Update of distribution maps of harbour porpoises in the North Sea

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FINAL REPORT

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1. Task description

This project aimed to update density surface layers for harbour porpoises in the North Sea by enlarging an existing database from the period 2005-2013 (Gilles et al. 2016) with dedicated aerial survey data from 2014-2019.

2. Data sources and processing and model

Aerial line-transect survey data were successfully collected from participating countries/parties in Belgium (BE), the Netherlands (NL), Germany (GE) and Denmark (DK), as part of national monitoring programmes, as well as from the SCANS-III survey (see appendix for overview and maps of effort and sightings). Survey effort and sightings data were checked for errors and, in the case of the Belgium data only, were converted into the needed format to be imported into the common dataframe. All surveys followed the same field protocol and all, except for Belgium, used the same data collection software (Scheidat et al. 2008; Gilles et al. 2009, 2016; Hammond et al. 2013, 2017).

The model approach as detailed in Gilles et al. 2016 was closely followed, including the same candidate set of habitat variables or predictors, which are bathymetry and topography related predictors, closest distance to coast, distance to sandeel (*Ammodytes* spp.) fishing grounds and, as dynamic predictors, sea surface temperature (SST) and spatial and temporal standard deviation (SD) of SST (as proxies for fronts).

Below, only the main points of data processing and method are described (for full details we refer to Gilles et al. 2016):

1. Segments of searching effort were created from the raw data (i.e., 4 sec on the aerial surveys): Segments of effort (here, target length 10 km) with associated sightings were spatially referenced by linking the effort data files to the geographical positions.

2. Sighting-condition-specific estimates of effective strip width (esw) were linked to these segments based on the sighting conditions prevailing during that search period (could also differ between observer side depending on sighting conditions). These estimates of esw took account of detection probability less than 1 on the transect line (commonly known as g(0), referring to availability and perception bias), providing a correction for missed animals on the

transect within varying sighting conditions (see Hiby and Lovell 1998, Hiby 1999, Scheidat et al. 2008 for details).

3. The effective area searched in each short section of effort was calculated as esw (incl. g(0)) multiplied by the distance effectively travelled. The natural logarithm of the effective area searched (in km^2) was included as an offset in the models to account for both varying segment lengths and varying detection probabilities based on recorded sighting conditions during the survey day.

4. Predictors were linked to the midpoint of the segment.

5. These effort segments formed the sampling unit for the habitat-based density surface modelling.

3. Model framework, selection and prediction

Generalized additive models (GAMs) were fitted in R 3.5.3 (R Core Team 2019) using the package mgcv 1.8.-31 (Wood 2011). The number of porpoise groups encountered per segment was defined as the response variable. Restricted maximum likelihood (REML) with automatic term selection (Marra & Wood 2011) was used for smoothing parameter estimation. The negative binomial distribution was ultimately selected for the final models. Model selection for best model was done as in Gilles et al. (2016), where (1) candidate predictors to include in the model were identified using goodness of fit criteria (e.g. AIC) and (2) a final model was selected from the candidate models based on predictive performance (cross-validation across years). Predictions were made on a spatial grid holding static and dynamic covariates at a resolution of 5 × 5 km, limiting the grid to an area of about 406,451 km^2 that included all covered transects to avoid predicting outside of the range of covariates used in model fitting. Harbour porpoise group densities were predicted on a daily basis for each survey period in each year resulting in 521 daily predictions for the summer periods. We subsequently averaged daily group densities within summer and multiplied by the mean observed group size in summer (see Table 1) to estimate densities (Ind./km^2).

4. Results

A total of 112 survey (effort) days conducted from March to October within the study period 2014-2019 were included in this study. We aggregated 80,221 km of on-effort survey data with 5758 sightings of harbour porpoise groups (see details in Appendix, Table A1).

Since by far lower survey effort has been conducted in spring and autumn (Fig. A6) in the recent period, and then only in Belgium and partly in the German EEZ, we decided to concentrate on preparing an updated porpoise density surface layer for summer, representing the latest survey period, i.e. from 2014-2019.

For summer, a total effective search effort of 56,915 km could be aggregated, leading to 3882 harbour porpoise sightings (Table 1). From this, a total of 5644 effort segments, with a median segment length of 10.1 km, were included in the modelling.

Table 1: Summary of 2014–2019 aerial survey data, collected in summer, used for model development in the North Sea study area: effective survey effort (km in good or moderate conditions) as well as number of sightings of harbour porpoise (hp) groups and individuals (ind.) mean group size are shown.

source	season	effort (km)	hp sightings/groups	hp ind.	mean group size	SD group size	years
BE	summer	3955	268	360	1.34	0.46	2014-2019
DK		6026	450	576	1.28	0.51	2014-2019
GE		17,747	1303	1604	1.23	0.43	2014-2019
NL		13,872	922	1424	1.54	0.76	2014-2019
SCANSIII		15,315	939	1234	1.31	0.53	2016
sum		**56,915**	**3882**	**5198**	1.34	0.57	2014-2019

Model selection

The first step of model selection yielded a total of four candidate models (Table 2). These models either included an isotropic bivariate function of spatial location (x and y) or a three-dimensional tensor product and either distance to coast or depth or both. During the second step of model selection, model 3 was selected as the "best" model because it had the best model diagnostics and goodness of fit measures; as shown by the lowest AIC and the highest explained deviance.

This best model explained 13.5% of the deviance using a negative binomial error distribution and a three-dimensional tensor product smooth of location and SST, a smooth of distance to sandeel grounds, average water depth, distance to coast, SST-SD-Space20 and SST-SD-Time (ordered according to decreasing Chi-square scores; Fig. 1).

Table 2: Candidate models fitted to the full suite of survey data, using the no. porpoise sightings as response variable, and associated goodness of fit measures. Theta = value of adjustment parameter identified from the negative binomial distribution. Offset = log(effective area searched in km^2). REML, Restricted maximum likelihood; AIC, Akaike's information criterion; %Dev, percentage of deviance explained by the model.

Model	Theta	Model formula	REML	AIC (Δ AIC)	% Dev.
1	0.71	s(x, y) + offset(log(Effort_km2))	6186.2	12313.16 (268.1)	6.55
2	0.66	te(avg_depth_m, coastdist_km, k = 5) + offset(log(Effort_km2))	6209	12380.85 (335.79)	4.64
3	0.85	te(x, y, mursst.mean) + s(mursst.SDtime) + s(mursst.SDspace20) + s(avg_depth_m) + s(coastdist_km) + s(dist2fish_km) + offset(log(Effort_km2))	6090.6	12045.06 (0)	13.49
4	0.84	te(x, y, mursst.mean) + s(mursst.SDtime) + s(mursst.SDspace20) + te(avg_depth_m, coastdist_km, k = 5) + s(dist2fish_km) + offset(log(Effort_km2))	6089.2	12059.26 (14.2)	13.01
5	0.71	s(mursst.mean) + s(mursst.SDtime) + s(mursst.SDspace20) + s(avg_depth_m) + offset(log(Effort_km2))	6174.4	12291.12 (246.06)	6.84

Model No. 3 revealed that the tensor product smooth of location and SST proved to be an important predictor. Densities generally increased with SST-SD-Time, that means with a higher probability for SST-fronts, also seen in the predictor SST-SD-Space (SST spatial gradient/variability). Furthermore, harbour porpoise densities increased, and decreased with distance to sandeel grounds (Fig. 1).

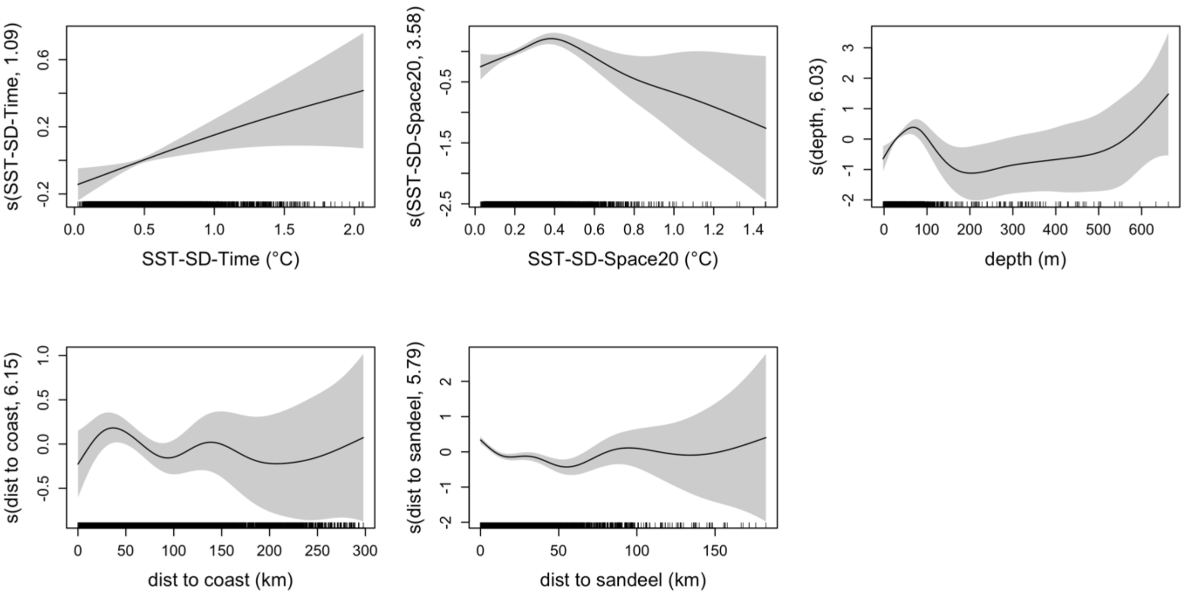

Figure 1: Functional plots of environmental variables relative to harbour porpoise density as indicated by the estimated smooth functions for the selected covariates in the best model. Plots of 1-dim smooths are shown, whereas the 3-dim tensor product smooth of location and SST (te(x, y, SST)) cannot be displayed. Estimated degrees of freedom (edf) for nonlinear fits are provided in parentheses on the y-axes. Hatch marks on the x-axes show sample values and range of samples. The shaded areas (2× standard error bands) denote the 95% Bayesian confidence intervals (CI). For interpretation, please note that some CIs tend to be very large at the higher edges of the observed covariate values, where sampling was limited.

For summer, the prediction showed a hotspot of high porpoise density in the south and south-western part of the study area (Fig. 2). In comparison to the summer density surface from the previous period (Gilles et al. 2016), the hotspot off the northern German coast (SAC Sylt Outer Reef) and off the coast of Jutland in Denmark seems to be lower in intensity. The overall model-based abundance estimate of 384,864 individuals (CV=0.08) seems reasonable and is similar to the previous estimate from Gilles et al. (2016) for the period 2005-2013 (361,146; CV=0.20) and the design-based estimate from SCANS-III (2016) for the ICES assessment unit ‘North Sea’ (345,373; CV=0.18; Hammond et al. 2017).

Since the addition of the recent survey data in spring and autumn did not result in a major change of the predicted density surface, probably due to low and restricted effort, we advise to use the product layers from Gilles et al. (2016) for spring and autumn, respectively.

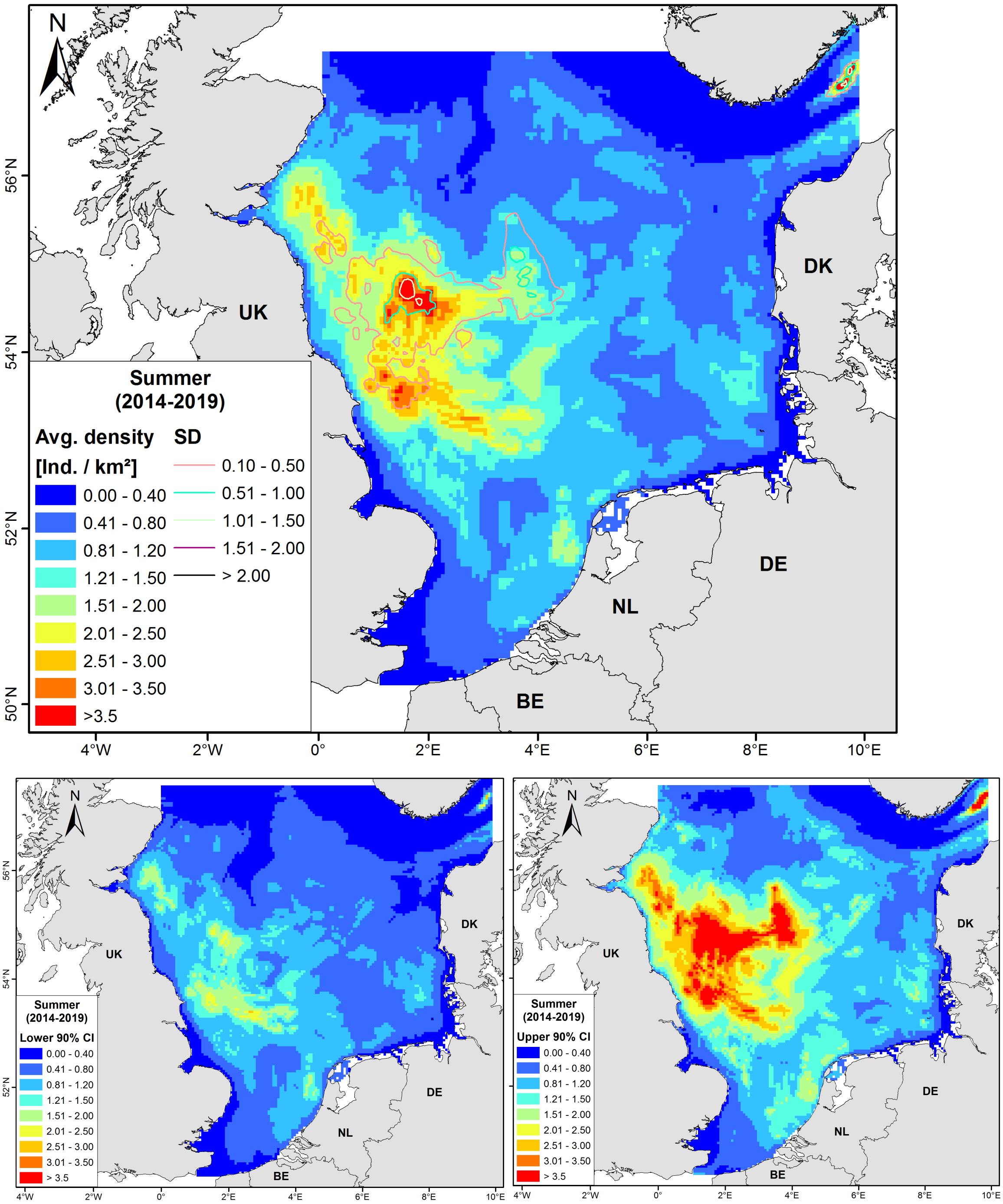

Figure 2: Predicted harbour porpoise densities in the North Sea in summer (Mar.–May) in the period 2014-2019. Upper panel: The overlaid contours are associated jackknife standard deviations (SD). Lower panel, left and right: Lower and upper lognormal 90% confidence intervals (Lower 90% CI and Upper 90% CI) for the seasonal density based on the jackknife samples.

5. Acknowledgments

Besides survey data collected during the German national monitoring programme for marine vertebrates (funded by Federal Agency for Nature Conservation BfN), data from the following contributors were collated: Steve Geelhoed, Meike Scheidat (Wageningen Marine Research), Signe Sveegaard (Department of Bioscience, Aarhus University) and Jan Haelters (Royal Belgian Institute of Natural Sciences), as well as Philipp Hammond and Claire Lacey (Sea Mammal Research Unit, University St Andrews) for the SCANS-III survey data. We thank all funding agencies responsible for the national monitoring programmes. We thank Rijkswaterstaat NL for funding this task and especially Niels Kinneging for project commission.

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7. Appendix

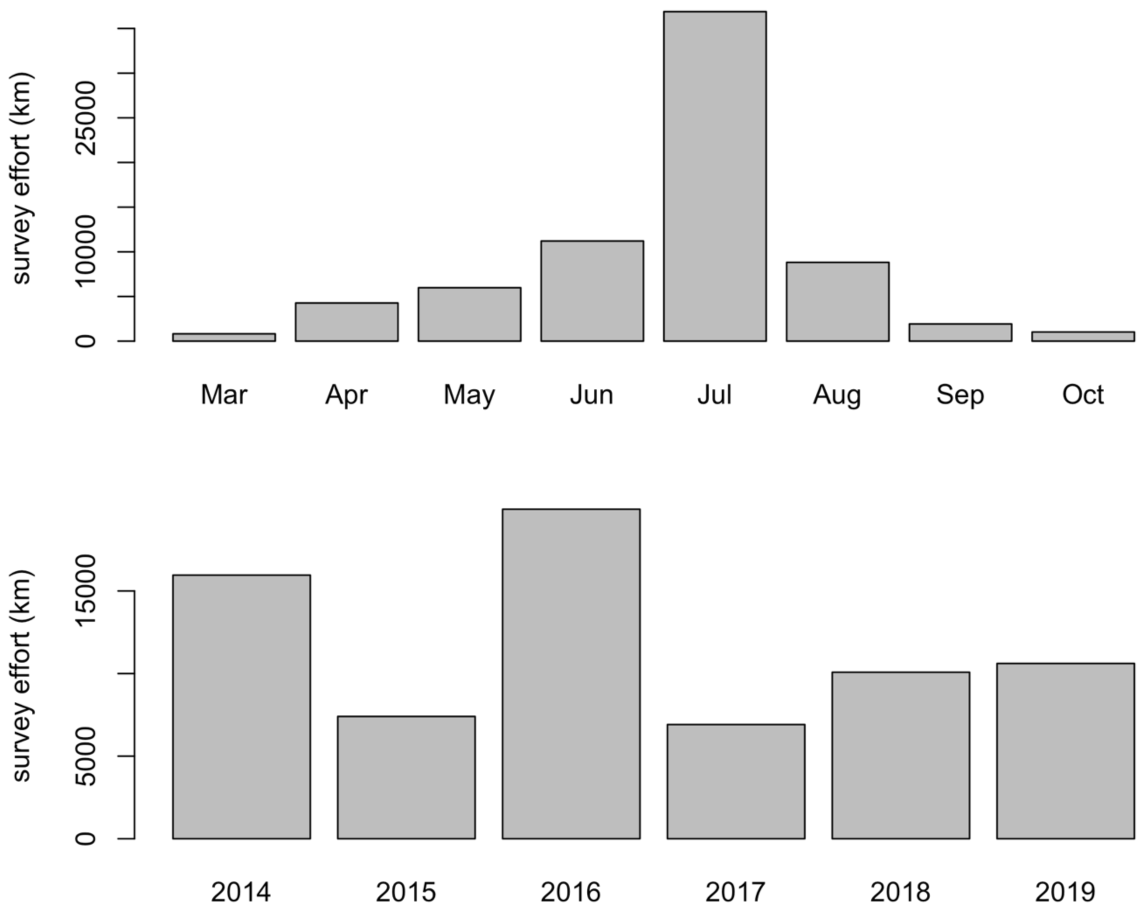

Figure A1. Overview of available monthly (top) and yearly (bottom) aerial survey data in the period 2014-2019 in the North Sea study area, displayed as effective survey effort (km), conducted under good or moderate sighting conditions (see Gilles et al. 2009, 2016 for definition of subjective sighting conditions).

Table A1. Overview of available yearly, monthly effort data as well as harbour porpoise (hp) number of sightings, individuals (ind.) and calves in the period 2014-2019; stratified by source. Only effort conducted under good or moderate conditions is shown. Please note that the no. of calves is included in the number of individuals.

year	month	source	effort (km)	hp sightings	hp ind.	calves
2014	3	GE	813.73	37	42	0
	4	BE	668.34	304	331	0
	4	GE	1236.01	64	68	0
	5	GE	1823.67	219	239	0
	6	GE	3547.14	308	364	22
	7	DK	832.43	112	132	10
	7	GE	2761.17	224	291	28
	7	NL	2820.22	127	148	10
	9	BE	1318.49	46	60	4

year	month	source	effort (km)	hp sightings	hp ind.	calves
	10	BE	139.69	2	4	0
2015	5	GE	606.92	17	19	1
	6	GE	728.99	28	33	1
	7	GE	442.48	18	19	1
	7	NL	2592.79	136	165	12
	8	DK	831.78	22	26	1
	8	GE	2199.08	165	194	12
2016	4	BE	705.06	99	104	0
	5	GE	973.50	114	129	0
	6	BE	644.55	47	69	8
	6	SCANSIII	3870.62	204	260	11
	7	GE	2315.24	137	172	11
	7	SCANSIII	20,741.41	954	1283	75
2017	5	GE	559.40	20	25	2
	6	BE	707.56	85	116	21
	7	NL	3005.56	209	293	21
	8	BE	683.70	33	41	2
	8	DK	1353.16	66	106	13
	9	BE	604.75	17	21	1
2018	4	BE	708.16	372	404	0
	5	GE	1458.97	168	186	0
	6	GE	1368.32	123	149	11
	7	BE	580.16	32	41	5
	7	DK	759.89	31	47	3
	7	GE	708.88	55	64	4
	7	NL	2876.35	310	509	58
	8	DK	736.70	34	41	2
	10	BE	883.24	33	56	2
2019	4	GE	950.93	48	54	0
	5	GE	558.38	97	118	7
	6	BE	698.05	39	52	6
	7	DK	736.28	66	83	5
	7	GE	2894.52	206	273	12
	7	NL	1760.17	109	271	10
	8	BE	640.83	32	41	6
	8	DK	775.92	119	141	6
	8	GE	780.83	39	45	0
	8	NL	817.13	31	38	2
sum			**80,221.18**	**5758**	**7367**	**406**

*note that SCANS-III survey blocks outside the North Sea area (S, T, U & V) were not included in modelling but listed in full in table A1 and shown below in the maps of survey coverage.

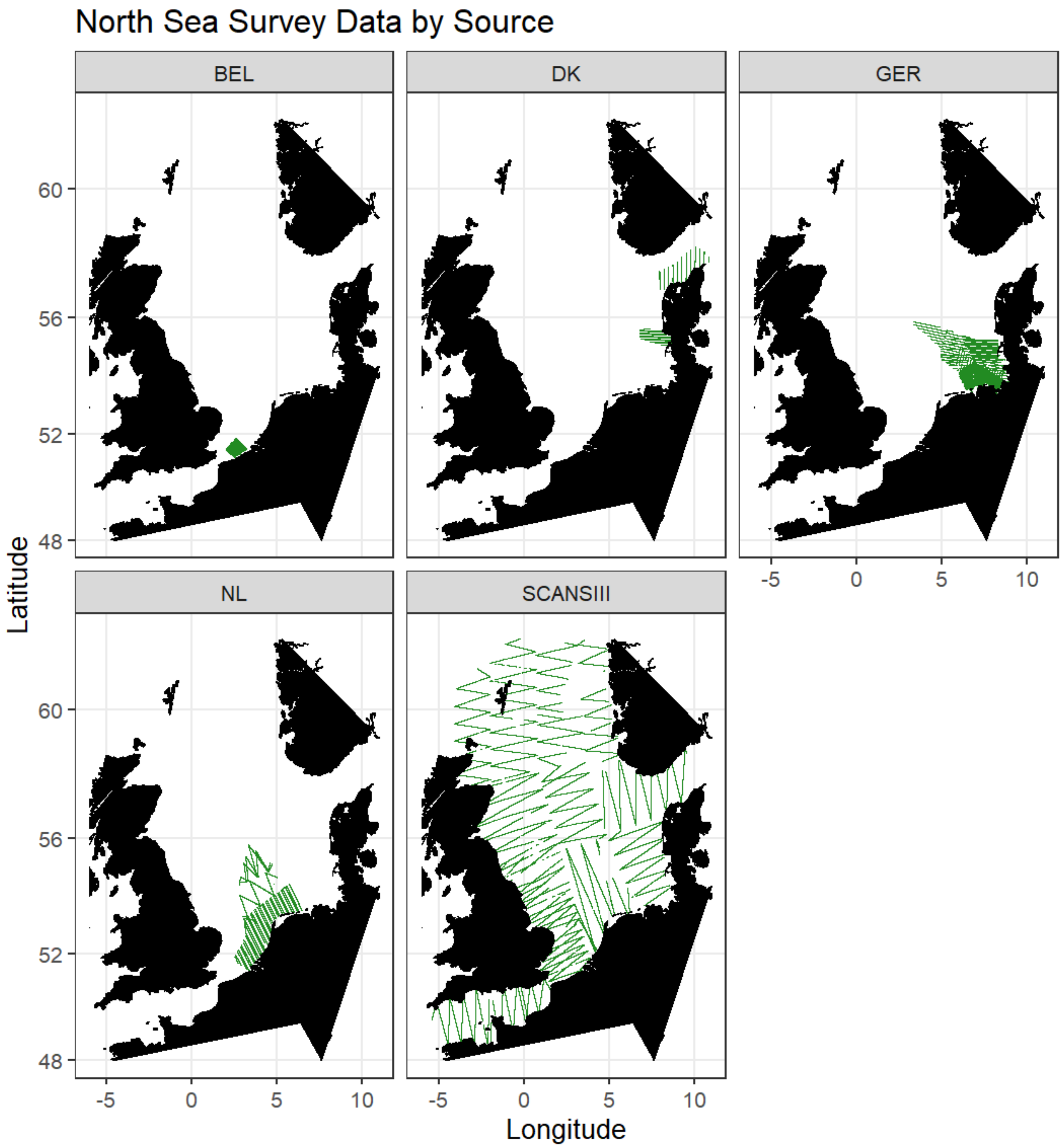

Figure A2. Survey coverage of transect segments for the period 2014-2019 for each source/country BEL (Belgium), DK (Denmark), GER (Germany), NL (Netherlands) and SCANSIII (aerial) in the North Sea. Effort segments are shown in green.

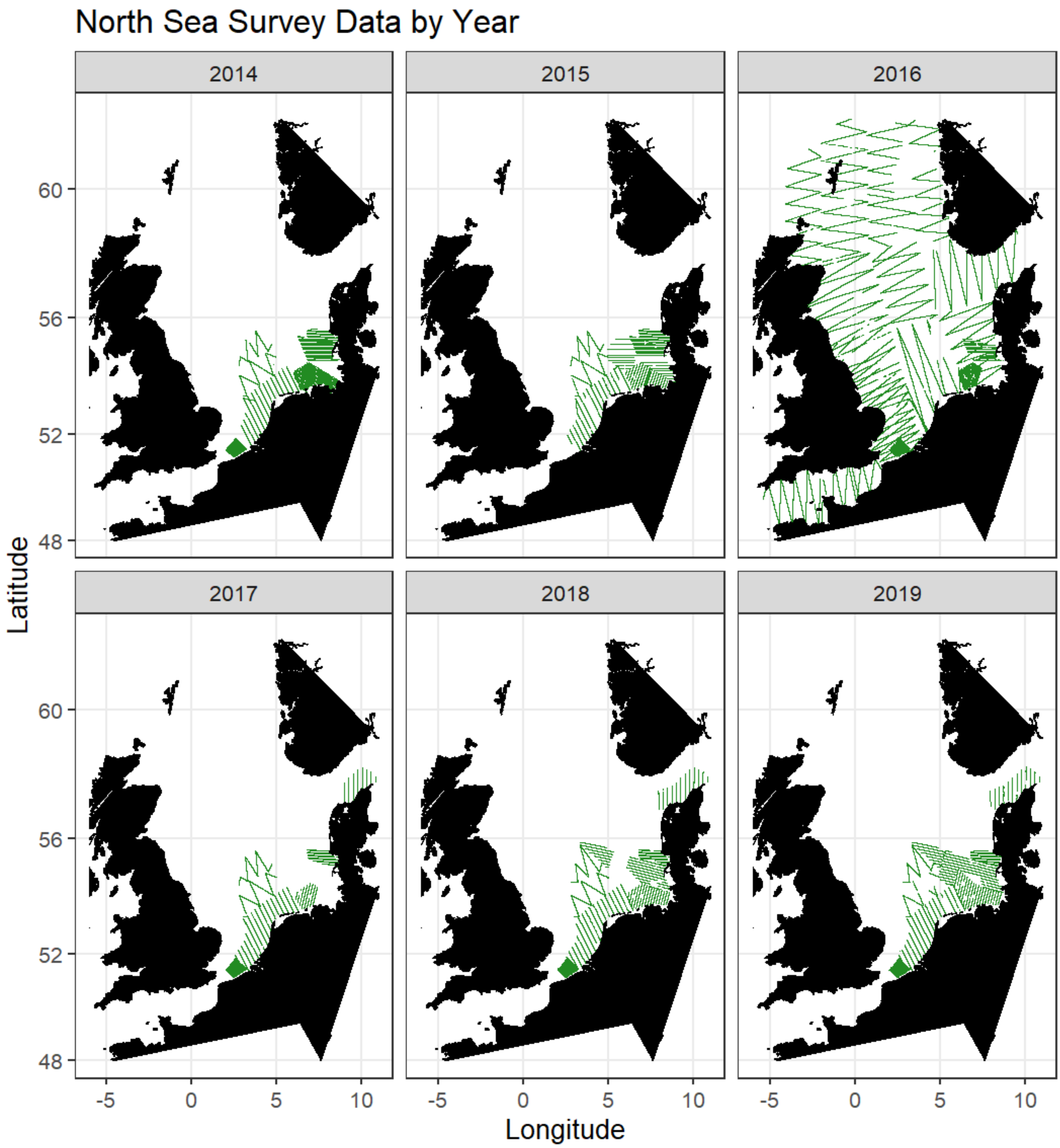

Figure A3. Survey coverage of transect segments by year for the period 2014-2019. Effort segments are shown in green.

Harbour porpoise summary by year and source can be found in Table A1, the maps below summarise the porpoise group sightings.

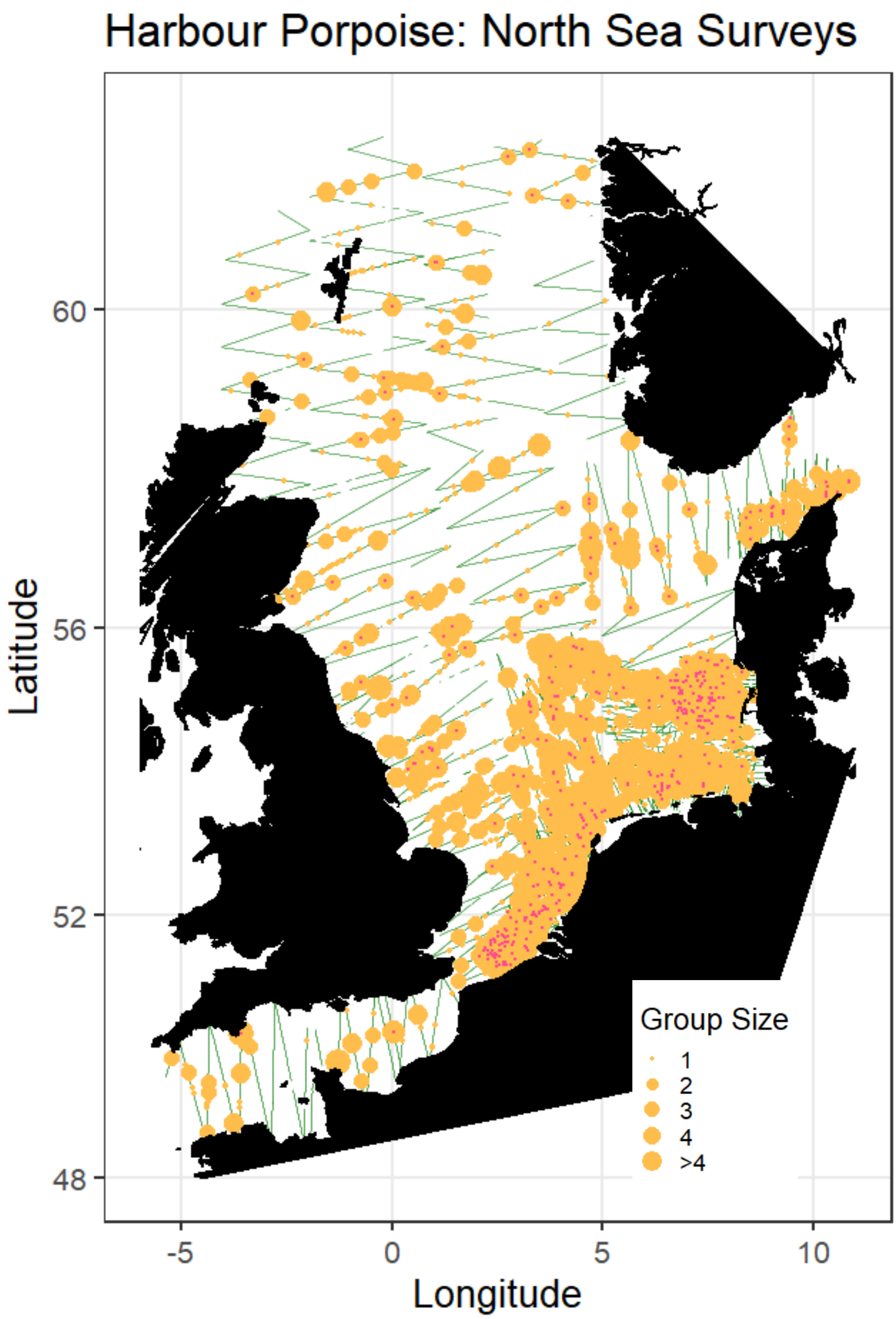

Figure A3. Effort coverage and harbour porpoise available sightings in 2014-2019. Effort segments are shown in green, porpoise sighting positions in orange and mother-calf pair positions overlaid in red.

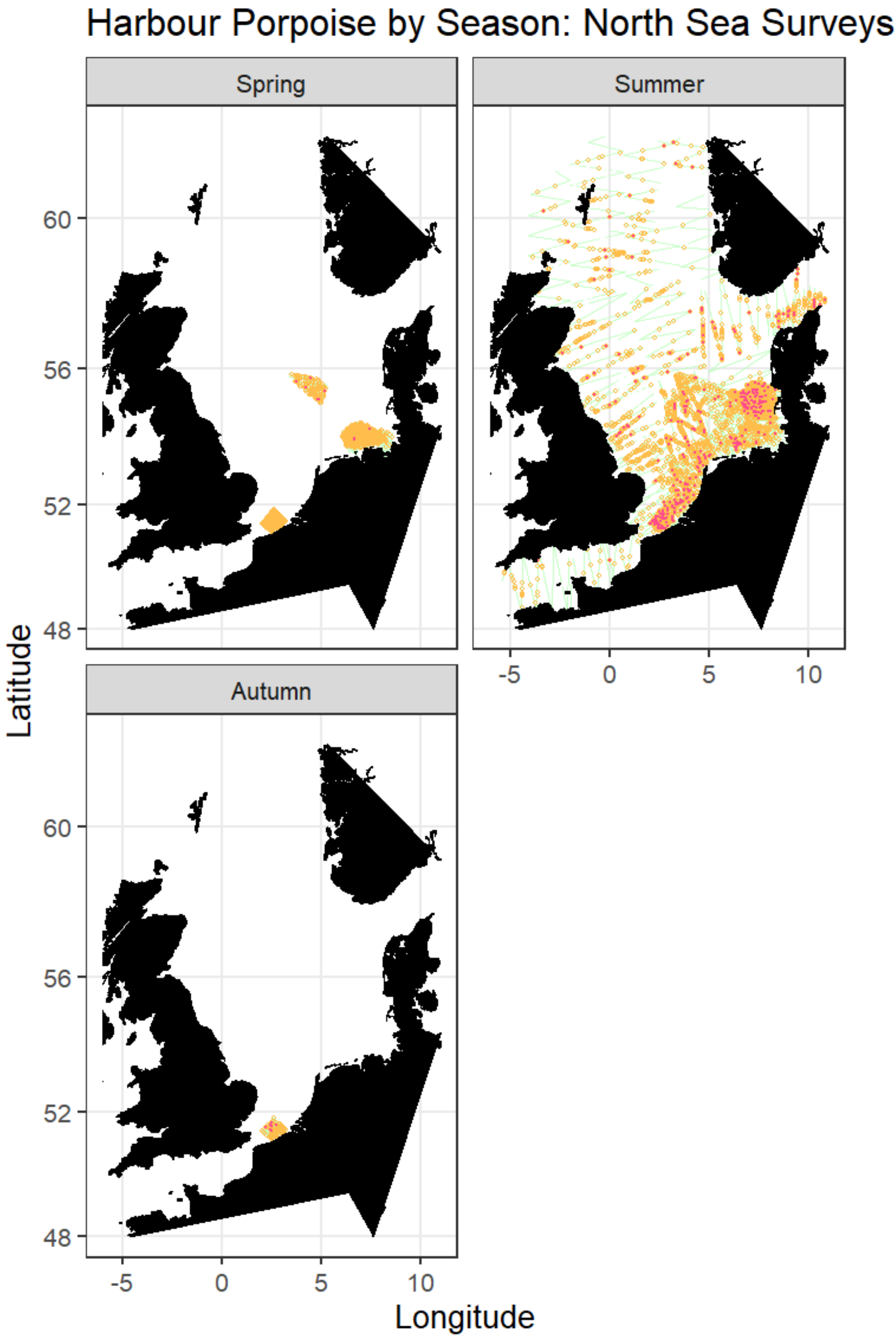

Figure A4. Effort coverage and harbour porpoise available sightings by season in 2014-2019. Effort segments are shown in green, sighting positions in orange and mother-calf pair positions overlaid in red.