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Seabird Survey Designs for the East Coast of Scotland

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Executive Summary

A range of survey designs are considered for the detection of seabird population changes and estimation of Flight Height Distributions (FHD) off the Eastern coast of Scotland. The investigations are based on simulations, with data from the SEAPOP, MERP and JCP modelling projects and survey platform parameters in line with current digital aerial surveying technology. The simulations demonstrate the amount of surveying effort that is required to meet a range of power objectives for seven bird species and harbour porpoise. Survey designs for collecting data for FHD estimation using tandem LiDAR and digital cameras are also presented.

Power to detect changes for some species and seasons is very low, whereas for more abundant species good power to detect 20-30% changes can be achieved with coverage proportions of <10% for some regions and seasons. This translates to modest numbers of days surveying. Robust FHD estimation can also be reasonably achieved for several species with modest amounts of survey effort. Further, spatio-temporally varying FHD estimation can be achieved in many cases.

All results are predicated on species' density maps and their associated uncertainty. Comparison of sources of density information show marked differences and any advice arising is sensitive to this. The LiDAR surveys in particular are sensitive to the underlying assumed density models, however, indicative figures can be drawn and software tools for bespoke design have been developed and are freely available.

Introduction

We present here analyses to inform the design of digital aerial surveys off the East Coast of Scotland, with the objective of monitoring seabird populations and for determining species-specific Flight Height Distributions (FHD). In addition, one marine mammal species (harbour porpoise) is considered for population monitoring.

Currently the survey approaches to counting birds and determining their FHD are not coincident, so separate analyses are considered for these objectives. In either case, the problem is approached here through extensive simulation, where bird populations are simulated, along with surveys with differing properties.

The surveying platforms here are either:

- Digital aerial video/still camera for the classification and counting of animals.
- Digital aerial video/still camera for the location and classification of birds on the wing, coupled with LiDAR to determine their height from the sea.

Digital aerial surveying is state of the art and no other variants are considered. These have the desirable property of near complete detection for birds (i.e. all available animals in swath are found) and misclassification is low, due to careful post-processing of collected images.

We present here:

- The objectives of the two survey types.
- The general scope of analyses.
- The simulation designs.
- The inputs required to populate the simulations.
- The summarised results and outputs.
- Caveats to the current works and sensitivities.
- Discussion/conclusions with future works and questions arising.

Study objectives

For population monitoring, we seek to establish the efficacy of various survey designs, mainly differing in intensity. Efficacy here is deemed to be the ability to detect changes in population size - in essence, statistical power. The analyses here will consider a range of potential changes in population and calculate the ability of different survey designs to detect these. Power of 80% is a standard reference point, so survey designs which achieve this for a particular species are identified. In addition, a reference of figure of a 30% population shift is also to be reported on.

For FHD estimation, we seek the amount of survey effort required in a particular area and time, to capture sufficient individuals for a robust FHD curve. Robustness is subject to definition, and we adopt the opinion in Cook *et al.* (2018), that at least 100 individuals be required for robust FHD estimation.

Scope of survey design

Survey designs were considered for four regions off the Eastern Coast of Scotland. These are referred to as the following, and plotted in Figure 1:

- Wider Forth and Tay survey area (Region 1).
- Wider Moray and Forth survey area (Region 2).
- East Coast of Scotland survey area (Region 3).
- East Herman to Berwick survey area (region 4).

For ease of use, these may be referred to in the report as Regions 1-4, in line with increasing size.

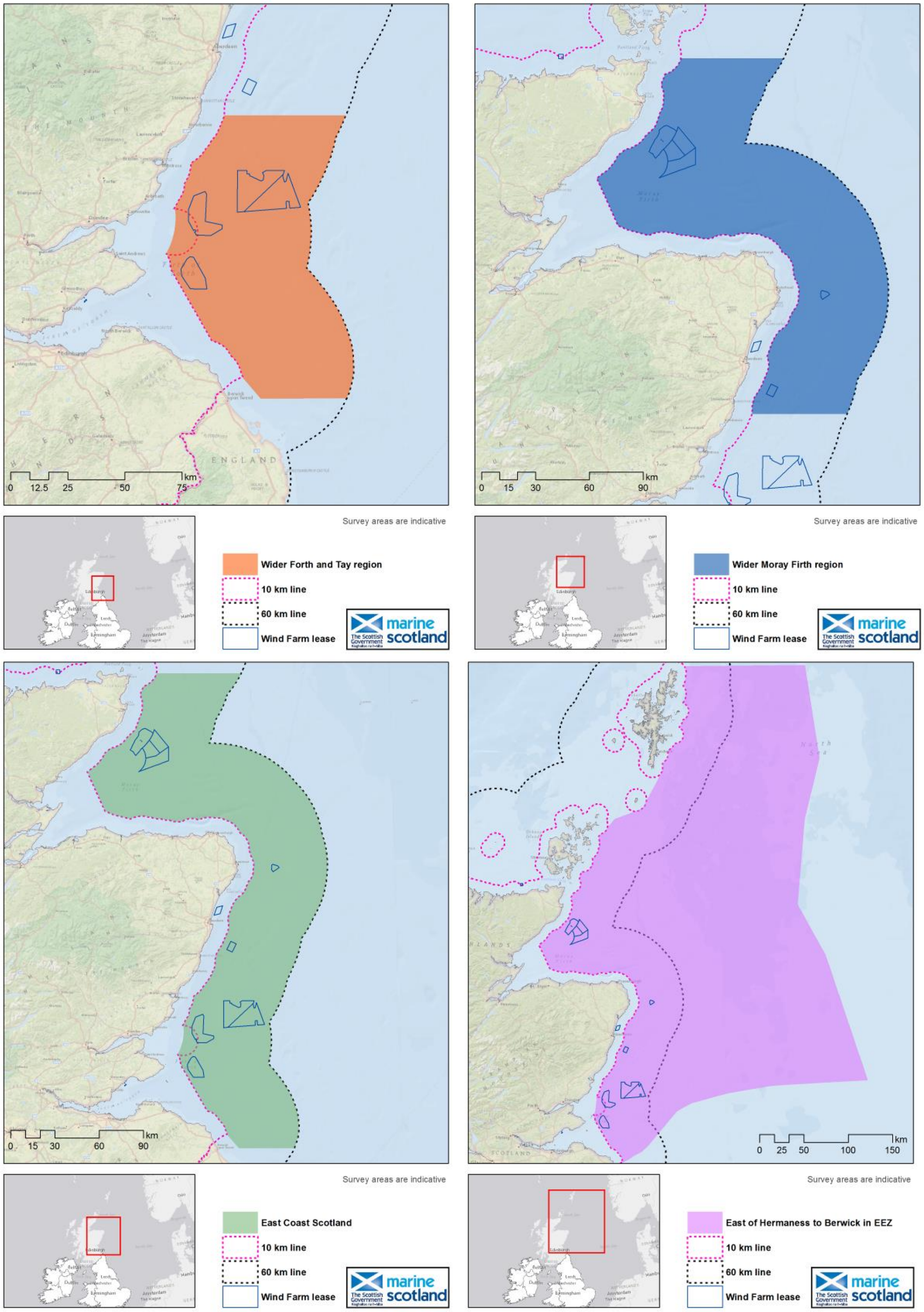


Figure 1: Four survey regions under consideration.

Survey species

The following seven seabird species, and one marine mammal, are considered in developing the survey designs:

- Northern gannet (*Morus bassanus)*
- Black-legged kittiwake (*Rissa tridactyla*)
- Common guillemot (*Uria aalge)*
- Razorbill (*Alca torda)*
- Puffin (*Fratercula arctica)*
- Herring gull (*Larus argentatus)*
- Great black-backed gull (*Larus marinus)*
- Harbour porpoise (*Phocoena phocoena*)

Data

The analysis approach is based on simulations, described later, which require a range of data and parameter estimates. Mainly these are estimated animal density surfaces, with uncertainty, and parameters relating to the survey platform's capabilities. The nature and source of these data are expanded upon in turn.

Animal density information

Both surveying objectives (FHD and population changes) are predicated on some knowledge of the spatial distribution of birds. This is not fully known, but there are various estimates available, generally based on modelling and extant survey data. Here we consider three sources of density information:

1. The SEAPOP mapping programme.
2. The Marine Ecosystems Research Programme (MERP).
3. The Joint Cetacean Protocol (JCP).

SEAPOP density surfaces

At-sea bird densities are drawn from the models given by the SEAPOP seabird mapping program (SEAPOP[1]). Modelled densities extend from the North and Western Coasts of Scandinavia across the North Sea to the eastern UK. Estimates are on a 10×10 km grid, covering three to four seasons (spring/summer are combined) with uncertainty measures (Figure 2 and Figure **3**). The data come in shapefiles for each season and contain 12 species (Table 1)

[1] http://www.seapop.no/en/distribution-status/distribution/at-sea/

Table 1

Species coverage of the SEAPOP at-sea bird density models.

Common name	**Specific name**
Razorbill	*Alca torda*
Little auk	*Alle alle*
Common gull	*Larus canus*
Herring gull	*Larus argentatus*
Northern fulmar	*Fulmarus glacialis*
Northern gannet	*Morus bassanus*
Black-legged kittiwake	*Rissa tridactyla*
Common guillemot	*Uria aalge*
Atlantic puffin	*Fratercula arctica*
Brünnich's guillemot	*Uria lomvia*
Glaucous gull	*Larus hyperboreus*
Great black-backed gull	*Larus marinus*

Examples are given for one species (black-legged kittiwake) in
Figure **3**, showing the seasonable variability in densities and the uncertainty, as expressed by upper and lower 95% confidence intervals.

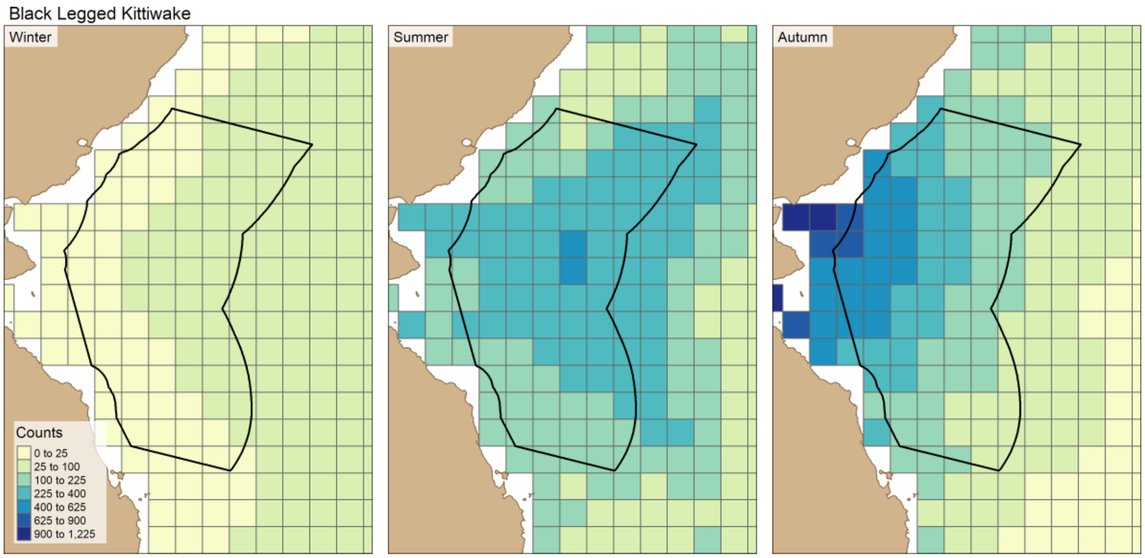


Figure 2: Example SEAPOP at-sea bird density estimates. The species presented is black-legged kittiwake. Estimates are counts per 100 km^2 and cover the three seasons as defined in SEAPOP.

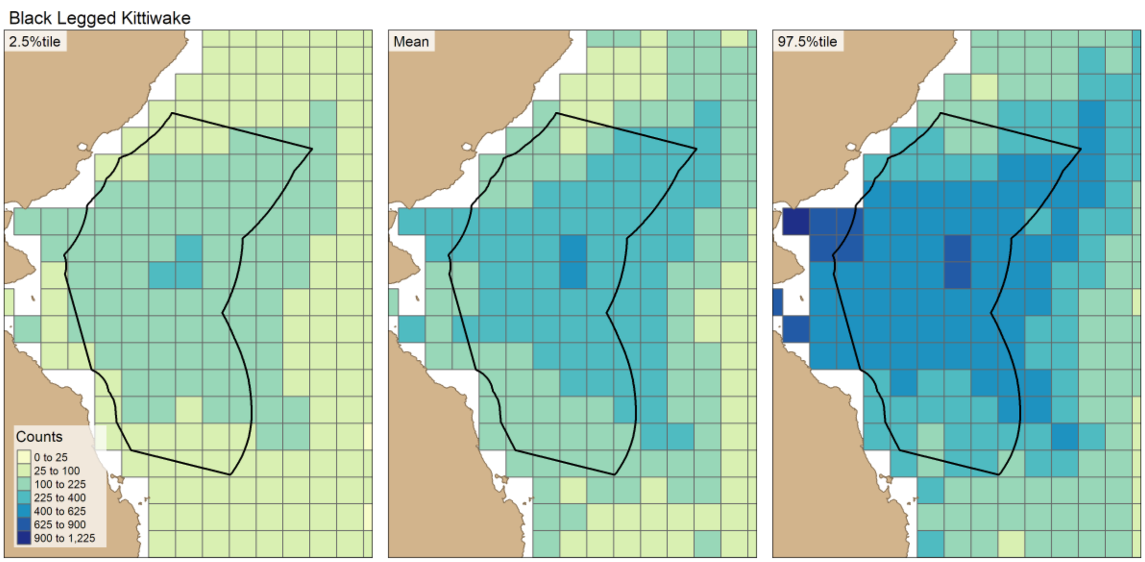


Figure 3: Example SEAPOP at-sea bird density estimates. The species presented is black-legged kittiwake. Estimates are counts per 100 km^2. The centre plot gives the mean surface, with left and right plots giving the lower and upper 95% confidence bounds respectively.

The implied estimated population sizes for each of the four survey regions are given in Table 2 contrasting one relatively rare (great black-backed gull) and one abundant species (common guillemot).

Table 2

Summary of SEAPOP at-sea bird estimates for two species by region and season.

Species	Region	Season	N	Density per km^2
Great black-backed gull	Region 1	autumn	418	0.044
		summer	17	0.002
		winter	639	0.067
	Region 2	autumn	451	0.024
		summer	140	0.007
		winter	1095	0.058
	Region 3	autumn	846	0.031
		summer	156	0.006
		winter	1680	0.061
	Region 4	autumn	1285	0.010
		summer	403	0.003
		winter	4169	0.034
Common guillemot	Region 1	autumn	67490	7.104
		summer	73054	7.690
		winter	19875	2.092
	Region 2	autumn	62084	3.302
		summer	104050	5.535
		winter	26561	1.413
	Region 3	autumn	125468	4.562
		summer	172324	6.266
		winter	44779	1.628
	Region 4	autumn	193688	1.561
		summer	238193	1.919
		winter	73146	0.589

MERP data

The Marine Ecosystems Research Programme (MERP) includes a large-scale modelling exercise that covers the North-East Atlantic, extending from Norway to Portugal. In terms of density models, it is to cover 12 of the most common bird species and 12 of the most common cetaceans. Publication of the bird modelling results is imminent, with the bird density maps being pre-emptively released for consideration here (*pers. comm.* J Waggitt, April, 2019). Similar to SEAPOP this provides estimated densities with uncertainties (95% confidence intervals). However, the spatial extent is larger than that of SEAPOP and the temporal resolution much finer (monthly versus roughly seasonal). Six of the seven species within the scope are modelled by both SEAPOP and MERP.

The MERP data give estimated bird densities at 10 km grid resolution at a monthly level.

Table 3

Species made available from MERP for this project – all have predicted monthly density estimates with associated uncertainty.

Common name	Specific
Razorbill	*Alca torda*
Herring gull	*Larus argentatus*
Northern fulmar	*Fulmarus glacialis*
Northern gannet	*Morus bassanus*
Black-legged kittiwake	*Rissa tridactyla*
Common guillemot	*Uria aalge*
Atlantic puffin	*Fratercula arctica*
European shag	*Phalacrocorax aristotelis*
European storm petrel	*Hydrobates pelagicus*
Great Skua	*Stercorarius skua*
Lesser black-backed gull	*Larus fuscus*
Manx shearwater	*Puffinus puffinus*

Examples are given for one species (black-legged kittiwake) in
Figure 3. To make comparable to the SEAPOP estimates previously shown, the months have been averaged to give seasons matching SEAPOP.

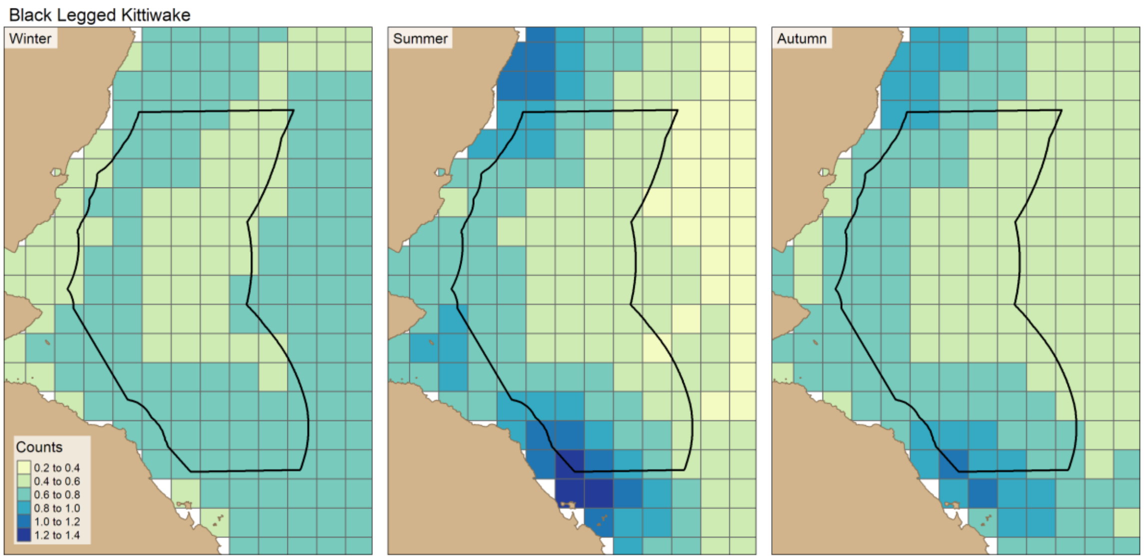


Figure 4: Example MERP at-sea bird density estimates. The species presented is the black-legged kittiwake. Estimates are counts per 100 km^2 and cover the three seasons as defined in SEAPOP.

Marine mammals from the JCP phase 3 data

Harbour porpoise abundance data were sourced from the JNCC's Data Resource Analysis Phase III (Paxton *et al.*, 2016). Data were extracted for the four survey regions, and consist of point estimates of density and associated uncertainty. The predicted abundances are per 5x5 km grid-cell, extending continental shelf edge west of Ireland to the Kattegat. For harbour porpoise, these are summer estimates and include uncertainty as 95% confidence intervals (derived from the packaged bootstrap estimates).

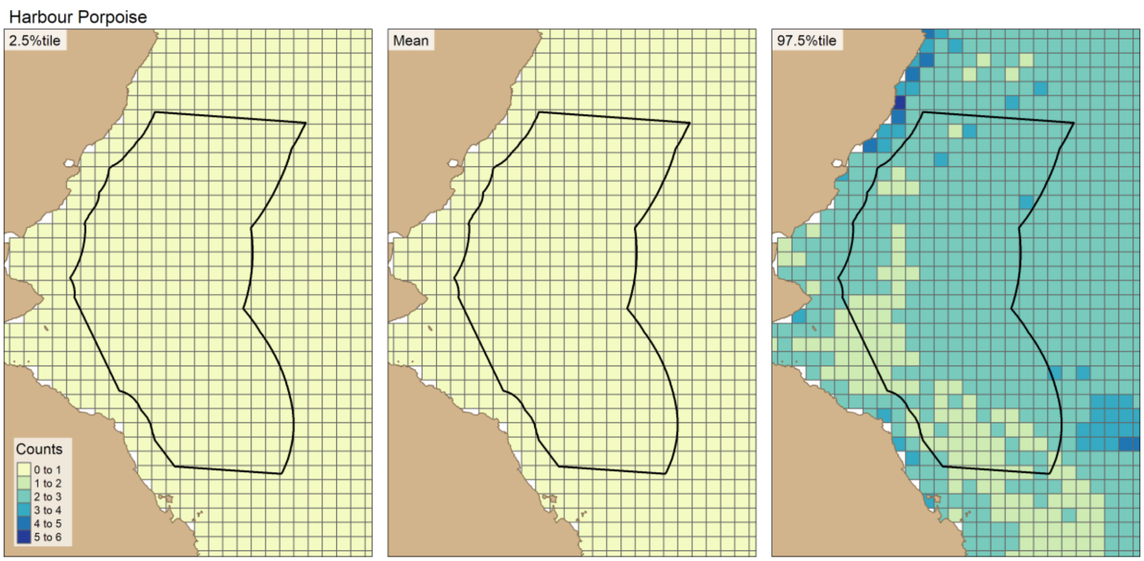


Figure 5: Example JCP phase III harbour porpoise density estimates. Estimates are counts per 25 km^2. Lower plots are the associated 95% confidence intervals.

The estimates from the JCP have had a number of corrections applied for comparability over different surveys/designs. In particular there have been corrections for the detectability of animals, but also availability i.e. the proportion of time that an animal is available for detection by a particular platform. This has consequences for how the data is treated in survey simulations, as indicated later.

Survey platforms

Surveying for density estimation (digital video/photography) or for FHD would currently be conducted by different platforms – the latter flying lower with both camera and LiDAR. The simulations were consequently parameterised differently for the two survey objectives.

Parameters for digital aerial surveying for abundance estimates were provided by a commercial digital aerial surveying company (*pers. comm.* A Webb, HiDef Aerial Surveying Ltd, June 2019). It is assumed that a swath of 500 m is surveyed, with full detection of birds within this. Survey speeds are approximately 200 knots (370 km/h), with approximately seven hours surveying within a day, given pilot and day-light constraints. This equates to approximately 2500 km, or 1250 km^2 per day, with some losses to any off-effort requirements e.g. looping at the end of transects, commuting to base and other logistical constraints.

LiDAR surveying for the purposes of FHD are assumed to have a swath of 250m, based on the experimental surveying conducted by Cook *et al.* (2018). A swath of 300 m was assumed in that study (dictated by the LiDAR), but with some decay in detection noted beyond 250 m. As this is not formally quantified, the simulations here truncate at 250 m, where full detection is expected. Flight speeds in this study were 240 km/h – similar limits on flight-times in a day will be assumed as above. This equates to approximately 1600 km, or 400 km^2, per day, similarly with some losses to any off-effort requirements.

Perfect detection is assumed in all simulated surveys. This will be close to reality for digital aerial survey, where imagery is available for careful post-processing – very few animals are likely to be overlooked. In the case of diving animals, in particular the harbour porpoise, availability will play a role. Availability will be assumed to be 100% for all birds in the simulations – the impact of this is discussed and explored in the results section.

Misclassification of detected objects is not considered here i.e. all detected animals will be as recorded.

Survey design methodology – density estimation

The survey designs are assessed by statistical simulation. All coding is in the open-source statistical programming language R v3.4+ (R Core Team, 2018). Extensive use is made of many packages, as indicated in the software repository. All code is maintained transparently, and version-controlled via Github and Git for future development.

Simulation structure – population monitoring

The simulations primarily consisted of:

1. A realisation of the bird population based on the relevant density map.
2. A simulated survey using the platform properties and sampling intensity. The surveys are North-East systematically sampled transects i.e. evenly spaced with constrained random start position.
3. An estimation of the population size with uncertainty from the simulated survey. This consists of simple scaling to the full survey area, along with 1000 bootstrapped survey transects to provide uncertainty measures.

This is repeated 100 times for each set of survey properties e.g. sampling intensity (number of transects), a level of population change, the survey region, species of interest, mean density surface and its upper/lower confidence bounds. The range of simulations is given in Table 4. For example, Species A would have three density surfaces for three SEAPOP seasons for four regions. 100 simulated surveys would be conducted for five different sampling intensities and 11 changes in population sizes – giving 100x36x5x11 = 198,000 simulated surveys, with embedded bootstraps. Over eight species, this is in the order of 1.5 m simulated surveys.

Table 4

Scope of simulations for population monitoring.

Simulation component	Levels	Comment
Species	8	7 bird + harbour porpoise, as indicated in scope
Region	4	East-coast regions as indicated in scope
Season	3	SEAPOP has three seasons (two traditional seasons are grouped)
Density surface	3	Mean surface + lower and upper 95% confidence
Sampling effort	500m to 5.5km by 1km	Spacing between transects, systematic random sampling. Given 250m sampling either side of trackline, this is 100% coverage to approximately 10%
Population shifts	-0.5 to 0.5 by 0.1	A halving to a doubling of the population, by 10% increments
Population realisations	100	For each combination of parameters
Surveys conducted	100	For each combination of parameters
Bootstrap estimates	1000	For the uncertainty about population size estimates for a single survey realisation

Example realisations of a single survey simulation are given in Figure 6.

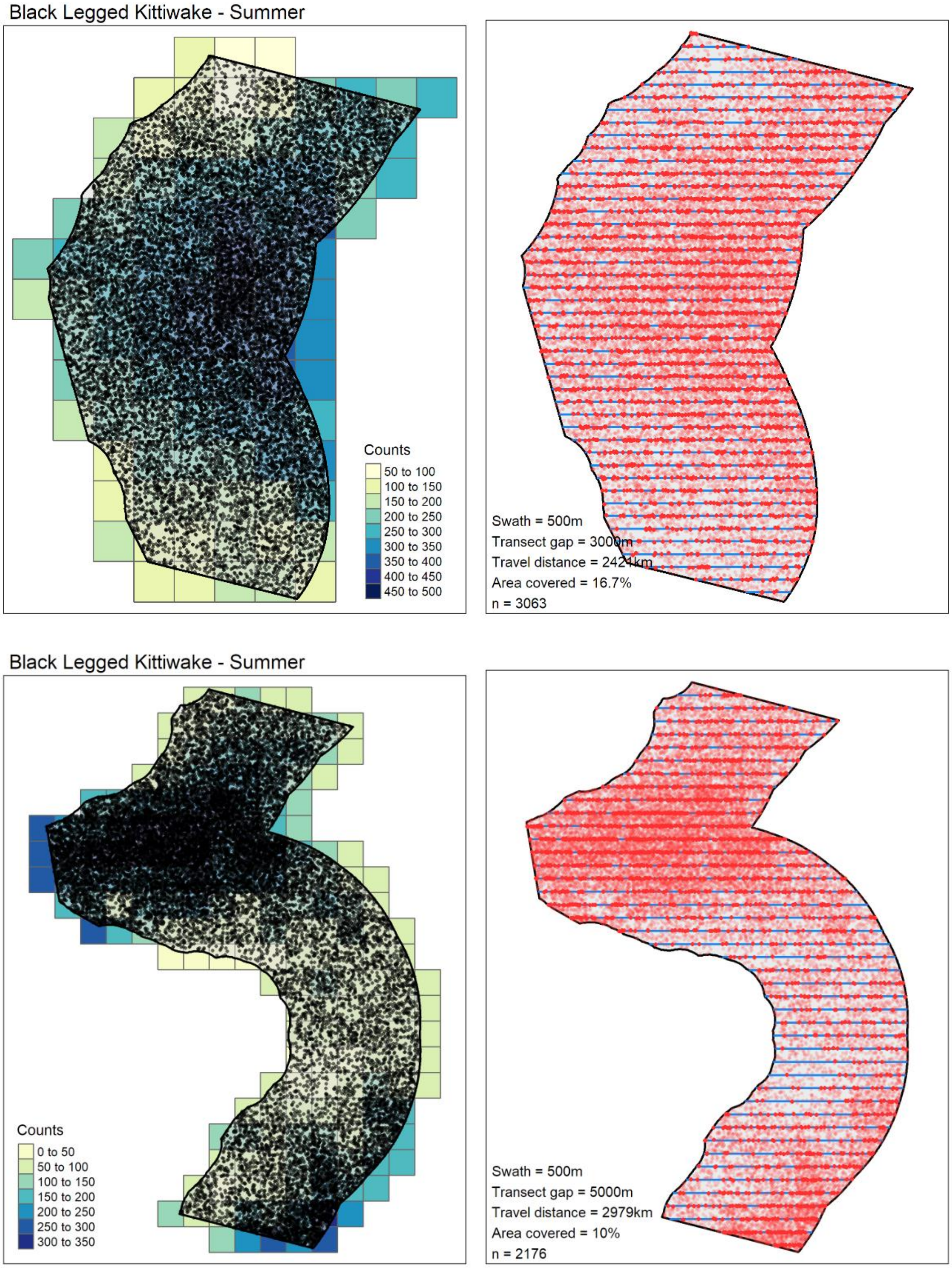


Figure 6: Example realisations of the simulation process, for summer black-legged kittiwakes in two regions (Region 1 top, Region 2 bottom). Left hand plots give the density maps overlaid with points of a poplation realisation. Right hand plots give the N-E transects with detections (red) and non-detections (blue).

LiDAR

Surveying for FHD is fundamentally different, as a minimum number of flying individuals is sought to give a robust estimate of the FHD. This can be achieved more quickly for more abundant and/or airborne species and in higher density areas. For abundant species, some spatially-temporally specific FHD might be estimated, whereas rarer animals may not permit such specific FHD, or even a single general one.

The simulations here are predicated on the surveying being targeted at higher density areas, to give a priori the best chance of obtaining minimum numbers for the FHD. Cook *et al.* (2018) indicates that 100+ flying animals are required to give a robust estimate of a FHD. To be conservative, the process followed here seeks regions that are likely to contain 200+.

The simulation process seeks to find the minimum amount of area surveyed, to give approximately 200 flying individuals for each species. In some cases this may be achieved for a number of different regions and seasons – for rarer species, no amount of surveying will produce the required number.

Simulation process:

1. Obtain a population map for species/season/region of interest.
2. Merge neighbouring grid-cells until 200+ individuals are encompassed.
3. Remove the region with minimum area.
4. Repeat on remaining map.

This process indicates approximate minimum amount of surveying required to achieve the objective, as well as the area most likely to offer this. Subsequent iterations indicate whether spatially varying FHD are possible.

The simulations necessarily need to focus on flying birds. The density surfaces provided through SEAPOP are not specifically flying or separable into surface/flying. For the purposes of LiDAR surveying simulations, SEAPOP was taken as the local abundance, with the proportion of flying animals taken from species-specific estimates found by HiDef Aerial Surveying Ltd (A Webb, *pers. comm.,* June 2019). These are given in

Table **5** and were estimated from high-definition imagery. No uncertainly has been considered in this conversion, nor are temporal or spatial variants available.

Table 5

Scaling factors to derive numbers of flying birds in LiDAR simulations. N indicates the number of animals used to derive the estimates from digital imagery.

Species / species group	Scientific name	%-age flying	N
Northern gannet	*Morus bassanus*	44%	42121
Black-legged kittiwake	*Rissa tridactyla*	33%	74294
Common guillemot	*Uria aalge*	4%	173258
Common guillemot/razorbill	*Alca torda/Uria aalge*	5%	19757
Atlantic puffin	*Fratercula arctica*	14%	42799
Herring gull	*Larus argentatus*	27%	69639
Great black-backed gull	*Larus marinus*	29%	24658

An example output from the simulation process is given in Figure 7. This indicates that a spatio-temporally varying FHD is feasible for this species over autumn and summer, however a single FHD for winter would be challenging to obtain, given the predicted abundances.

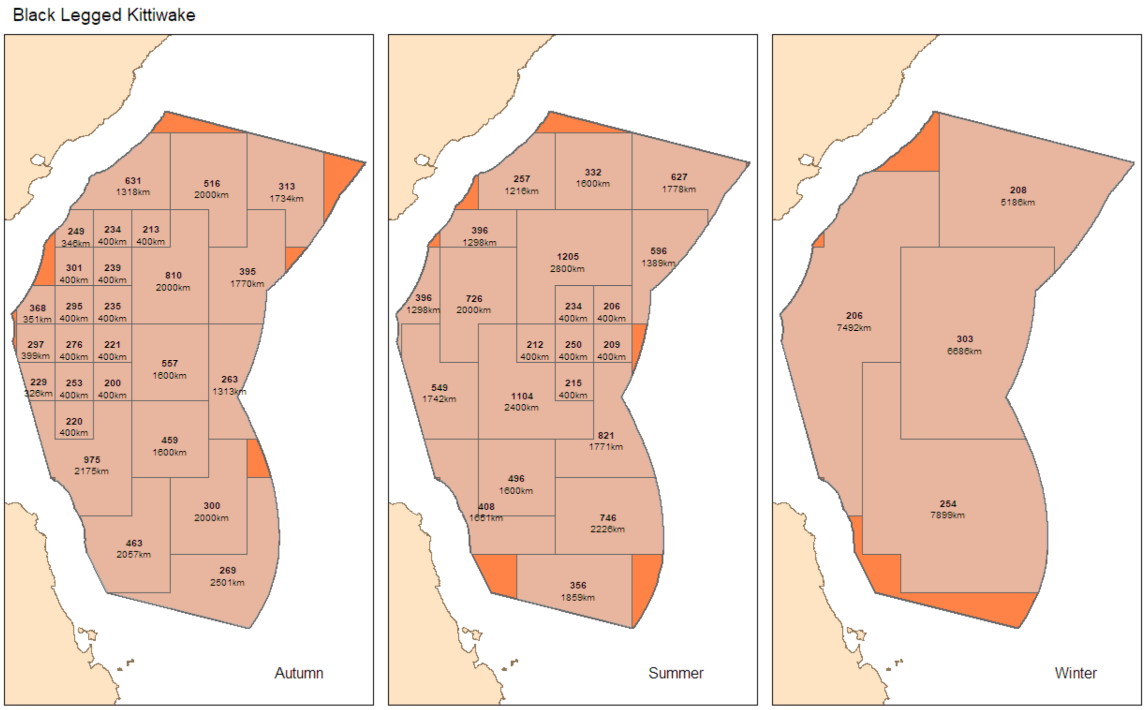


Figure 7: Example realisations of the LiDAR design process, for three SEAPOP seasons of black-legged kittiwake in Region 1. Segments give the number of kms surveyed (assuming the LiDAR platform properties previously outlined) and the number of individuals captured.

Computation

The simulation approach here is computationally demanding, but amenable to parallelisation. Computations were parallelised and conducted over a range of computers:

- Xeon 28 core 3+ MHz, 64Gb RAM.
- Amazon cloud computing AWS, using two 72-core instances and one 96-core instance (approximately 3 MHz clock-speeds).

For the density estimation simulations presented here, more than 300 hours of actual computing time were required over the cloud and local resources. This equates to 20,000-30,000 CPU hours – or approximately more than 80 days for a more commonplace 10-core desktop.

While the simulation of surveying for density estimation was computationally demanding, LiDAR survey investigations were very fast (on the order of minutes).

Design results

Results are presented here for surveys focussing on population monitoring and the LiDAR derived FHD.

Population surveying

The simulation results for the population monitoring surveys are voluminous – a series of six power curves for each of four regions, eight species, three seasons and three density surfaces (mean, upper and lower 95% CI). This equates to 288 plots giving 1728 power curves. These are given in graphical form in the appendix for estimated mean surfaces. For concision, only Atlantic puffin are presented here as an exemplar, covering two SEAPOP seasons, winter and summer (Figure 8). Reference values of 80% power to detect a 30% shift in population size are used (*pers. comm.* T Evans, Marine Scotland).

From these plots it can be seen there is no real power to detect changes over the winter period. Even with 100% coverage of the Wider Forth and Tay (approximately 14500 km of survey effort), power is below 80% except for a halving of the winter population.

In contrast, a modest amount of survey effort will detect the reference 30% change in population size with greater than 80% power. Surveys of <10% of the area (approximately 1320km of surveying, less than one day), would have 80% power of detecting a 25% change. Intensive surveying would be required to detect changes of less than 10%.

The full set of power analyses for the SEAPOP and JCP density mean data are presented in the appendix, with summaries in Table 6 to Table 9. The results are distilled in these tables to reflect the reference power figures above and translated into approximate survey effort required to achieve these, if possible.

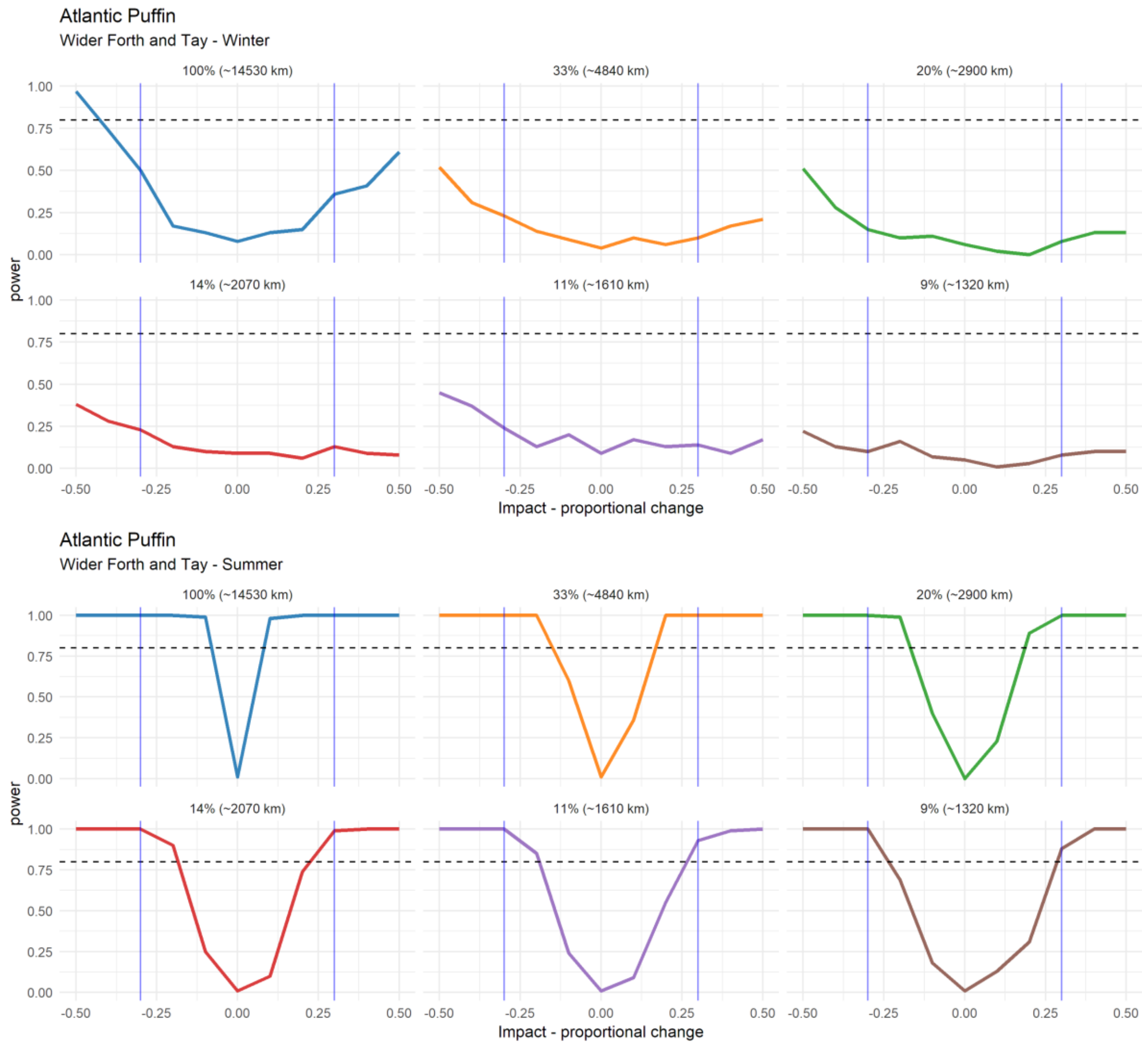


Figure 8: Power curves for Atlantic puffin, indicating the amount of survey effort required to detect a particular population impact under five surveying intensities. Top series of plots are SEAPOP winter, the lower series of plots are SEAPOP's summer. Vertical blue lines indicate 30% shifts in population size. The black dashed line gives the 80% power reference point.

Table 6

Summary of power analyses – SEAPOP and JCP density data. A blank entry indicates power is below 80% even at 100% sampling or data is not available. Approximate survey distance is rounded to the nearest 100 for Regions 1-3, nearest 1000 for Region 4. Approximate survey days assume 2000 km surveying per day.

			Minimum sampling proportion to detect 30% pop^n shift with 80% power			Mean surface		Lower surface		Upper surface	
Species	**Region**	**SEAPOP season**	**Mean surface**	**Lower 95% CI**	**Upper 95% CI**	**Approximate survey distance (km)**	**Approximate survey days**	**Approximate survey distance (km)**	**Approximate survey days**	**Approximate survey distance (km)**	**Approximate survey days**
Northern gannet	Region 1	Autumn	0.12	0.09	0.17	1700	1	2500	1	1300	1
		Summer	0.12	0.10	0.16	1700	1	2300	1	1500	1
		Winter	0.67	0.24	1.00	9700	5	14500	7	3500	2
	Region 2	Autumn	0.13	0.10	0.24	3800	2	7100	4	3000	2
		Summer	0.33	0.27	0.67	9900	5	19900	10	8000	4
		Winter	1.00	0.67	1.00	29800	15	29800	15	19900	10
	Region 3	Autumn	0.12	0.10	0.15	5200	3	6400	3	4500	2
		Summer	0.15	0.15	0.22	6400	3	9800	5	6400	3
		Winter	0.27	0.17	0.67	11800	6	29500	15	7600	4
	Region 4	Autumn	0.09	0.09	0.09	21000	11	21000	11	21000	11
		Summer	0.09	0.09	0.09	21000	11	21000	11	21000	11
		Winter	0.09	0.09	0.10	21000	11	23000	12	21000	11
Black-legged kittiwake	Region 1	Autumn	0.09	0.09	0.09	1300	1	1300	1	1300	1
		Summer	0.09	0.09	0.09	1300	1	1300	1	1300	1
		Winter	0.09	0.09	0.09	1300	1	1300	1	1300	1
	Region 2	Autumn	0.09	0.09	0.10	2700	1	3000	2	2700	1
		Summer	0.09	0.09	0.09	2700	1	2700	1	2700	1
		Winter	0.09	0.09	0.09	2700	1	2700	1	2700	1
	Region 3	Autumn	0.09	0.09	0.09	4000	2	4000	2	4000	2
		Summer	0.09	0.09	0.09	4000	2	4000	2	4000	2
		Winter	0.09	0.09	0.09	4000	2	4000	2	4000	2
	Region 4	Autumn	0.09	0.09	0.10	21000	11	23000	12	21000	11
		Summer	0.09	0.09	0.09	21000	11	21000	11	21000	11
		Winter	0.09	0.09	0.09	21000	11	21000	11	21000	11

Table 7

Summary of power analyses – SEAPOP and JCP density data. A blank entry indicates power is below 80% even at 100% sampling or data is not available. Approximate survey distance is rounded to the nearest 100 for Regions 1-3, nearest 1000 for Region 4. Approximate survey days assume 2000 km surveying per day.

			Minimum sampling proportion to detect 30% pop^n shift with 80% power			Mean surface		Lower surface		Upper surface	
Species	**Region**	**SEAPOP season**	**Mean surface**	**Lower 95% CI**	**Upper 95% CI**	**Approximate survey distance (km)**	**Approximate survey days**	**Approximate survey distance (km)**	**Approximate survey days**	**Approximate survey distance (km)**	**Approximate survey days**
Common guillemot	Region 1	Autumn	0.09	0.09	0.09	1300	1	1300	1	1300	1
		Summer	0.09	0.09	0.09	1300	1	1300	1	1300	1
		Winter	0.09	0.09	0.09	1300	1	1300	1	1300	1
	Region 2	Autumn	0.09	0.09	0.09	2700	1	2700	1	2700	1
		Summer	0.09	0.09	0.09	2700	1	2700	1	2700	1
		Winter	0.09	0.09	0.09	2700	1	2700	1	2700	1
	Region 3	Autumn	0.09	0.09	0.09	4000	2	4000	2	4000	2
		Summer	0.09	0.09	0.09	4000	2	4000	2	4000	2
		Winter	0.09	0.09	0.09	4000	2	4000	2	4000	2
	Region 4	Autumn	0.09	0.09	0.09	21000	11	21000	11	21000	11
		Summer	0.09	0.09	0.09	21000	11	21000	11	21000	11
		Winter	0.09	0.09	0.09	21000	11	21000	11	21000	11
Razorbill	Region 1	Autumn	0.15	0.12	0.27	2100	1	3900	2	1700	1
		Summer	0.09	0.09	0.12	1300	1	1700	1	1300	1
		Winter	0.67	0.27	1.00	9700	5	14500	7	3900	2
	Region 2	Autumn	0.09	0.09	0.09	2700	1	2700	1	2700	1
		Summer	0.09	0.09	0.10	2700	1	3000	2	2700	1
		Winter	0.67	0.24	0.67	19900	10	19900	10	7100	4
	Region 3	Autumn	0.09	0.09	0.09	4000	2	4000	2	4000	2
		Summer	0.09	0.09	0.09	4000	2	4000	2	4000	2
		Winter	0.16	0.12	0.33	6900	3	14800	7	5200	3
	Region 4	Autumn	0.09	0.09	0.09	21000	11	21000	11	21000	11
		Summer	0.09	0.09	0.09	21000	11	21000	11	21000	11
		Winter	0.17	0.15	0.24	39000	20	55000	28	33000	17

Table 8

Summary of power analyses – SEAPOP and JCP density data. A blank entry indicates power is below 80% even at 100% sampling or data is not available. Approximate survey distance is rounded to the nearest 100 for Regions 1-3, nearest 1000 for Region 4. Approximate survey days assume 2000 km surveying per day.

			Minimum sampling proportion to detect 30% pop^n shift with 80% power			Mean surface		Lower surface		Upper surface	
Species	**Region**	**SEAPOP season**	**Mean surface**	**Lower 95% CI**	**Upper 95% CI**	**Approximate survey distance (km)**	**Approximate survey days**	**Approximate survey distance (km)**	**Approximate survey days**	**Approximate survey distance (km)**	**Approximate survey days**
Atlantic puffin	Region 1	Autumn	0.12	0.09	0.17	1700	1	2500	1	1300	1
		Summer	0.09	0.09	0.10	1300	1	1500	1	1300	1
		Winter									
	Region 2	Autumn	0.12	0.09	0.16	3500	2	4600	2	2700	1
		Summer	0.15	0.12	0.27	4300	2	8000	4	3500	2
		Winter									
	Region 3	Autumn	0.09	0.09	0.10	4000	2	4500	2	4000	2
		Summer	0.15	0.21	0.15	6400	3	6400	3	9400	5
		Winter		1.00						44300	22
	Region 4	Autumn	0.09	0.09	0.09	21000	11	21000	11	21000	11
		Summer	0.09	0.09	0.09	21000	11	21000	11	21000	11
		Winter	0.27	0.22	0.67	61000	31	153000	77	51000	26
Herring gull	Region 1	Autumn	1.00	0.27		14500	7	0	0	3900	2
		Summer	1.00	0.27	1.00	14500	7	14500	7	3900	2
		Winter	0.09	0.09	0.16	1300	1	2300	1	1300	1
	Region 2	Autumn	1.00	0.60	1.00	29800	15	29800	15	17900	9
		Summer	0.24	0.22	0.60	7100	4	17900	9	6600	3
		Winter	0.09	0.09	0.10	2700	1	3000	2	2700	1
	Region 3	Autumn	0.60	0.16	1.00	26600	13	44300	22	6900	3
		Summer	0.22	0.15	0.27	9800	5	11800	6	6400	3
		Winter	0.09	0.09	0.09	4000	2	4000	2	4000	2
	Region 4	Autumn	0.27	0.12	1.00	61000	31	229000	115	27000	14
		Summer	0.24	0.22	0.67	55000	28	153000	77	51000	26
		Winter	0.09	0.09	0.09	21000	11	21000	11	21000	11

Table 9

Summary of power analyses – SEAPOP and JCP density data. A blank entry indicates power is below 80% even at 100% sampling or data is not available. Approximate survey distance is rounded to the nearest 100 for Regions 1-3, nearest 1000 for Region 4. Approximate survey days assume 2000 km surveying per day.

			Minimum sampling proportion to detect 30% pop^n shift with 80% power			Mean surface		Lower surface		Upper surface	
Species	Region	SEAPOP season	Mean surface	Lower 95% CI	Upper 95% CI	Approximate survey distance (km)	Approximate survey days	Approximate survey distance (km)	Approximate survey days	Approximate survey distance (km)	Approximate survey days
Great black-backed gull	Region 1	Autumn	0.67	0.16	1.00	9700	5	14500	7	2300	1
		Summer				0	0	0	0	0	0
		Winter	0.24	0.13	0.67	3500	2	9700	5	1800	1
	Region 2	Autumn	0.67	0.24	1.00	19900	10	29800	15	7100	4
		Summer	1.00	1.00		29800	15	0	0	29800	15
		Winter	0.15	0.12	0.27	4300	2	8000	4	3500	2
	Region 3	Autumn	0.17	0.10	0.67	7600	4	29500	15	4500	2
		Summer	1.00	1.00	1.00	44300	22	44300	22	44300	22
		Winter	0.09	0.09	0.15	4000	2	6400	3	4000	2
	Region 4	Autumn	0.10	0.09	0.27	23000	12	61000	31	21000	11
		Summer	0.27	0.24	1.00	61000	31	229000	115	55000	28
		Winter	0.09	0.09	0.09	21000	11	21000	11	21000	11
Harbour porpoise	Region 1	Summer					0				
	Region 2	Summer	1			29800	15				
	Region 3	Summer	1			44300	22				
	Region 4	Summer	0.11			25000	13				

Availability considerations

Availability, being the proportion of time animals are available for detection by a particular platform, has been assumed to be one throughout (i.e. fully available). For several species this is incorrect and power calculations may be sensitive to this, if availability is low. For some diving birds, there may be a substantive proportion of animals unavailable for detection at a particular time, and for harbour porpoise, diving is a significant activity.

Estimates for diving bird availability are not widely established. Here we consider common guillemots and razorbills, species known to commonly dive and for which there are unpublished results. Availability estimates of 0.87 and 0.89 respectively (*pers. comm.* O Anderson, 2019) have been applied to the simulations for these species – the power curves for the autumnal Wider Forth and Tay are given below, along with their unadjusted counterparts (Figure **9** and Figure **10**).

At these small levels of availability adjustment, no marked changes are observed in the power calculations. What small changes are observed might be simple simulation variation. Nonetheless, low levels of availability will certainly affect power calculations as it directly reduces the data (observed animals) from which population shifts must be inferred.

Availability of harbour porpoise was similarly set to be one (fully available), which is certainly untrue. However, power was very low for the data available, meaning almost full coverage was required in any case. Less availability exacerbates this, so was deemed uninteresting in terms of conclusions. More generally, availability should be considered for harbour porpoise and there are various estimates available.

Estimates of 0.12 can be inferred for harbour porpoise, on the basis of surfacing/diving ratios reported in the JCP phase 3 report (Paxton *et al.,* 2016). Williamson *et al.* (2016) estimated 0.61 in the Moray Firth if surveying with digital aerial survey. Teilmann *et al*. (2013) offered seasonally varying estimates for the top 2 m of the water column from telemetry, ranging from 0.62 to 0.43. Actual proportions of time at the surface were estimated in the same study as being between 0.06 and 0.03.

Availability will be platform dependent, as suggested by the previous harbour porpoise figures. The ability of downwards-facing cameras to see into the water column results in increased availability compared to surface platforms, although water clarity will also play a role.

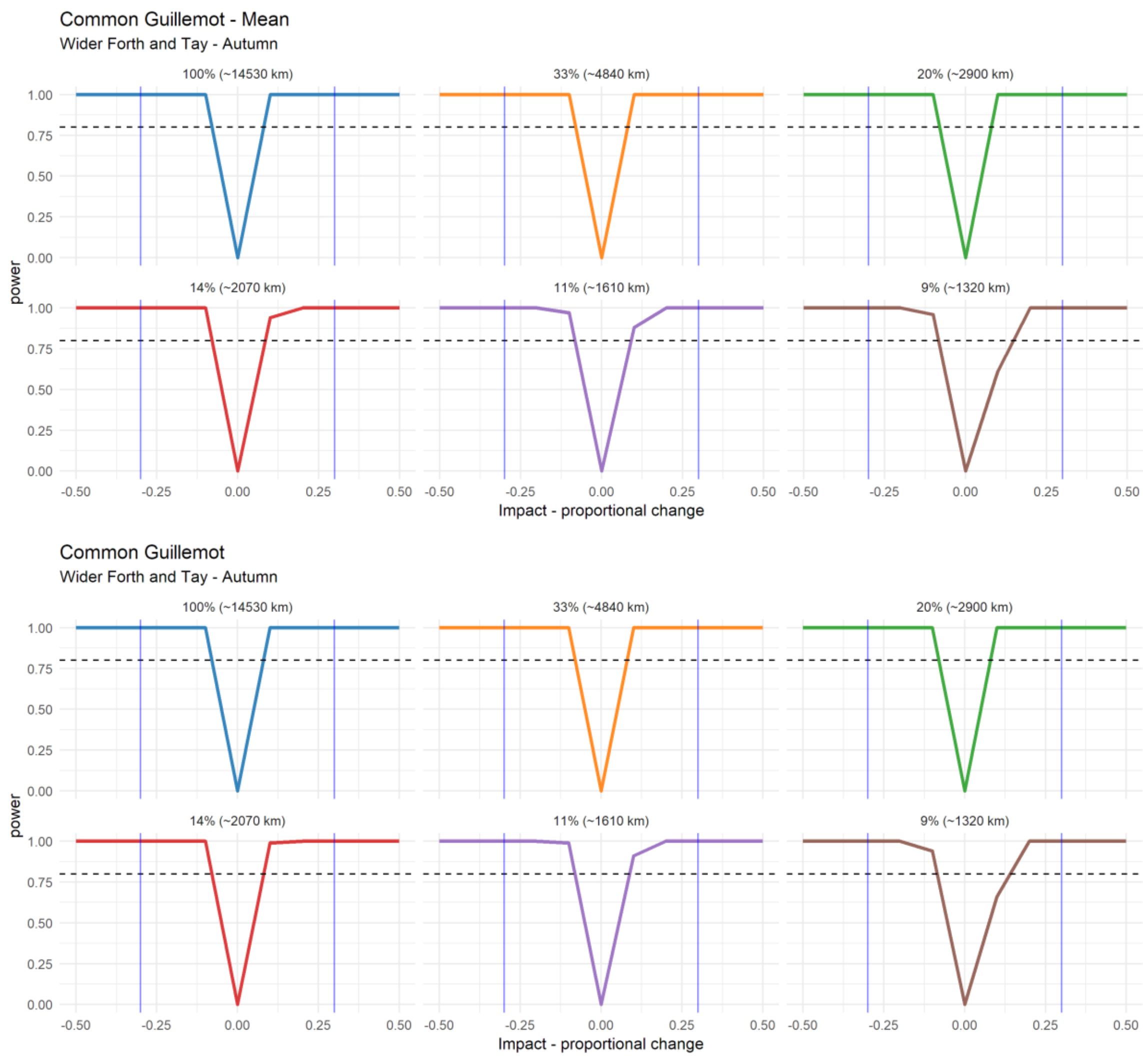


Figure 9: Power curves for common guillemot, indicating the amount of survey effort required to detect a particular population impact under six surveying intensities. Upper set of six plots are adjusted for availability of 0.87, the lower plots assume full availability. Vertical blue lines indicate 30% shifts in population size. The black dashed line gives the 80% power reference point.

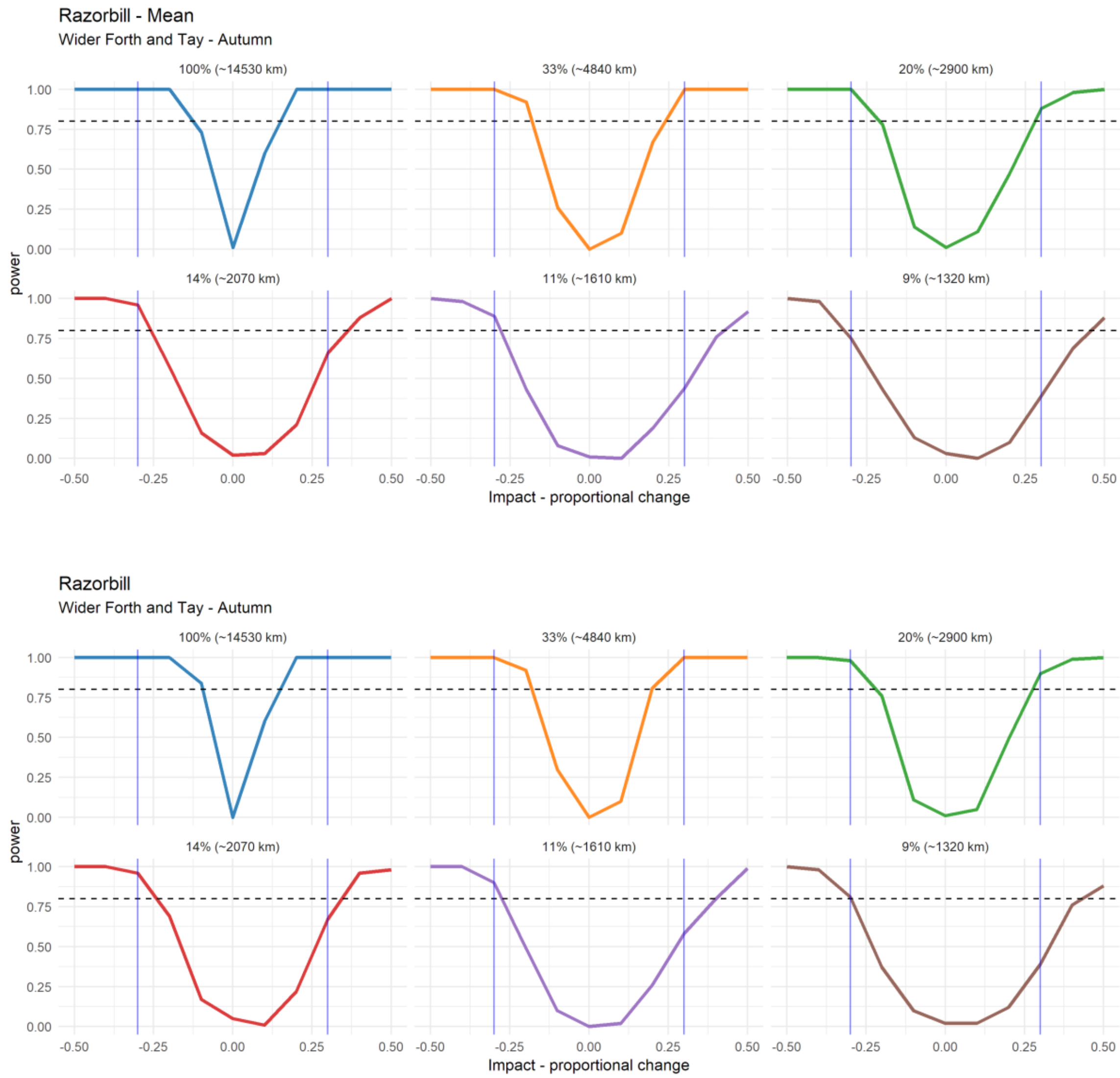


Figure 10: Power curves for razorbill, indicating the amount of survey effort required to detect a particular population impact under six surveying intensities. Upper set of six plots are adjusted for availability of 0.89, the lower plots assume full availability. Vertical blue lines indicate 30% shifts in population size. The black dashed line gives the 80% power reference point.

Flight height distribution surveying

Example results for three species are presented graphically and summarised here. Note that if sufficient numbers can be found for the smallest survey region, then this will be an equivalent solution for the larger survey regions, if the former is a sub-region. The spatial details of the regions will generally be of interest, so the simulation maps would require consulting.

Table 10

Summary of FHD surveying simulations based on SEAPOP data. Approximate survey distance required to achieve objectives as well as approximate survey days, assuming 1600 km surveying per day.

			Minimum survey length to achieve n = 200+	Approximate survey days
Species	**Region**	**SEAPOP season**	**Mean surface**	**Mean surface**
Common guillemot	Region 1	Summer	8149	5
		Autumn	5493	3
		Winter	24370	15
	Region 2	Summer	8622	5
		Autumn	13374	8
		Winter	40704	25
	Region 3	Summer	8151	5
		Autumn	5493	3
		Winter	24309	15
	Region 4	Summer	8640	5
		Autumn	5528	3
		Winter	29050	18

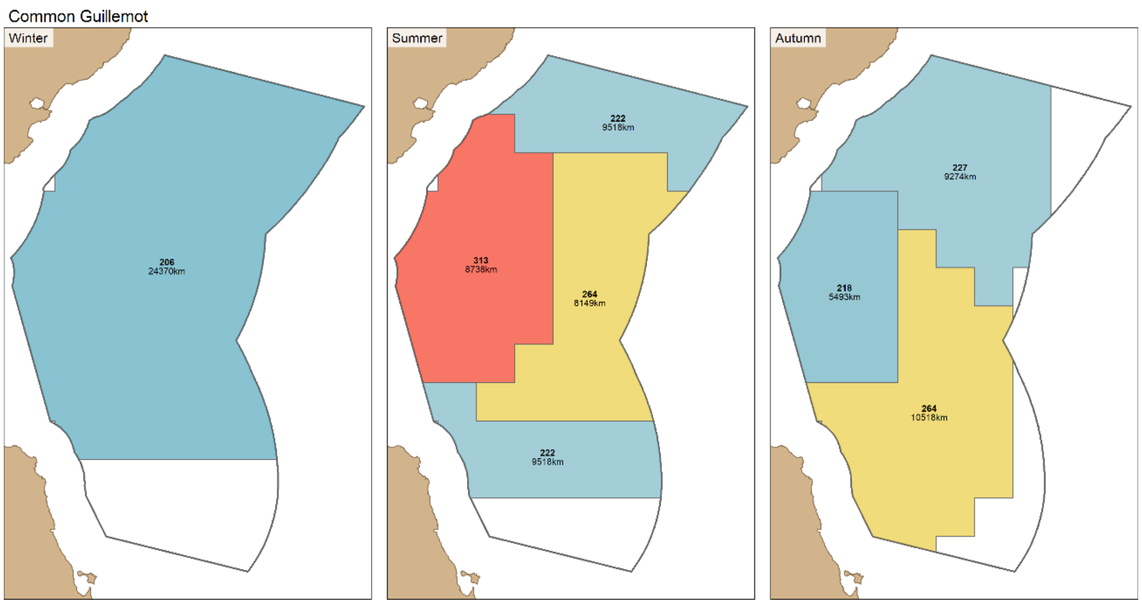
Table 11

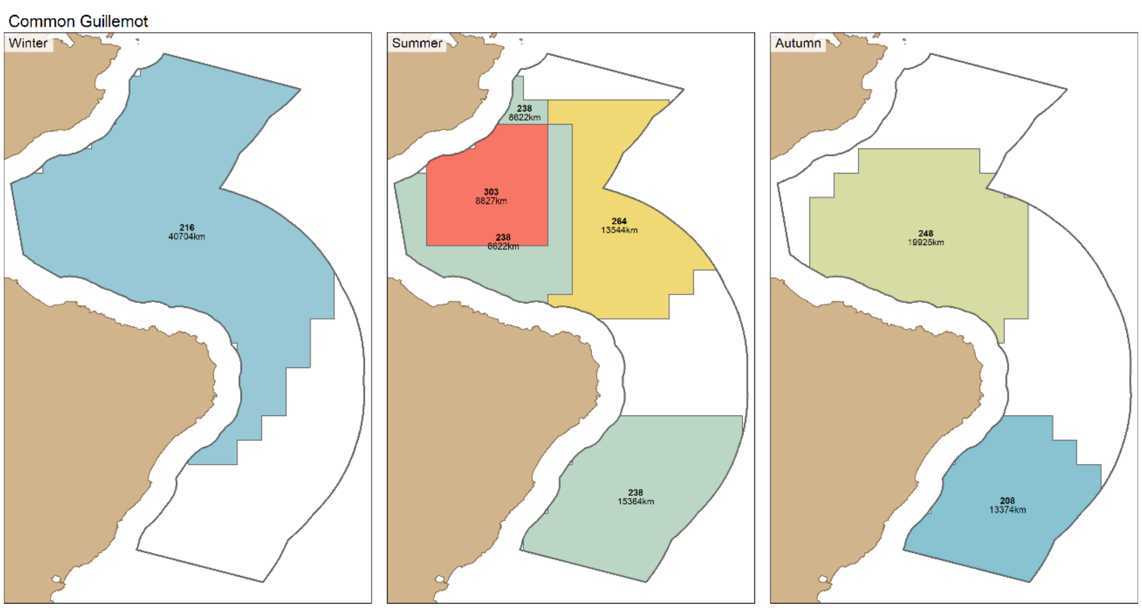
Summary of FHD surveying simulations based on SEAPOP data. Approximate survey distance required to achieve objectives as well as approximate survey days, assuming 1600 km surveying per day.

Species	Region	SEAPOP season	Minimum survey length to achieve n = 200+ Mean surface	Approximate survey days Mean surface
Black-legged kittiwake	Region 1	Summer	400	1
		Autumn	400	1
		Winter	5186	4
	Region 2	Summer	1221	1
		Autumn	1271	1
		Winter	4924	4
	Region 3	Summer	1215	1
		Autumn	400	1
		Winter	4927	4
	Region 4	Summer	400	1
		Autumn	400	1
		Winter	3600	3
Atlantic puffin	Region 1	Summer	29034	19
		Autumn	29034	19
		Winter	29034	19
	Region 2	Summer	59563	38
		Autumn	59563	38
		Winter	59563	38
	Region 3	Summer	88506	56
		Autumn	88506	56
		Winter	88506	56
	Region 4	Summer	362724	227
		Autumn	362724	227
		Winter	362724	227

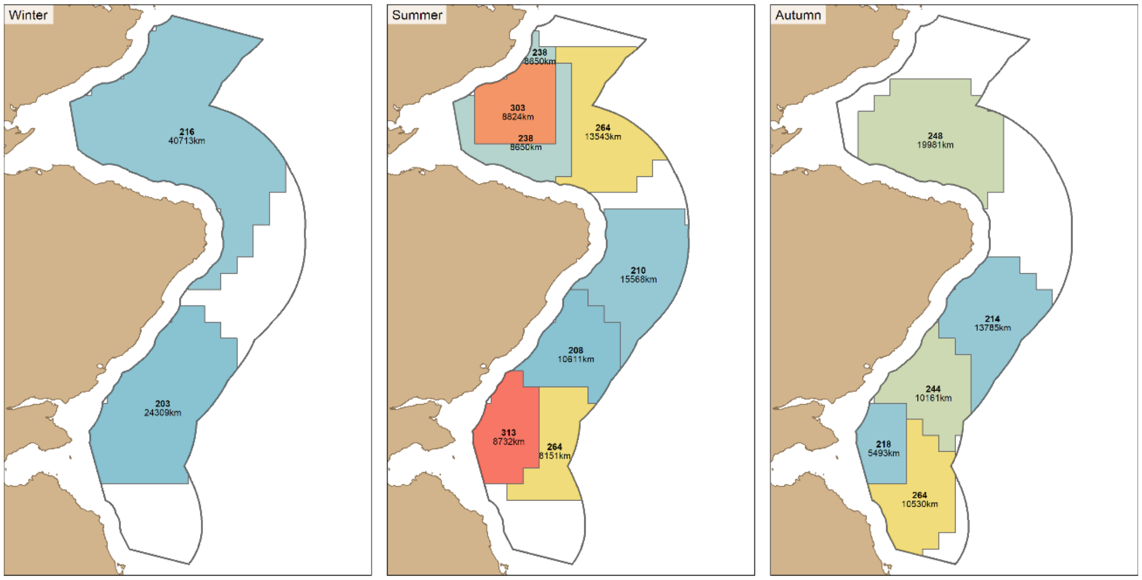
The following series of plots give FHD simulation outputs, based on mean surfaces only for example species. Upper and lower 95% confidence variants are available electronically.

Each plot consists of subdivisions of the survey area, such that they encompass the number of individuals required for a robust FHD (Cook *et al.*, 2018).

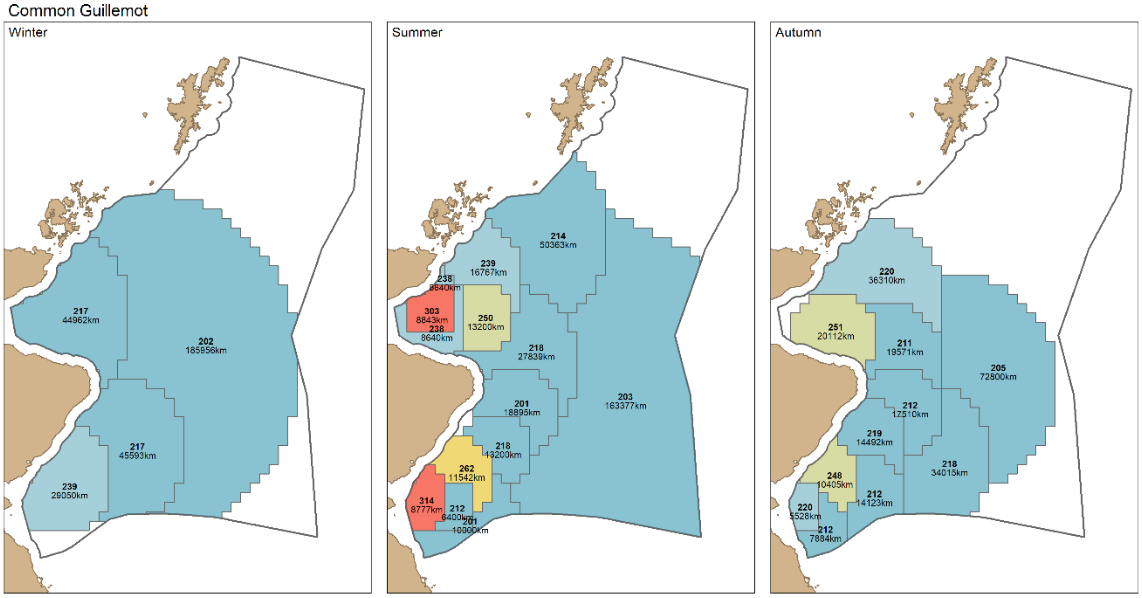




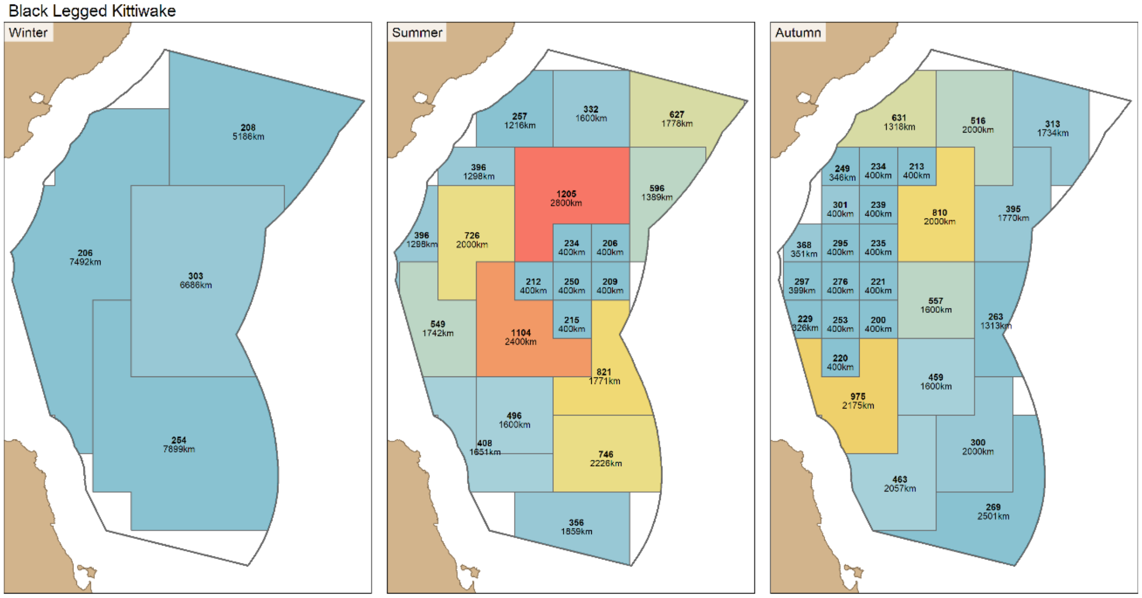
Common Guillemot



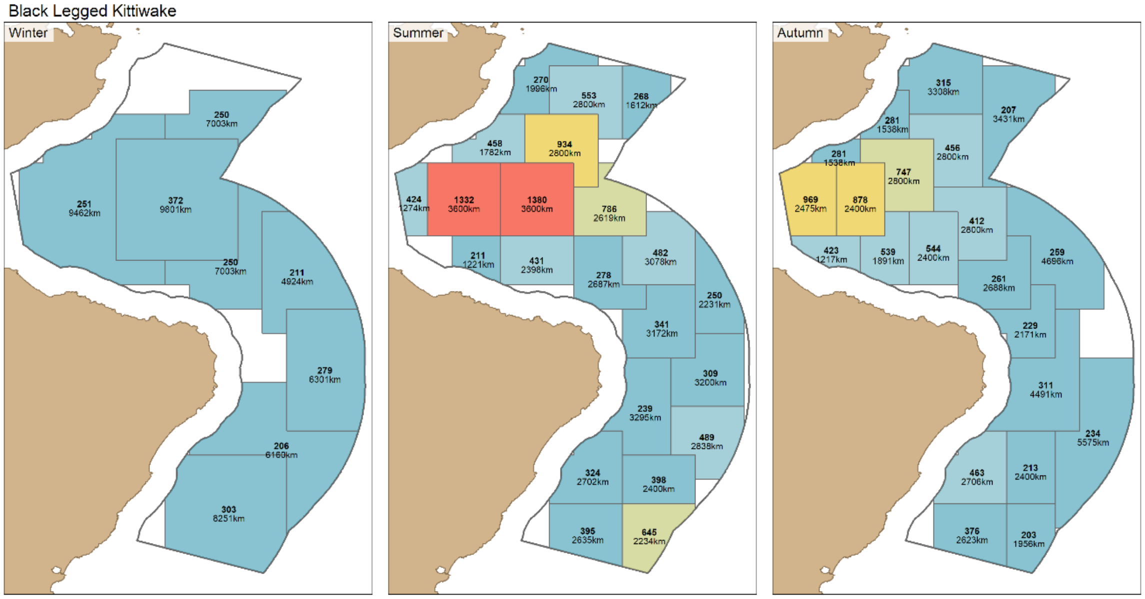
Common Guillemot



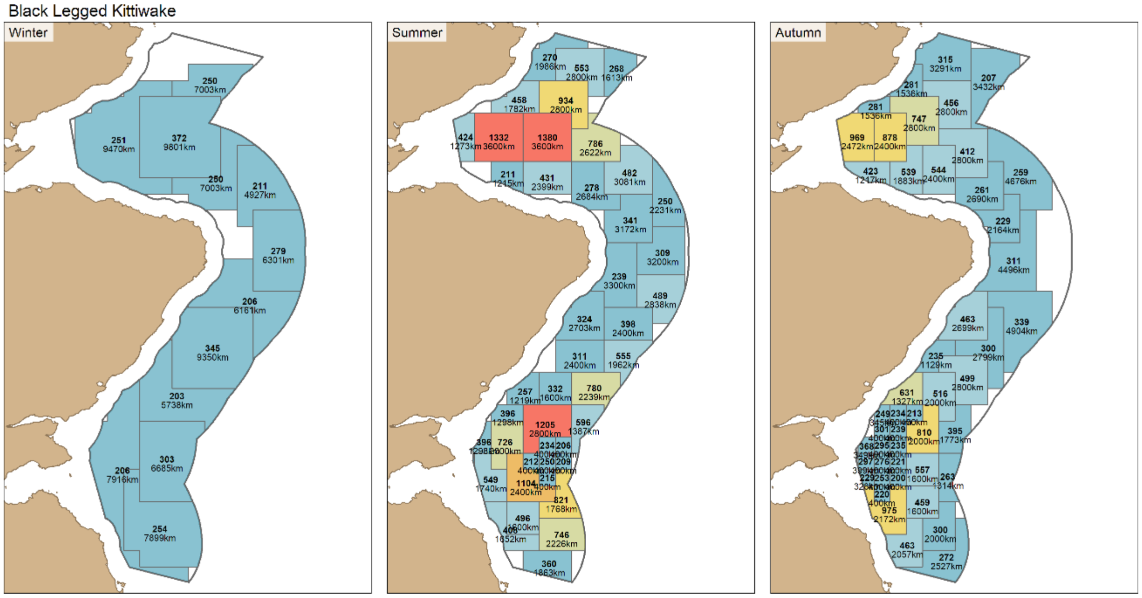
Black Legged Kittiwake



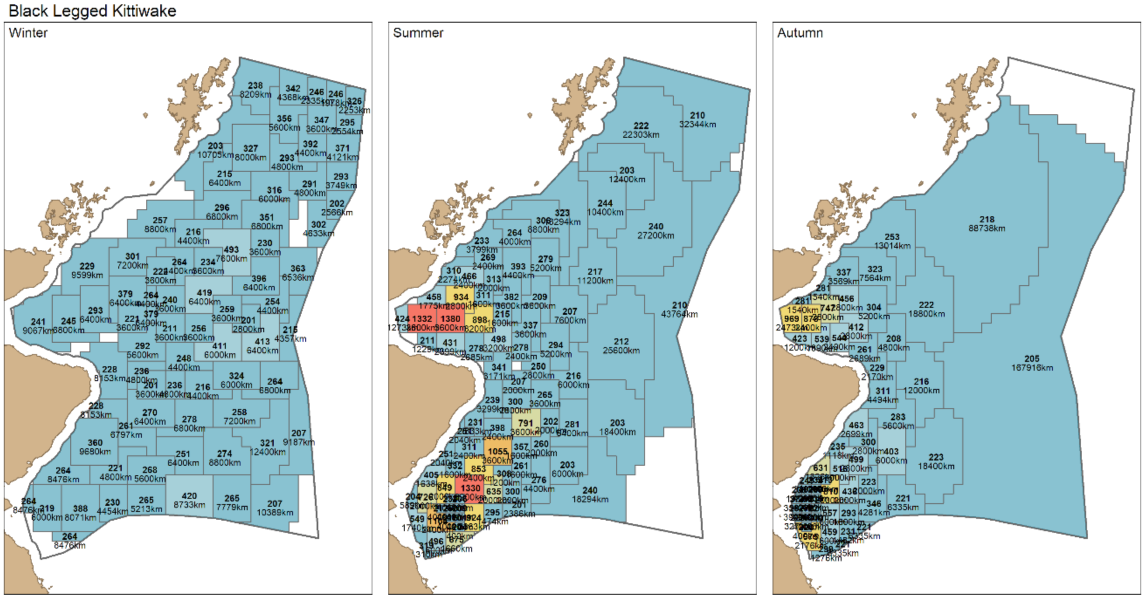
Black Legged Kittiwake



Black Legged Kittiwake

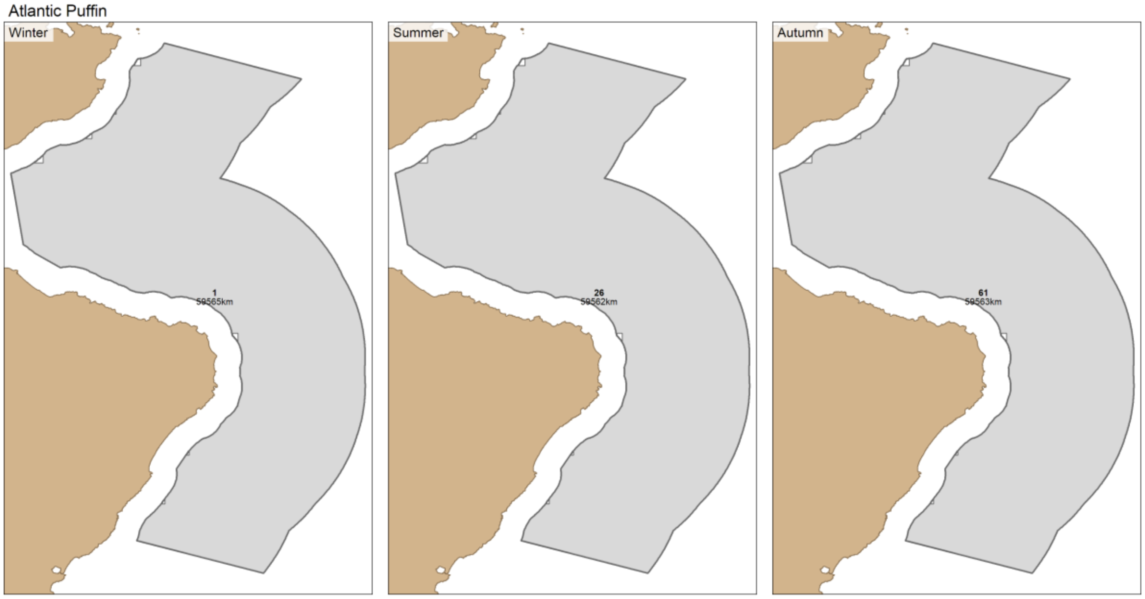


Black Legged Kittiwake



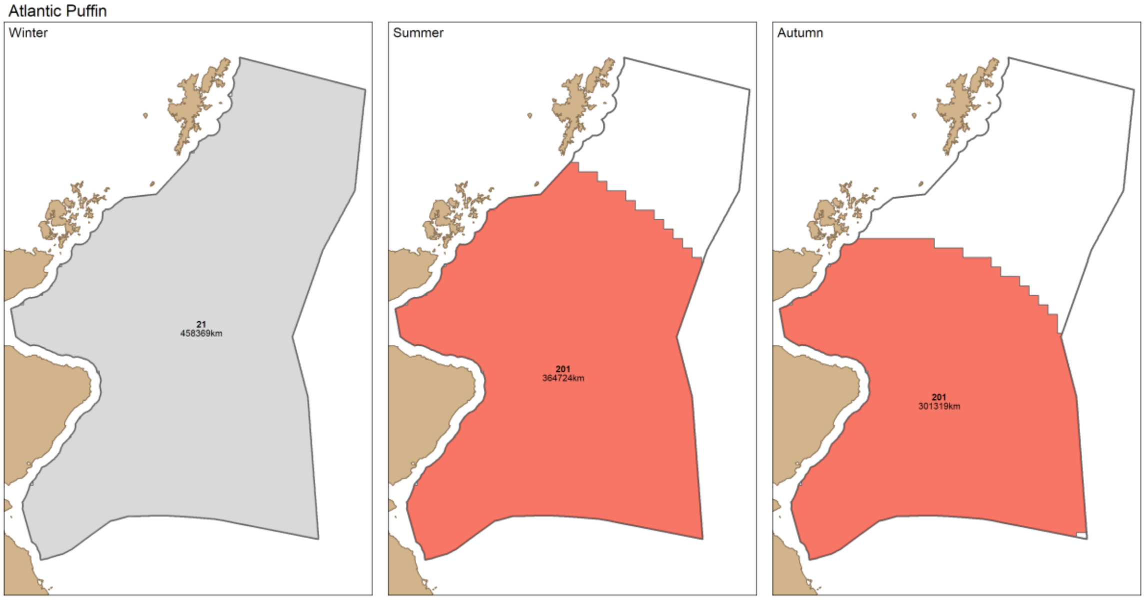
Atlantic Puffin

Atlantic Puffin



Atlantic Puffin

Atlantic Puffin



Discussion and Conclusions

We have presented a series of simulation works which offer guidance for survey design for the purposes of population monitoring or the estimation of Flight Height Distributions (FHD). Subject to a number of assumptions, these give indicative figures for the amount of digital aerial surveying required to achieve power objectives in the case of seabird (and harbour porpoise) population monitoring. In the case of FHD estimation, indicative figures are arrived at for the amount of surveying required to get sufficient numbers for fitting a robust curve.

The simulation basis to this work required a large amount of computation. In addition to the results presented here for specific cases, the project code can be utilised for other cases there is code that can be used for other cases e.g. different species.

Fully prescriptive survey designs are not given, although those underlying the simulations could be emulated. There are a range of practical logistical aspects of aerial surveying which will dictate what is achievable in reality, so these analyses should serve as general guidance. It is expected that platform operators will have a range of logistic reasons for designing a particular survey, whilst still achieving the same broad objectives captured by the simulations.

Below we:

- Summarise the findings.
- Expand on how these simulations would tie to actual survey design.
- Discuss the assumptions and sensitivities underpinning the works, along with important questions that arise.

Findings

The following summaries of the findings are predicated on the simulations being broadly realistic. There are a number of strong assumptions made, so the following should be considered in light of the sensitivities and assumptions section presented later.

Surveying for population monitoring

For the reference figures of 80% power for a 30% population shift, there are a number of species that could be theoretically monitored for at least some seasons based on the mean estimated density maps. In terms of feasibility, the surveying effort can be high for some species as a proportion of area covered, but for the smaller regions this does not appear prohibitive.

The largest region considered (Region 4 - East Herman to Berwick) is very large, requiring >200,000 kms to survey once fully. Feasibility would be defined in part by budgetary concerns, and even 10% coverage might prove infeasible for repeated monitoring.

Power is influenced strongly by the abundance of the animals in question, so will be *a priori* low for some species. Taking the lower confidence bound surfaces for the density maps also has a correspondingly depressive effect on power. Whether these conservative estimates be used would be an important decision.

Regardless, smaller scale shifts in abundance, e.g. 10% appear difficult to detect, even with high intensity of surveying for most species, seasons and regions.

Surveying for FHD estimation

Simulations suggest that a number of species can be successfully surveyed, with modest effort, to achieve sufficient numbers to support a FHD curve. Further, it seems feasible to sample for spatially or seasonally varying FHD, if this were required. Conversely, some species do not appear to have sufficient flying numbers for feasible FHD estimation even generally e.g. Atlantic Puffin. The broader utility of the work here would be the software underpinning the simulations. Users can easily select an area they wish to focus on, and a minimally sized survey area can be generated.

Guidance for survey design

The surveys underpinning the simulations are not expected to be prescriptive as there are a number of factors that must be considered in real-world digital aerial surveying. However, they offer general guidance with regards sampling intensity and other general guidance follows.

The simulations assume a simple North-to-East transect structure, distributed as a systematic random sample i.e. a constrained random start transect, then regularly spaced thereafter. In practice transects might take different orientations, without any particular impact on results. However, it would be generally good practice to operate perpendicular to suspected ecological gradients – in this case we have operated roughly perpendicular to Scotland's eastern coast, as this is likely to be the major defining gradient for animals.

For multiple day surveys, the simulations make no distinction between surveying a sub-region, or using interleaving transects over successive days. The logistics of actual surveying is likely to lead to subregions being surveyed, given the off-effort time that might used in setting up transects far apart. No strong preference is expressed here.

As the simulations are based mainly on SEAPOP distribution maps, there is no inherent change in the underlying distributions at a sub-seasonal level. So in this regard the surveying could be conducted at any point within the season and still be consistent with the simulations presented. However, given there will be sub-seasonal fluctuations in reality, a good temporal spread is desirable, if many days surveying are planned.

Given an objective of population monitoring, a multiple season or multiple year survey would be best conducted along the same transects. This will offer some reduction in variability attributable to spatial elements, which would add noise to any population shifts.

Assumptions and sensitivities

For both types of surveying considered here, the underlying density maps are a key assumption and sensitivity, particularly for the FHD surveying where the region surveyed is dependent on this, not just intensity. Both survey types are considered in turn.

Surveying for population monitoring

The principal bird density data used here was from the SEAPOP modelling exercise, which offers abundance estimates and their uncertainty for much of the North Sea at a 10 km grid resolution and for three seasons (two standard seasons being combined). This was the main data used for two main reasons:

1. It was readily available, whereas MERP is not currently in the public domain – although able to be arranged by personal communication.

2. The computations were fewer. MERP data is on a much finer temporal scale (monthly versus 3-6 monthly). Given the computations scale linearly with the number of density scenarios, the already large computational time would be prohibitive under the current approach and resources. However, this does not preclude a temporal coarsening of the MERP data, nor a larger computation exercise in the future.

A small comparison was conducted, where MERP was aggregated to a seasonal level for a species analysed using SEAPOP densities. The differences are marked, even prior to analysis – there are large differences in the magnitude of predicted densities and the distribution maps differ in pattern. This is undoubtedly due to the different covariates that underpin the models.

The simulated population monitoring surveys also produced markedly different results in keeping with this. Survey effort for the same level of power to detect change was substantially larger when predicated on the MERP data compared to SEAPOP.

Animals in the simulations were generally considered to be fully available for detection. *A priori* this is incorrect for several species and is expected to be a marked sensitivity where animals have low availability. For two bird species where availability estimates were obtained (common guillemot and razorbill), availability was high and no practical impact on power was observed. For harbour porpoise, availability differs markedly by platform and season and can be very low. However, for the input data here, power was very poor even with assuming full availability, so also of little practical consequence. Results here notwithstanding, availability is generally a sensitivity for power calculations and platform-specific estimates are lacking in the literature for diving birds.

Other assumptions underpinning the simulations are less concerning. The parameters for the simulated platforms are based on actual survey platforms and not subject to much uncertainty. If platforms are to operate with markedly different properties, such as speed/swath, this will not affect the coverage advice, rather just the metric of effort e.g. the number of kms to cover will change predictably. However, the detection properties offer more sensitivity – for example, visual aerial survey would require more careful consideration, as the effective strip width would require calculating, itself requiring knowledge of the species-specific detection function.

The impacts being sought under the power analyses here are simple changes in the overall population sizes. The underlying spatial distributions remain static, so no explicit displacement scenarios are considered, although these can be explored under the same framework by simulating specific displacement scenarios. However, as for any power analysis, this alternative hypothesis (speculative impact) needs to be completely specified. This may be non-trivial as many scenarios might be relevant, although it is envisaged that situations like displacements from development footprints might be clear. Other modelling tools (e.g. the MRSeaPower package, Mackenzie, *et al.,* 2017) might be relevant and combined with the simulation tools here for such cases.

Surveying for FHD estimation

The objectives of the LiDAR surveying make it particularly sensitive to the input density data. Surveying is designed to achieve a number of individuals thought sufficient to provide a robust FHD estimate. This is most efficiently achieved by targeting high-density areas – indeed, it may only be feasible for some species if there are aggregations of the animals. Low densities require large surveying effort. So *a priori* survey designs concentrate on the peaks of the modelled densities.

Multi-species design

All simulations and resultant designs here are done on a species-by-species basis. If a design is sought that is in some way optimal over multiple species, this is not naturally generated. In the case of estimating animal density and impacts, it is feasible to use the individual species' designs to produce a single design that fits requirements and logistics e.g. given a particular budget or priority species, power for species A to D will also be achieved by design X. In the case of designs for FHD estimation, this is much more complex. A set of survey areas would be sought that maximised the probability of obtaining 100+ individuals of several species, for minimal survey effort. This is beyond the scope of the study, but the basic software tools are found within the project's code repository, which is open-source and available for community development.

Conclusion

The simulations presented here offer a range of insights into the power that might be reasonably expected from a range of survey designs, species, seasons and impact sizes. It also presents effort figures which can be used to bound the feasibility, in terms of cost or simple logistics, of particular questions about species. Similarly, indicative figures can be drawn about the amount of effort required for robust, species-specific, FHD estimation and the level of spatio-temporal specificity that might be achieved for these.

While general advice has been provided through extensive simulation, equally important is the code developed to implement these simulations. This is open-source, version-controlled and available for community development. This allows specific cases to be calculated for e.g. additional species, alternative data sources etc. In particular, the LiDAR simulation tools are of great utility. It seems likely that alternative density maps might be preferred for particular regions, and that the FHD be developed for a very specific region e.g. the footprint of a prospective windfarm development.

Clearly the results presented here are only as robust as the data underpinning the simulations, with density maps being the point of greatest sensitivity. The disparity between SEAPOP and MERP suggests careful consideration is needed before settling on a particular set of density figures.

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Appendix 1

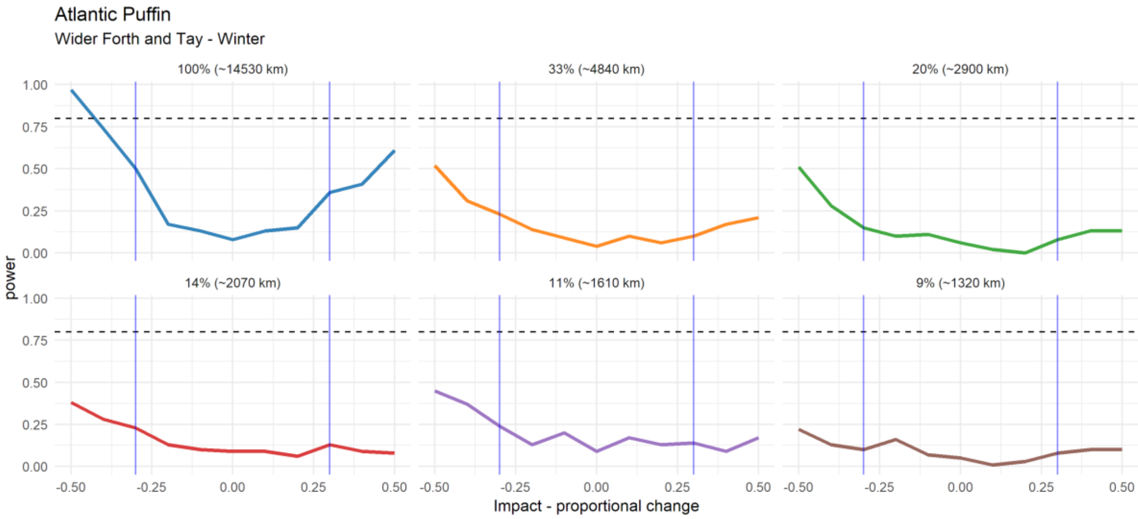
Power outputs

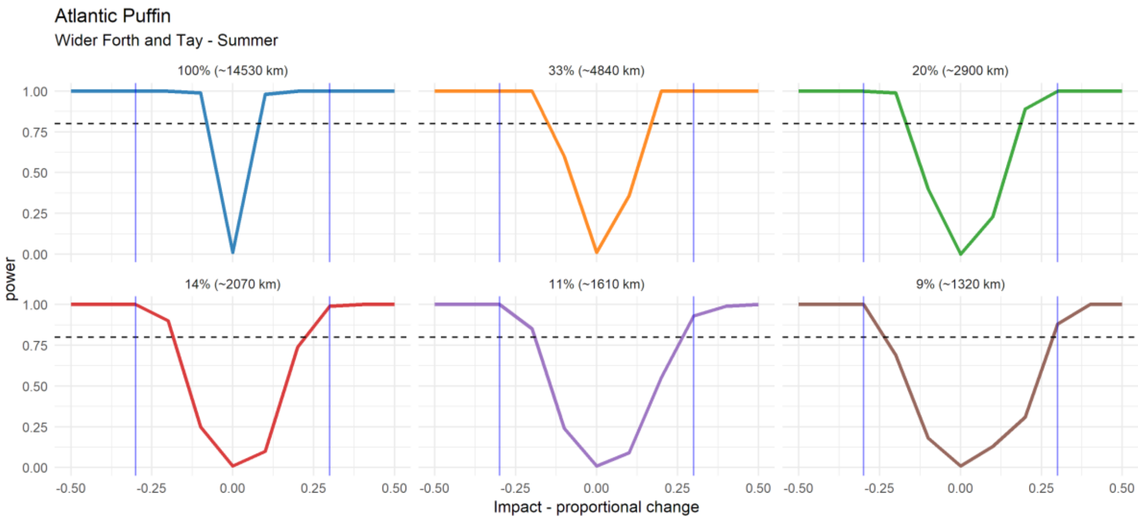
Plots were generated for the power curves for each of the eight species, over three SEAPOP seasons, for four regions and three density surfaces (mean, upper and lower 95% CI). MERP estimates for common guillemot are given for an aggregated autumn for comparison, but MERP-derived results have not been generally run, as explained in the body of the report.

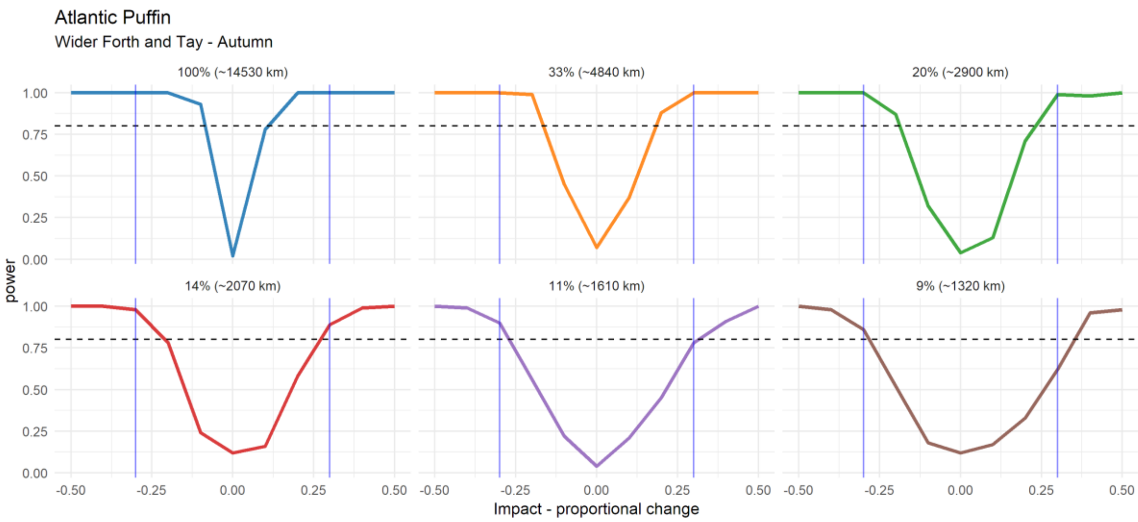
Each plot consists of six power curves, indicating the amount of survey effort required to detect a particular population impact under six surveying intensities. Vertical blue lines indicate the reference 30% shift in population size. The black dashed line gives the 80% power reference point.

NB - in the interests of brevity, only the power plots for the mean surfaces are presented here. The upper and lower CIs are summarised in the body of the report and available electronically.

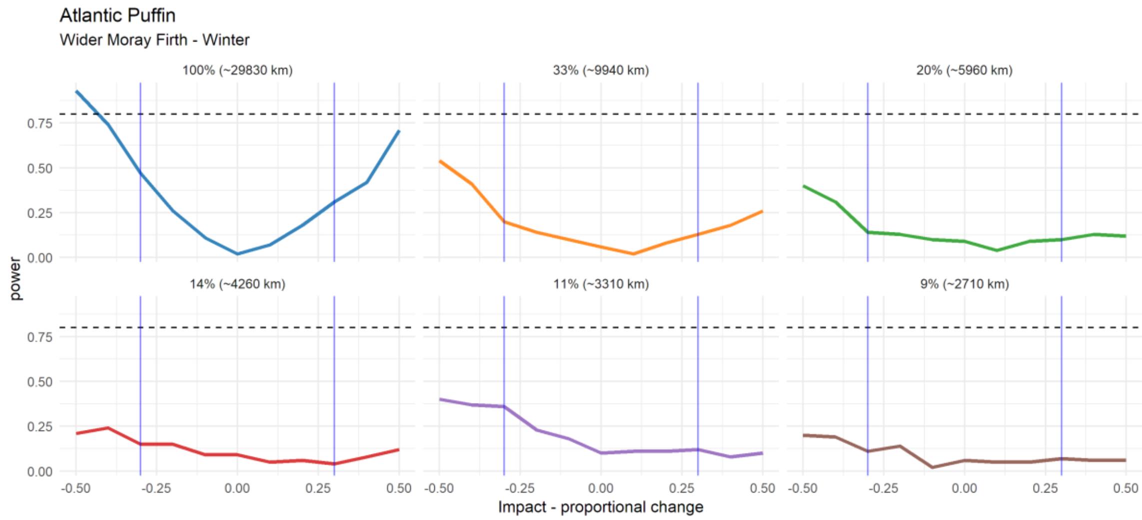
Power Plots –Wider Forth and Tay (Region 1) – seasonal Atlantic puffin

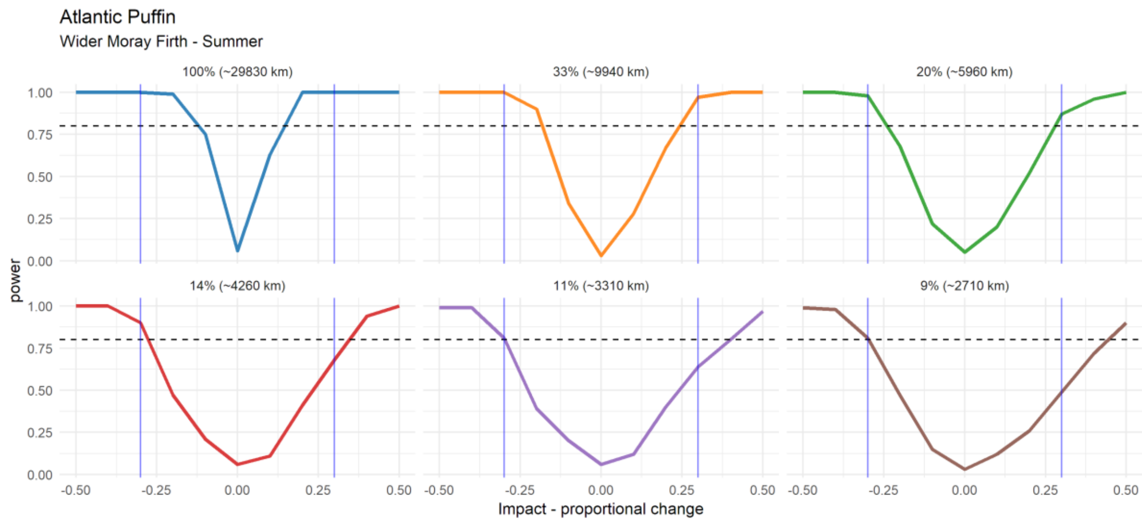


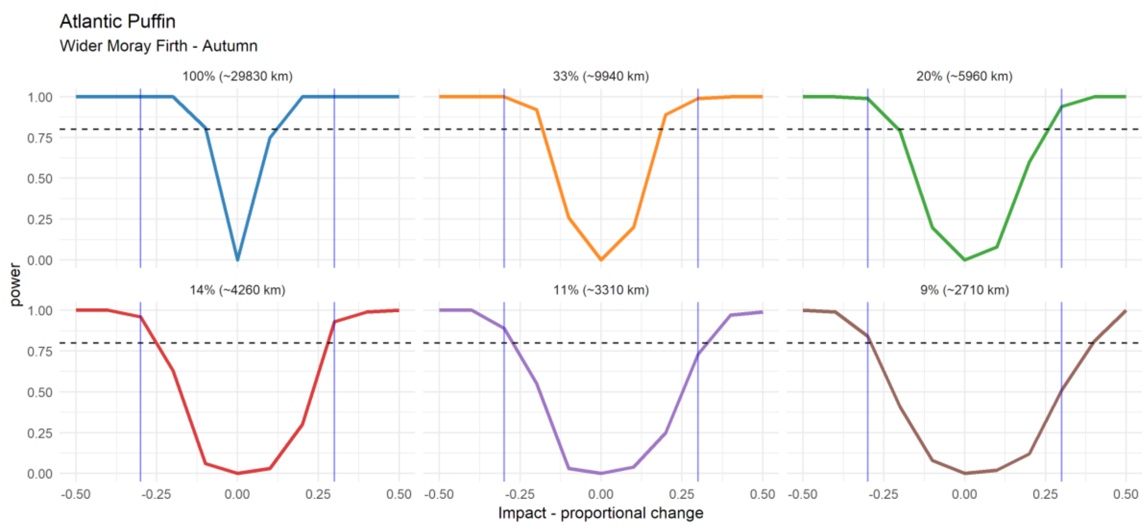




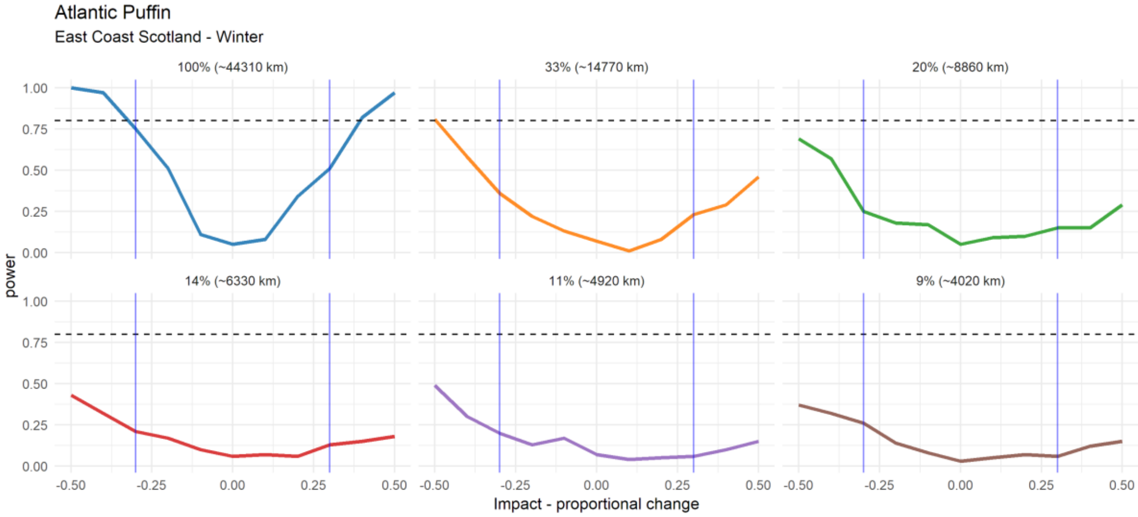
Power Plots –Wider Moray Firth (Region 2) – seasonal Atlantic puffin

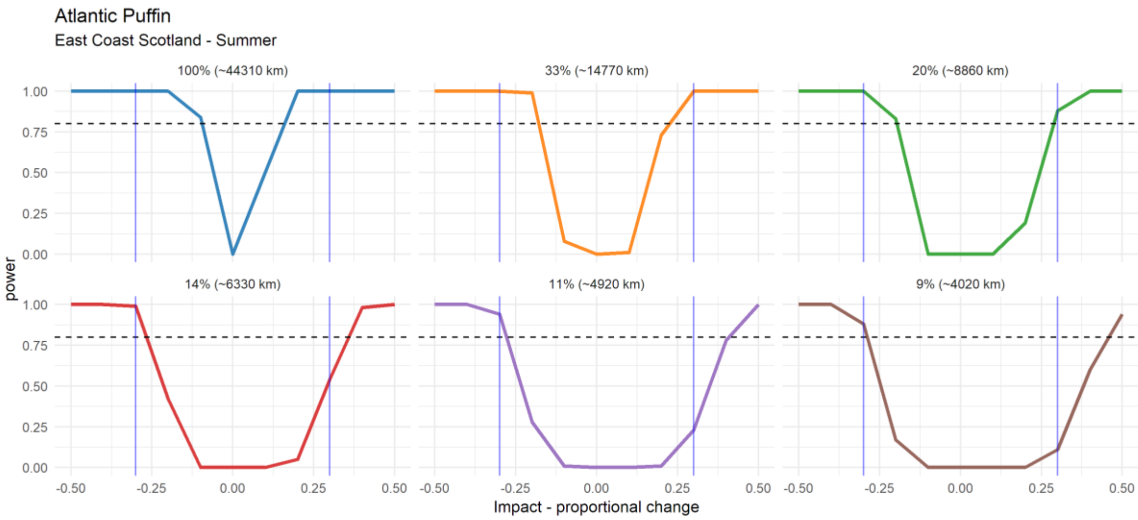


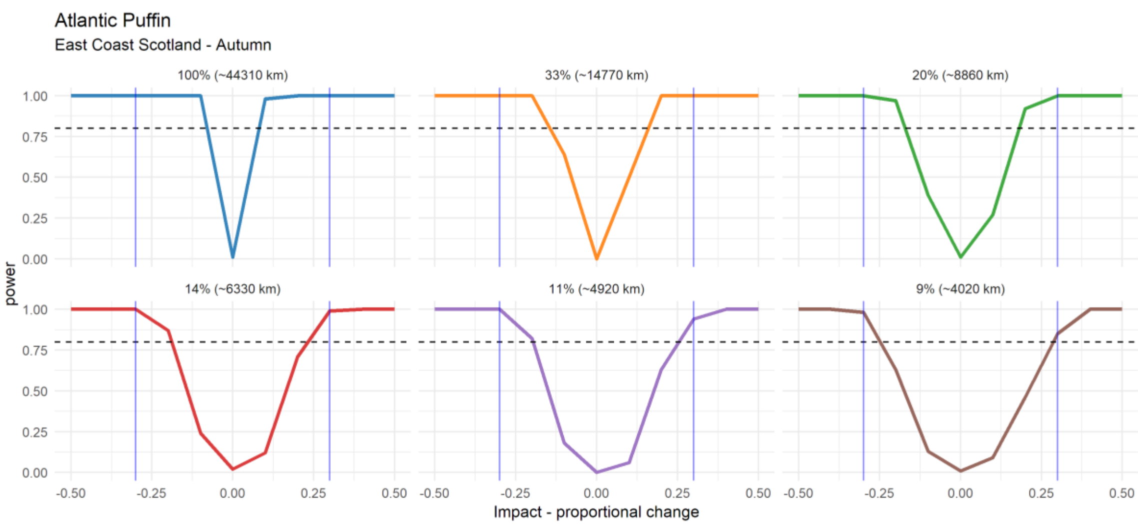




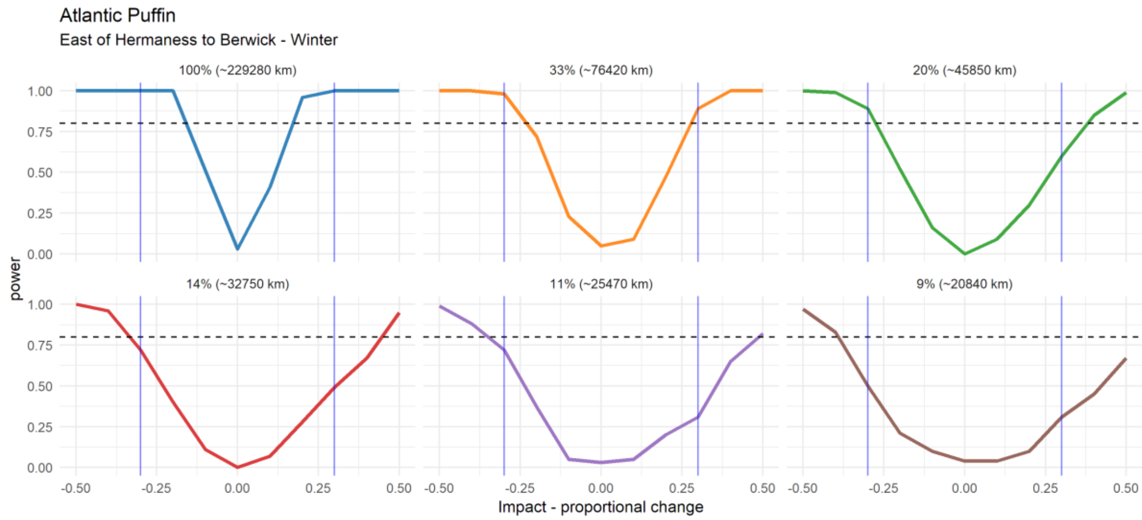
Power Plots – East Coast Scotland (Region 3) – seasonal Atlantic puffin

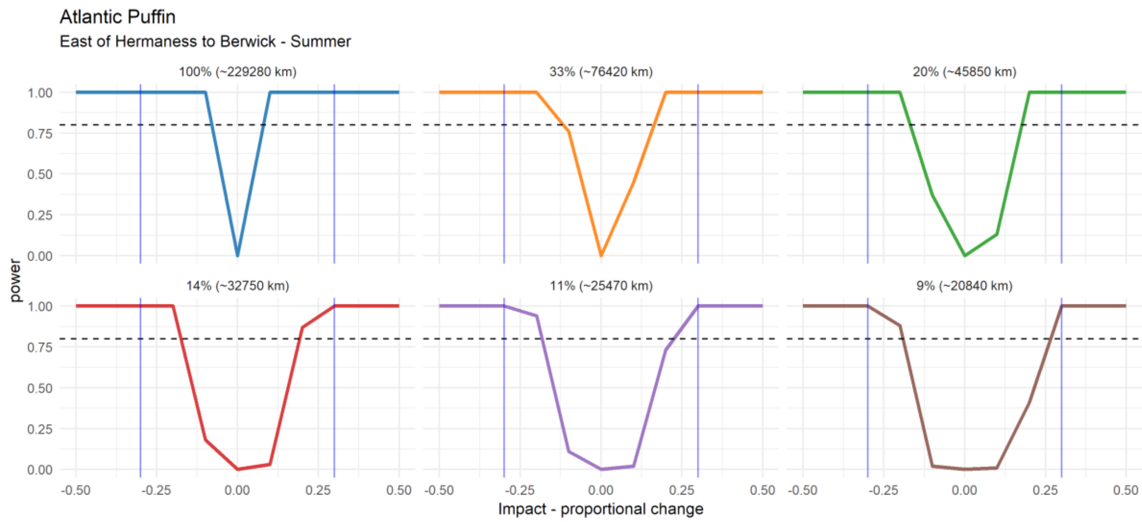


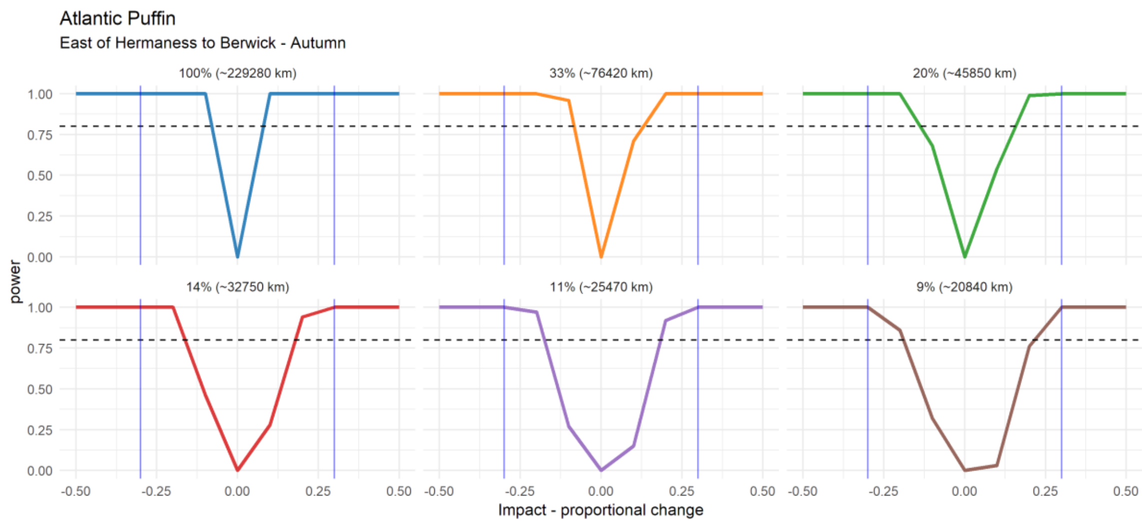




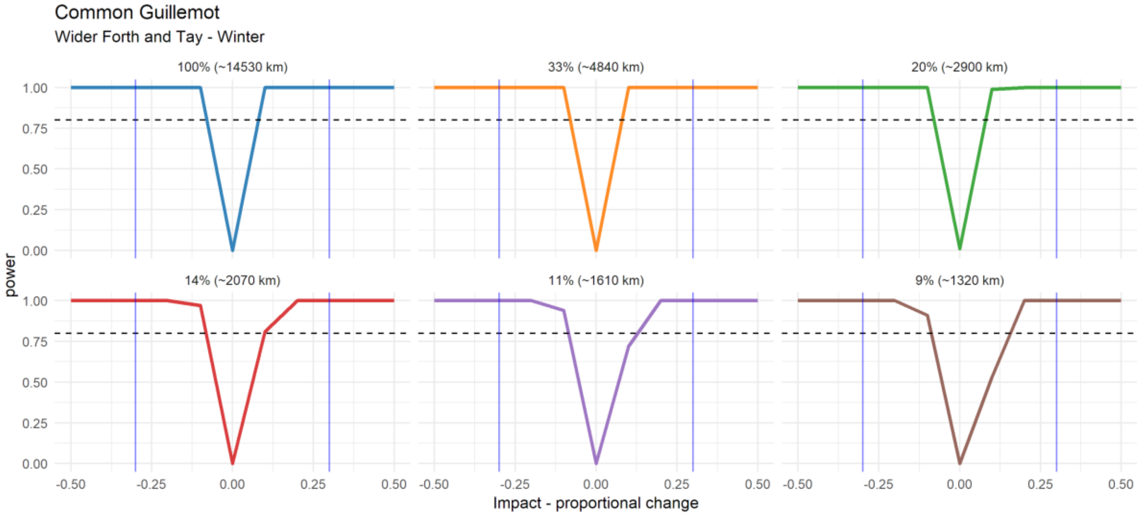
Power Plots – East of Hermaness to Berwick (Region 4) – seasonal Atlantic puffin

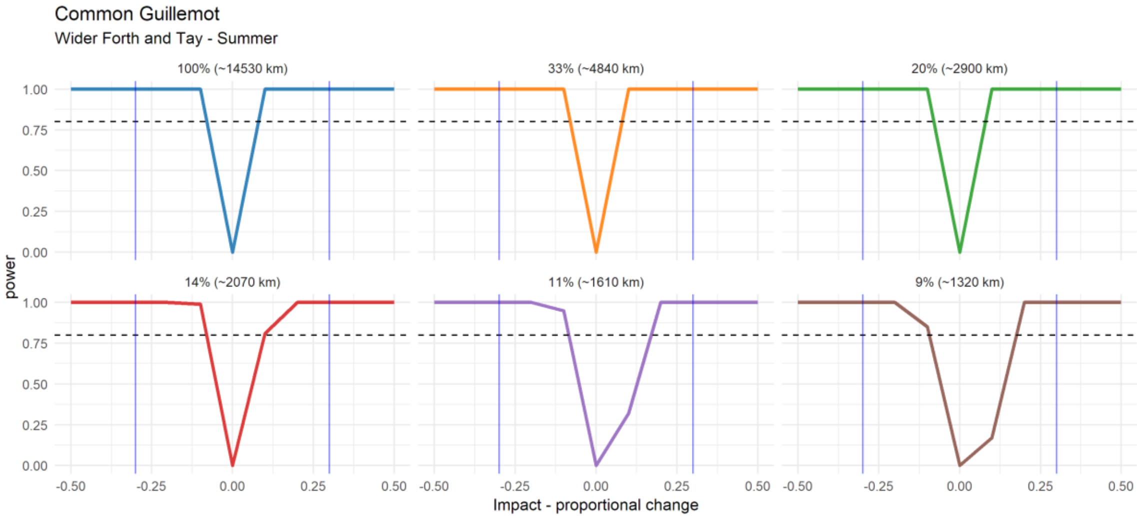


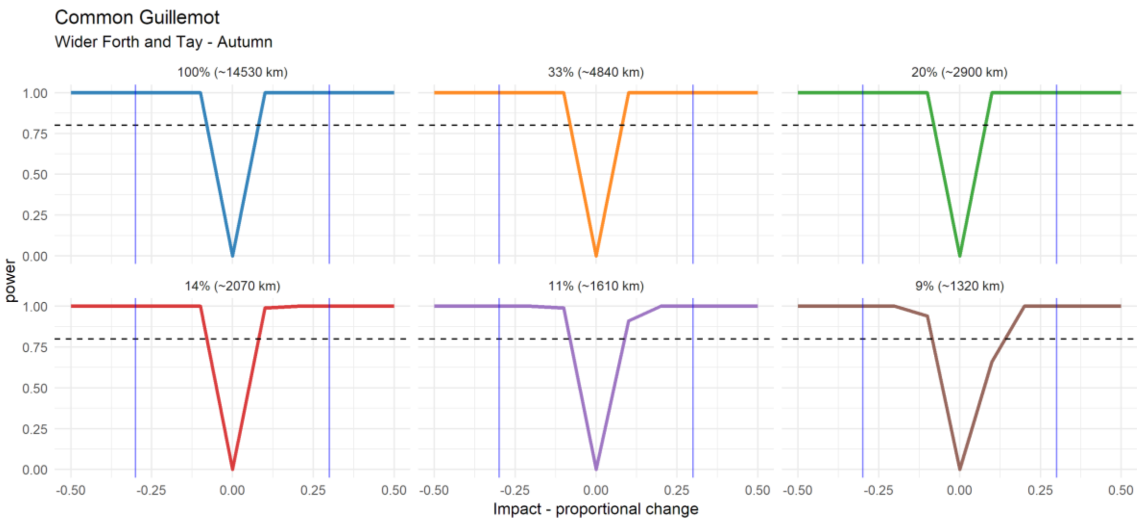




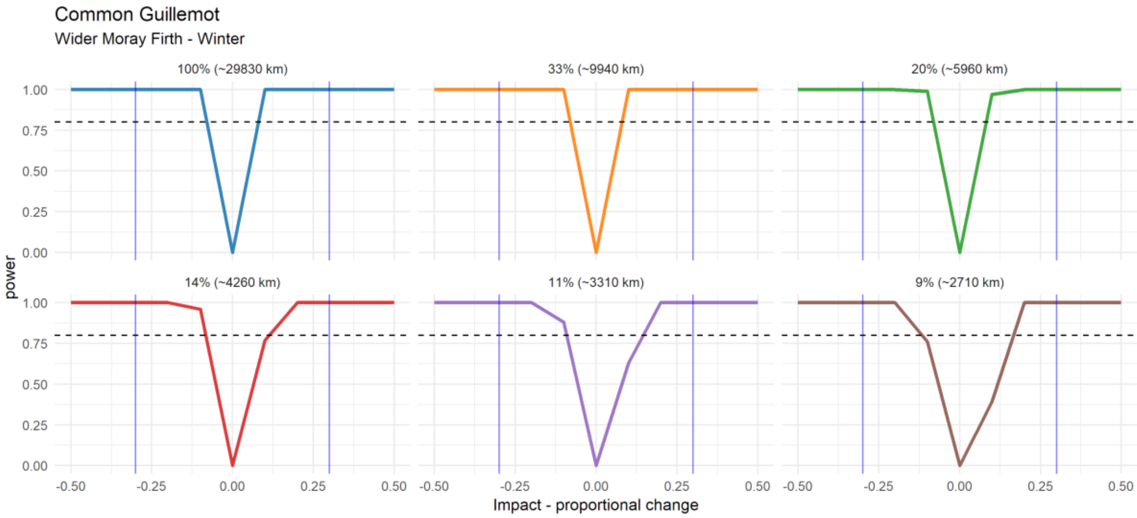
Power Plots –Wider Forth and Tay (Region 1) – seasonal common guillemot

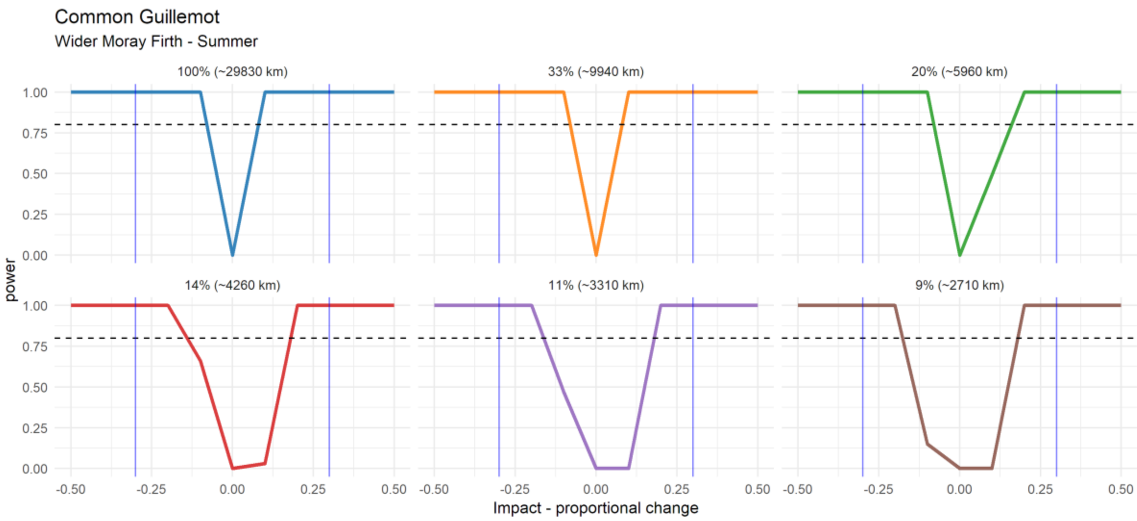


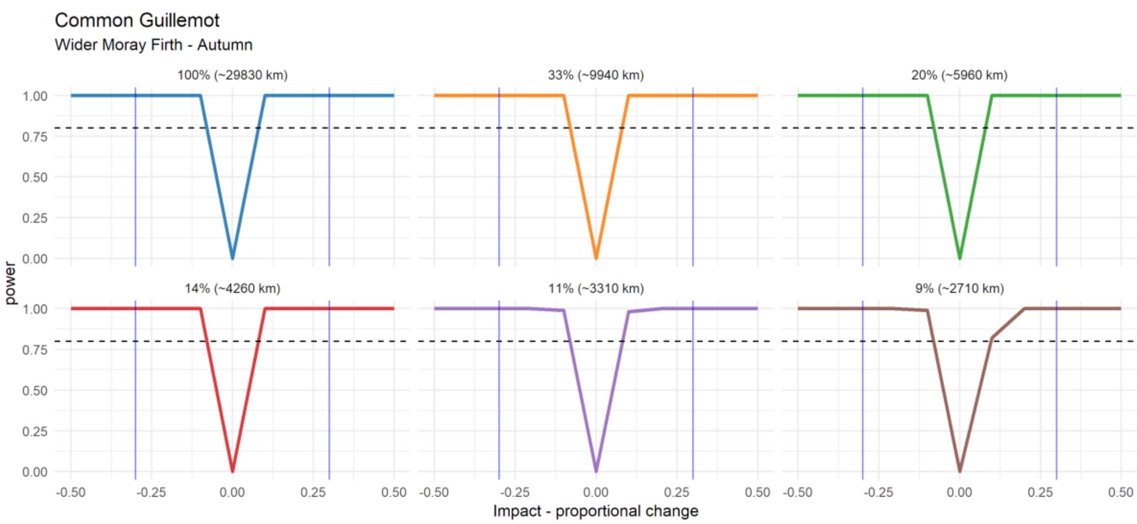




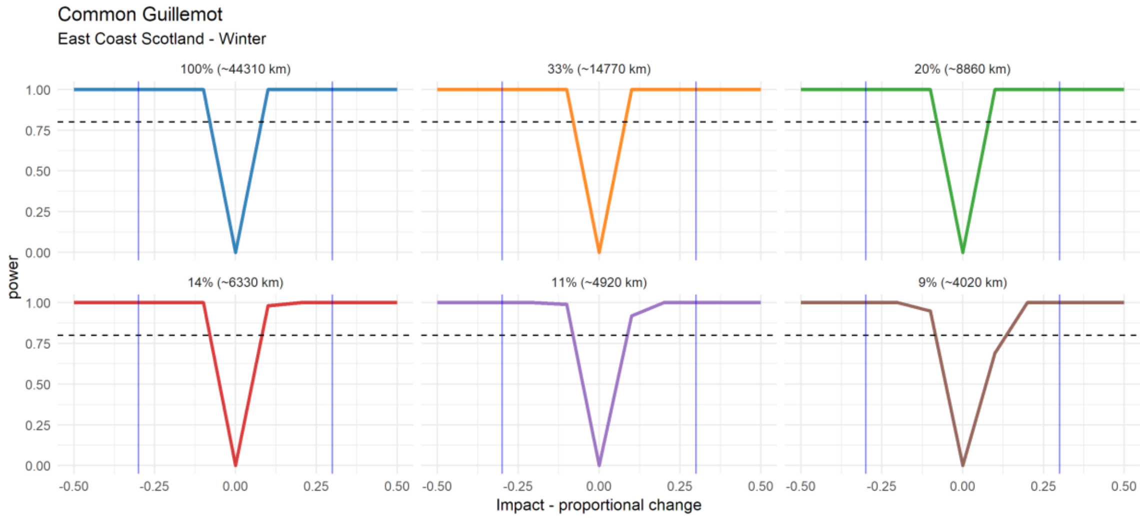
Power Plots –Wider Moray Firth (Region 2) – seasonal common guillemot

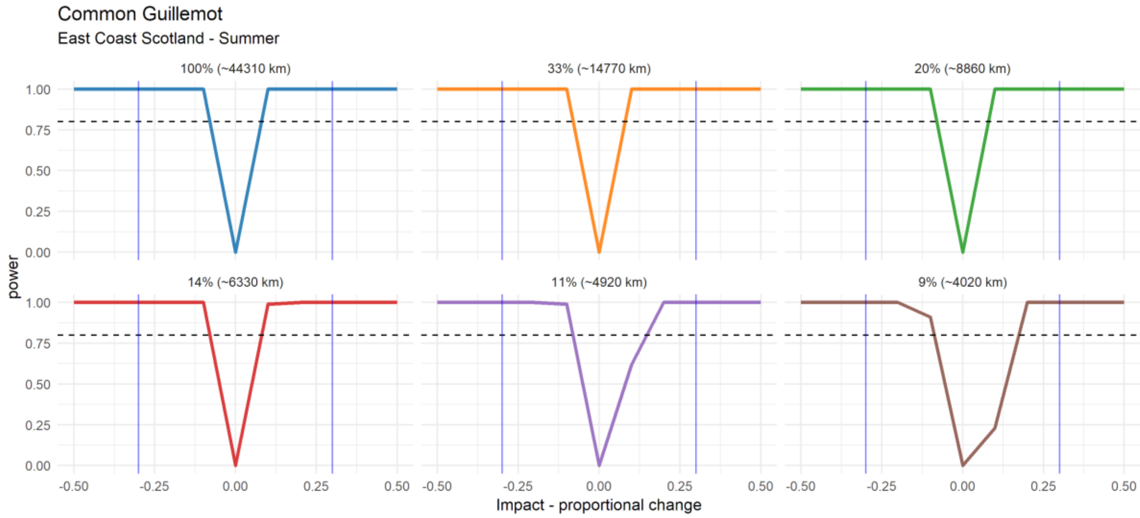


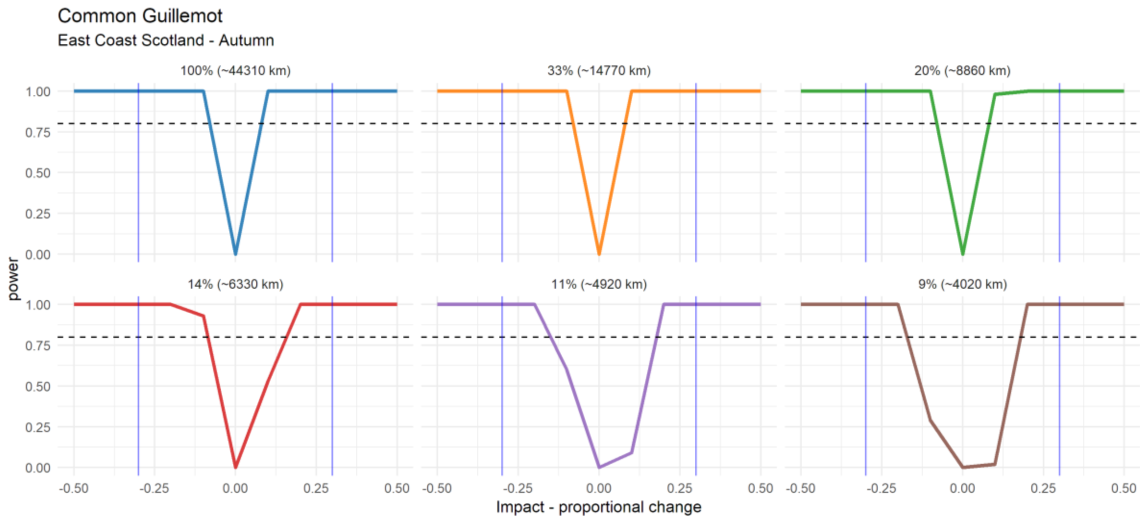




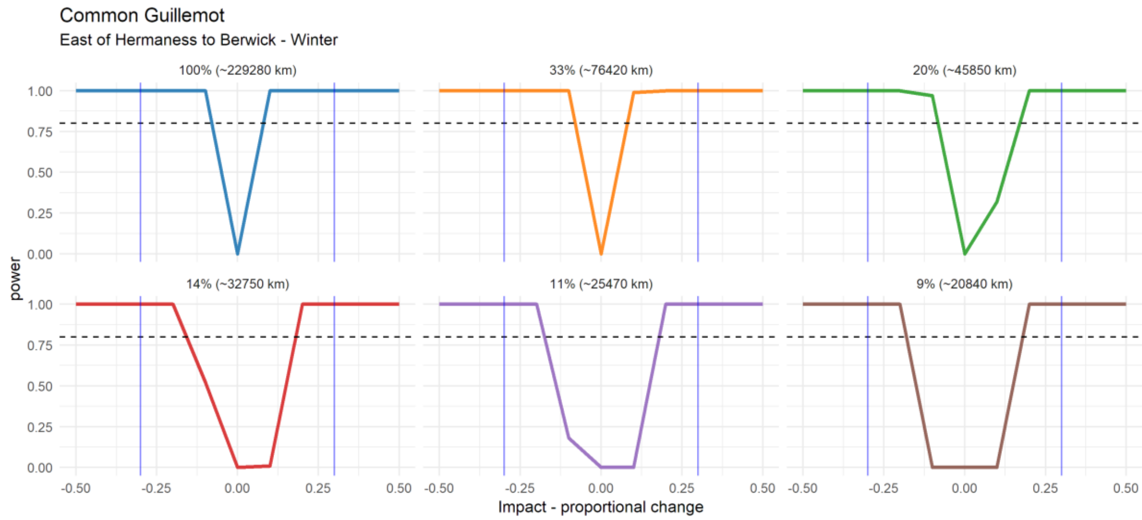
Power Plots – East Coast Scotland (Region 3) – seasonal common guillemot

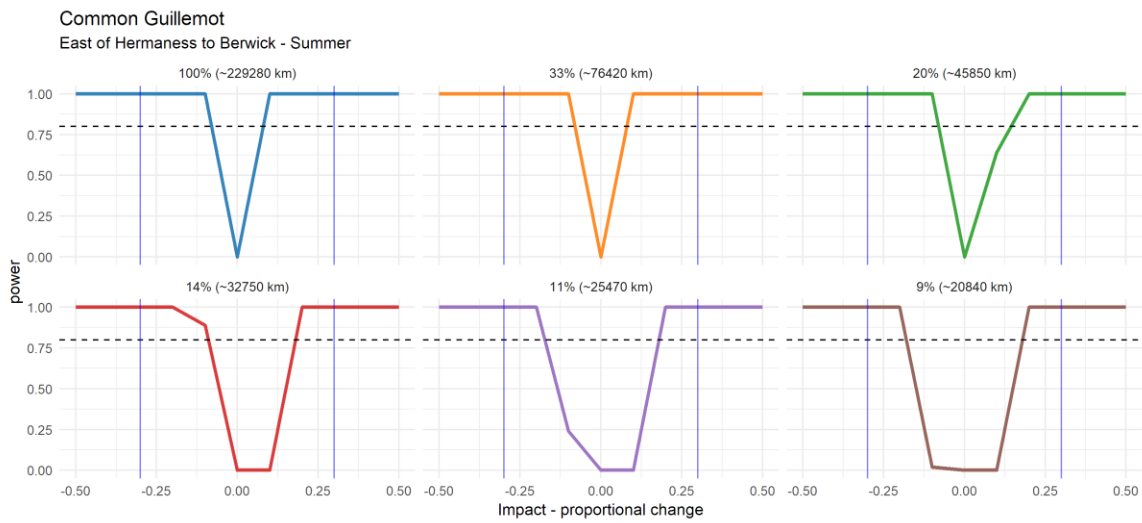


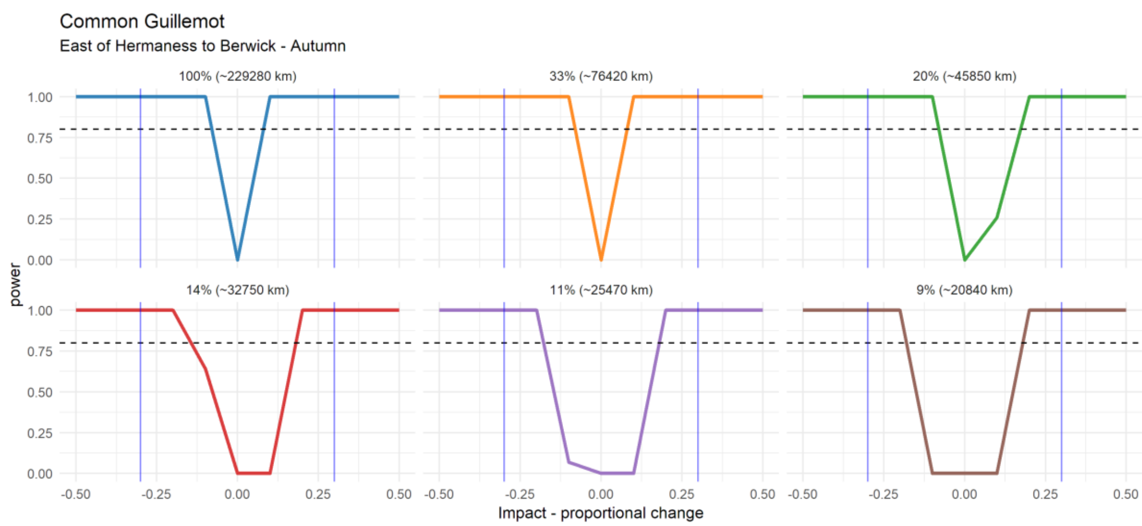




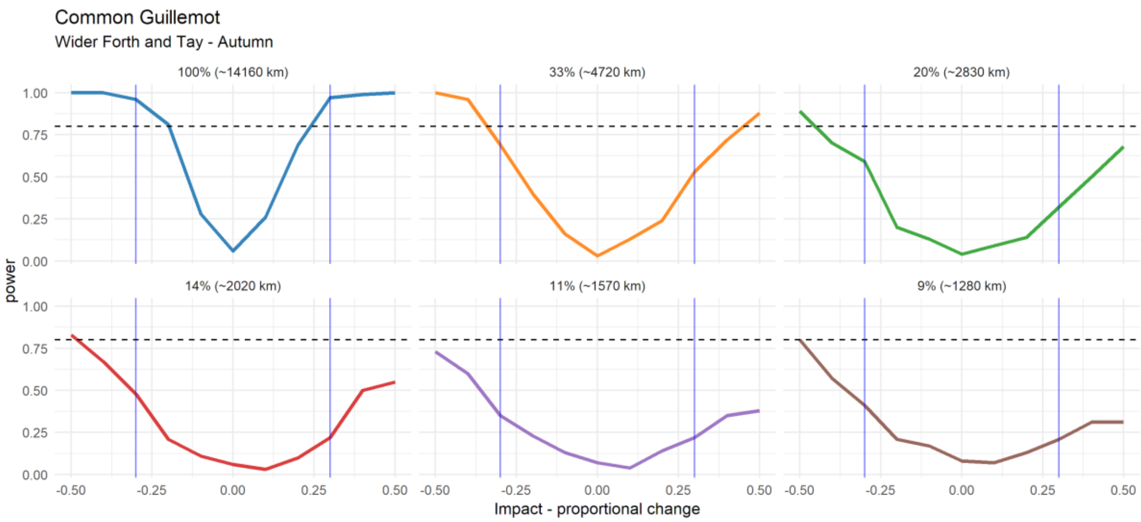
Power Plots – East of Hermaness to Berwick (Region 4) – seasonal common guillemot



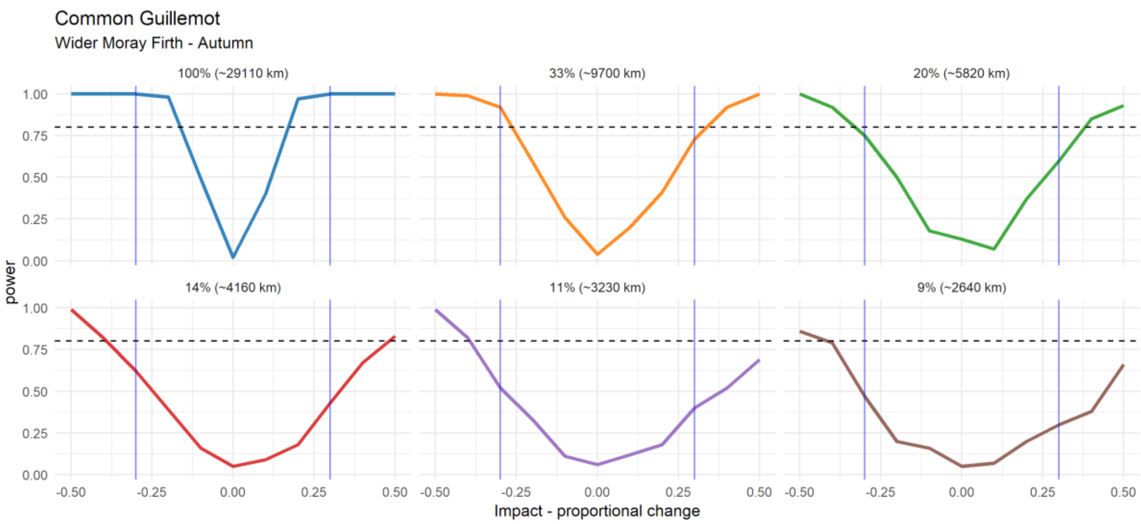




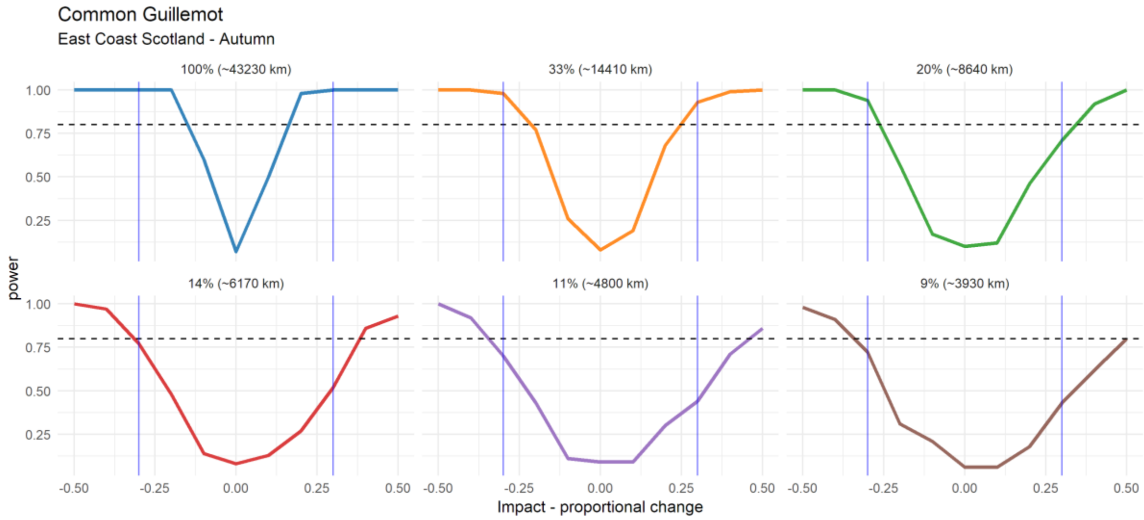
Power Plots –Wider Forth and Tay (Region 1) – MERP common guillemot



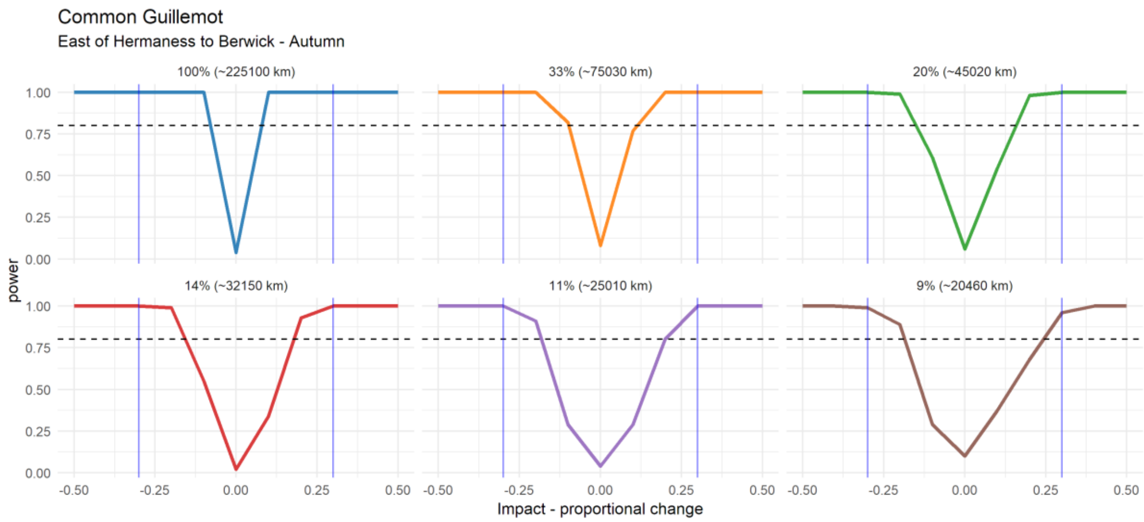
Power Plots –Wider Moray Firth (Region 2) – MERP common guillemot



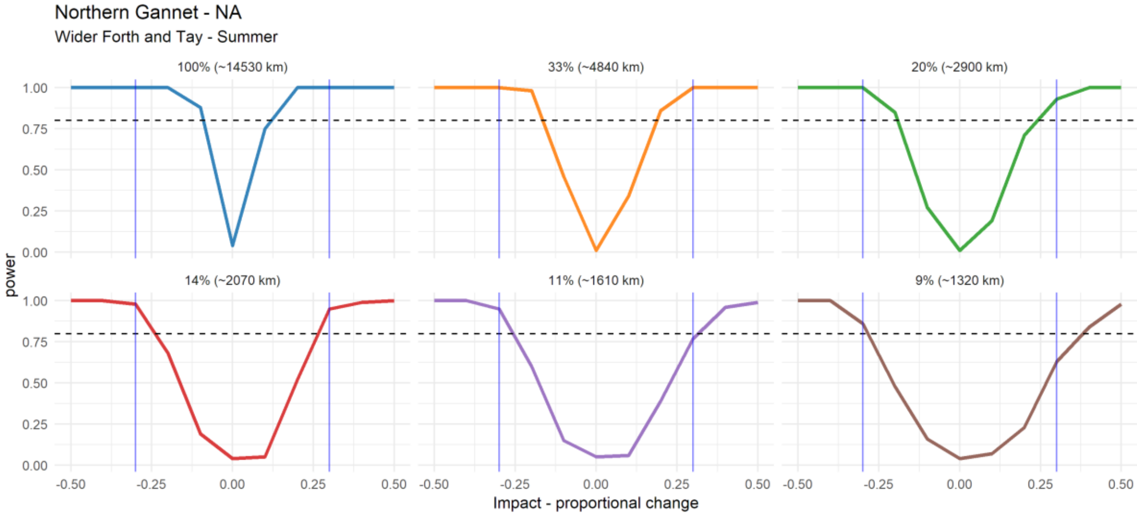
Power Plots – East Coast Scotland (Region 3) – MERP common guillemot

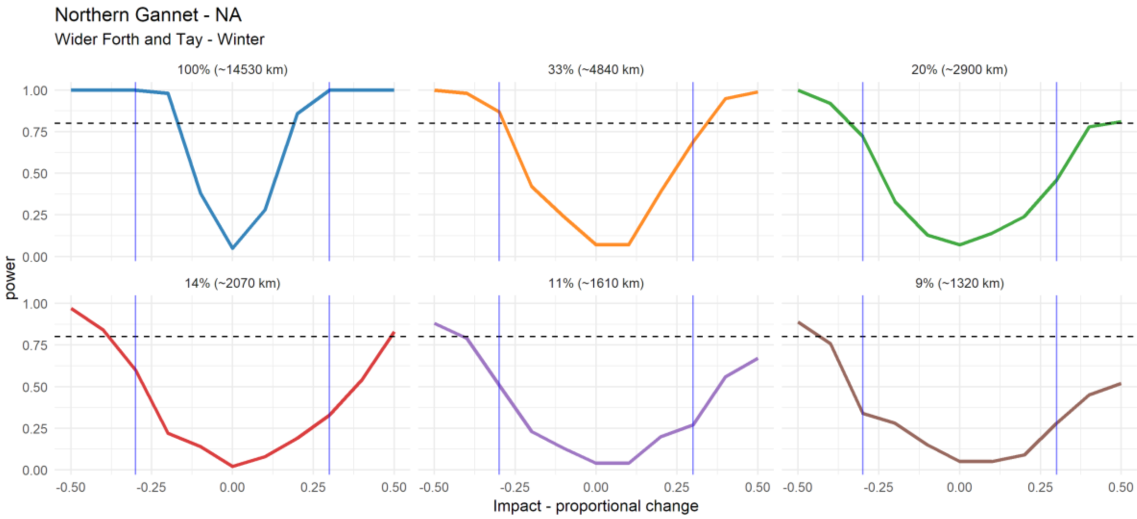


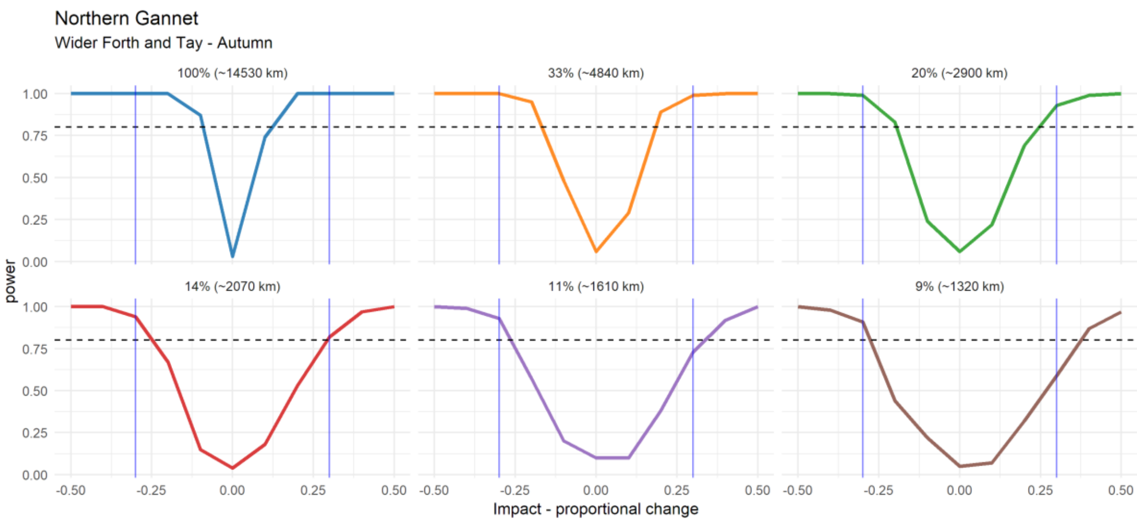
Power Plots – East of Hermaness to Berwick (Region 4) – seasonal common guillemot



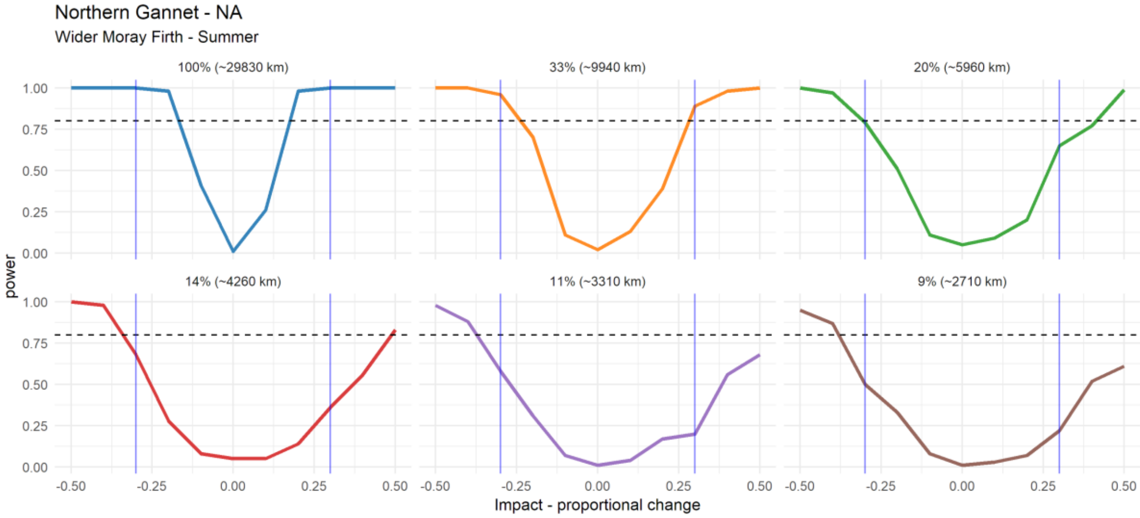
Power Plots –Wider Forth and Tay (Region 1) – seasonal Northern gannet

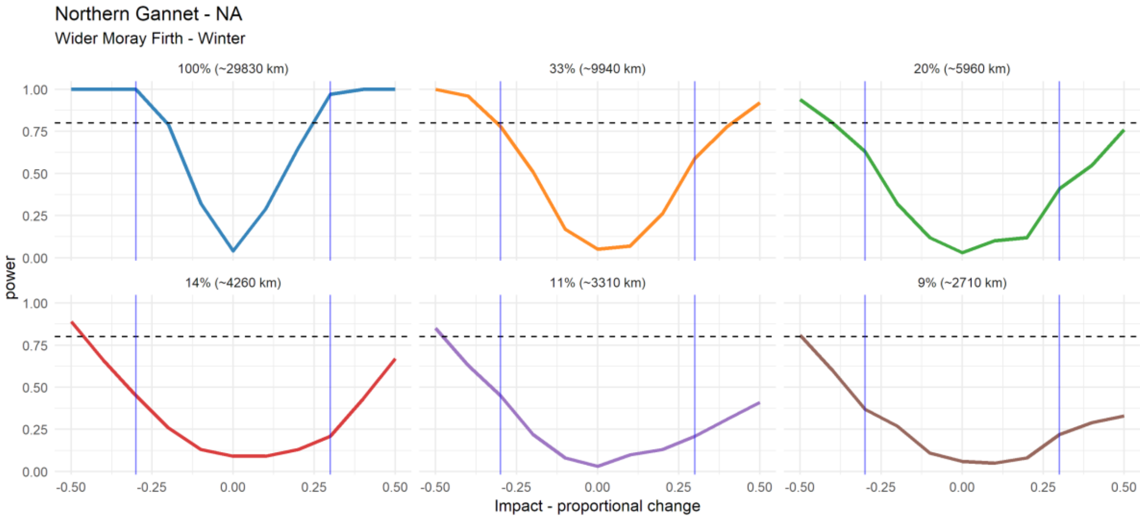


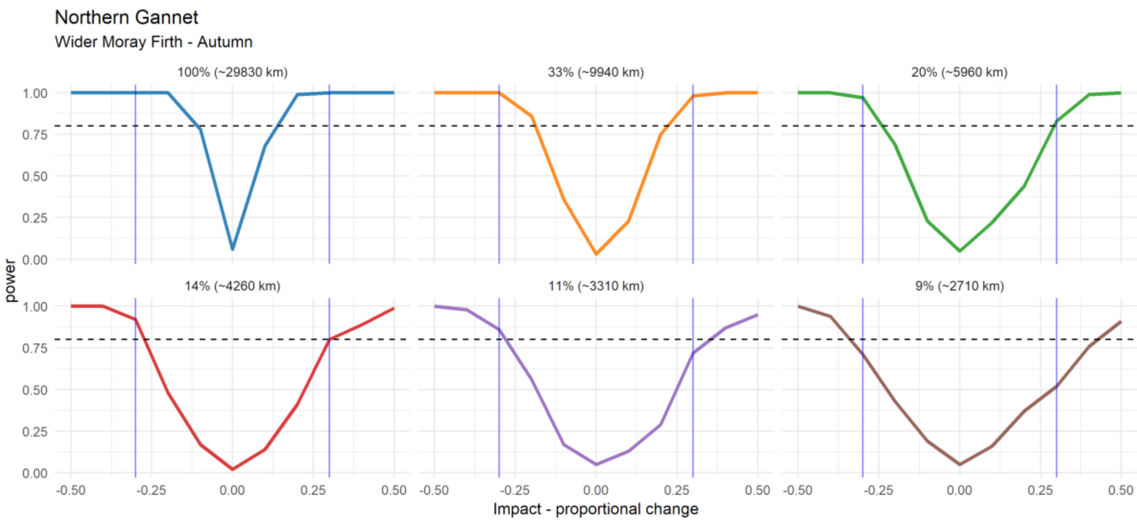




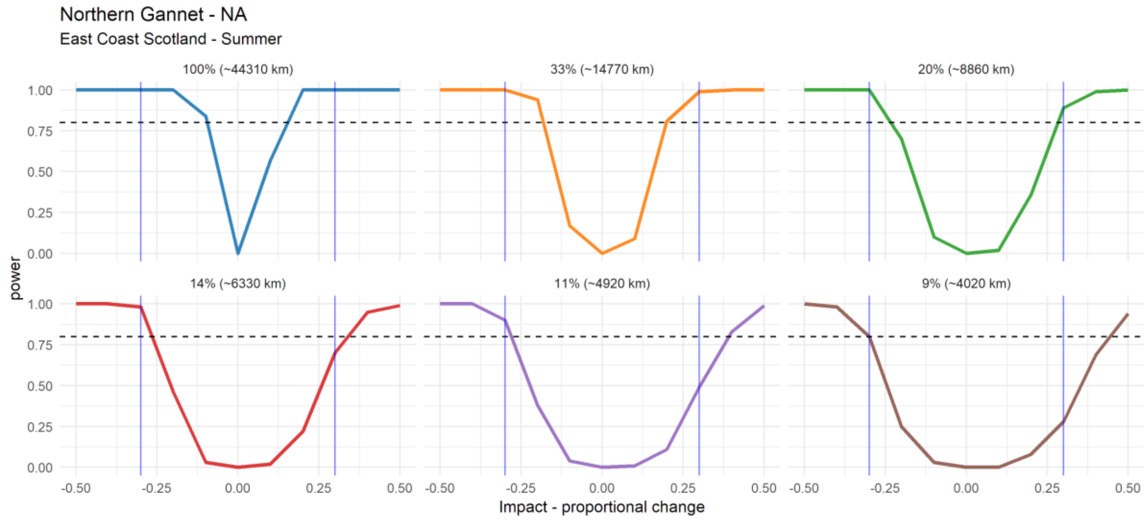
Power Plots –Wider Moray Firth (Region 2) – seasonal Northern gannet

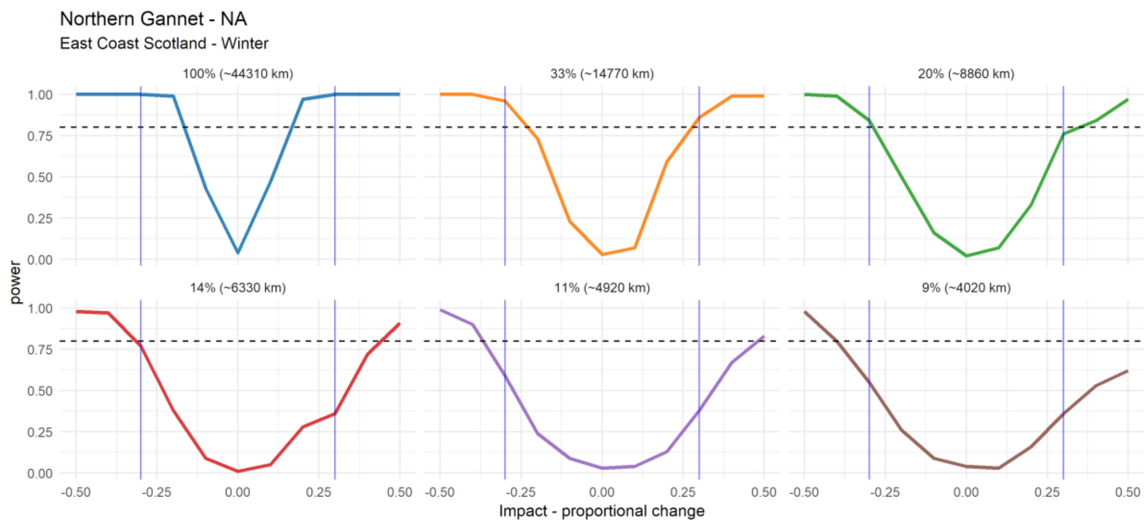


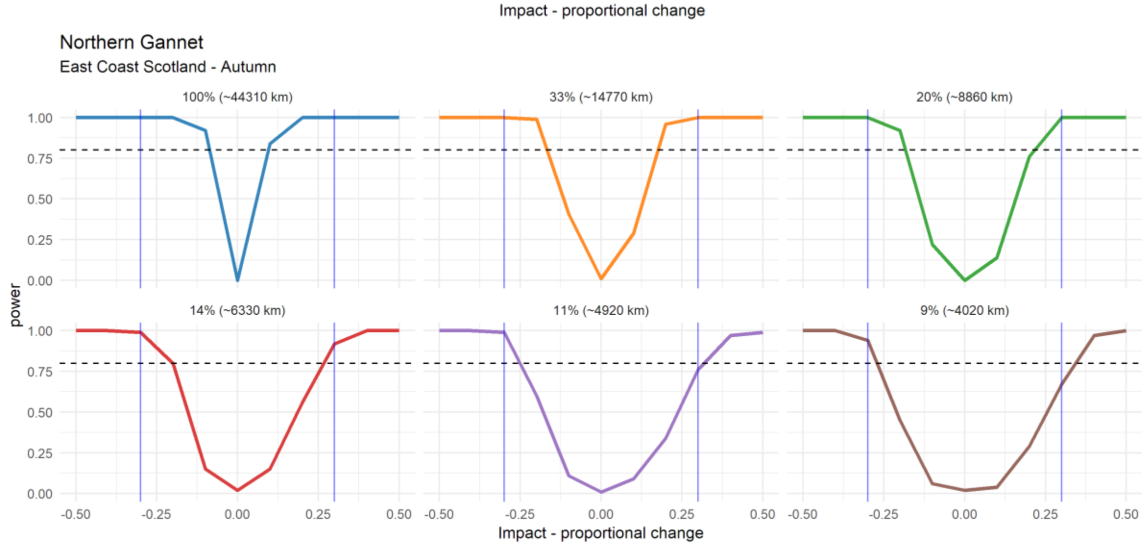




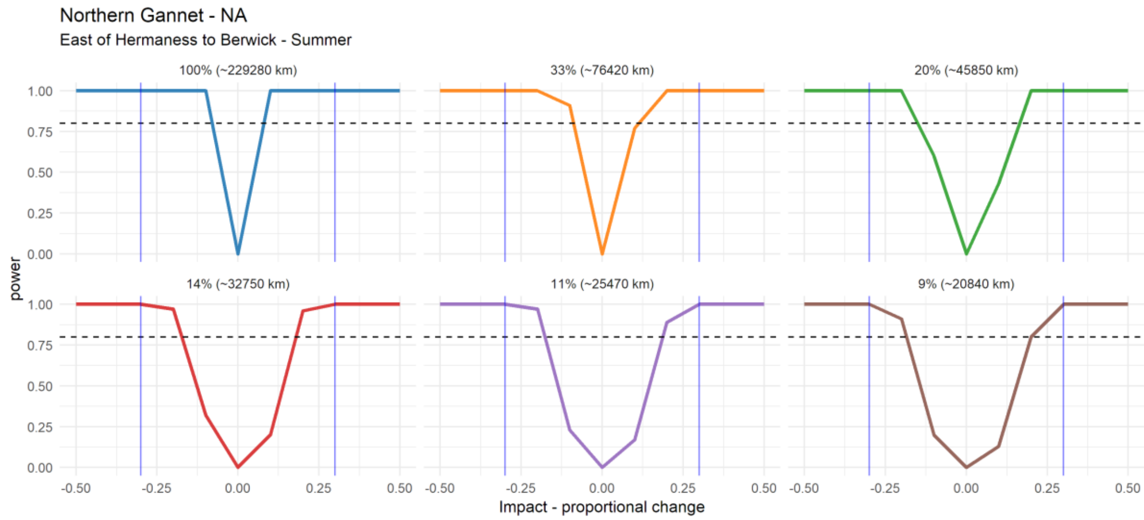
Power Plots – East Coast Scotland (Region 3) – seasonal Northern gannet

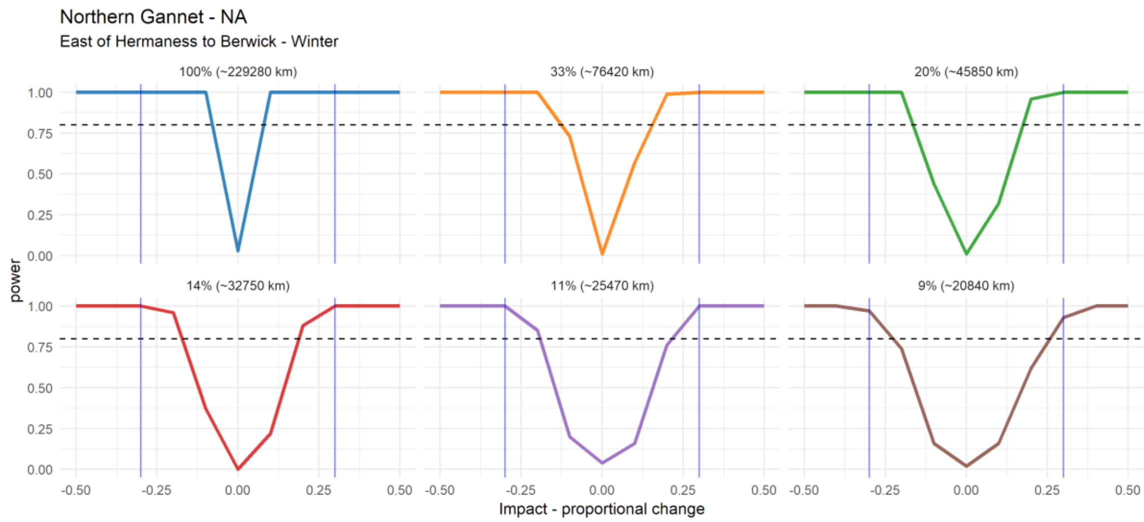


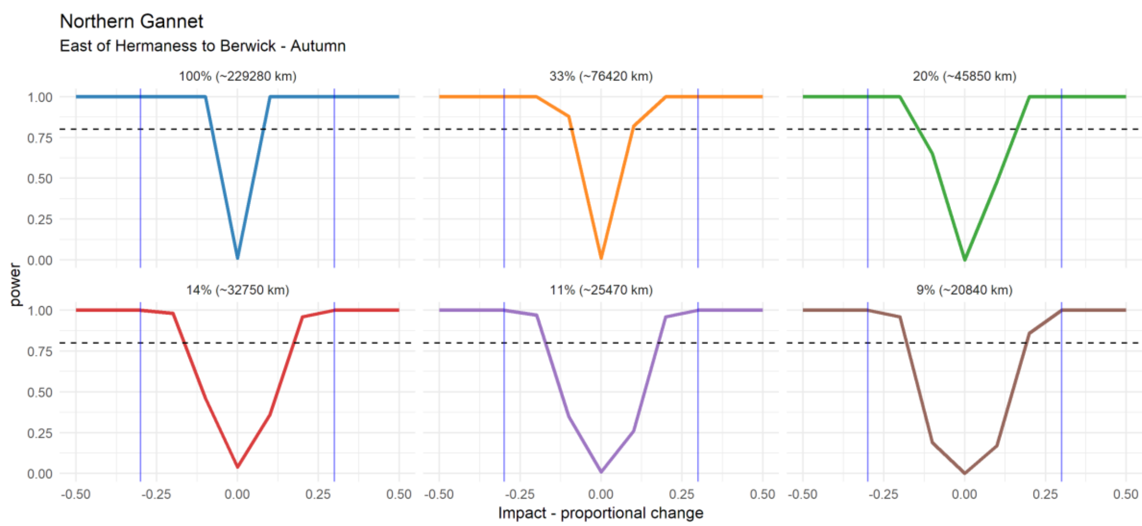




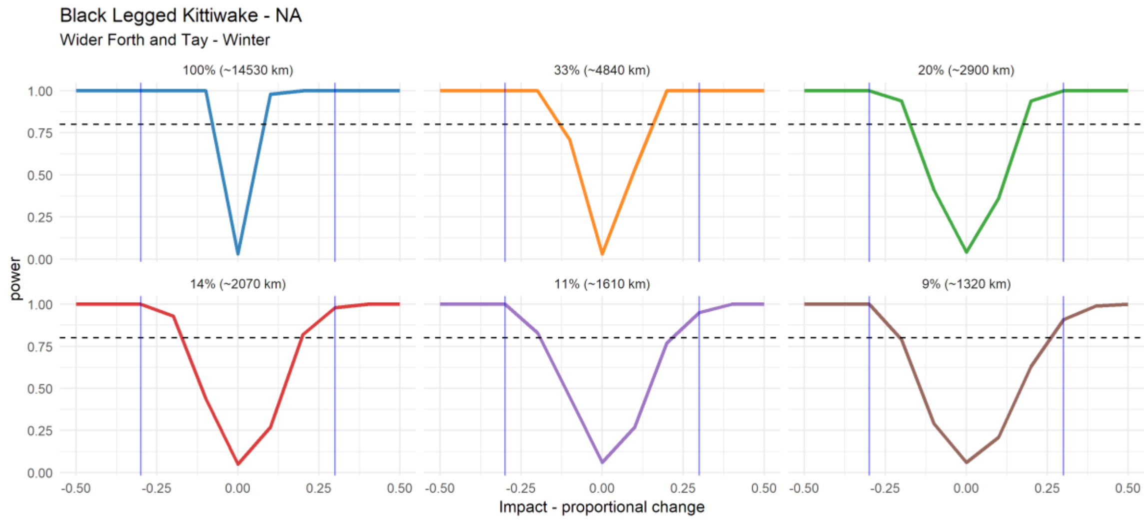
Power Plots – East of Hermaness to Berwick (Region 4) – seasonal Northern gannet

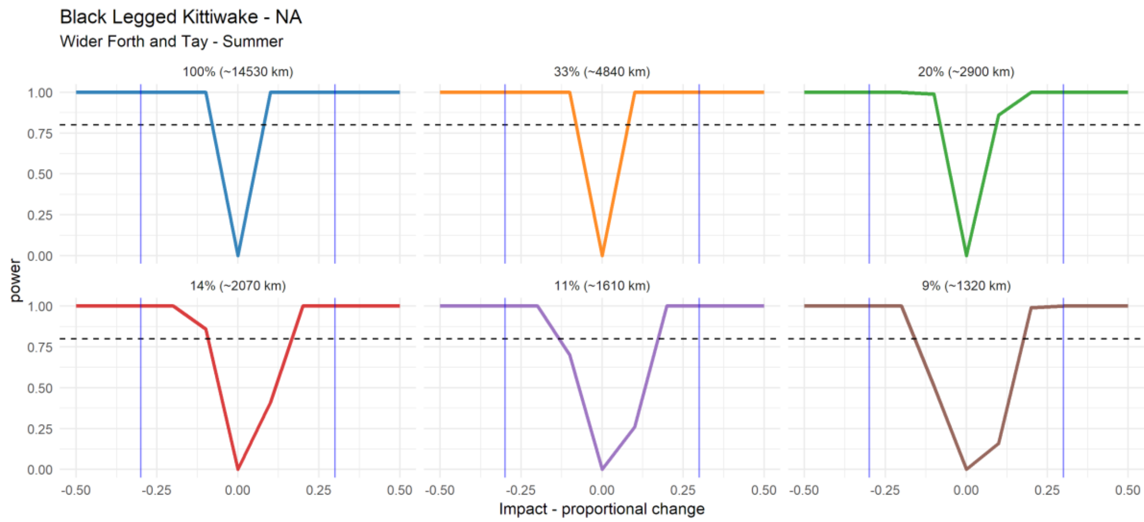


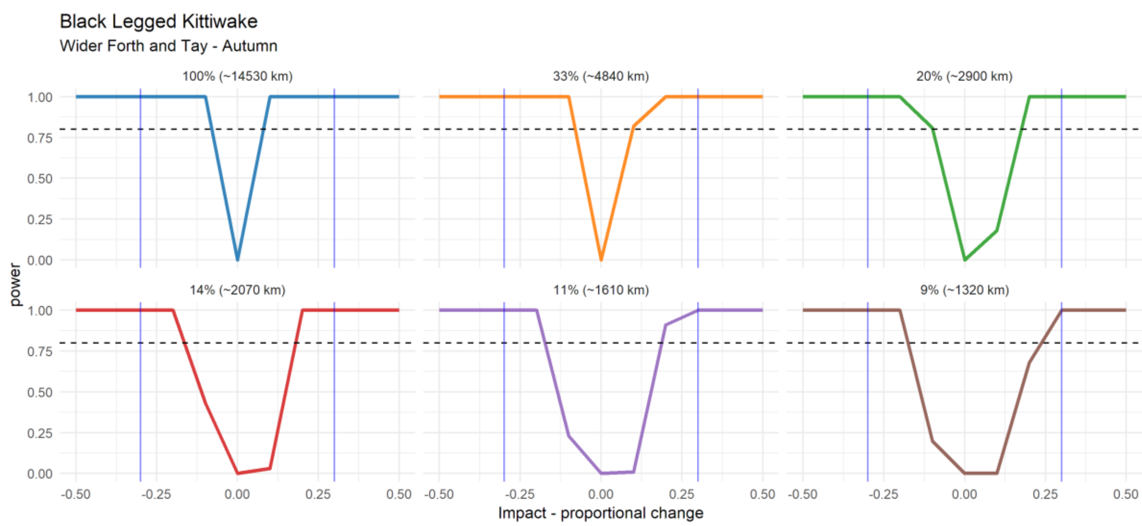




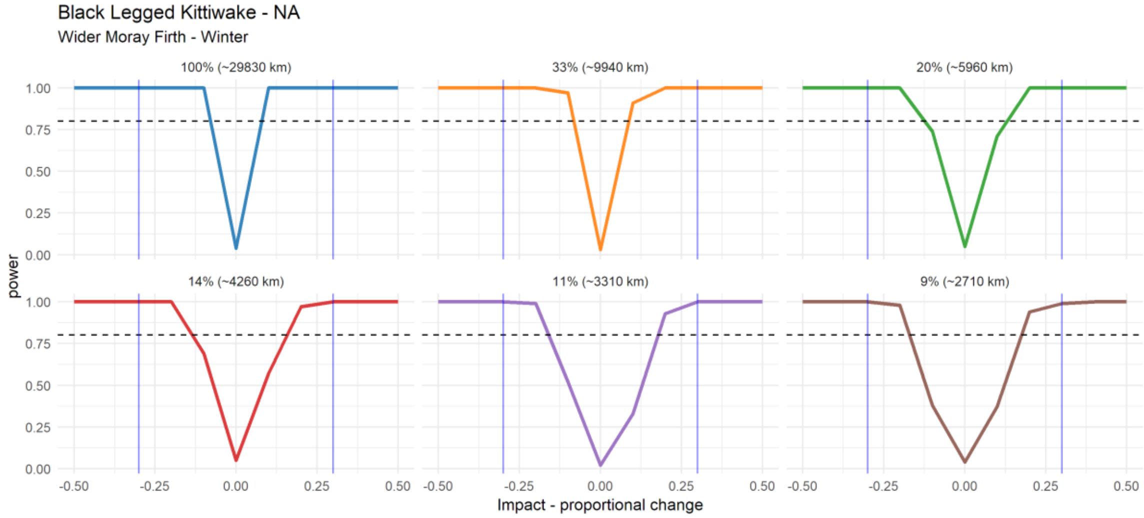
Power Plots – Wider Forth and Tay (Region 1) – seasonal black-legged kittiwake

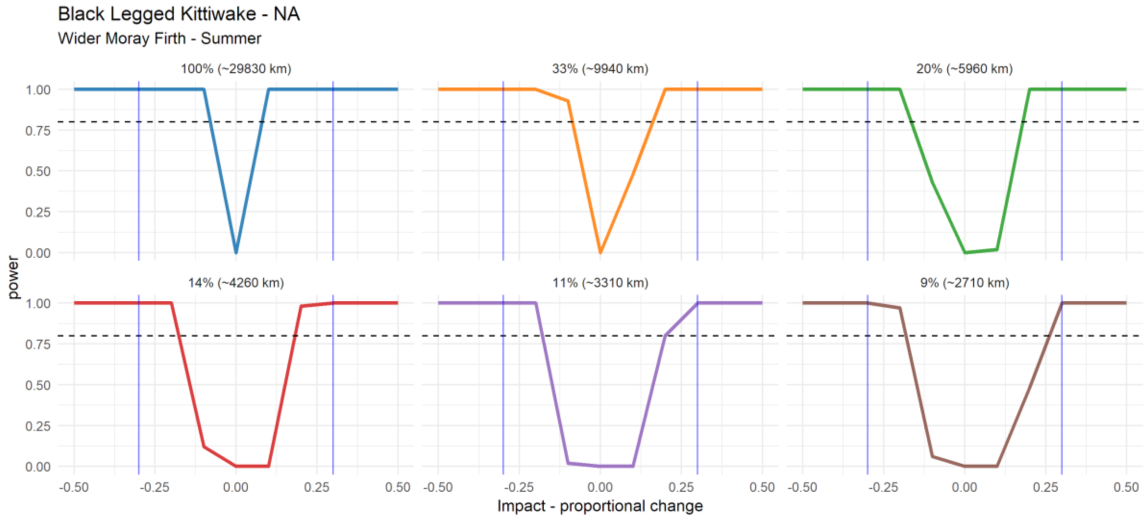


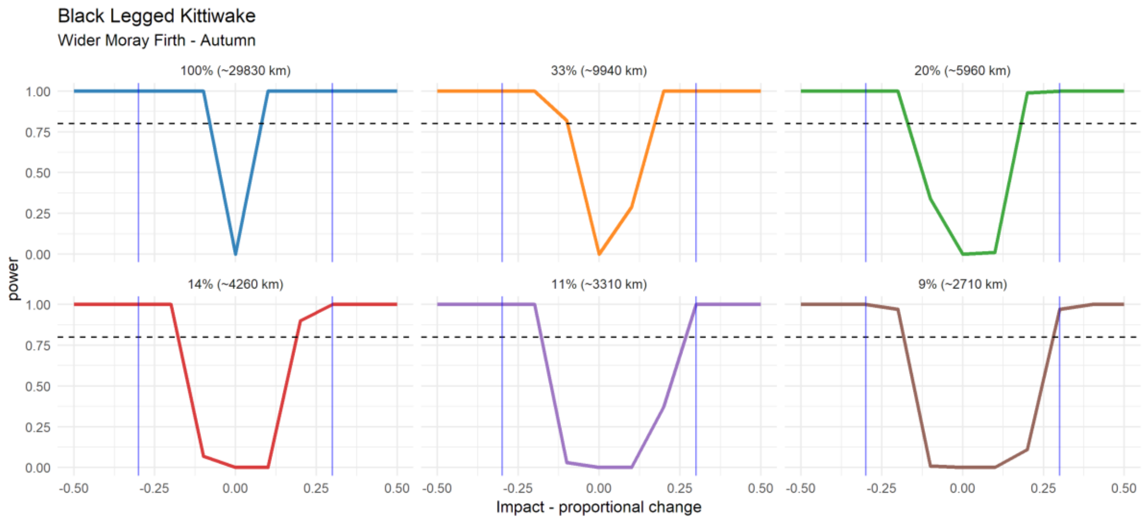




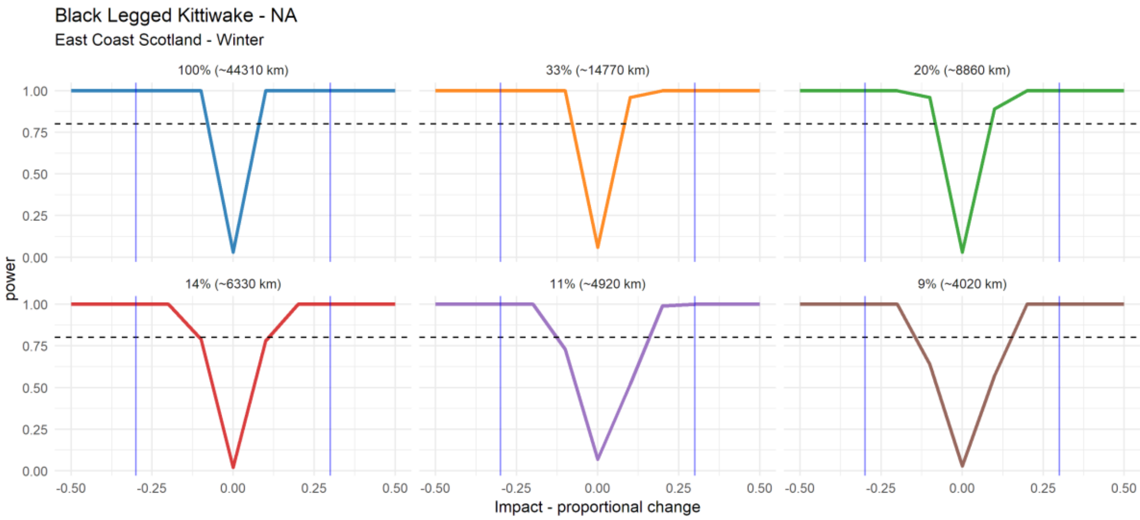
Power Plots – Wider Moray Firth (Region 2) – seasonal black-legged kittiwake

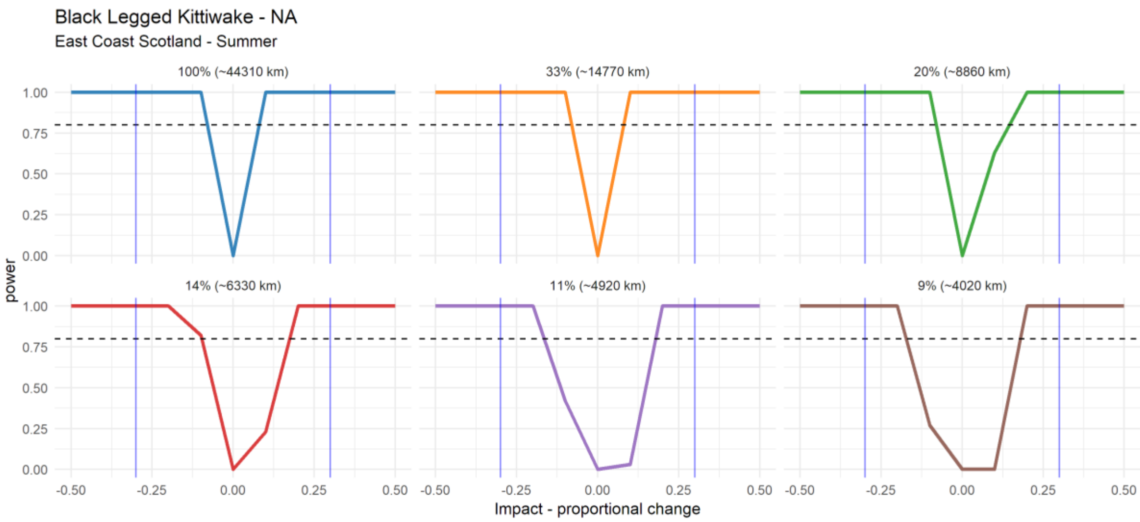


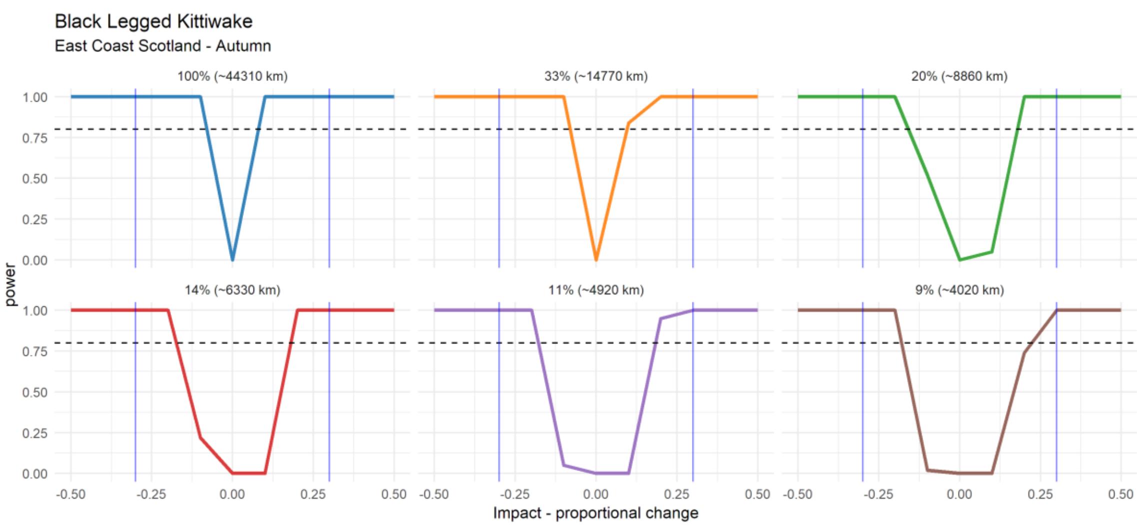




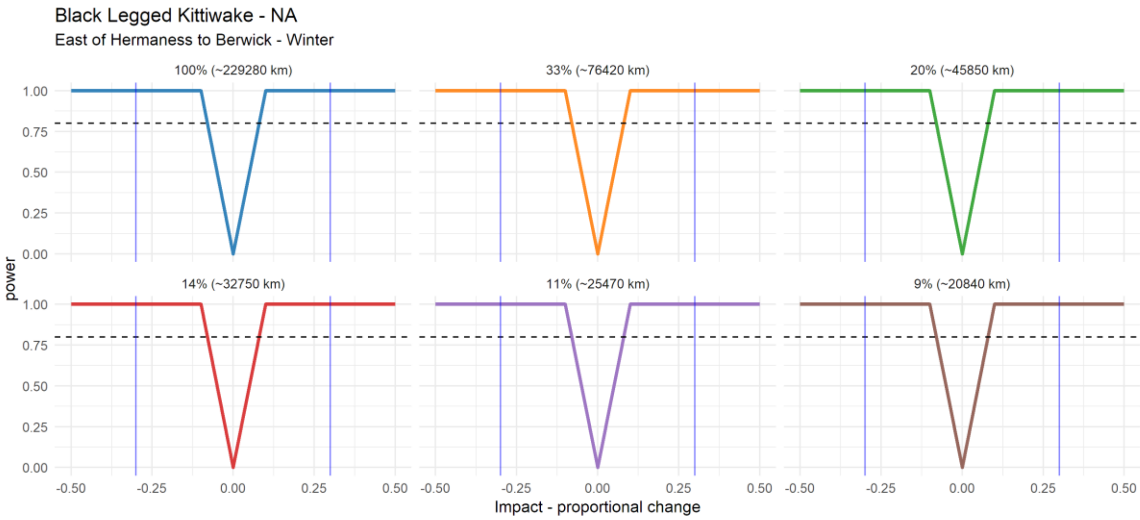
Power Plots – East Coast Scotland (Region 3) – seasonal black-legged kittiwake

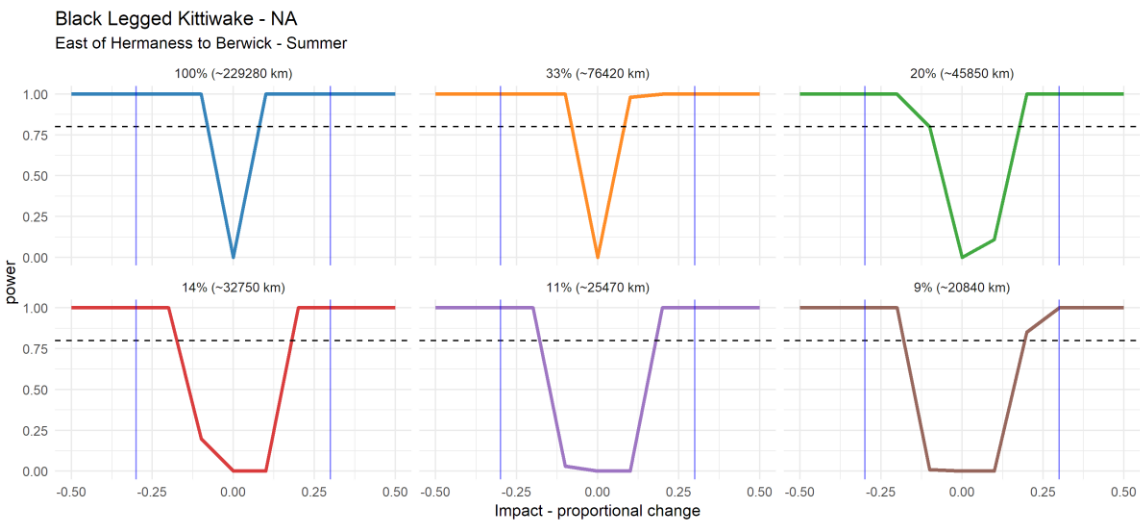


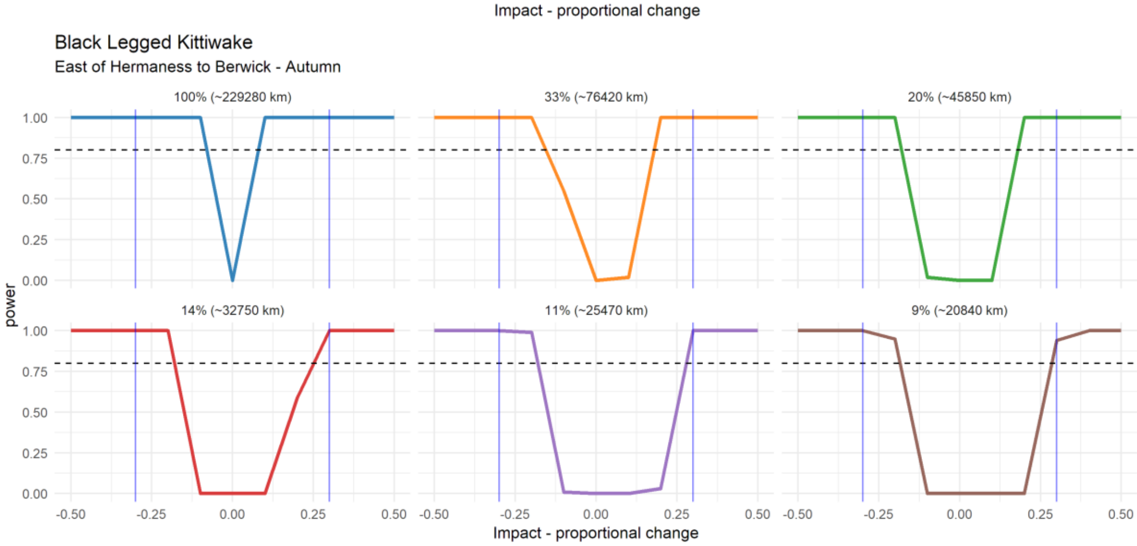




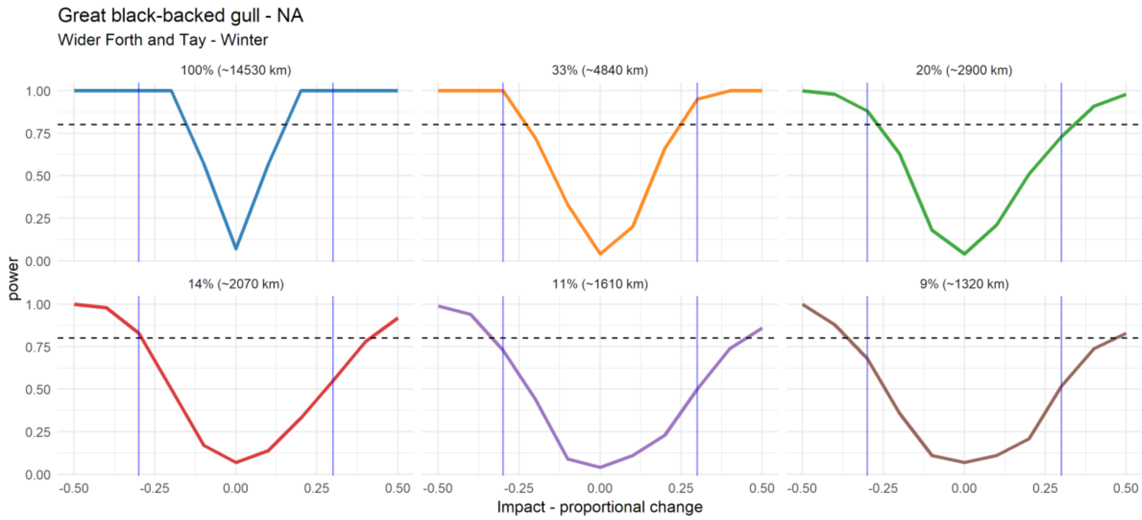
Power Plots – East of Hermaness to Berwick (Region 4) – seasonal black-legged kittiwake

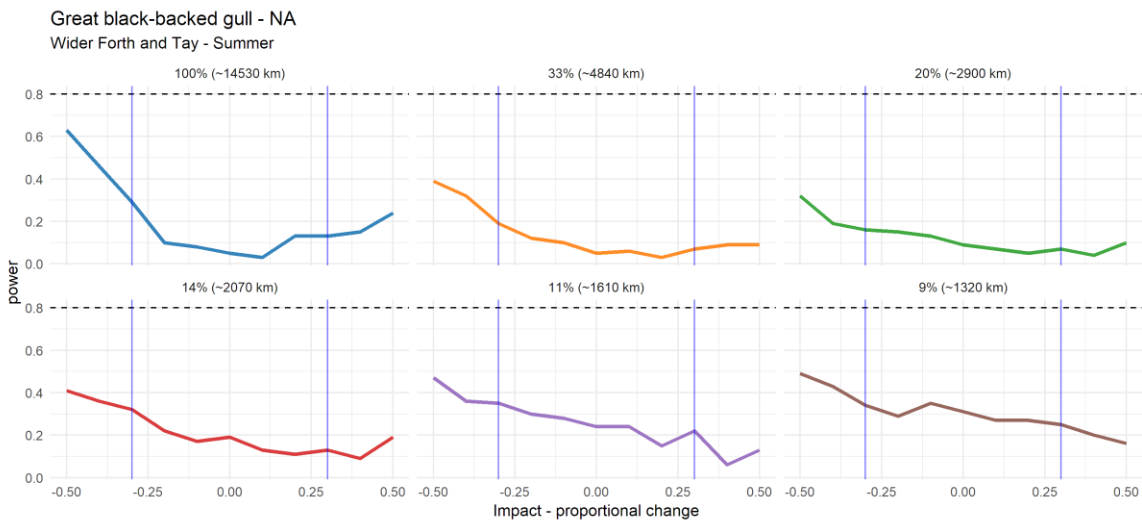


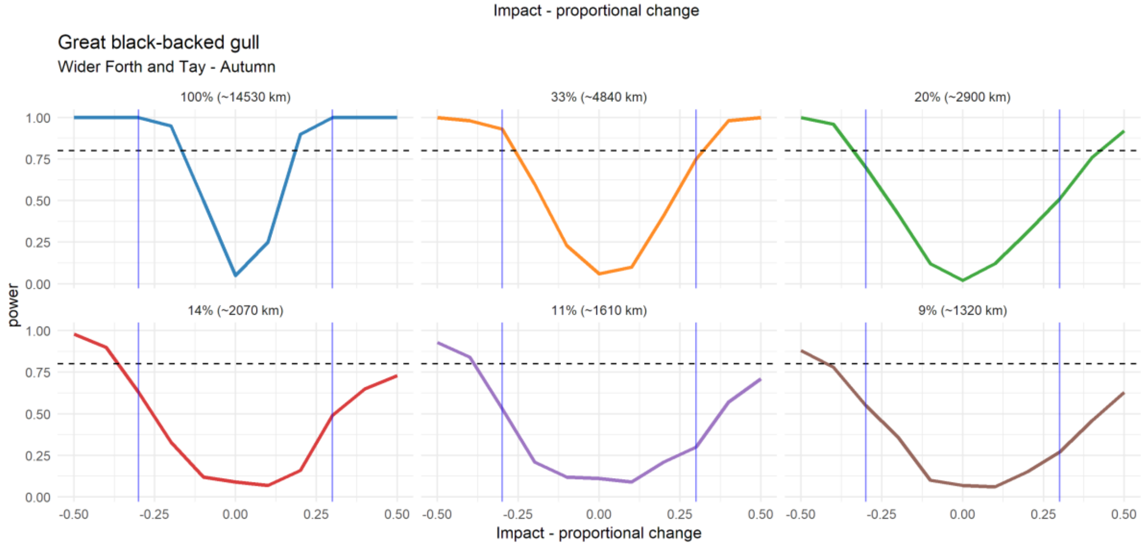




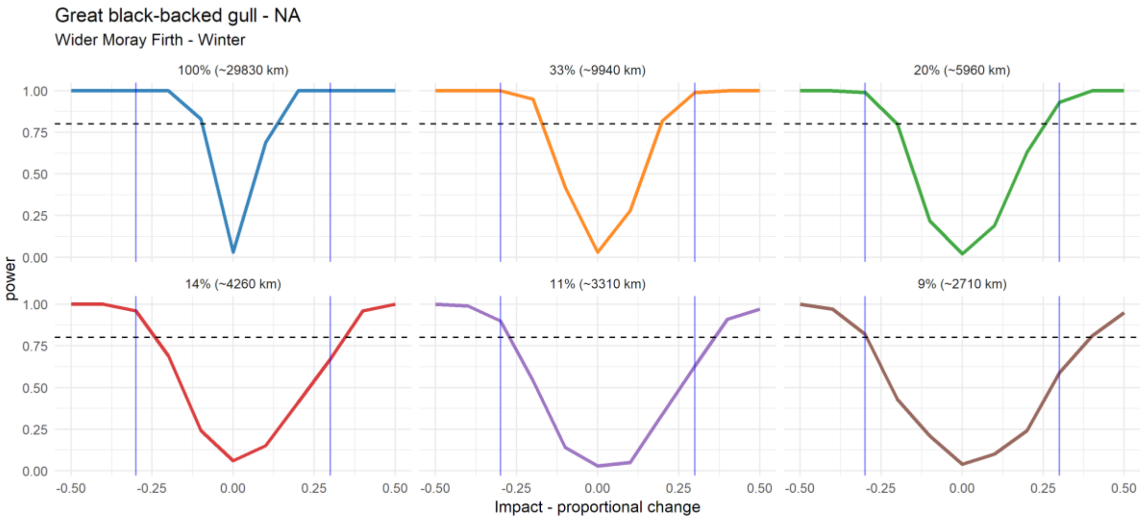
Power Plots – Wider Forth and Tay (Region 1) – seasonal great black-backed gull

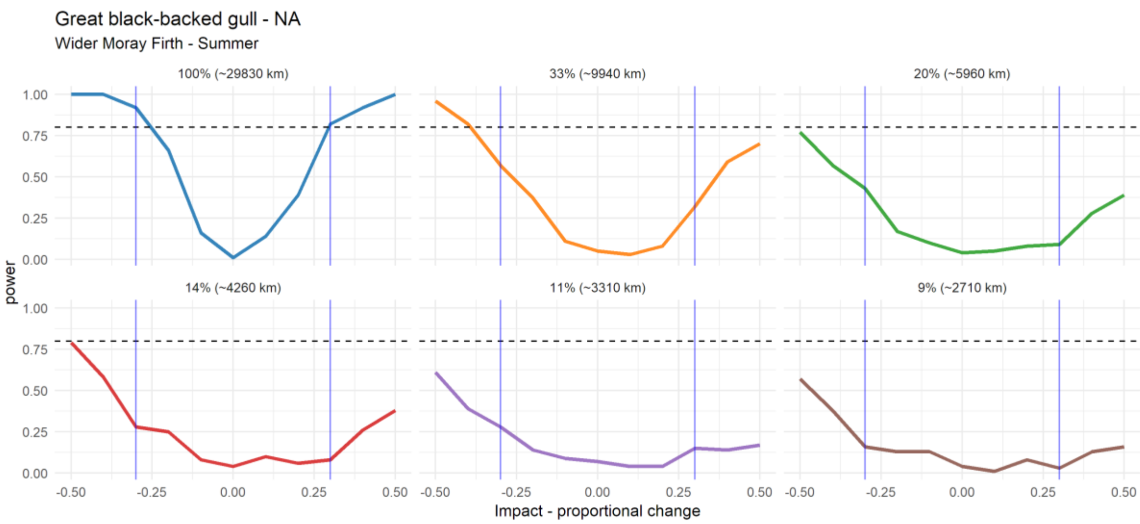


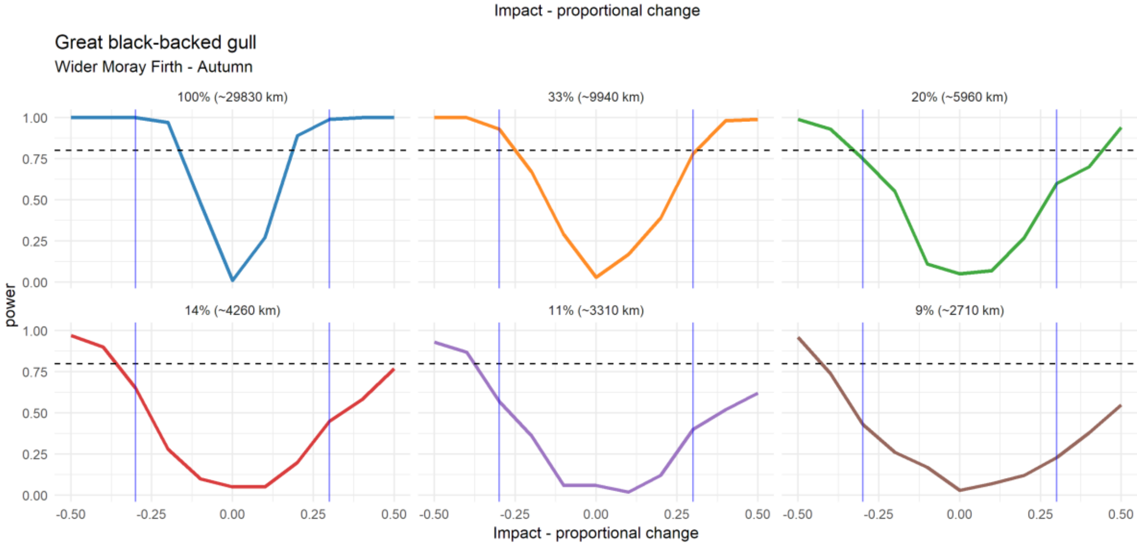




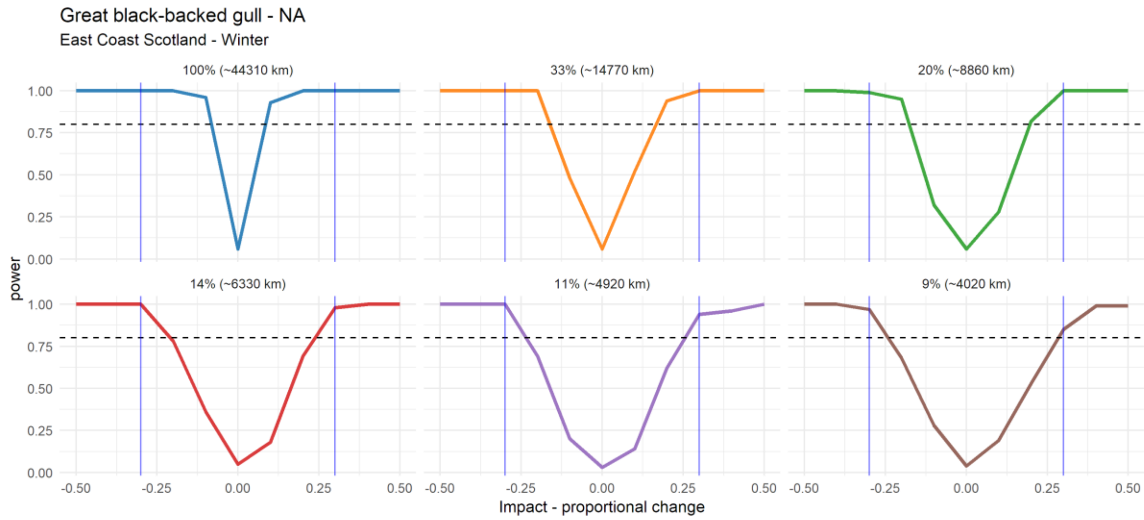
Power Plots – Wider Moray Firth (Region 2) – seasonal great black-backed gull

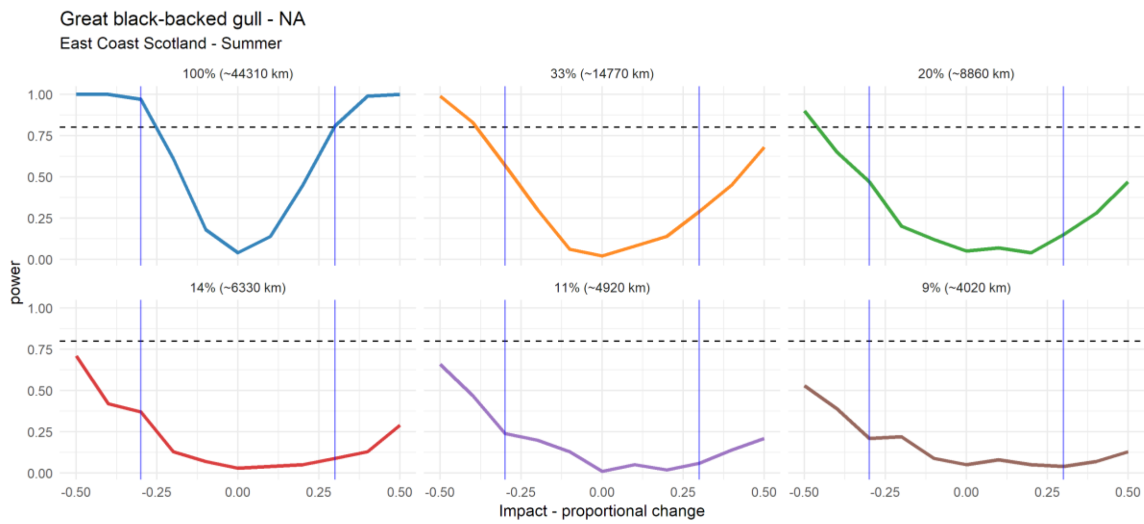


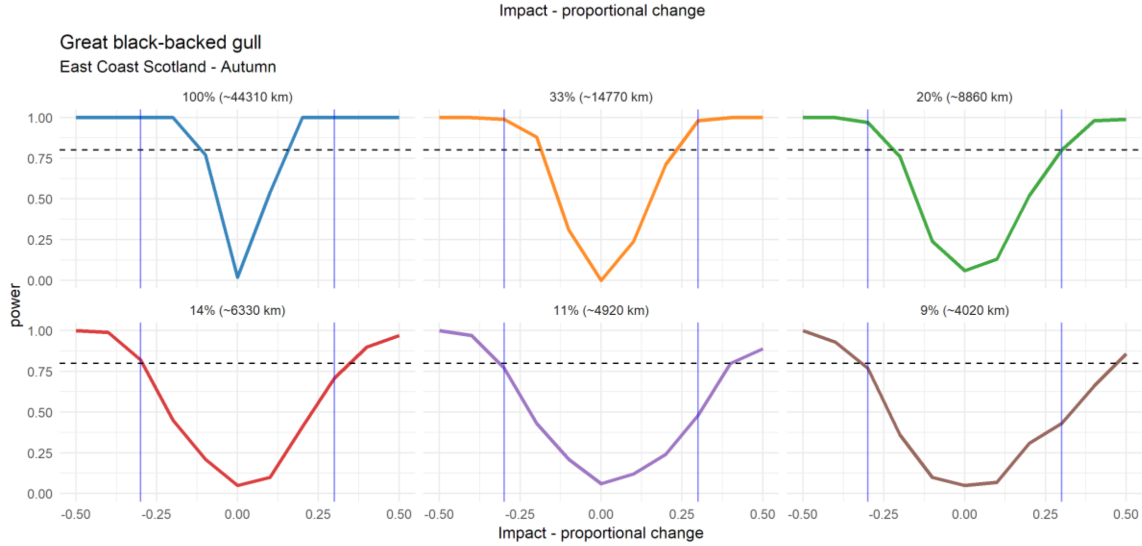




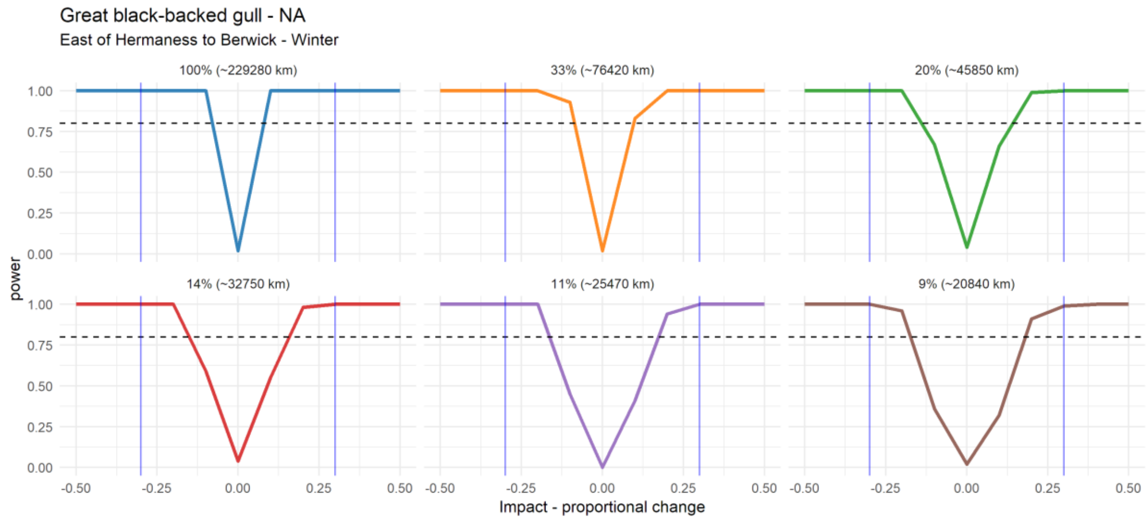
Power Plots – East Coast Scotland (Region 3) – seasonal great black-backed gull

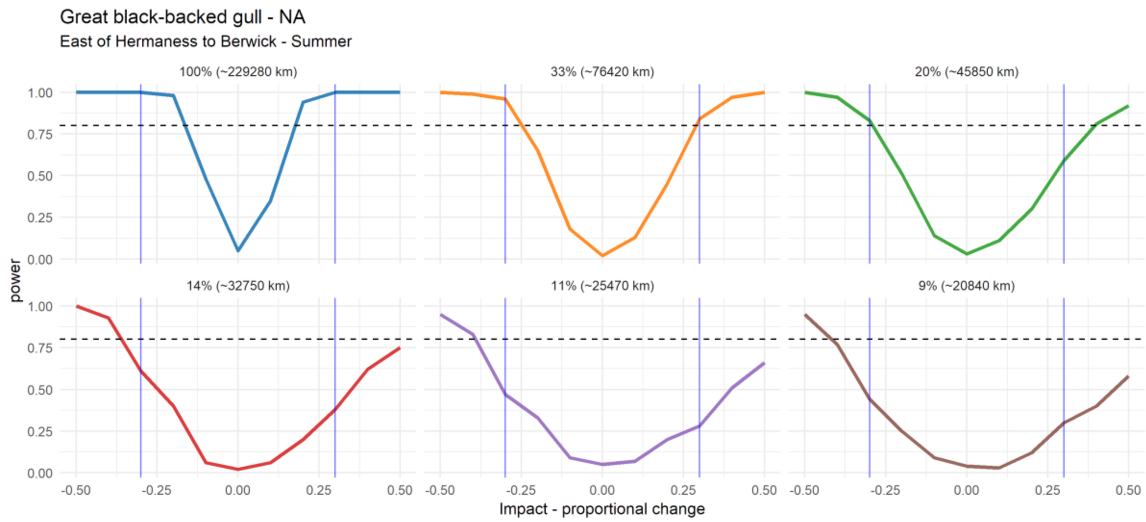


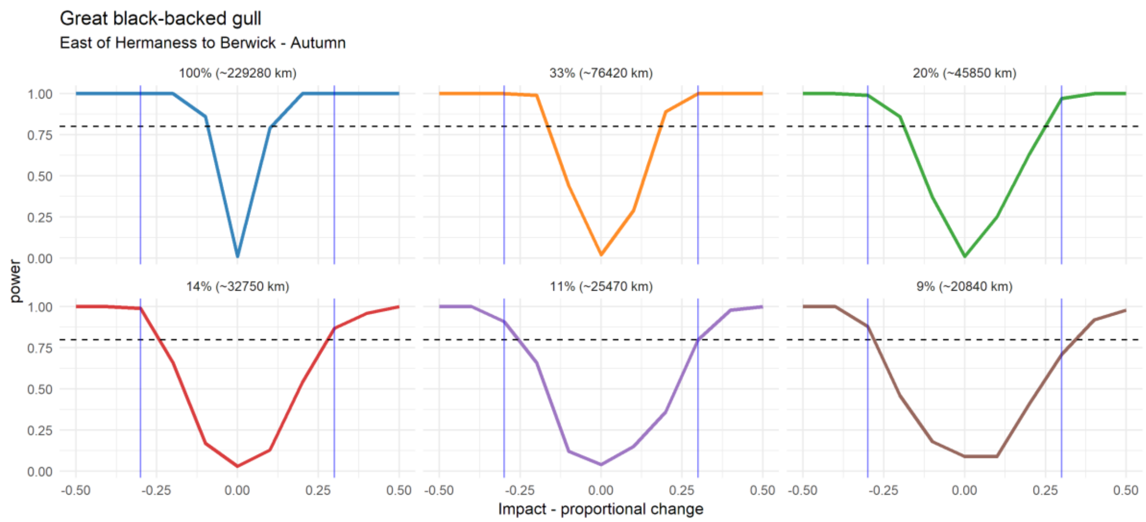




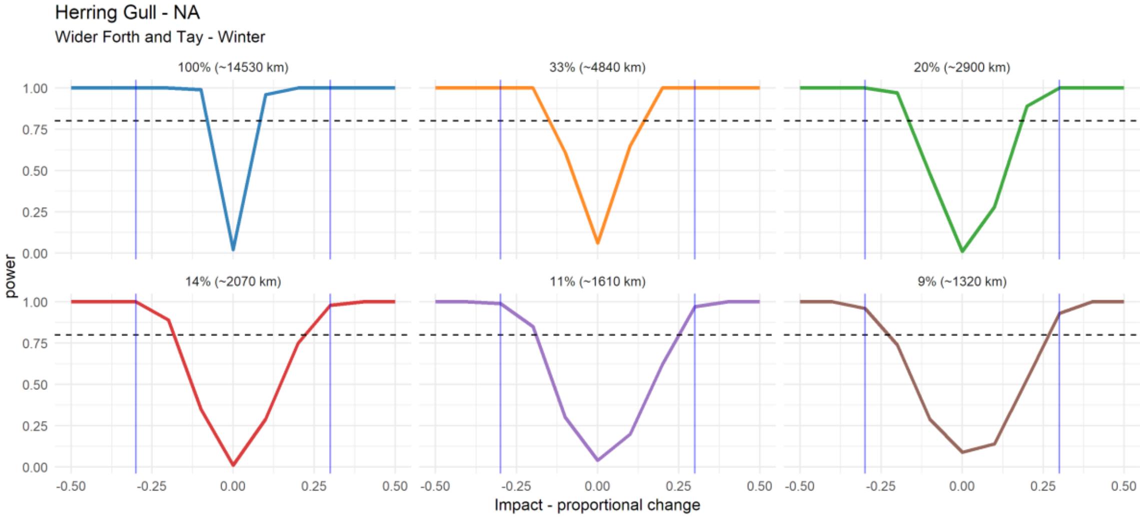
Power Plots – East of Hermaness to Berwick (Region 4) – seasonal great black-backed gull

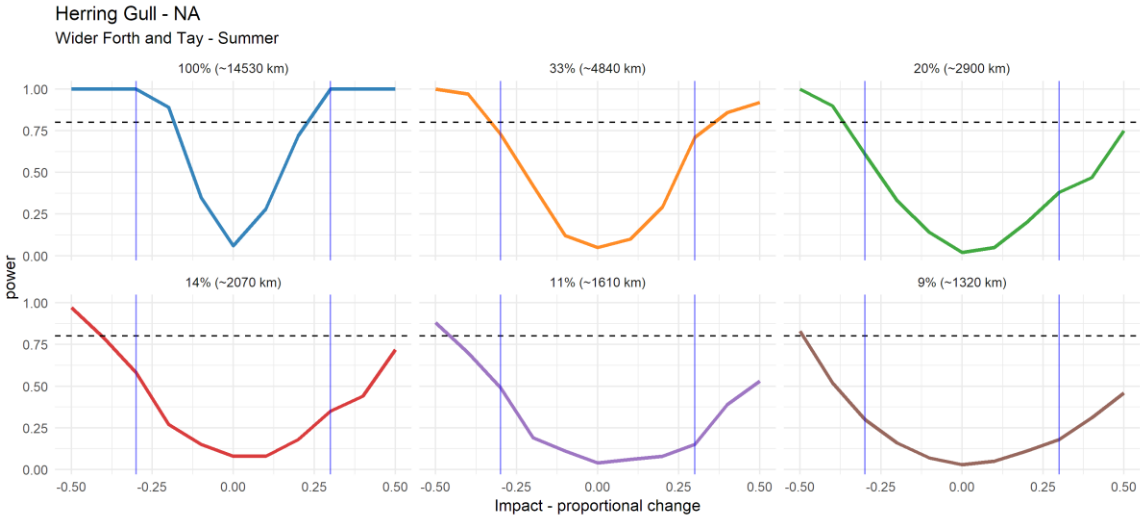


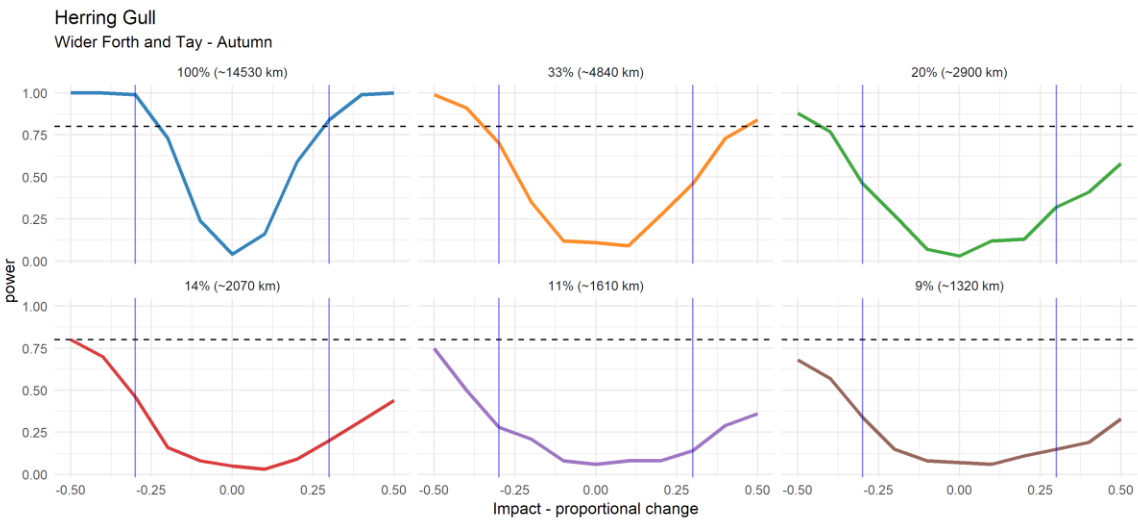




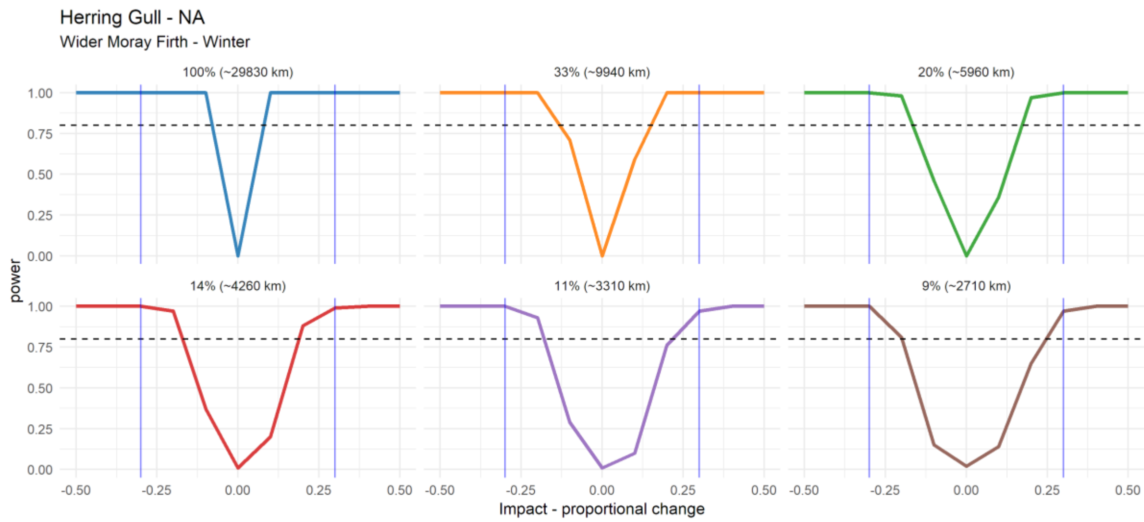
Power Plots – Wider Forth and Tay (Region 1) – seasonal herring gull

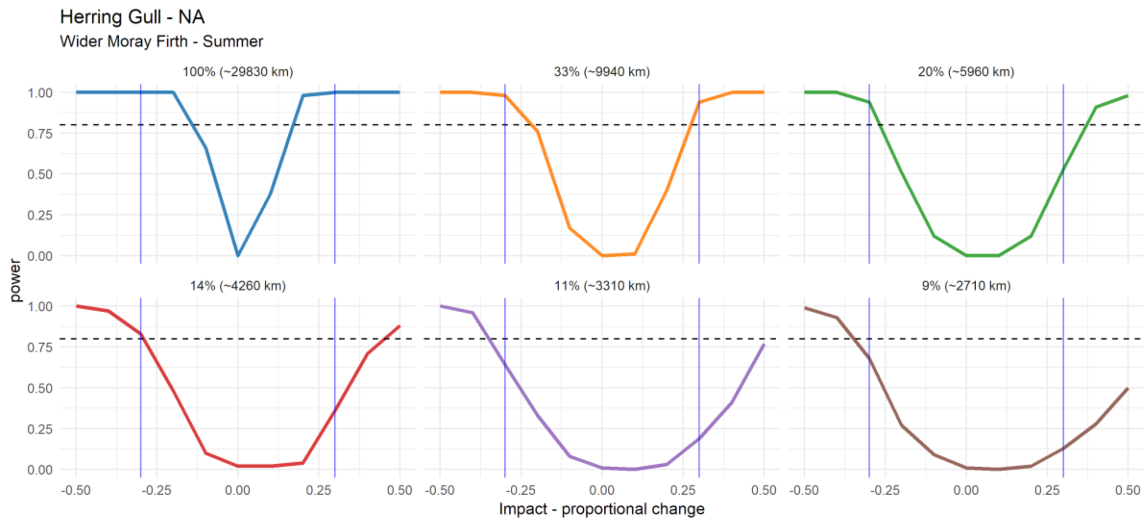


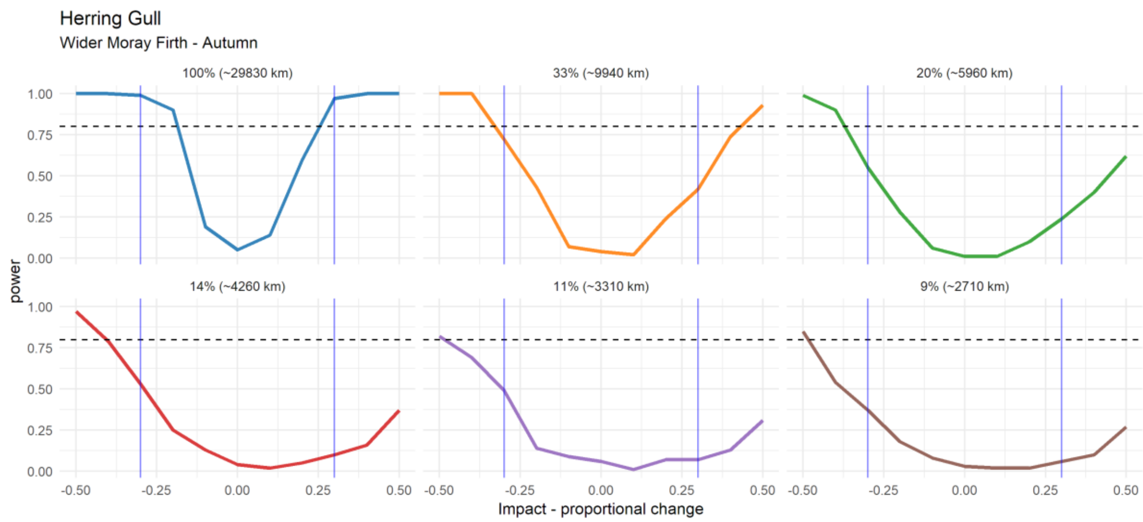




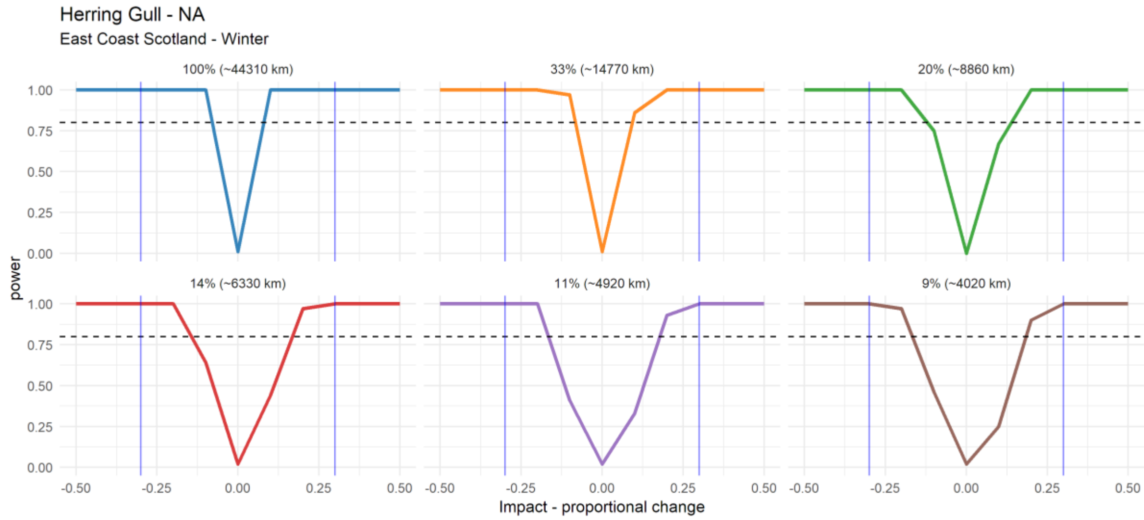
Power Plots – Wider Moray Firth (Region 2) – seasonal herring gull

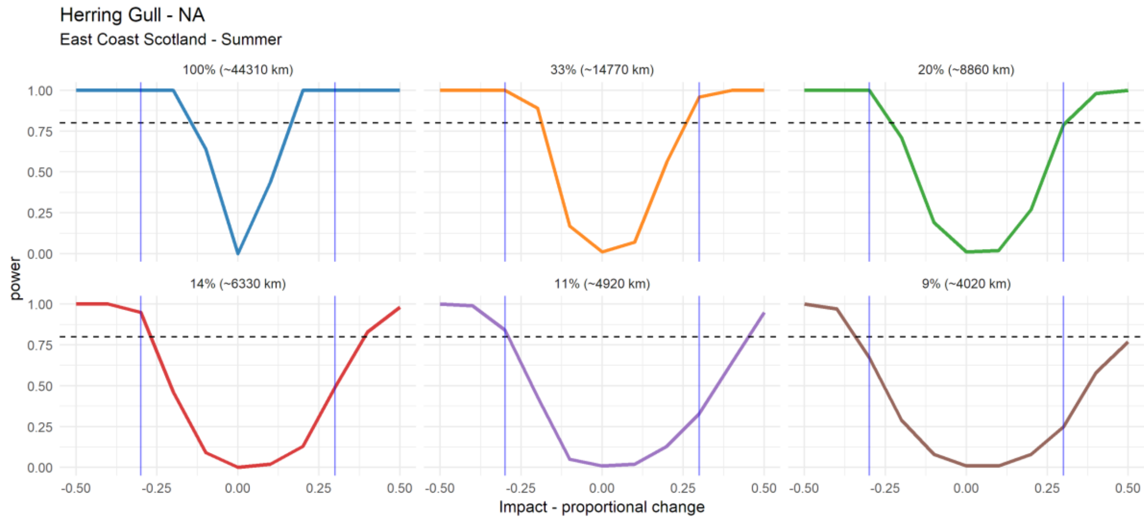


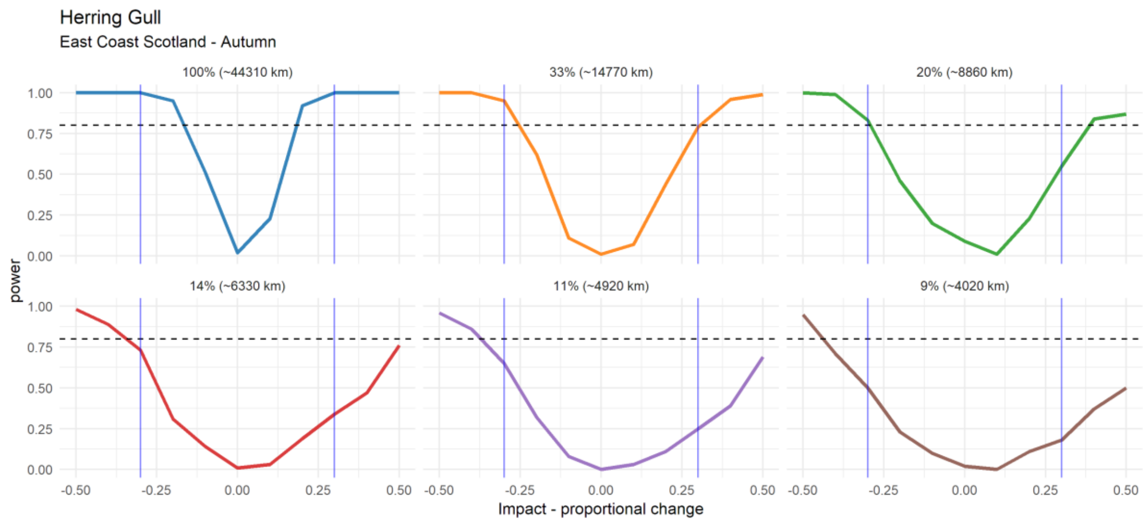




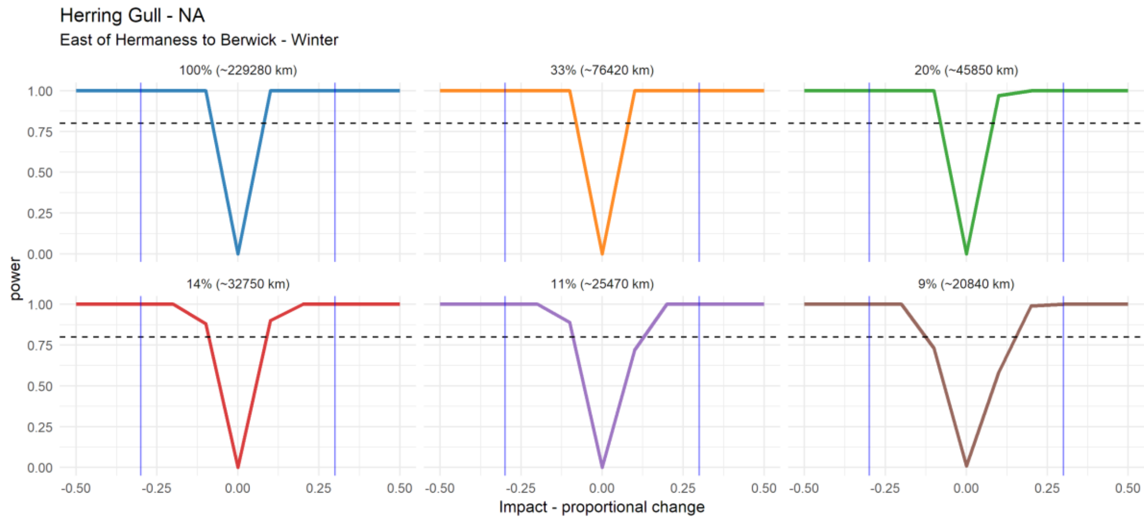
Power Plots – East Coast Scotland (Region 3) – seasonal herring gull

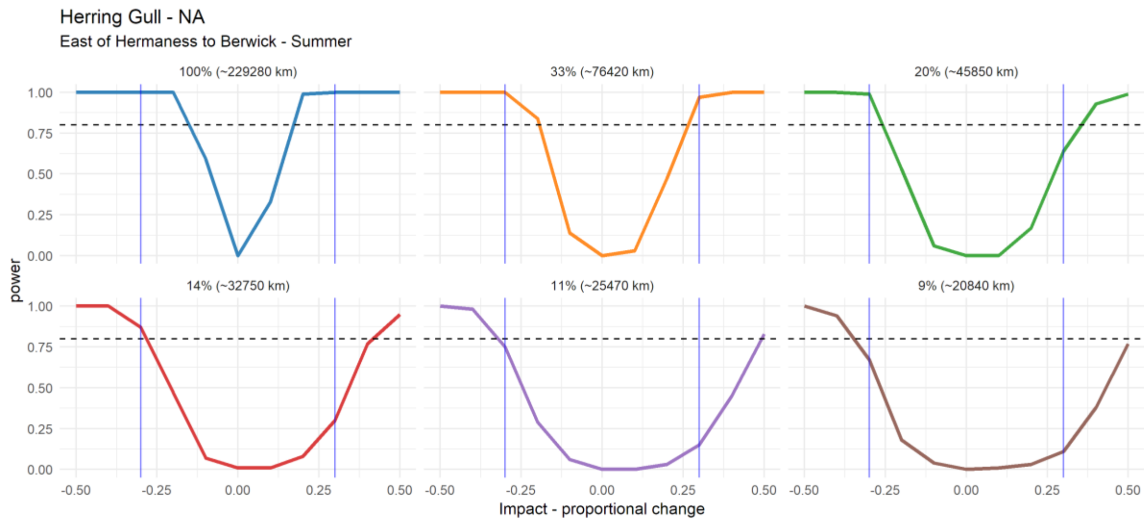


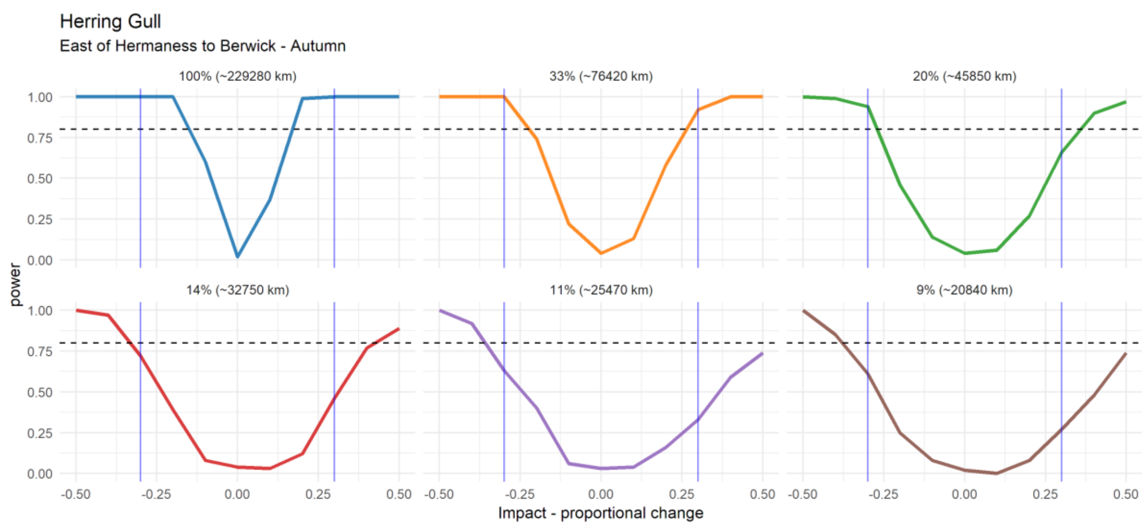




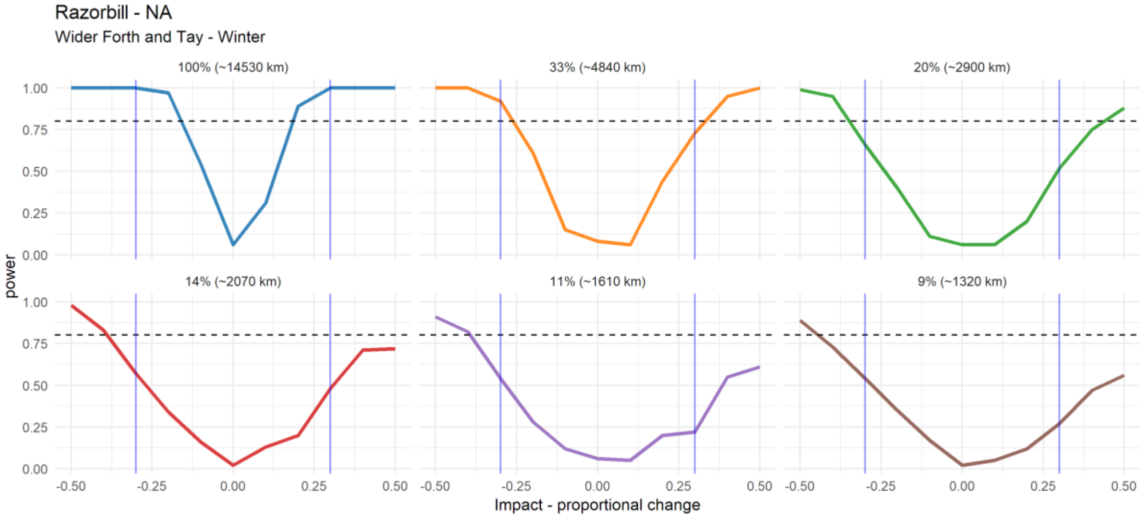
Power Plots – East of Hermaness to Berwick (Region 4) – seasonal herring gull

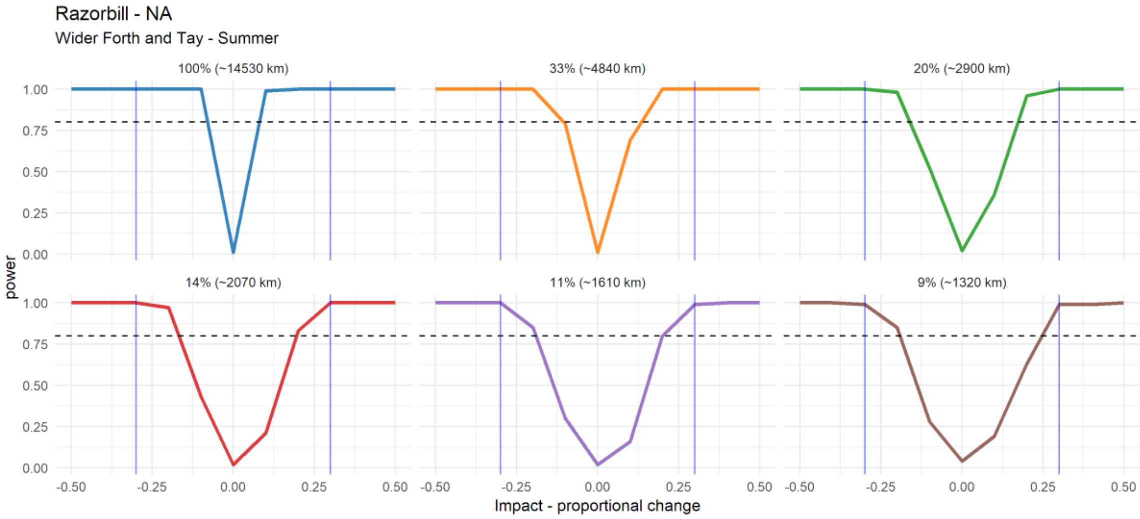


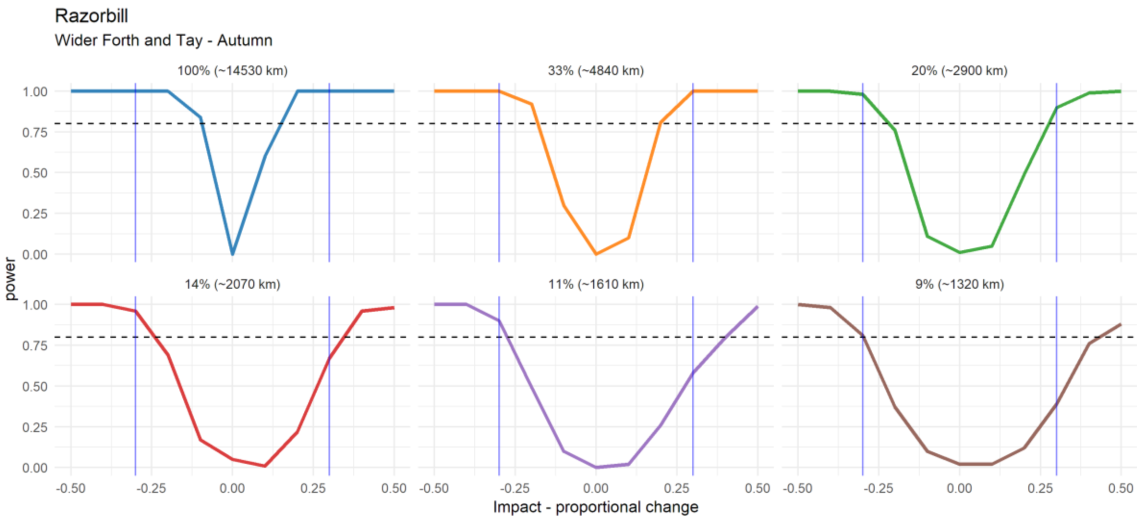




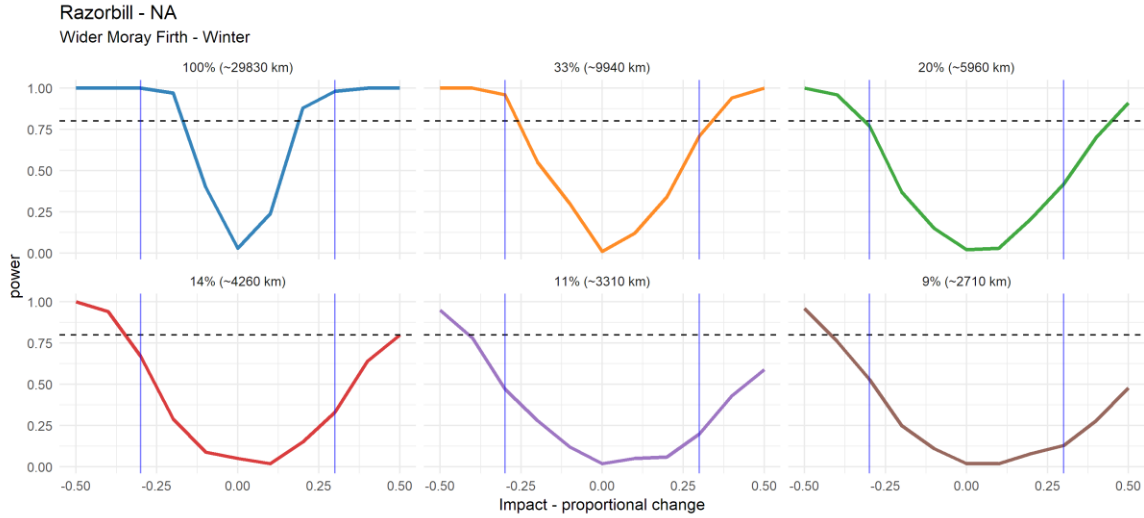
Power Plots – Wider Forth and Tay (Region 1) – seasonal razorbill

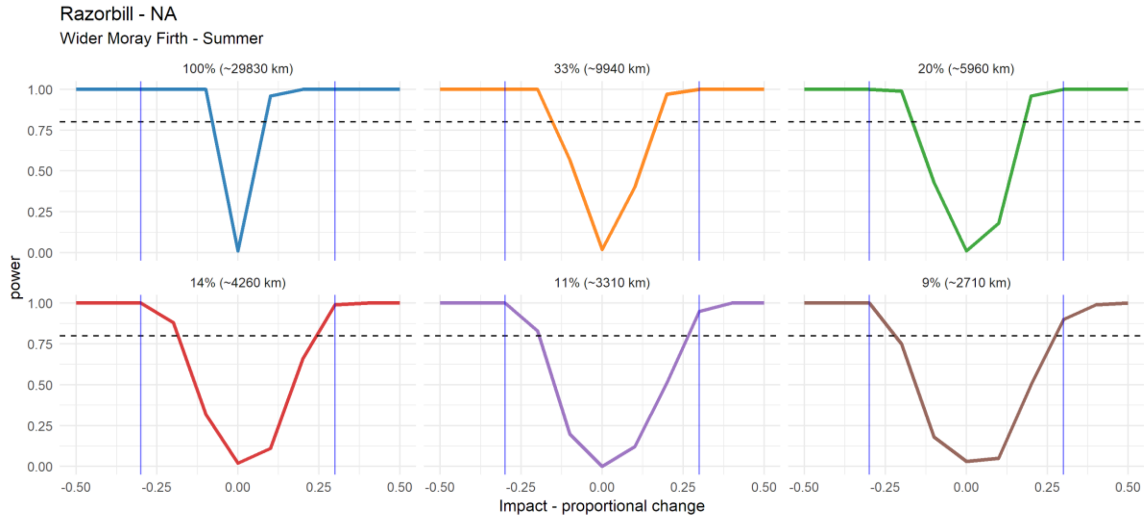


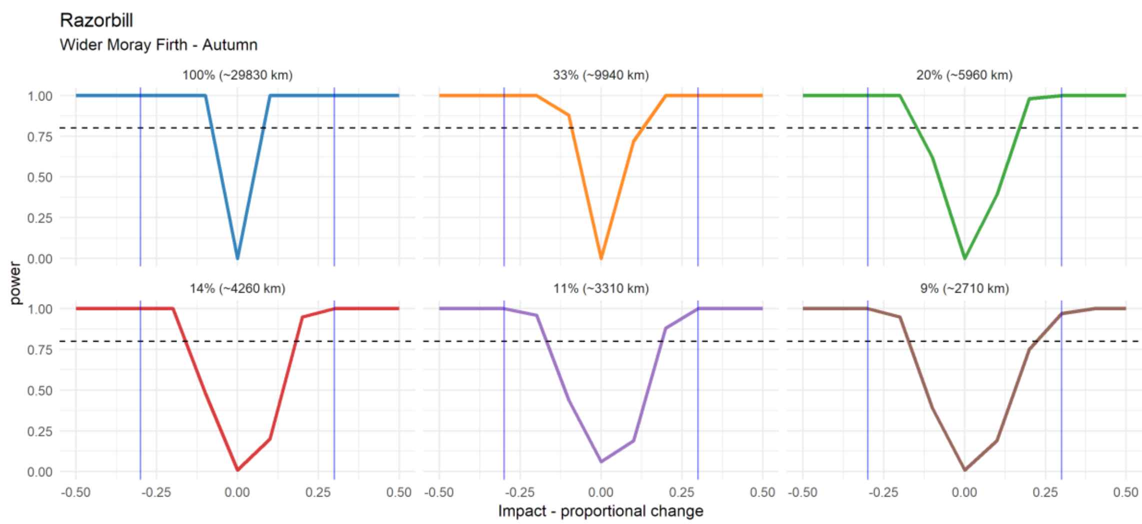




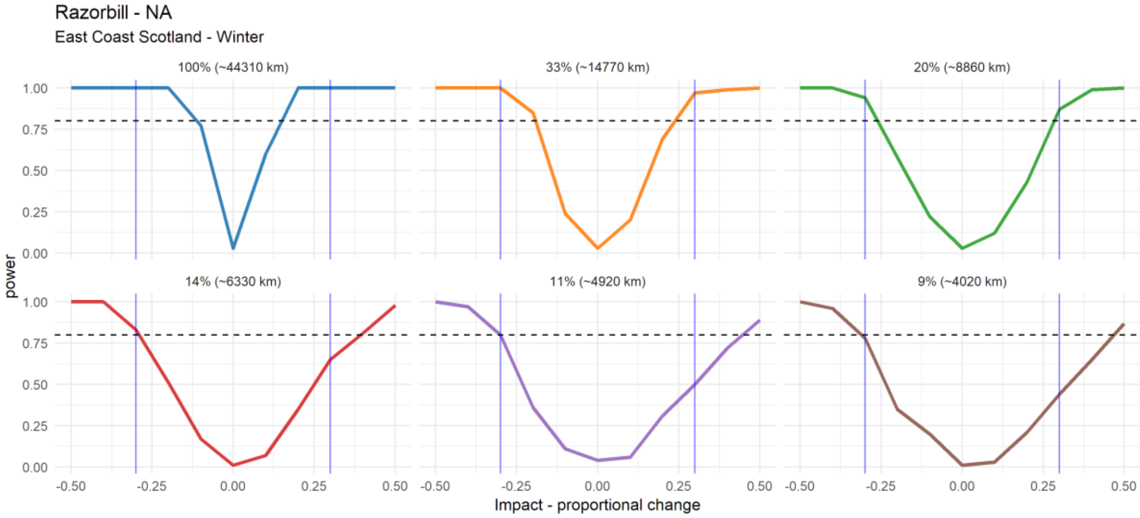
Power Plots – Wider Moray Firth (Region 2) – seasonal razorbill

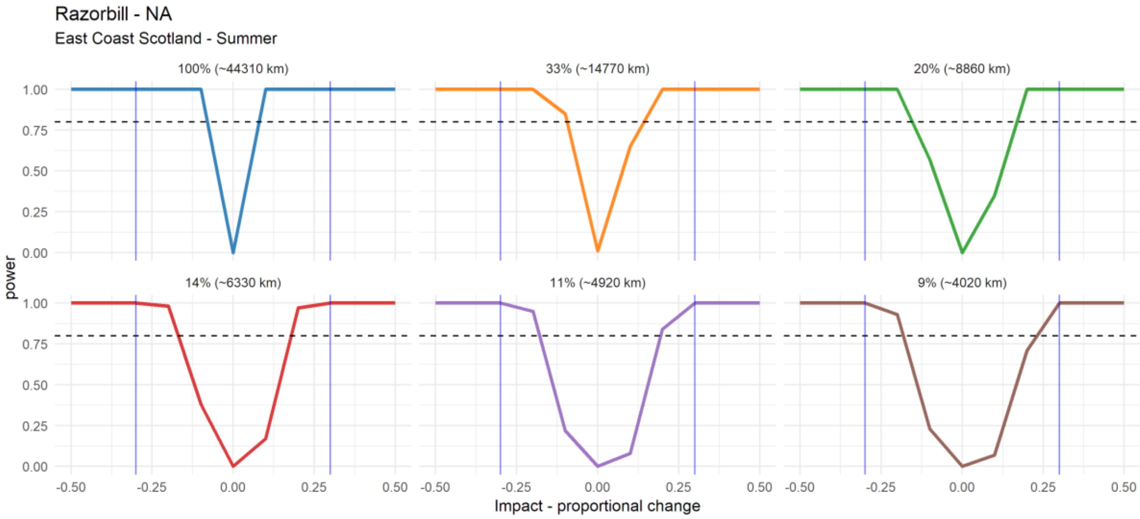


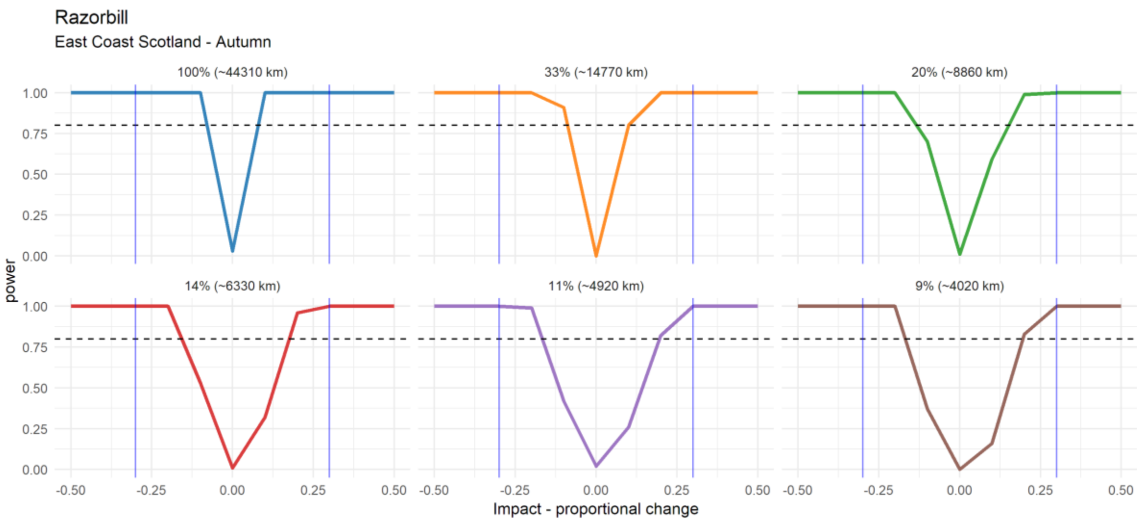




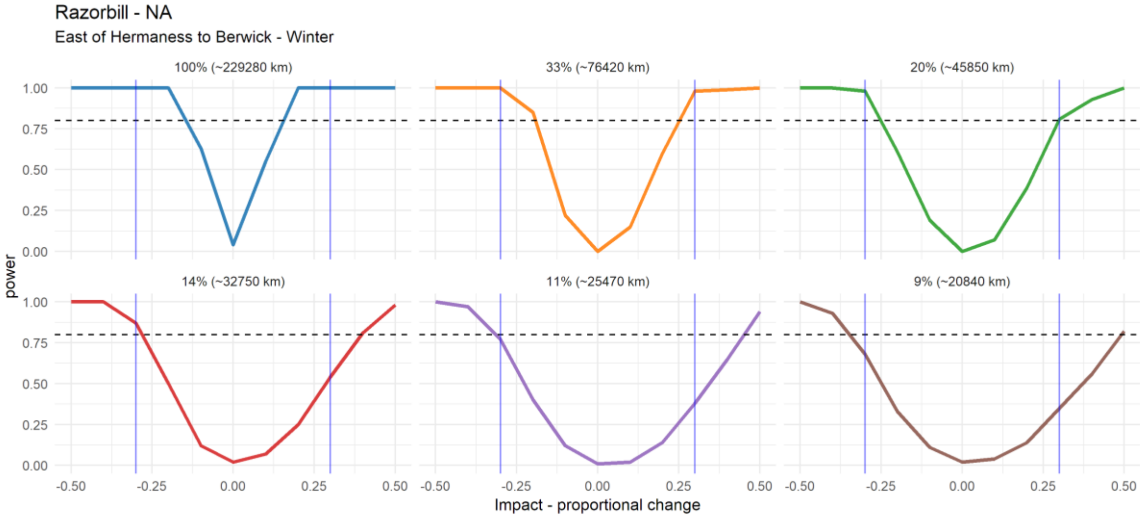
Power Plots – East Coast Scotland (Region 3) – seasonal razorbill

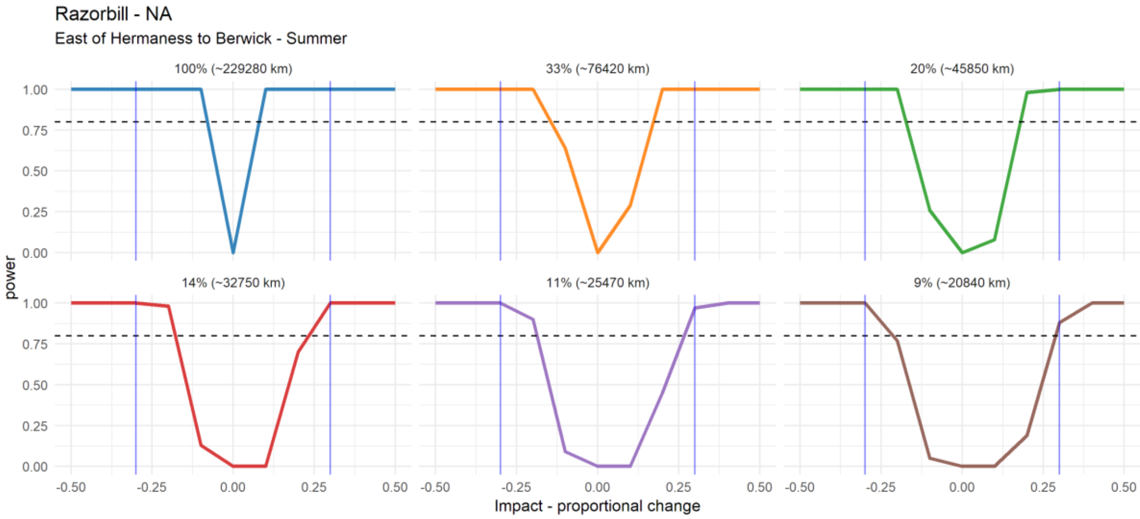


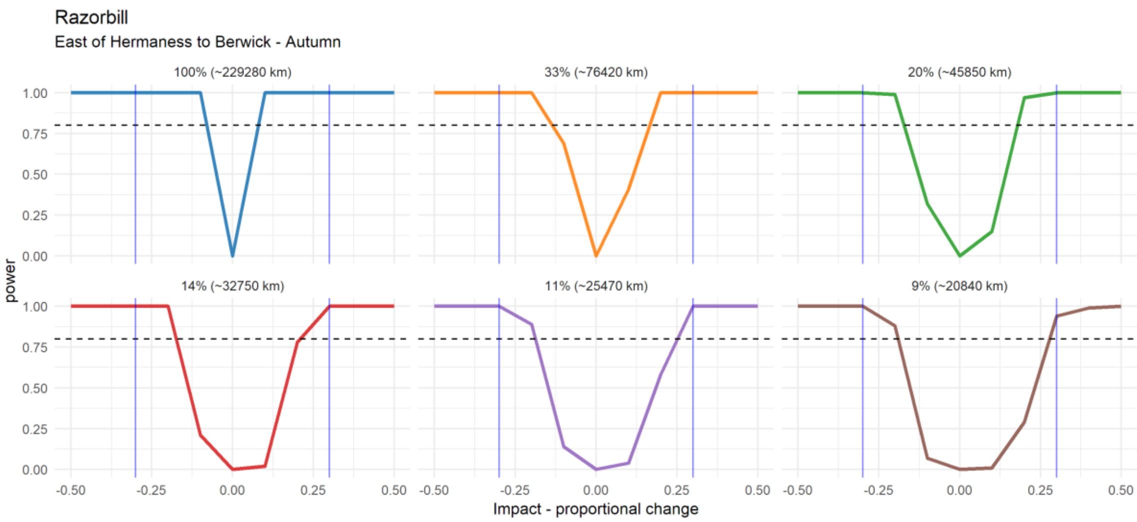




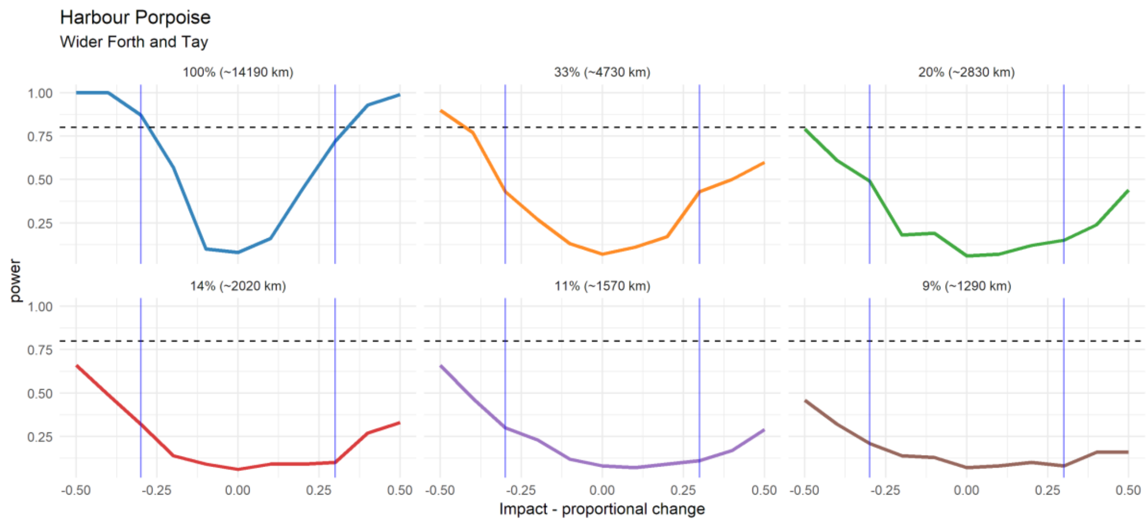
Power Plots – East of Hermaness to Berwick (Region 4) – seasonal razorbill



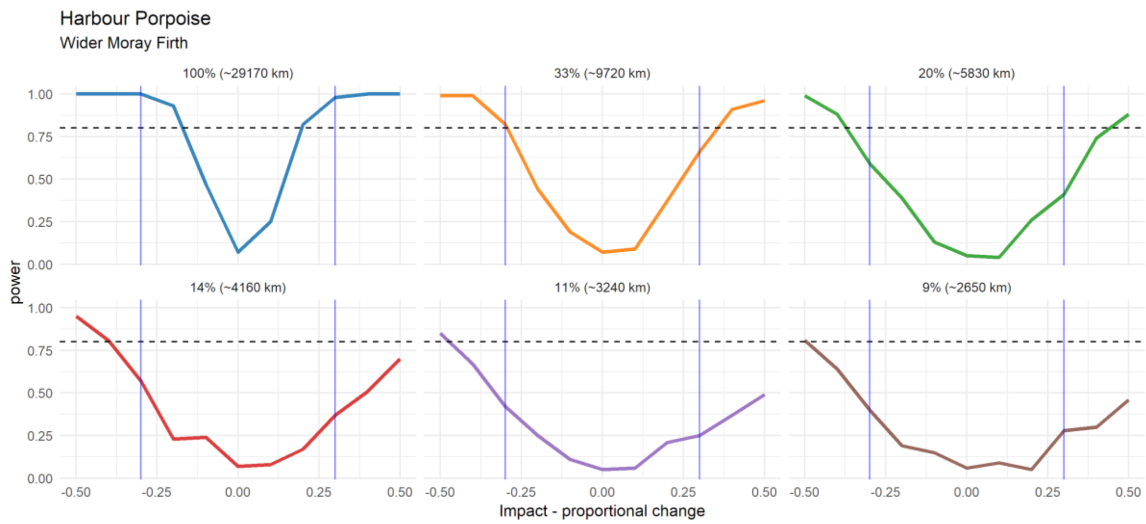




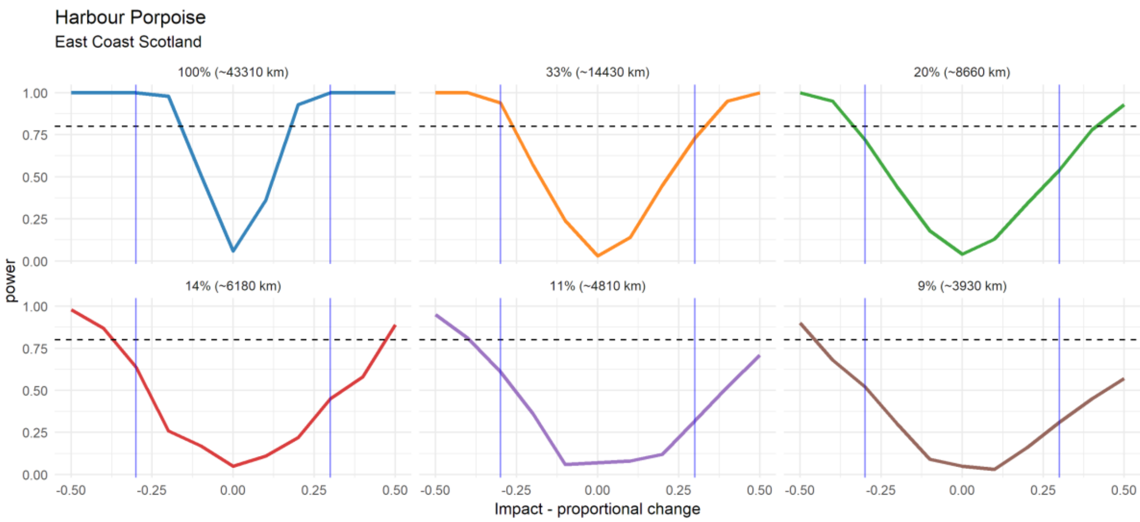
Power Plots – Wider Forth and Tay (Region 1) – harbour porpoise



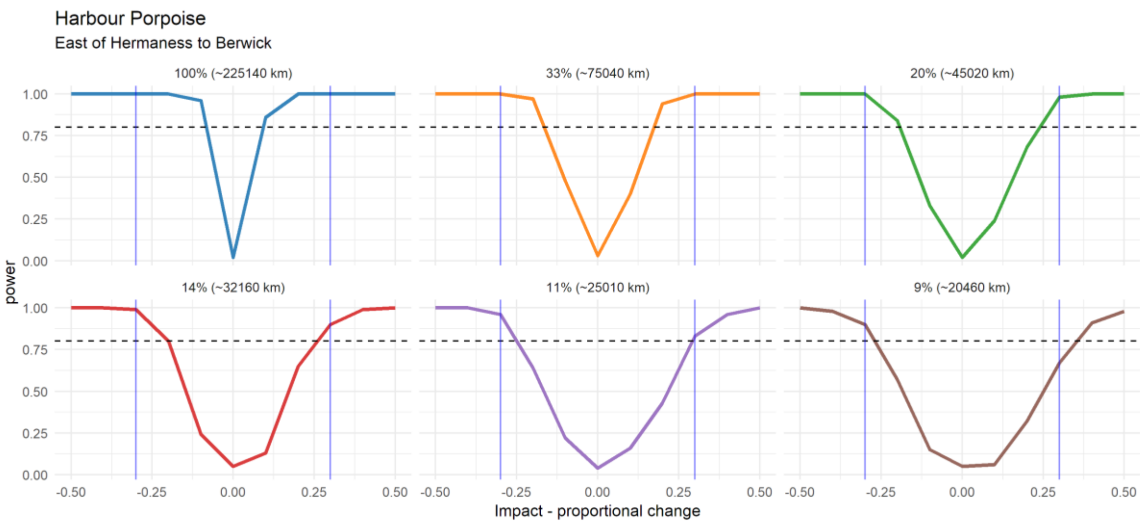
Power Plots – Wider Moray Firth (Region 2) – harbour porpoise



Power Plots – East Coast Scotland (Region 3) – harbour porpoise



Power Plots – East of Hermaness to Berwick (Region 4) – harbour porpoise



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