance’ (v. 1.1-9) using a raster with 500m grid cells, where each cell could be water, a haulout, or land. The “cost” of transition to sea, haulouts, and land were set to 1, 5 and 100, respectively. Transitions to haulouts were made five times more costly then travelling at sea in order to reflect the difficulty of having to move some distance on land. Transitions to land were made 100 times more costly than travelling at sea but possible. This was to allow seals to cross small channels of water that may have been converted to land when turning the map into a grid (instead of taking, for example, a 100km detour). Transitions were allowed from a cell to its eight surrounding neighbours (eight directions). The distances between each derived landlocked location and the location at sea immediately preceding and following it were calculated for each of the two alternatives. The location with the smallest sum of squared-distances was selected. Start and end dates were also trimmed by visual inspection to exclude inappropriate locations (e.g. locations after tag failure/detachment). The median usable lifespan of the tags was 94 days (range: 32 days to 284 days).

2.2.2.3.2 ARGOS haulouts

Using the track data, each time-stamped haulout was assigned a location. If there were any valid ARGOS locations during a haulout, the median coordinates were used for the haulout. If there were none, the ARGOS locations immediately preceding and immediately following the haulout were used to interpolate (linearly) the haulout location. For some haulouts, locations used for interpolation were distant in time. Interpolated haulout locations with the longest time intervals (top 5%) were excluded. The remaining locations were then snapped to the nearest coastline.

2.2.2.4 Defining haulout site clusters

Some interpolated haulout locations were far from the coast. This could be due to location error, the linear interpolation being carried out on locations that occurred long before and long after the seal had hauled out, or to extended surface intervals at-sea (ESI’s (Ramasco *et al.*, 2014)) that appear as haulout events. Haulout locations over 2km from the nearest coastline were assumed to be ESI’s and therefore excluded.

In order to identify distinct haulouts, haulout events were grouped using a clustering algorithm (UPGMC). The minimum distance between the centroid of haulout clusters was set at 3km. This threshold was selected to identify as many distinct haulout sites as possible while staying beyond the likely location error of ARGOS haulouts. In total, 70 haulout clusters were produced and their coordinates were snapped to the nearest coastline again (Figure 2).

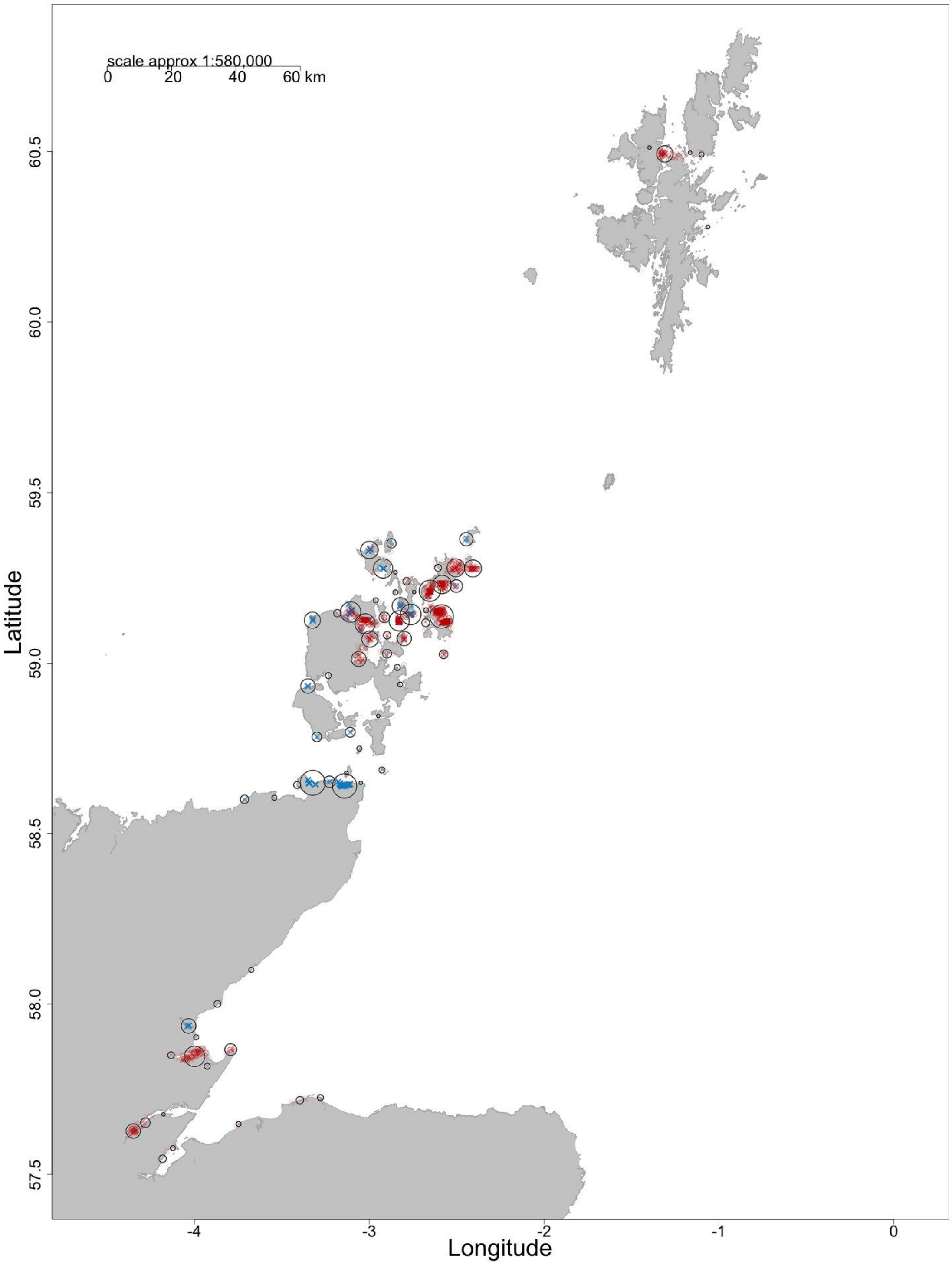

Figure 2. Haulout site clusters from the 41 harbour seal tags. Individual haulout events from ARGOS tags are shown in red (N=1485) and those from GPS tags in blue (N=1800). Black circles show the centroids of haulout sites after clustering, and the size of circles shows the number of haulout events assigned to each cluster.

2.2.2.5 Trip assignment

A trip was defined as 'not-hauled-out for at least 10 min', and having moved at least 2km away from the last haul out, as smaller changes in locations could be simple location error. Thus the entire track of a seal was divided exclusively into trip and haulout states.

2.2.2.6 Construction of transition matrices

2.2.2.6.1 Maximum likelihood

The trip data were used to construct matrices of transition probabilities among haulouts to model the movement of seals. These probabilities are shown in matrix form (Figure 3), where each cell illustrates the probability of transition from rows to columns. The maximum likelihood estimate for transition probabilities from each starting haulout site (row) is simply the number of trips to each destination divided by the total number of trips starting at that site. A transition matrix was obtained for each animal in order to preserve individual variability.

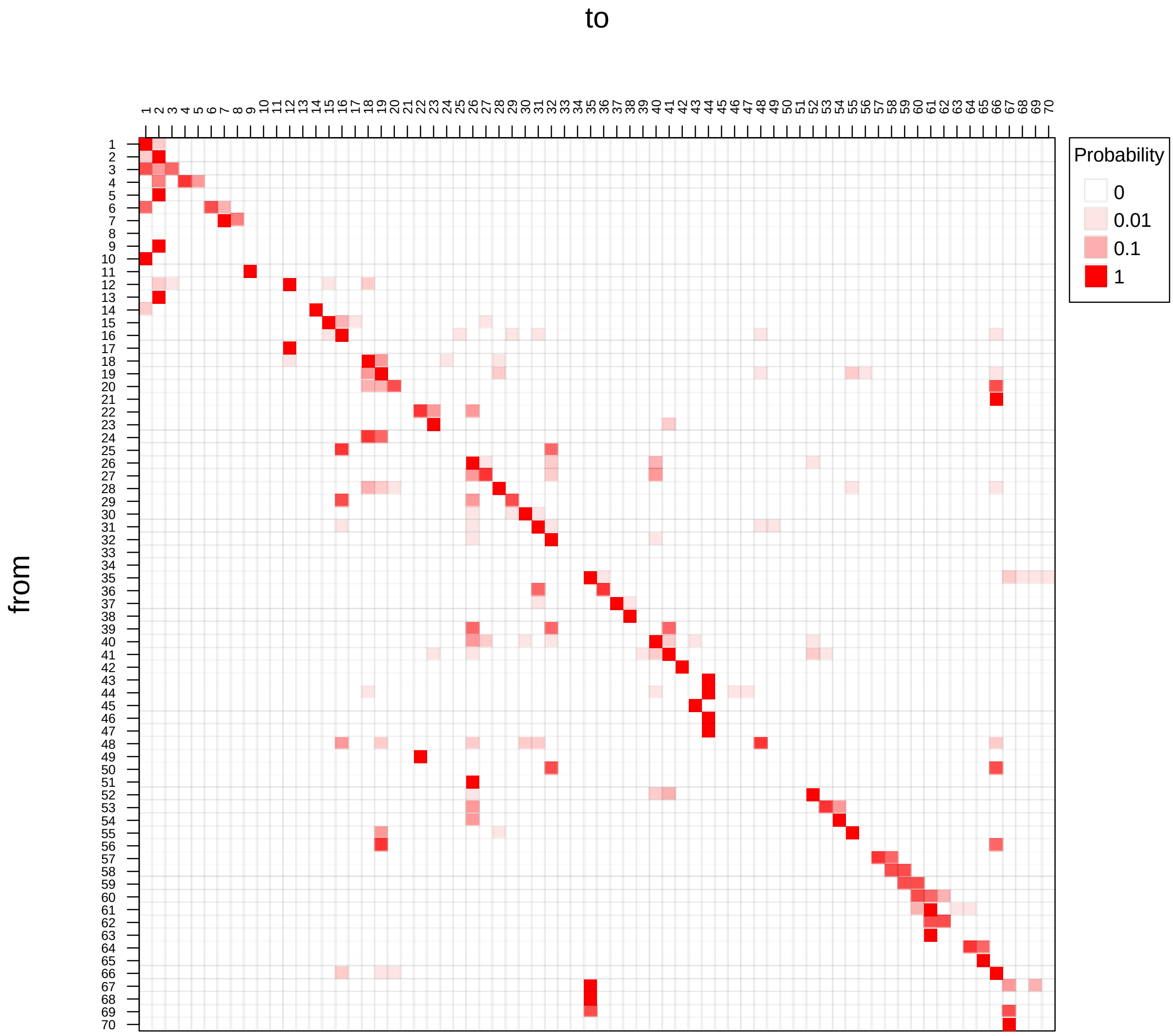

Figure 3. The probability of transitions from one haulout site cluster (rows) to another (columns) using data from 41 harbour seal tracks. These are the maximum likelihood estimates.

2.2.2.6.2 Modelling transition probability

The transition matrices contain a large number of zero probabilities – trips between haulouts that were never observed. While some may correspond to trips that will never occur, many are likely to happen given a longer time period. In addition, seals have hauled out at sites from which no trips have been observed. In order to fill in these gaps, the transition probability was modelled as a function of distance between sites (shortest sea route) and the use of the site (from aerial survey counts). The shortest sea route between haulout sites was calculated as above (Section 2.2.2.3). The use at each haulout site was estimated from long-term aerial surveys from 1996 to 2014 (Duck and Morris, 2012). The number of seals counted within 1.5km of a haulout site was counted for each year, and the median count for all available years was obtained. Transition probability was modelled using a zero-one inflated beta distribution using the R package 'zoib' (v.1.3.3) using the population level trips (in order to have sufficient data). The model explained 49% of the variance. The modelled transition probabilities were used to fill in gaps in the next step.

2.2.2.6.3 Estimating the number of missed haulouts and assigning new trips

Because tracks are only available for a limited time (~ two months), only a sample of the haulouts visited by each seal were observed. Should the animals have been tracked longer, the number of unique haulouts and trips would almost certainly be higher than observed. The number of unique haulout sites visited by each seal was estimated by fitting a discovery curve. The number of unique haulout sites (N_{unique}) was modelled as a function of the number of haulout events (N_{events}) using the non-linear equation:

$$N_{unique} = \beta_0 - e^{(-\beta 1 * Nevents)}$$

where β_0 is the maximum number of unique haulout sites that an animal visits and β_1 is the rate of discovery. For each seal, haulouts were resampled with replacement 500 times and the curve was fitted to each bootstrap sample. This yielded a distribution of β_0, the expected number of unique haulout sites visited and was summarised by a log-normal distribution for each animal. At the start of each simulation iteration the number of missed unique haulouts (n_{missed}) was drawn randomly from this distribution, with the constraint that at least one haulout was missed. The identity of each new unique haulout was drawn from a multinomial distribution, where the probability of a haulout being selected equalled the sum of the modelled transition probabilities (see Section 2.2.2.6.2.) from an animal's observed haulouts.

A trip ending at the new haulout (E) was then added. The starting haulout (S) was drawn from among the observed haulouts. The probability of S being selected was proportional to the modelled probability of transition from S to E and the matrices of transition probability were then recalculated. Because there are no data for trips originating from a new haulout, the modelled probability of transition was used for each new haulout.

2.2.2.6.4 Adding a temporal dimension

To account for variable haulout and trip durations, at-sea states indexed by the haulout site of departure were added to the transition matrices. For each of the 41 (the number of individual seal tracks) matrices, the median duration of haulouts and at-sea trips were used to estimate the hourly probability of remaining in each state. These *time-based* transition probabilities were then used to populate a haulout/trip transition matrix as illustrated in Figure 4. The upper left quadrant of the matrix refers to the probability of remaining at a haulout (diagonal with probabilities close to 1). The upper right quadrant refers to the probability of leaving a haulout and entering the appropriate at-sea state, indexed by the location of the departure haulout site (diagonal with probabilities close to 1). The lower right quadrant refers to the probability of remaining in an at-sea state (diagonal with probabilities close to 1). The lower left quadrant refers to the probability of hauling out at a site given the previous site. Seals cannot directly transit from one haulout site to another without first having transitioned via an at-sea state (indexed by its departure haulout site).

2.2.2.6.5 Tidal influence

In most areas, seals haulout more frequently at low tide. In order to reproduce this tendency, a tidal modifier (11h cycle) was added to the probability of starting and ending a trip: the right half of the transition matrix (Figure 4). The maximum difference in the probability of hauling out (low vs high water) was set to 2 on the logit scale; an approximation from time lapse photos obtained at two haulout sites (SMRU, unpublished data).

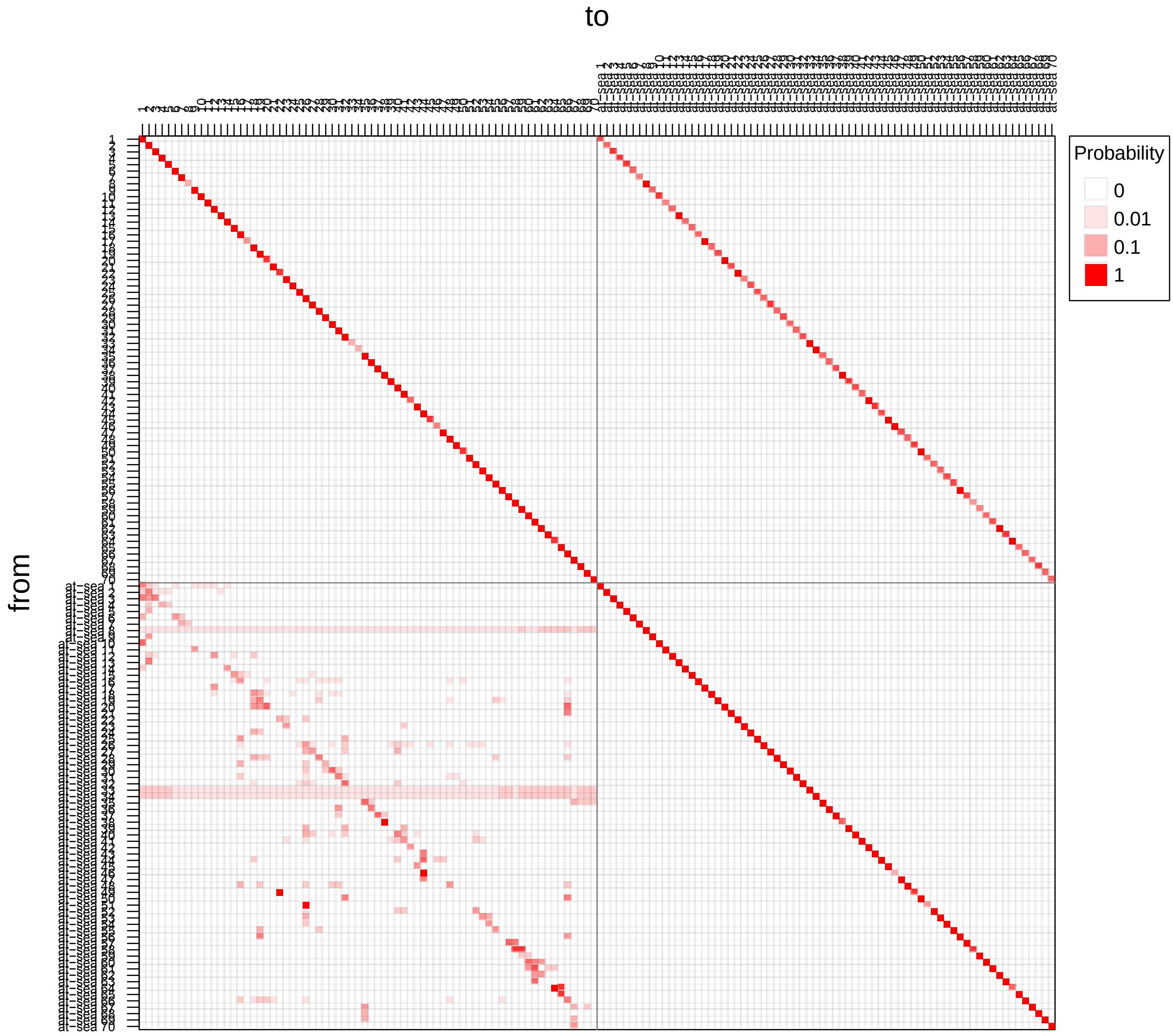

Figure 4. Example of a two-class (haulout and at-sea) transition matrix. The elements represent the hourly probability of state transition. The upper left quadrant shows the probability of remaining at a haulout. The upper right quadrant: probability of leaving a haulout and entering the at-sea state indexed by the location of the departure haulout site. The lower right quadrant shows the probability of remaining in an at-sea state (remaining at sea). The lower left quadrant shows the probability of hauling out at a site given the previous site; these probabilities were smoothed by resampling the discovery curve at each iteration.

2.2.2.7 Simulations

The simulations described below have not yet been completed. However, the strategy being adopted is outlined below.

2.2.2.7.1 Simulated population

The simulations will be run for a population size estimated by aerial surveys data from 1996 to 2014 (Duck and Morris, 2012): The sum of median survey counts (within 1.5km from the defined haulouts) amounted to 599 seals, which was rounded to 600.

At the start of a simulation, the simulated population will be randomly assigned to one of the 70 haulout sites. The probability of starting at a given site will be proportional to the median aerial survey count for that site. Once assigned to haulout sites, virtual seals will be randomly associated with one of the 41 transition matrices. At a given haulout site, the probability of being associated to a transition matrix will be proportional to the proportion of time that the tagged animal spent at that site.

Random unique haulouts and associated trips will be drawn randomly for each of the 41 different transition matrices to simulate uncertainty in missed trips (Section 2.2.2.6.3). This will yield 41 different vectors of abundances, each representing the distribution of virtual seals at the 70 haulouts and each with their respective transition matrices. At each (hourly) time step, these vectors of abundances will be updated by drawing transition events from their respective matrix of transition probabilities to simulate seal movements. Simulations will be run for a period of 12 weeks to obtain a steady state distribution of seals over haulout sites. Confidence intervals for the seal counts at each haulout site will be obtained by running 500 iterations of the simulations.

2.2.2.7.2 Disturbing the haulout network

The primary aim of this study is to simulate disturbance at a particular haulout site in turn to predict the effect at another (target) site. Here, a disturbed site will be made unavailable for hauling out as would be the case if, for example, access is blocked by anthropogenic activity. Such site closure will be achieved by setting each element in the 'to column' for this site to zero. Each 'from row' will then be appropriately adjusted so that the 'from row' probabilities still sum to one. The disturbance will be set to start on week 8 so that the distribution of virtual seals with and without the disturbance can be compared for a period of 4 weeks. The disturbance will be simulated for each of the haulout sites in turn. For each of the 70 (71 – 1) non-disturbed sites the effect of disturbance (the change in the number of hauled out seals) will be recorded over four weeks post-disruption.

2.2.3 Future tasks

The principal outstanding task is to run the simulations that will provide the data necessary to fulfil deliverables 1 and 2. Running these simulations has proved difficult, due to the unanticipated high computational overheads. Currently, the required number of simulations is taking many days of computer time. However, the code has recently been adapted to run on a multi-threaded computer cluster in the University of St Andrews which should dramatically reduce the run time.

2.3 Individual Based Modelling

2.3.1 Introduction

This section explores the feasibility of constructing and populating a scalable harbour seal IBM to model harbour seal movements and ultimately to predict changes in their distribution in relation to man-made or natural environmental change. This compliments the work of section 2.2, in which inter-haulout transition rates (IHTRs) are modelled. A limitation of the IHRT approach is that animals can only remember one step (transition) back which is unlikely to be true in real seals. Also, the IHRT approach is purely empirical; that is, the model is not based upon individual seals' strategies to achieve their energetic requirements through foraging and resting in a variable biological and social environment.

An IBM is a set of simple, biologically-derived rules that are applied a population of simulated animals. The resulting patterns of movement and behaviour are referred to as the IBM's *emergent properties*. Examples of such properties include various summary statistics of movement, distribution and activity budgets. These properties may be compared with independent data to assess the model fit and to guide changes to the model structure. The IBM rules should be comprehensive enough to realistically predict seal behaviour under a number of 'what if' scenarios. On the other hand, too many rules will produce an over-fitted model which will lack generality. Recent developments in IBM methodology have provided tools to determine optimal model complexity for a given purpose and to estimate model parameters (Railsback and Grimm, 2011).

Whilst IBMs are challenging to build and data hungry to parameterise, they do offer an opportunity to synthesise environmental and biological processes and data over a spectrum of temporal (from dive behaviour to seasonal trends) and spatial scales, and thus offer the prospect of more credible and defensible predictions of the effect of natural or anthropogenic change (Grimm and Railsback, 2012). It is important to note that the aim of an IBM is to fit its emergent properties to data, so that credibility is given to the underling rules. This aim is not to mimic the exact behaviour of individuals.

An IBM has been used to explore effect of noise on the movements of harbour porpoises (*Phocoena phocoena*) in Denmark (Nabe-Nielsen *et al.*, 2013; Nabe-Nielsen *et al.*, 2014), and referred to here as the *porpoise model*. However, there are basic differences in the biology of harbour seals and porpoises which must be reflected in the model structure. Also, the quantity and quality of data available for model validation and parameter estimation is far greater for harbour seals.

2.3.1.1 Project scope

The aim of this study is to identify the components of a plausible harbour seal movement model and to identify the data that would be required to tune it into a useful predictive model. In addition to determining proof of concept and the production of a road map for further development, work that has been carried out towards this end is also reported here.

2.3.2 IBM development

2.3.2.1 Biology

An IBM should be based upon known (or estimated) biological properties and behaviour of the target species. The pertinent features of harbour seal biology are summarised here.

Harbour seals need to maintain both short-term condition (through foraging–resting cycles) and long-term condition (for females sufficient to produce a viable pup each year). The strategy seals use to attain these goals is both enabled and constrained by their physiology (for example ingestion / digestion rates (Sparling *et al.*, 2007) and swimming speeds), information (spatial memory map of the perceived status of known foraging and haulout sites), exploratory behaviour, and the behaviour of conspecifics and competitors. The strategy is also affected by environmental factors – in particular the changing availability of prey items.

Harbour seals haul out on land at a variety of haulout sites, forming groups from one to many hundreds at one site. Some haulout sites may not be available during high water tides. A seal may haulout out for six hours or so. There then follows a foraging trip of one to five days, typified by a directed travelling phase, an area restricted search (ARS) phase and then a return phase of directed travel. Few foraging trips extend further than 50 km from the departure site. Usually the seal will return to the same haulout site and the ‘central place’ foraging pattern is repeated. This implies both navigational skills and the use of a spatial memory map. However, harbour seals occasionally move to alternative (occasionally distant) haulout sites – resulting in a larger total area being used. Interruption of at-sea foraging with a terrestrial haulout may be ultimately driven by a seal’s ability to ingest food faster than it can digest it.

In summary, the activity of harbour seals may be grouped into three mutually exclusive states: resting (both ashore and at sea), directed travelling and foraging (Russell *et al.*, 2015). This is in contrast to the nomadic foraging of porpoises (Nabe-Nielsen *et al.*, 2014), and so the porpoise model must be restructured accordingly.

2.3.2.2 Data

For an IBM to be a useful management tool it must be capable of being informed, challenged and modified by data. Three primary types of data exist for UK harbour seals:

- Over 300 telemetry tracks (including haulout and dive records) of tagged seals. Their mean duration is about 50 days.
- Annual (though temporally and spatially irregular) counts of harbour seals hauled out during their annual moult (August) around the UK.
- Dietary and energy requirements.

2.3.2.3 Model structure

A proposed model structure is summarised in Figure 5. The model is based on an individual alternating between *foraging* at sea and *hauling out* ashore, based (primarily) on its state (internal properties such as condition). In this figure behavioural intentions are coloured as yellow; behavioural activities (the realisation of biological intentions) as blue; decision functions as white; and internal properties as orange.

Model variable classes and names are shown in *italics.* There are three classes of variable*: global::* referring to all individuals*, individual::* individual specific variables, and *landscape::* referring to the spatial and temporal distribution of physical (e.g. haulout sites) and biological (e.g. prey) variables. Variable [units] are enclosed in square brackets.

An outline of the model follows with further details are given in the subsequent sections.

IBM’s simulate using discrete time steps. The simulation step in this model is currently one hour and is represented by the *increment-timer* function (top centre in Figure 5).

If a seal is in a directed travelling activity (*forage-patch-travel, or haulout-site-travel*) then it will continue in this activity until the target is reached. It will not be influenced by information gathered en-route. If not in a travelling activity, it will choose an intended behaviour based upon its internal condition.

If the behavioural intention is to forage (*forage-intent*) then it will first determine whether it is at a prey patch. If so, it will enter forage activity. If not, then it will attempt to move to a prey patch, either by choosing from a profitable previously visited patch in its memory *(choose-target-patch*) or by initiating a search strategy. Memory is the preferred option, unless; a) the seal is naïve and has little experience, or b) using memory has consistently been unsuccessful. Success here means that over a period of, say, a week, the seal has maintained or increased its energy stores (*blubber-energy*). The choice of target is based upon a function that includes distance and previous profitability. The seal will then enter a directed travel activity (*forage-patch-travel*) until it reaches the chosen target. If memory is not used then it will enter a search activity (*forage-patch-search*).

If the behavioural intention is to haulout (*hauled-out-intent*), there is an identical decision making structure. If the behavioural intention is *resting-at-sea* it will immediately take on that activity until *choose-behaviour-intention* chooses otherwise.

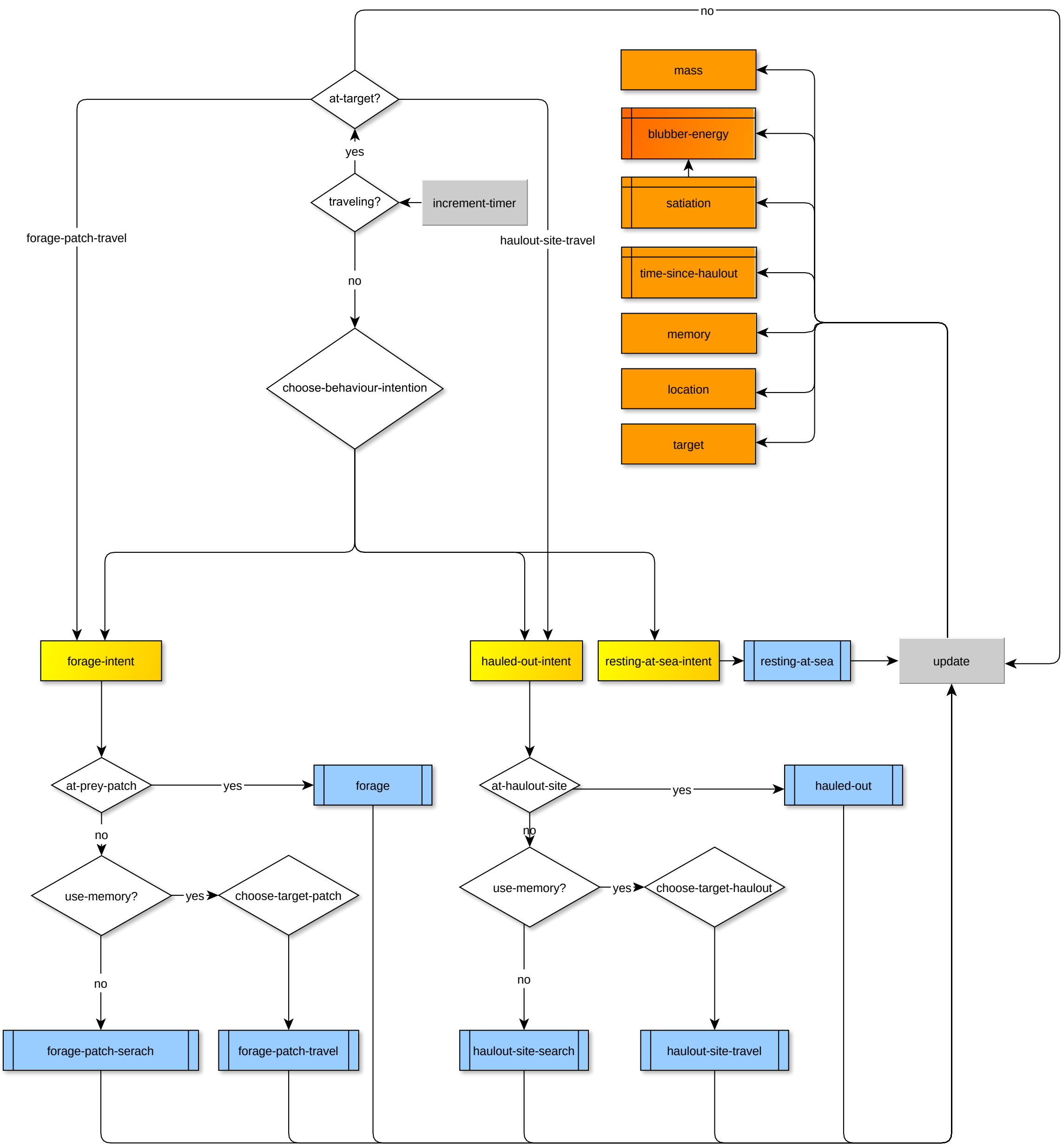

Figure 5. Outline of proposed harbour seal IBM structure. Behavioural intentions are coloured as yellow, behavioural activities as blue, decision functions as white and intrinsic states as orange. See text for an explanation.

The following sections present more detail.

2.3.2.4 Individual properties

Each individual seal is assigned seven intrinsic properties as shown in Figure 5 and Table 2. Units, where applicable, are shown in square brackets.

Table 2. Individual properties.

individual property	**description**
satiation	Short-term energetic condition that influences the start and end of foraging trips: It is the amount of undigested food in the stomach expressed as a *proportion* of the maximum food that the stomach (whose volume is scaled by *individual::mass*) can hold. It will decrement by the *global*::*digestion-rate* [kg/h]. It will increment in relation to *landscape::foraging-patches* value but at a maximum ingestion rate of *global::ingestion-rate* [kg/h].
blubber-energy	Long-term energetic condition. This is primarily related to the energy stored and available in the blubber [J].
mass	Total mass (used to scale energy expenditure and stomach satiation) [kg].
time-since-haulout	Whilst the motivation for foraging is the acquisition of energy, the role of hauling out on land is less clear. Being on land may have energetic benefits, allow, social interaction, or may control parasites. Here the motivation to haulout is influenced by this simple latent variable which records the elapsed time since the end of the last haulout [h].
memory	Each seal has two spatial memory map structures: for haulout sites and prey patches respectively. For each cell visited each map contains a value indicating the quality of the targeted resource. For prey patches this is affected, inter *alia,* by prey density. It is assumed that one of the benefits derived from a haulout is the presence of conspecifics. As the number of conspecifics increases the proportion of time that an individual devotes to alertness is reduced. Thus the number of conspecifics hauled out concurrently with an individual seal at a specific site will contribute to the quality of that site in that seal's haulout memory map. Unless a seal visits all cells within the geographic extent of the model's landscape, its individual memory will be a subset of the global distribution and quality of haulout sites or foraging patches that are stored in the landscape rasters. Thus a naïve seal (at the start of a model run – equivalent to a new born pup with no maternal assistance) would have no memory of haulout sites or prey patches and so would rely initially on search strategy (see Section 2.3.2.10). The data in both memories will be forced to decay with time (Nabe-Nielsen *et al.*, 2014). This is for two reasons. First, the value of the spatial memory data decays through time due to changes in the landscape environment. Second, an animal's ability to remember decays through time.
location	The current location [latitude, longitude].
target	When memory mode (see 2.3.2.10) is chosen, a target destination (either a haulout site or a prey patch) is chosen. This target is held constant during the passage towards it. For example, when a seal is in transit it will not be diverted by any opportunistic discoveries made en-route.

2.3.2.5 Global properties.

Global properties that refer to generic seals (rather than specific individuals – Section 2.3.2.4) are shown in Table 3.

Table 3. Global properties.

global properties	**description**
movement	Frequency distributions of speeds and turning angles, indexed by *behavioural-activity*.
energy-out	Mass-specific metabolic rates indexed by *behavioural-activity* [$J.s^{-1}.kg^{-1}$].
energy-in	The gross energy gained during the *forage* activity may be based on information from tagged harbour seals from populations that are not in decline. Movement and behavioural data from tagged seals can be used to infer behavioural activity (Russell *et al.*, 2015). It may be cautiously assumed that seals tagged in the months preceding breeding will, at the very least, not lose body condition on average. Using this conservative assumption and the mean proportion of time classified as *foraging* from the tag data, the mean (or minimum) gross energy gain rate during foraging may be estimated. It may be possible to rank the energy gain from different patches on the basis of a) repeated consecutive visits and b) the simulations use of a set of foraging patches by several individuals[3].
digestion-rate	The rate at which food is digested [kg/h].
ingestion arte	The maximum rate at which food may be ingested [kg/h].

2.3.2.6 Landscape properties

The environmental landscape is represented as a raster of discrete cells with a set granularity, in this instance, of 1 km^2 and whose geographical extent is shown in Figure 1. Landscape has four properties as shown in Table 4.

Table 4. Landscape properties.

landscape property	**description**
land	
haulout sites	Derived from aerial counts at harbour seal haulout sites and haulout sites used by tagged harbour seals. Note that the aerial counts are generally only available for the moult season (August).
foraging-patches	Derived from • known foraging patches of tagged harbour seals, • synoptic characterisation using environmental covariates, and • modelling the distribution of prey species based on fish surveys. It is acknowledged that there will be a high degree of uncertainty in the size of foraging patches. In the initial IBM, this raster will be static, but in future versions it could be modified to be depleted and/or grow.
shortest-sea-route	Rasters of vectors used to direct seal travel from any starting point to a predetermined destination target (haulout site or foraging patch) using the shortest path that avoids travel overland. For each target a raster of vectors is created such that, from any starting point in the raster, following successive vectors results in a cell-by-cell route that is the shortest distance to the target. An example of a *shortest-sea-route* raster layer (based on the R library ‘gdistance’) is shown in Figure 6.

[3] The latter data could form a set of simultaneous equations whose solution could estimate relative net energy gain from different patches.

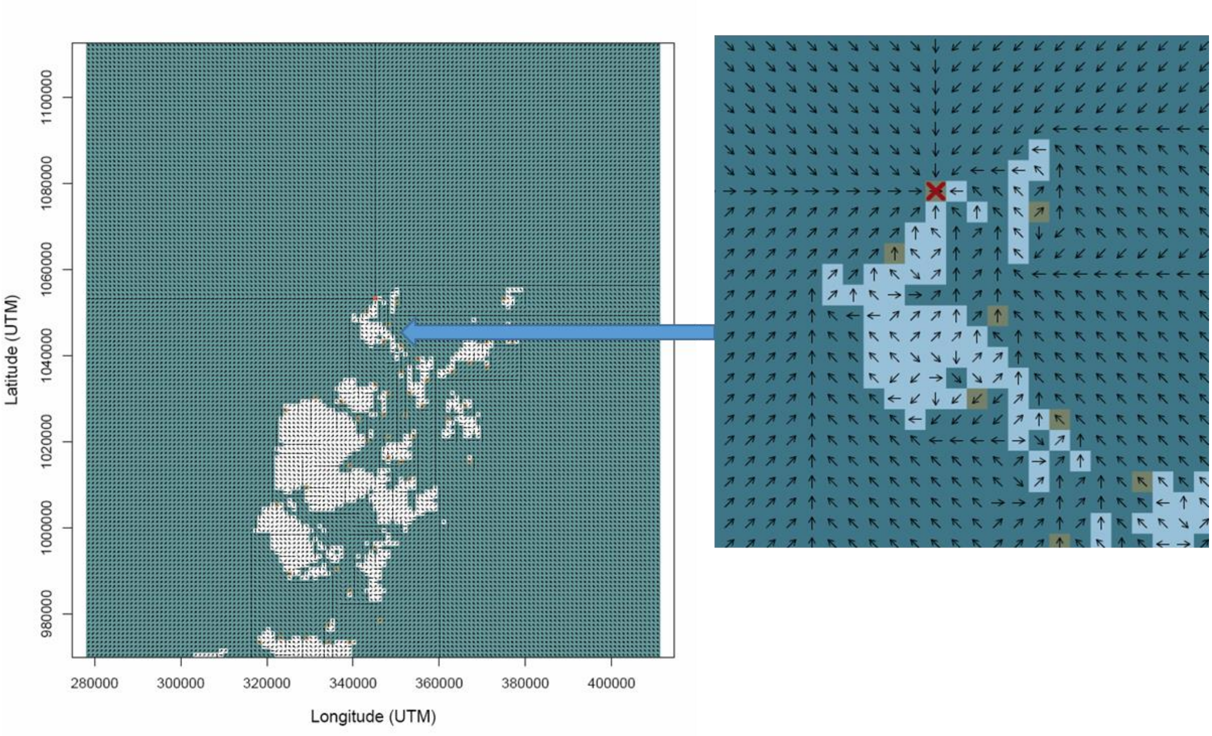

Figure 6. Example of a shortest-sea-routes raster (see Table 4). The arrows show direction vectors routing the seals to a target (here specified by the red cross). Vectors on land have no meaning.

2.3.2.7 Behavioural intentions

Each seal is assigned a behavioural intention based upon its individual properties. The output can be one of three intended activities:

- *Forage-intent*
- *Hauled-out-intent*
- *Resting-at-sea-intent* Resting bouts may occur while at sea (Ramasco *et al.*, 2014)

2.3.2.8 Behavioural activities

There may be a delay from the start of a behavioural intention (for instance, to haulout) and its realisation into a behavioural activity (the seal may have to swim for a day to get to a target haulout site).

Each seal is assigned a behavioural activity which can be set to one of seven states (see Table 5). This table also shows how the behavioural activity affects the updating of *individual::location* every model step.

Table 5. Behavioural activities.

behavioural activity	description	movement characteristics (TA=turning angle)
forage	Fine scale area restricted searching. Successful prey capture is not necessarily assumed.	speed: slow[4] TA variance: high
hauled-out	Hauled out on land.	speed: zero TA: zero
forage-patch-search	Search for foraging patch (without recourse to long-term *seal::foraging-patches-memory*).	Move off-shore and carry out a planar search strategy. (see 2.3.2.9.6)
forage-patch-travel	Travel by shortest sea route to chosen *forage-patch target*. A seal will ignore other food patches en route.	speed: fast TA: determined by *landscape:: shortest-sea-routes* vectors
haulout-site-search	Search for haulout site (without recourse to long-term *seal:: haulout-sites-memory*).	Move on-shore and carry out a linear search strategy. (see 2.3.2.9.6)
haulout-site-travel	Travel by shortest sea route to chosen *haulout-site target*. A seal will ignore other haulout sites en-route.	speed: fast TA: determined by *landscape:: shortest-sea-routes* vectors
resting-at-sea	Rest at sea in between feeding bouts. No attempt to travel to a haulout site.	speed: zero TA: zero

2.3.2.9 *Behavioural functions*

The behavioural-intentions and -activities of a seal are based upon a number of choice functions (shown as diamond boxes in Figure 5). An outline of the seven behavioural functions follows.

2.3.2.9.1 choose-behaviour-intention

Input	*seal::*(*satiation, blubber mass, time-since-haulout*)
Output	*forage-intent* or *hauled-out-intent* or *resting-at-sea-intent*
Description	Determines the behavioural intention. For *forage-intent* or *hauled-out-intent* the corresponding behavioural activity may be delayed due to a need to relocate and/or search.

2.3.2.9.2 at-prey-patch

Input	*seal::location, landscape::foraging-patches*
Output	Yes or no
Description	Is the seal at a patch with food?

2.3.2.9.3 at-haulout-site

Input	*seal::location, landscape::haulout-sites*
Output	Yes or no
Description	Is the seal at haulout site?

2.3.2.9.4 patch-memory-strategy

Input	*seal::*(*location, memory-prey-patches*), *landscape::prey-patches*
Output	Yes or no
Description	Chooses whether to use memory or search strategy to find profitable prey patches. The choice will favour memory, but search will be used where the recent use of memory has failed to find profitable prey patches.

[4] Speeds and turning angle will be randomly selected from empirical probability distributions of movement data from tagged seals whose behaviour is classified as foraging.

2.3.2.9.5 choose-target-patch

Input	*seal::*(*location, memory-prey-patches*), *landscape::*(*prey-patches, shortest-sea-route*)
Output	Patch *target*
Description	Choose a target foraging patch. This will be based up a function of distance (using *shortest-sea-route*) and profitability of candidate patches

2.3.2.9.6 haulout-site-memory-strategy

Input	*seal::(location, memory-haulout-sites), landscape::haulout-sites*
Output	Yes or no
Description	Chooses whether to use memory or search strategy to find profitable haulout sites. The choice will favour memory, but search will be used where the recent use of memory has failed to find profitable haulout sites.

2.3.2.9.7 choose-target-haulout

Input	*seal::*(*location, memory-haulout-sites*), *landscape::*(*haulout-sites, shortest-sea-route*)
Output	Haulout site *target*
Description	Choose a target haulout site. This will be based up a function of distance (using *shortest-sea-route*) and profitability of candidate haulout sites.

2.3.2.10 Spatial memory or search strategies

In Nabe-Nielsen *et al.* (2013) porpoise foraging behaviour was determined by either choosing a foraging patch that had previously been profitable or by undertaking a search strategy. This approach is used in the harbour seal IBM. In general, memory is used in preference, unless that strategy has proved unsuccessful over a period of approximately one week.

2.3.2.10.1 Spatial memory

See *individual::memory* in Table 2.

2.3.2.10.2 Search strategies

There are two targets: haulouts on a linear feature (the coastline) and prey patches on a planar feature (the sea). The search strategies for each of these features is currently being determined.

2.3.3 Model parameterisation and validation

Constructing a simulation model to generate a variety of outputs is of limited use. To be a useful predictor of behavioural response to environmental change, the model of the appropriate complexity must be validated and its parameters must be robustly estimated (Thiele, 2014).

In both model validation and parameter estimation, it is the emergent properties of multi-individual simulations that are fitted to corresponding properties of data obtained from tagged seals and haulout counts. Candidate data properties include:

- foraging trip duration patterns and auto-correlation[5]
- foraging trip extent patterns and auto-correlation
- proportion and variability of activity budgets (rest, directed travel, foraging, hauled out)
- proportion and variability of haulout duration
- patterns of inter-haulout movement transitions (as derived in Section 2.2)
- inter-individual synchrony in haulout site and foraging patch usage

This list is provisional and will probably be extended.

The analytical methods to be used for model validation and parameter estimation are currently under development.

[5] For example, the repeated use of a particular foraging patch (temporal and spatial auto-correlation) would tend to suggest that an animal is using memory rather than carrying out multiple independent searches.

2.3.4 Geographical extent

The proposed initial geographical extent of the IBM is the same as that used in the Inter-Haulout Transition Rate Modelling in Section 2.2.

2.3.5 Initial results

The model described here is currently in development, although a preliminary model has been constructed. In this model, all seals have perfect knowledge of their environment, and prey patches are 'constant' i.e. prey is always available there at a consistent rate. An example of the initial results is shown in Figure 7. This simple model can clearly reproduce some elements of two dimensional seal movement, but it is very sensitive to the fine-tuning of the parameters in the expressions that are used to calculate motivations and states. At this stage therefore no attempt has been made to validate the model by comparison with empirical data.

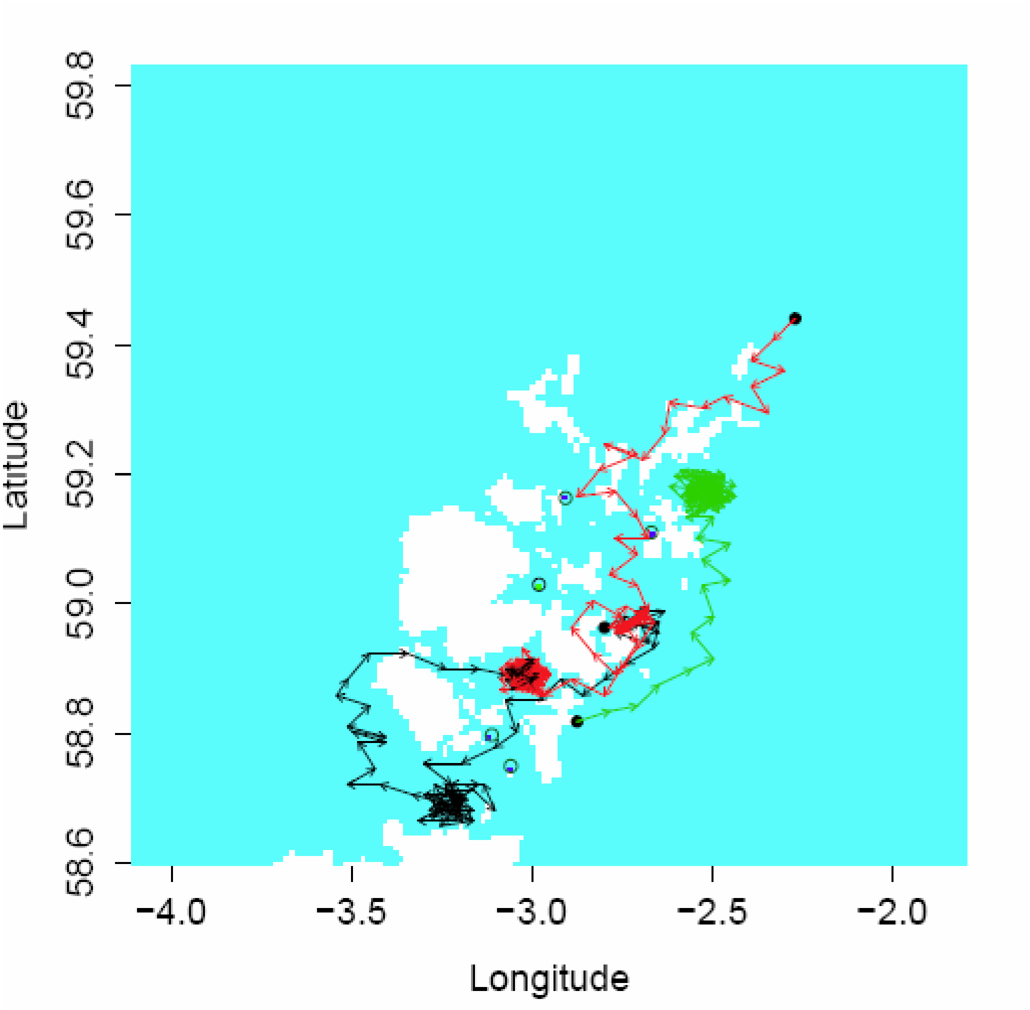

Figure 7. Simulated tracks based upon three haulout sites and three proposed foraging areas.

2.3.6 Proof of concept and future tasks

The harbour seal IBM is still in development and whilst it has not yet reached the stage where 'proof of concept' can be determined, a plausible structure has been developed which captures what are considered to be the major biological and environmental processes affecting movement in harbour seals. Substantial code has been written in both R and Netlogo (Thiele *et al.*, 2012).

To complete proof of concept the following tasks will be undertaken:

- Compilation of plausible global and individual and landscape parameters.
- Development of memory-based and search-based movement algorithms.
- Propose candidate methods and data properties that will enable model validation and parameter estimation.
- Production of a plausible simulation of harbour seal movement using the IBM approach.

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3 MRE1.3 - Estimating collision risk using available information

3.1 Introduction

Harbour seals are a species of particular conservation concern and there are sub populations of harbour seals associated with almost all potential tidal energy sites in Scotland. As a result of targeted funding from Scottish Government, Scottish Natural Heritage (SNH) and the Natural Environment Research Council (NERC) there are now substantial data sets on seal movements and diving behaviour at several such sites. A description of the fine scale movement patterns and a detailed analysis of the effects of tidal flow on seal movements at Kyle Rhea have been completed under the previous project and in collaboration with NERC funded studies. In addition, an initial assessment of the collision risk at a proposed tidal array in the Pentland Firth has been derived using the detailed telemetry data on movement and dive behaviour in combination with recent population assessments. This data derived estimate of collision risk can be compared with the output of various collision risk models to assess their effectiveness. The intention is to extend the data derived estimates of collision risk to all sites for which sufficient telemetry based movement and survey based population data is available. This work will be carried out under SMRU's NERC core project and as a continuation of work under NERC's EBAO (Optimising Array Form for Energy Extraction and Environmental Benefit) project.

3.2 Proposed methodology

The estimated collision risk is apparently sensitive to fine scale local distribution of seal activity. It is therefore proposed to extend these analyses to provide the same detailed collision risk assessment for all sites for which sufficient telemetry and population data exist. This will include sites in the Sound of Islay, Kyle Rhea and various sites within the Orkney archipelago.

3.3 Amalgamation of reporting

Since the outputs of MRE 1.3 are primarily feeding into a separate Marine Scotland funded project (CR/2014/12 - Update of collision risk estimation for harbour seals and tidal turbines), it was agreed that CR/2014/12 would be the delivery route for this task and the steering group would comment accordingly on the reporting outputs, with the deliverables for MRE1.3 incorporated into CR/2014/12.