Density Model for Killer Whale (*Orcinus orca*) for the U.S. East Coast: Supplementary Report

Duke University Marine Geospatial Ecology Lab*

Model Version 1.2 - 2015-09-26

Citation

When referencing our methodology or results generally, please cite our open-access article:

Roberts JJ, Best BD, Mannocci L, Fujioka E, Halpin PN, Palka DL, Garrison LP, Mullin KD, Cole TVN, Khan CB, McLellan WM, Pabst DA, Lockhart GG (2016) Habitat-based cetacean density models for the U.S. Atlantic and Gulf of Mexico. Scientific Reports 6: 22615. doi: 10.1038/srep22615

To reference this specific model or Supplementary Report, please cite:

Roberts JJ, Best BD, Mannocci L, Fujioka E, Halpin PN, Palka DL, Garrison LP, Mullin KD, Cole TVN, Khan CB, McLellan WM, Pabst DA, Lockhart GG (2015) Density Model for Killer Whale (*Orcinus orca*) for the U.S. East Coast Version 1.2, 2015-09-26, and Supplementary Report. Marine Geospatial Ecology Lab, Duke University, Durham, North Carolina.

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Revision History

Version	Date	Description of changes
1	2015-01-31	Initial version.
1.1	2015-05-14	Updated calculation of CVs. Switched density rasters to logarithmic breaks. No changes to the model.
1.2	2015-09-26	Updated the documentation. No changes to the model.

*For questions, or to offer feedback about this model or report, please contact Jason Roberts (jason.roberts@duke.edu)

Survey Data

Survey	Period	Length (1000 km)	Hours	Sightings
NEFSC Aerial Surveys	1995-2008	70	412	0
NEFSC NARWSS Harbor Porpoise Survey	1999-1999	6	36	0
NEFSC North Atlantic Right Whale Sighting Survey	1999-2013	432	2330	2
NEFSC Shipboard Surveys	1995-2004	16	1143	2
NJDEP Aerial Surveys	2008-2009	11	60	0
NJDEP Shipboard Surveys	2008-2009	14	836	0
SEFSC Atlantic Shipboard Surveys	1992-2005	28	1731	0
SEFSC Mid Atlantic Tursiops Aerial Surveys	1995-2005	35	196	0
SEFSC Southeast Cetacean Aerial Surveys	1992-1995	8	42	0
UNCW Cape Hatteras Navy Surveys	2011-2013	19	125	0
UNCW Early Marine Mammal Surveys	2002-2002	18	98	0
UNCW Jacksonville Navy Surveys	2009-2013	66	402	0
UNCW Onslow Navy Surveys	2007-2011	49	282	0
UNCW Right Whale Surveys	2005-2008	114	586	0
Virginia Aquarium Aerial Surveys	2012-2014	9	53	0
Total		895	8332	4

Table 2: Survey effort and sightings used in this model. Effort is tallied as the cumulative length of on-effort transects and hours the survey team was on effort. Sightings are the number of on-effort encounters of the modeled species for which a perpendicular sighting distance (PSD) was available. Off effort sightings and those without PSDs were omitted from the analysis.

Season	Months	Length (1000 km)	Hours	Sightings
All_Year	All	897	8332	4

Table 3: Survey effort and on-effort sightings having perpendicular sighting distances.

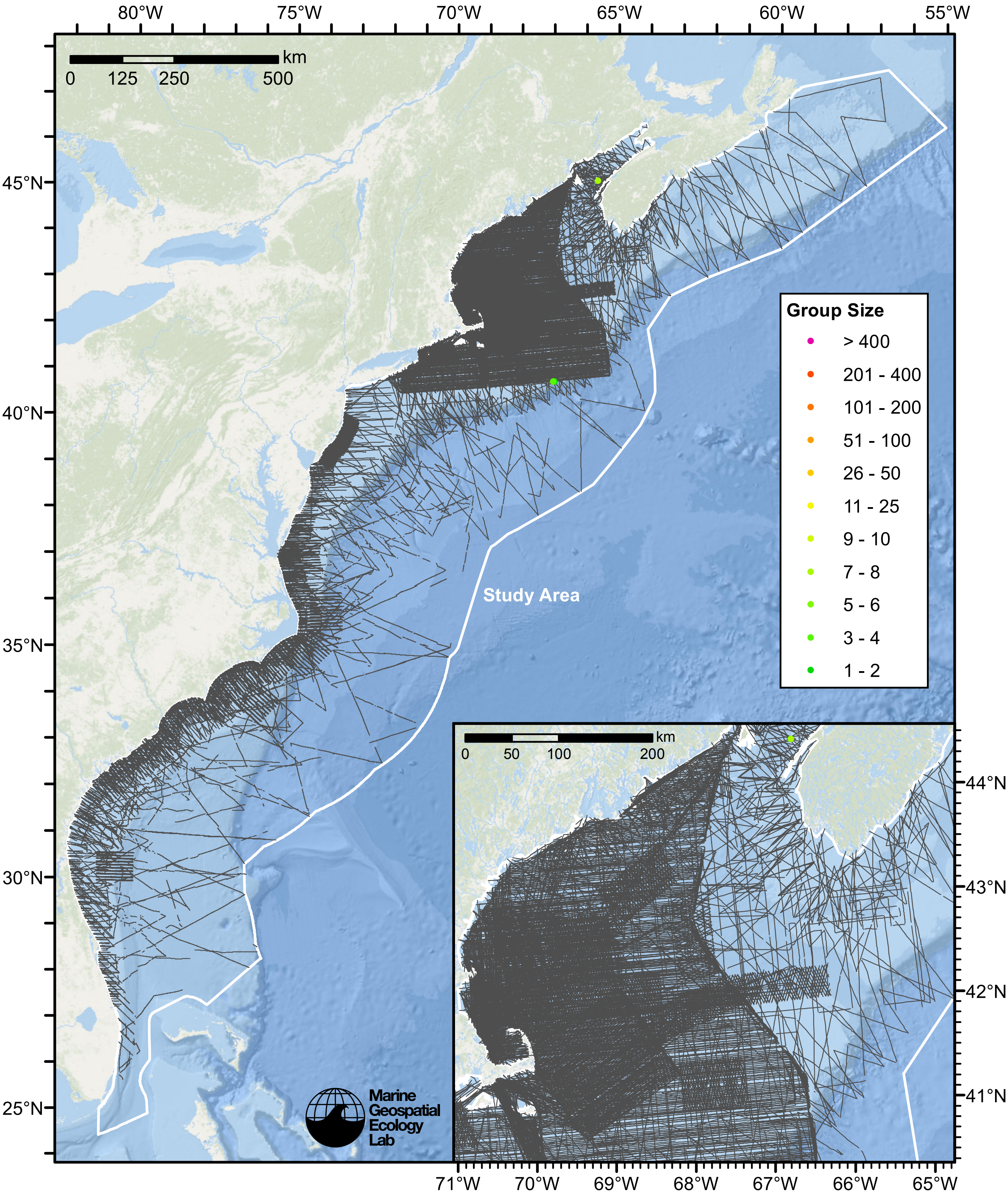

Figure 1: Killer whale sightings and survey tracklines.

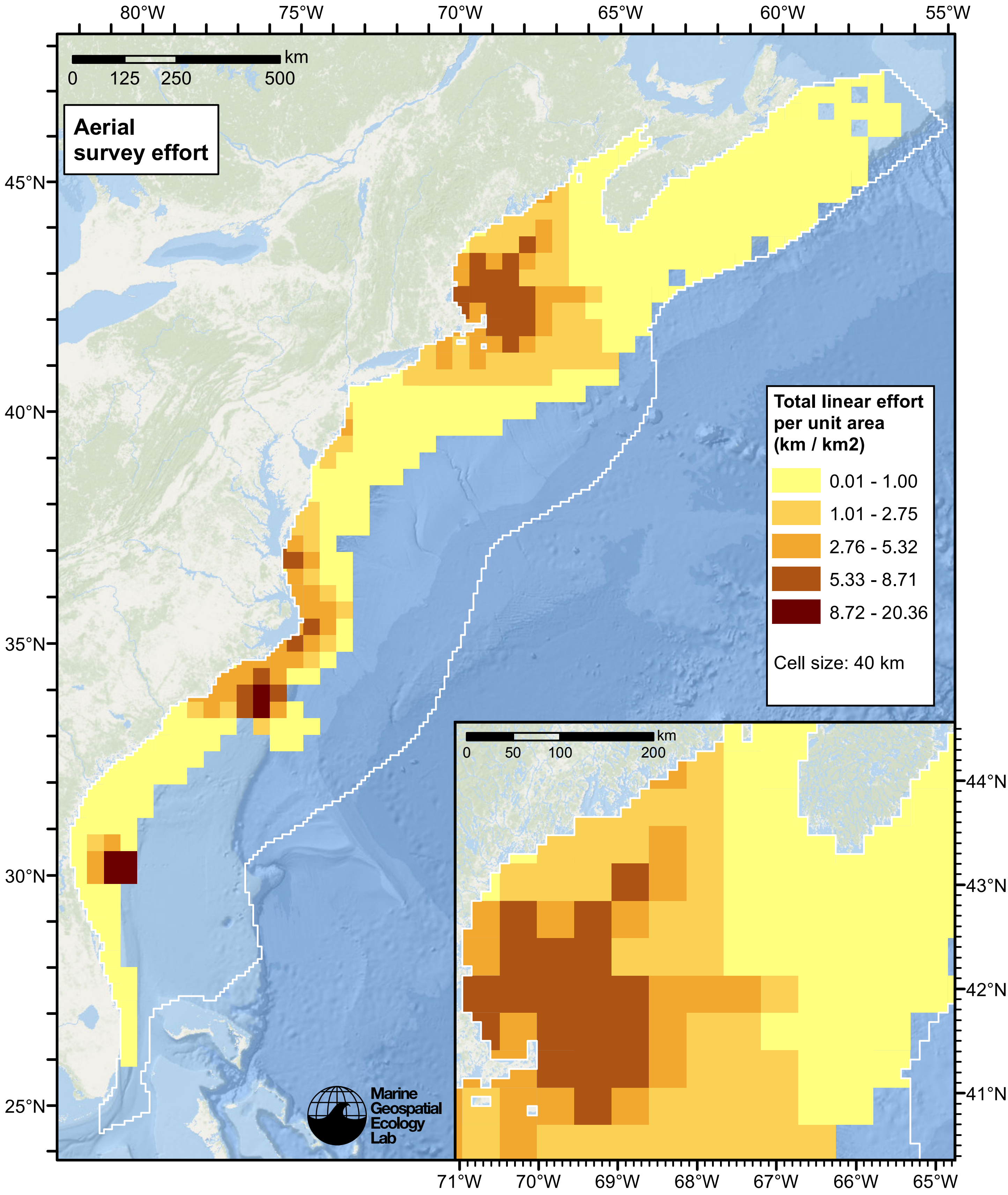

Figure 2: Aerial linear survey effort per unit area.

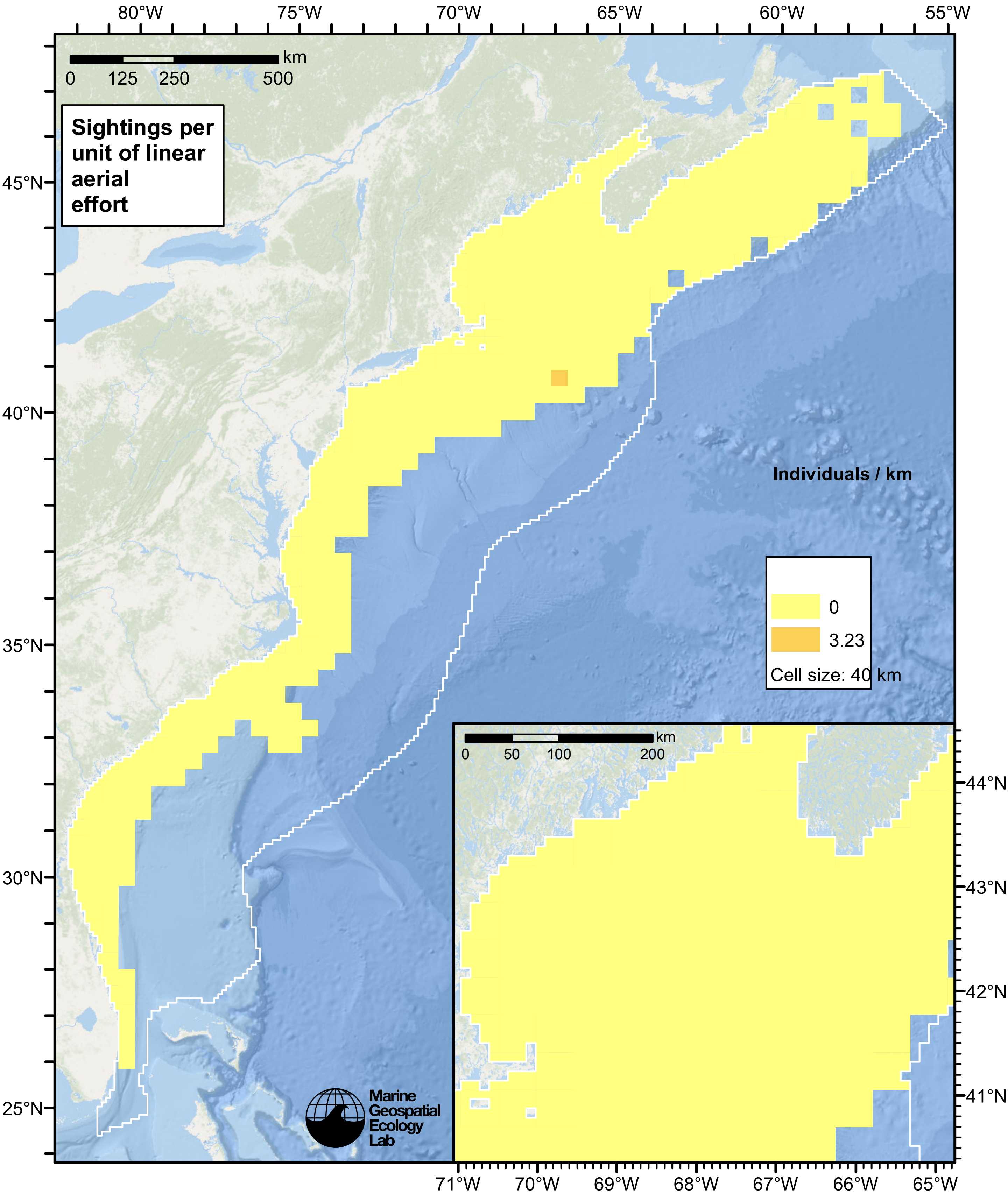

Figure 3: Killer whale sightings per unit aerial linear survey effort.

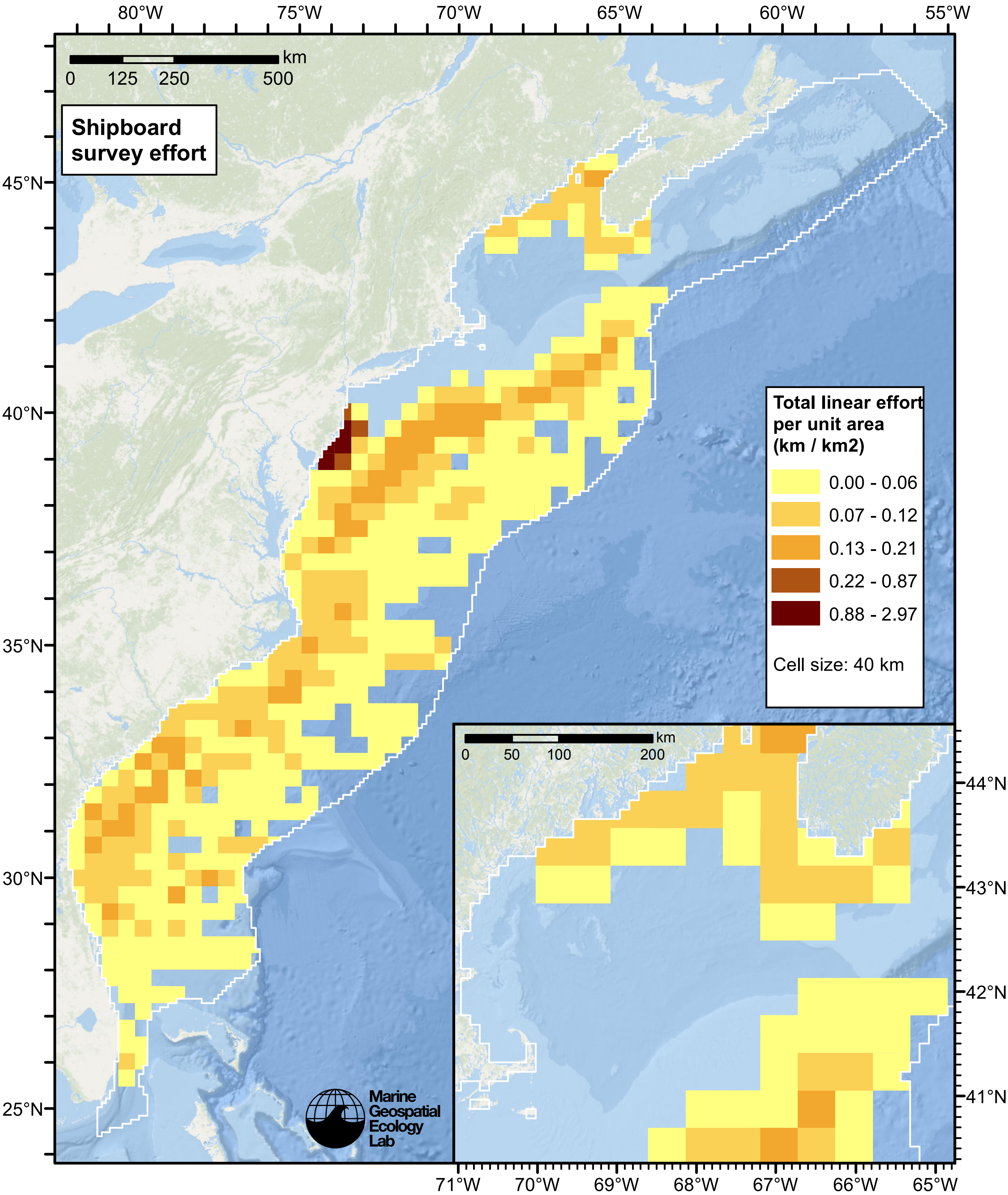

Figure 4: Shipboard linear survey effort per unit area.

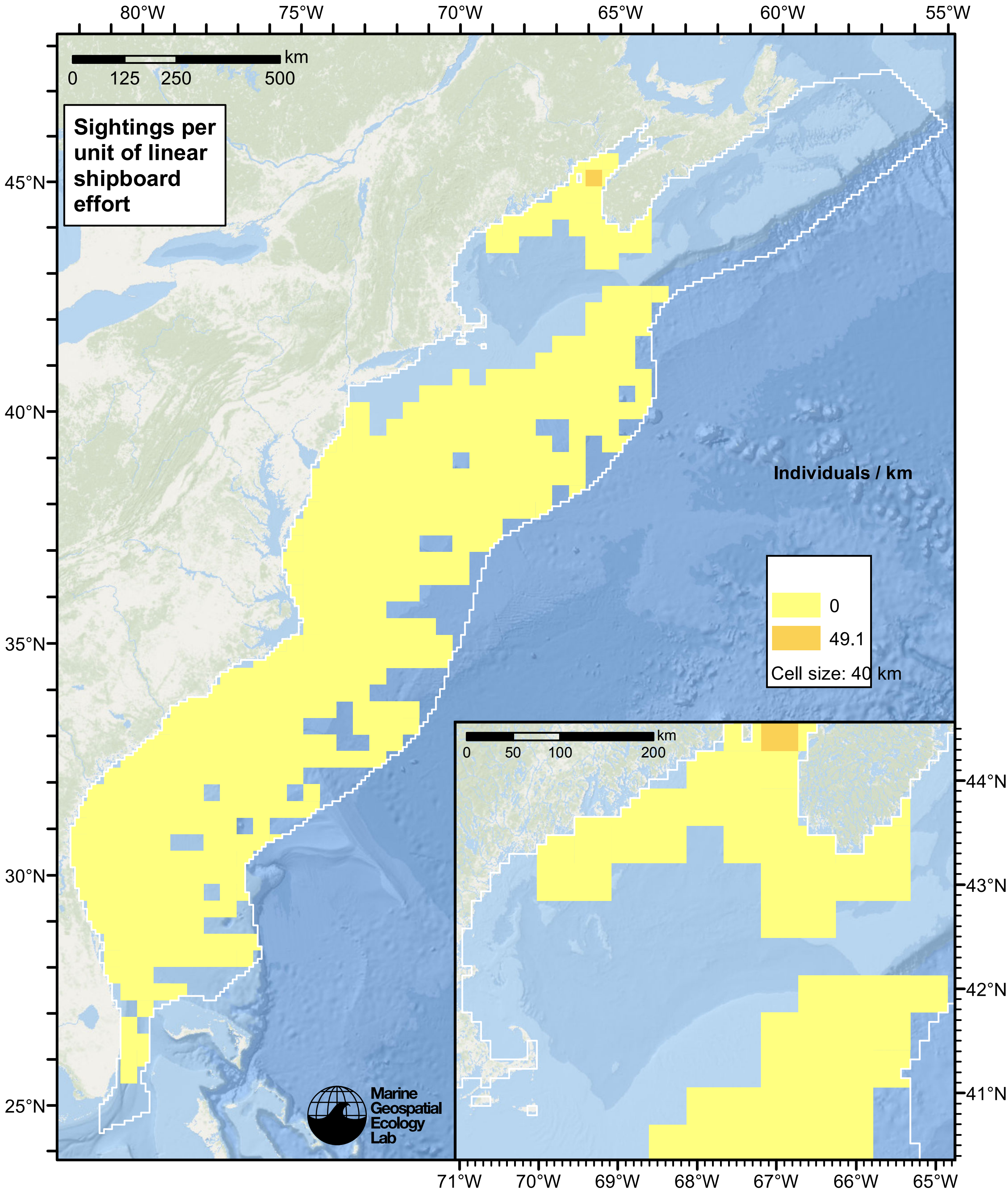

Figure 5: Killer whale sightings per unit shipboard linear survey effort.

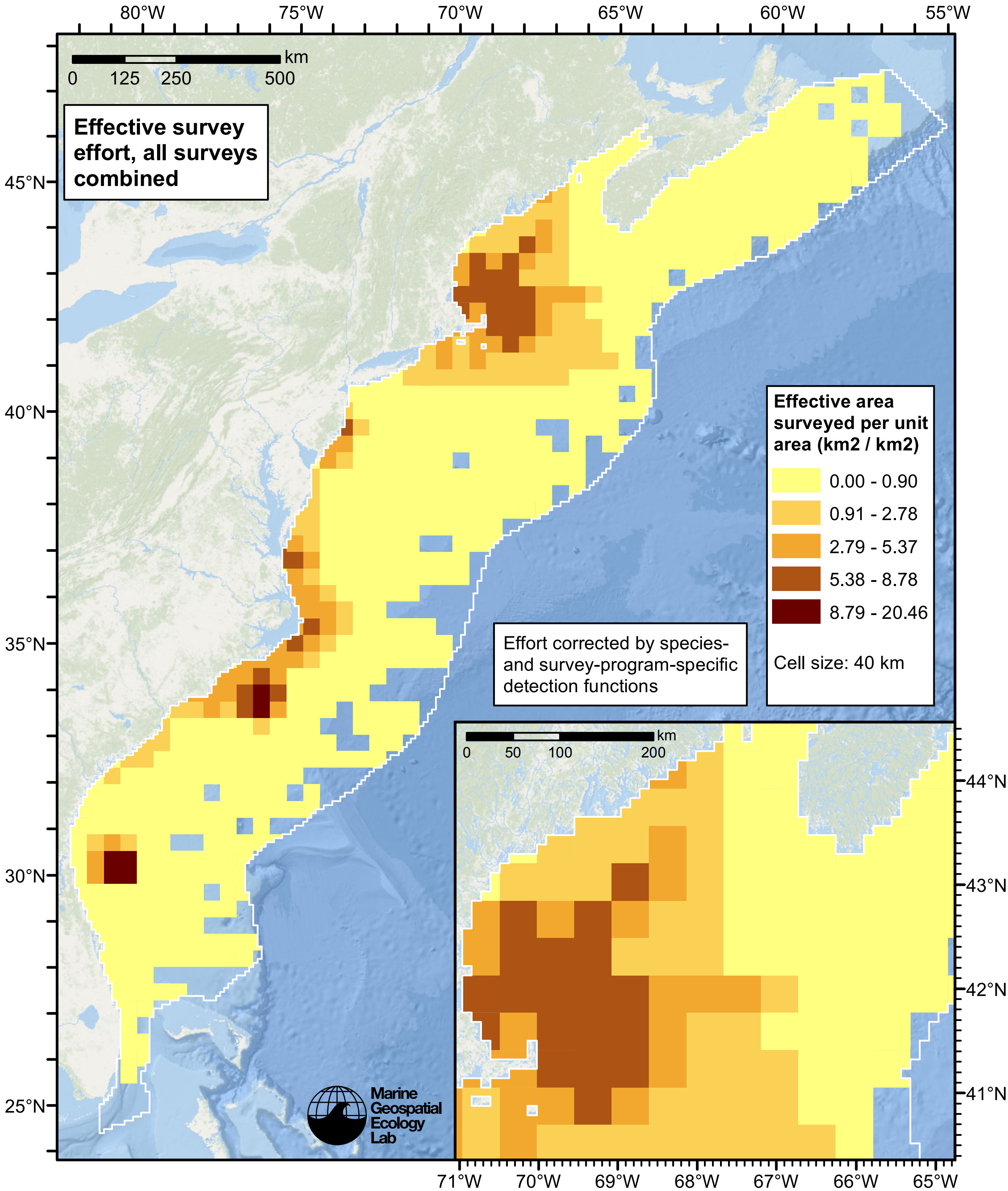

Figure 6: Effective survey effort per unit area, for all surveys combined. Here, effort is corrected by the species- and survey-program-specific detection functions used in fitting the density models.

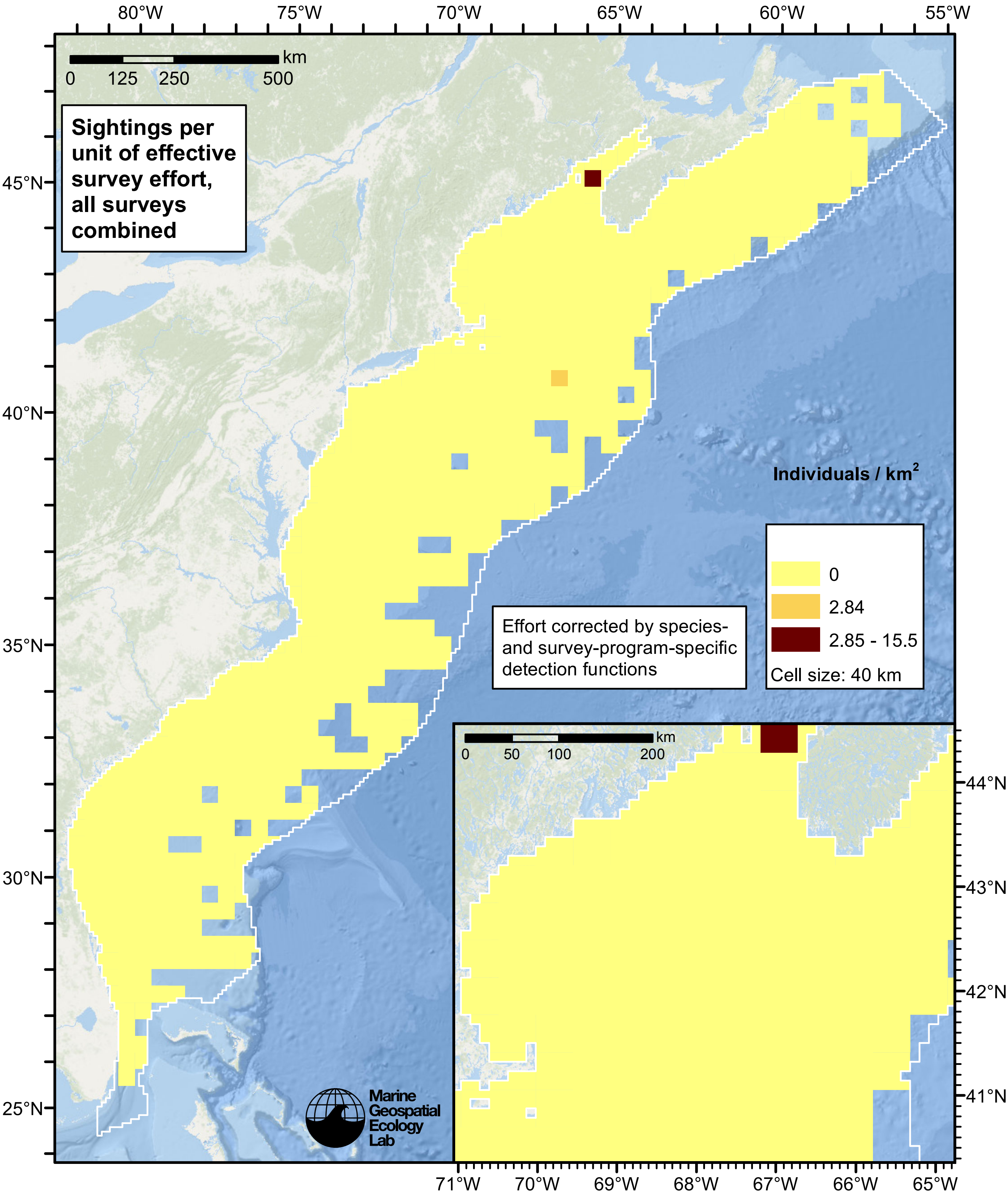

Figure 7: Killer whale sightings per unit of effective survey effort, for all surveys combined. Here, effort is corrected by the species- and survey-program-specific detection functions used in fitting the density models.

Detection Functions

The detection hierarchy figures below show how sightings from multiple surveys were pooled to try to achieve Buckland et. al's (2001) recommendation that at least 60-80 sightings be used to fit a detection function. Leaf nodes, on the right, usually represent individual surveys, while the hierarchy to the left shows how they have been grouped according to how similar we believed the surveys were to each other in their detection performance.

At each node, the red or green number indicates the total number of sightings below that node in the hierarchy, and is colored green if 70 or more sightings were available, and red otherwise. If a grouping node has zero sightings–i.e. all of the surveys within it had zero sightings–it may be collapsed and shown as a leaf to save space.

Each histogram in the figure indicates a node where a detection function was fitted. The actual detection functions do not appear in this figure; they are presented in subsequent sections. The histogram shows the frequency of sightings by perpendicular sighting distance for all surveys contained by that node. Each survey (leaf node) recieves the detection function that is closest to it up the hierarchy. Thus, for common species, sufficient sightings may be available to fit detection functions deep in the hierarchy, with each function applying to only a few surveys, thereby allowing variability in detection performance between surveys to be addressed relatively finely. For rare species, so few sightings may be available that we have to pool many surveys together to try to meet Buckland's recommendation, and fit only a few coarse detection functions high in the hierarchy.

A blue Proxy Species tag indicates that so few sightings were available that, rather than ascend higher in the hierarchy to a point that we would pool grossly-incompatible surveys together, (e.g. shipboard surveys that used big-eye binoculars with those that used only naked eyes) we pooled sightings of similar species together instead. The list of species pooled is given in following sections.

Shipboard Surveys

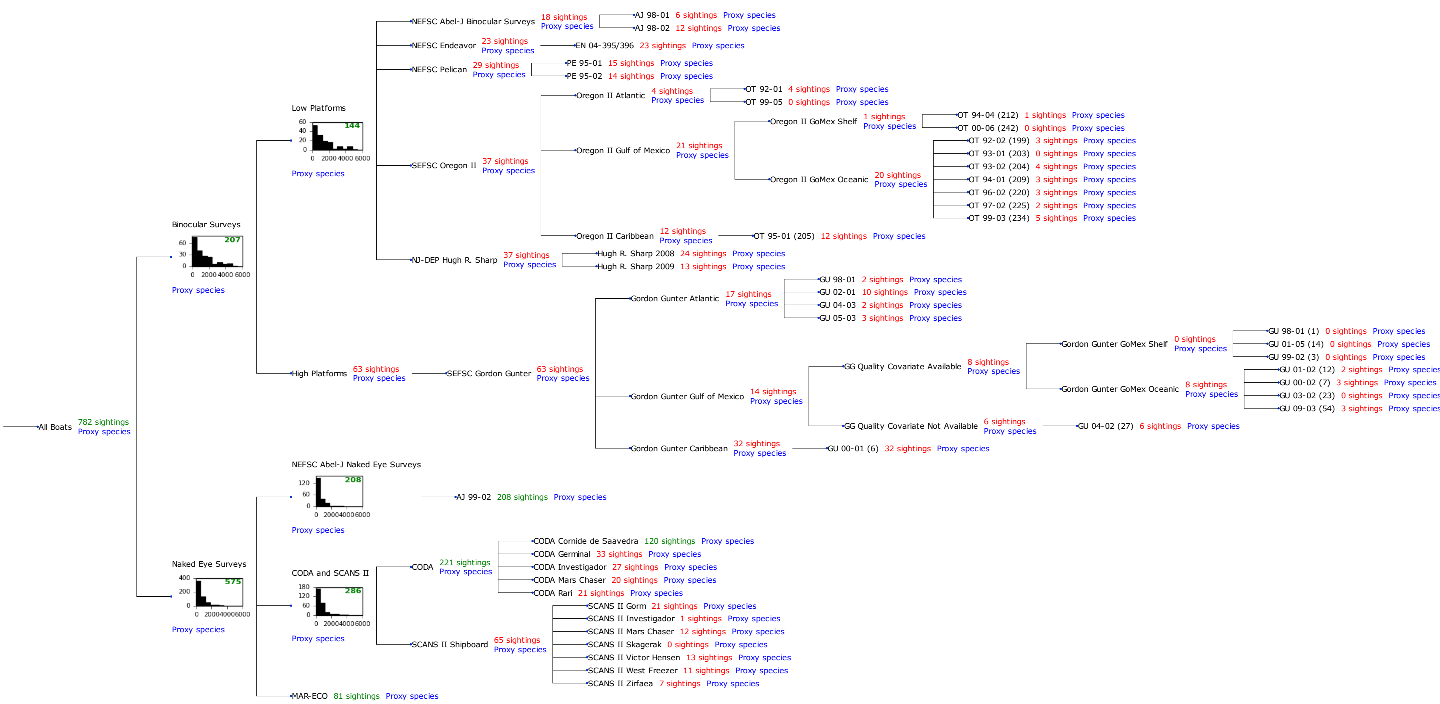

Figure 8: Detection hierarchy for shipboard surveys

Binocular Surveys

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	8
Balaenoptera acutorostrata	Minke whale	4
Balaenoptera borealis	Sei whale	4
Balaenoptera borealis/edeni	Sei or Bryde's whale	6
Balaenoptera borealis/physalus	Fin or Sei whale	0
Balaenoptera edeni	Bryde's whale	21
Balaenoptera musculus	Blue whale	0
Balaenoptera physalus	Fin whale	98
Eubalaena glacialis	North Atlantic right whale	4
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	46
Orcinus orca	Killer whale	16
Total		207

Table 4: Proxy species used to fit detection functions for Binocular Surveys. The number of sightings, n, is before truncation.

The sightings were right truncated at 5500m.

Covariate	Description
beaufort	Beaufort sea state.
size	Estimated size (number of individuals) of the sighted group.
vessel	Vessel from which the observation was made. This covariate allows the detection function to account for vessel-specific biases, such as the height of the survey platform.

Table 5: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hr	poly	2		Yes	0.00	1242
hr	poly	4		Yes	0.30	1229
hr				Yes	1.55	1436
hr			beaufort	Yes	3.54	1439
hn	cos	2		Yes	3.91	1779
hr			vessel	Yes	6.82	1585
hr			beaufort, vessel	Yes	8.65	1612
hn	cos	3		Yes	11.95	1743
hn			vessel	Yes	19.94	2284

hn				Yes	22.38	2297
hn			beaufort	Yes	24.09	2296
hn			size	Yes	24.31	2391
hn			beaufort, size	Yes	26.18	2393
hn	herm	4		No		
hr			size	No		
hn			beaufort, vessel	No		
hr			beaufort, size	No		
hn			vessel, size	No		
hr			vessel, size	No		
hn			beaufort, vessel, size	No		
hr			beaufort, vessel, size	No		

Table 6: Candidate detection functions for Binocular Surveys. The first one listed was selected for the density model.

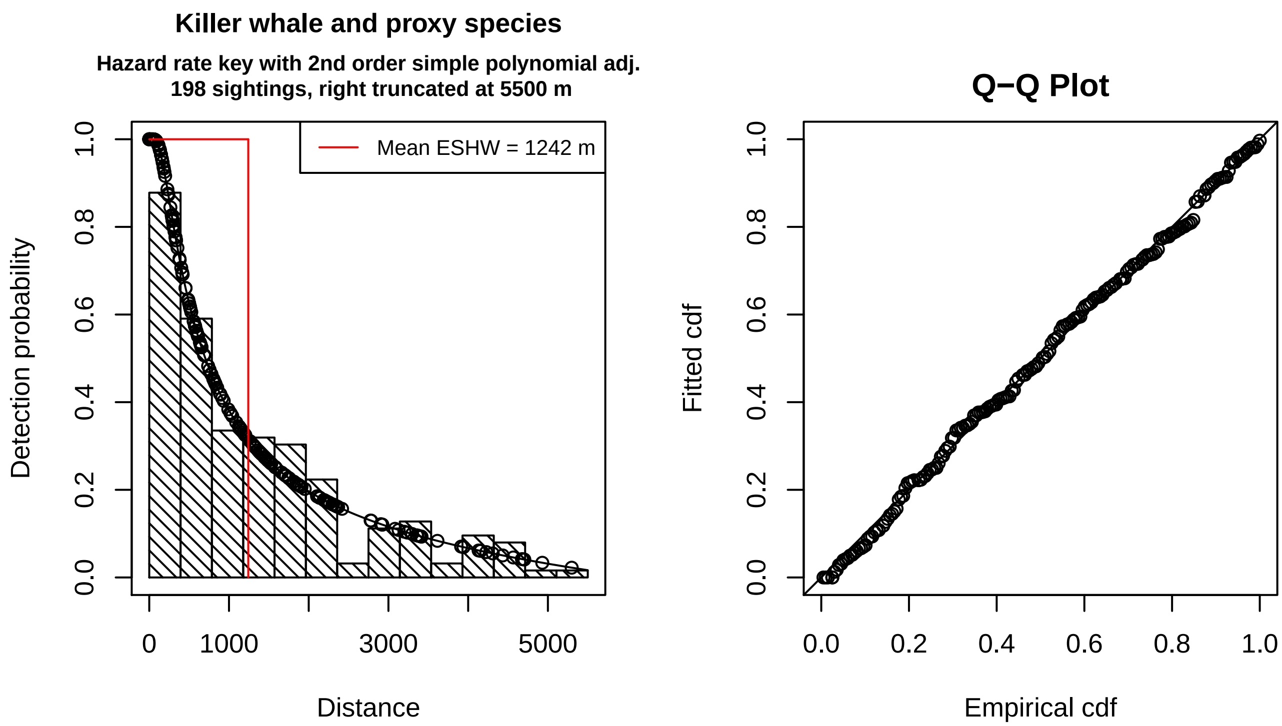

Figure 9: Detection function for Binocular Surveys that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  198
Distance range         :  0  -  5500
AIC                    :  3236.988
```

```
Detection function:
 Hazard-rate key function with simple polynomial adjustment term of order 2

Detection function parameters
Scale Coefficients:
            estimate        se
(Intercept) 6.208035 0.3983556

Shape parameters:
                estimate        se
(Intercept) 7.232938e-08 0.2156364

Adjustment term parameter(s):
                estimate        se
poly, order 2 -0.8083684 0.2376731


Monotonicity constraints were enforced.
                       Estimate           SE        CV
Average p             0.2257848   0.03930841 0.1740968
N in covered region 876.9410383 162.22190631 0.1849861

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

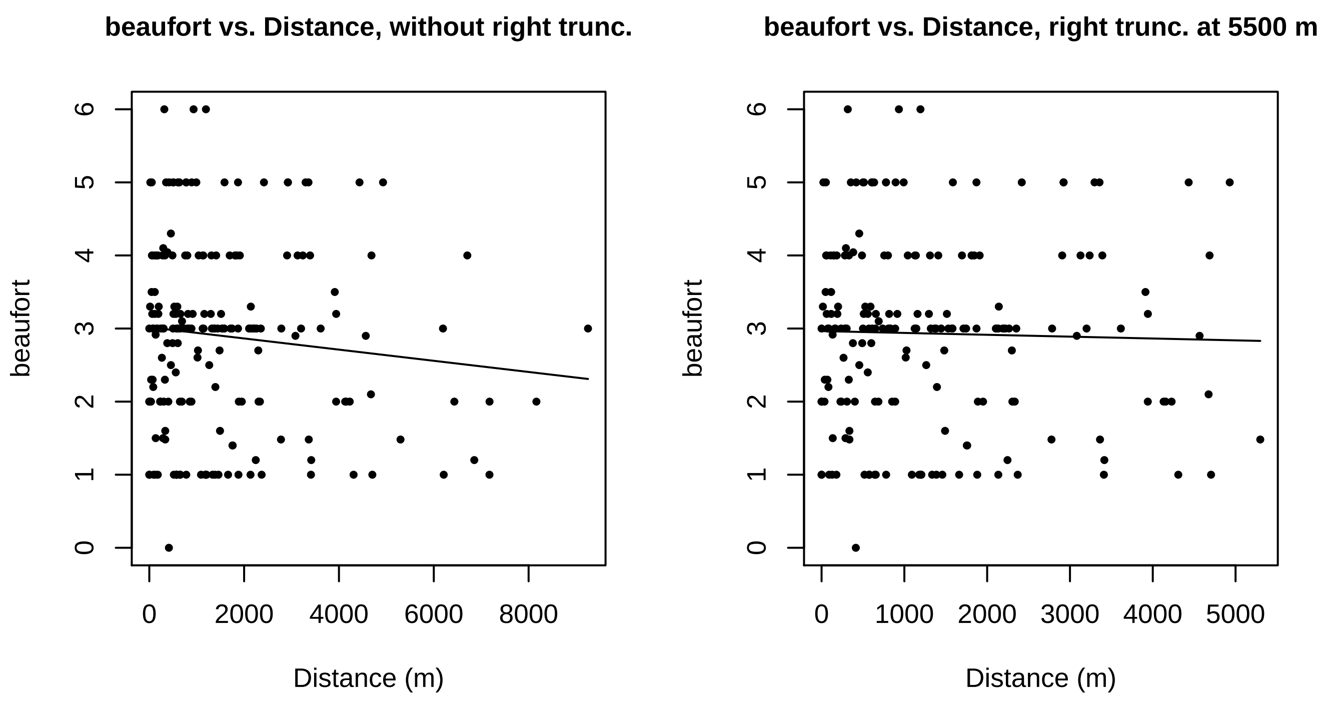

Figure 10: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

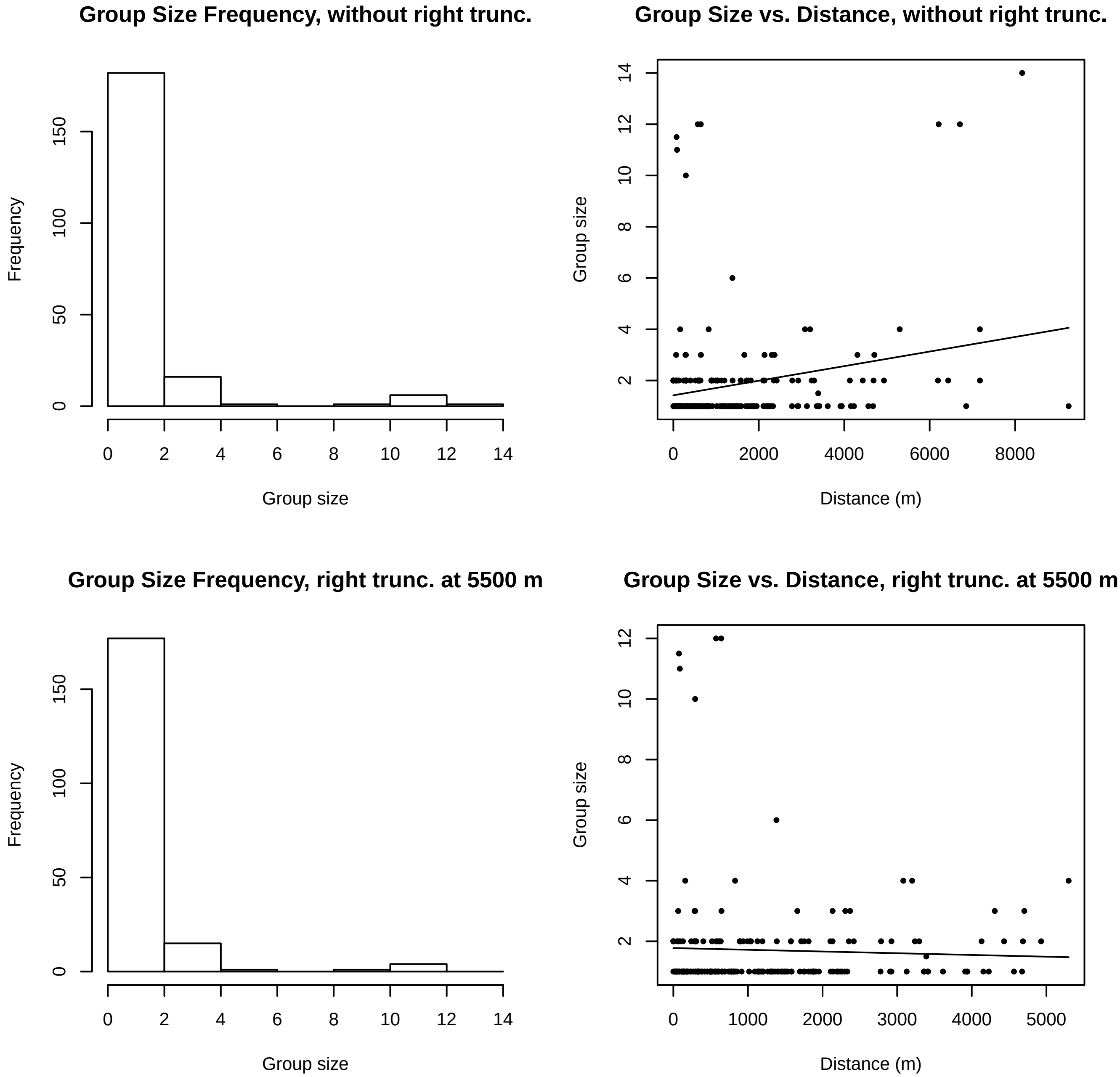

Figure 11: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

Low Platforms

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	1
Balaenoptera acutorostrata	Minke whale	3

Balaenoptera borealis	Sei whale	4
Balaenoptera borealis/edeni	Sei or Bryde's whale	5
Balaenoptera borealis/physalus	Fin or Sei whale	0
Balaenoptera edeni	Bryde's whale	7
Balaenoptera musculus	Blue whale	0
Balaenoptera physalus	Fin whale	86
Eubalaena glacialis	North Atlantic right whale	3
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	23
Orcinus orca	Killer whale	12
Total		144

Table 7: Proxy species used to fit detection functions for Low Platforms. The number of sightings, n, is before truncation.

The sightings were right truncated at 5500m.

Covariate	Description
beaufort	Beaufort sea state.
size	Estimated size (number of individuals) of the sighted group.
vessel	Vessel from which the observation was made. This covariate allows the detection function to account for vessel-specific biases, such as the height of the survey platform.

Table 8: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hr				Yes	0.00	1513
hn	cos	2		Yes	0.75	1702
hr	poly	4		Yes	1.76	1486
hr	poly	2		Yes	1.80	1481
hr			vessel	Yes	2.52	1684
hn	cos	3		Yes	11.32	1722
hn			vessel	Yes	13.50	2249
hn			vessel, size	Yes	17.39	2318
hn			size	Yes	17.44	2366
hn				Yes	17.80	2268
hn			beaufort, size	Yes	19.36	2366
hn			beaufort	Yes	19.37	2266
hn	herm	4		No		

hr	beaufort	No
hr	size	No
hn	beaufort, vessel	No
hr	beaufort, vessel	No
hr	beaufort, size	No
hr	vessel, size	No
hn	beaufort, vessel, size	No
hr	beaufort, vessel, size	No

Table 9: Candidate detection functions for Low Platforms. The first one listed was selected for the density model.

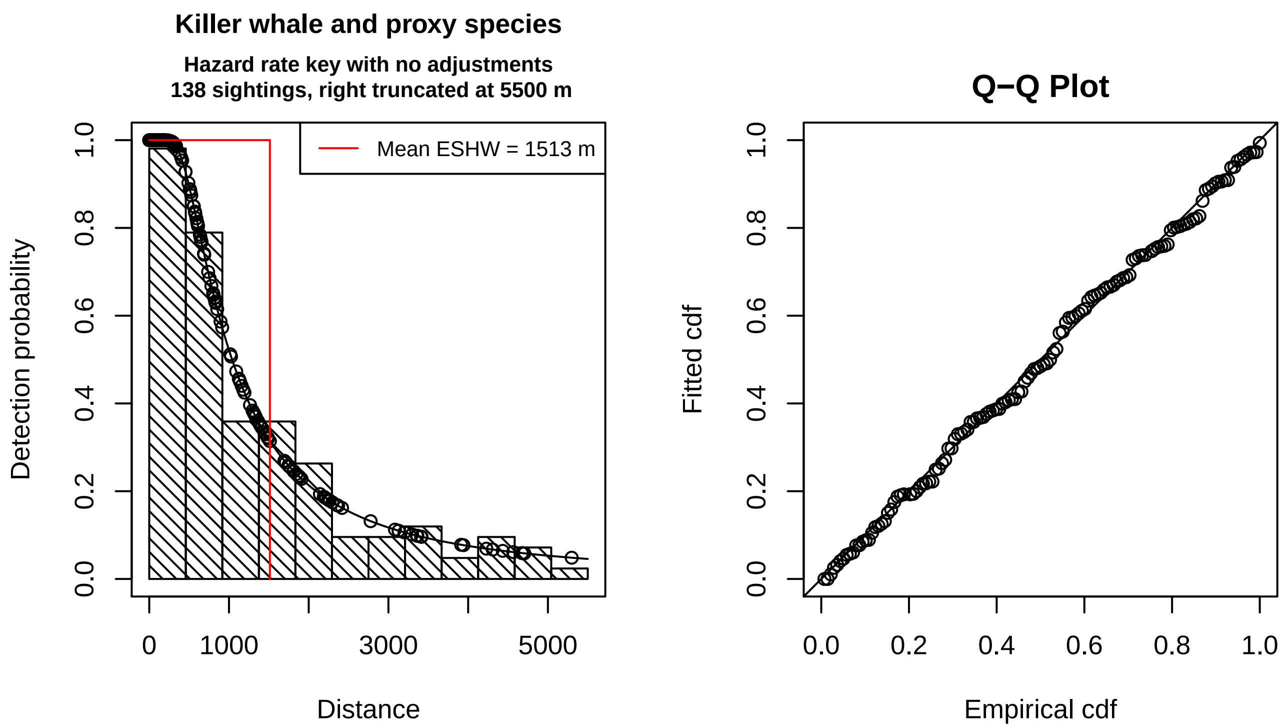

Figure 12: Detection function for Low Platforms that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  138
Distance range         :  0  -  5500
AIC                    :  2251.335

Detection function:
 Hazard-rate key function

Detection function parameters
Scale Coefficients:
            estimate        se
```

```
(Intercept) 6.718977 0.2321353

Shape parameters:
            estimate        se
(Intercept) 0.480695 0.1553973

                       Estimate          SE        CV
Average p             0.2751198  0.03724143 0.1353644
N in covered region 501.5996387 77.01845894 0.1535457
```

Additional diagnostic plots:

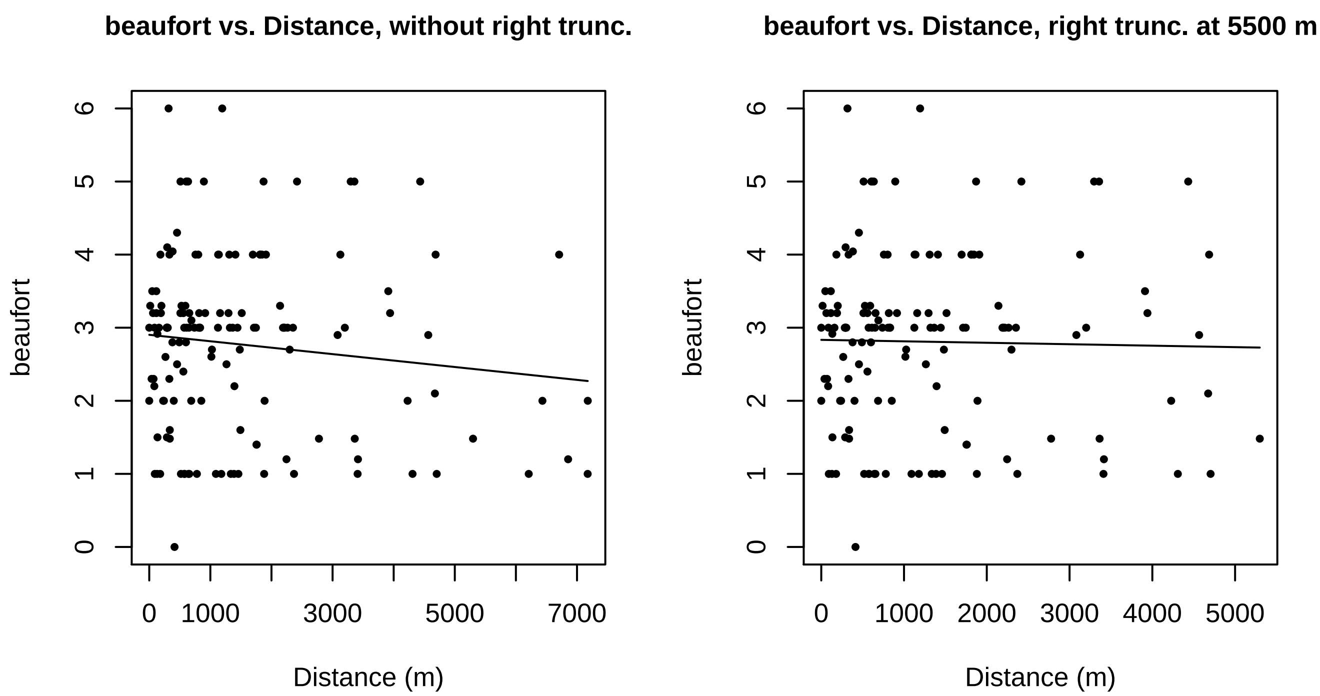

Figure 13: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

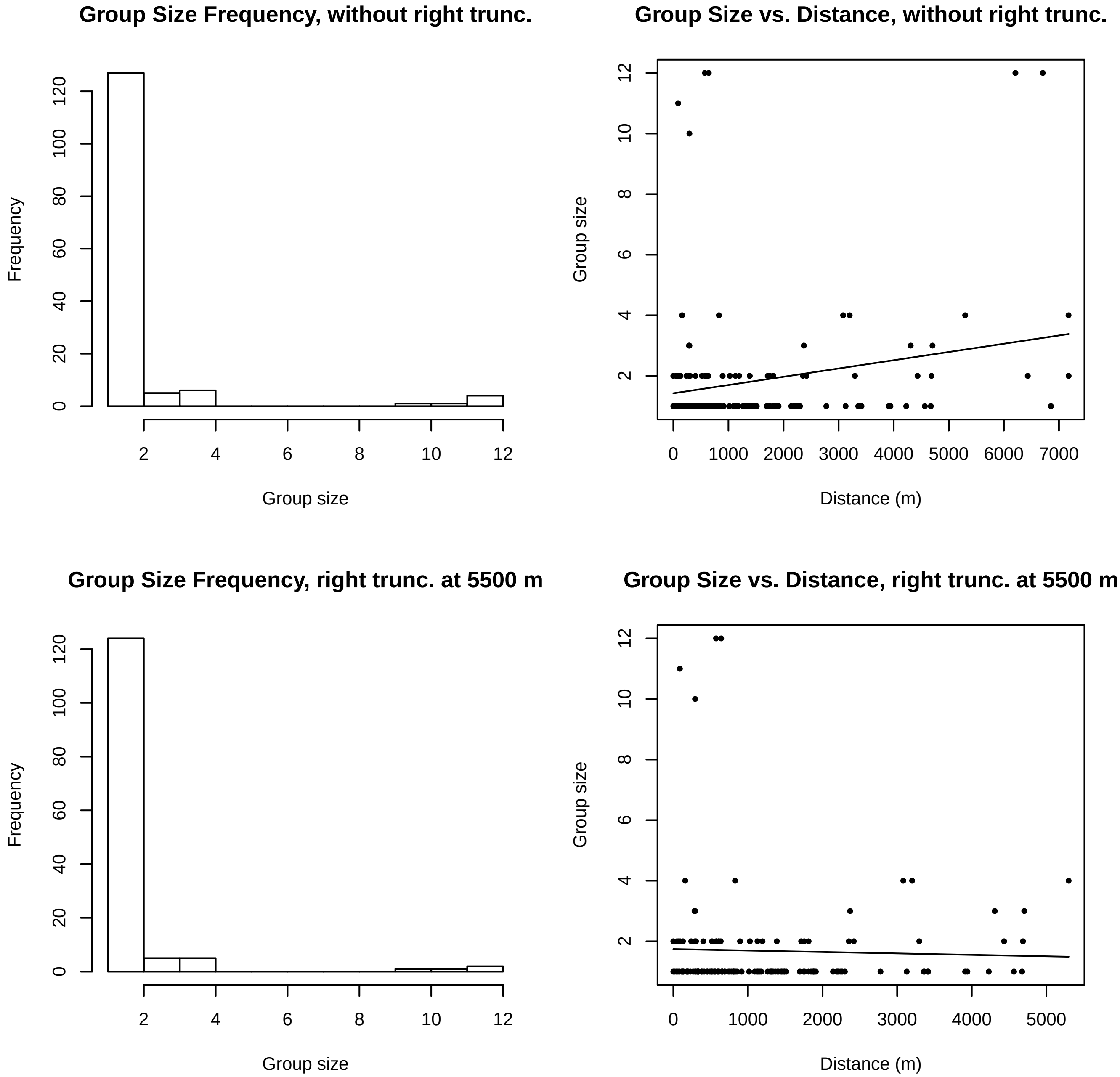

Figure 14: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

Naked Eye Surveys

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	7
Balaenoptera acutorostrata	Minke whale	177

Balaenoptera borealis	Sei whale	68
Balaenoptera borealis/edeni	Sei or Bryde's whale	0
Balaenoptera borealis/physalus	Fin or Sei whale	4
Balaenoptera edeni	Bryde's whale	1
Balaenoptera musculus	Blue whale	5
Balaenoptera physalus	Fin whale	261
Eubalaena glacialis	North Atlantic right whale	10
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	38
Orcinus orca	Killer whale	4
Total		575

Table 10: Proxy species used to fit detection functions for Naked Eye Surveys. The number of sightings, n, is before truncation.

The sightings were right truncated at 2500m.

Covariate	Description
beaufort	Beaufort sea state.
size	Estimated size (number of individuals) of the sighted group.

Table 11: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hn	cos	2		Yes	0.00	784
hr	poly	2		Yes	3.99	792
hr	poly	4		Yes	4.13	807
hr				Yes	5.69	836
hr			size	Yes	6.29	876
hn	cos	3		Yes	12.98	768
hn			size	Yes	22.94	953
hn			beaufort, size	Yes	24.90	953
hn				Yes	29.69	948
hn			beaufort	Yes	31.41	948
hn	herm	4		No		
hr			beaufort	No		
hr			beaufort, size	No		

Table 12: Candidate detection functions for Naked Eye Surveys. The first one listed was selected for the density model.

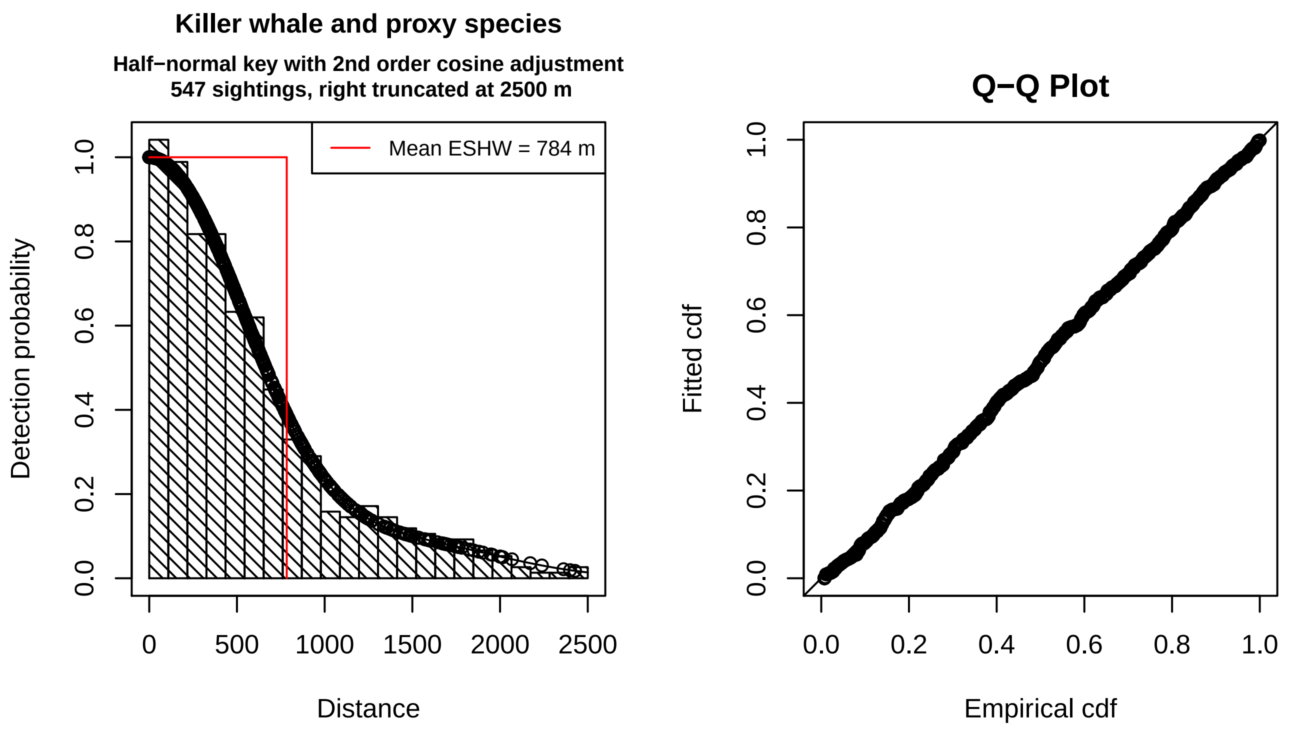

Figure 15: Detection function for Naked Eye Surveys that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  547
Distance range         :  0  -  2500
AIC                    :  8011.685

Detection function:
 Half-normal key function with cosine adjustment term of order 2

Detection function parameters
Scale Coefficients:
            estimate         se
(Intercept)  6.75079 0.03895579

Adjustment term parameter(s):
              estimate         se
cos, order 2 0.4171605 0.06990221


Monotonicity constraints were enforced.
                        Estimate          SE        CV
Average p              0.3135628  0.01172703 0.0373993
N in covered region 1744.4669776 89.86325917 0.0515133

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

Figure 16: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

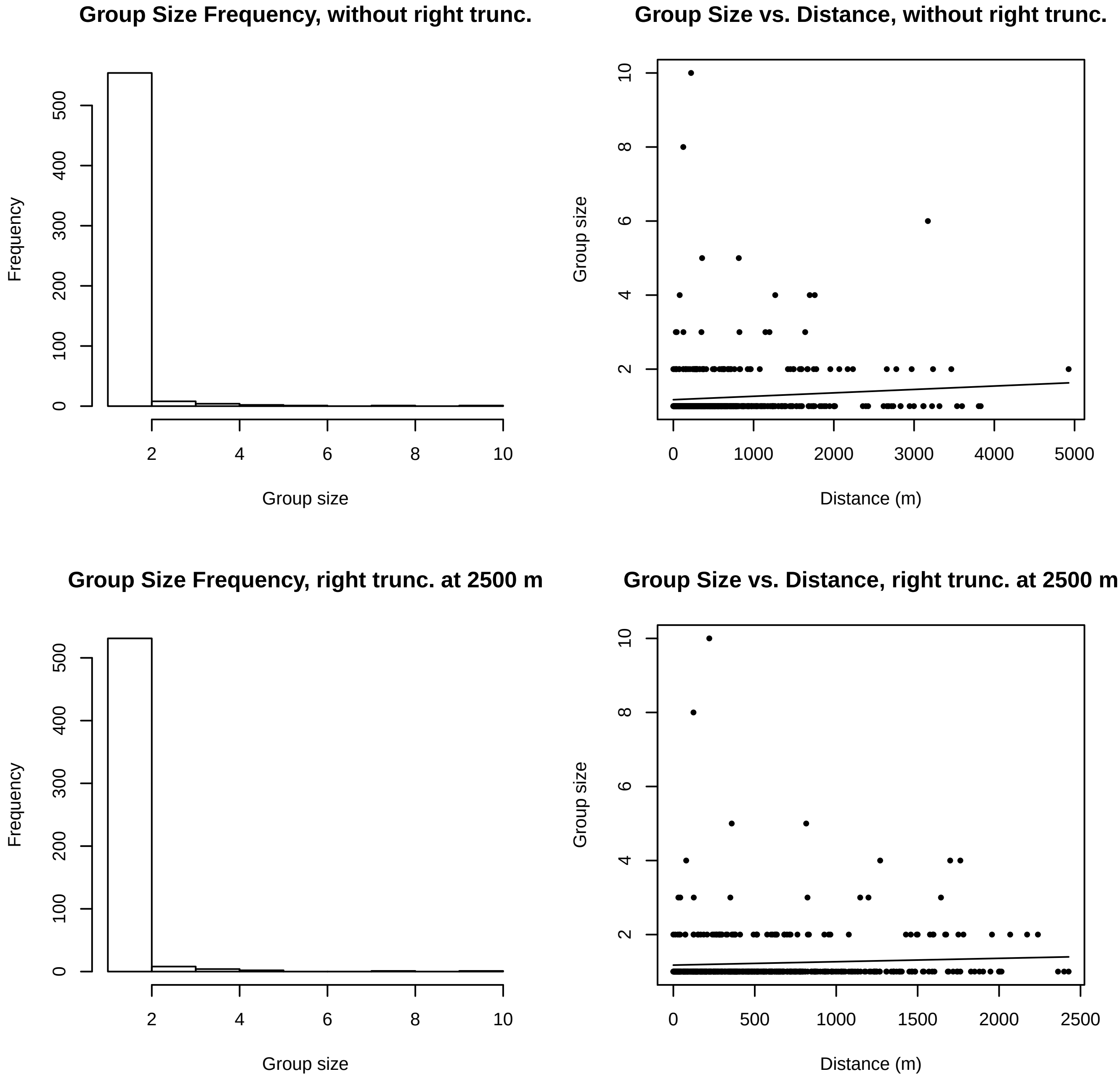

Figure 17: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

NEFSC Abel-J Naked Eye Surveys

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	0
Balaenoptera acutorostrata	Minke whale	100

Balaenoptera borealis	Sei whale	2
Balaenoptera borealis/edeni	Sei or Bryde's whale	0
Balaenoptera borealis/physalus	Fin or Sei whale	0
Balaenoptera edeni	Bryde's whale	0
Balaenoptera musculus	Blue whale	0
Balaenoptera physalus	Fin whale	57
Eubalaena glacialis	North Atlantic right whale	10
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	37
Orcinus orca	Killer whale	2
Total		208

Table 13: Proxy species used to fit detection functions for NEFSC Abel-J Naked Eye Surveys. The number of sightings, n, is before truncation.

The sightings were right truncated at 2500m.

Covariate	Description
beaufort	Beaufort sea state.
quality	Survey-specific index of the quality of observation conditions, utilizing relevant factors other than Beaufort sea state (see methods).
size	Estimated size (number of individuals) of the sighted group.

Table 14: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hn	cos	2		Yes	0.00	710
hr				Yes	0.82	751
hr	poly	4		Yes	0.82	730
hr	poly	2		Yes	1.11	716
hn	cos	3		Yes	2.60	661
hn			size	Yes	8.50	859
hn			quality, size	Yes	10.21	858
hn				Yes	11.08	841
hn			quality	Yes	12.98	841
hn	herm	4		No		
hn			beaufort	No		
hr			beaufort	No		
hr			quality	No		
hr			size	No		

hn	beaufort, quality	No
hr	beaufort, quality	No
hn	beaufort, size	No
hr	beaufort, size	No
hr	quality, size	No
hn	beaufort, quality, size	No
hr	beaufort, quality, size	No

Table 15: Candidate detection functions for NEFSC Abel-J Naked Eye Surveys. The first one listed was selected for the density model.

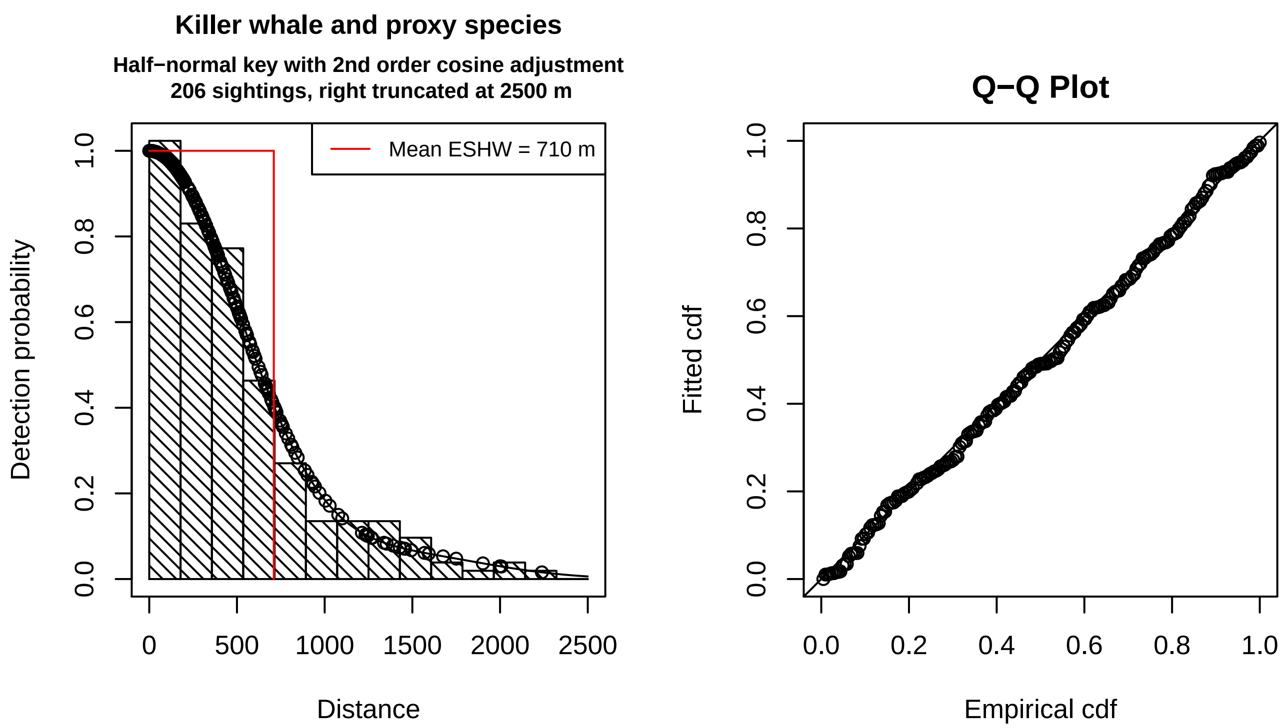

Figure 18: Detection function for NEFSC Abel-J Naked Eye Surveys that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  206
Distance range         :  0  -  2500
AIC                    :  2970.995

Detection function:
 Half-normal key function with cosine adjustment term of order 2

Detection function parameters
Scale Coefficients:
             estimate         se
(Intercept) 6.663426 0.06935711
```

```
Adjustment term parameter(s):
              estimate        se
cos, order 2 0.4738454 0.1225081


Monotonicity constraints were enforced.
                       Estimate          SE         CV
Average p             0.2840856  0.01516015 0.05336471
N in covered region 725.1334366 57.66112492 0.07951795

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

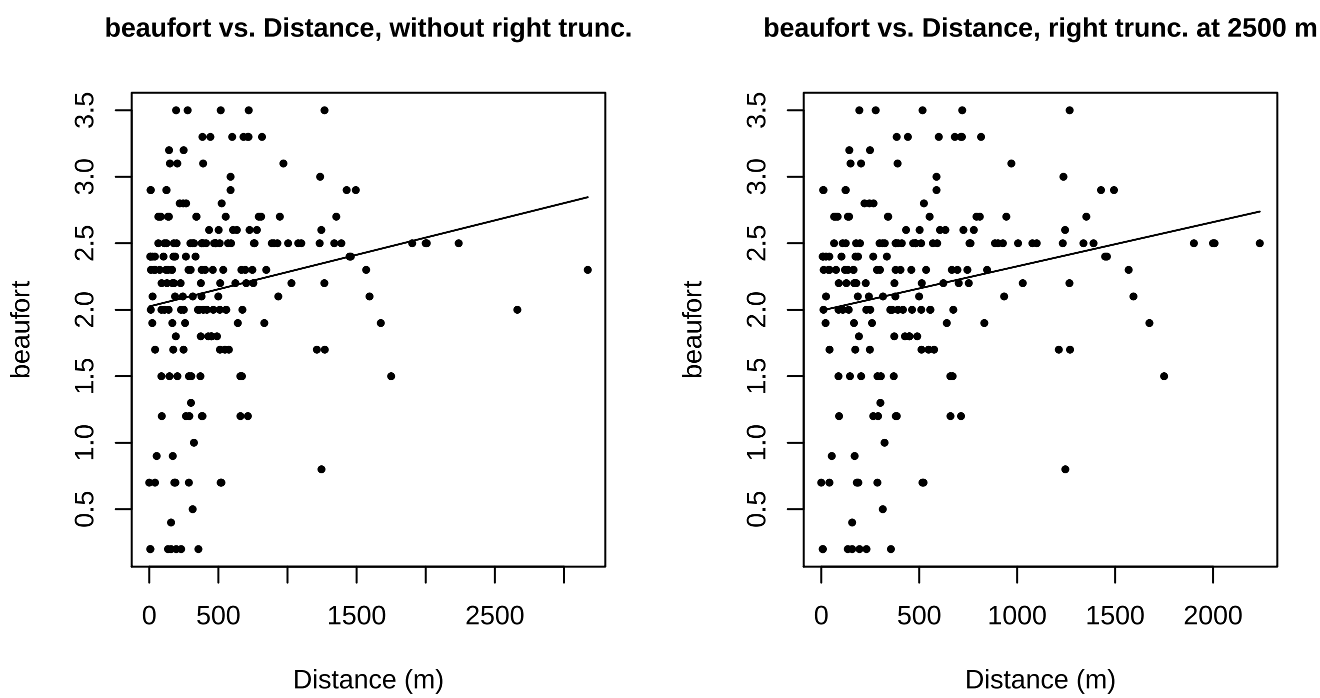

Figure 19: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

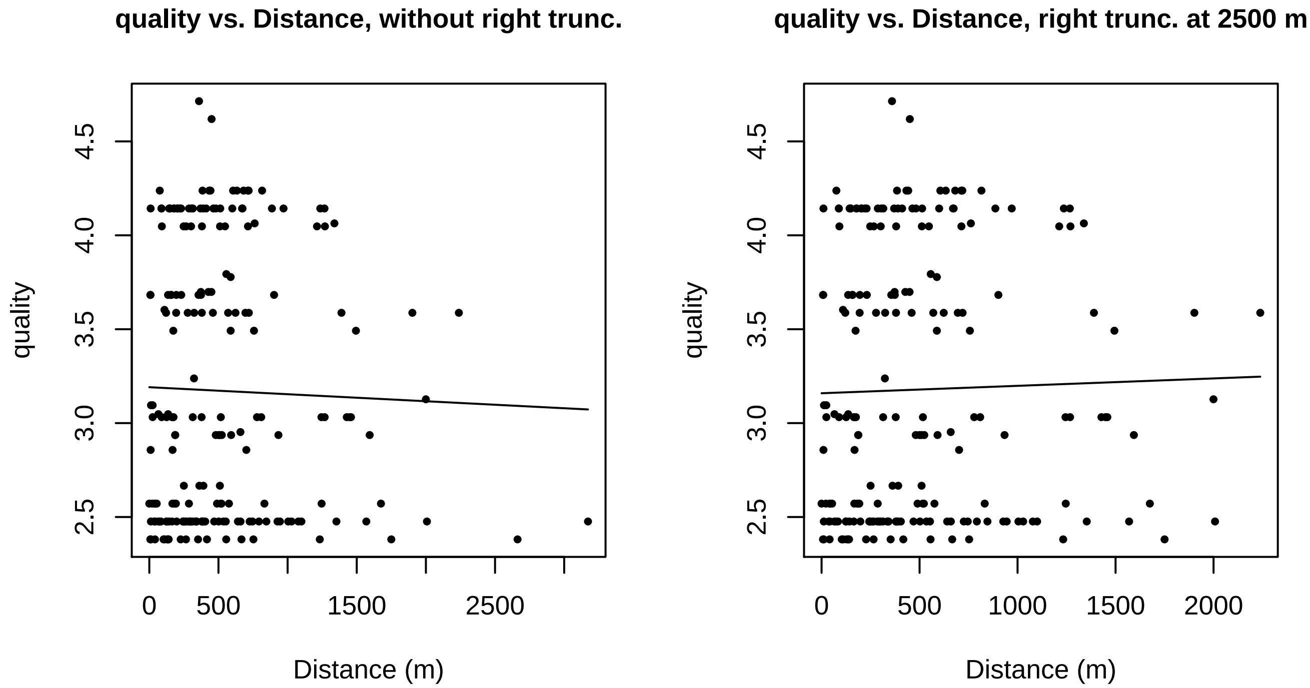

Figure 20: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions. The line is a simple linear regression.

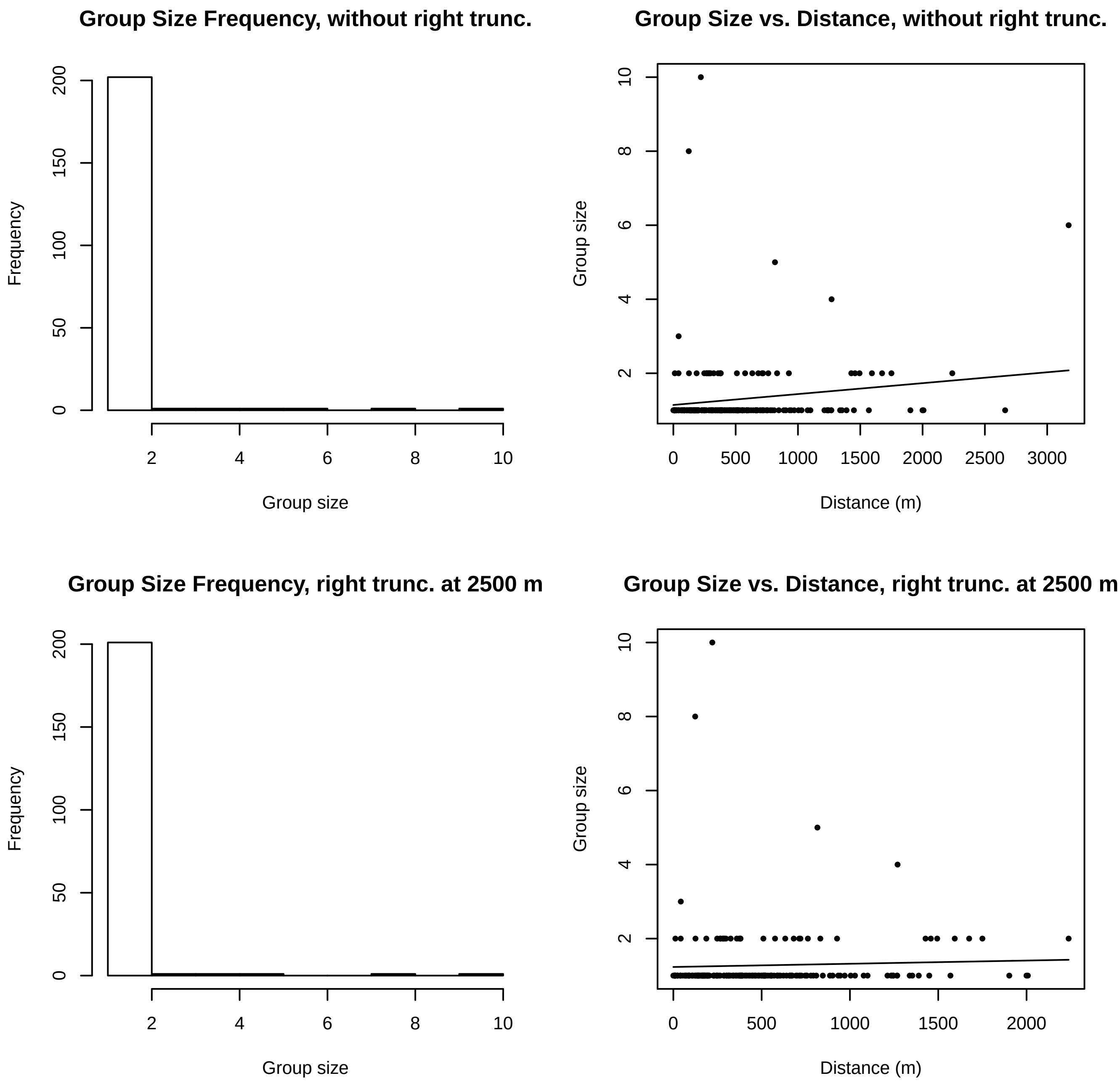

Figure 21: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

CODA and SCANS II

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These “proxy species” are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	0
Balaenoptera acutorostrata	Minke whale	76

Balaenoptera borealis	Sei whale	12
Balaenoptera borealis/edeni	Sei or Bryde's whale	0
Balaenoptera borealis/physalus	Fin or Sei whale	4
Balaenoptera edeni	Bryde's whale	0
Balaenoptera musculus	Blue whale	1
Balaenoptera physalus	Fin whale	192
Eubalaena glacialis	North Atlantic right whale	0
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	0
Orcinus orca	Killer whale	1
Total		286

Table 16: Proxy species used to fit detection functions for CODA and SCANS II. The number of sightings, n, is before truncation.

The sightings were right truncated at 2500m.

Covariate	Description
beaufort	Beaufort sea state.
quality	Survey-specific index of the quality of observation conditions, utilizing relevant factors other than Beaufort sea state (see methods).
size	Estimated size (number of individuals) of the sighted group.

Table 17: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hn	cos	2		Yes	0.00	793
hn	cos	3		Yes	4.32	810
hn				Yes	4.49	899
hr	poly	2		Yes	4.88	825
hn			size	Yes	5.01	899
hr				Yes	5.35	924
hr	poly	4		Yes	5.95	862
hn	herm	4		No		
hn			beaufort	No		
hr			beaufort	No		
hn			quality	No		
hr			quality	No		
hr			size	No		
hn			beaufort, quality	No		

hr	beaufort, quality	No
hn	beaufort, size	No
hr	beaufort, size	No
hn	quality, size	No
hr	quality, size	No
hn	beaufort, quality, size	No
hr	beaufort, quality, size	No

Table 18: Candidate detection functions for CODA and SCANS II. The first one listed was selected for the density model.

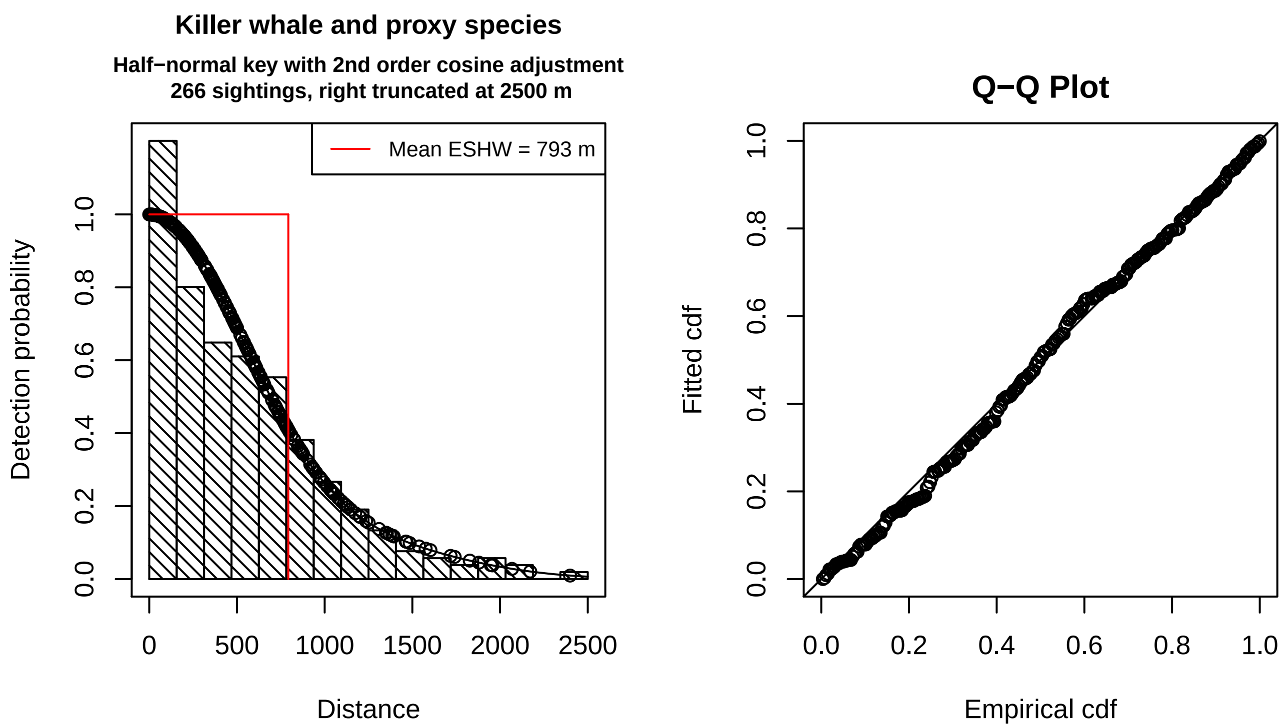

Figure 22: Detection function for CODA and SCANS II that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  266
Distance range         :  0  -  2500
AIC                    :  3880.079

Detection function:
 Half-normal key function with cosine adjustment term of order 2

Detection function parameters
Scale Coefficients:
            estimate         se
(Intercept) 6.669385 0.05438951
```

```
Adjustment term parameter(s):
             estimate        se
cos, order 2 0.294739 0.1071401


Monotonicity constraints were enforced.
                       Estimate          SE         CV
Average p             0.3171721  0.01840233 0.05802001
N in covered region 838.6613057 64.60057080 0.07702820

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

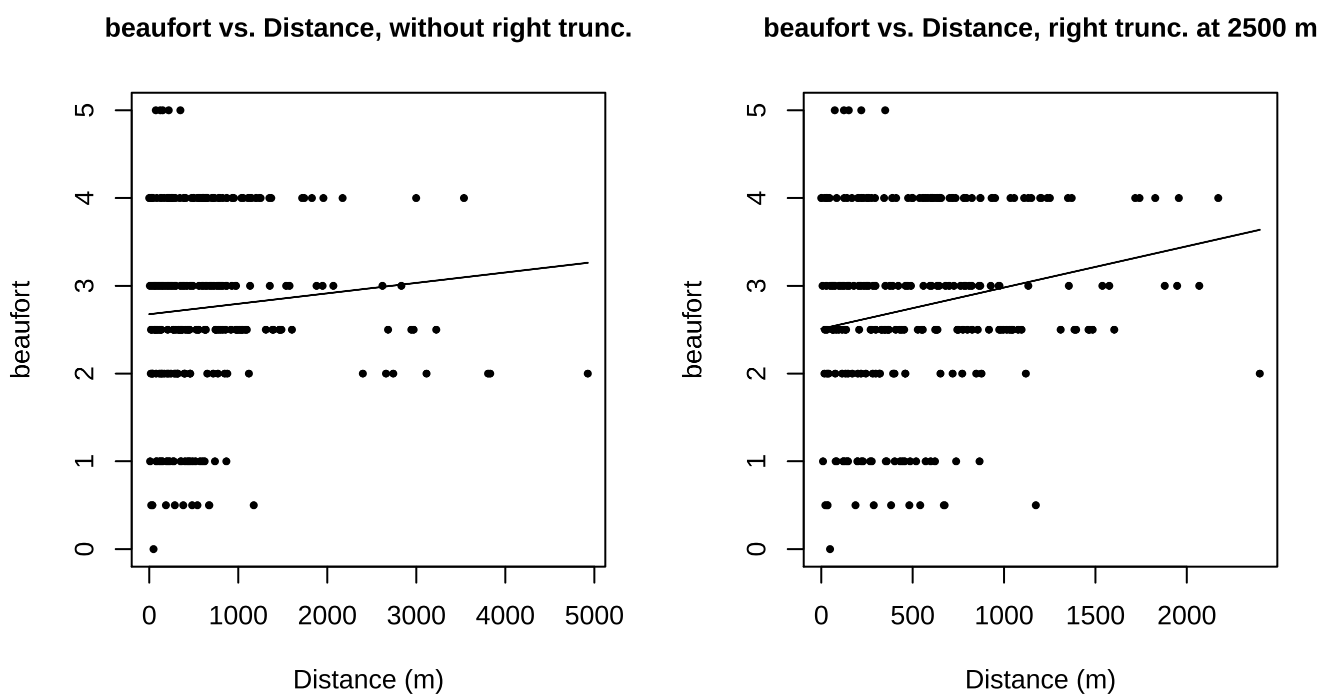

Figure 23: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

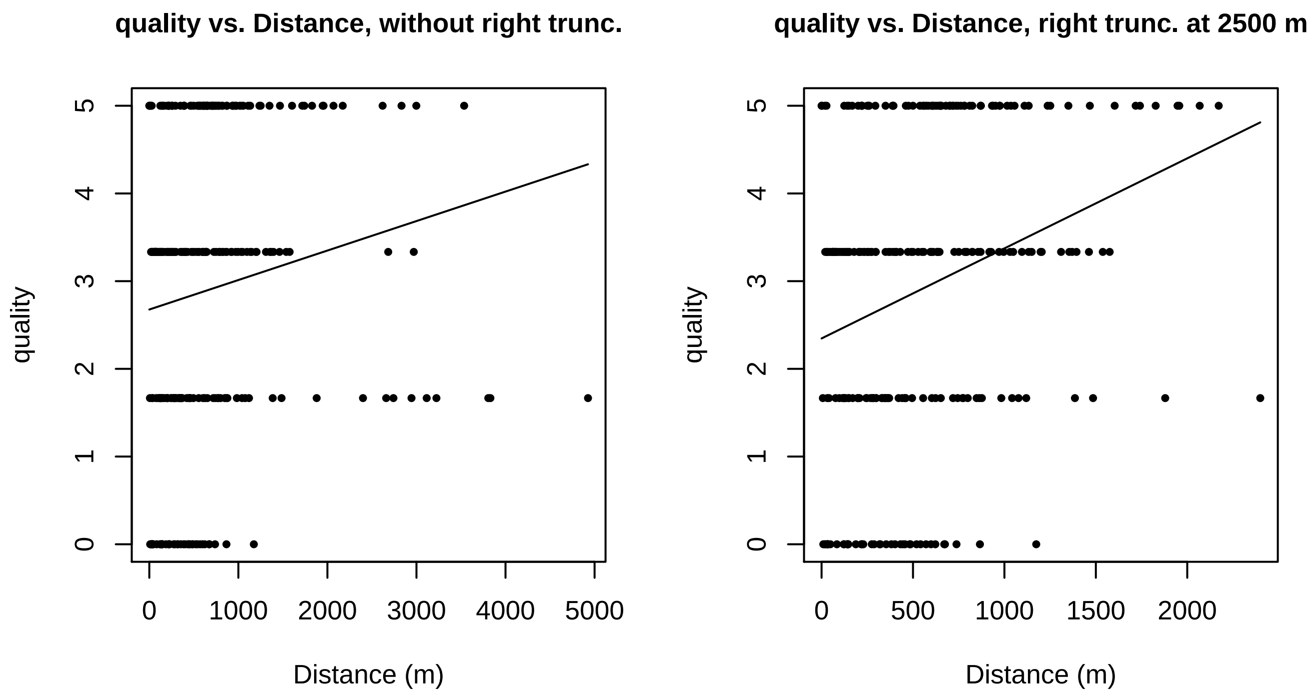

Figure 24: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions. The line is a simple linear regression.

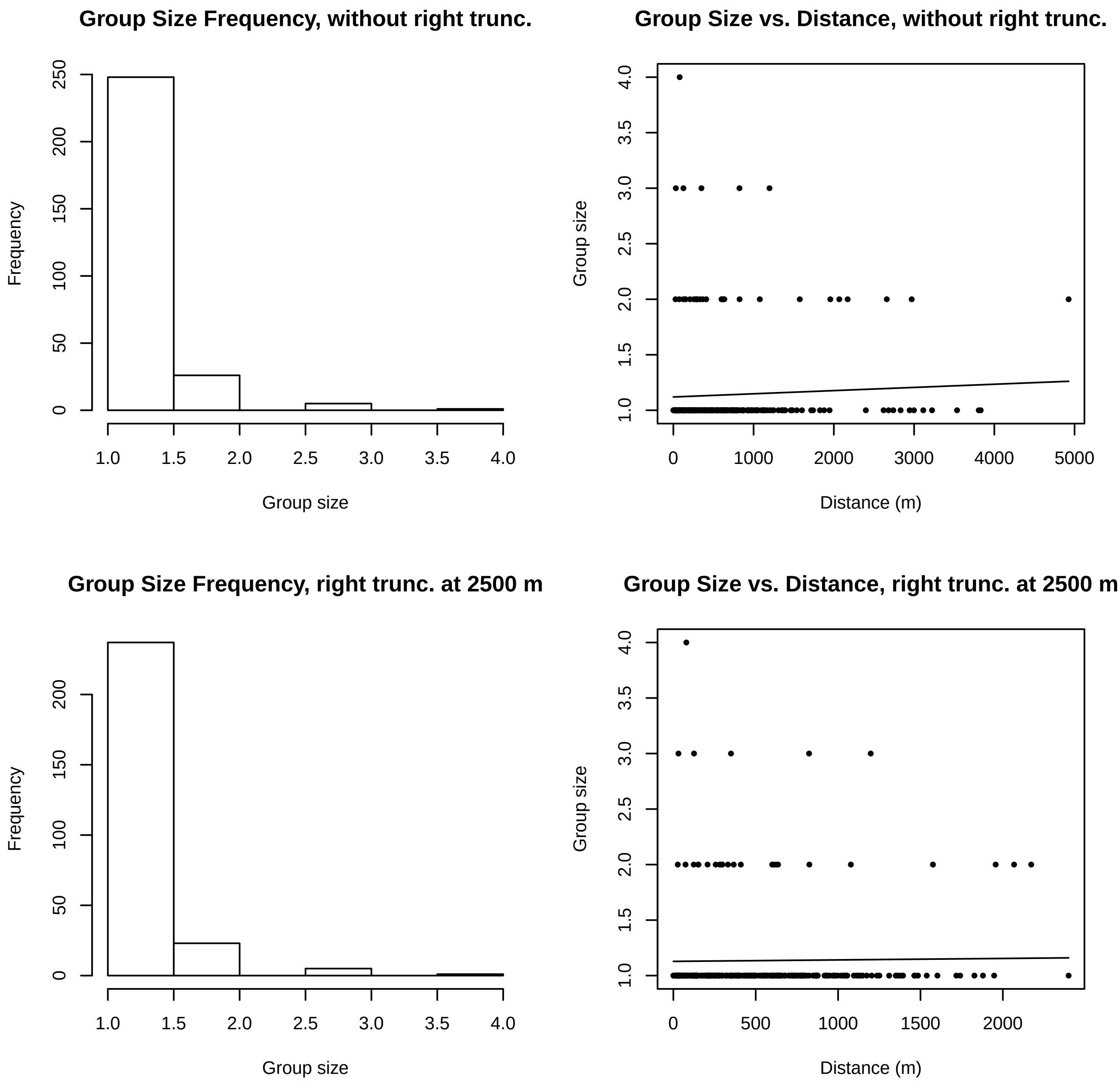

Figure 25: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

Aerial Surveys

Figure 26: Detection hierarchy for aerial surveys

With Belly Observers

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	2
Balaenoptera acutorostrata	Minke whale	97
Balaenoptera borealis	Sei whale	14
Balaenoptera borealis/edeni	Sei or Bryde's whale	0
Balaenoptera borealis/physalus	Fin or Sei whale	0

Balaenoptera edeni	Bryde's whale	2
Balaenoptera musculus	Blue whale	1
Balaenoptera physalus	Fin whale	235
Eubalaena glacialis	North Atlantic right whale	43
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	198
Orcinus orca	Killer whale	0
Total		592

Table 19: Proxy species used to fit detection functions for With Belly Observers. The number of sightings, n, is before truncation.

The sightings were right truncated at 2000m.

Covariate	Description
beaufort	Beaufort sea state.
size	Estimated size (number of individuals) of the sighted group.

Table 20: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hn	cos	2		Yes	0.00	594
hr	poly	2		Yes	1.71	598
hr	poly	4		Yes	1.86	609
hr			size	Yes	6.10	632
hr				Yes	7.37	627
hn	cos	3		Yes	11.15	585
hn			size	Yes	22.91	705
hn				Yes	23.39	703
hn	herm	4		No		
hn			beaufort	No		
hr			beaufort	No		
hn			beaufort, size	No		
hr			beaufort, size	No		

Table 21: Candidate detection functions for With Belly Observers. The first one listed was selected for the density model.

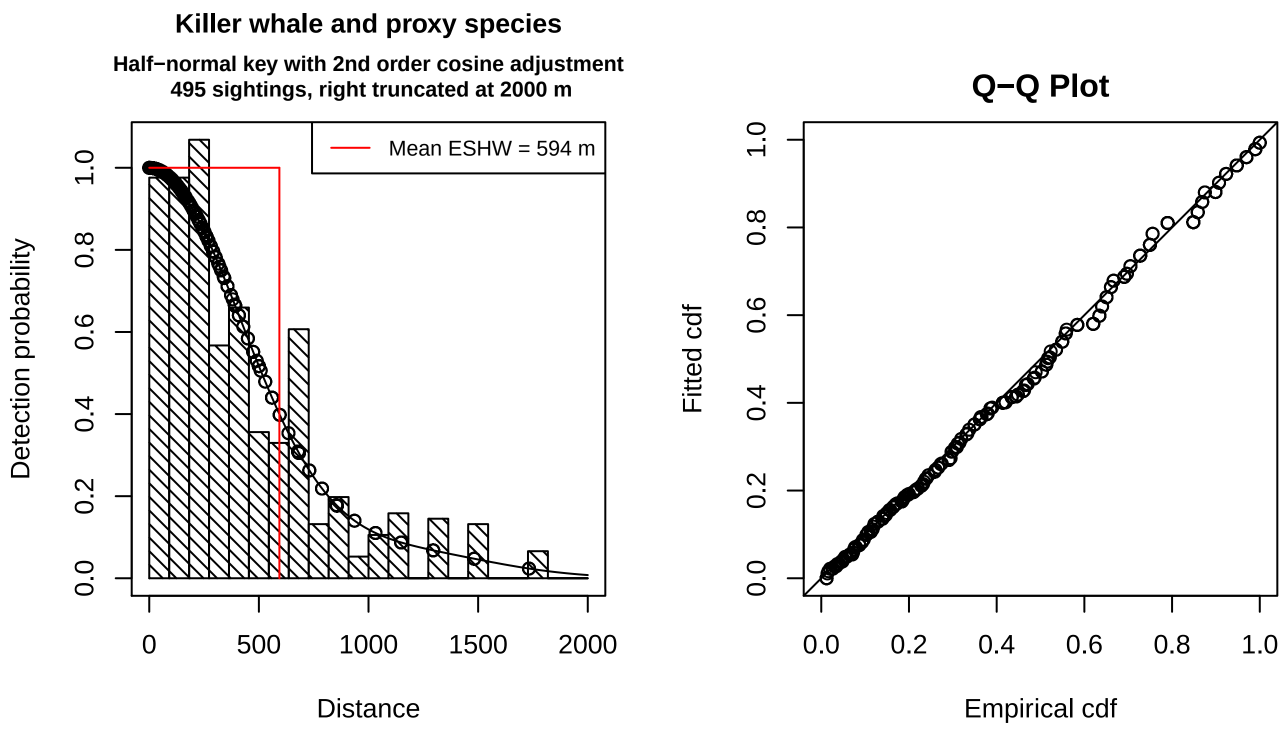

Figure 27: Detection function for With Belly Observers that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  495
Distance range         :  0  -  2000
AIC                    :  6960.823

Detection function:
 Half-normal key function with cosine adjustment term of order 2

Detection function parameters
Scale Coefficients:
            estimate         se
(Intercept) 6.464817 0.04316341

Adjustment term parameter(s):
              estimate        se
cos, order 2 0.4286651 0.0797525


Monotonicity constraints were enforced.
                        Estimate          SE         CV
Average p              0.2967565  0.01131844 0.03814048
N in covered region 1668.0343266 89.44444872 0.05362267

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

Figure 28: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

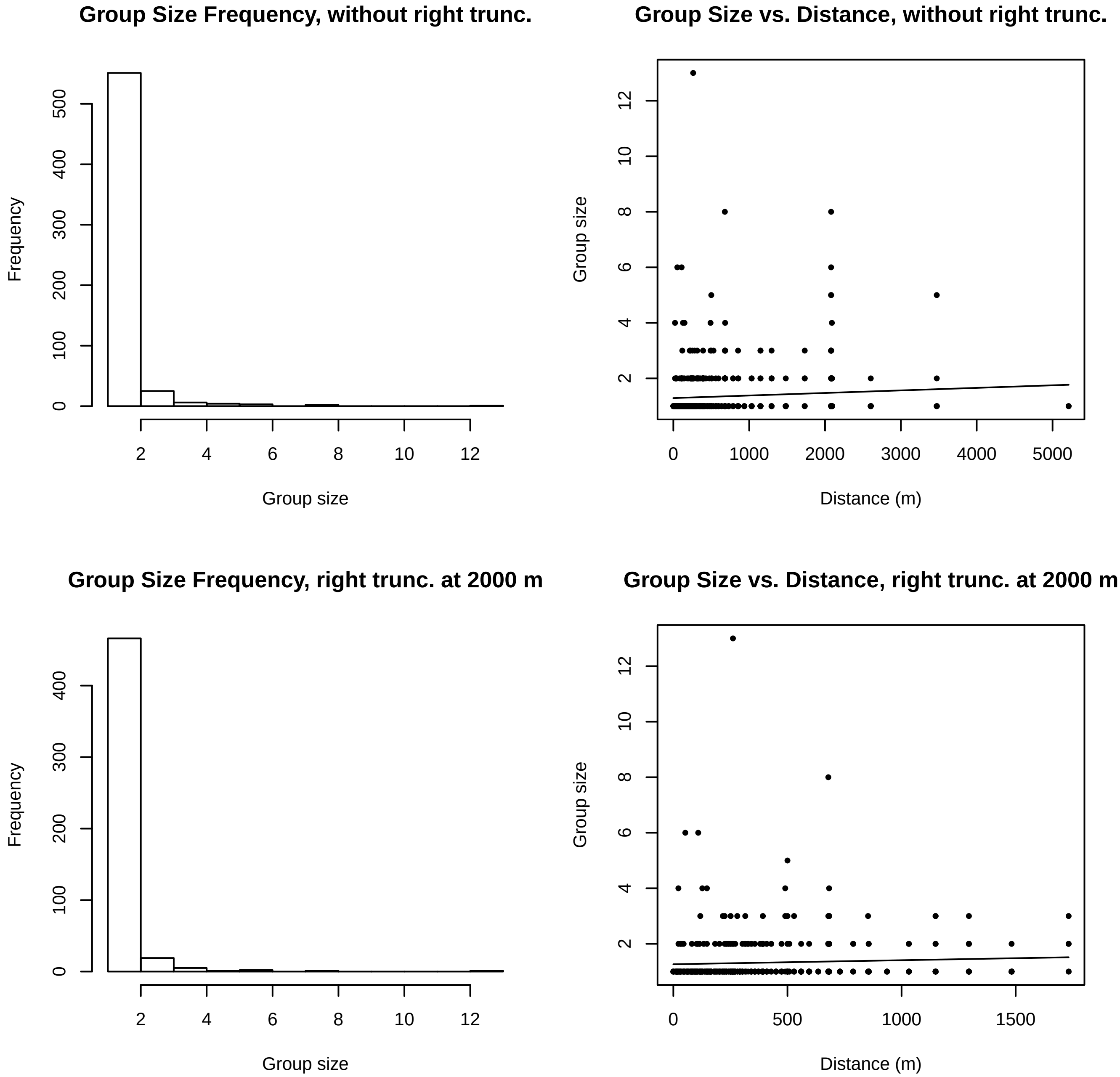

Figure 29: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

Without Belly Observers - 600 ft

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	2
Balaenoptera acutorostrata	Minke whale	8

Balaenoptera borealis	Sei whale	0
Balaenoptera borealis/edeni	Sei or Bryde's whale	0
Balaenoptera borealis/physalus	Fin or Sei whale	0
Balaenoptera edeni	Bryde's whale	0
Balaenoptera musculus	Blue whale	0
Balaenoptera physalus	Fin whale	15
Eubalaena glacialis	North Atlantic right whale	2
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	16
Orcinus orca	Killer whale	2
Physeter macrocephalus	Sperm whale	10
Total		55

Table 22: Proxy species used to fit detection functions for Without Belly Observers - 600 ft. The number of sightings, n, is before truncation.

The sightings were right truncated at 600m. Due to a reduced frequency of sightings close to the trackline that plausibly resulted from the behavior of the observers and/or the configuration of the survey platform, the sightings were left truncted as well. Sightings closer than 32 m to the trackline were omitted from the analysis, and it was assumed that the the area closer to the trackline than this was not surveyed. This distance was estimated by inspecting histograms of perpendicular sighting distances.

Covariate	Description
beaufort	Beaufort sea state.
size	Estimated size (number of individuals) of the sighted group.

Table 23: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hn				Yes	0.00	285
hr				Yes	0.95	304
hr			beaufort	Yes	0.97	315
hn			beaufort	Yes	1.09	285
hn	cos	3		Yes	1.58	304
hn	herm	4		Yes	1.93	284
hn	cos	2		Yes	1.94	270
hr	poly	4		Yes	2.95	304
hr	poly	2		Yes	2.95	304
hn			size	No		
hr			size	No		
hn			beaufort, size	No		
hr			beaufort, size	No		

Table 24: Candidate detection functions for Without Belly Observers - 600 ft. The first one listed was selected for the density model.

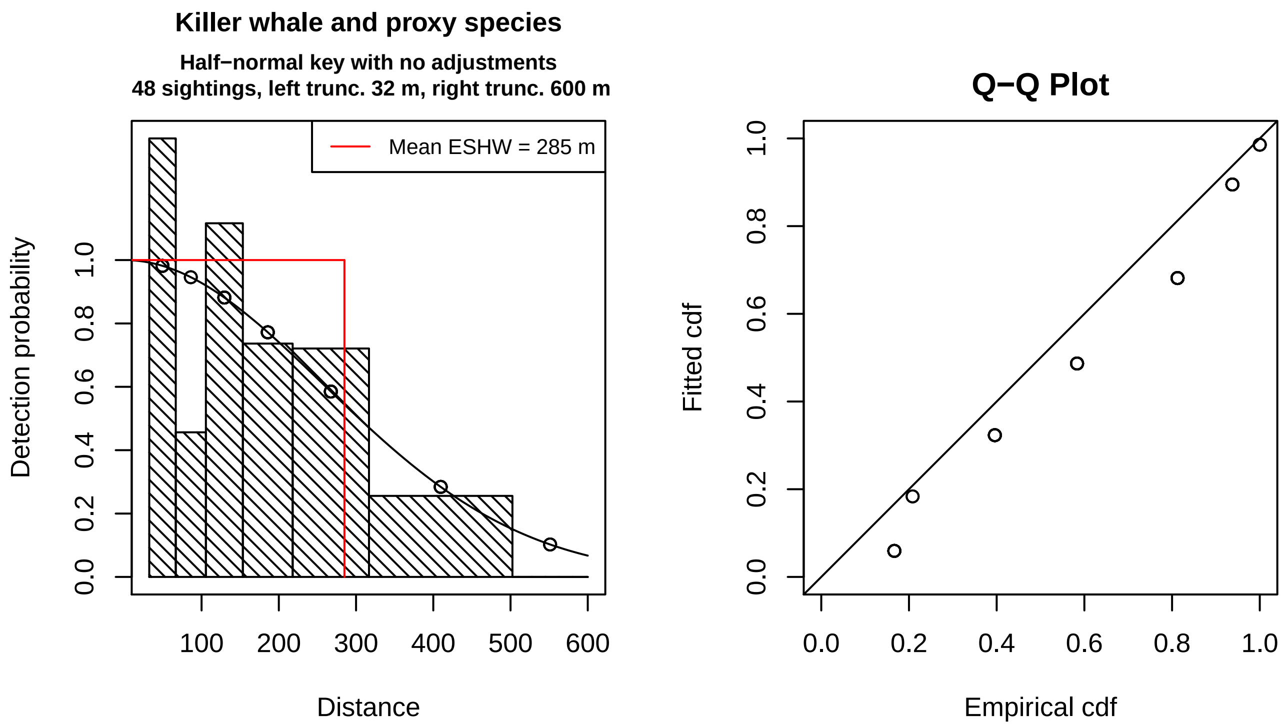

Figure 30: Detection function for Without Belly Observers - 600 ft that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  48
Distance range         :  32.24668  -  600
AIC                    :  185.0831

Detection function:
 Half-normal key function

Detection function parameters
Scale Coefficients:
            estimate        se
(Intercept) 5.553853 0.1259755

                       Estimate          SE        CV
Average p             0.4749316  0.05807637 0.1222837
N in covered region 101.0671778 16.26277838 0.1609106
```

Additional diagnostic plots:

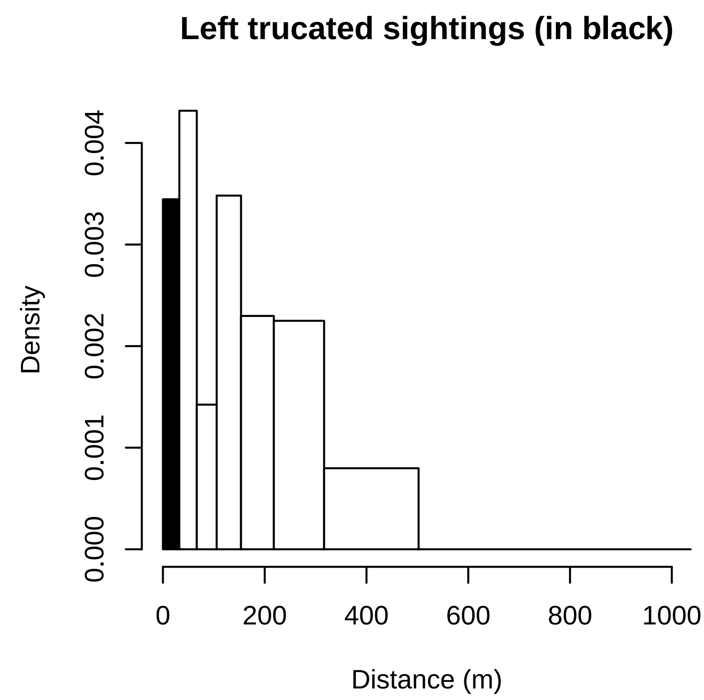

Figure 31: Density of sightings by perpendicular distance for Without Belly Observers - 600 ft. Black bars on the left show sightings that were left truncated.

Figure 32: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

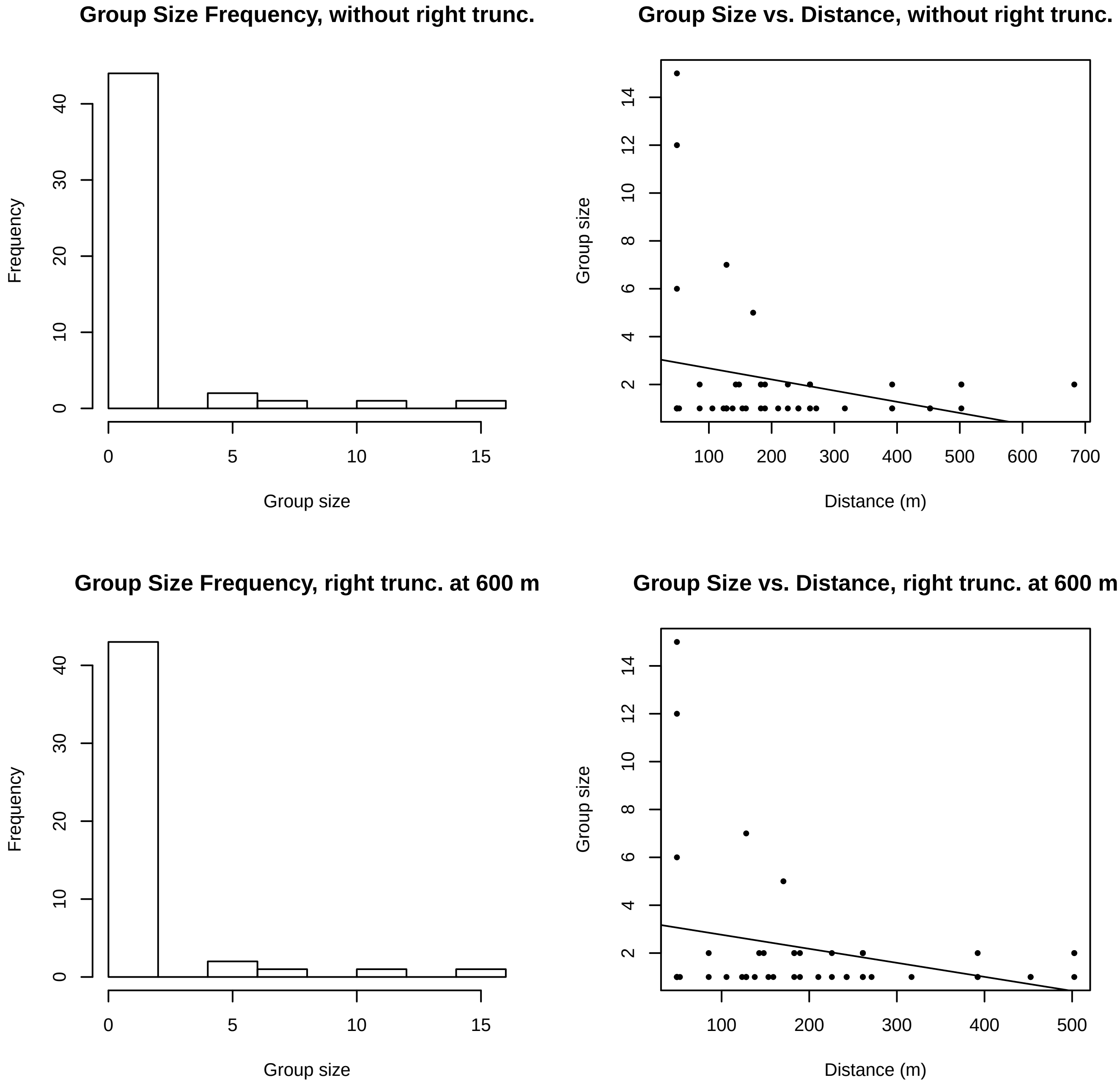

Figure 33: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

Without Belly Observers - 750 ft

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	1
Balaenoptera acutorostrata	Minke whale	0

Balaenoptera borealis	Sei whale	0
Balaenoptera borealis/edeni	Sei or Bryde's whale	2
Balaenoptera borealis/physalus	Fin or Sei whale	0
Balaenoptera edeni	Bryde's whale	3
Balaenoptera musculus	Blue whale	0
Balaenoptera physalus	Fin whale	2
Eubalaena glacialis	North Atlantic right whale	0
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	6
Orcinus orca	Killer whale	0
Physeter macrocephalus	Sperm whale	37
Total		51

Table 25: Proxy species used to fit detection functions for Without Belly Observers - 750 ft. The number of sightings, n, is before truncation.

The sightings were right truncated at 600m. Due to a reduced frequency of sightings close to the trackline that plausibly resulted from the behavior of the observers and/or the configuration of the survey platform, the sightings were left truncted as well. Sightings closer than 40 m to the trackline were omitted from the analysis, and it was assumed that the the area closer to the trackline than this was not surveyed. This distance was estimated by inspecting histograms of perpendicular sighting distances. The vertical sighting angles were heaped at 10 degree increments, so the candidate detection functions were fitted using linear bins scaled accordingly.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hn	cos	2		Yes	0.00	216
hr				Yes	0.59	251
hn	cos	3		Yes	2.31	255
hn	herm	4		Yes	2.46	316
hr	poly	2		Yes	2.59	251
hr	poly	4		Yes	2.60	259
hn				No		

Table 26: Candidate detection functions for Without Belly Observers - 750 ft. The first one listed was selected for the density model.

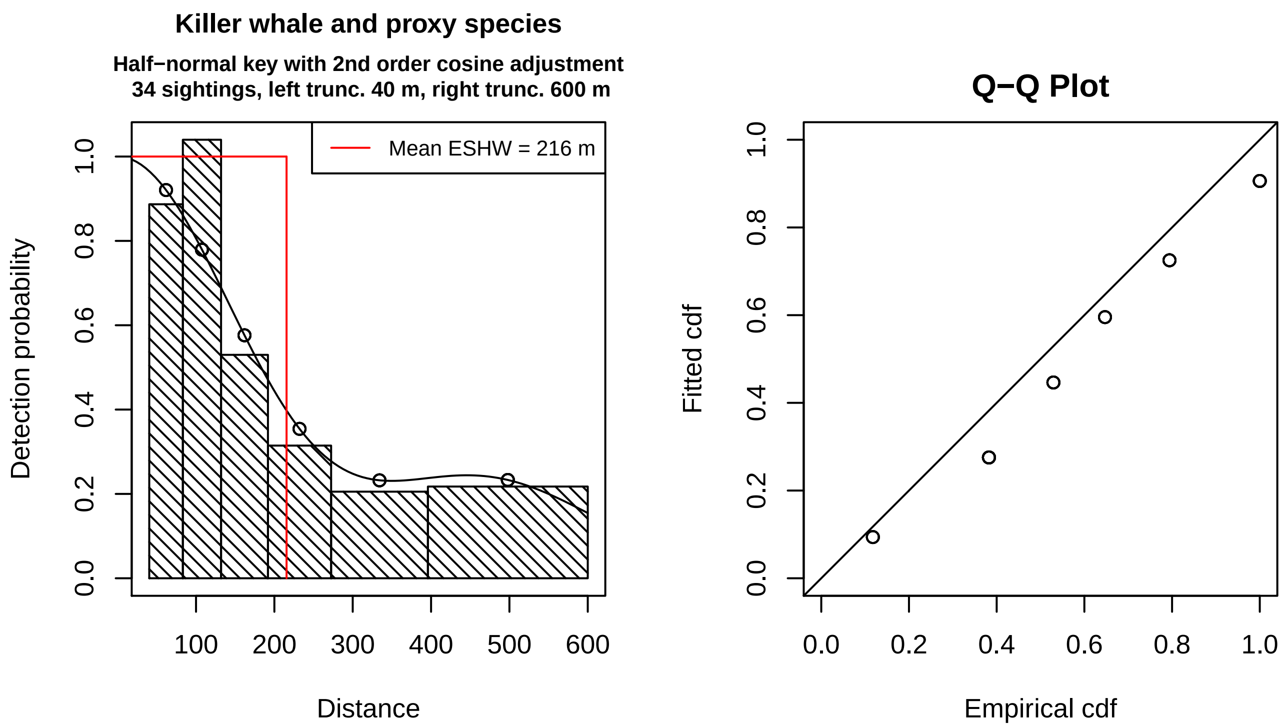

Figure 34: Detection function for Without Belly Observers - 750 ft that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  34
Distance range         :  40.30835  -  600
AIC                    :  124.984

Detection function:
 Half-normal key function with cosine adjustment term of order 2

Detection function parameters
Scale Coefficients:
            estimate        se
(Intercept) 5.738324 0.1838281

Adjustment term parameter(s):
              estimate       se
cos, order 2 0.4333816 0.242253


Monotonicity constraints were enforced.
                      Estimate         SE        CV
Average p            0.3592782  0.0870934 0.2424122
N in covered region 94.6341959 26.3634677 0.2785829

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

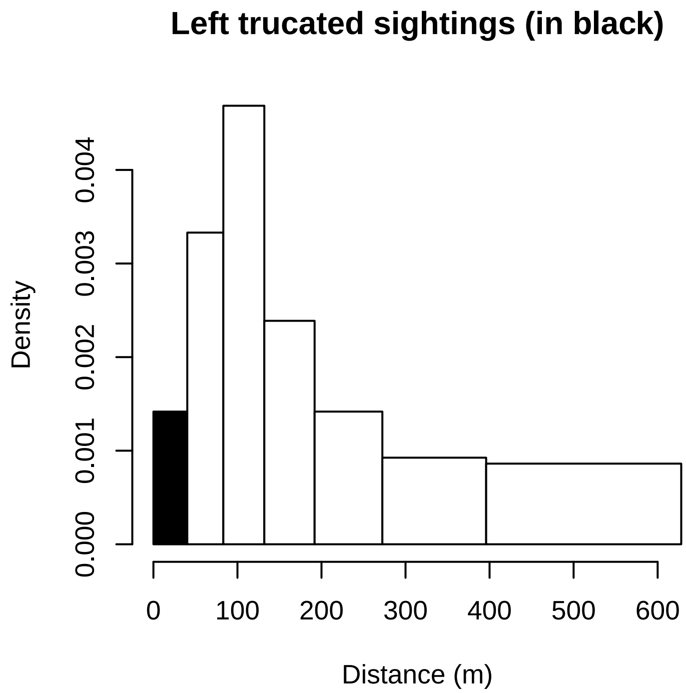

Figure 35: Density of sightings by perpendicular distance for Without Belly Observers - 750 ft. Black bars on the left show sightings that were left truncated.

Without Belly Observers - 1000 ft

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	1
Balaenoptera acutorostrata	Minke whale	16
Balaenoptera borealis	Sei whale	0
Balaenoptera borealis/edeni	Sei or Bryde's whale	0
Balaenoptera borealis/physalus	Fin or Sei whale	0
Balaenoptera edeni	Bryde's whale	0
Balaenoptera musculus	Blue whale	0
Balaenoptera physalus	Fin whale	32
Eubalaena glacialis	North Atlantic right whale	34
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	30
Orcinus orca	Killer whale	0
Total		113

Table 27: Proxy species used to fit detection functions for Without Belly Observers - 1000 ft. The number of sightings, n, is before truncation.

The sightings were right truncated at 1500m.

Covariate	Description
beaufort	Beaufort sea state.
quality	Survey-specific index of the quality of observation conditions, utilizing relevant factors other than Beaufort sea state (see methods).
size	Estimated size (number of individuals) of the sighted group.

Table 28: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hr				Yes	0.00	434
hr	poly	4		Yes	1.58	424
hn	cos	2		Yes	1.71	462
hr	poly	2		Yes	1.92	427
hr			quality	Yes	1.96	433
hn	cos	3		Yes	3.64	418
hn				Yes	11.03	585
hn	herm	4		No		
hn			beaufort	No		
hr			beaufort	No		
hn			quality	No		
hn			size	No		
hr			size	No		
hn			beaufort, quality	No		
hr			beaufort, quality	No		
hn			beaufort, size	No		
hr			beaufort, size	No		
hn			quality, size	No		
hr			quality, size	No		
hn			beaufort, quality, size	No		
hr			beaufort, quality, size	No		

Table 29: Candidate detection functions for Without Belly Observers - 1000 ft. The first one listed was selected for the density model.

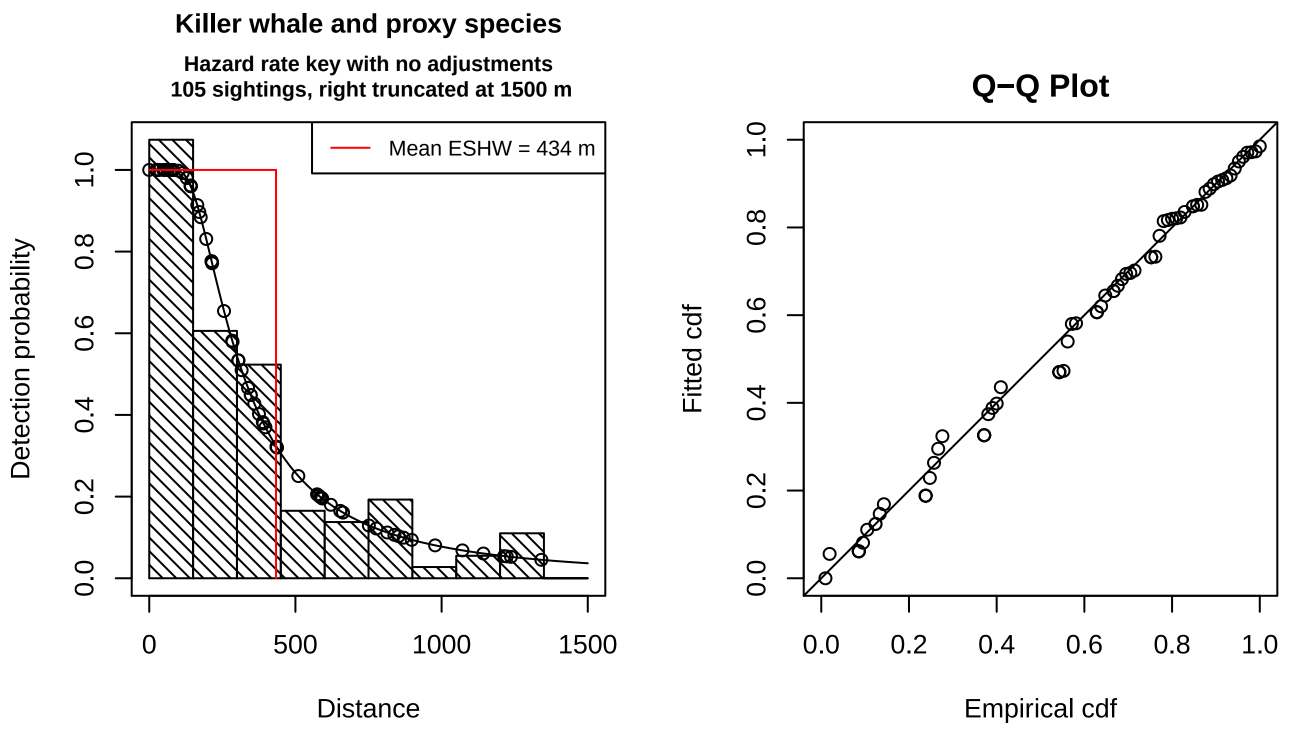

Figure 36: Detection function for Without Belly Observers - 1000 ft that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  105
Distance range         :  0  -  1500
AIC                    :  1432.491

Detection function:
 Hazard-rate key function

Detection function parameters
Scale Coefficients:
            estimate        se
(Intercept) 5.576432 0.2232183

Shape parameters:
             estimate        se
(Intercept) 0.6374087 0.1752092

                       Estimate          SE        CV
Average p             0.2891295  0.03984493 0.1378100
N in covered region 363.1591175 58.28878285 0.1605048
```

Additional diagnostic plots:

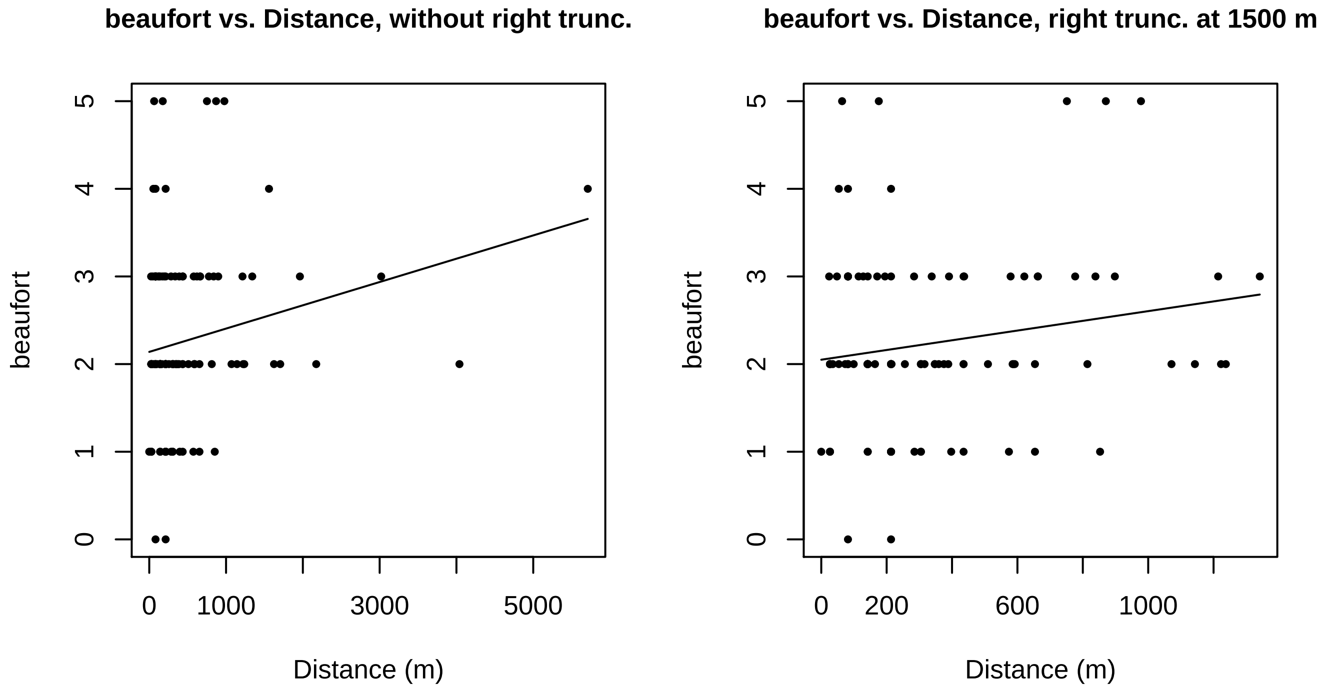

Figure 37: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

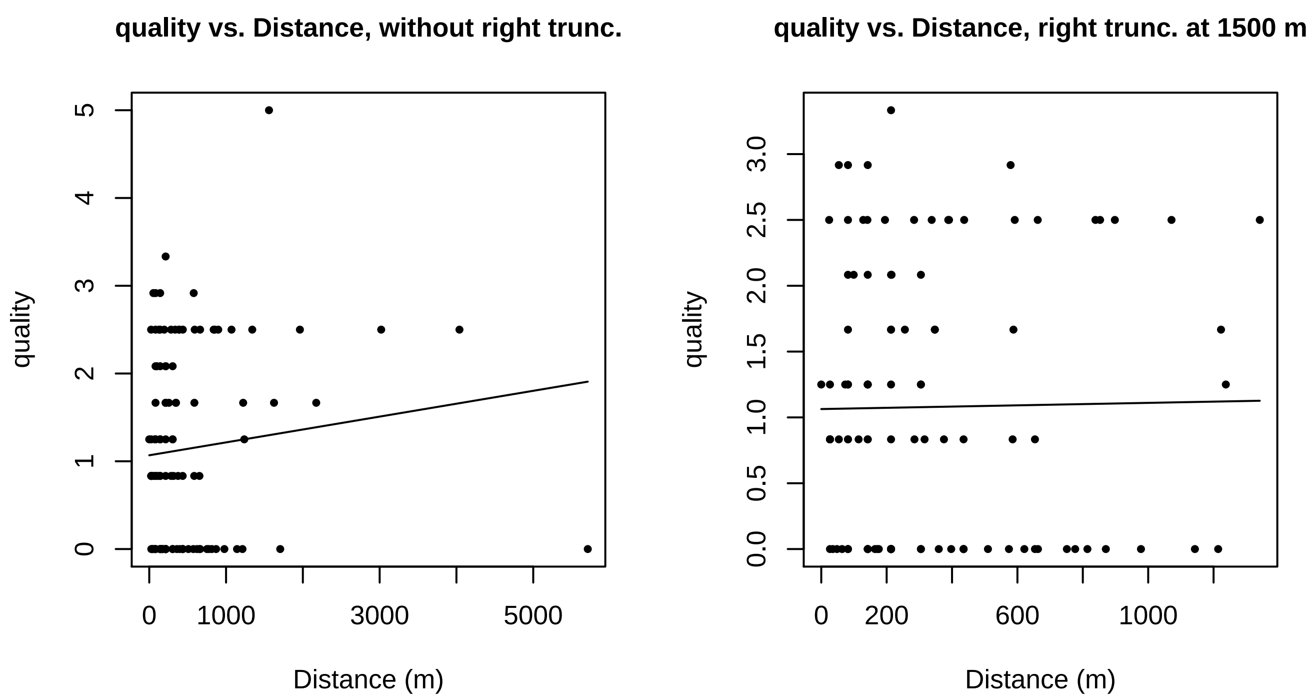

Figure 38: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions. The line is a simple linear regression.

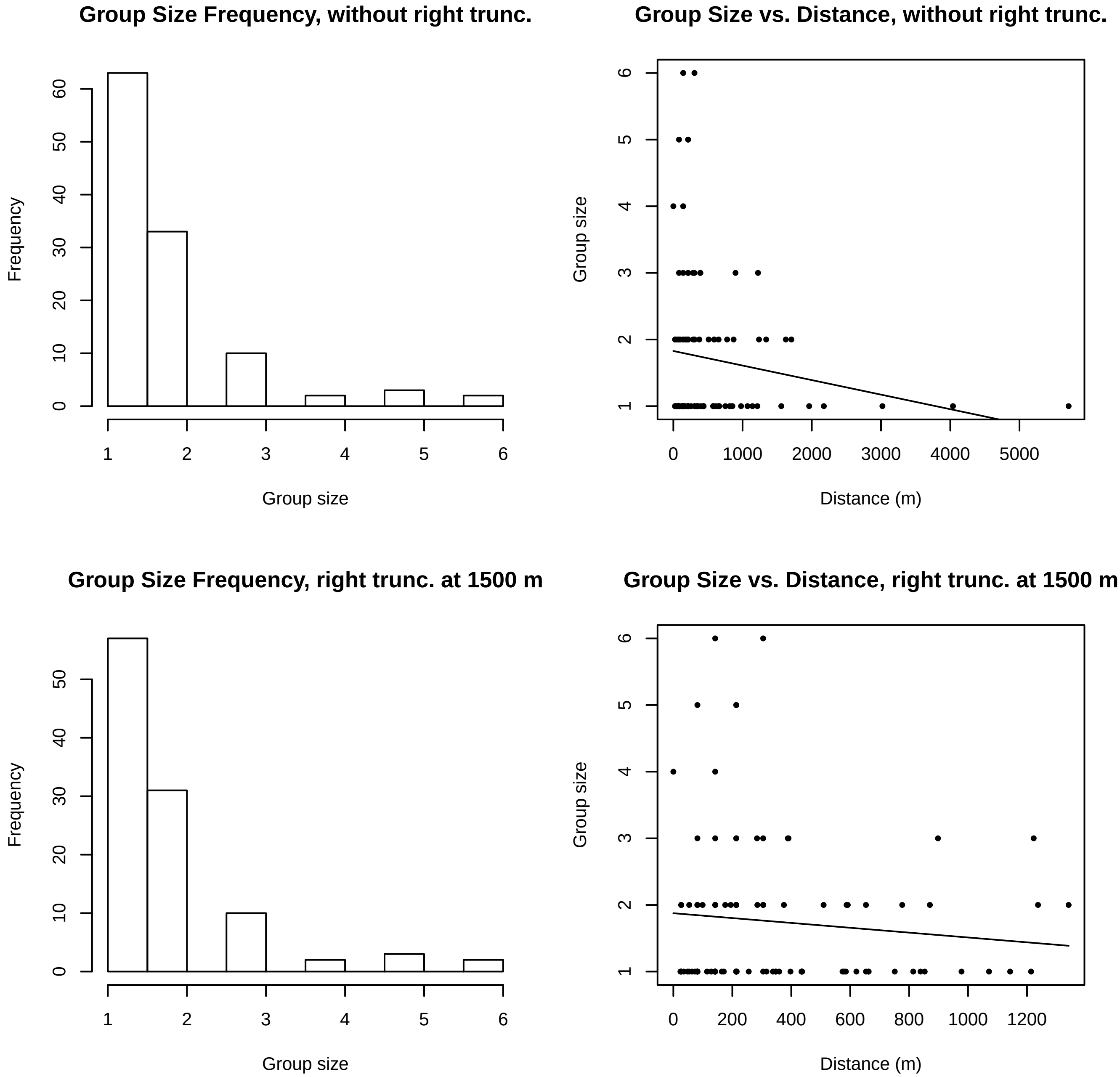

Figure 39: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

UNCW Aerial Surveys

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	1
Balaenoptera acutorostrata	Minke whale	15

Balaenoptera borealis	Sei whale	0
Balaenoptera borealis/edeni	Sei or Bryde's whale	0
Balaenoptera borealis/physalus	Fin or Sei whale	0
Balaenoptera edeni	Bryde's whale	0
Balaenoptera musculus	Blue whale	0
Balaenoptera physalus	Fin whale	19
Eubalaena glacialis	North Atlantic right whale	31
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	23
Orcinus orca	Killer whale	0
Total		89

Table 30: Proxy species used to fit detection functions for UNCW Aerial Surveys. The number of sightings, n, is before truncation.

The sightings were right truncated at 1500m.

Covariate	Description
beaufort	Beaufort sea state.
quality	Survey-specific index of the quality of observation conditions, utilizing relevant factors other than Beaufort sea state (see methods).
size	Estimated size (number of individuals) of the sighted group.

Table 31: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hn	cos	3		Yes	0.00	358
hr				Yes	0.01	397
hr	poly	4		Yes	0.85	391
hr	poly	2		Yes	1.03	386
hn	cos	2		Yes	1.24	409
hr			quality	Yes	1.55	396
hn				Yes	5.53	480
hn			quality	Yes	7.53	480
hn	herm	4		No		
hn			beaufort	No		
hr			beaufort	No		
hn			size	No		
hr			size	No		
hn			beaufort, quality	No		

hr	beaufort, quality	No
hn	beaufort, size	No
hr	beaufort, size	No
hn	quality, size	No
hr	quality, size	No
hn	beaufort, quality, size	No
hr	beaufort, quality, size	No

Table 32: Candidate detection functions for UNCW Aerial Surveys. The first one listed was selected for the density model.

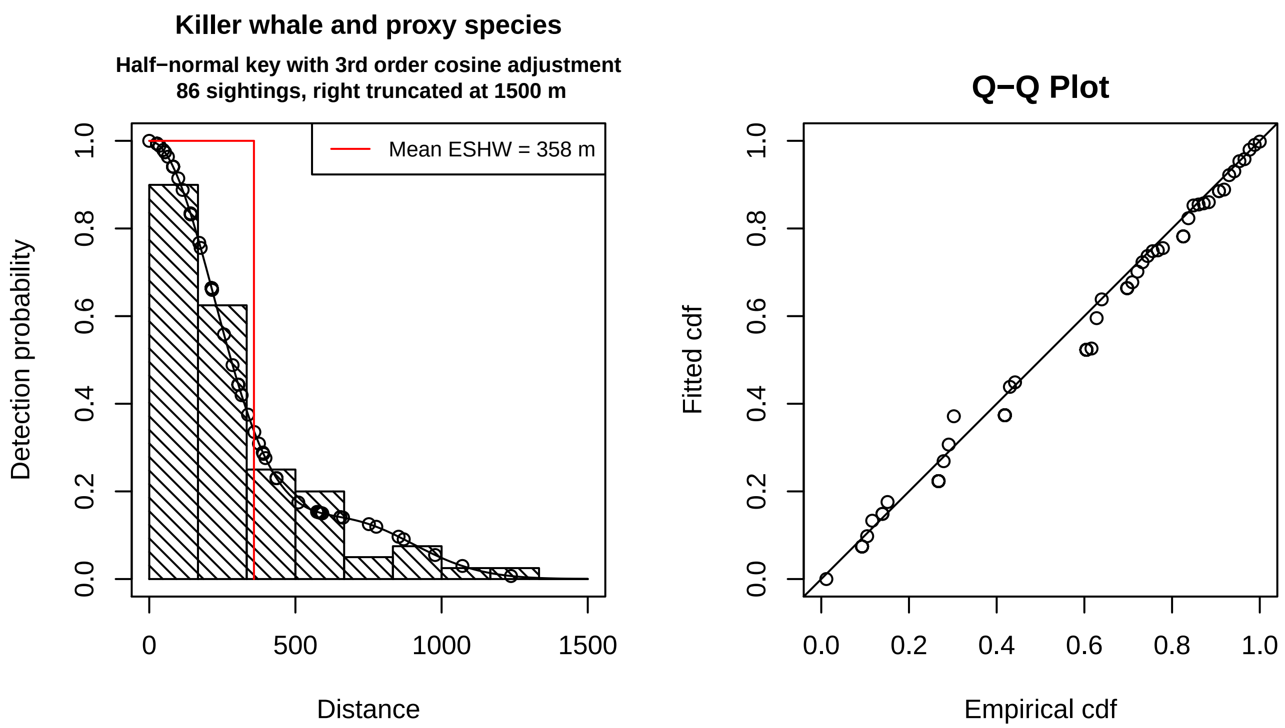

Figure 40: Detection function for UNCW Aerial Surveys that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  86
Distance range         :  0  -  1500
AIC                    :  1144.166

Detection function:
 Half-normal key function with cosine adjustment term of order 3

Detection function parameters
Scale Coefficients:
            estimate         se
(Intercept) 6.006457 0.06897785
```

```
Adjustment term parameter(s):
              estimate        se
cos, order 3 0.4451317 0.1512901


Monotonicity constraints were enforced.
                       Estimate          SE        CV
Average p             0.2387636  0.02505434 0.1049337
N in covered region 360.1889349 50.76321130 0.1409350

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

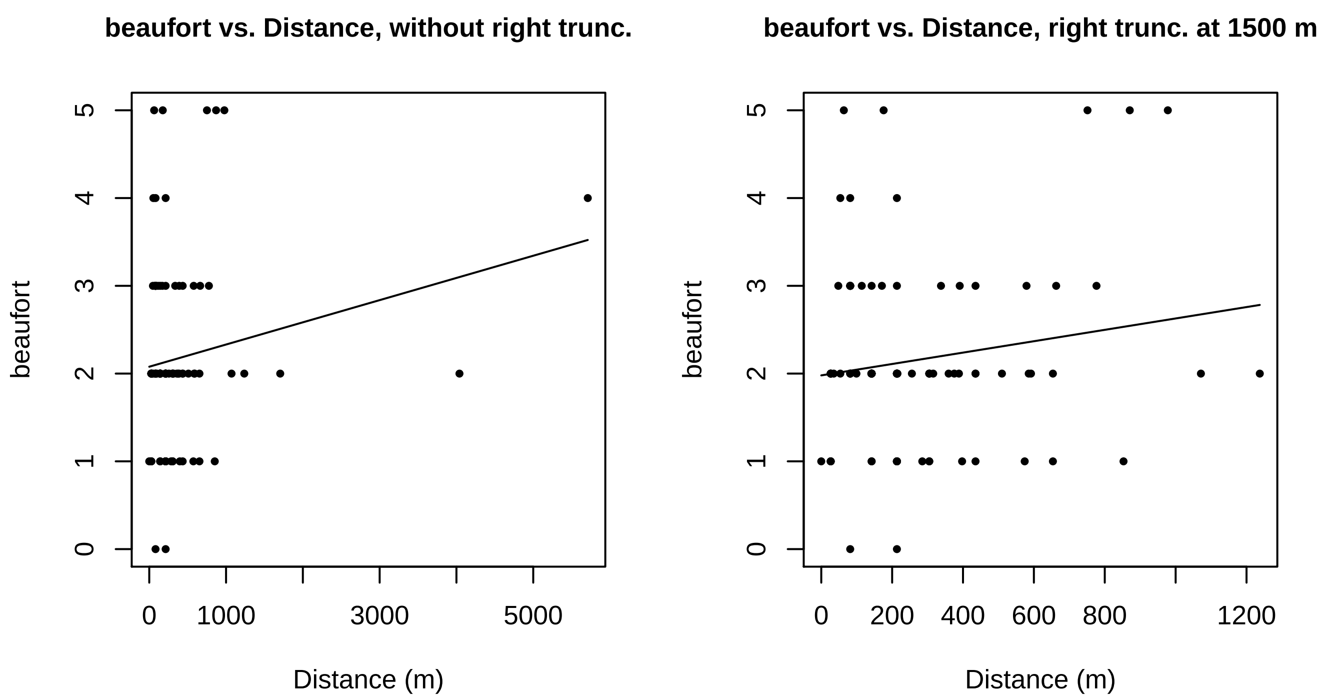

Figure 41: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

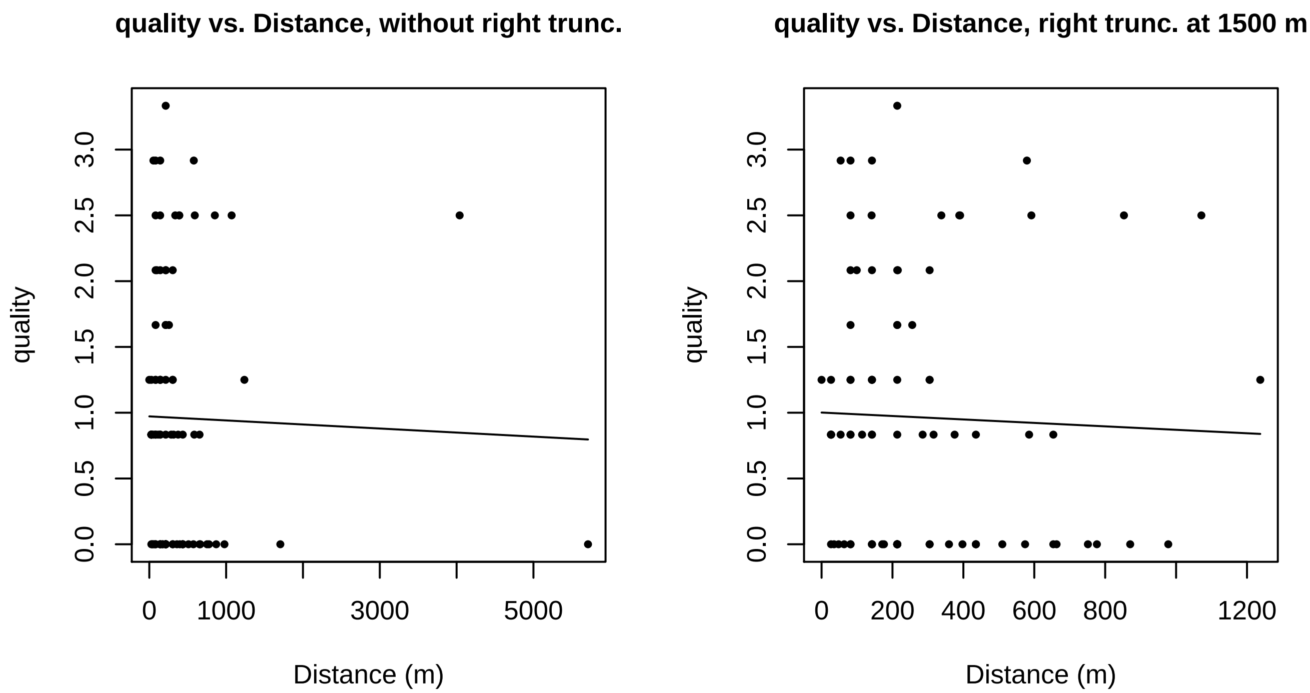

Figure 42: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions. The line is a simple linear regression.

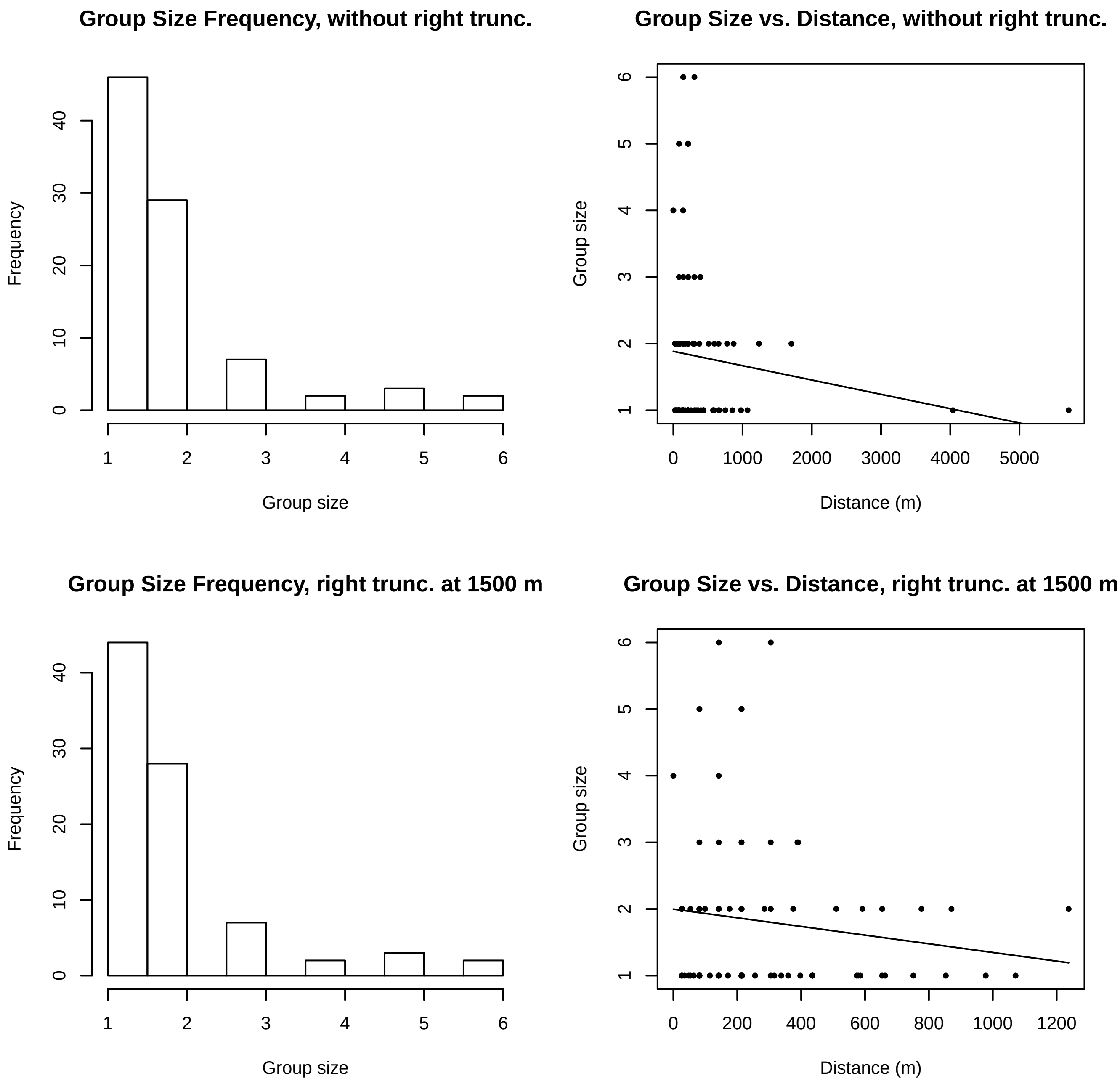

Figure 43: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

NARWSS Grummans

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	0
Balaenoptera acutorostrata	Minke whale	88

Balaenoptera borealis	Sei whale	101
Balaenoptera borealis/edeni	Sei or Bryde's whale	0
Balaenoptera borealis/physalus	Fin or Sei whale	0
Balaenoptera edeni	Bryde's whale	0
Balaenoptera musculus	Blue whale	0
Balaenoptera physalus	Fin whale	149
Eubalaena glacialis	North Atlantic right whale	113
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	153
Orcinus orca	Killer whale	0
Total		604

Table 33: Proxy species used to fit detection functions for NARWSS Grummans. The number of sightings, n, is before truncation.

The sightings were right truncated at 3000m. Due to a reduced frequency of sightings close to the trackline that plausibly resulted from the behavior of the observers and/or the configuration of the survey platform, the sightings were left truncted as well. Sightings closer than 107 m to the trackline were omitted from the analysis, and it was assumed that the the area closer to the trackline than this was not surveyed. This distance was estimated by inspecting histograms of perpendicular sighting distances.

Covariate	Description
beaufort	Beaufort sea state.
quality	Survey-specific index of the quality of observation conditions, utilizing relevant factors other than Beaufort sea state (see methods).
size	Estimated size (number of individuals) of the sighted group.

Table 34: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hr			quality, size	Yes	0.00	676
hr			size	Yes	0.23	664
hr	poly	2		Yes	1.31	499
hr	poly	4		Yes	1.46	528
hr			beaufort, size	Yes	2.18	663
hr			quality	Yes	5.01	612
hr				Yes	5.18	607
hr			beaufort	Yes	7.18	607
hn	cos	2		Yes	22.92	797
hn	cos	3		Yes	44.94	730
hn			size	Yes	76.90	1049

hn			quality, size	Yes	78.25	1049
hn				Yes	83.16	1045
hn			quality	Yes	84.79	1044
hn	herm	4		No		
hn			beaufort	No		
hn			beaufort, quality	No		
hr			beaufort, quality	No		
hn			beaufort, size	No		
hn			beaufort, quality, size	No		
hr			beaufort, quality, size	No		

Table 35: Candidate detection functions for NARWSS Grummans. The first one listed was selected for the density model.

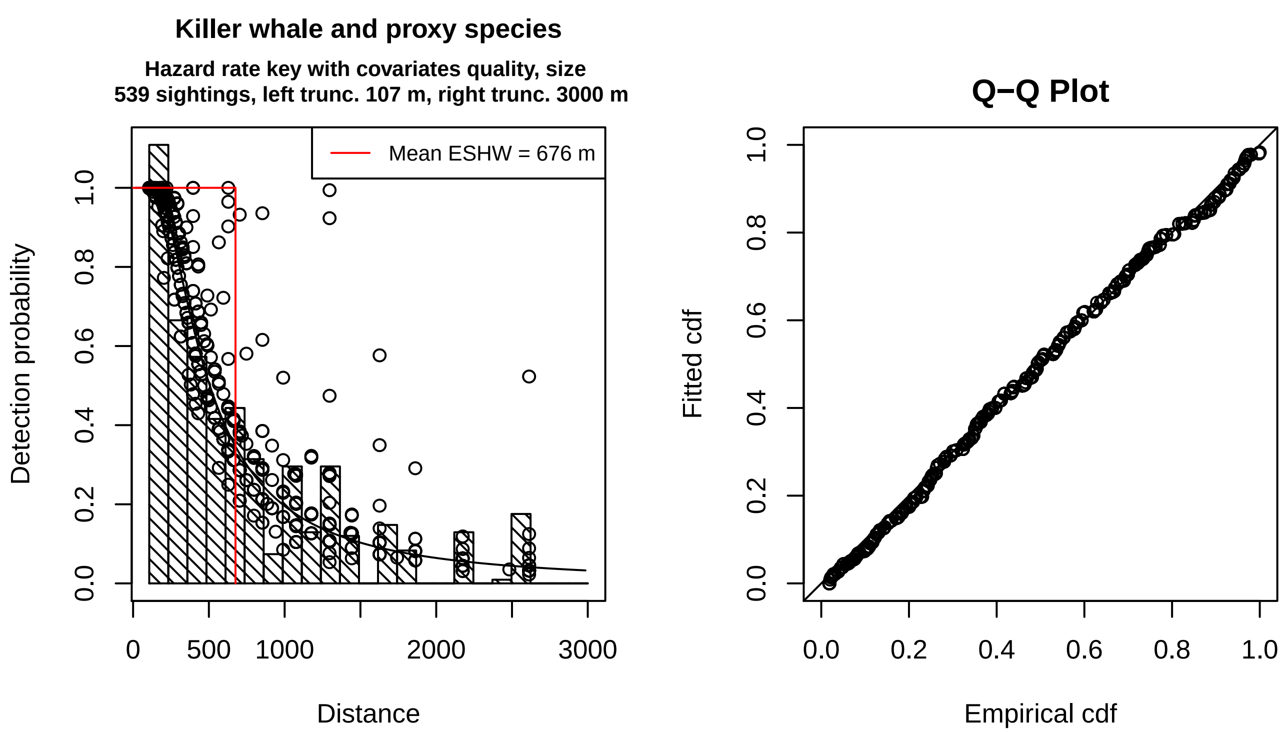

Figure 44: Detection function for NARWSS Grummans that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  539
Distance range         :  106.5979  -  3000
AIC                    :  7998.478

Detection function:
 Hazard-rate key function
```

```
Detection function parameters
Scale Coefficients:
              estimate         se
(Intercept)  5.9530450 0.18080430
quality     -0.1635689 0.09769324
size         0.1950236 0.06116755

Shape parameters:
             estimate         se
(Intercept) 0.5736025 0.07152729

                        Estimate           SE         CV
Average p              0.2088055   0.01869493 0.08953274
N in covered region 2581.3500409 251.79075785 0.09754228
```

Additional diagnostic plots:

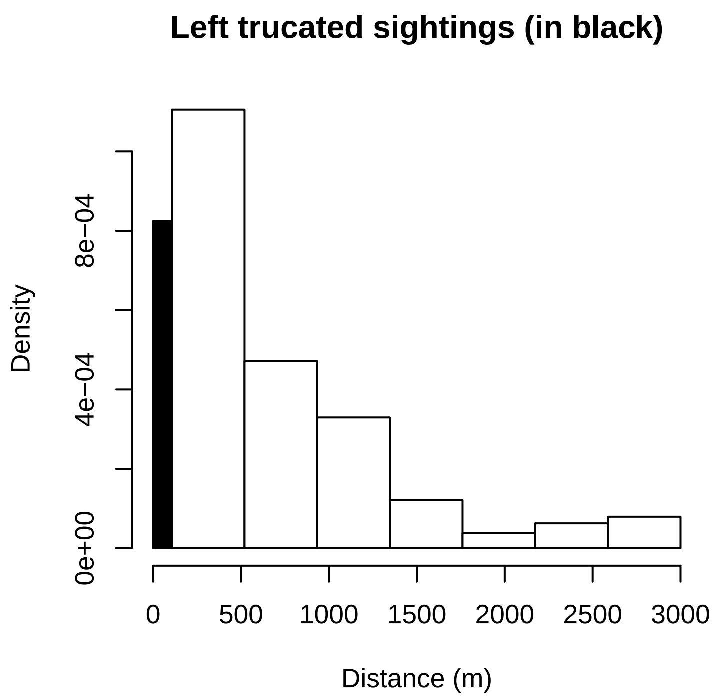

Figure 45: Density of sightings by perpendicular distance for NARWSS Grummans. Black bars on the left show sightings that were left truncated.

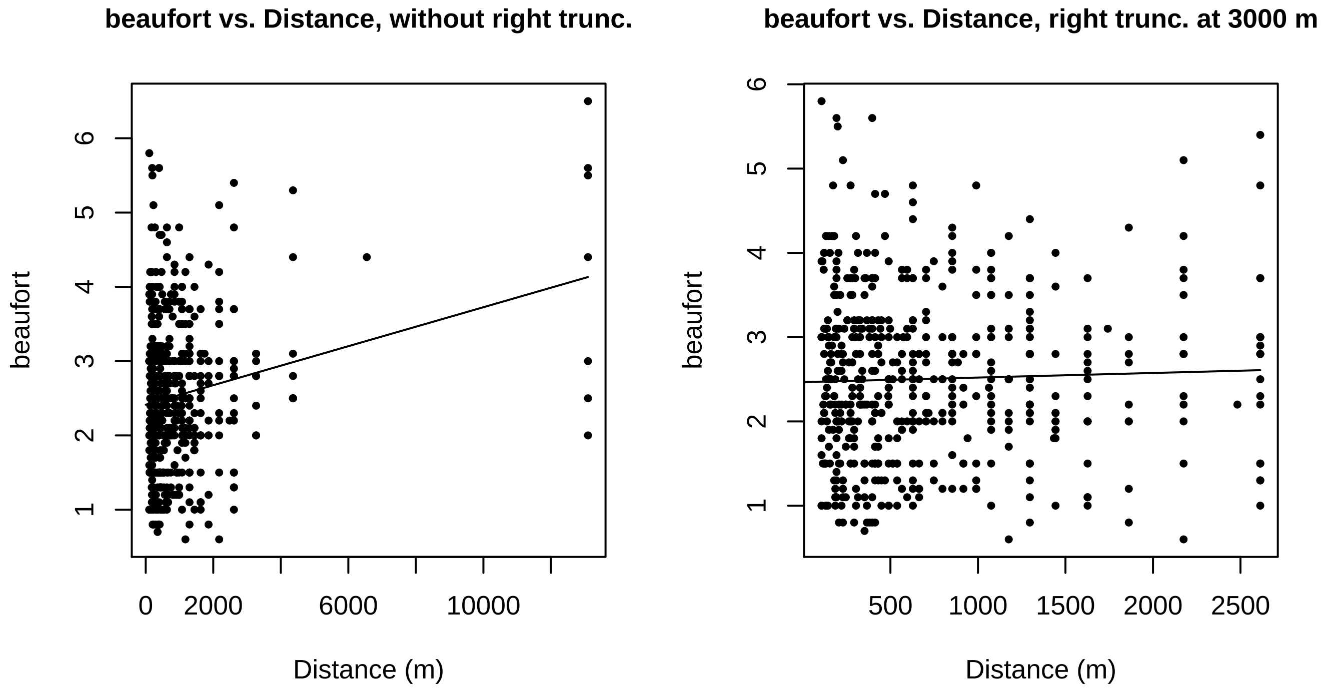

Figure 46: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

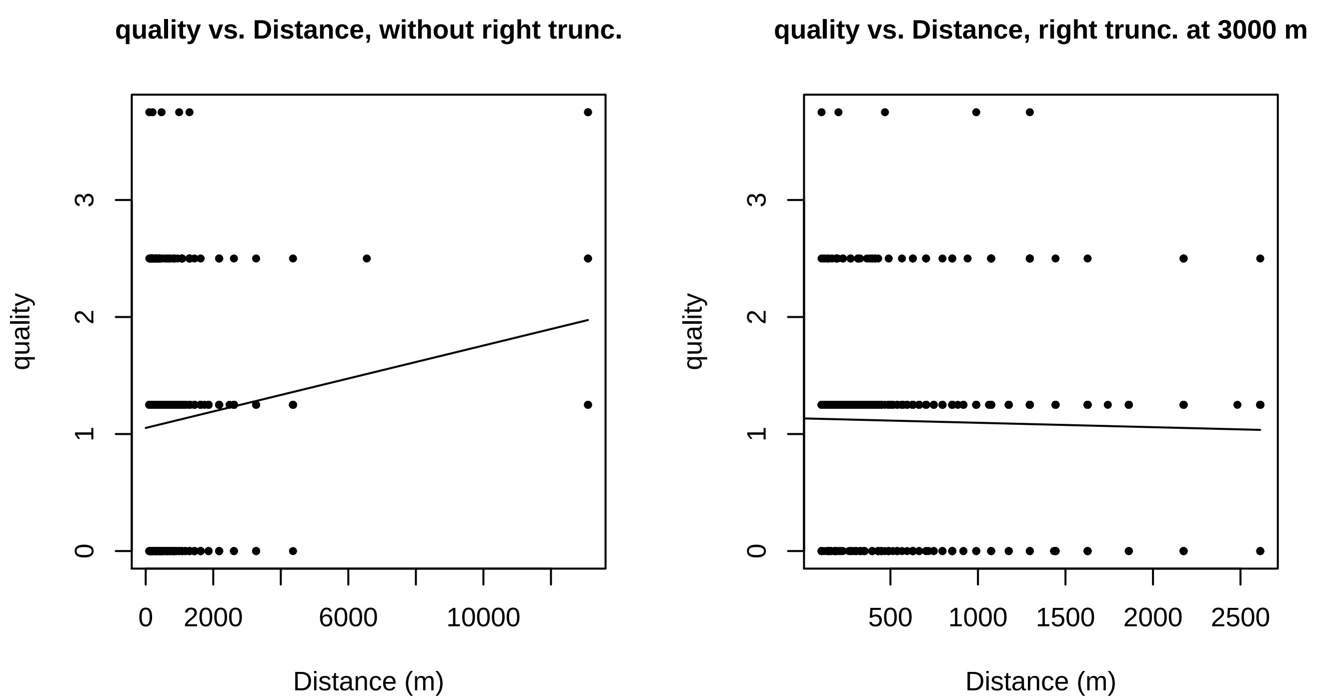

Figure 47: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions. The line is a simple linear regression.

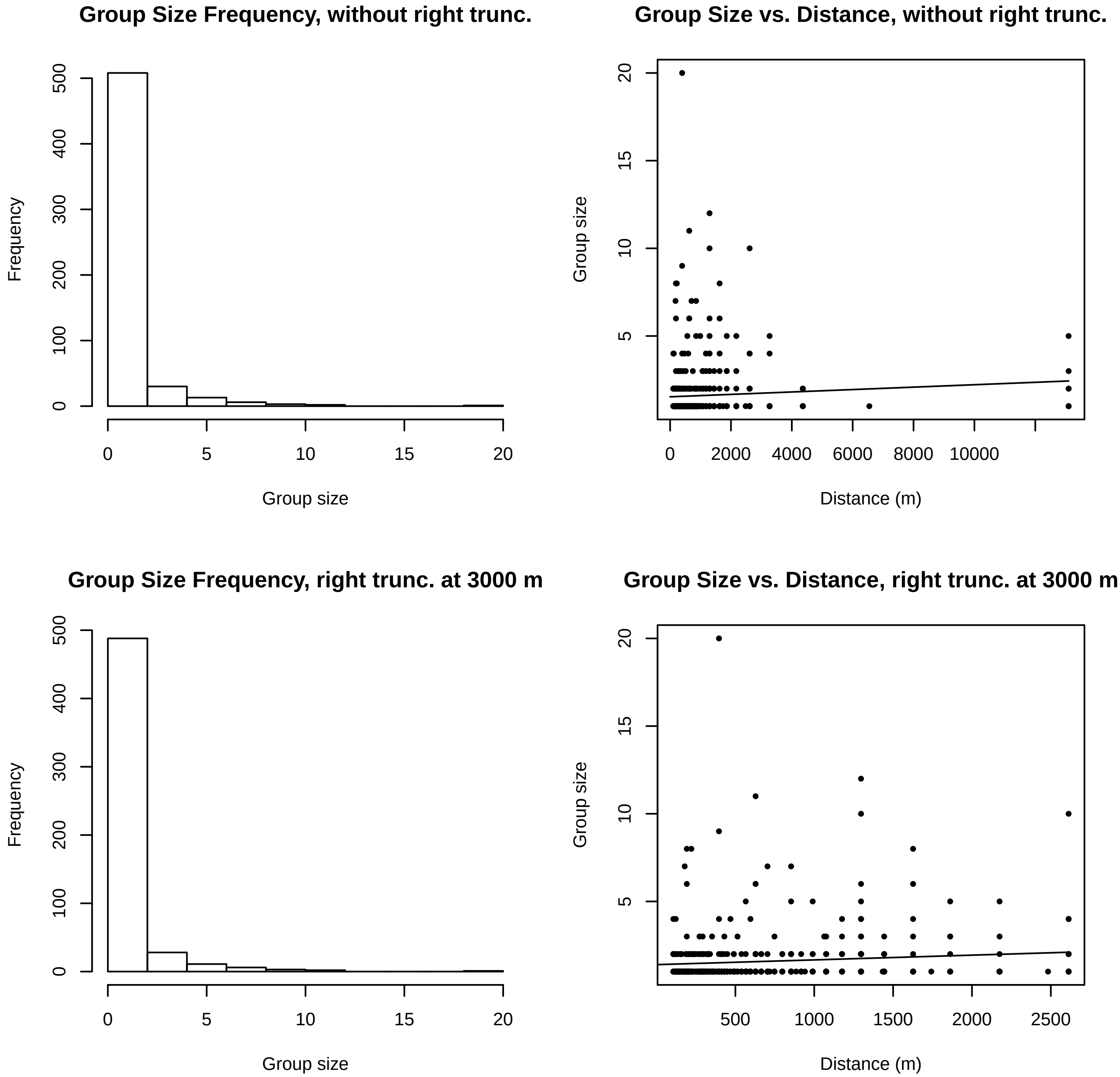

Figure 48: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

NARWSS Twin Otters

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Balaenoptera	Balaenopterid sp.	0
Balaenoptera acutorostrata	Minke whale	731

Balaenoptera borealis	Sei whale	696
Balaenoptera borealis/edeni	Sei or Bryde's whale	0
Balaenoptera borealis/physalus	Fin or Sei whale	0
Balaenoptera edeni	Bryde's whale	0
Balaenoptera musculus	Blue whale	7
Balaenoptera physalus	Fin whale	1545
Eubalaena glacialis	North Atlantic right whale	1430
Eubalaena glacialis/Megaptera novaeangliae	Right or humpback whale	0
Megaptera novaeangliae	Humpback whale	2308
Orcinus orca	Killer whale	2
Total		6719

Table 36: Proxy species used to fit detection functions for NARWSS Twin Otters. The number of sightings, n, is before truncation.

The sightings were right truncated at 5000m. Due to a reduced frequency of sightings close to the trackline that plausibly resulted from the behavior of the observers and/or the configuration of the survey platform, the sightings were left truncted as well. Sightings closer than 107 m to the trackline were omitted from the analysis, and it was assumed that the the area closer to the trackline than this was not surveyed. This distance was estimated by inspecting histograms of perpendicular sighting distances. The vertical sighting angles were heaped at 10 degree increments up to 80 degrees and 1 degree increments thereafter, so the candidate detection functions were fitted using linear bins scaled accordingly.

Covariate	Description
beaufort	Beaufort sea state.
quality	Survey-specific index of the quality of observation conditions, utilizing relevant factors other than Beaufort sea state (see methods).
size	Estimated size (number of individuals) of the sighted group.

Table 37: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hr			size	Yes	0.00	1632
hr	poly	4		Yes	43.86	1396
hr	poly	2		Yes	55.53	1456
hr				Yes	125.46	1494
hn	cos	3		Yes	202.85	1778
hn	cos	2		Yes	212.87	1938
hn	herm	4		Yes	411.14	2330
hn				Yes	417.26	2338
hn			beaufort	No		
hr			beaufort	No		
hn			quality	No		

hr	quality	No
hn	size	No
hn	beaufort, quality	No
hr	beaufort, quality	No
hn	beaufort, size	No
hr	beaufort, size	No
hn	quality, size	No
hr	quality, size	No
hn	beaufort, quality, size	No
hr	beaufort, quality, size	No

Table 38: Candidate detection functions for NARWSS Twin Otters. The first one listed was selected for the density model.

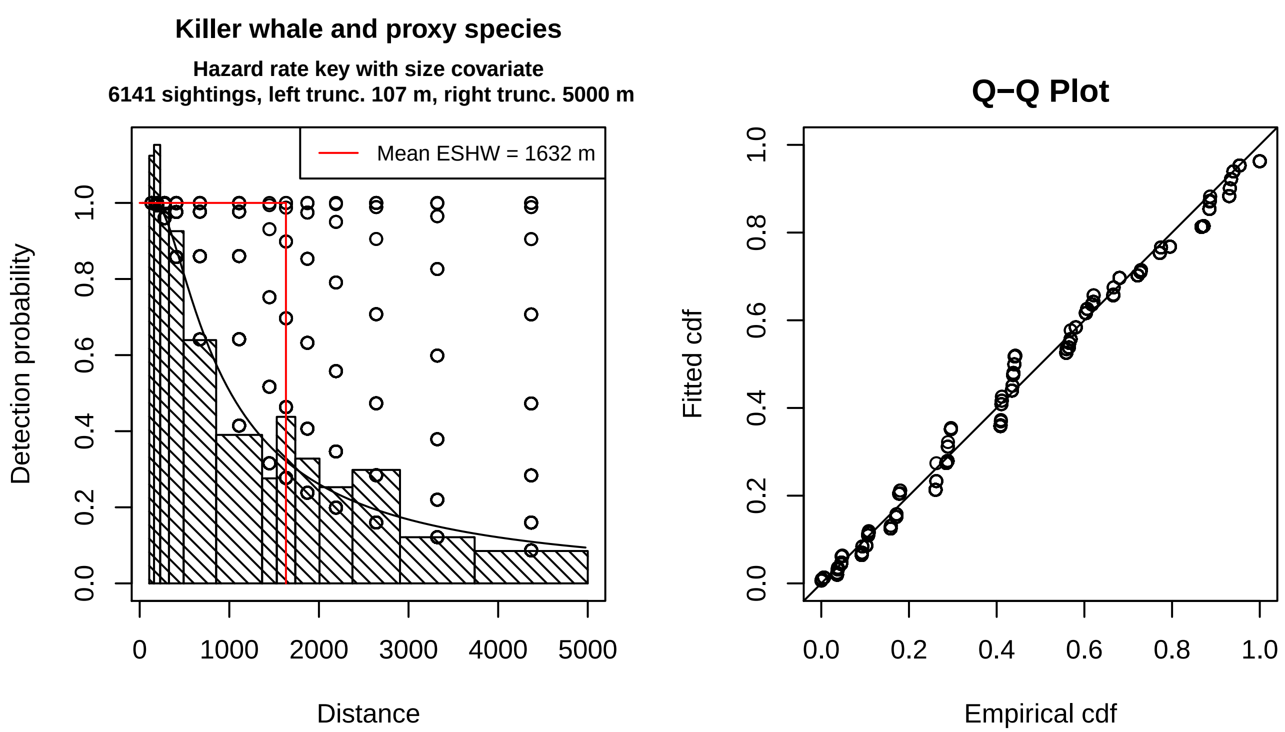

Figure 49: Detection function for NARWSS Twin Otters that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  6141
Distance range         :  106.5979  -  5000
AIC                    :  30341.61

Detection function:
 Hazard-rate key function
```

```
Detection function parameters
Scale Coefficients:
             estimate         se
(Intercept) 6.0262922 0.09543969
size        0.6306969 0.06345544

Shape parameters:
             estimate         se
(Intercept) 0.2579345 0.03040472

                        Estimate           SE         CV
Average p           3.012936e-01 9.423404e-03 0.03127648
N in covered region 2.038211e+04 6.747926e+02 0.03310710
```

Additional diagnostic plots:

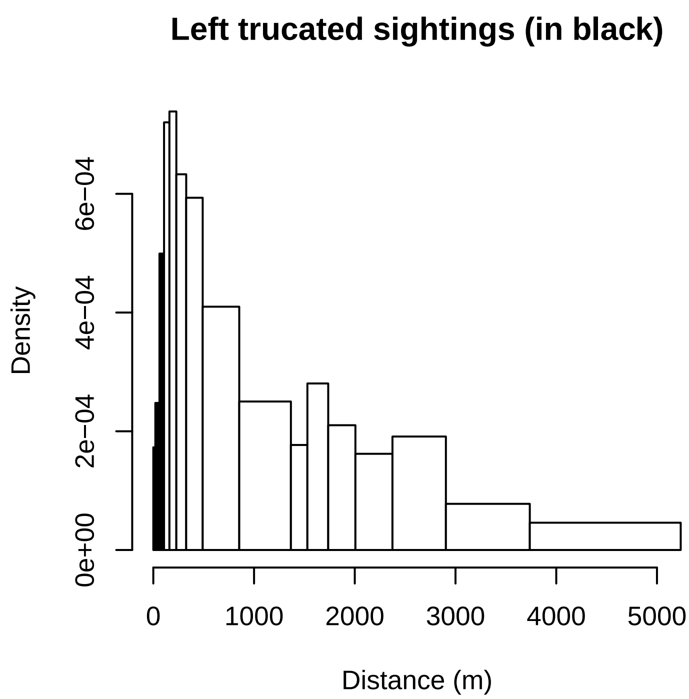

Figure 50: Density of sightings by perpendicular distance for NARWSS Twin Otters. Black bars on the left show sightings that were left truncated.

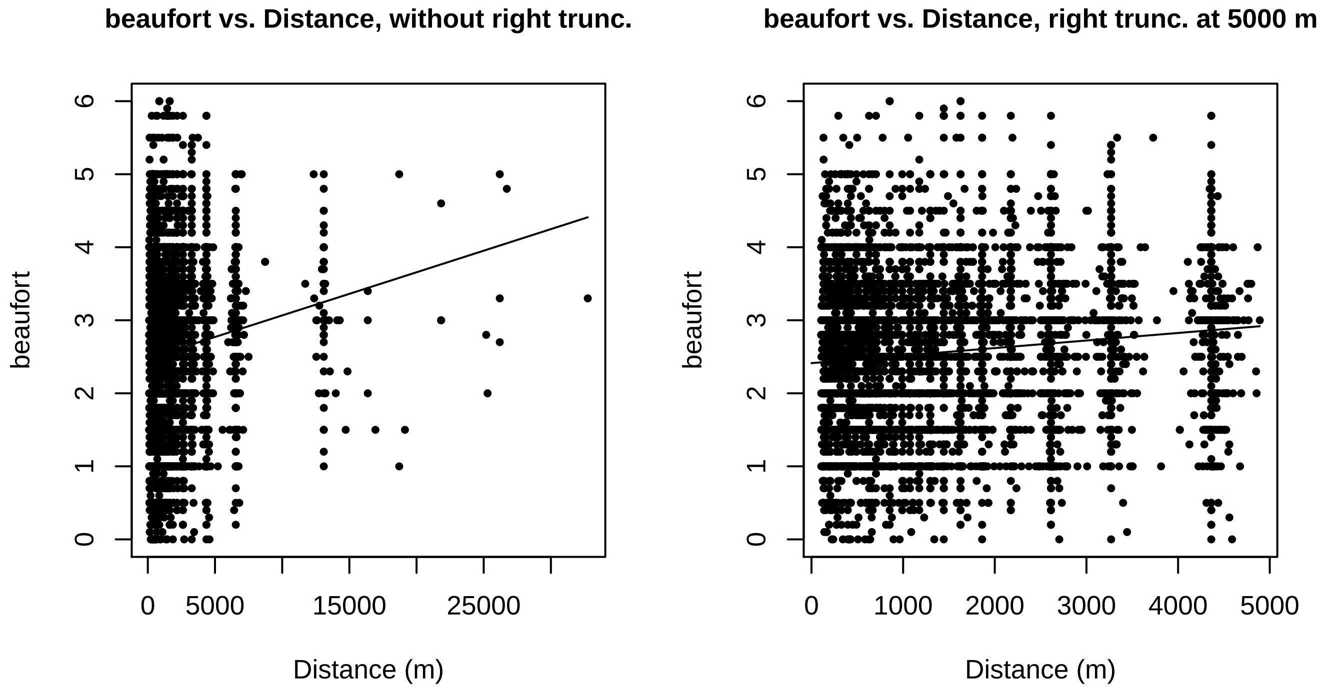

Figure 51: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

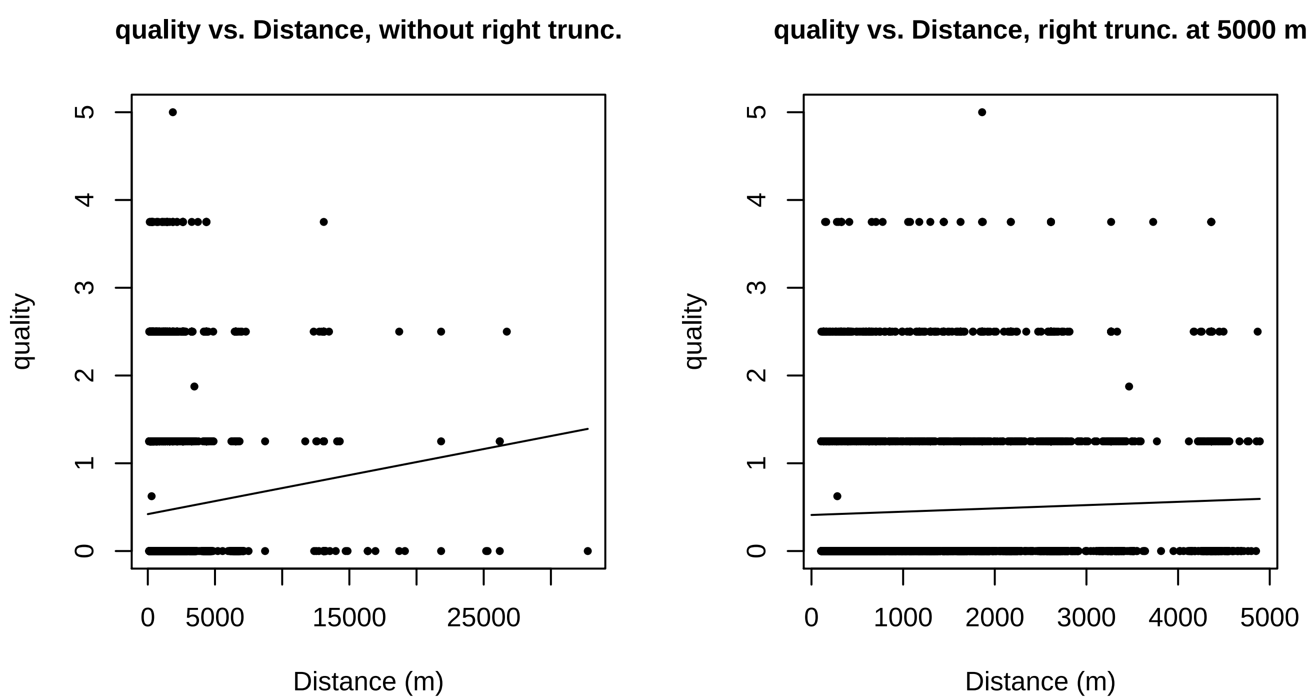

Figure 52: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions. The line is a simple linear regression.

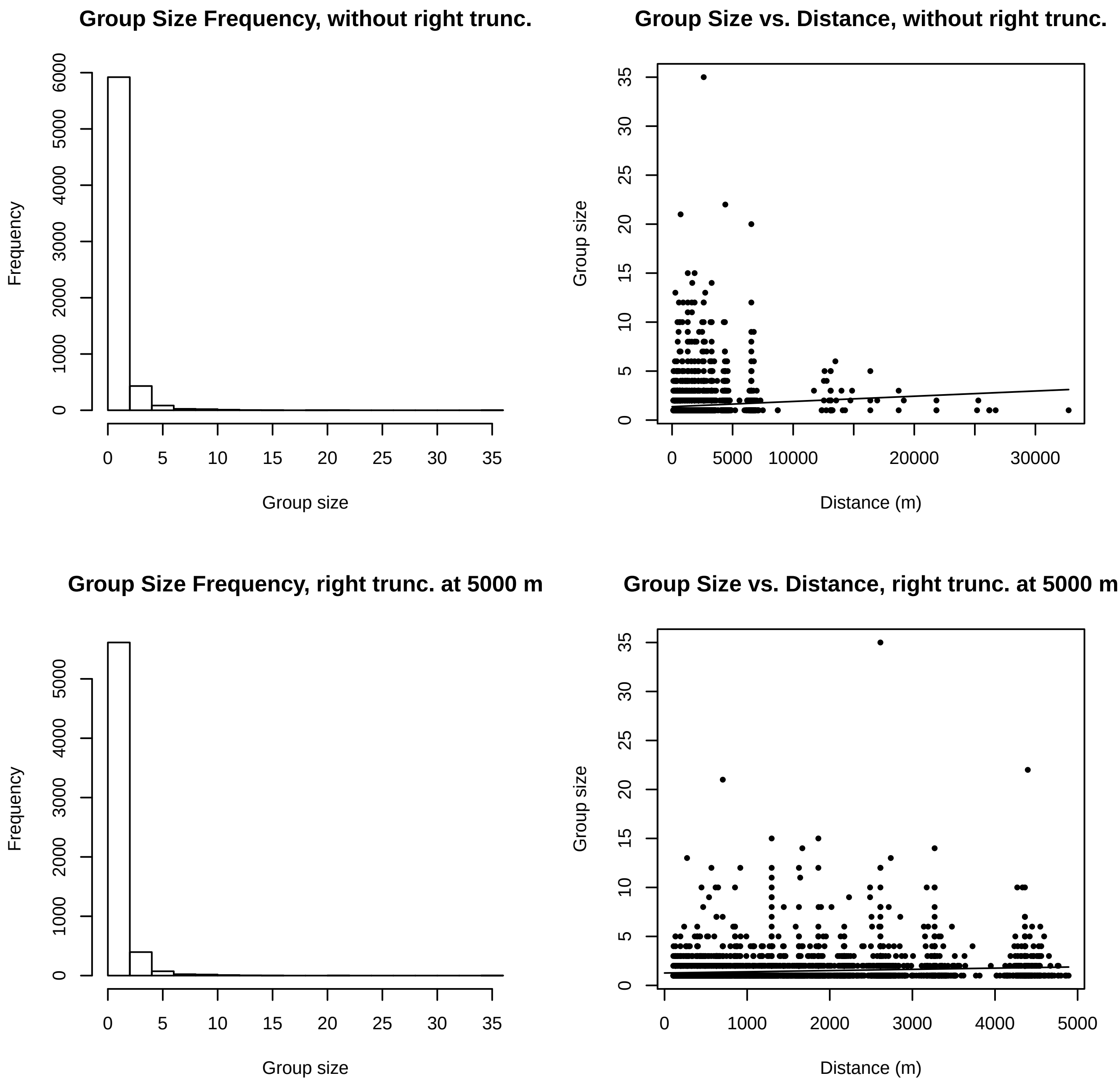

Figure 53: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

g(0) Estimates

Platform	Surveys	Group Size	*g(0)*	Biases Addressed	Source
Shipboard	All	Any	0.921	Perception	Barlow and Forney (2007)
Aerial	All	Any	0.78	Availability	Hooker et al. (2012)

Table 39: Estimates of *g(0)* used in this density model.

No species- or survey-specific estimates of g(0) were available for killer whales for any surveys in our study. For shipboard surveys, we used Barlow and Forney's (2007) estimate (0.921) for large whales (including killer whales) produced from several years of dual-team surveys in the Pacific ocean that used similar binoculars and protocols to the binocular surveys in our study. We also applied this estimate to the naked eye surveys in our study, as we found no estimate of g(0) in the literature for killer whales observed by naked eye from shipboard surveys.

This estimate accounted for perception bias but not availability bias, but we do not believe availability to be a major factor affecting detectability of killer whales from shipboard surveys, as they are not a particularly long-diving species. For long diving cetaceans such as sperm whales, Kogia spp., and beaked whales, Barlow and Forney (2007) used Barlow's (1999) model of g(0) that incorporated dive behavior. Barlow parameterized that model such that the median duration of long dives ranged from 10.9-28.6 min, depending on the species, based on prior observational studies. By comparison, Baird et al. (2005) reported that mean dive durations for 41 fish-eating killer whales for dives >= 1 min in duration was 2.3-2.4 min. Miller et al. (2010) studied the diving behavior of 12 mammal-eating killer whales, which exhibited longer dives. The authors did not report dive duration statistics but noted that the whales spent 50% of their time 8 m or shallower and 90% of their time 40 m or shallower. Hooker et al. (2012) reported that unspecified killer whales spent 78% of their time between 0-10 m. Finally, Sivle et al. (2012) characterized killer whales as a "shallow-diving" odontocete; by contrast, they characterized pilot whales as "intermediate diving" and sperm whales as "deep diving" odontocetes.

We did not find a species-specific g(0) estimate for killer whales observed by aircraft in the literature. Palka (2006) estimated of g(0) for groups of 1-5 large whales from from two years of aerial surveys using the Hiby (1999) circle- back method. This estimate accounted for both availability and perception bias, but pooled sightings of several species together to provide a generic estimate for all large whales, due to sample-size limitations. Most of these species undertake longer dives than killer whales; we believe Palka's g(0) was dominated by availability bias of such species and thus underestimates killer whale detectability. Instead, we used Hooker et al.'s (2012) report that an unspecified number and type of killer whales spent 78% of time between 0-10 m and set g(0)=0.78.

We note that percent time spent at 0-10 m does not necessarily equate to "percent time detectable by aerial observation". Hooker et al.'s data appear to be those reported by Kvadsheim et al. (2012). The four killer whales monitored in that study performed roughly 20x more dives to 1-30 m than to 30-200 m; the mean depth of the 1-30 m dives was only 2.6-3.6 m.

Density Model

Killer whales are widely distributed throughout the world's oceans and are found in tropical, temperate, and high-latitude waters, in both pelagic and coastal habitats (Forney and Wade 2006). They are considered rare in the Gulf of Mexico, U.S. Atlantic waters, and the Bay of Fundy, uncommon but seasonally regular in Labrador and Newfoundland, and common in the Canadian Arctic (Forney and Wade 2006). A recent comprehensive analysis of available systematic and opportunistic sightings in the northwest Atlantic between 40-60 N, 40-75 W concurred with this view (Lawson and Stevens 2014). These authors reported that almost all of the sightings in this region occurred at depths less than 200m, but that this might reflect a bias in the distribution of observation effort, and that killer whales have been reported in mid-Atlantic waters at depths exceeding 3000m (Lawson and Stevens 2014). For the latitudes 25-45 N, the Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP) database reported sightings at depths ranging from less than 10m to more than 5000m; sightings were concentrated in the northern half of the region but were not absent from the southern half (http://seamap.env.duke.edu/species/180469, accessed January 30, 2015). Lawson and Stevens (2014) also reported that killer whales were sighted in their study area during all months of the year.

The surveys in our database reported only four killer whale sightings within our east coast study area. With so few sightings, we could not attempt to model abundance from environmental predictors. The wide distribution of sightings of killer whales, both globally and within our study area, suggested that our entire east coast study area is killer whale habitat, so we included the entire area in our stratified model.

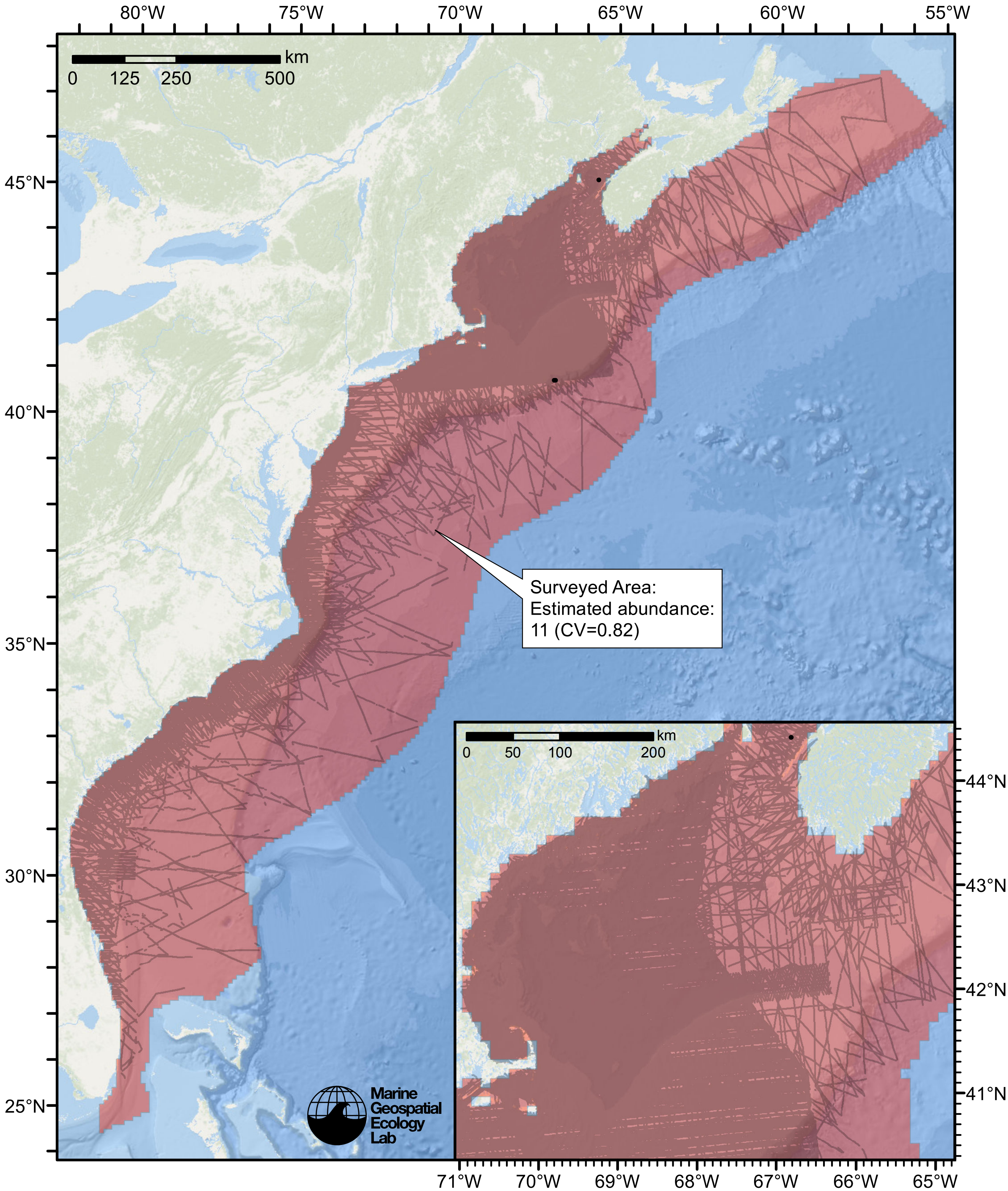

Figure 54: Killer whale density model schematic. All sightings are shown, including those that were truncated when detection functions were fitted. The coefficient of variation (CV) underestimates the true uncertainty of our estimate, as it only incorporated the uncertainty of the GAM stage of our model. Other sources of uncertainty include the detection functions and g(0) estimates. It was not possible to incorporate these into our CV without undertaking a computationally-prohibitive bootstrap; we hope to attempt that in a future version of our model.

Abundance Estimates

Dates	Model or study	Estimated abundance	CV	Assumed g(0)=1	In our models
1992-2014	Our model	11	0.82	No	
1972-2012?	Minimum estimate for 40-60 N, 40-75 W from photo ID (Lawson and Stevens 2014)	67			

Table 40: Estimated mean abundance within the study area for our model and independent estimates from NOAA and/or the scientific literature. The Dates column gives the dates to which the estimates apply. For our model, these are the years for survey data were available. Our coefficient of variation (CV) estimates are probably too low, as they only incorporated the uncertainty of the GAM stage of our models. Other sources of uncertainty include the detection functions and g(0) estimates. It was not possible to incorporate these into our CVs without undertaking a computationally-prohibitive bootstrap; we hope to attempt that in a future version of our models. The Assumed g(0)=1 column specifies whether the abundance estimate assumed that detection was certain along the survey trackline. Studies that assumed this did not correct for availability or perception bias, and therefore underestimated abundance. The In our models column specifies whether the survey data from the study was also used in our models. If not, the study provides a completely independent estimate of abundance. Note that our abundance estimates are averaged over the whole year, while the other estimates apply to specific months or seasons. Please see the Discussion section below for our evaluation of our models compared to the other estimates.

Discussion

At the time of this analysis, the most recent NOAA stock assessment report for the Western North Atlantic Stock of killer whales was from 2000 and it did not offer an abundance estimate. Lawson and Stevens (2014) reported a minimum number of 67 killer whales for the region 40-60 N, 40-75 W based on photographic identification of individuals, but that this is is an underestimate of the true population. Of the 1700 photographs available, over 70% were not of sufficient quality to make an identification. They did not offer an estimate of the upper bound for the population but concluded that the northwestern Atlantic population is not as large as the northeastern Atlantic population, which may be close to 10,000 whales (Lawson and Stevens 2014).

In light of the uncertainty surrounding the population size but the general agreement that killer whales are rare within our study area, we believe our abundance estimate is not unreasonable.

References

Baird RW, Hanson MB, Dill LM (2005) Factors influencing the diving behaviour of fish-eating killer whales: sex differences and diel and interannual variation in diving rates. Can J Zool. 83: 257-267.

Barlow J (1999) Trackline detection probability for long diving whales. In: Marine Mammal Survey and Assessment Methods (Garner GW, Amstrup SC, Laake JL, Manly BFJ, McDonald LL, Robertson DG, eds.). Balkema, Rotterdam, pp. 209-221.

Barlow J, Forney KA (2007) Abundance and density of cetaceans in the California Current ecosystem. Fish. Bull. 105: 509-526.

Forney KA, Wade PR (2007) Worldwide Distribution and Abundance of Killer Whales. In: Whales, whaling and ocean ecosystems (Estes JA, DeMaster DP, Doak DF, Williams TM, Brownell RL, eds). University of California Press, Berkeley, California. pp. 145-162.

Hiby L (1999) The objective identification of duplicate sightings in aerial survey for porpoise. In: Marine Mammal Survey and Assessment Methods (Garner GW, Amstrup SC, Laake JL, Manly BFJ, McDonald LL, Robertson DG, eds.). Balkema, Rotterdam, pp. 179-189.

Hooker SK, Fahlman A, Moore MJ, Soto NA de, Quiros YB de, Brubakk AO, et al. (2012) Deadly diving? Physiological and behavioural management of decompression stress in diving mammals. Proc R Soc B 279: 1041-1050.

Kvadsheim P, Miller PJO, Tyack PL, Sivle LD, Lam FPA, Fahlman A (2012) Estimated tissue and blood N2 levels and risk of decompression sickness in deep-, intermediate-, and shallow-diving toothed whales during exposure to naval sonar. Frontiers in Physiology 3.

Lawson JW, Stevens TS (2014) Historic and current distribution patterns, and minimum abundance of killer whales (Orcinus orca) in the north-west Atlantic. Journal of the Marine Biological Association of the United Kingdom 94: 1253-1265.

Miller PJO, Shapiro AD, Deecke VB (2010) The diving behaviour of mammal-eating killer whales (Orcinus orca): variations with ecological not physiological factors. Canadian Journal of Zoology 88: 1103-1112.

Palka DL (2006) Summer Abundance Estimates of Cetaceans in US North Atlantic Navy Operating Areas. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 06-03: 41 p.

Sivle LD, Kvadsheim PH, Fahlman A, Lam FPA, Tyack PL, Miller PJO (2012) Changes in dive behavior during naval sonar exposure in killer whales, long-finned pilot whales, and sperm whales. Frontiers in Physiology 3.