

## **Supplementary Appendix A**

This supplementary appendix contains several tables displaying key results. Results for each of two directional vectors (expanding haddock and expanding all non-cod outputs) are presented separately.

**Table A1. Summary Statistics for Production Frontiers Calculated When Expanding Haddock**

FY	Region	Unique Strata	N Observations per Frontier			
			Mean	SD	Min	Max
2007	GOM	37	37.86	26.59	11	115
2008	GOM	34	48.06	39.82	10	138
2009	GOM	35	44.23	30.51	9	108
2010	GOM	29	34.17	25.59	10	106
2011	GOM	40	42.38	45.76	10	223
2012	GOM	28	36.68	29.80	10	145
2013	GOM	31	37.32	41.31	12	210
2014	GOM	25	37.76	35.87	10	156
2007	GB	47	165.38	123.76	16	507
2008	GB	51	171.31	129.91	15	525
2009	GB	42	157.07	145.33	11	578
2010	GB	32	56.94	43.23	10	169
2011	GB	40	60.18	49.34	10	246
2012	GB	20	35.05	30.86	13	145
2013	GB	28	43.57	28.38	9	99
2014	GB	21	48.48	34.82	13	118
All	GOM	259	40.14	35.24	9	223
All	GB	281	107.74	112.81	9	578
All	GOM & GB	540	75.32	91.37	9	578

Note: Unique strata are area-month combinations for which 10 or more tows were observed and production frontiers constructed. Mean, standard deviation, minimum and maximum number of observations per frontier were calculated including only observations with solutions to linear programming problems (7) and (8). For a small number of observations ( $n = 20$ ), solutions to linear programming problems were infeasible or numerical failures were encountered. All strata with fewer than 10 tows were discarded prior to constructing production frontiers; a minimum of fewer than ten observations per frontier indicates solutions could not be found for one or more observations in that strata.

**Table A2. Summary Statistics for Production Frontiers Calculated When Expanding All Non-Cod Outputs**

FY	Region	Unique Strata	N Observations per Frontier			
			Mean	SD	Min	Max
2007	GOM	37	37.84	26.57	11	115
2008	GOM	34	48.03	39.75	10	138
2009	GOM	35	44.26	30.48	10	108
2010	GOM	29	34.17	25.59	10	106
2011	GOM	40	42.38	45.76	10	223
2012	GOM	28	36.68	29.80	10	145
2013	GOM	31	37.32	41.31	12	210
2014	GOM	25	37.76	35.87	10	156
2007	GB	47	165.36	123.71	16	506
2008	GB	51	171.31	129.89	15	525
2009	GB	42	157.05	145.35	11	578
2010	GB	32	56.97	43.28	10	169
2011	GB	40	60.13	49.33	10	246
2012	GB	20	35.05	30.86	13	145
2013	GB	28	43.57	28.38	9	99
2014	GB	21	48.48	34.82	13	118
All	GOM	259	40.14	35.22	10	223
All	GB	281	107.73	112.80	9	578
All	GOM & GB	540	75.31	91.36	9	578

Note: Unique strata are area-month combinations for which 10 or more tows were observed and production frontiers constructed. Mean, standard deviation, minimum and maximum number of observations per frontier were calculated including only observations with solutions to linear programming problems (7) and (8). For a small number of observations ( $n = 24$ ), solutions to linear programming problems were infeasible or numerical failures were encountered. All strata with fewer than 10 tows were discarded prior to constructing production frontiers; a minimum of fewer than ten observations per frontier indicates solutions could not be found for one or more observations in that strata.

**Table A3. Summary Statistics for Efficiency Scores Calculated When Expanding Haddock**

FY	Region	Mean	SD	Q1	Q2	Q3
2007	GOM	0.43	0.47	0.00	0.14	1.00
2008	GOM	0.41	0.46	0.00	0.12	1.00
2009	GOM	0.41	0.46	0.00	0.10	1.00
2010	GOM	0.40	0.47	0.00	0.00	1.00
2011	GOM	0.31	0.44	0.00	0.00	1.00
2012	GOM	0.38	0.46	0.00	0.00	1.00
2013	GOM	0.42	0.46	0.00	0.15	1.00
2014	GOM	0.55	0.46	0.00	0.66	1.00
2007	GB	0.28	0.38	0.00	0.05	0.53
2008	GB	0.30	0.39	0.00	0.05	0.63
2009	GB	0.31	0.40	0.00	0.05	0.65
2010	GB	0.45	0.44	0.00	0.29	1.00
2011	GB	0.47	0.45	0.00	0.32	1.00
2012	GB	0.45	0.46	0.00	0.26	1.00
2013	GB	0.49	0.46	0.00	0.40	1.00
2014	GB	0.62	0.43	0.10	0.98	1.00
All	GOM	0.41	0.46	0.00	0.05	1.00
All	GB	0.34	0.41	0.00	0.09	0.81
All	GOM & GB	0.36	0.43	0.00	0.08	0.94

Note: Efficiency scores were calculated by dividing observed haddock catch by this value plus the distance in output space to the weak output disposal efficient production frontier. A score of one, corresponding to  $\beta = 0$ , indicated the observation defined the efficient frontier. Observations of zero haddock catch had efficiency scores of zero. Mean, standard deviation, and quartile values were calculated considering efficiency scores for all observed tows.

**Table A4. Summary Statistics for Efficiency Scores Calculated When Expanding All Non-Cod Outputs**

FY	Region	Mean	SD	Q1	Q2	Q3
2007	GOM	0.95	0.09	0.94	1.00	1.00
2008	GOM	0.92	0.14	0.90	1.00	1.00
2009	GOM	0.94	0.10	0.92	1.00	1.00
2010	GOM	0.91	0.20	0.93	1.00	1.00
2011	GOM	0.86	0.25	0.86	1.00	1.00
2012	GOM	0.95	0.11	0.96	1.00	1.00
2013	GOM	0.92	0.16	0.90	1.00	1.00
2014	GOM	0.96	0.08	0.96	1.00	1.00
2007	GB	0.77	0.24	0.59	0.86	1.00
2008	GB	0.77	0.24	0.59	0.85	1.00
2009	GB	0.77	0.24	0.59	0.85	1.00
2010	GB	0.94	0.12	0.93	1.00	1.00
2011	GB	0.89	0.17	0.82	1.00	1.00
2012	GB	0.94	0.10	0.92	1.00	1.00
2013	GB	0.91	0.15	0.88	1.00	1.00
2014	GB	0.90	0.15	0.82	1.00	1.00
All	GOM	0.92	0.16	0.92	1.00	1.00
All	GB	0.80	0.23	0.64	0.91	1.00
All	GOM & GB	0.83	0.22	0.71	0.96	1.00

Note: Efficiency scores were calculated by dividing observed total catch of non-cod outputs by this value plus four times the distance in output space to the weak output disposal efficient production frontier (our directional distance function expanded all four non-cod outputs simultaneously). A score of one, corresponding to  $\beta = 0$ , indicated the observation defined the efficient frontier. Observations of zero total non-cod catch had efficiency scores of zero. Mean, standard deviation, and quartile values were calculated considering efficiency scores for all observed tows.

**Table A5. Summary Statistics for  $\phi$  Calculated When Expanding Haddock**

FY	Region	N Obs	Median	Mean	SD	Max	> 0
2007	GOM	1134	21.12	62.59	110.38	825.42	74%
2008	GOM	1319	55.75	121.66	198.53	2121.13	77%
2009	GOM	1320	48.59	122.11	178.09	1105.55	76%
2010	GOM	974	25.41	1231.65	3687.39	21530.15	73%
2011	GOM	1650	29.91	320.58	772.96	5041.80	77%
2012	GOM	1009	9.32	37.81	90.90	744.19	75%
2013	GOM	1147	28.53	293.57	722.16	3970.54	75%
2014	GOM	899	34.75	96.85	156.51	1263.53	74%
2007	GB	4786	1539.98	2136.69	2045.99	10591.09	92%
2008	GB	5956	1900.22	3523.17	4117.47	20675.84	92%
2009	GB	4719	1261.45	2471.90	4017.32	32570.17	91%
2010	GB	1712	291.44	856.90	1212.17	6884.03	84%
2011	GB	2345	134.24	660.43	1260.81	9050.32	82%
2012	GB	691	52.37	433.18	1095.02	6042.61	77%
2013	GB	1213	288.92	874.90	1529.19	9858.09	80%
2014	GB	1018	276.03	1100.49	1713.79	10440.87	79%
All	GOM	9452	28.85	273.29	1302.92	21530.15	75%
All	GB	22440	938.00	2155.60	3235.74	32570.17	89%
All	GOM & GB	31892	304.11	1597.73	2934.08	32570.17	85%

Note: Number of observations, median, mean, standard deviation, maximum, and percent  $\phi$  greater than zero were calculated considering  $\phi$  from tows by vessels who ultimately transitioned to catch shares (FYs 2007-2009) or were fishing under catch shares (FYs 2010-2014). Minimum values of zero for both regions in all FYs are not shown. Values of  $\phi$  are in lbs.

**Table A6. Summary Statistics for  $\phi$  Calculated When Expanding All Non-Cod Outputs**

FY	Region	N Obs	Median	Mean	SD	Max	> 0
2007	GOM	1133	14.60	37.64	58.47	387.58	74%
2008	GOM	1319	30.91	61.85	84.10	522.74	77%
2009	GOM	1321	26.14	57.35	80.54	570.13	76%
2010	GOM	974	17.41	101.31	235.87	1778.21	73%
2011	GOM	1650	16.87	60.80	124.39	1102.96	76%
2012	GOM	1009	5.11	22.15	50.59	440.26	75%
2013	GOM	1147	14.92	62.12	127.13	1022.54	75%
2014	GOM	899	22.68	48.85	73.63	485.95	73%
2007	GB	4784	45.11	109.78	150.69	1124.90	87%
2008	GB	5956	87.13	182.49	285.13	2409.28	90%
2009	GB	4719	94.03	183.30	225.70	1620.13	87%
2010	GB	1713	20.00	50.20	70.44	423.93	81%
2011	GB	2343	18.21	65.21	112.34	779.99	77%
2012	GB	691	17.61	44.97	57.74	279.08	74%
2013	GB	1213	42.32	84.79	120.89	945.65	76%
2014	GB	1018	38.39	68.92	85.39	559.15	75%
All	GOM	9452	16.43	56.76	117.77	1778.21	75%
All	GB	22437	50.79	130.14	207.11	2409.28	85%
All	GOM & GB	31889	34.62	108.39	188.18	2409.28	82%

Note: Number of observations, median, mean, standard deviation, maximum, and percent  $\phi$  greater than zero were calculated considering  $\phi$  from tows by vessels who ultimately transitioned to catch shares (FYs 2007-2009) or were fishing under catch shares (FYs 2010-2014). Minimum values of zero for both regions in all FYs are not shown. Values of  $\phi$  are in lbs.

**Table A7. Quantile Regression Results for  $\phi$  Calculated When Expanding Haddock for Tows in the Gulf of Maine**

Variable	Coefficient	SE	P-value
Intercept	-74.49	103.45	0.47
Statistical area 512	11.66	17.60	0.51
Statistical area 513	9.64	16.23	0.55
Statistical area 514	43.65	20.19	0.03
Statistical area 515	14.26	15.46	0.36
February	34.91	52.40	0.51
March	102.51	72.81	0.16
April	-1.15	13.14	0.93
May	-9.79	12.98	0.45
June	-6.91	11.20	0.54
July	-5.07	11.80	0.67
August	-4.35	12.09	0.72
September	0.49	12.92	0.97
October	20.95	13.84	0.13
November	-5.59	11.94	0.64
December	3.29	12.31	0.79
Haul duration	0.32	0.62	0.61
Crew size	9.40	4.95	0.06
ln(Haddock SSB)	3.67	11.03	0.74
Catch shares	-0.67	7.19	0.93
Observations	9,452		
Coefficients	145		
Pseudo R <sup>2</sup>	0.04		

Note: Quantile regressions estimated the conditional median of  $\phi$  as a function of vessel, area, and month fixed effects; variable input factors; spawning stock biomass (SSB); and a catch share policy indicator. Standard errors were constructed using a clustered bootstrap, clustering by area-month-FY strata. Estimates of vessel fixed effects are not shown but are available from the authors upon request. Pseudo R<sup>2</sup> was calculated following Koenker and Machado (1999) as one minus the ratio of the weighted sum of absolute residuals for the full model to that of an intercept only model.



**Table A8. Quantile Regression Results for  $\phi$  Calculated When Expanding Haddock for Tows in Georges Bank**

Variable	Coefficient	SE	P-value
Intercept	-6453.28	2271.10	0.00
Statistical area 522	155.05	185.80	0.40
Statistical area 525	541.35	381.42	0.16
Statistical area 526	-1213.64	343.82	0.00
Statistical area 561	667.03	479.41	0.16
Statistical area 562	3548.70	2530.65	0.16
February	476.20	368.53	0.20
March	93.42	301.67	0.76
April	511.80	381.60	0.18
May	1453.49	485.95	0.00
June	719.42	342.38	0.04
July	309.31	324.44	0.34
August	389.21	672.13	0.56
September	624.16	526.48	0.24
October	262.62	379.65	0.49
November	32.58	373.52	0.93
December	472.05	351.59	0.18
Haul duration	51.73	20.62	0.01
Crew size	66.30	83.99	0.43
ln(Haddock SSB)	380.71	178.77	0.03
Catch shares	-953.26	165.94	0.00
Observations	22,440		
Coefficients	137		
Pseudo R <sup>2</sup>	0.13		

Note: Quantile regressions estimated the conditional median of  $\phi$  as a function of vessel, area, and month fixed effects; variable input factors; spawning stock biomass (SSB); and a catch share policy indicator. Standard errors were constructed using a clustered bootstrap, clustering by area-month-FY strata. Estimates of vessel fixed effects are not shown but are available from the authors upon request. Pseudo R<sup>2</sup> was calculated following Koenker and Machado (1999) as one minus the ratio of the weighted sum of absolute residuals for the full model to that of an intercept only model.

**Table A9. Quantile Regression Results for  $\phi$  Calculated When Expanding All Non-Cod Outputs for Tows in the Gulf of Maine**

Variable	Coefficient	SE	P-value
Intercept	-33.13	29.35	0.26
Statistical area 512	19.03	8.12	0.02
Statistical area 513	19.51	7.61	0.01
Statistical area 514	38.96	10.37	0.00
Statistical area 515	21.39	7.22	0.00
February	10.99	15.10	0.47
March	27.69	12.94	0.03
April	-5.29	8.97	0.55
May	-11.61	8.19	0.16
June	-8.51	7.78	0.27
July	-8.46	7.67	0.27
August	-10.15	7.79	0.19
September	-7.80	7.43	0.29
October	2.44	8.50	0.77
November	-9.96	8.44	0.24
December	-2.42	9.09	0.79
Haul duration	0.66	0.40	0.10
Crew size	2.75	2.49	0.27
ln(Cod SSB)	0.62	3.04	0.84
Catch shares	-3.92	4.54	0.39
Observations	9,452		
Coefficients	145		
Pseudo R <sup>2</sup>	0.08		

Note: Quantile regressions estimated the conditional median of  $\phi$  as a function of vessel, area, and month fixed effects; variable input factors; spawning stock biomass (SSB); and a catch share policy indicator. Standard errors were constructed using a clustered bootstrap, clustering by area-month-FY strata. Estimates of vessel fixed effects are not shown but are available from the authors upon request. Pseudo R<sup>2</sup> was calculated following Koenker and Machado (1999) as one minus the ratio of the weighted sum of absolute residuals for the full model to that of an intercept only model.

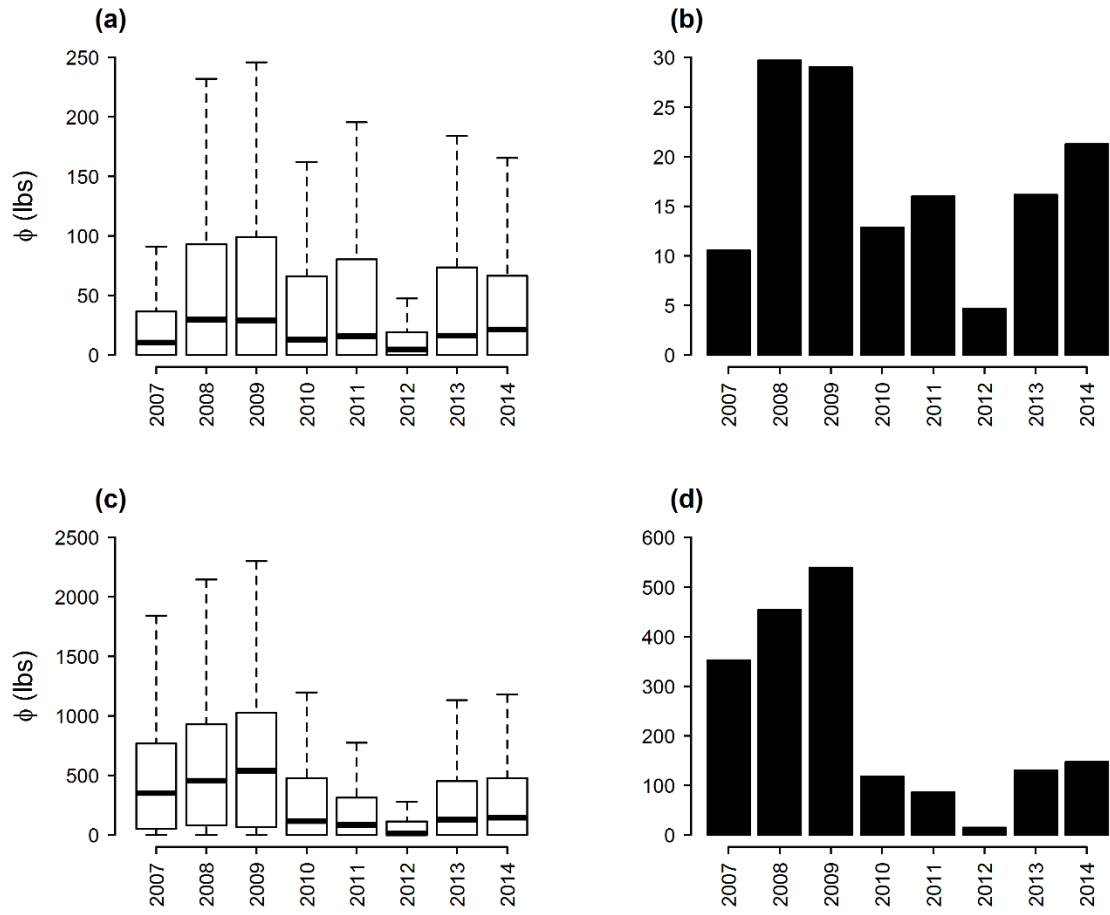
**Table A10. Quantile Regression Results for  $\phi$  Calculated When Expanding All Non-Cod Outputs for Tows in Georges Bank**

Variable	Coefficient	SE	P-value
Intercept	388.85	252.72	0.12
Statistical area 522	34.57	8.63	0.00
Statistical area 525	-43.38	8.17	0.00
Statistical area 526	-68.86	15.68	0.00
Statistical area 561	21.00	20.32	0.30
Statistical area 562	-73.75	11.25	0.00
February	20.49	12.95	0.11
March	2.16	9.68	0.82
April	2.01	8.54	0.81
May	1.55	11.78	0.90
June	31.76	12.09	0.01
July	6.17	12.66	0.63
August	10.58	26.55	0.69
September	75.86	17.98	0.00
October	31.62	25.71	0.22
November	26.92	20.45	0.19
December	15.47	9.63	0.11
Haul duration	3.31	0.92	0.00
Crew size	6.02	3.47	0.08
ln(Cod SSB)	-46.45	28.52	0.10
Catch shares	-61.46	15.03	0.00
Observations	22,437		
Coefficients	137		
Pseudo R <sup>2</sup>	0.11		

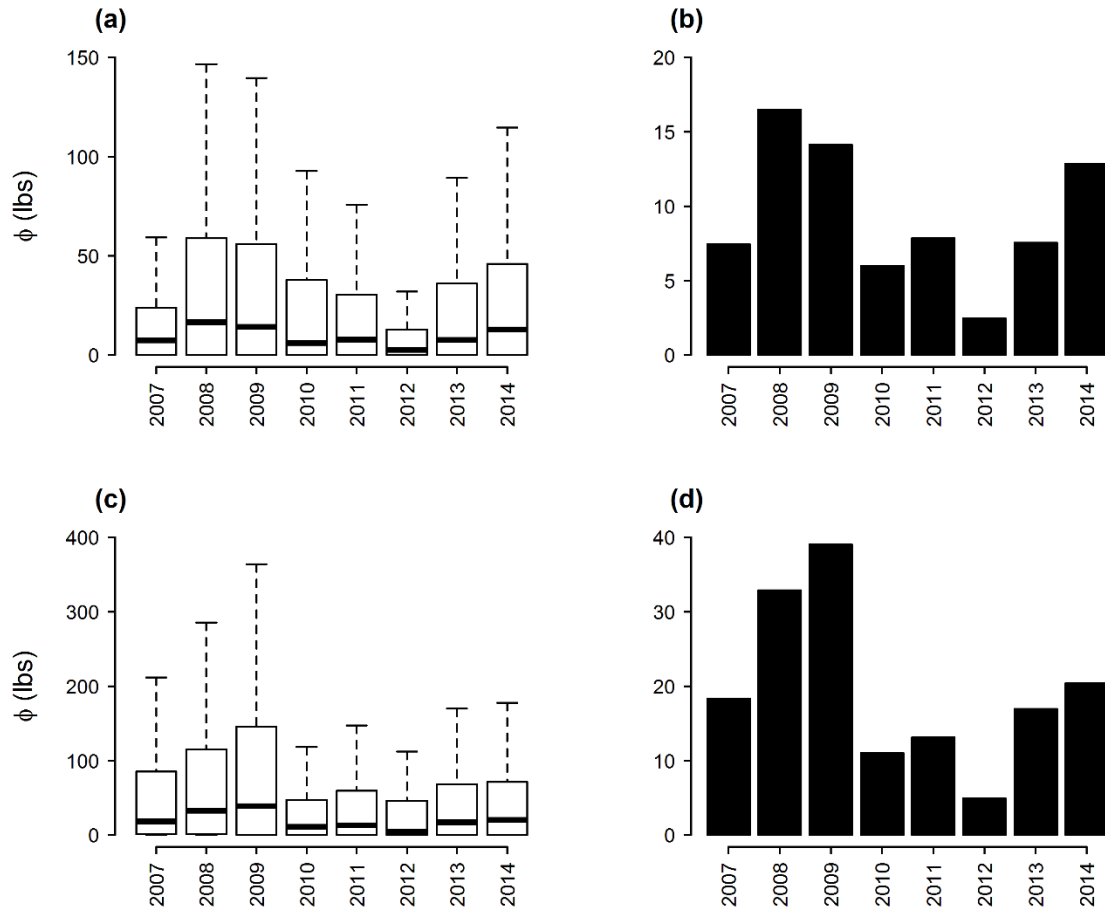
Note: Quantile regressions estimated the conditional median of  $\phi$  as a function of vessel, area, and month fixed effects; variable input factors; spawning stock biomass (SSB); and a catch share policy indicator. Standard errors were constructed using a clustered bootstrap, clustering by area-month-FY strata. Estimates of vessel fixed effects are not shown but are available from the authors upon request. Pseudo R<sup>2</sup> was calculated following Koenker and Machado (1999) as one minus the ratio of the weighted sum of absolute residuals for the full model to that of an intercept only model.

## **Supplementary Appendix B**

The following figures and tables correspond to values of  $\phi$  calculated after removing all observations whose total catch fell within the upper and lower deciles. This was done to evaluate model results and validate conclusions once outlier observations had been removed.



**Figure B1. Boxplots (a, c) and median values (b, d) of  $\phi$  by FY using a directional vector to expand haddock only** Note:  $\phi$  values correspond to the increase in haddock catch per tow under efficient production and strong non-haddock disposal. Panels depict measures calculated from observed tows in the Gulf of Maine (a, b) and Georges Bank (c, d) by catch share bottom trawlers. For boxplots: box covers the interquartile range with a heavy bar at the median and whiskers extending to extreme data points that are no more than 1.5 times the interquartile range. All FY median values were statistically different from zero based on 10,000 bootstrapped samples.



**Figure B2. Boxplots (a, c) and median values (b, d) of  $\phi$  by FY using a directional vector to expand haddock, roundfish, flatfish, and the aggregate of species managed outside the multispecies FMP** Note:  $\phi$  values correspond to the increase in non-cod catch per output per tow under efficient production and strong cod disposal. Panels depict measures calculated from observed tows in the Gulf of Maine (a, b) and Georges Bank (c, d) by catch share bottom trawlers. For boxplots: box covers the interquartile range with a heavy bar at the median and whiskers extending to extreme data points that are no more than 1.5 times the interquartile range. All FY median values were statistically different from zero based on 10,000 bootstrapped samples.

**Table B1. Median Values of  $\phi$  Before (FYs 2007-2009) and After (FYs 2010-2014)**

**Introduction of Catch Share Management**

Area (Output Expansion)	FYs 2007-2009	FYs 2010-2014	$\Delta \phi$	QR $\beta_{cs}$
Gulf of Maine (Haddock)	20.48	12.22	-8.26***	-2.26
Gulf of Maine (Non-Cod)	11.90	6.11	-5.79***	-2.76
Georges Bank (Haddock)	440.91	93.41	-347.50***	-271.33***
Georges Bank (Non-Cod)	29.24	12.65	-16.59***	-19.62***

Note: Direction of output expansion is specified in parentheses. Mood's median tests were used to determine if median values differed significantly, with a null hypothesis of equal medians.

Catch share policy indicator parameter estimates from quantile regressions also presented.

Asterisk (\*), double asterisk (\*\*), and triple asterisk (\*\*\*) denote statistical significance at the 10%, 5%, and 1% levels, respectively.