Density Model for Blue Whale (*Balaenoptera musculus*) for the U.S. East Coast: Supplementary Report

Duke University Marine Geospatial Ecology Lab*

Model Version 1.3 - 2015-09-26

Citation

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

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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 Blue Whale (*Balaenoptera musculus*) for the U.S. East Coast Version 1.3, 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	2015-01-06	Initial version.
1.1	2015-03-06	Updated the documentation. No changes to the model.
1.2	2015-05-14	Updated calculation of CVs. Switched density rasters to logarithmic breaks. No changes to the model.
1.3	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	1
NEFSC NARWSS Harbor Porpoise Survey	1999-1999	6	36	0
NEFSC North Atlantic Right Whale Sighting Survey	1999-2013	432	2330	7
NEFSC Shipboard Surveys	1995-2004	16	1143	0
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	8

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	8

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

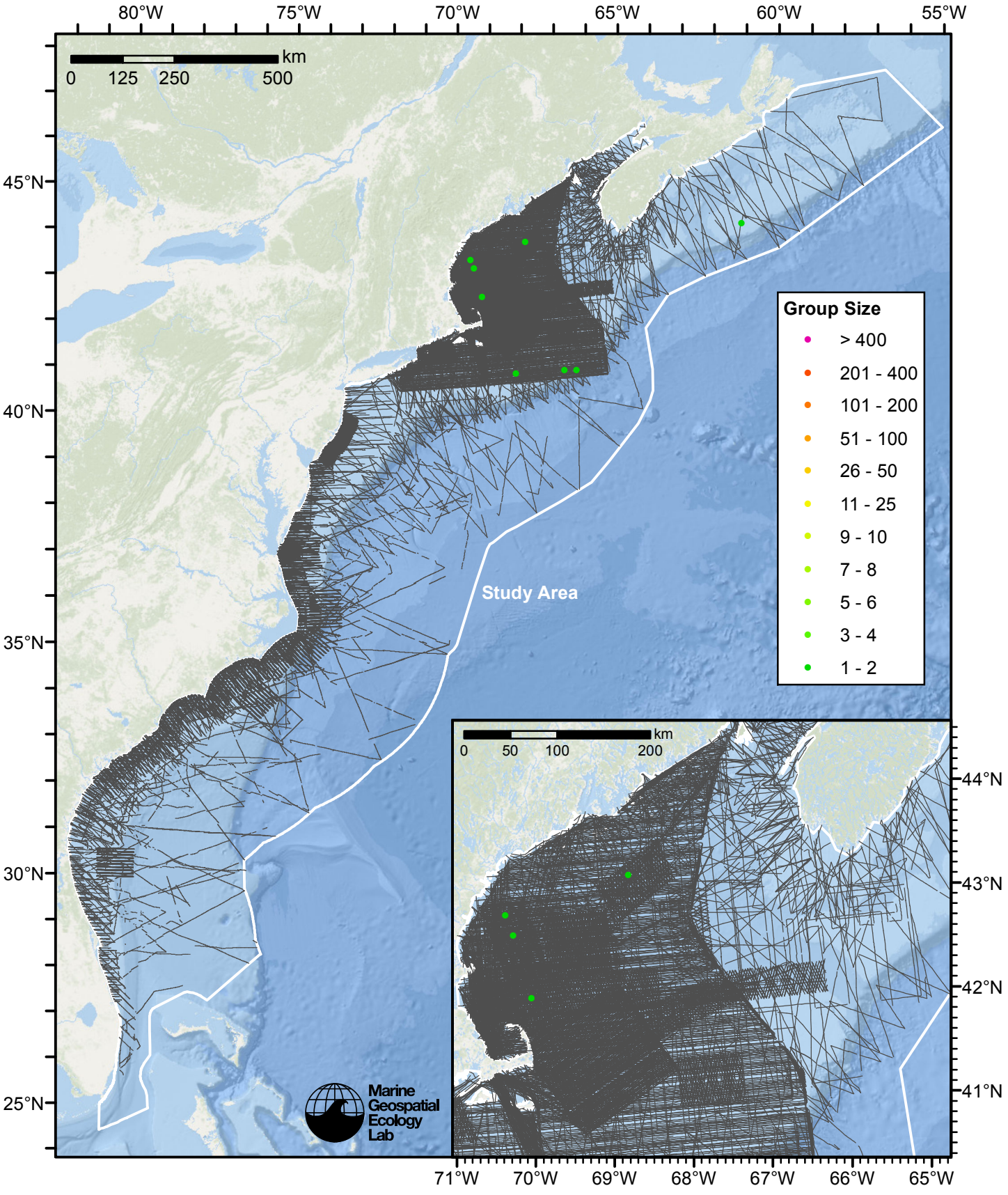

Figure 1: Blue whale sightings and survey tracklines.

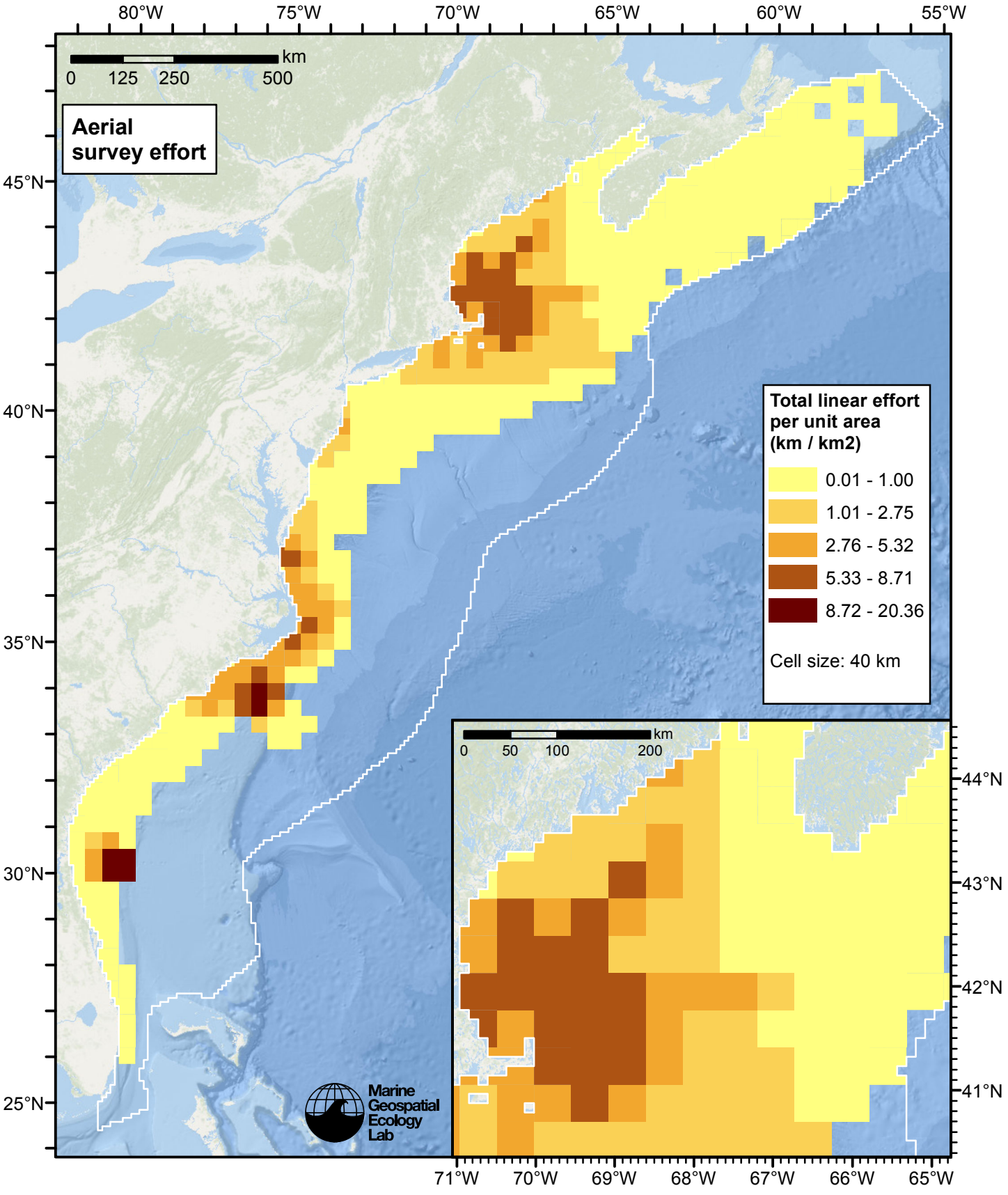

Figure 2: Aerial linear survey effort per unit area.

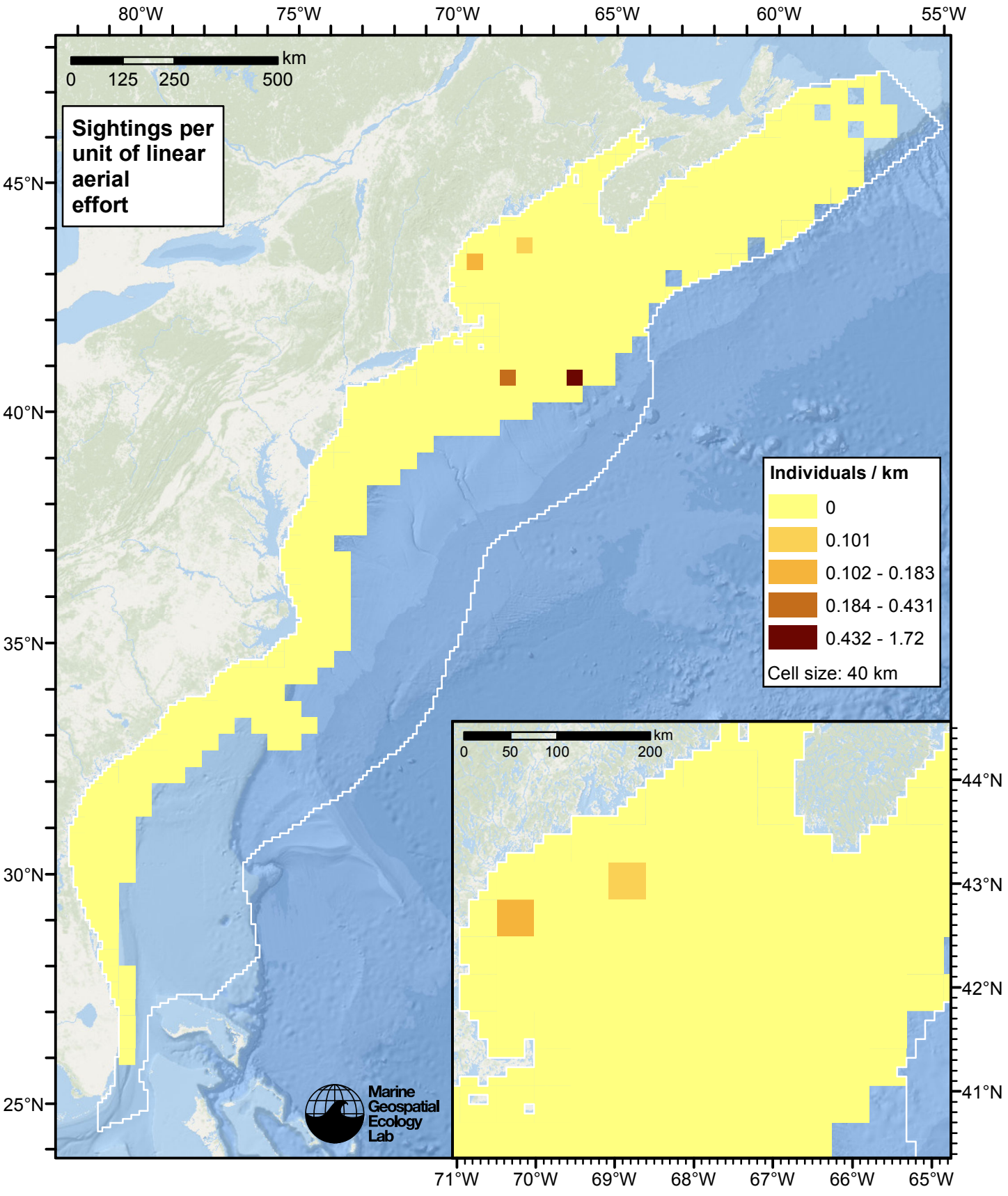

Figure 3: Blue whale sightings per unit aerial linear survey effort.

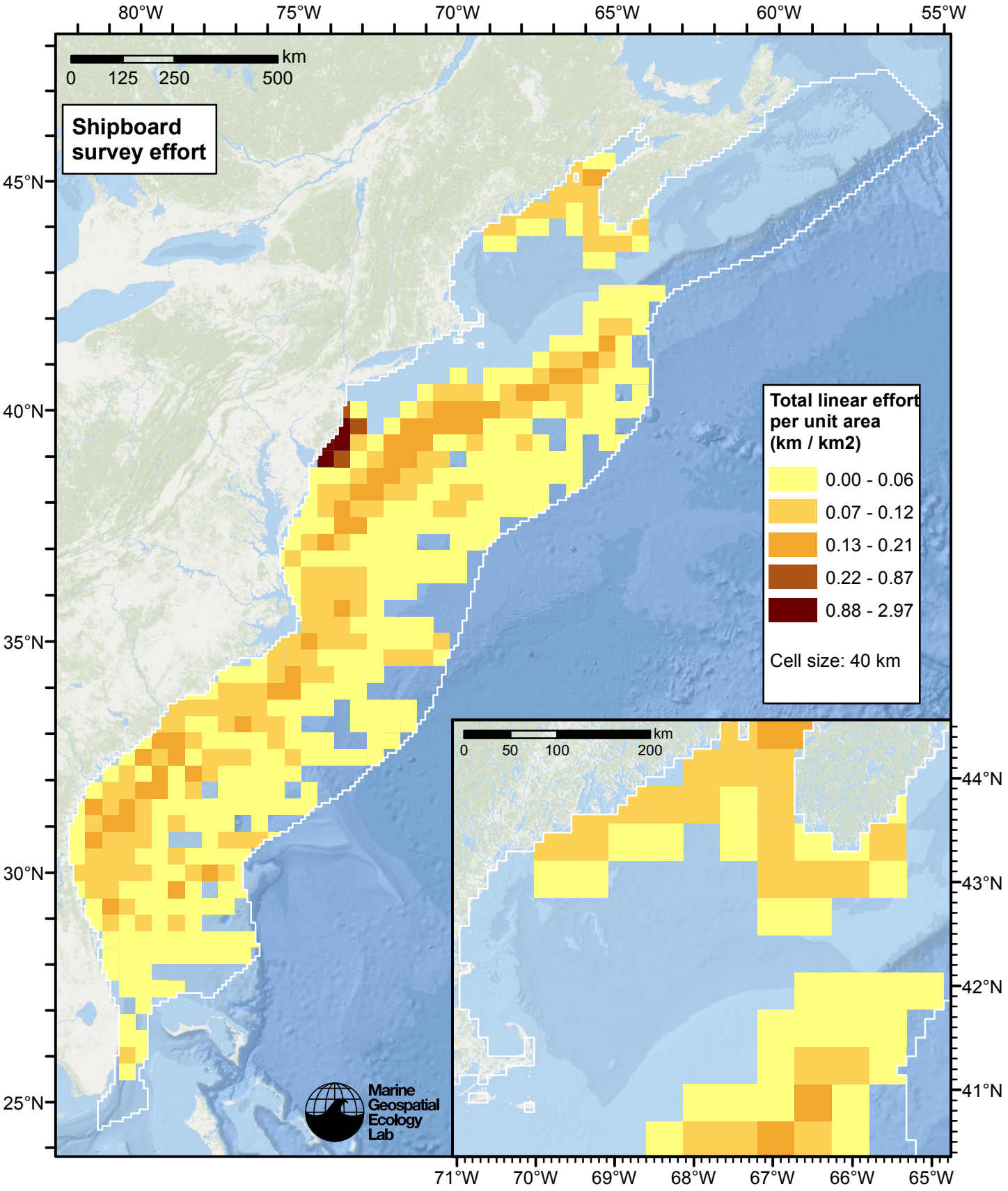

Figure 4: Shipboard linear survey effort per unit area.

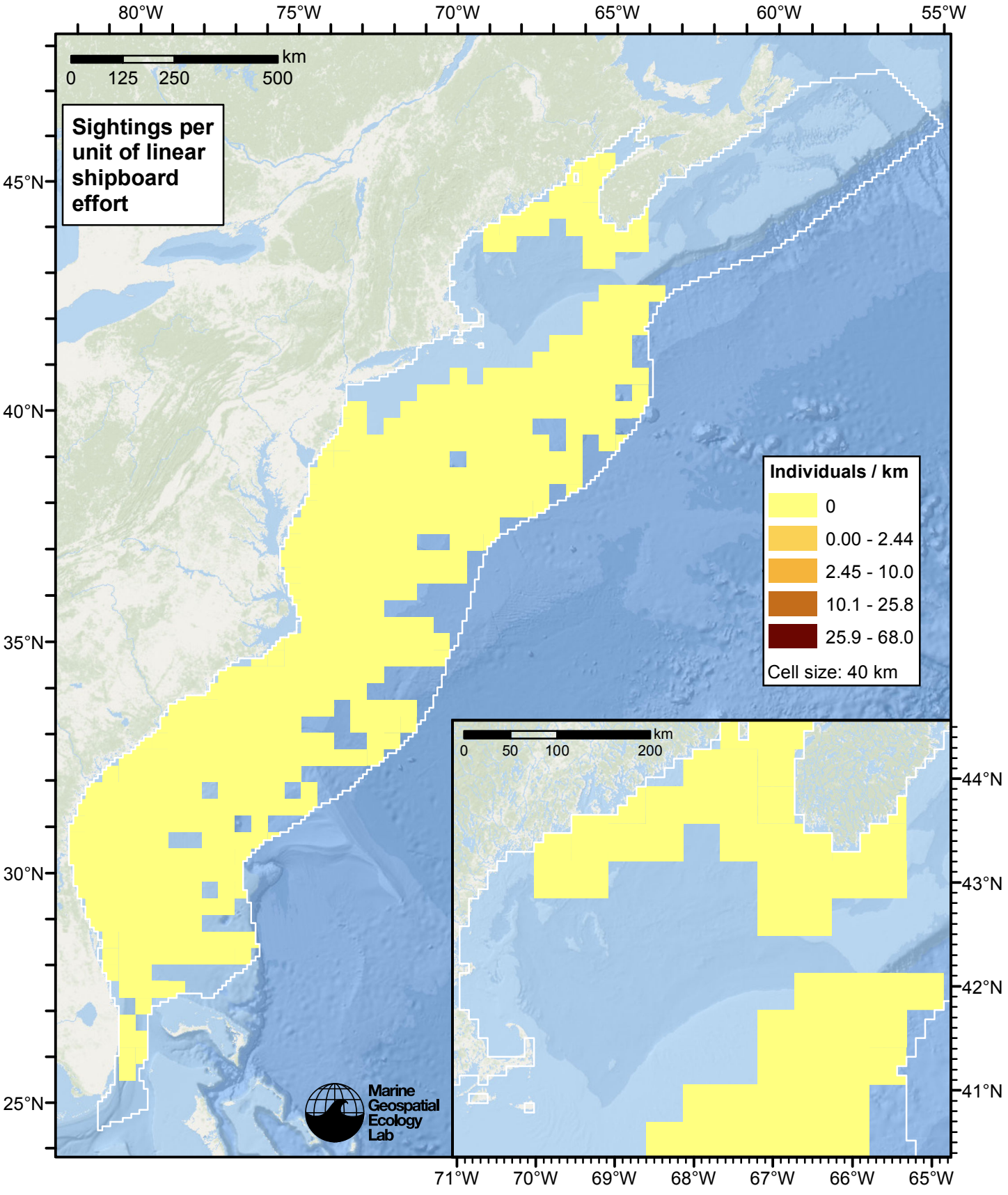

Figure 5: Blue whale sightings per unit shipboard linear survey effort.

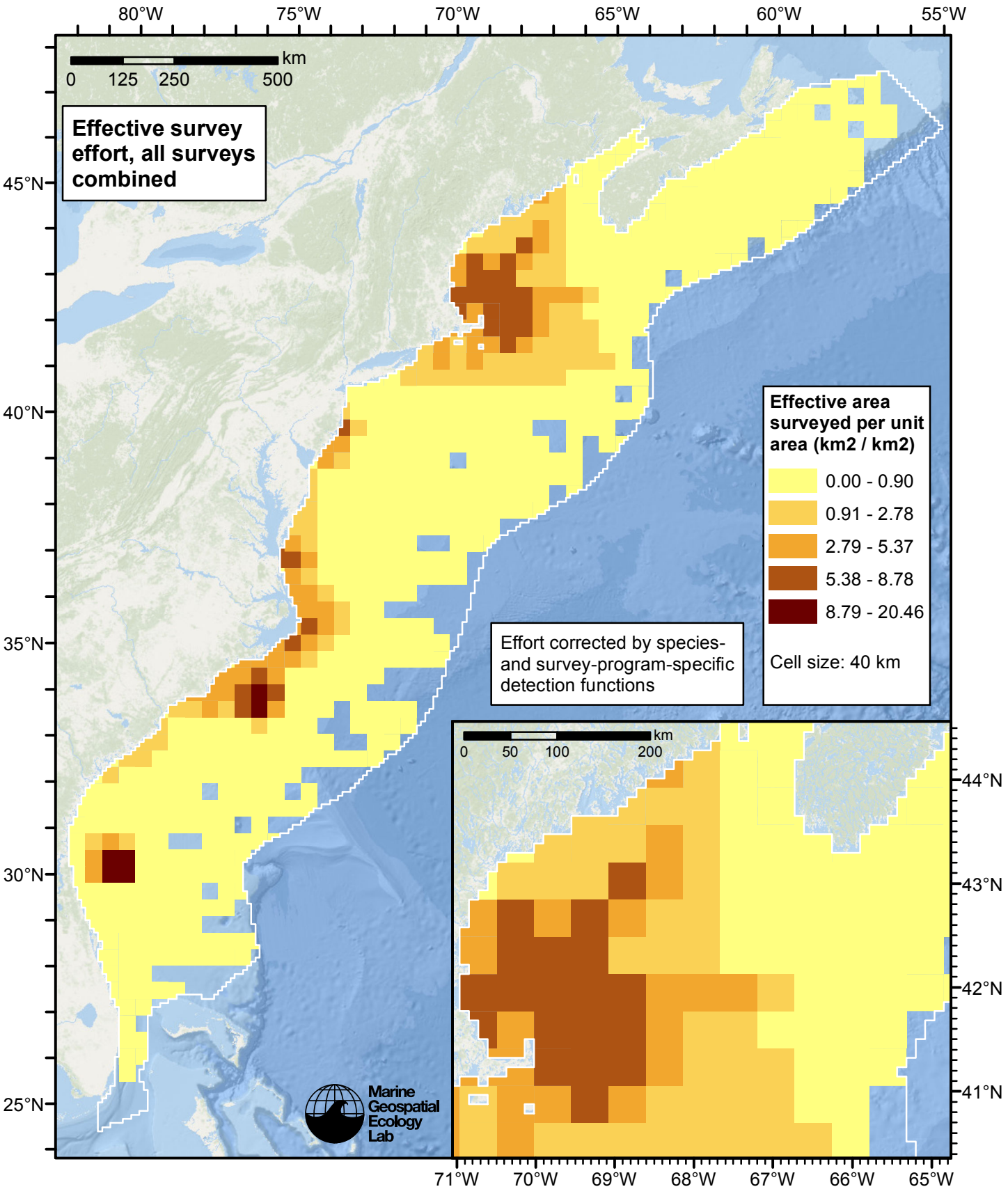

Figure 6: Effective survey effort per unit area, for all surveys combined. Here, effort is corrected by the species- and survey-program-specific detection functions used in fitting the density models.

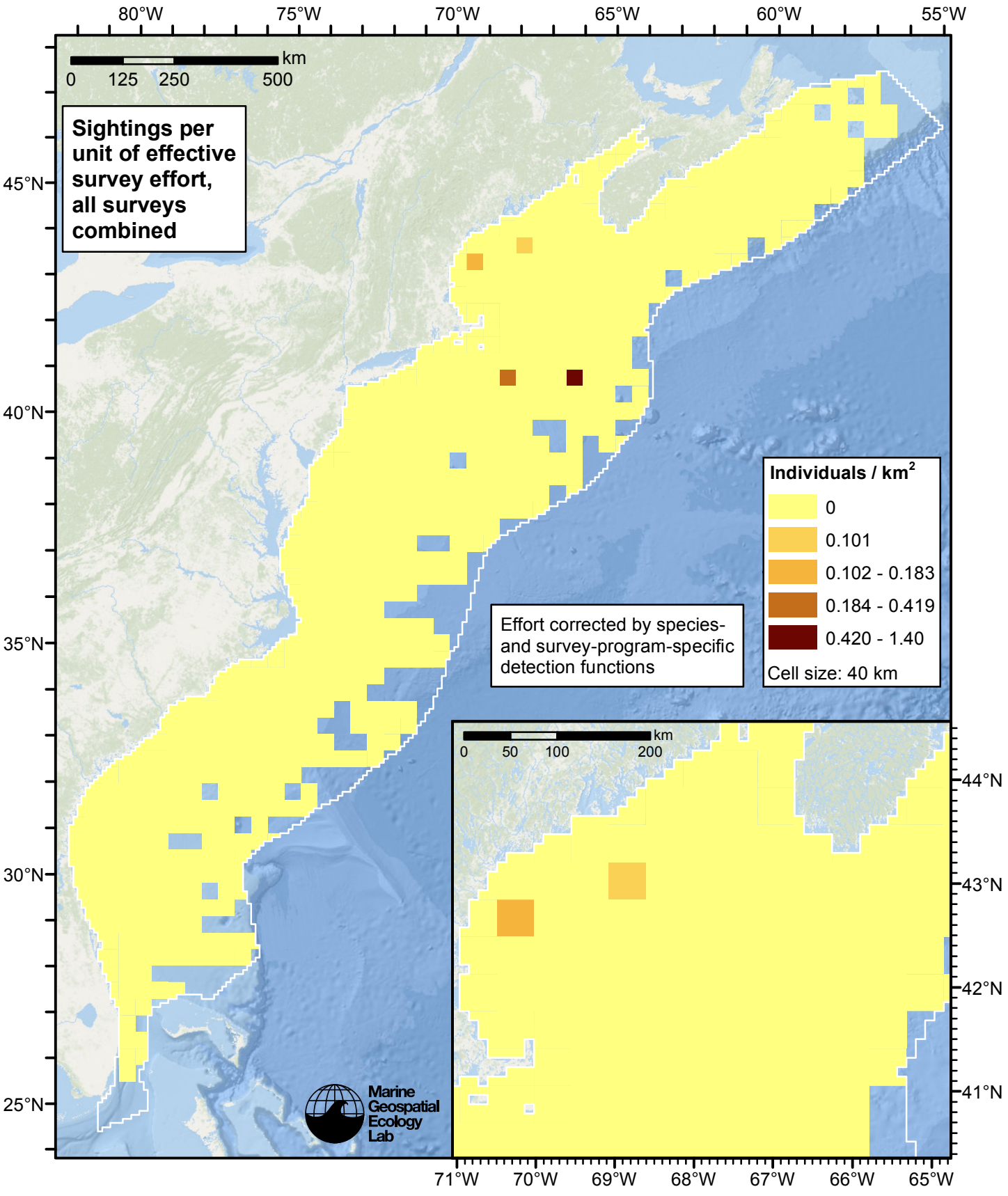

Figure 7: Blue whale sightings per unit of effective survey effort, for all surveys combined. Here, effort is corrected by the species- and survey-program-specific detection functions used in fitting the density models.

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

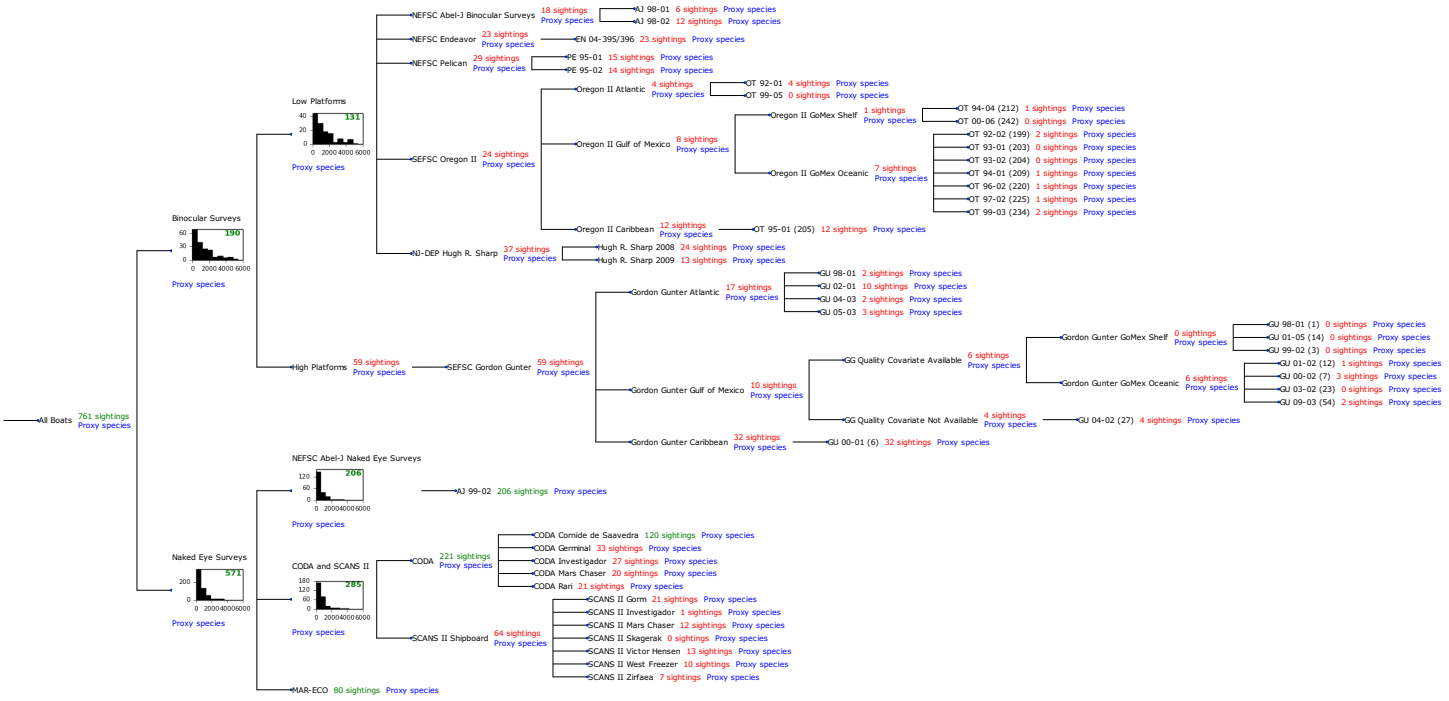

Figure 8: Detection hierarchy for shipboard surveys

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
Total		191

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	1309
hr	poly	4		Yes	0.47	1354
hr			size	Yes	0.78	1757
hr				Yes	0.80	1542
hn	cos	2		Yes	1.99	1802
hr			beaufort, size	Yes	2.64	1780
hr			beaufort	Yes	2.71	1553
hr			vessel, size	Yes	6.31	1920
hr			vessel	Yes	6.89	1605
hr			beaufort, vessel, size	Yes	8.03	1952

hr			beaufort, vessel	Yes	8.50	1675
hn	cos	3		Yes	9.91	1787
hn			size	Yes	11.86	2317
hn			beaufort, size	Yes	13.68	2319
hn			vessel, size	Yes	15.29	2299
hn			vessel	Yes	17.57	2301
hn				Yes	17.60	2311
hn			beaufort	Yes	19.19	2310
hn	herm	4		No		
hn			beaufort, vessel	No		
hn			beaufort, vessel, size	No		

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

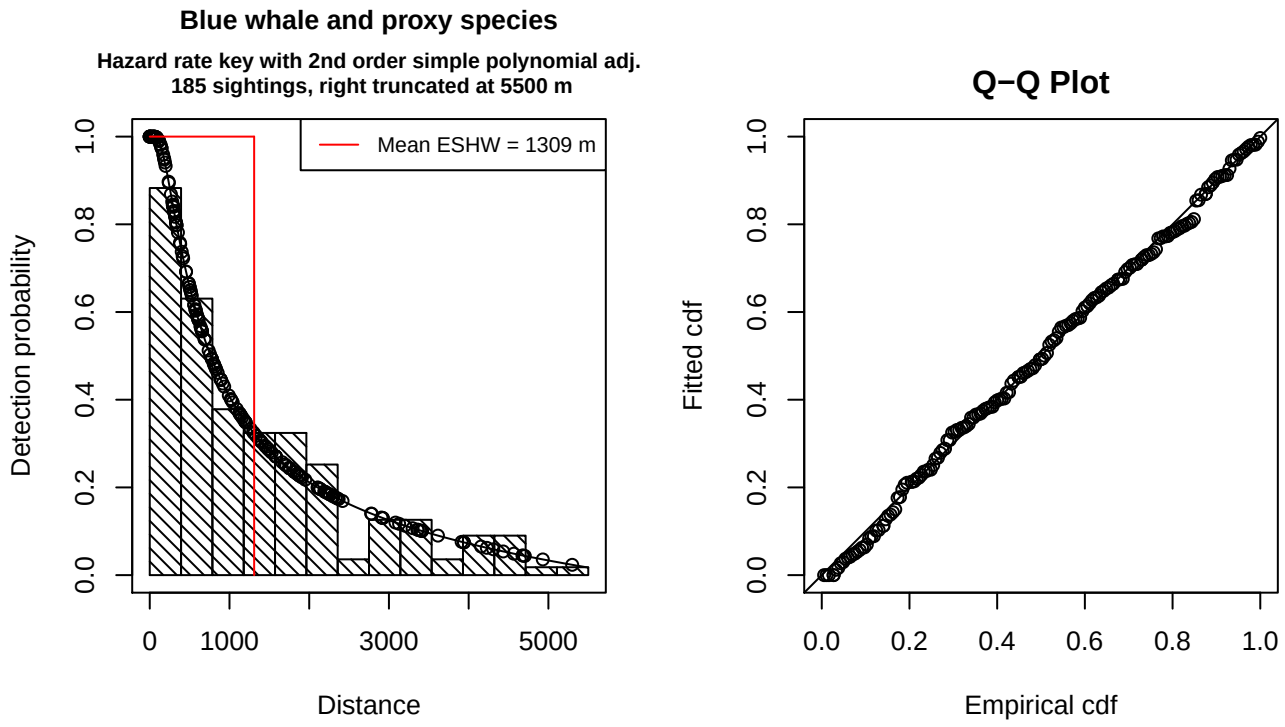

Figure 9: Detection function for Binocular Surveys that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  185
Distance range         :  0  -  5500
AIC                    :  3029.944

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

```
Detection function parameters
Scale Coefficients:
            estimate       se
(Intercept)  6.29521 0.405821

Shape parameters:
                estimate        se
(Intercept) 1.061317e-07 0.2305982

Adjustment term parameter(s):
               estimate        se
poly, order 2 -0.816334 0.2362928


Monotonicity constraints were enforced.
                     Estimate           SE        CV
Average p            0.238058   0.04195362 0.1762328
N in covered region 777.121684 145.75247927 0.1875543

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.

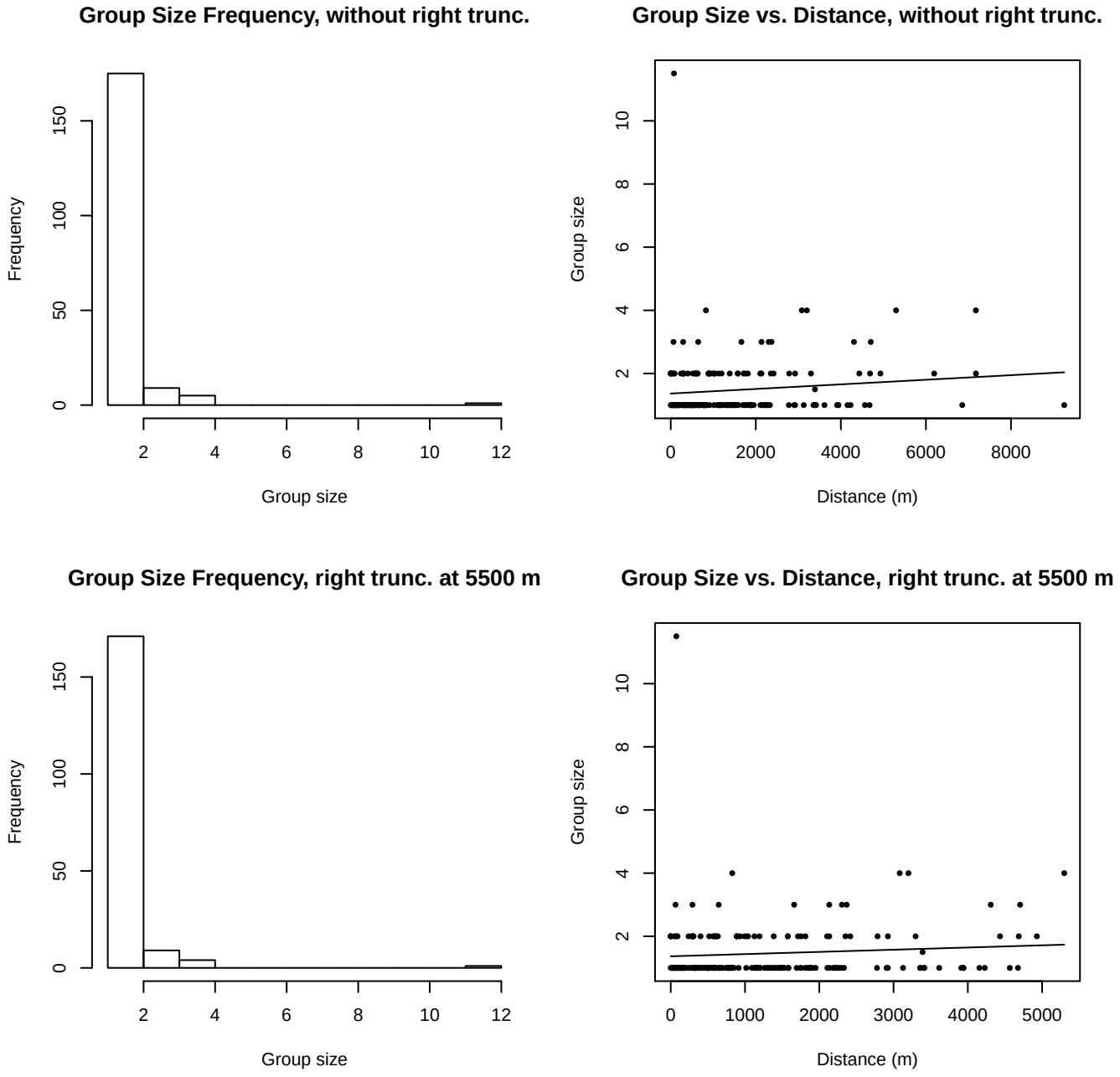

Figure 11: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

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
Total		132

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			size	Yes	0.00	1851
hn	cos	2		Yes	1.87	1764
hr				Yes	1.95	1652
hr			beaufort, size	Yes	1.99	1858
hr			vessel, size	Yes	2.55	2107
hr	poly	4		Yes	3.84	1634
hr	poly	2		Yes	3.89	1634
hr			beaufort, vessel, size	Yes	4.48	2116
hr			vessel	Yes	5.62	1830
hn			size	Yes	6.79	2311
hr			beaufort, vessel	Yes	7.51	1860
hn			vessel, size	Yes	8.30	2288
hn			beaufort, size	Yes	8.64	2312
hn	cos	3		Yes	11.49	1819

hn			vessel	Yes	13.80	2330
hn				Yes	15.66	2345
hn			beaufort	Yes	17.02	2343
hn	herm	4		No		
hr			beaufort	No		
hn			beaufort, vessel	No		
hn			beaufort, vessel, size	No		

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

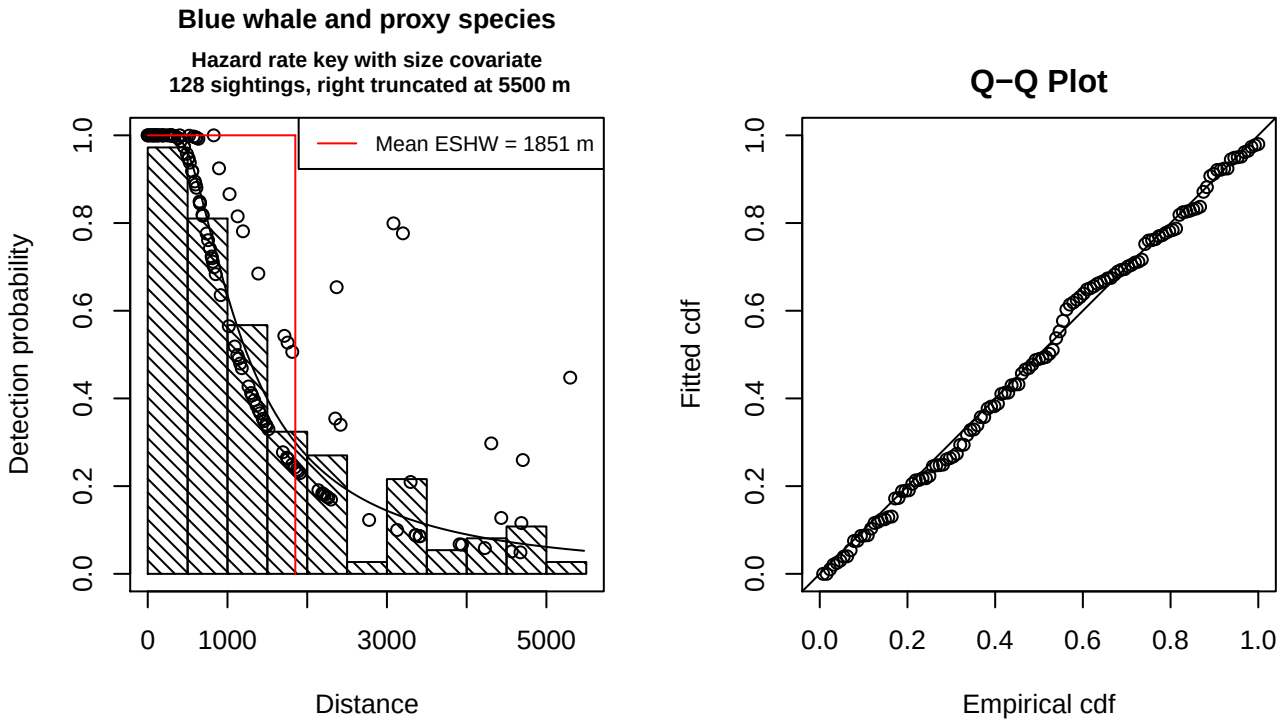

Figure 12: Detection function for Low Platforms that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  128
Distance range         :  0  -  5500
AIC                    :  2096.769

Detection function:
 Hazard-rate key function

Detection function parameters
Scale Coefficients:
             estimate        se
(Intercept) 6.3348086 0.3715707
size        0.4890754 0.2062362
```

```
Shape parameters:
             estimate        se
(Intercept) 0.6087008 0.1772532

                        Estimate          SE        CV
Average p              0.3142815  0.03980905 0.1266668
N in covered region 407.2782102 59.82362021 0.1468864
```

Additional diagnostic plots:

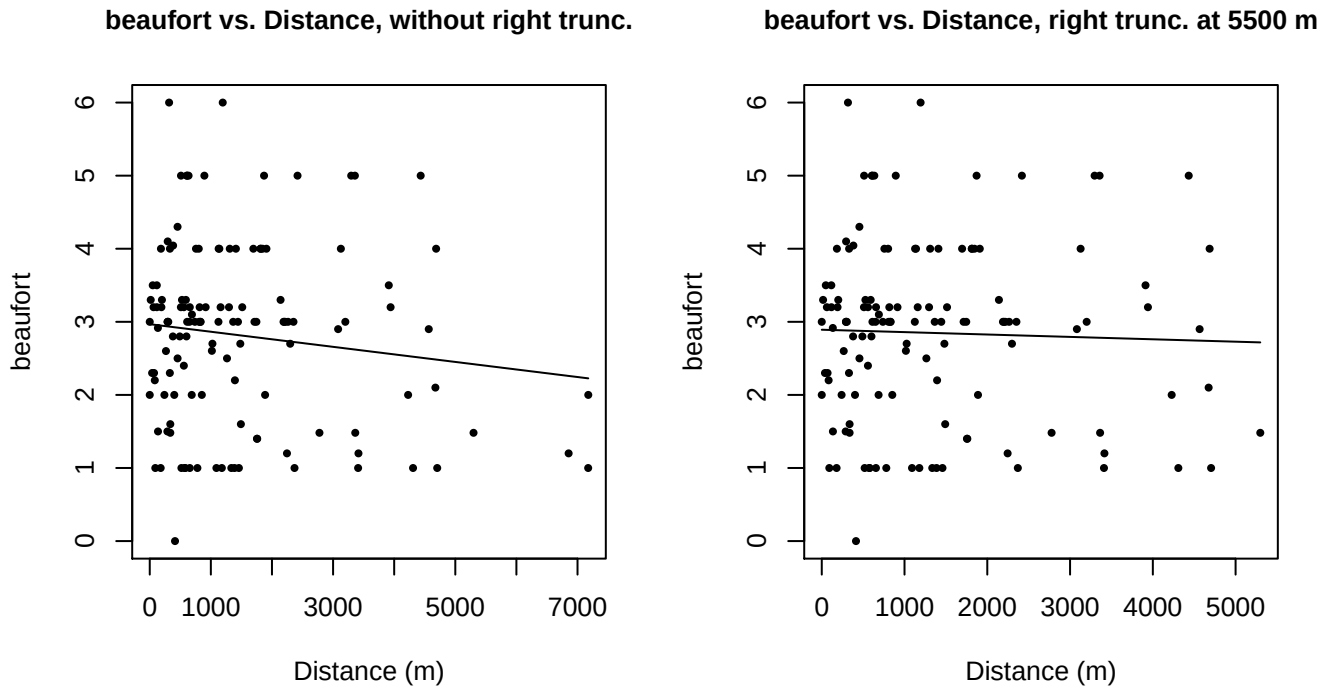

Figure 13: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

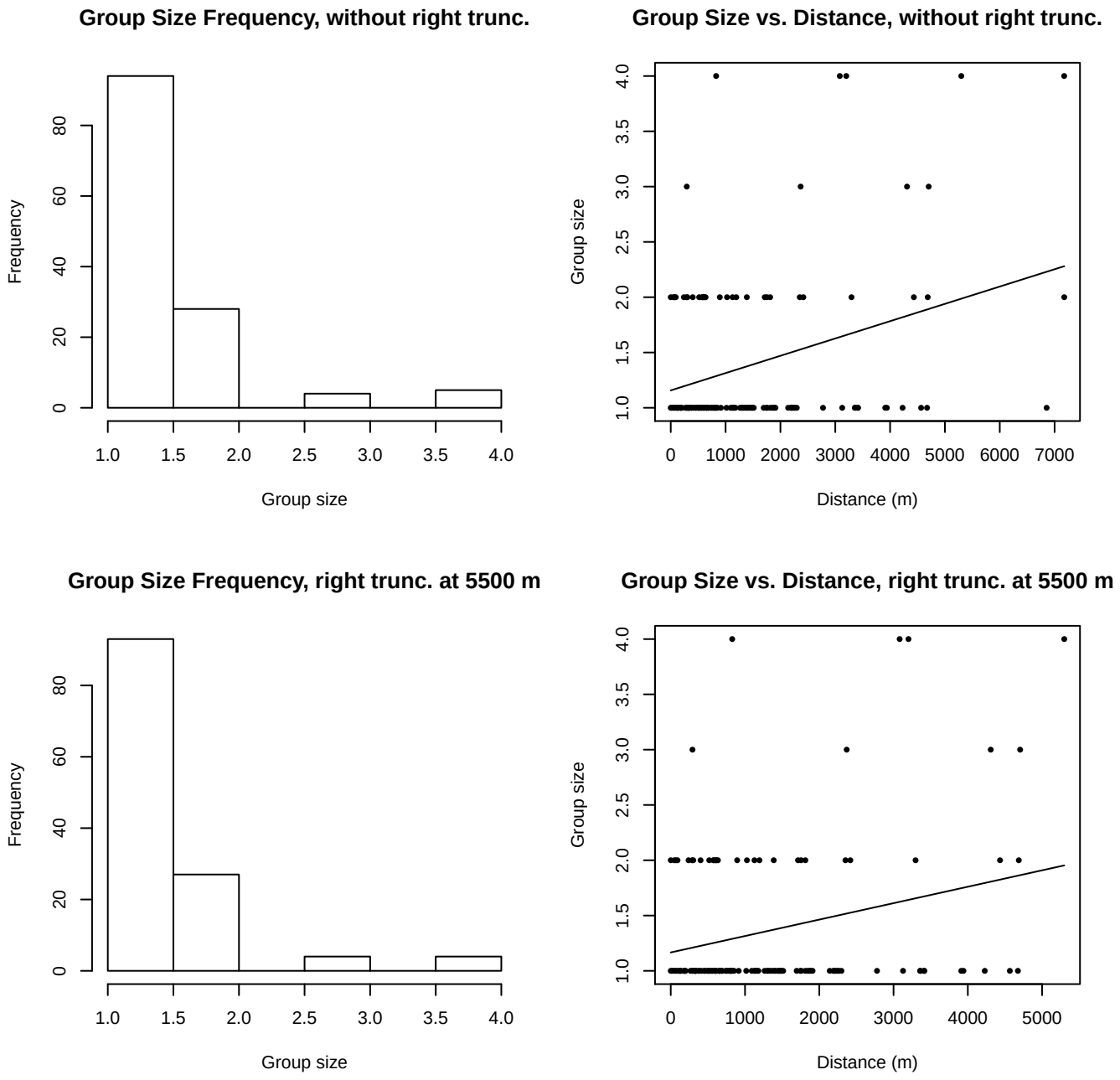

Figure 14: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

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
Total		571

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	788
hr			size	Yes	0.23	881
hr	poly	2		Yes	4.00	802
hr	poly	4		Yes	4.09	816
hr				Yes	5.53	844
hn	cos	3		Yes	12.95	774
hn			size	Yes	17.09	953
hn			beaufort, size	Yes	19.06	953
hn				Yes	28.40	951
hn			beaufort	Yes	30.12	951
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.

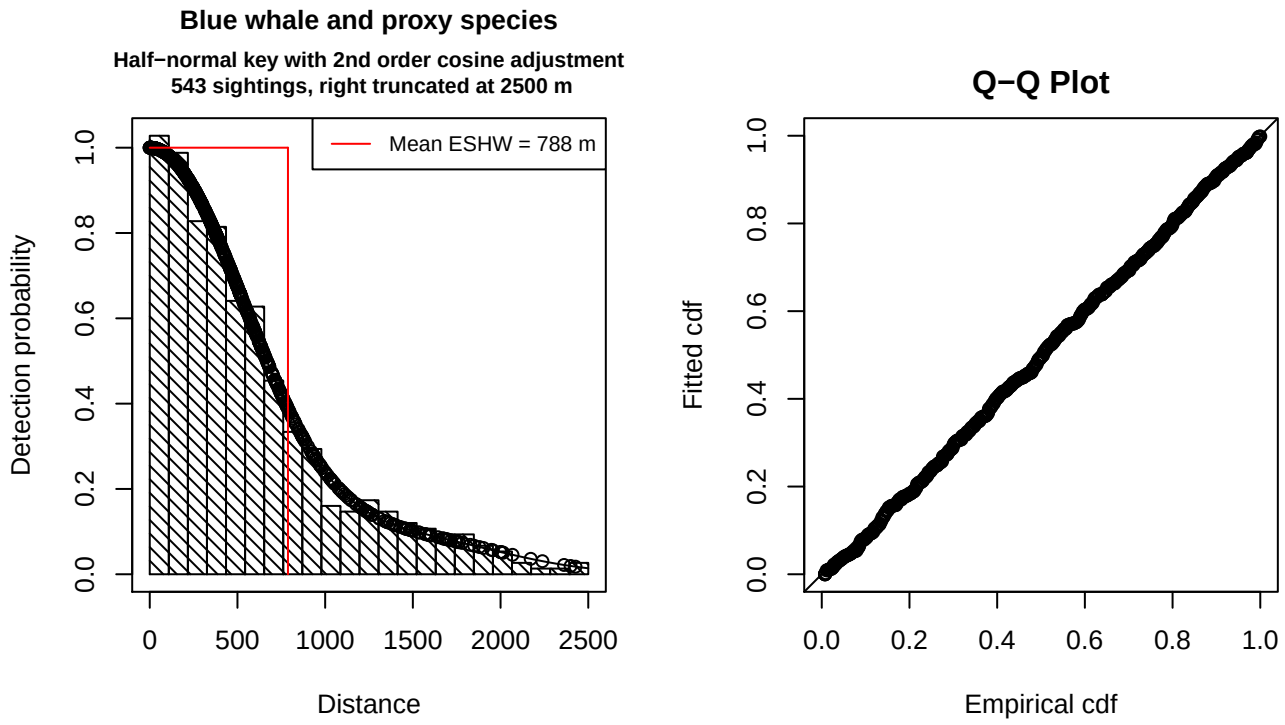

Figure 15: Detection function for Naked Eye Surveys that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  543
Distance range         :  0  -  2500
AIC                    :  7957.87

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

Detection function parameters
Scale Coefficients:
            estimate         se
(Intercept) 6.752179 0.03907979

Adjustment term parameter(s):
              estimate         se
cos, order 2 0.4104348 0.07032499


Monotonicity constraints were enforced.
                        Estimate          SE         CV
Average p              0.3152004  0.01193711 0.03787151
N in covered region 1722.7138013 89.43842935 0.05191717

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

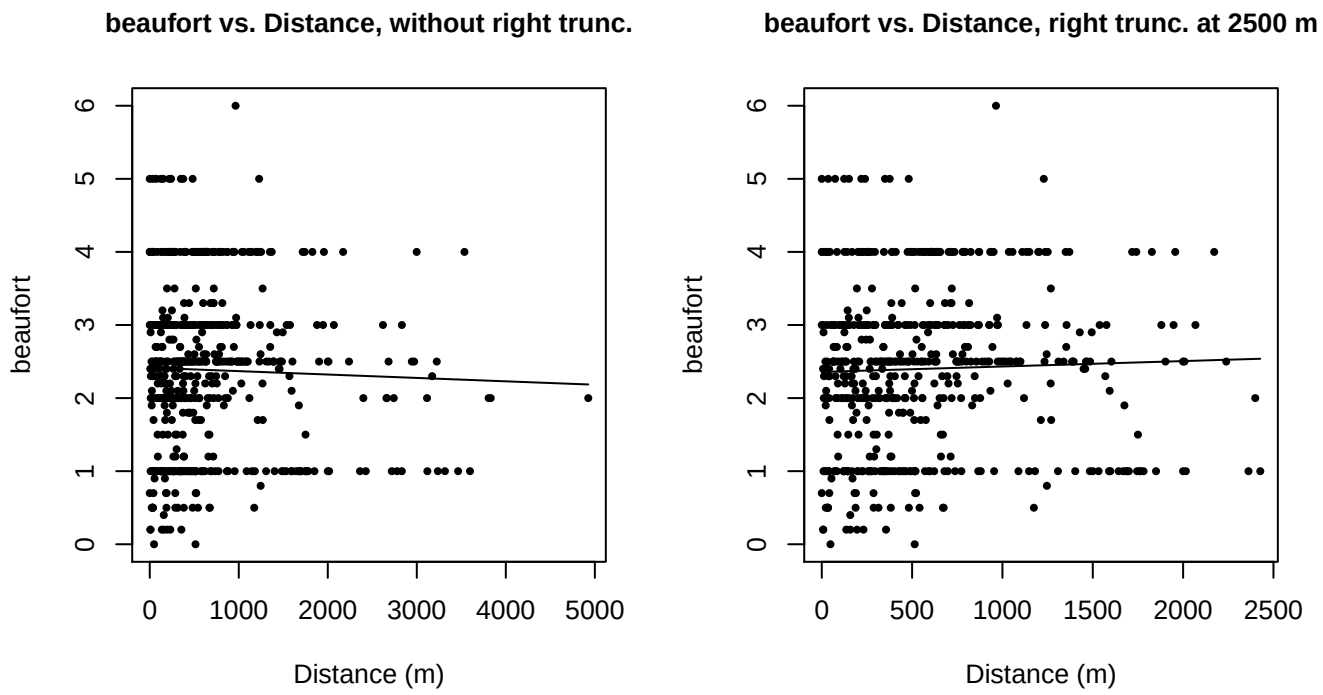

Figure 16: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

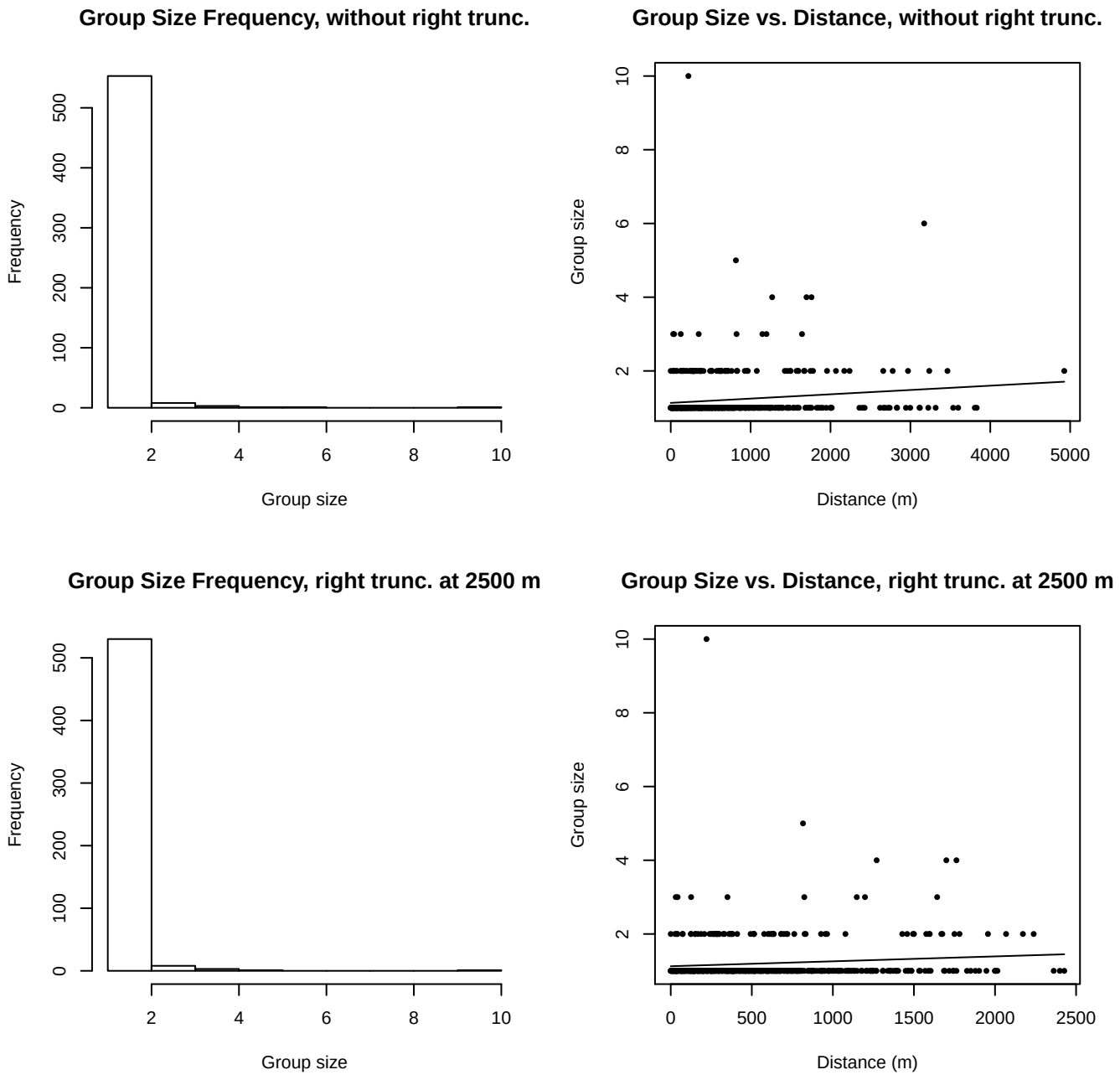

Figure 17: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

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
Total		206

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	714
hr			size	Yes	0.04	799
hr				Yes	0.63	760
hr	poly	4		Yes	0.75	741
hr	poly	2		Yes	1.11	728
hn	cos	3		Yes	2.84	669
hn			size	Yes	5.20	855
hn			quality, size	Yes	6.85	854
hn				Yes	10.43	845
hn			quality	Yes	12.24	845
hn	herm	4		No		
hn			beaufort	No		
hr			beaufort	No		
hr			quality	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.

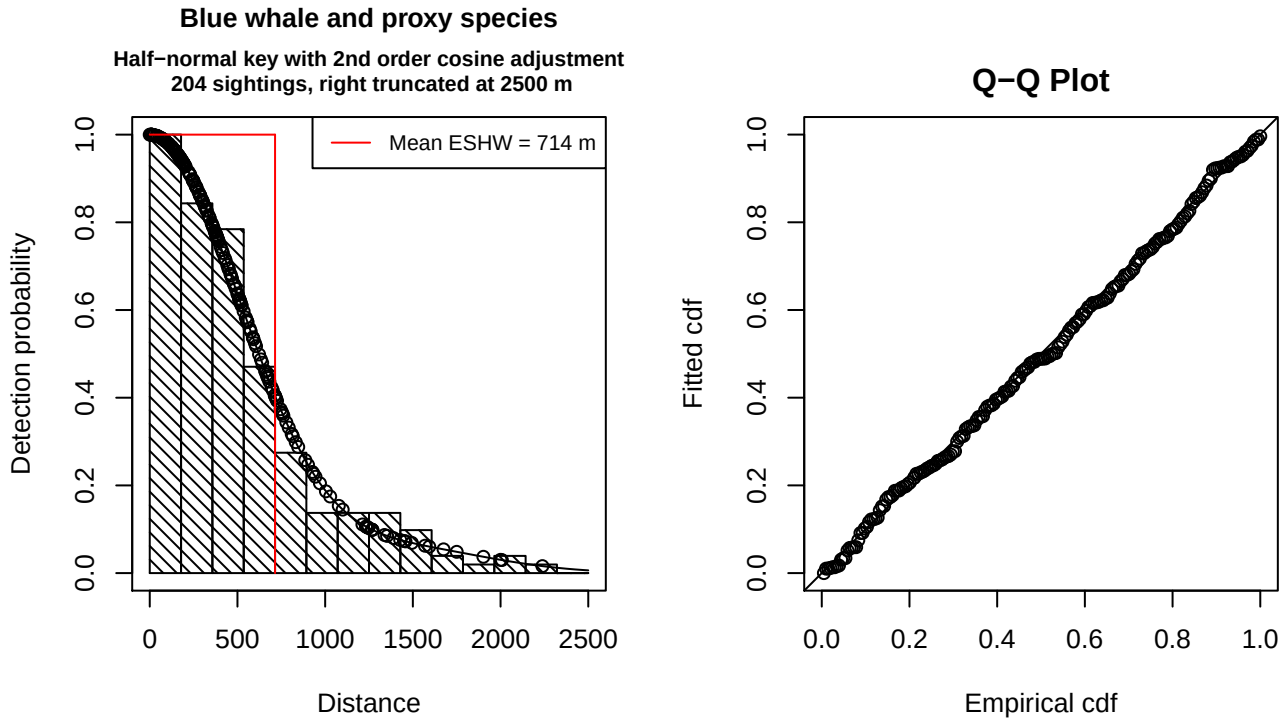

Figure 18: Detection function for NEFSC Abel-J Naked Eye Surveys that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  204
Distance range         :  0  -  2500
AIC                    :  2944.665

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

Detection function parameters
Scale Coefficients:
            estimate         se
(Intercept) 6.665111 0.06962659

Adjustment term parameter(s):
```

```
              estimate        se
cos, order 2 0.4654075 0.1236342


Monotonicity constraints were enforced.
                        Estimate          SE         CV
Average p             0.2857526  0.01551915 0.05430974
N in covered region 713.9042362 57.33838189 0.08031663

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

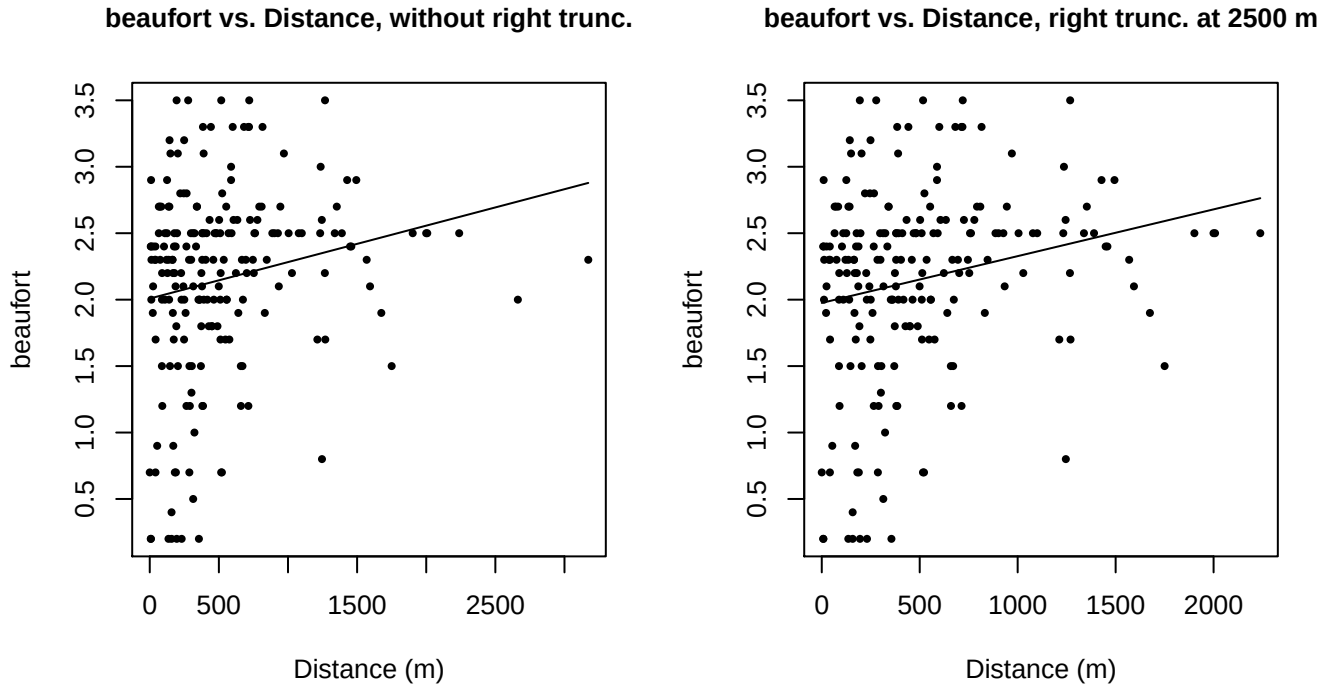

Figure 19: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

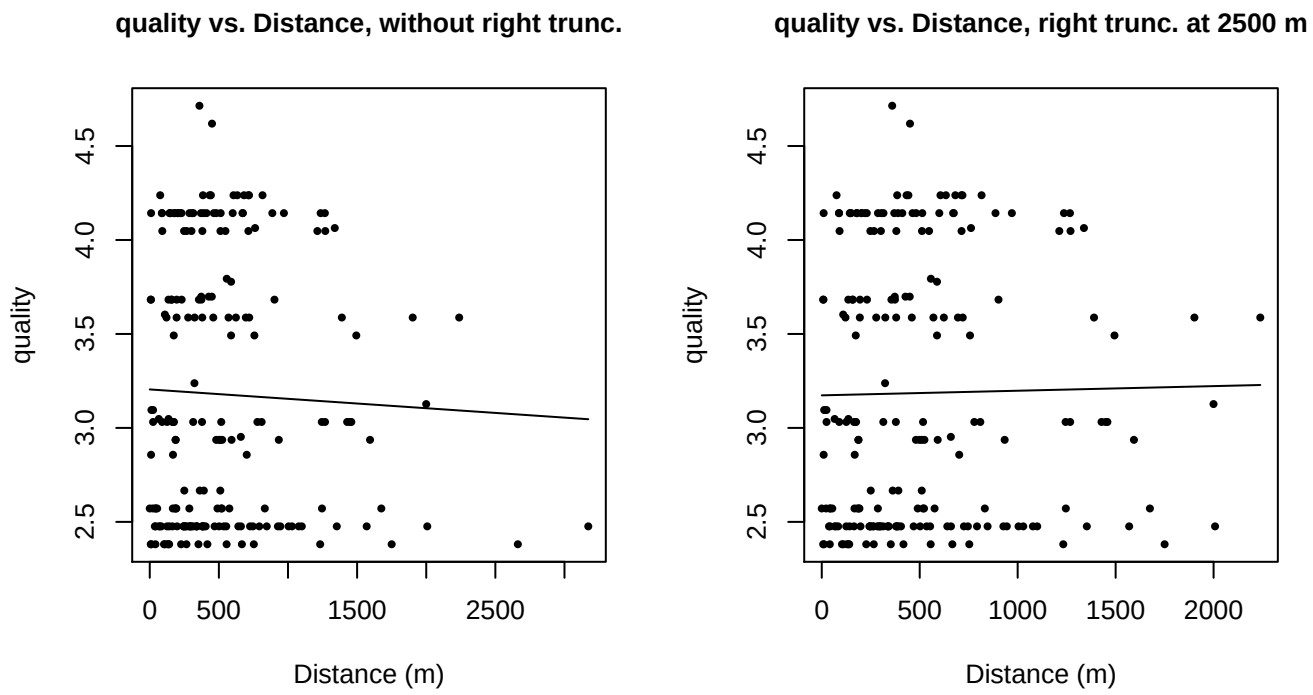

Figure 20: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions.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

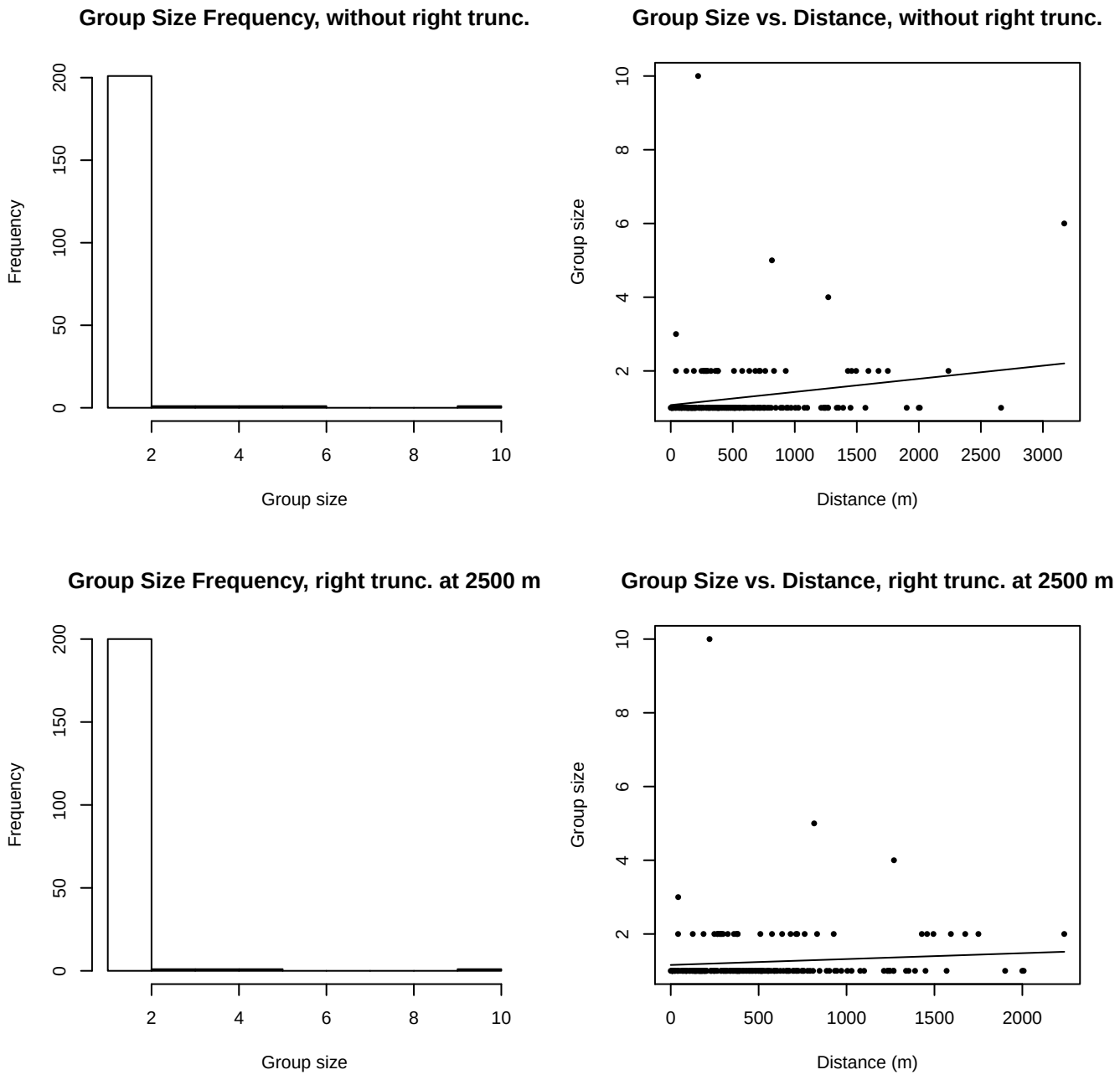

Figure 21: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

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
Total		285

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	796
hn			size	Yes	3.86	900
hn				Yes	4.25	901
hn	cos	3		Yes	4.27	815
hr	poly	2		Yes	4.81	836
hr				Yes	5.06	929
hr	poly	4		Yes	5.80	872
hr			size	Yes	7.05	931
hn	herm	4		No		
hn			beaufort	No		
hr			beaufort	No		
hn			quality	No		
hr			quality	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.

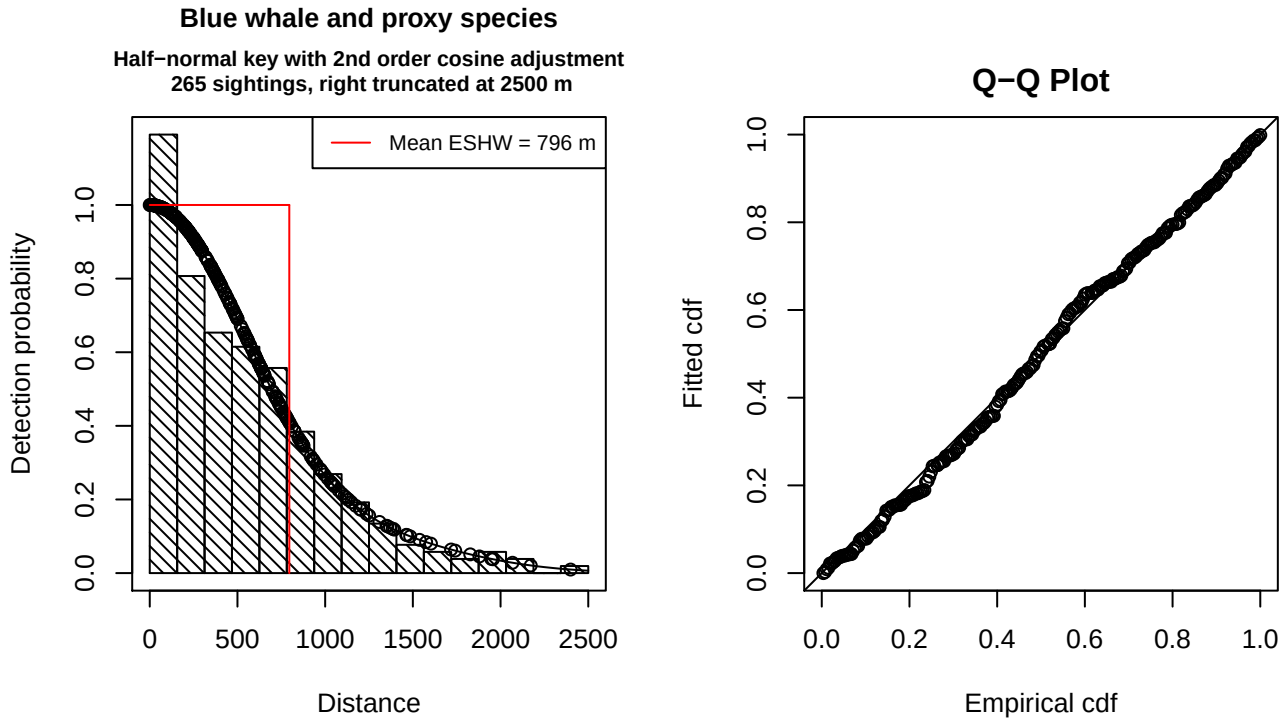

Figure 22: Detection function for CODA and SCANS II that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  265
Distance range         :  0  -  2500
AIC                    :  3866.705

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

Detection function parameters
Scale Coefficients:
            estimate         se
(Intercept) 6.669743 0.05443104

Adjustment term parameter(s):
```

```
              estimate        se
cos, order 2 0.2900289 0.1074259


Monotonicity constraints were enforced.
                        Estimate          SE         CV
Average p             0.3182232  0.01860504 0.05846537
N in covered region 832.7488117 64.45573775 0.07740118

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

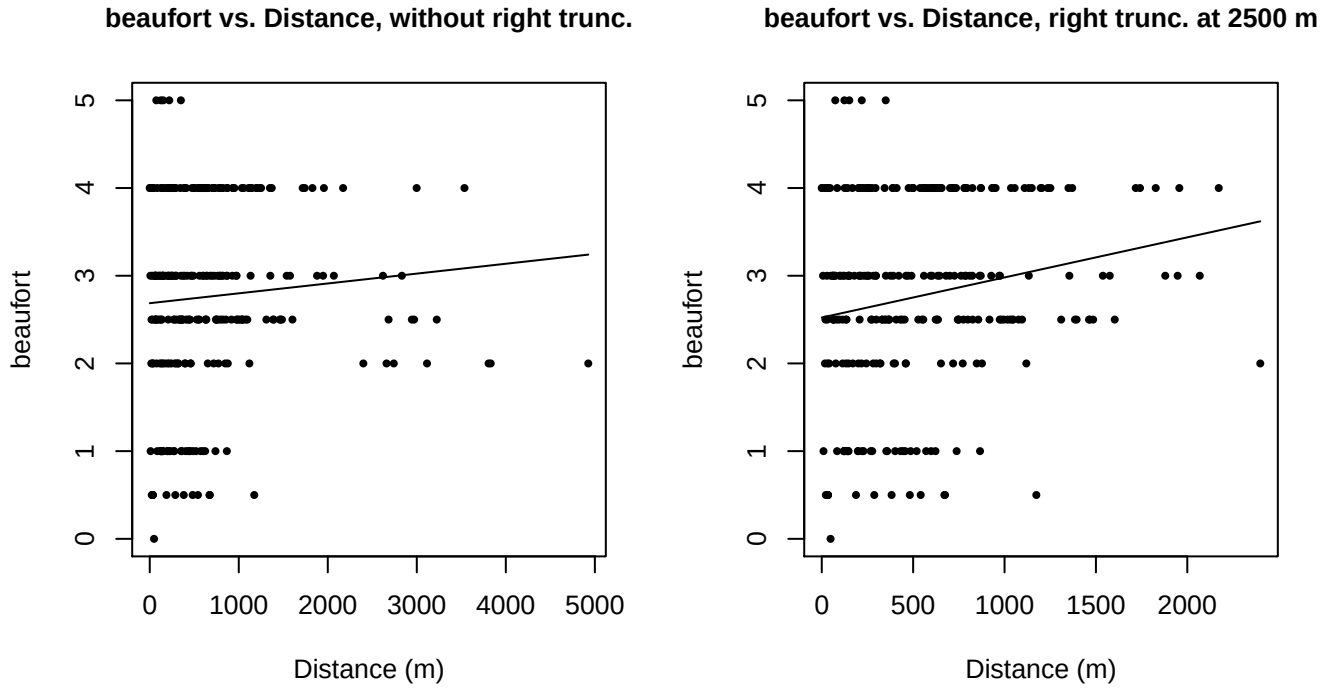

Figure 23: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

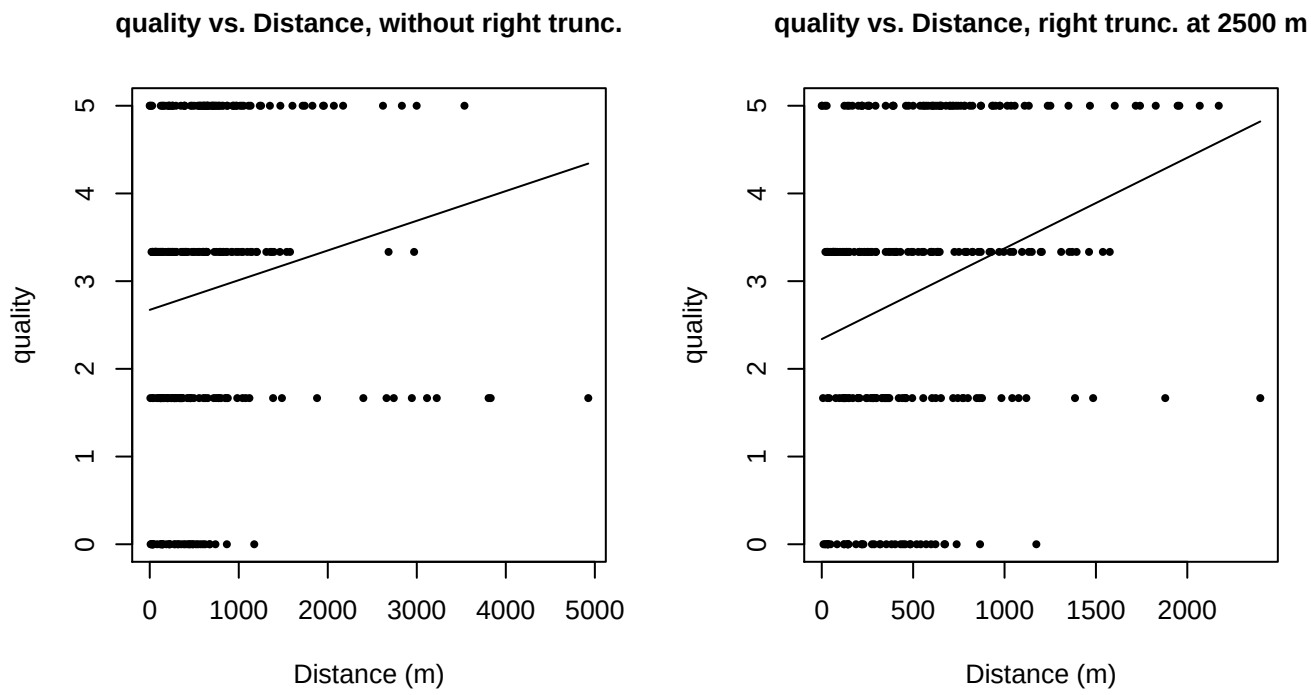

Figure 24: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions.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

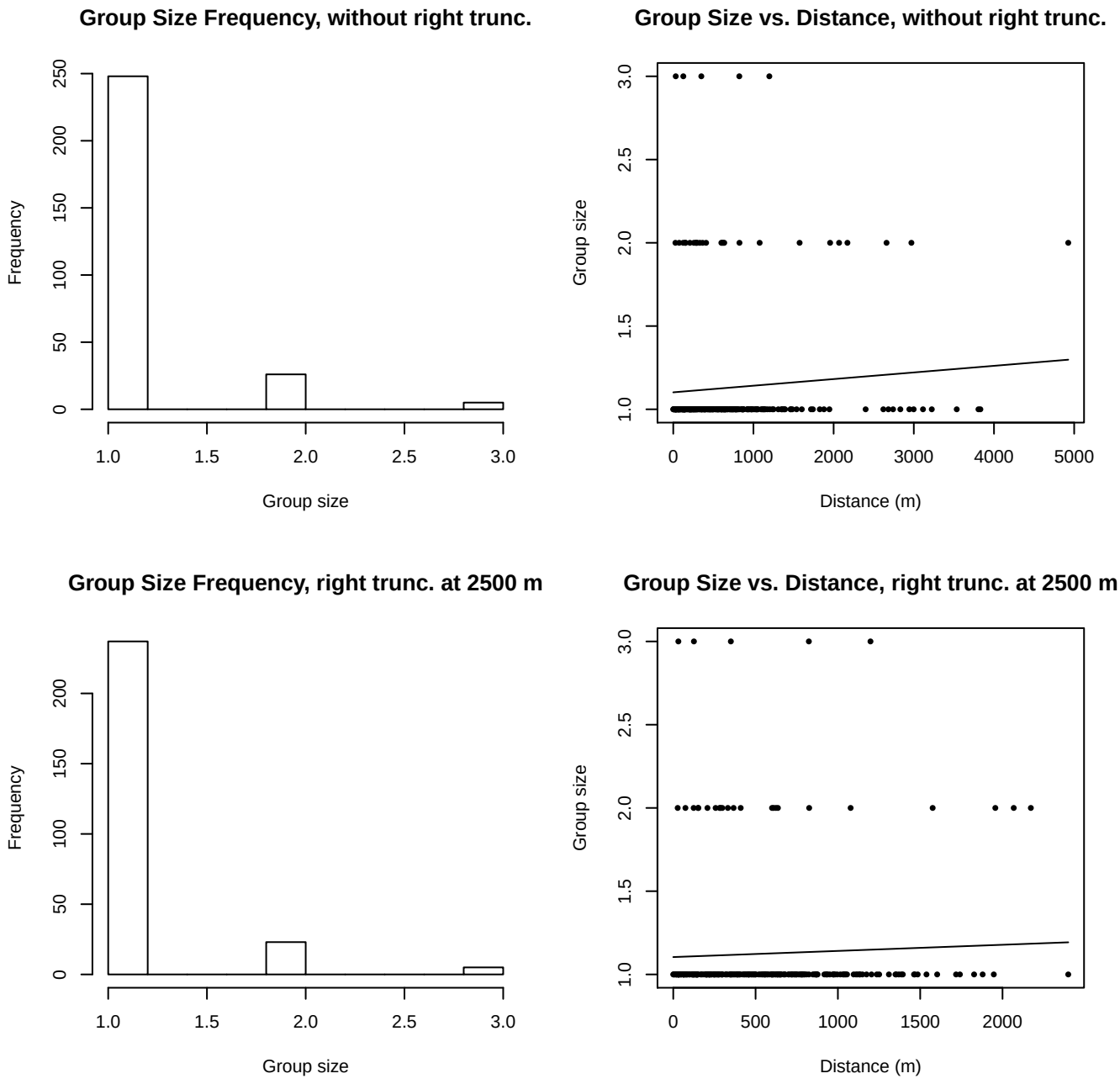

Figure 25: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

Aerial Surveys

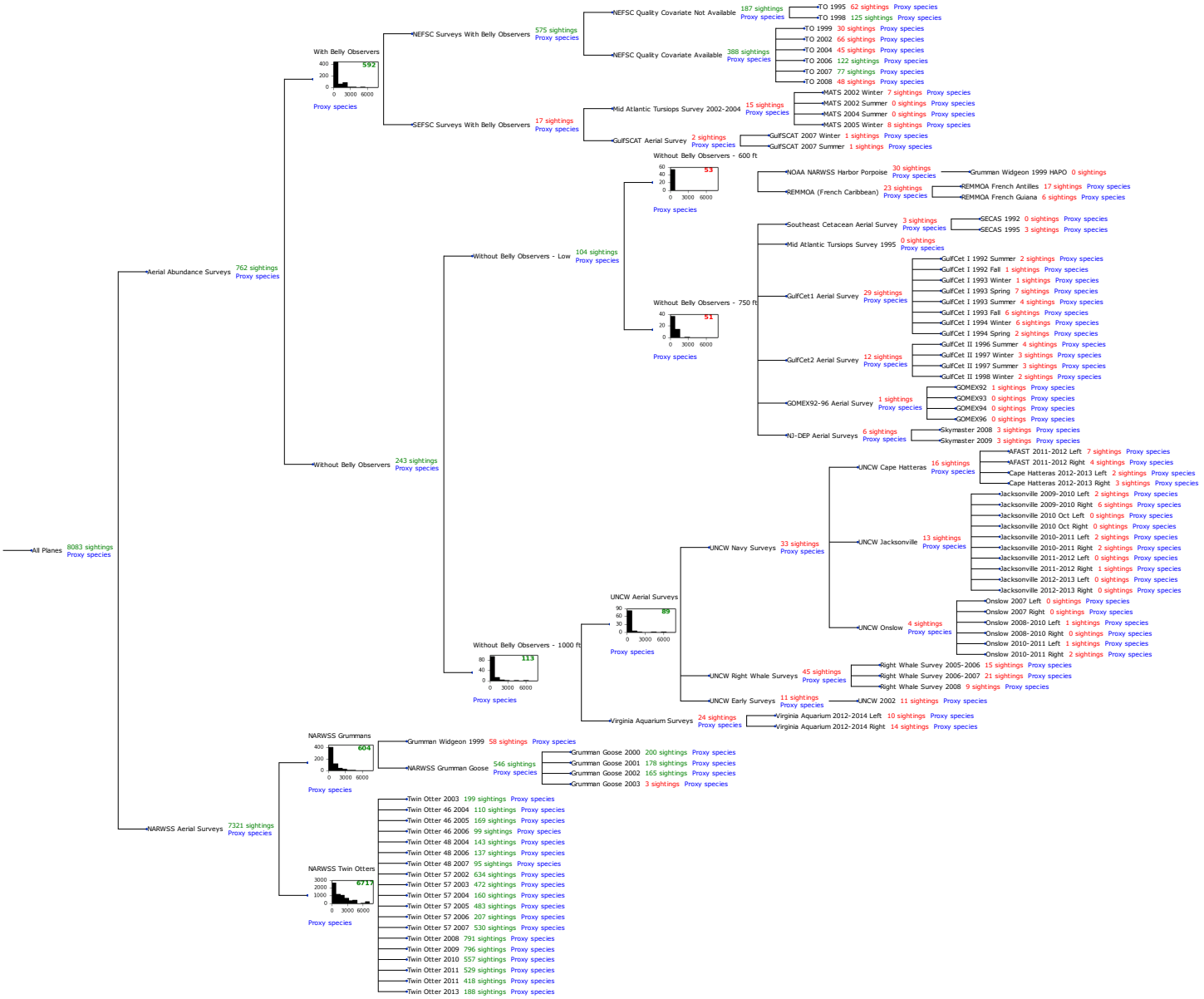

Figure 26: Detection hierarchy for aerial surveys

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
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.

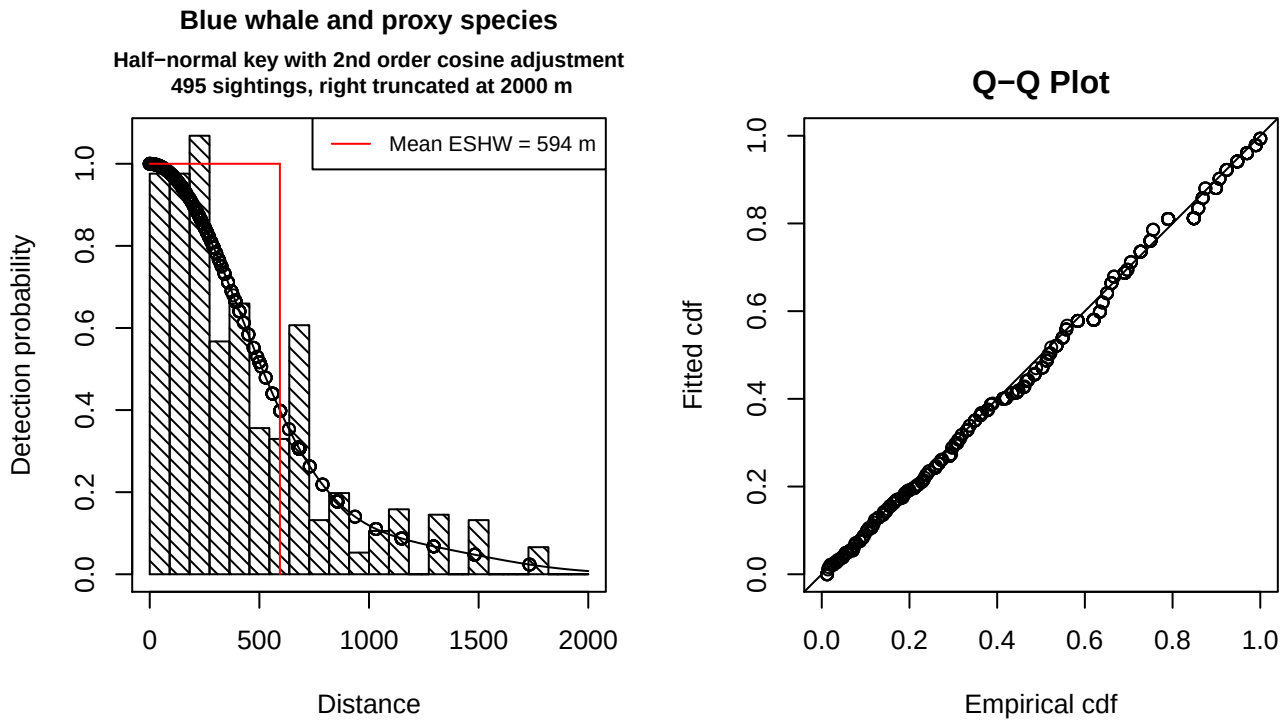

Figure 27: Detection function for With Belly Observers that was selected for the density model

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 0.4286652 0.0797525


Monotonicity constraints were enforced.
                        Estimate          SE         CV
Average p              0.2967565  0.01131843 0.03814048
N in covered region 1668.0343783 89.44444687 0.05362266

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.

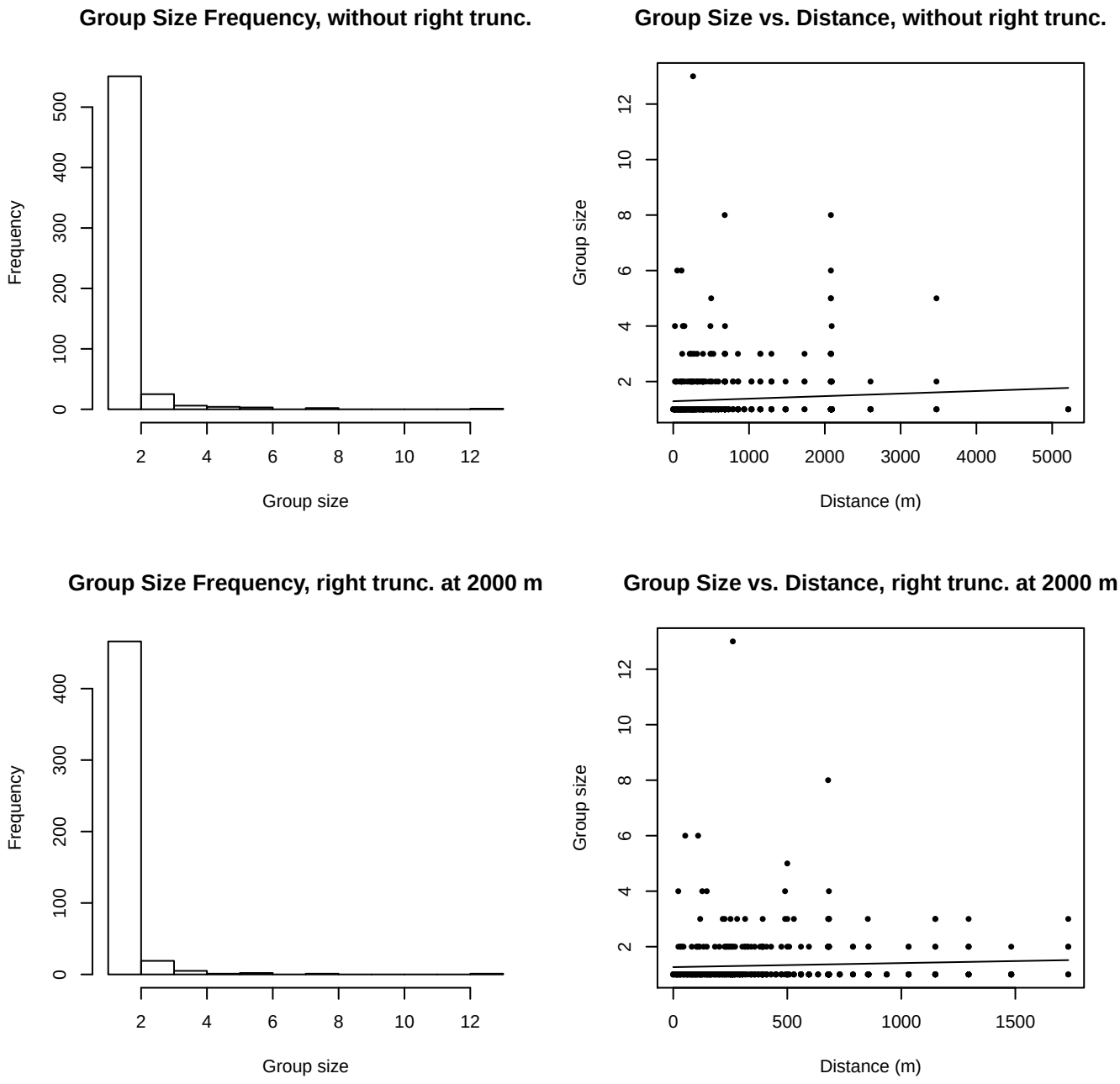

Figure 29: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

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
Physeter macrocephalus	Sperm whale	10
Total		53

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	293
hr				Yes	1.14	318
hn			beaufort	Yes	1.57	293
hn	cos	3		Yes	1.65	311
hn	herm	4		Yes	1.93	291
hr			beaufort	Yes	1.97	326
hn	cos	2		Yes	1.97	283
hr	poly	2		Yes	3.14	318
hr	poly	4		Yes	3.14	318
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.

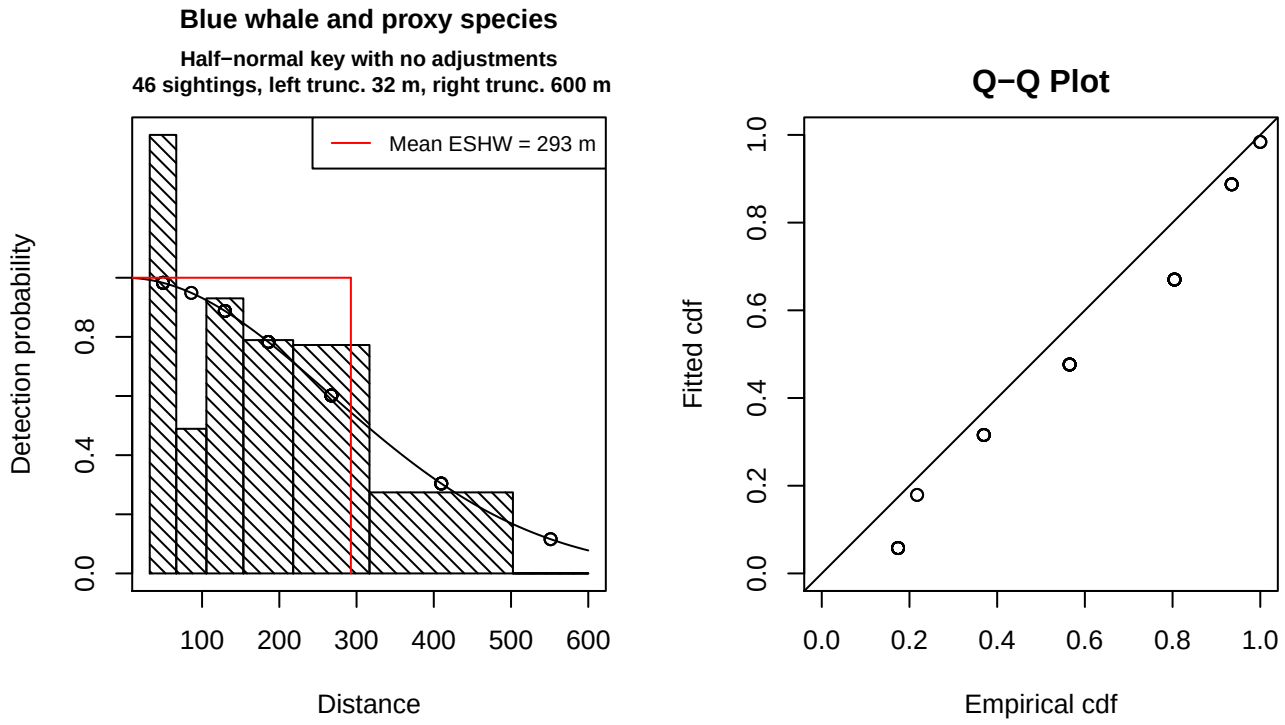

Figure 30: Detection function for Without Belly Observers - 600 ft that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  46
Distance range         :  32.24668  -  600
AIC                    :  177.4011

Detection function:
 Half-normal key function

Detection function parameters
Scale Coefficients:
            estimate        se
(Intercept) 5.581559 0.1339955

                     Estimate          SE        CV
Average p            0.487738  0.06208134 0.1272842
N in covered region 94.312922 15.59372100 0.1653402
```

Additional diagnostic plots:

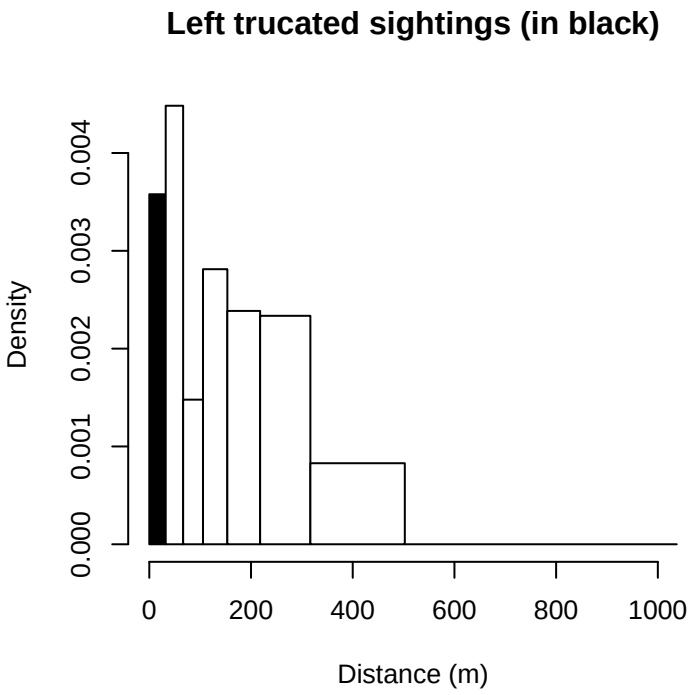

Figure 31: Density of sightings by perpendicular distance for Without Belly Observers - 600 ft. Black bars on the left show sightings that were left truncated.

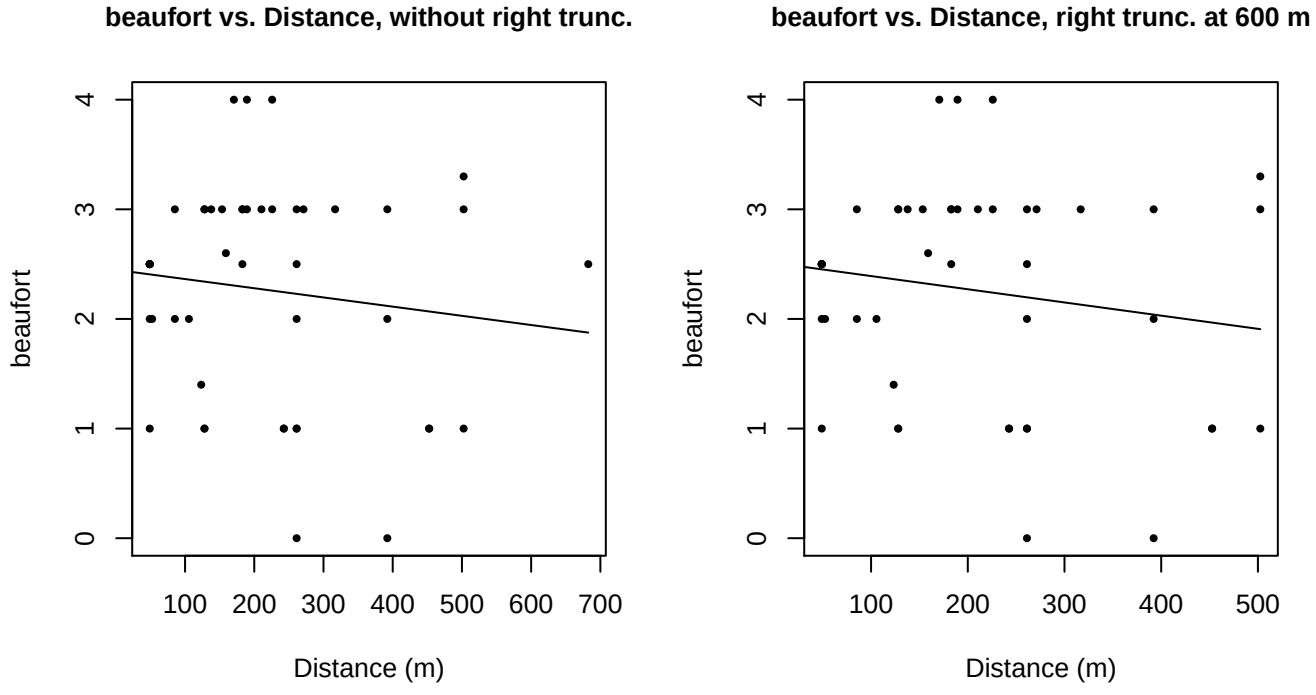

Figure 32: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

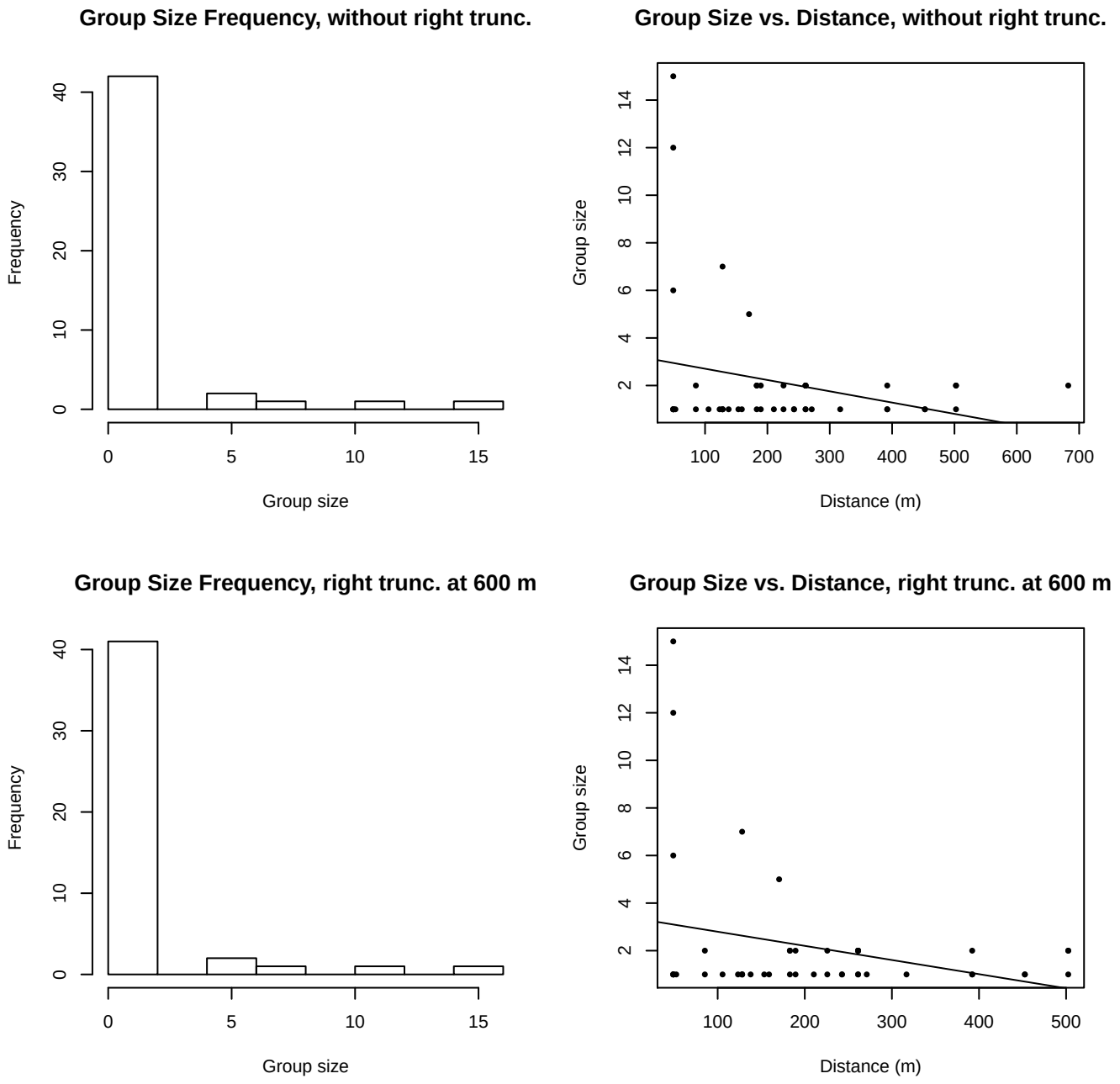

Figure 33: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

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
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	2.59	253
hn				No		

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

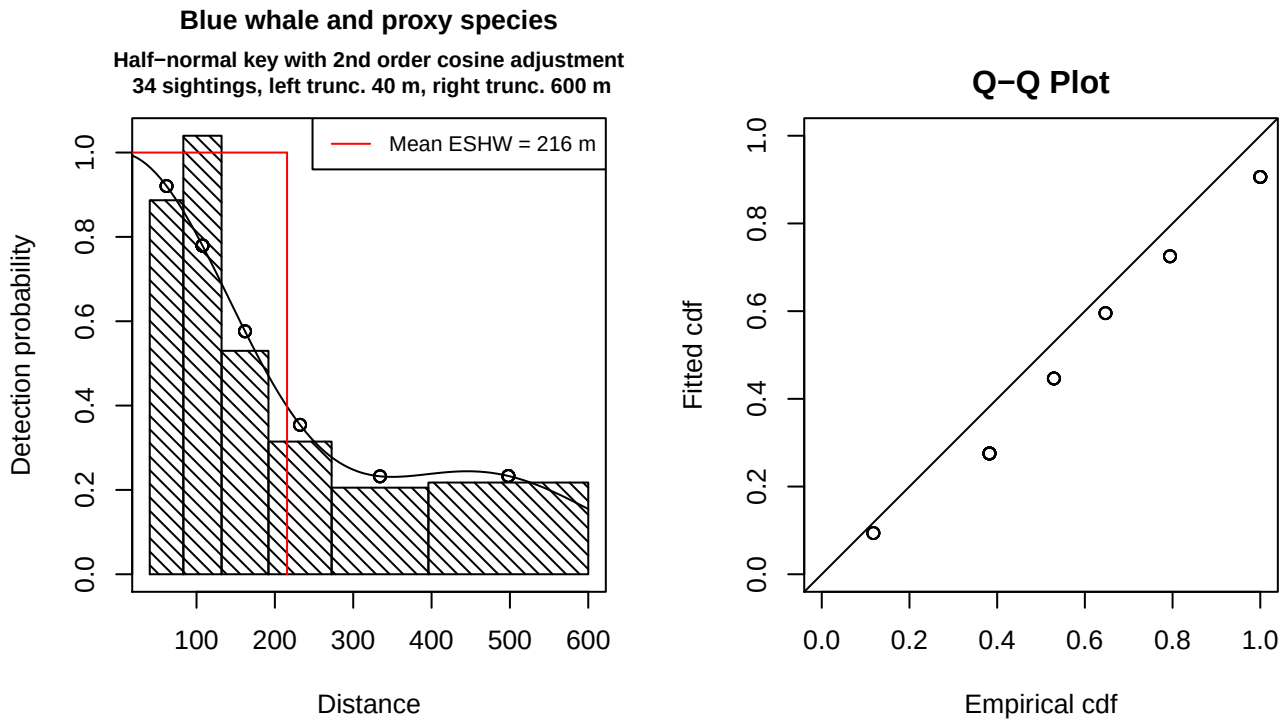

Figure 34: Detection function for Without Belly Observers - 750 ft that was selected for the density model

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) 5.738325 0.1838281

Adjustment term parameter(s):
              estimate       se
cos, order 2 0.4333818 0.242253


Monotonicity constraints were enforced.
                      Estimate         SE        CV
Average p            0.3592782  0.0870934 0.2424122
N in covered region 94.6341930 26.3634655 0.2785829

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

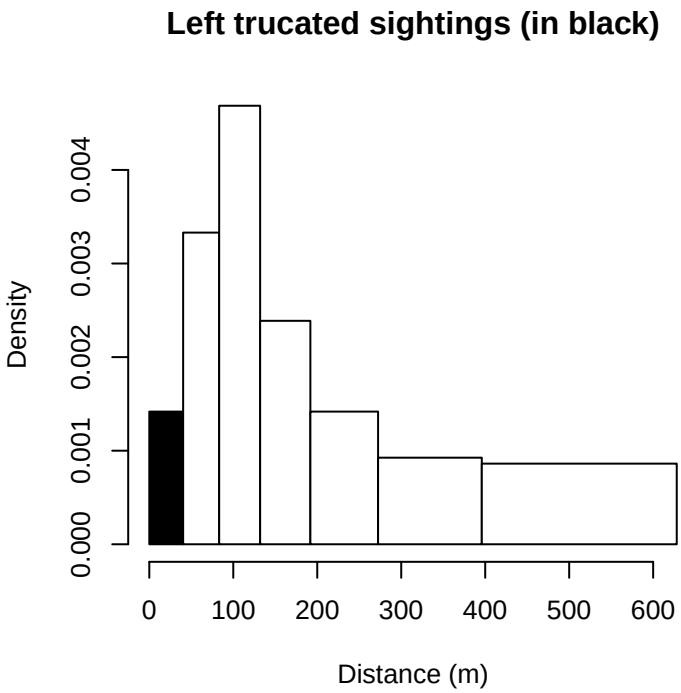

Figure 35: Density of sightings by perpendicular distance for Without Belly Observers - 750 ft. Black bars on the left show sightings that were left truncated.

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
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.

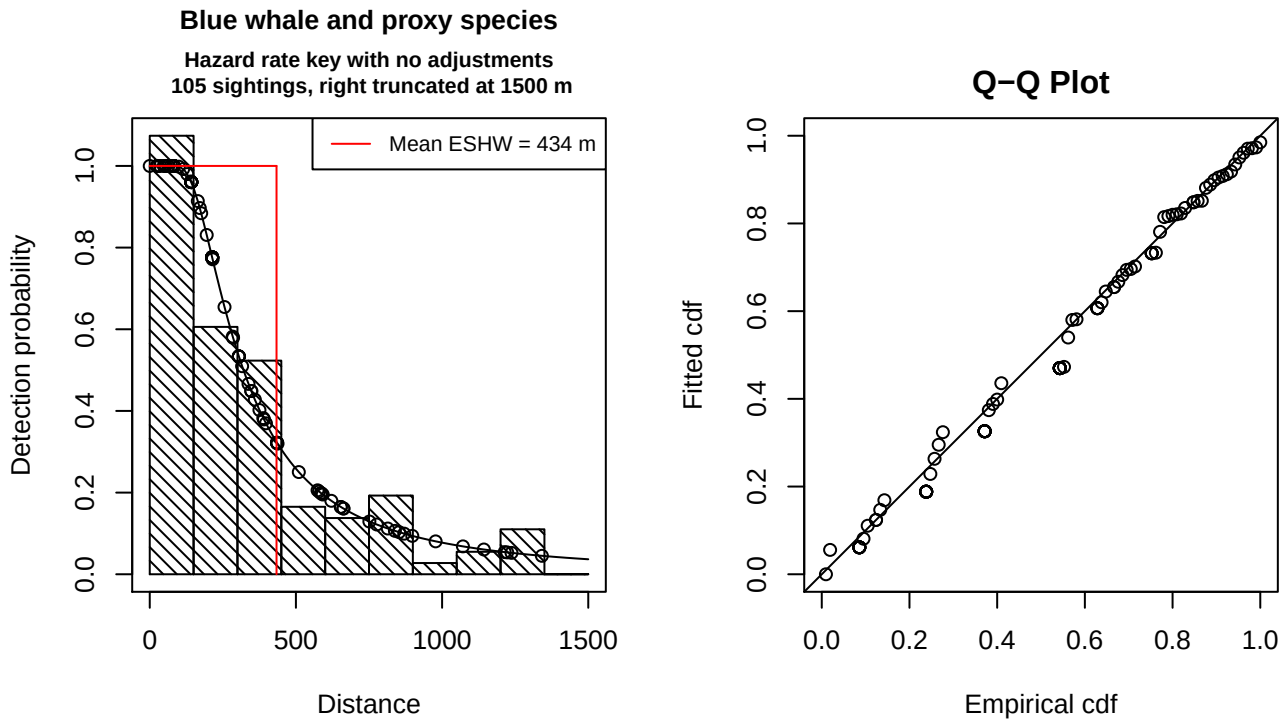

Figure 36: Detection function for Without Belly Observers - 1000 ft that was selected for the density model

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:

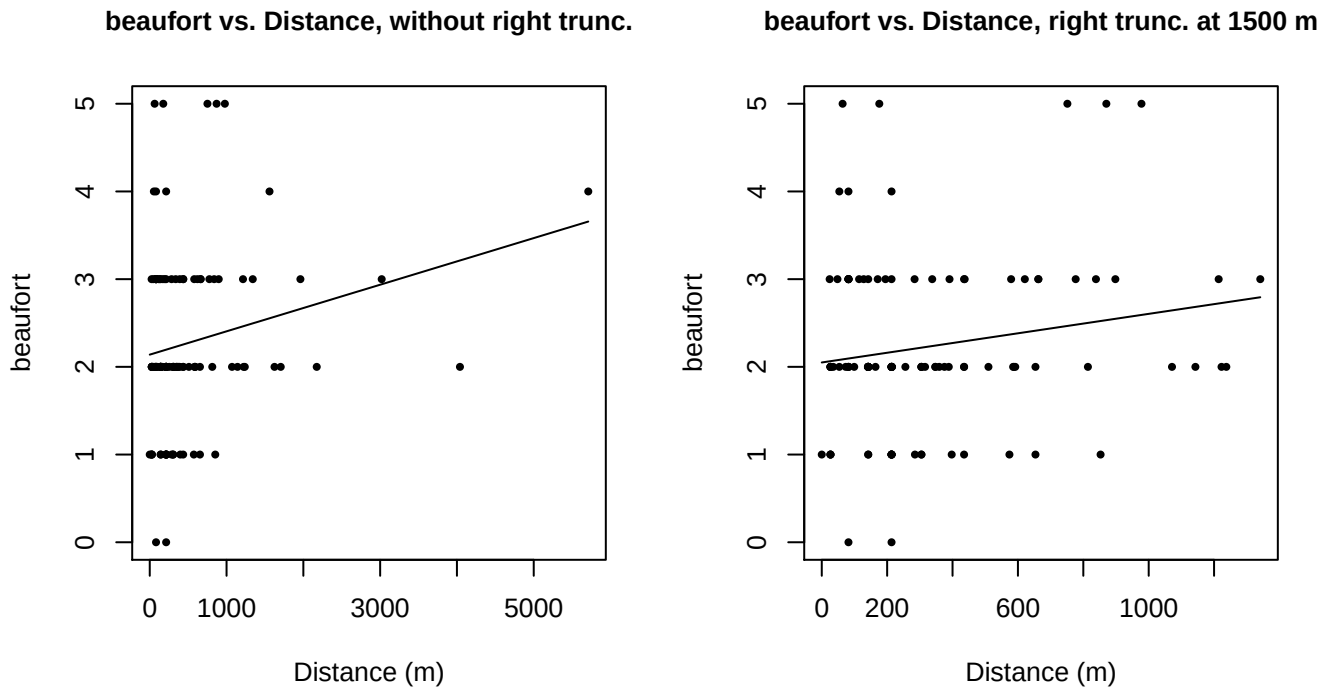

Figure 37: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

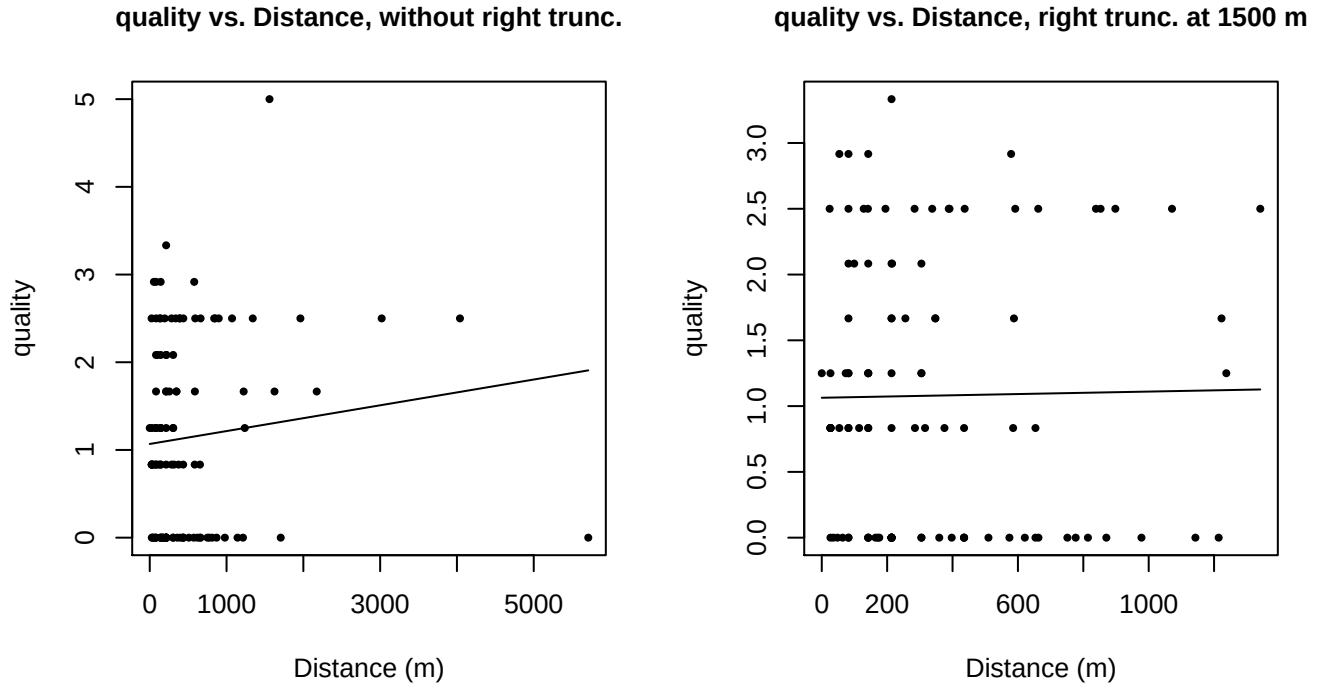

Figure 38: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions.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

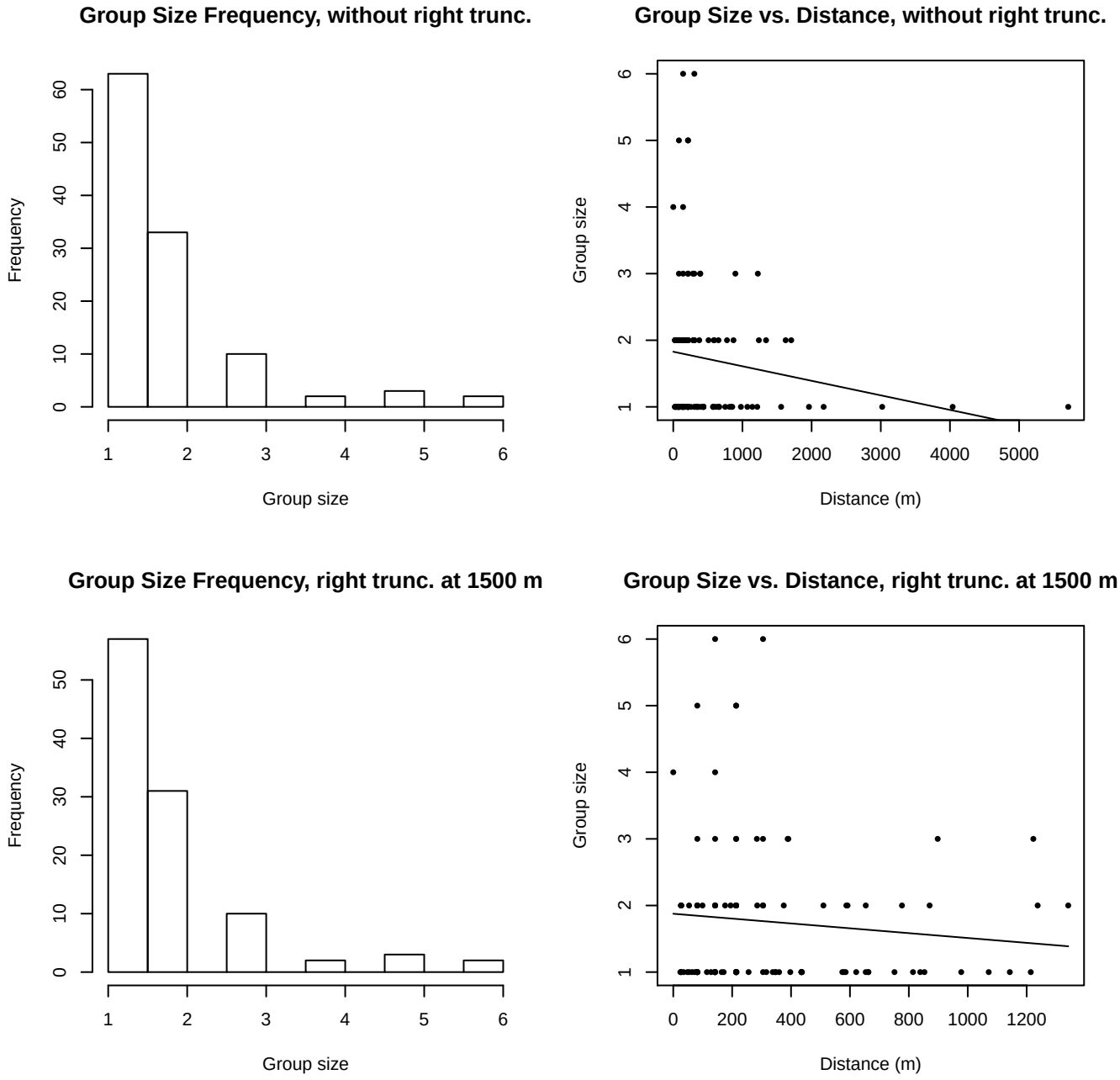

Figure 39: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

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
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.

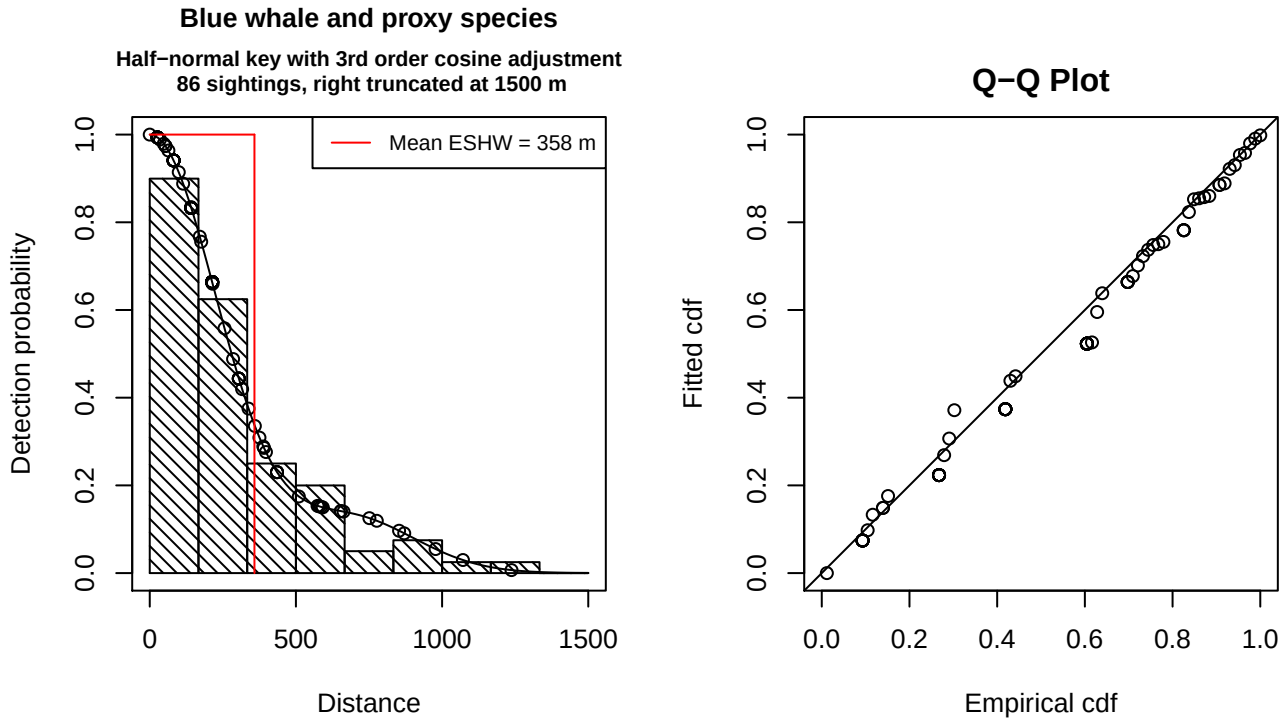

Figure 40: Detection function for UNCW Aerial Surveys that was selected for the density model

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 0.4451316 0.1512901


Monotonicity constraints were enforced.
                        Estimate          SE        CV
Average p              0.2387636  0.02505434 0.1049337
N in covered region 360.1889023 50.76321007 0.1409350

Monotonicity constraints were enforced.
```

Additional diagnostic plots:

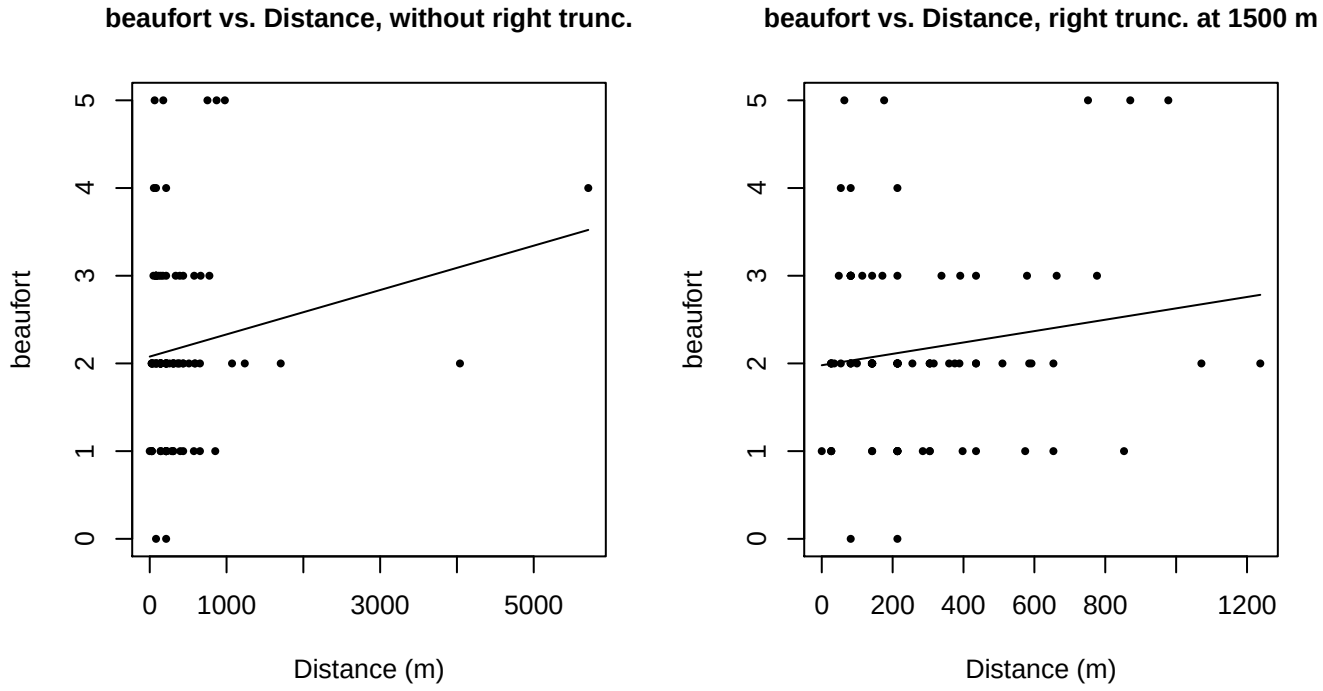

Figure 41: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

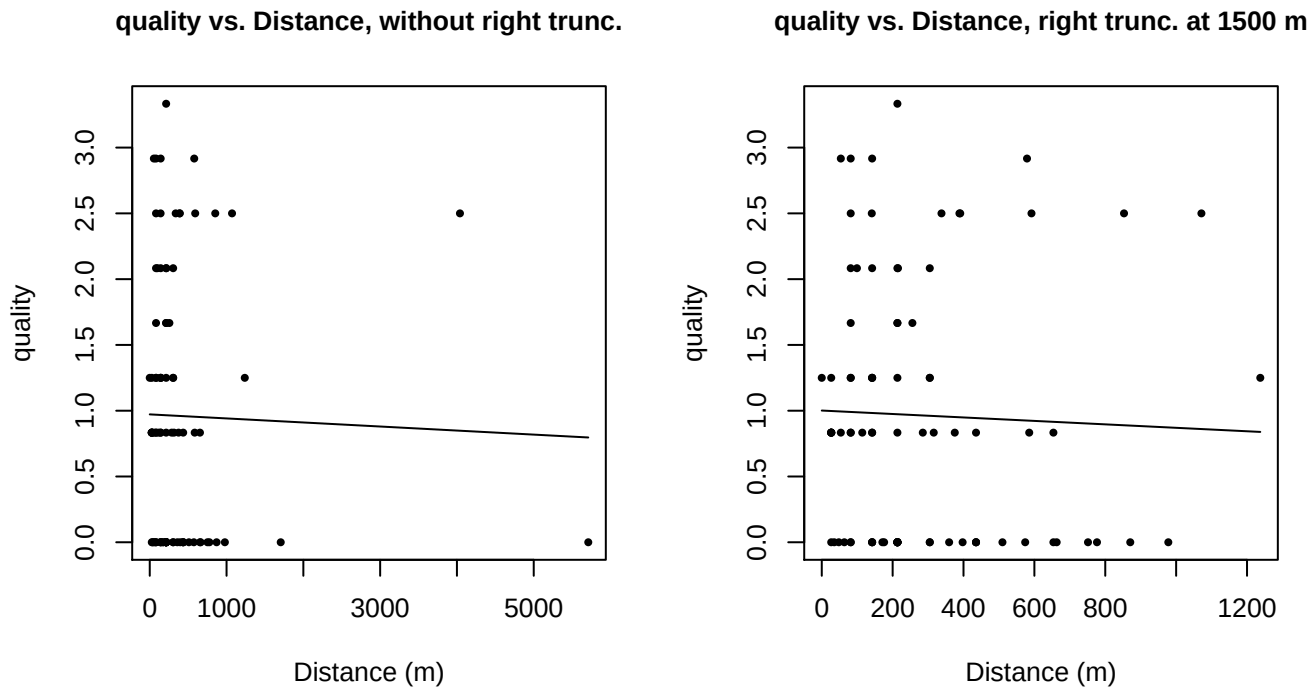

Figure 42: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions.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

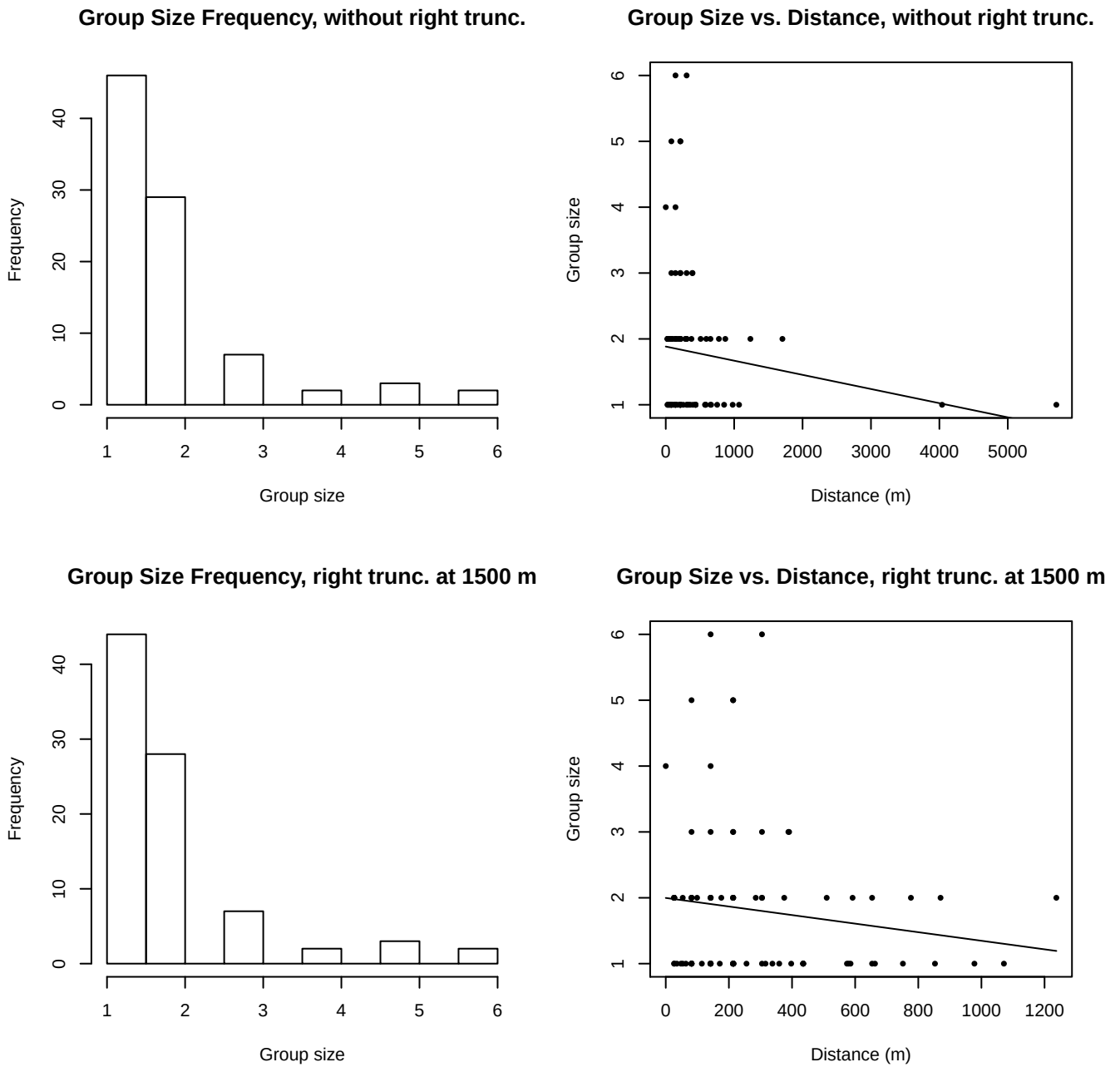

Figure 43: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

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
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.

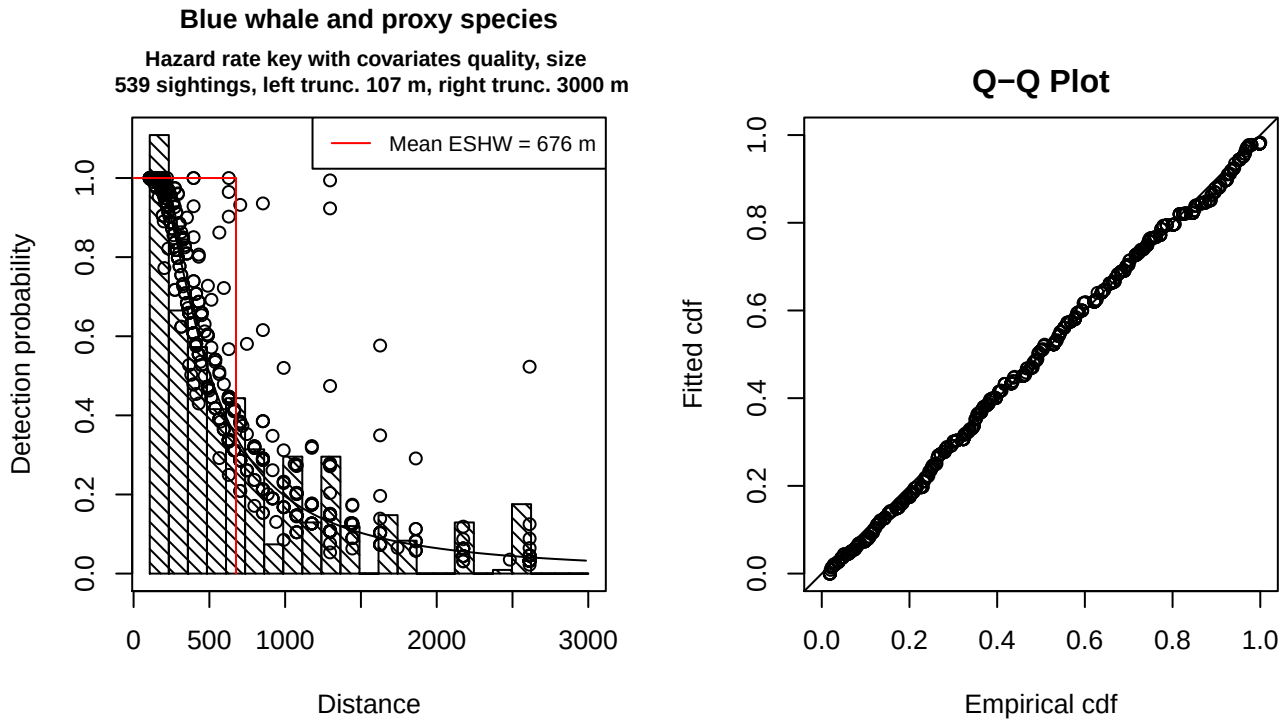

Figure 44: Detection function for NARWSS Grummans that was selected for the density model

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:

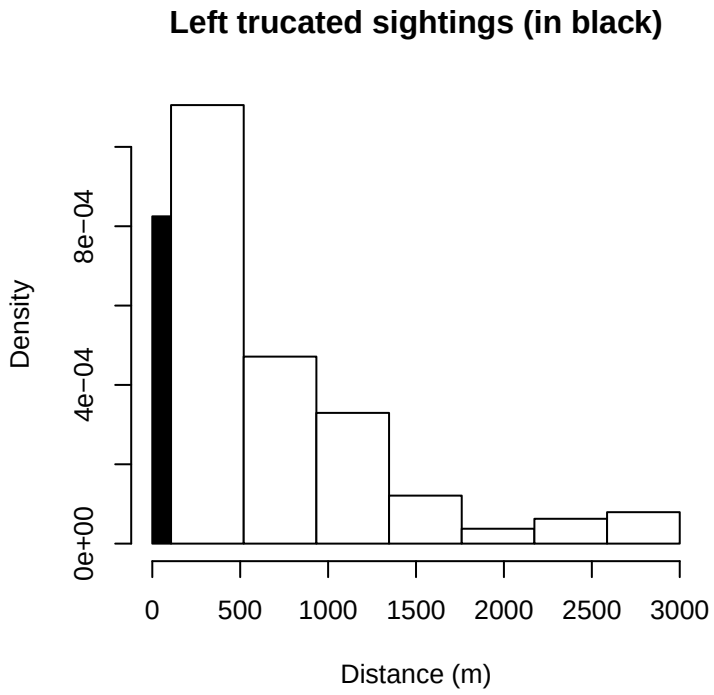

Figure 45: Density of sightings by perpendicular distance for NARWSS Grummans. Black bars on the left show sightings that were left truncated.

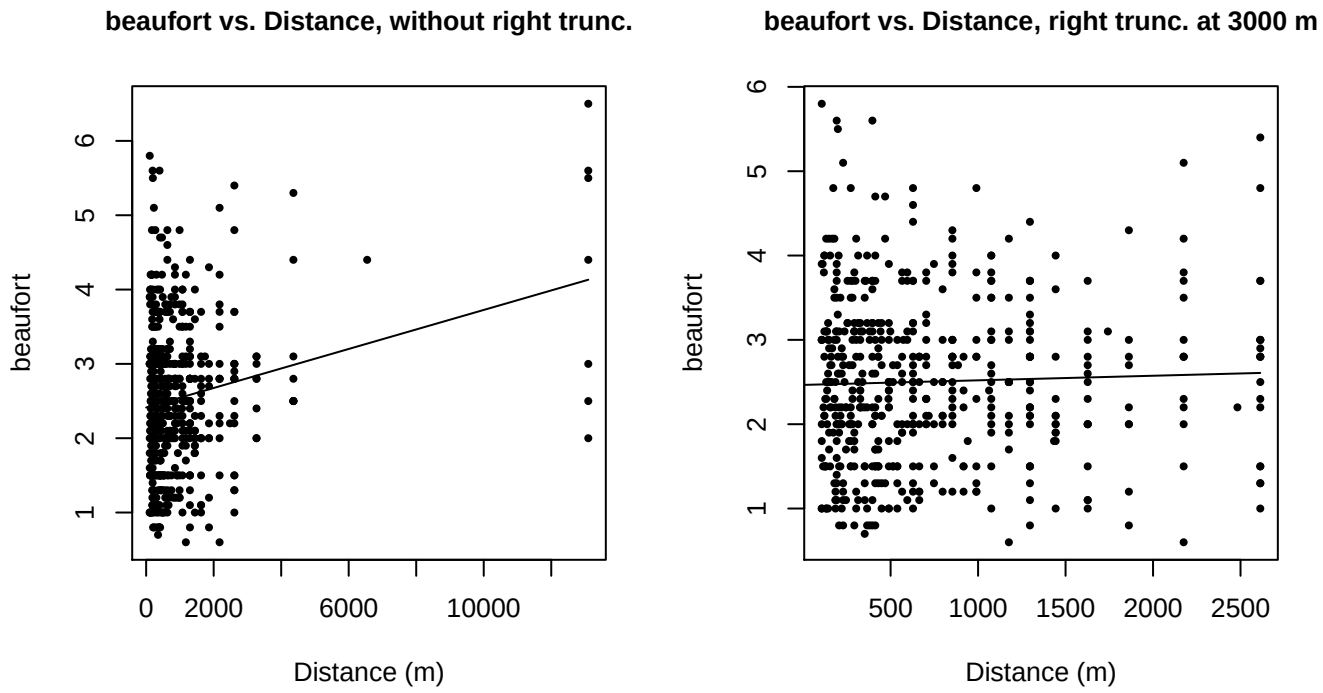

Figure 46: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

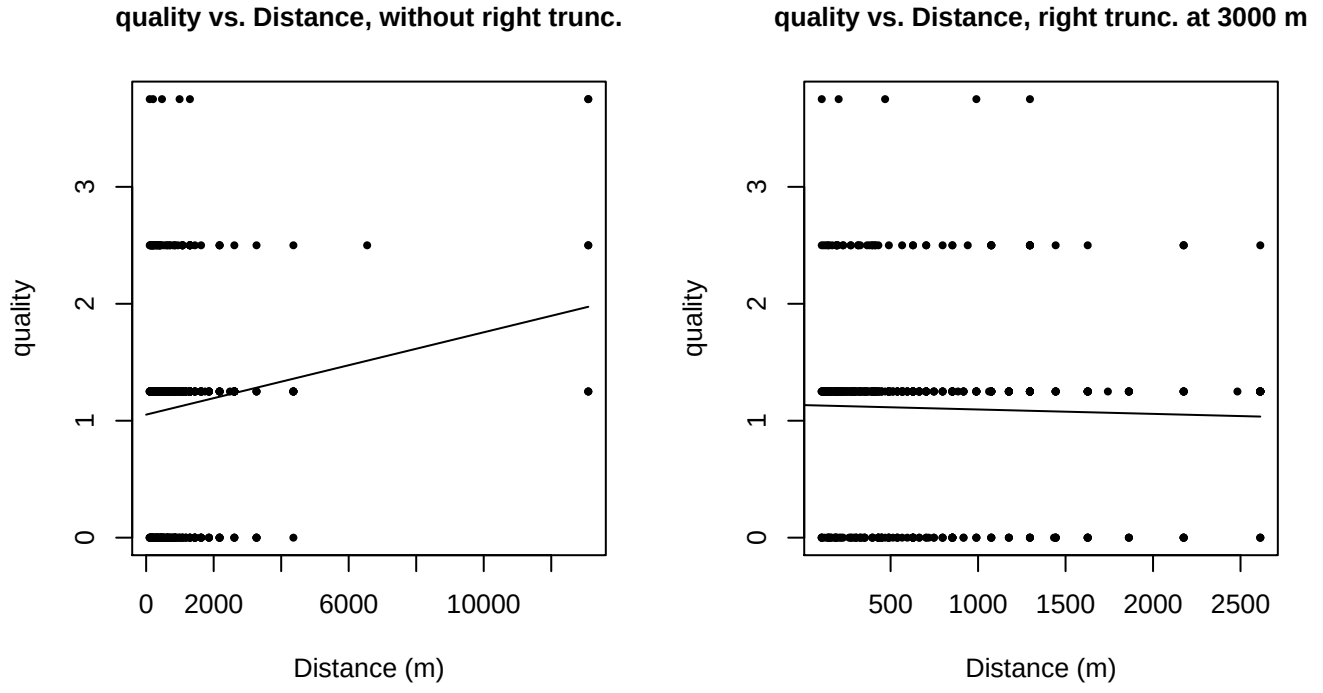

Figure 47: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions.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

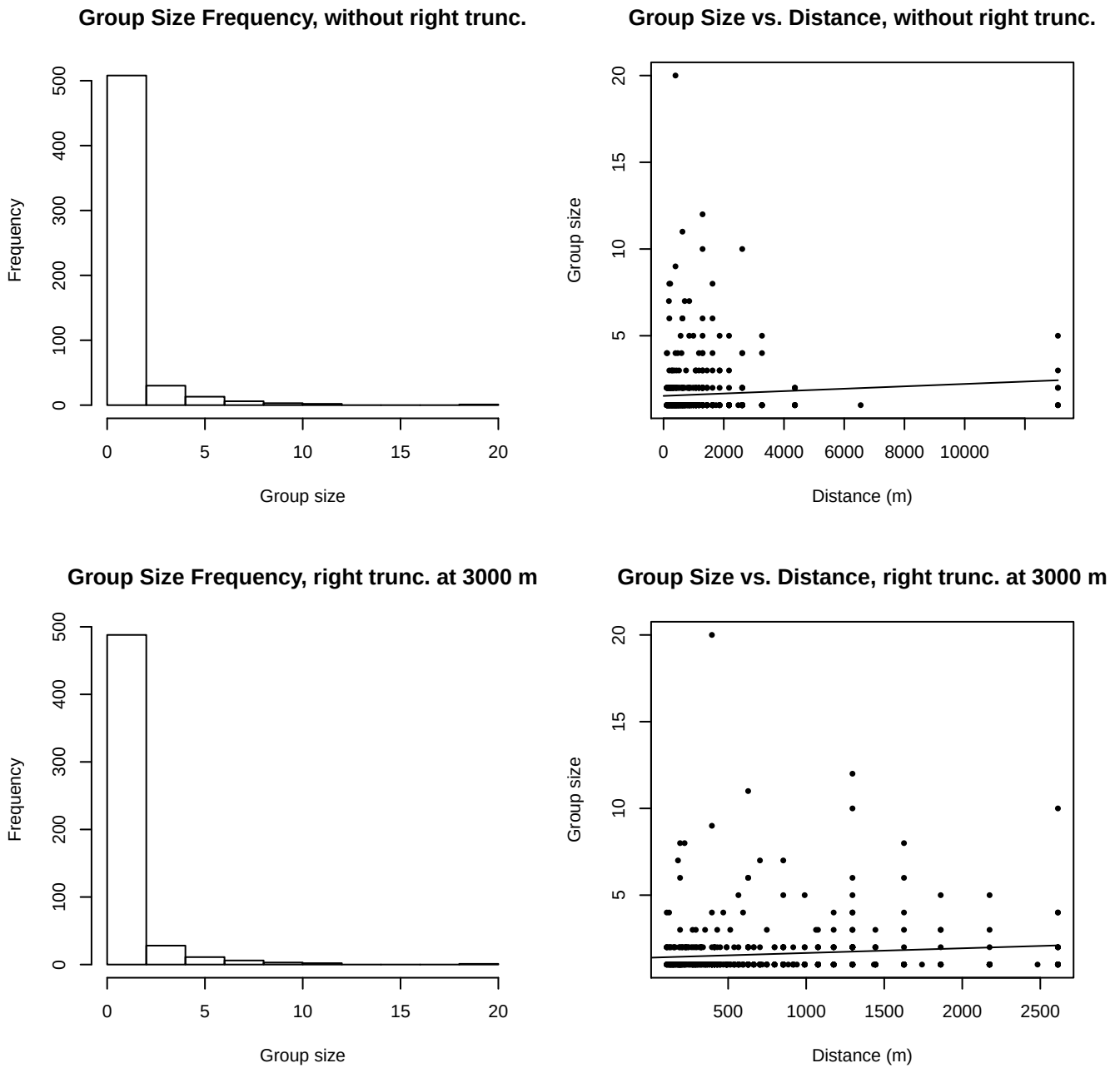

Figure 48: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

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
Total		6717

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	1633
hr	poly	4		Yes	44.60	1396
hr	poly	2		Yes	56.37	1456
hr				Yes	126.36	1493
hn	cos	3		Yes	203.66	1778
hn	cos	2		Yes	213.74	1938
hn	herm	4		Yes	411.54	2331
hn				Yes	417.65	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.

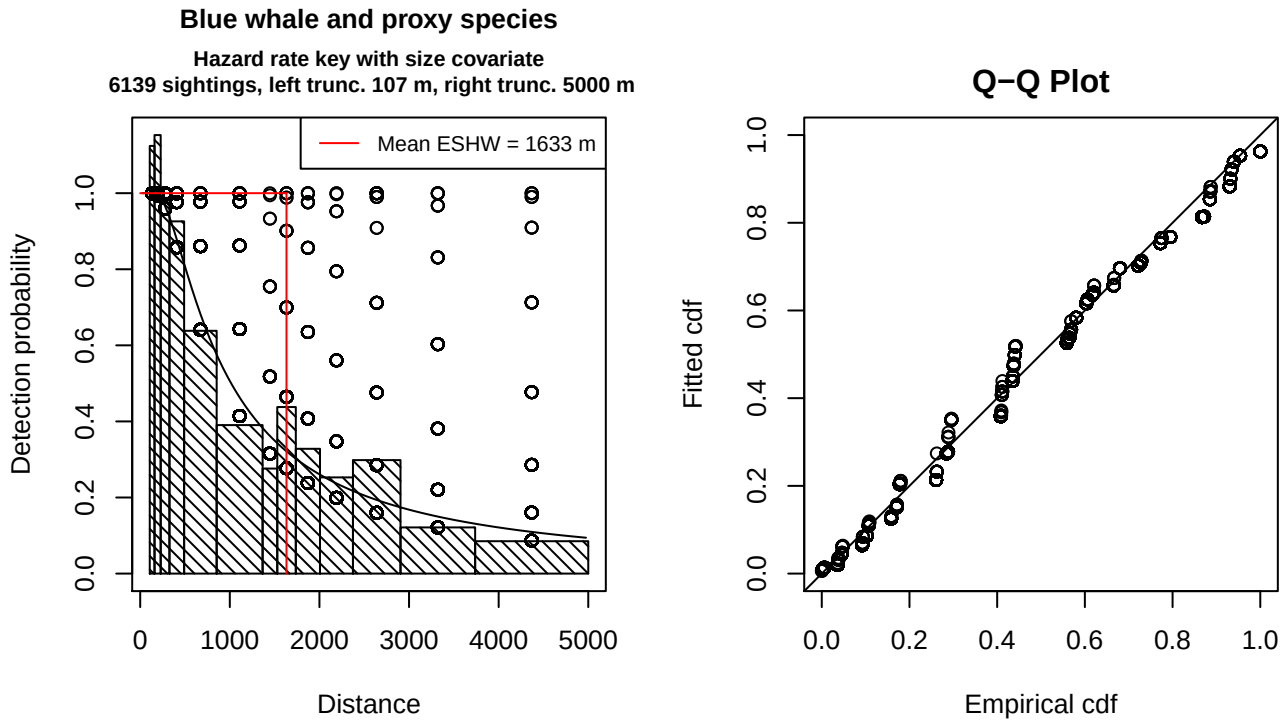

Figure 49: Detection function for NARWSS Twin Otters that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  6139
Distance range         :  106.5979  -  5000
AIC                    :  30333.52

Detection function:
 Hazard-rate key function

Detection function parameters
Scale Coefficients:
```

```
             estimate         se
(Intercept) 6.0219883 0.09573340
size        0.6348279 0.06376505

Shape parameters:
             estimate         se
(Intercept) 0.2576457 0.03041452

                         Estimate           SE         CV
Average p           3.012445e-01 9.430788e-03 0.03130609
N in covered region 2.037879e+04 6.752763e+02 0.03313623
```

Additional diagnostic plots:

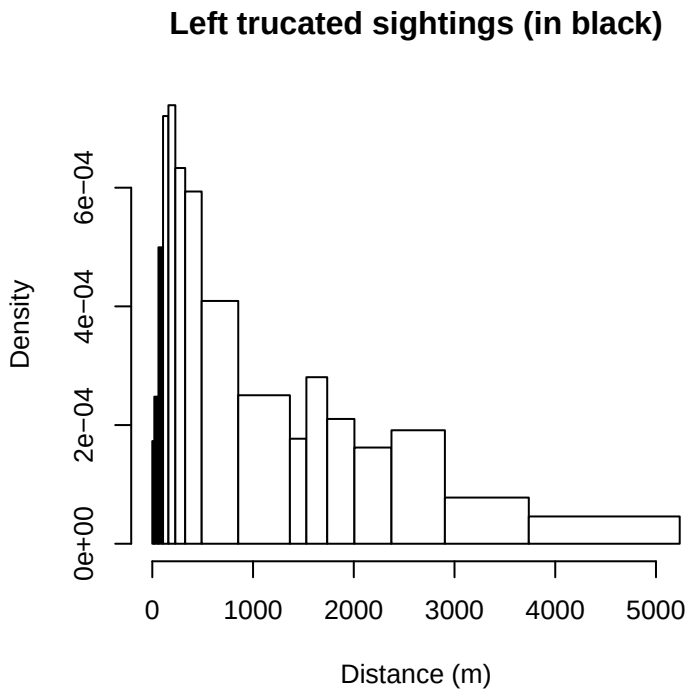

Figure 50: Density of sightings by perpendicular distance for NARWSS Twin Otters. Black bars on the left show sightings that were left truncated.

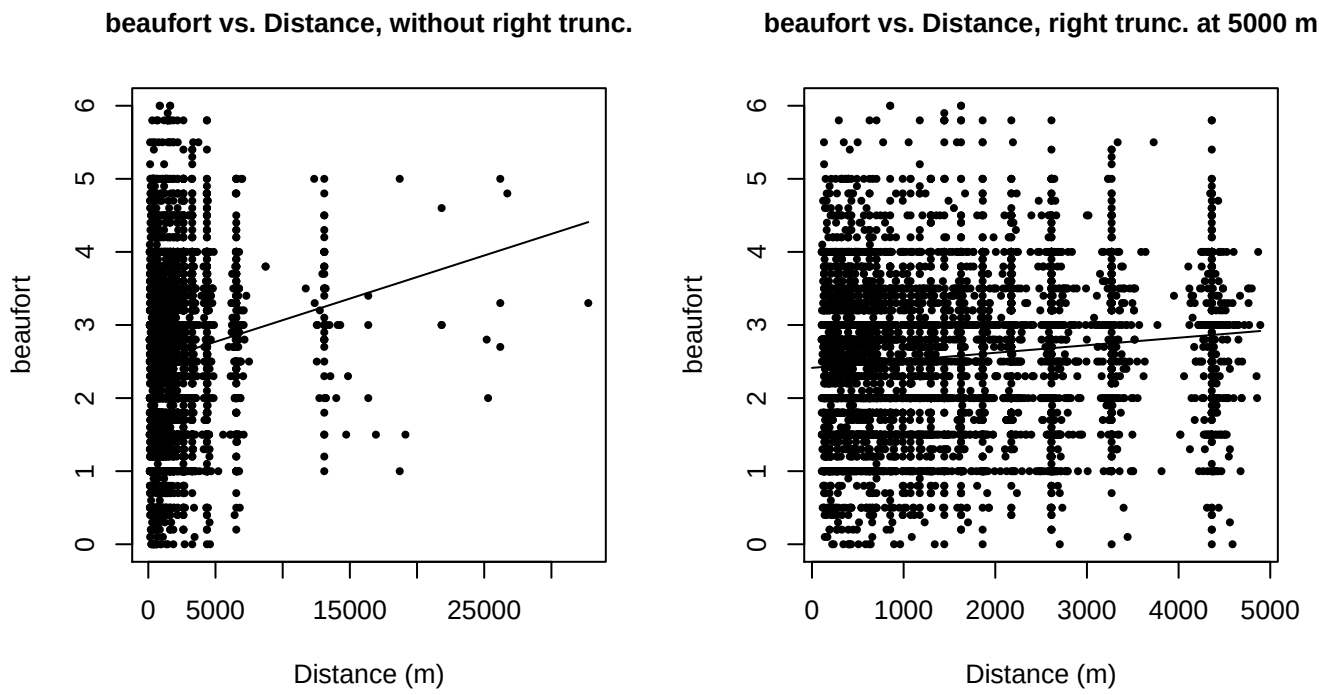

Figure 51: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

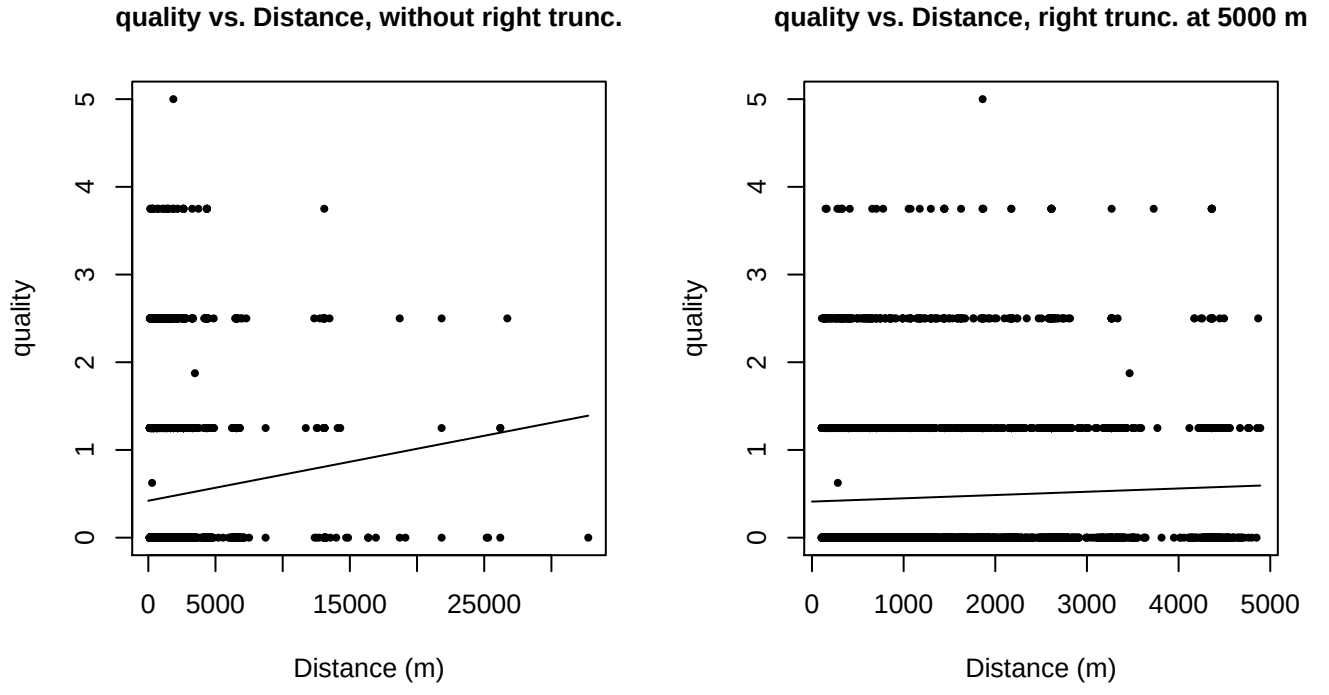

Figure 52: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions.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

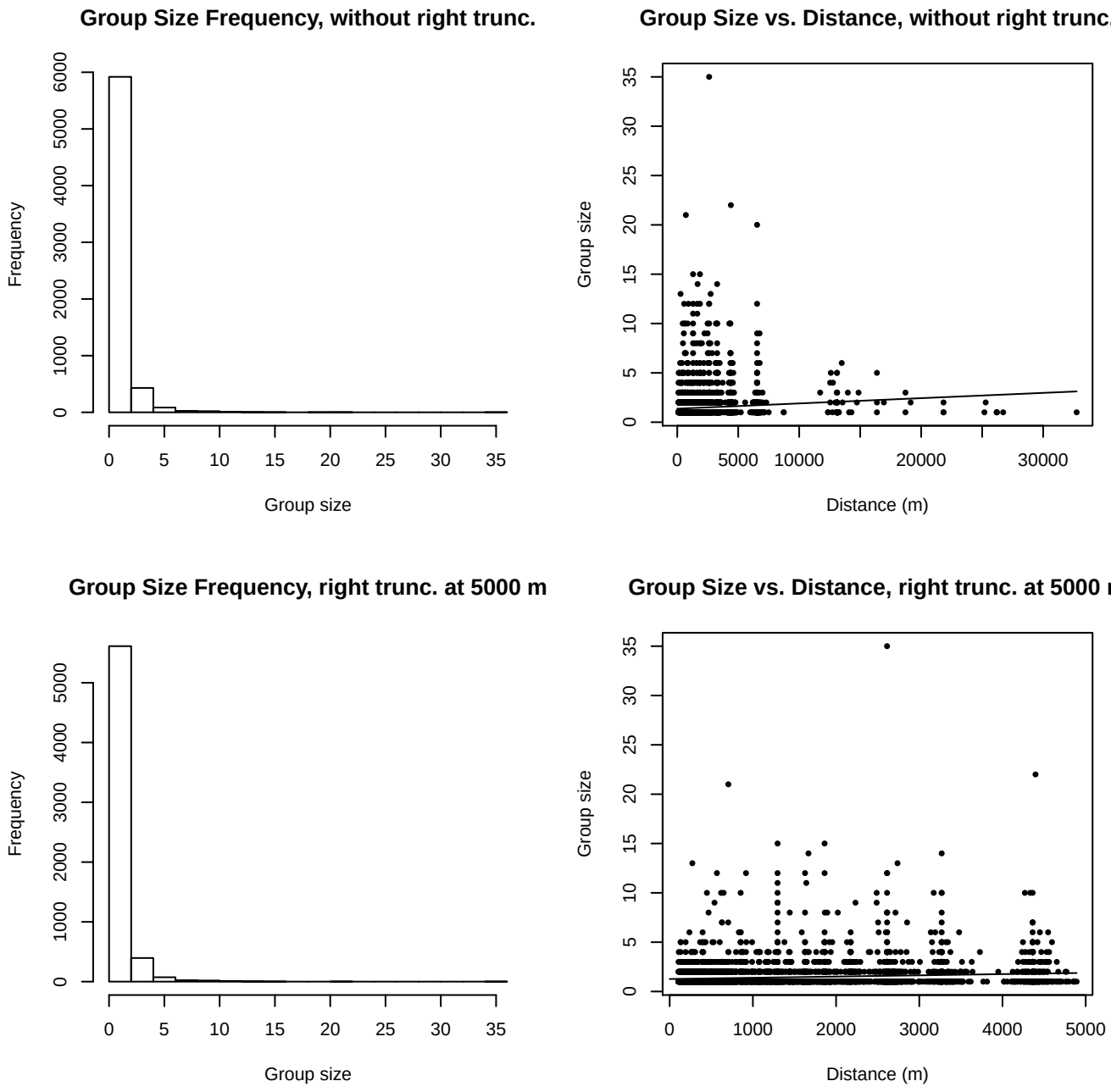

Figure 53: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

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	0.407	Availability	Carretta et al. (2000)

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

No species- or survey-specific estimates of g(0) were available for blue whales for any surveys in our study. For shipboard surveys, we used Barlow and Forney's (2007) estimate (0.921), 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. This estimate accounted for perception bias but not availability bias. 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 blue whales observed by naked eye from shipboard surveys. In any case, the shipboard g(0) estimate has little influence our density estimate for the East Coast region, as no blue whales were sighted by shipboard surveys there.

4 blue whale groups were sighted on the MAR-ECO mid-Atlantic ridge survey, and 1 group was sighted by the European CODA survey. These were naked eye surveys, but were only eligible for use in our AFTT model; please see the documentation for that model to determine if they were actually used.

For aerial surveys, we used Carretta et al.'s (2000) estimate of the availability bias component of g(0) for blue whales, estimated from dive data (Barlow et al. 1997) for aerial surveys conducted with two observers with bubble windows at an altitude of 213 m (700 ft) and an airspeed of 185 km/hr (100 kts). Carretta et al. did not estimate the perception bias component of g(0), asserting that perception bias for whales is expected to be negligible since they are rarely missed on the trackline.

Density Model

The distribution of the blue whale in the North Atlantic generally extends from the Arctic to at least mid-latitude waters, but the actual southern limit of the species' range is unknown (Waring et al. 2011). Blue whales may migrate toward the pole to feed in summer and toward the tropics to breed in winter, but such a migration has not been well described for the North Atlantic.

The surveys used in our study reported only a few sightings. All occurred in the vicinity of the Gulf of Maine between April and November, both on continental shelf and along the shelf break. The species is relatively abundant in the in the Gulf of St. Lawrence in spring, summer, and fall (Waring et al. 2011); the Gulf Maine may represent the southern extent of the blue whale's range during feeding season.

In winter, blue whales have been detected and tracked acoustically by the U.S. Navy's SOSUS program throughout much of the North Atlantic, including in subtropical waters north of the West Indies and in deep water east of the US Atlantic EEZ (Clark 1995; Waring et al. 2011). Historical observations from whaling ships reported blue whales reported blue whales between the Bahamas and Cape Hatteras between January and March, both off and on the continental shelf (Reeves et al. 2004).

With so few sightings, we could not fit a habitat-based density model, only a stratified model. We suspect that in feeding season, blue whales are probably present only north of the Gulf Stream, where cold, nutrient-rich water promotes production of their prey. With more sightings, we could attempt a two-season model that reflects this hypothesis. But if we did that with the data currently available, our winter model would show them absent everywhere, since we had no sightings from December-March. This would somewhat contradict what is suggested by the acoustic and historic observations.

Given the few sightings available and the evidence suggesting blue whales are present both north and south of the Gulf Stream (albeit probably at different times of year) and off and on the continental shelf, the best we can do at this time is provide a mean density estimate for the entire study area.

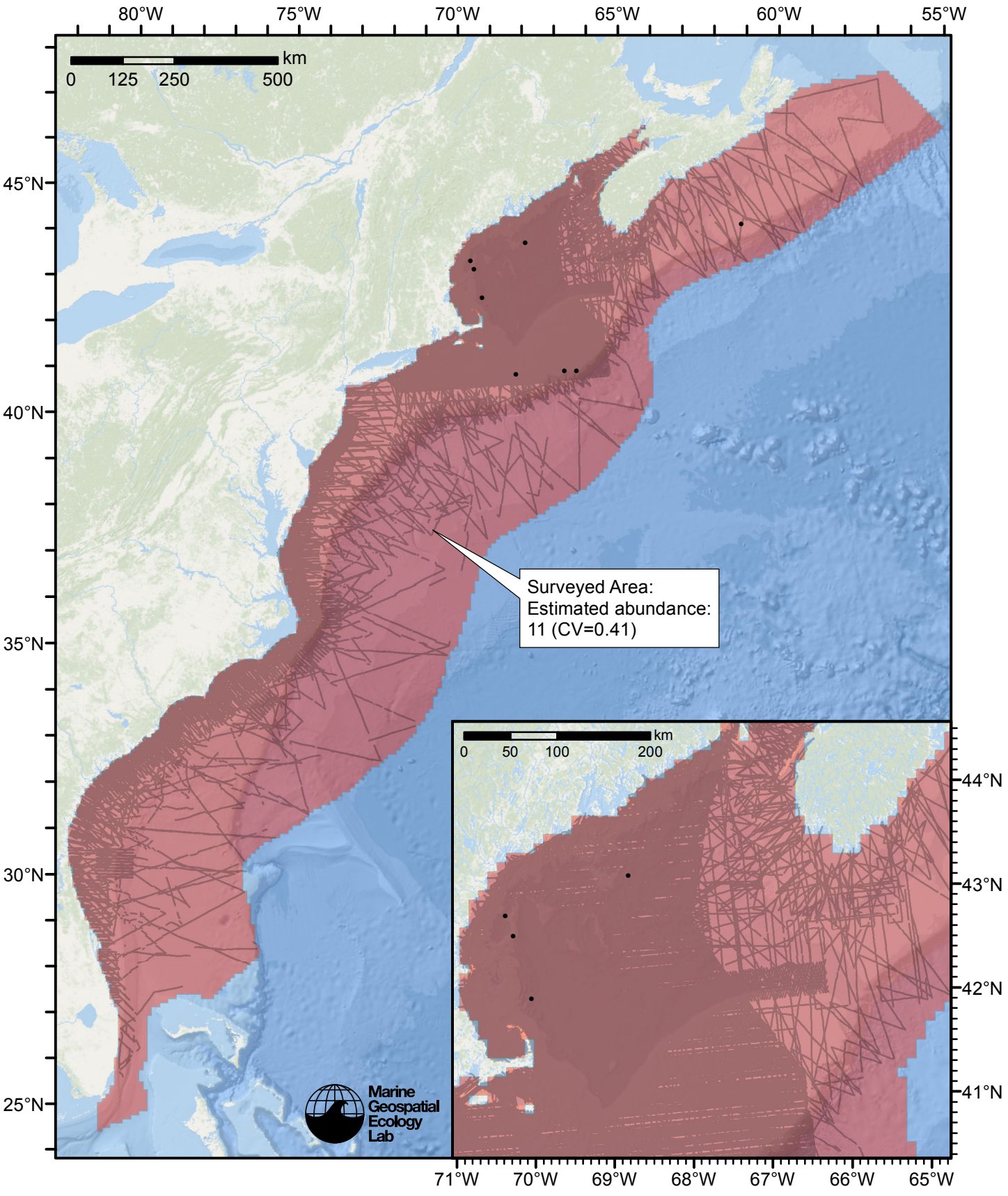

Figure 54: Blue whale density model schematic. All sightings are shown, including those that were truncated when detection functions were fitted. The coefficient of variation (CV) underestimates the true uncertainty of our estimate, as it only incorporated the uncertainty of the GAM stage of our model. 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	0.41	No	
1979-2009	Individuals in Gulf of St. Lawrence identified by photo-ID (Waring et al. 2011)	440			No

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

Our model resulted in a very low total abundance estimate. The only abundance estimate we located for comparison was for the Gulf of St. Lawrence component of the Canadian stock, which was 440 whales counted by photo ID over a 30 year census period–an order of magnitude higher than our estimate. We believe our estimate is consistent with the hypothesis that the northern part of our study area represents the southernmost limit of the blue whale's summertime range.

Although we included the entire study area in our density estimate (we describe our rationale in the Density Model section above), we note that all of our sightings occurred north of 40 N and in the months of April through November. We advise ocean users who wish to minimize possible impacts on blue whales to proceed with additional caution in that region during those months.

References

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Barlow J, Forney KA, Von Saunder A, Urban-Ramirez J (1997) A report of cetacean acoustic detection and dive interval studies (CADDIS) conducted in the southern Gulf of California. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-250. 48 p.

Carretta JV, Lowry MS, Stinchcomb CE, Lynn MS, Cosgrove RE (2000) Distribution and abundance of marine mammals at San Clemente Island and surrounding offshore waters: results from aerial and ground surveys in 1998 and 1999. Administrative Report LJ-00-02, available from Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA USA 92038. 44 p.

Reeves RR, Smith TD, Josephson EA, Clapham PJ, Woolmer G (2004) Historical Observations of Humpback and Blue Whales in the North Atlantic Ocean: Clues to Migratory Routes and Possibly Additional Feeding Grounds. Marine Mammal Science 20: 774-786.

Waring GT, Josephson E, Maze-Foley K, Rosel PE, eds. (2011) U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments – 2010. NOAA Tech Memo NMFS NE 219; 595 p.