Twine-Top Modifications of Sea-Scallop Dredges: Reducing Yellowtail-Flounder Bycatch

Kelli A. Milleville

*College of William and Mary - Virginia Institute of Marine Science*

Follow this and additional works at: [https://scholarworks.wm.edu/etd](https://scholarworks.wm.edu/etd)

Part of the Fresh Water Studies Commons, Ocean Engineering Commons, and the Oceanography Commons

**Recommended Citation**


[https://dx.doi.org/doi:10.25773/v5-qh0g-mf29](https://dx.doi.org/doi:10.25773/v5-qh0g-mf29)

This Thesis is brought to you for free and open access by the Theses, Dissertations, & Master Projects at W&M ScholarWorks. It has been accepted for inclusion in Dissertations, Theses, and Masters Projects by an authorized administrator of W&M ScholarWorks. For more information, please contact scholarworks@wm.edu.
Twine-Top Modifications of Sea-Scallop Dredges: Reducing Yellowtail-Flounder Bycatch

A Thesis
Presented to

The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Masters of Science

by
Kelli A. Milleville
2008
This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science

Kelli A. Milleville
(Sign on line above your name)

Approved by the Committee, August 2008

William D. DuPaul, Ph.D.
Committee Chairman/Advisor

Ryan B. Carnegie, Ph.D.

John M. Hoenig, Ph.D.

James E. Kirkley, Ph.D.

Thomas A. Munroe, Ph.D.
Smithsonian Institution
Washington, D.C.
This paper is dedicated to my family,
for always being there for me.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>ix</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>MATERIALS AND METHODS</td>
<td></td>
</tr>
<tr>
<td>Data Collection</td>
<td>7</td>
</tr>
<tr>
<td>Data Analysis</td>
<td>10</td>
</tr>
<tr>
<td>RESULTS</td>
<td>29</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>36</td>
</tr>
<tr>
<td>APPENDICES</td>
<td></td>
</tr>
<tr>
<td>I: Using the Delta Method</td>
<td>46</td>
</tr>
<tr>
<td>II: Analysis of Other flatfish</td>
<td>49</td>
</tr>
<tr>
<td>III: Modifying Twine-Top Length to Reduce Flatfish Bycatch</td>
<td>53</td>
</tr>
<tr>
<td>IV: Management of Atlantic Sea Scallops</td>
<td>57</td>
</tr>
<tr>
<td>in the Context of Rebuilding Yellowtail-Flounder Stocks</td>
<td></td>
</tr>
<tr>
<td>LITERATURE CITED</td>
<td>94</td>
</tr>
<tr>
<td>VITA</td>
<td>100</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

This project was funded through the Atlantic Sea Scallop Research Set-Aside Program.

I thank my major advisor, Dr. William DuPaul, for providing the idea, scheduling the fieldwork and introducing me to the scallop industry. To my committee, Drs. John Hoenig, Jim Kirkley, Tom Munroe and Ryan Carnegie, I also owe a debt of gratitude for their patience and guidance. The work would have been excruciating without the analytical knowledge and wealth of support provided by Dr. Hoenig, the economic understanding of Dr. Kirkley, the probing questions of Dr. Munroe and the supportive confidence of Dr. Carnegie. These men are truly excellent teachers.

An abundance of gratitude to individuals associated with the F/V Celtic, including: the owner, Charles Quinn; Capt. Paul DesMarais; and the crew. I also thank Dr. Todd Gedamke, Dr. Christopher Hager and Timothy Winchenbach for their assistance in research conducted at sea. Since this fieldwork often included foul weather and long hours, their work was particularly appreciated.

I also take this opportunity to thank the following individuals for their help: David Rudders, who provided an immeasurable amount of guidance and support; Cheryl Teagle, who organized the surrounding chaos above and beyond the call of duty; Dianne Roberts and Holly Buckle, who assisted in the dreaded task of data entry; Dr. Christopher Legault, Kurt Wilhelm, and Erin Kupcha for the information they provided; and Barbara Monteith, for her excellent editorial assistance.

Several other people assisted me during my career at VIMS. Many thanks to: Louise Lawson, Dr. Iris Anderson, Dr. Peter Van Veld, Dr. John Olney, Kevin Kiley, Justine Woodward, Ana Verissimo, Sally Upton, Chip Cotton, Dave Hewitt, Dr. George Gilchrist, Dr. Mary Fabrizio, and Paul Nichols.

This paper was written in loving memory of my grandparents, Vernon and Earlis Reddell, for their unique practicality and stoicism. It could not have been written without the unwavering support of my mother, Sharon Milleville; the quiet strength of my brother, Mike Milleville; the graceful intelligence of my sister, Jennifer Hoddinott; and the encouraging optimism of my fiancé, Mathew Wright. Near or far, they shall always be a source of strength in my life.
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cruise Summary</td>
<td>62</td>
</tr>
<tr>
<td>2.</td>
<td>ANOVA Adjusted Means of Transformed and Retransformed Weight per Tow</td>
<td>63</td>
</tr>
<tr>
<td>3.</td>
<td>Yellowtail Parameter Estimates of Model Three</td>
<td>64</td>
</tr>
<tr>
<td>4.</td>
<td>Scallop Parameter Estimates of Model Three</td>
<td>65</td>
</tr>
<tr>
<td>5.</td>
<td>Other Flatfish Species</td>
<td>66</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>New Bedford Style Scallop Dredge</td>
<td>68</td>
</tr>
<tr>
<td>2.</td>
<td>Closed Areas Within Georges Bank</td>
<td>69</td>
</tr>
<tr>
<td>3.</td>
<td>Concept of Percent Change in Mean Catch-Weight Plot</td>
<td>70</td>
</tr>
<tr>
<td>4.</td>
<td>Percent TAC Achieved in CA2 and NLCA During the 2006 Fishing Season</td>
<td>71</td>
</tr>
<tr>
<td>5.</td>
<td>Average Catch-Weight per Cruise Using 60:34 and 90:34 Hanging Ratios</td>
<td>72</td>
</tr>
<tr>
<td>6.</td>
<td>Histograms of Percent Change in Catch-Weight per Tow, ( \Phi_i )</td>
<td>73</td>
</tr>
<tr>
<td>7.</td>
<td>Mean Percent Changes in Summed Count at Each Size Class, ( E_j )</td>
<td>75</td>
</tr>
<tr>
<td>8.</td>
<td>Difference in ANOVA Adjusted Means</td>
<td>77</td>
</tr>
<tr>
<td>9.</td>
<td>Sea-Scallop Residuals of Model Three by Cruise</td>
<td>78</td>
</tr>
<tr>
<td>10.</td>
<td>Observed Percent Changes in Mean Catch-Weights: Scallop Meats vs. Yellowtail Flounder</td>
<td>79</td>
</tr>
<tr>
<td>11.</td>
<td>Estimated Fishing Time vs. Scallop Landings Based on Linear Relationship</td>
<td>80</td>
</tr>
<tr>
<td>12.</td>
<td>Estimated Fishing Time vs. Scallop Landings Based on a Sigmoid Relationship</td>
<td>82</td>
</tr>
<tr>
<td>13.</td>
<td>Mean Catch-Weights of Flatfishes and Paired T-tests by Species, Cruise and Hanging ratio</td>
<td>84</td>
</tr>
</tbody>
</table>
14. Observed Percent Changes in Mean Catch-Weights:
   a. Scallop Meats vs. Four-Spot Flounder ......................................................85
   b. Scallop Meats vs. Gray Sole .....................................................................86
   c. Scallop Meats vs. Summer Flounder .......................................................87
   d. Scallop Meats vs. Windowpane Flounder ...............................................88
   e. Scallop Meats vs. Winter Flounder .........................................................89

15. Mean Catch-Weights of Flatfishes and
   Paired T-tests by Species and Twine-Top Length ...........................................90

16. Mean Catch-Weights of Scallop Meats
   Using Two Twine-Top Lengths ........................................................................91

17. Observed Percent Changes in Mean Catch-Weights
   When Twine-Top Length is Modified ...............................................................92
ABSTRACT

Atlantic sea scallops, *Placopecten magellanicus*, are harvested with sea-scallop dredges composed of a bag of linked, steel rings and a twine-mesh backing, called a twine top. Although the twine-top’s primary functions are to reduce weight and aid gear-setting, it also facilitates escapement of non-targeted species (bycatch) and small scallops, by creating openings larger than the rings’ diameter. Bycatch can include species, such as yellowtail flounder, *Pleuronectes ferrugineus*, for which Total Allowable Catch limits (TACs) exist. If the yellowtail-flounder TAC is reached before the scallop TAC, then fishing activity must cease. Prompted by the financial impact of early closures, research examined gear modifications to decrease yellowtail-flounder bycatch without significantly affecting sea-scallop catch. This study focused primarily on the modification of twine-top hanging ratio, or the ratio of meshes to connecting rings, because prior research was scarce, it served as a measure of mesh openness, and was unregulated. During three cruises aboard a commercial scallop vessel, two dredges were configured with either the standard hanging ratio (90:34) or a modified hanging ratio (60:34) and towed simultaneously. After accounting for variation caused by cruise and tow-within-cruise, analyses of variance indicated that, compared to the standard configuration, the 60:34 ratio had a significantly (p = 0.0435) reduced mean catch-weight of yellowtail flounder (7.37 kg/tow versus 7.90 kg/tow) and an insignificant (p = 0.1148) increase in the mean sea-scallop catch-weight (54.43 kg/tow versus 52.37 kg/tow). Based on the relationship between percent changes in mean catch-weights of yellowtail flounder and sea-scallop meats within each cruise, this study suggests that if enough of the fleet changed from a 90:34 ratio to a 60:34 ratio, the fleet as a whole could benefit from a reduced yellowtail-flounder catch rate.

A preliminary analysis (Appendix II) was made of the effect of the proposed hanging-ratio modification on additional flatfish species, namely four-spot flounder (*Paralichthys oblongus*), gray sole (*Glyptocephalus cynoglossus*), summer flounder (*Paralichthys dentatus*), windowpane flounder (*Scophthalmus aquosus*) and winter flounder (*Pseudopleuronectes americanus*). In changing to the 60:34 ratio, only winter-flounder bycatch would likely increase for a given amount of scallop meats per tow. Because these species were caught with less frequency, additional cruises would be necessary for confirmation of trends in catch rates for these flatfishes. A supplementary, preliminary study (Appendix III) compared two twine-top lengths (8½ meshes long and 5½ meshes long) to determine the relative effect on yellowtail bycatch and scallop catch. Although scallop catch-weight was significantly (p = 0.048) increased, so too was yellowtail catch-weight (p = 0.005). Given the relationship between the percent changes in mean catch-weights, shortened twine tops are likely detrimental to the industry; however, additional cruises are necessary to draw definite conclusions.
Twine-Top Modifications of Sea-Scallop Dredges: Reducing Yellowtail-Flounder Bycatch
INTRODUCTION

The Atlantic sea scallop (*Placopecten magellanicus*) is among the more important commercial species of the USA. In terms of landed ex-vessel values (NMFS 2007b, 2007a), sea scallops repeatedly ranked among the three most valuable species with domestic harvests. Management of this fishery is carried out through the Sea-Scallop Fishery Management Plan (FMP), which utilizes a variety of tactics including area closures that open to fishing on a rotating basis. These areas (called access areas when open and closed areas otherwise) are subject to total allowable catch limits (TACs) of both sea-scallop meats and yellowtail flounder (*Pleuronectes ferruginea*, also called yellowtail). The scallop TAC limits the fishing effort of the fleet within these areas. The yellowtail TAC limits yellowtail mortality as required by the Northeast Multi-Species FMP, which manages approximately a dozen groundfish species, including yellowtail flounder.

Once the fleet’s estimated biomass of either yellowtail flounder (extrapolated from observer data) or scallop meats reaches the area-specific TAC, the access area closes. If the yellowtail TAC is reached first, any unlanded portion of the scallop TAC within the area becomes inaccessible and, consequently, represents a loss of anticipated income for the fleet.

In 2006, two access areas, namely Closed Area II (CA2) and Nantucket Lightship Closed Area (NLCA), closed early when their respective yellowtail TACs were reached.
Both areas were scheduled to be open between 15 Jun 2006 and 31 Jan 2007 (NEFMC 2004). CA2 closed four months early, which left nearly 22% of its allotted scallop TAC unlanded (NOAA 2007a). NLCA closed five and a half months early (NOAA 2007b), which left approximately 26% of its allotted scallop TAC unlanded (K. Wilhelm, NOAA, personal communication). Assuming a constant ex-vessel price of US$14.42 per kg, or $6.54 per pound (NMFS 2007b), these unlanded scallops were worth $24.6 million in CA2 and $19.7 million in NLCA in 2006. Although vessels with unused or broken trips were allocated additional days at sea in open areas, lower growth rates and smaller densities of scallops than the access areas from which the vessels were displaced meant smaller landings (NEFMC 2006). Therefore, only a portion of these losses could be recouped.

If commercial scallop vessels could reduce the incidental catch (called bycatch) of yellowtail, then access areas could remain open longer, giving scallop fishers (also called scallopers) more time to catch a larger portion of the scallop TAC. Gear modifications that increase finfish escapement are one method by which this could be accomplished.

Taken mainly from the Mid-Atlantic Bight and Georges Bank, U.S. sea-scallop landings are harvested primarily with New Bedford style sea-scallop dredges (Hart 2006). Described by Bourne (1964), these dredges are composed of a bag of linked, steel rings attached to a metal frame and a twine-mesh backing (called a twine top) as shown in Figure 1. Although the twine-top’s primary functions are to reduce weight and aid gear-setting, it also facilitates escapement of both finfishes and small scallops from the dredge (Henriksen et al. 1997; DuPaul et al. 1999). The twine top holds substantial appeal for
modification because of the ease with which it is manipulated and its inexpensive cost relative to other steel dredge components.

Little regulatory action has been made to standardize twine tops. In 1994, Amendment 4 to the Sea-Scallop FMP established a minimum mesh size, which measures the stretched distance between knots, of 5.5 inches (13.97 cm) on twine tops (NEFMC 1993). The following year, the New England Fisheries Management Council (NEFMC) noticed that scallopers were attaching the twine top to run the entire length of the dredge so it stretched closed during use and presumably prevented escapement. As a result, NEFMC (1995) specified a minimum of seven rows of rings between the twine top and the club stick. When Framework Adjustment 11 granted limited access to CA2, twine-top mesh size was set at 10 inches (25.4 cm) in the access area and 8 inches (20.32 cm) outside it (NEFMC 1999). As additional access areas were created, similar dual mesh size requirements were established. It was not until 2004 that Amendment 10 increased twine-top mesh size to 10 inches everywhere (NEFMC 2003).

One possible reason that twine-top regulations are so sparse is lack of research. Bycatch reduction studies on New Bedford style scallop dredges are noticeably absent before the mid 1990s. Instead, studies focused on either size selectivity through ring size modification (Bourne 1965; DuPaul and Kirkley 1995; Brust et al. 1996; Goff 2002) or the determination of gear efficiency (Gedamke et al. 2004, 2005).

Eventually, studies on twine-top configurations and escapement began in the context of newly instituted area closures and bycatch reductions. Henriksen et al. (1997) compared 6-inch (15.24-cm) mesh twine tops that were oriented so that the meshes opened in diamond formations to 8-inch (20.32-cm) twine tops that were rotated
90 degrees so that the meshes instead formed squares. Although the larger twine tops and square formations reduced yellowtail bycatch, it was impossible to identify the cause of the reduction because both mesh size and orientation were altered. DuPaul et al. (1999) found little difference in finfish bycatch between 8-inch (20.32-cm) mesh twine tops hung with either the standard diamond or the modified square orientation. In general, such studies (Henriksen et al. 1997; DuPaul et al. 1999; Smolowitz et al. 2004) concluded that larger meshes yielded less finfish bycatch as well as some degree of scallop loss.

Smolowitz and DuPaul (1999) examined numerous other modifications, including the ratio between the number of meshes running parallel to the club stick and the number of rings on which those meshes were hung, known as the twine-top hanging ratio. They found that a twine top hung 34 meshes on 34 rings (34:34) caught less bycatch than one hung 60 meshes on 34 rings (60:34). This experiment, however, was part of a cursory examination of modifications and was only meant to provide suggestions for more rigorous analysis in the future. As such, the methodology was not as stringent as it might otherwise have been: multiple modifications were applied simultaneously so that effects could not be separated and dredges were not switched between vessel sides to account for side-to-side variations. Nonetheless, this study provided a foundation for further examination of hanging-ratio modifications.

Twine-top hanging ratios are undocumented, based on the vessel operator’s preference, and vary throughout the fleet. Discussions with scallopers led me to believe that a 90:34 hanging ratio was common. Although some vessels used as many as four or five meshes per ring, such high hanging ratios were thought to be less common. Therefore, the 90:34 hanging ratio was designated as the standard. This study compared
that standard to a 60:34 hanging ratio, which was used in the previous study by Smolowitz and DuPaul (1999), to assess the relative effect on both yellowtail bycatch and scallop catch. I hypothesized that the lower hanging ratio (60:34) would spread open more to increase escapement of yellowtail without a significant reduction in scallop catch. If, however, the proposed modification decreased scallop catch, additional tow time would be required to compensate for these losses. This increased effort could, in the long run, offset any time gained in delaying attainment of the yellowtail TAC. Consequently, I also examined the potential financial impact on the scallop industry if a modification in hanging ratio from 90:34 to 60:34 were implemented on a large scale.
METHODS AND MATERIALS

Data Collection Methodology

Data were collected during three cruises between the summer of 2006 and the fall of 2007 (Table 1). Each cruise took place aboard a full-time commercial fishing vessel, the F/V Celtic, making commercial landings in the Georges Bank access areas. Fishing occurred either in Closed Area I (CA1) or Closed Area II (CA2) (Table 1; Figure 2). The high abundances of yellowtail flounder in these two access areas, allowed me to better understand the ramifications of the studied gear modifications. Specific fishing locations in CA1 were located latitudinally between 41°00’ N and 41°30’ N and longitudinally between 66°35.8’ W and 67°20’ W. Specific fishing locations in CA2 were located latitudinally between 41°01’ N and 41°70’ N and longitudinally between 66°07.8’ W and 67°58.3’ W. Once the vessel reached the fishing grounds, it fished twenty-four hours per day until the trip limit on scallop meats (18,000 pounds or 8.16 metric tons) was reached.

Sampling occurred at various times of the day while the vessel was actively fishing. Wherever possible, sampling methodology incorporated the crew’s standard operating procedures to allow scientists to collect data in a quick and efficient manner without interfering with commercial operations. Ordinarily, scallop vessels make use of two dredges: one off the port side and one off the starboard side. Once the dredges are brought on board, the crew sorts through the catch. Market-sized scallops are set aside; undersized scallops and all other organisms/material are discarded. After deploying the
dredges again, the crew cuts each scallop (described in detail by Peters 1978), saves only the adductor muscles, and discards the remaining parts at sea until the dredges are emptied again. Periodically, scallop meats, which are rinsed in sea water, are packed into muslin sacks, which hold approximately 50 pounds (22.7 kg) each, and put on ice.

Using these standard practices, two 15-foot (4.6-m) wide New Bedford style dredges (depicted in Figure 1) were simultaneously deployed, one on each side of the vessel. Only the hanging ratio varied: one dredge was configured with the standard ratio (90:34) while the other dredge was configured with a 60:34 hanging ratio. Both ring size and mesh size were kept at their legal requirements of 4 inches (10.16 cm) and 10 inches (25.4 cm), respectively. To account for possible vessel side to side variability, dredges were switched from port to starboard, and vice versa, at the approximate midpoint of each cruise. For the sake of practicality, this occurred only once per cruise as it was a time-consuming and difficult task. For each tow, either the vessel’s captain or first mate recorded vessel position, tow duration, depth, velocity, heading and wind speed on a bridge log. Given the commercial nature of these trips, the researchers were unable to control any of the above conditions; however, such settings were as consistent as commercial productions allowed.

In all experiments, port and starboard dredge contents were emptied onto the corresponding side of the deck, where the catches could remain separate. The lead scientist randomly selected corresponding regions of the catches to be sampled. Then, the crew filled two baskets with scallops, including empty (clappers) and undersized scallops, from the designated regions. From these two baskets, scientists collected shell-height frequency data using counting boards, which measured shell height in
5-millimeter (mm) increments. All clappers were identified as such. Once the crew picked through the catch and selected market-sized scallops for shucking, scientists recorded the total volume (in number of baskets) of market-sized scallops (including those in the first two baskets).

All teleosts and batoids were identified and counted. All flatfishes were measured to the nearest centimeter. On the rare occasion that a fish was dismembered by the gear and all portions of the animal could not be found, the partial fish was counted as a whole; its length was estimated based on animals of similar size. If time and weather allowed, the remainder of the catch was examined to estimate the volume (in number of baskets) of discarded scallops and trash, including other invertebrates.

Sampling from commercial vessels was subject to a variety of unpredictable factors, such as weather and vessel limits on when, where and how often fishing could occur. The first cruise (cruise A) took place in September of 2006 within CA1. The last two cruises (cruises B and C) occurred at least 10 months after the first cruise, in July and August of 2007, respectively (Table 1). By that time, CA2 was inaccessible and additional rock chains (turtle chains) were required by the National Marine Fisheries Service to prevent the capture of sea turtles. To avoid the need for special permits, cruises B and C took place in CA1 (rather than CA2) and dredges utilized turtle chains. Because both dredges were rigged similarly and towed simultaneously, it was assumed that the catching ability of both dredges would be equally affected by area, sampling year and additional rock chains.
METHODS AND MATERIALS
Data Analyses Methodology

Size frequency data were collected on a sample of the sea-scallop catch from each dredge per tow; thus, these data were extrapolated by the ratio of numbers of baskets caught to the number of baskets measured. Since all yellowtail were measured, no extrapolation of yellowtail size frequency data was necessary. To compare the size frequencies (pooled within cruise across tows) between the two hanging ratios, a two-sample Kolmogorov-Smirnov test was used on both species with the null hypothesis of a common distribution between gear types (Zar 1999). Although the two gear types were paired, the size of caught individuals was assumed to be independent and random.

For each species, relative harvest efficiency between the two hanging ratios, \( E_i \), was examined with respect to each measured length interval, or size class \( l \) (Rudders et al. 1998). At each size class, \( E_i \) was estimated by calculating the percentage change in the number of individuals caught per cruise, relative to the catch in dredges rigged with the 90:34 ratio.

Scallop and yellowtail length data were transformed into weights. Because sea scallops were measured in 5-mm intervals, the midpoints of these shell-height intervals were used to estimate weights. In contrast, yellowtail flounders were measured to the nearest cm; therefore, these rounded lengths were used in weight estimation. Given that
yellowtail flounder were denoted when the $j$-subscript equaled one and sea scallops were denoted when the $j$-subscript equaled two, the following log-linear relationship was used:

$$\ln(w_{ij}) = a_j + b_j \ln(L_{ij})$$

(Eqn. 1)

where

- $w_{ij}$ (lowercase) is the estimated weight of the $i^{th}$ individual of the $j^{th}$ species;
- $L_{ij}$ is the measured length of the $i^{th}$ individual of the $j^{th}$ species;
- $b_j$ is a species-specific change in the expected value of $\ln(w_{ij})$ per one unit of $\ln(L_{ij})$; and
- $a_j$ is a species-specific value of $\ln(w_{ij})$ when $\ln(L_{ij})$ is zero.

For yellowtail, when length is in centimeters and weight is in kilograms, $a_y$ is -11.8381 and $b_y$ is 3.0559 (Wigley et al. 2003). For scallops, when shell height is in millimeters and meat weight is in grams, $a_s$ is -11.6038 and $b_s$ is 3.1221 (NEFSC 2004). In each tow, the estimated weights of either yellowtail flounders or sea-scallop meats were summed over all individuals within each dredge to find the catch-weight. For each species, catch-weight was calculated using Equation 2:

$$W_{kt} = \sum_{i=1}^{I_{kt}} w_{ikt}$$

(Eqn. 2)

where

- $k$ denotes a hanging ratio of either 90:34 (when $k$ is 90) or 60:34 (when $k$ is 60);
- $W_{kt}$ represents the summed weight of the species caught in the dredge configured with the $k^{th}$ hanging ratio during the $t^{th}$ tow;
- $w_{ikt}$ is the estimated weight of the $i^{th}$ individual of the species caught with the $k^{th}$ hanging ratio during the $t^{th}$ tow;
- $I_{kt}$ indicates the number of individuals of the species caught with the $k^{th}$ hanging ratio during the $t^{th}$ tow.
With this information, I quantified relative harvest efficiency with respect to each
tow t as $\Phi_t$, using catch-weights of either yellowtail or scallop meats (Rudders et al. 1998)
in Equation 3.

$$\Phi_t = \left( \frac{W_{60t} - W_{90t}}{W_{90t}} \right) 100\% \quad \text{(Eqn. 3)}$$

**ANOVA**

To determine if a significant difference existed between the mean catch-weights
of the two configurations, analyses of variance (ANOVAs) were performed by using the
PROC MIXED routine of the SAS® software. For both species, an ANOVA was run
using hanging ratio as the main treatment effect along with two random blocking effects,
namely cruise and tow-within-cruise. Both yellowtail and scallop data lacked variance
homogeneity and required transformation. Yellowtail catch-weight was transformed by
the natural log then squared, i.e., $(\ln(W^\text{lt}))^2$; scallop catch-weight was transformed by the
natural log, i.e., $\ln(W^\text{st})$. For each species, the fitted model was:

$$\omega_{ktu} = \mu + (\text{gear})_k + (\text{cruise})_u + (\text{tow(\text{cruise})})_i(u) + E_{ktu} \quad \text{(Model 1)}$$

where

- $\omega_{ktu}$ is the transformed catch-weight from the $k^{th}$ hanging ratio in the $t^{th}$ tow of the
  $u^{th}$ cruise;
- $\mu$ depicts the overall mean of catch-weight of the species;
- $(\text{gear})_k$ signifies the treatment effect of the $k^{th}$ level of hanging ratio;
- $(\text{cruise})_u$ signifies the random blocking effect of the $u^{th}$ cruise (where $u = 1$
  indicates cruise A, $u = 2$ indicates cruise B, and $u = 3$ indicates cruise C);
(tow(cruise))_{(u,t)} signifies the random blocking effect of the $t^{th}$ tow within the $u^{th}$ cruise (where $t = 1$ indicates the first tow, $t = 2$ indicates the second tow, ... and $t = n$ indicates the $n^{th}$ tow);

$E_{ktu}$ is the random error term of the $k^{th}$ hanging ratio in the $t^{th}$ tow of the $u^{th}$ cruise, where $E_{ktu} \sim N(0, \sigma_{E}^2)$.

**Linear Regression with Dummy Variables**

The average catch-weights of yellowtail and sea-scallop meats were also examined separately with SAS software using dummy variables in multiple linear regressions. Like analysis of covariance (ANCOVA), this analysis allowed identification of group differences in the relationship between response variable and covariate, as well as the examination of both magnitude and direction of treatment effects. However, use of dummy variables in linear regressions also allowed the assessment and identification of abrupt slope changes (Hardy 1993). With this in mind, the estimated model contained one covariate, four dummy variables, and two interaction dummy variables.

First, duration of each tow ($Towtime$) served as a measure of effort and was used as a covariate in the analysis. The paired dredges were assumed to collect organisms from the same population at the same time. Consequently, significant differences in slope, or the change in transformed catch-weight per towing hour, were considered differences in catch efficiency.

Next, dummy variables (in italics) were constructed from two independent variables (hanging ratio and cruise):

- $Gear60$ equaled one if data were collected with a 60:34 (modified) hanging ratio and zero if collected with a 90:34 (standard) hanging ratio.
- $CruiseA$ equaled one if data collection occurred during the first cruise (cruise A) and zero if it occurred during any other cruise.
- $CruiseB$ equaled one if data were collected on the second cruise (cruise B) and zero during any other cruise.
The member group referred to those observations where the dummy variable equaled one; the reference group referred to those observations where the dummy variable equaled zero. The overall reference group referred to data with all dummy variables equal to zero, specifically data collected with a 90:34 ratio during cruise C. The effect of side was not tested as it was assumed to be absent, as shown in previous research (Bourne 1965).

From these three dummy variables, two interaction dummy variables (in italics) were created: Gear60_x_CruiseA and Gear60_x_CruiseB. These interactions equaled one if both associated dummy variables were one, and zero if either dummy variable was zero. The interactions were meant to determine if the effects of using the modified hanging ratio, rather than the standard hanging ratio, were the same in each cruise. For each species, the estimated model is shown in Model 2.

\[
\omega_i = \left( \beta_0 + \beta_1 (\text{Gear60}) + \beta_2 (\text{CruiseA}) + \beta_3 (\text{CruiseB}) + \beta_4 (\text{Gear60}_x_{\text{CruiseA}}) + \beta_5 (\text{Gear60}_x_{\text{CruiseB}}) \right) + \left( \beta_6 + \beta_7 (\text{Gear60}) + \beta_8 (\text{CruiseA}) + \beta_9 (\text{CruiseB}) + \beta_{10} (\text{Gear60}_x_{\text{CruiseA}}) + \beta_{11} (\text{Gear60}_x_{\text{CruiseB}}) \right) \text{(Towtime)} + E_i
\]

(Model 2)

In Model 2:
- \(\omega_i\) is the transformed catch-weight of the \(i^{th}\) observation of the species;
- \(\beta_0\) is the expected y-intercept of the model, or value of \(\omega_i\) when towing time is theoretically zero, for the overall reference group (data collected with a 90:34 ratio during cruise C);
• $\beta_1$ indicates the change in the expected y-intercept of the model when a 60:34 ratio is used rather than a 90:34 ratio and all other dummy variables are held at their respective reference groups;
• $\beta_2$ and $\beta_3$ are the partial regression coefficients associated with CruiseA and CruiseB, respectively. Like $\beta_1$, when all other variables are controlled and $\beta_2$ or $\beta_3$ are considered individually, each coefficient indicates the difference in the expected y-intercept between the cruise member group (coded one) and its respective reference group (coded zero).
• $\beta_4$ and $\beta_5$ are the partial regression coefficients associated with the interaction between hanging ratio and cruise. $\beta_4$ indicates the change in the expected y-intercept when a 60:34 ratio is used rather than a 90:34 ratio during cruise A and all other variables are controlled. Similarly, $\beta_5$ indicates the change in the expected y-intercept when a 60:34 ratio is used rather than a 90:34 ratio during cruise B and all other variables are controlled.
• $\beta_6$ indicates the change in the expected value of $\omega_i$ per each additional hour of towing for the overall reference group, i.e., data collected with a 90:34 ratio during cruise C.
• $\beta_7$ denotes the estimated difference in $\omega_i$ per each additional hour of towing for catch from a dredge using a 60:34 ratio compared to a 90:34 ratio.
• $\beta_8$ and $\beta_9$ denote the estimated effect differences on $\omega_i$ each additional hour of towing caused by CruiseA and CruiseB, respectively, relative to their reference groups.
• $\beta_{10}$ and $\beta_{11}$ are the partial regression coefficients associated with the interaction between hanging ratio, cruise and tow time. $\beta_{10}$ indicates the change in the expected value of $\omega_i$ per each additional hour of towing when a 60:34 ratio is used rather than a 90:34 ratio during cruise A and all other variables are controlled. Similarly, $\beta_{11}$ indicates the change in the expected value of $\omega_i$ per each additional hour of towing when a 60:34 ratio is used rather than a 90:34 ratio during cruise B and all other variables are controlled.
• $E_i$ is the random error term of the $i^{th}$ observation of the species, where $E_i \sim N(0, \sigma^2_E)$.

For either yellowtail-flounder data or sea-scallop data, any one group’s regression line can be found using the sum of $\beta_0$, $\beta_1$, $\beta_2$, $\beta_3$, $\beta_4$, and $\beta_5$ as their y-intercept (expected value of $\omega_i$ when towing time theoretically equaled zero) and the sum of $\beta_6$, $\beta_7$, $\beta_8$, $\beta_9$, $\beta_{10}$ and $\beta_{11}$ as their slope (expected change in $\omega_i$ per hour of towing). To simplify analysis with SAS software, Model 2 was rearranged to form Model 3:
The multiplicative variables were created by multiplying Towtime with each of the original dummy variables. These new variables equaled Towtime when the associated dummy variables equaled one. Otherwise, they equaled zero. As such, the coefficients of Model 3 had equivalent meanings as those found in Model 2.

The reliability of hypothesis tests for these linear regression models was based on three assumptions regarding the error terms. First, errors were assumed to be normally distributed with an expected value of zero. Second, errors were assumed to have a constant, equal variance for each value of each independent variable. Third, errors were assumed to lack correlation between other observations and groups (Hardy 1993; Quinn and Keough 2002). The validity of each assumption was tested.

Initially, the yellowtail model and scallop model were estimated with PROC GLM to obtain the residuals. Using PROC CAPABILITY, probability plots and histograms were used to examine the distribution of the residuals. To confirm constant variances, these residuals were also graphed as a function of their predicted values. Both the yellowtail dataset and scallop dataset required transformation, but previously used transformations were insufficient to meet the assumptions. Hence, yellowtail catch-weights were log-transformed (with the natural log); scallop catch-weights were squared.
To ensure uncorrelated residuals, each residual was plotted against the previous observation’s residual and a generalized Durbin-Watson statistics was obtained using PROC AUTOREG. Because the two dredges were towed simultaneously, autocorrelation was present in both species’ models. When sorted by tow, both models required a correction for a correlation between dredges (one lag apart). In addition, the scallop model required a correction for a correlation between consecutive tows (two lags apart). Consequently, the error term within the yellowtail-flounder model was substituted with a first-order autoregressive model and the error term within the sea-scallop model was substituted with a second-order autoregressive model. These corrections were made using stepwise autoregression, or the BACKSTEP option, within PROC AUTOREG. Normality of the recalculated residuals of both species was confirmed with PROC UNIVARIATE. Finally, to confirm homoscedasticity between groups, one-way ANOVAs were performed on the absolute values of the divergence from the group medians (Hardy 1993). Significant group effects indicated heteroscedasticity.

Because a semilogarithmic equation was used to model yellowtail data, the percentage change in the effect of each variable on catch-weight depended on the variable with which the coefficient was associated. When the variable contained continuous values, i.e., 

\textit{Towtime}, this percentage change (relative to the overall reference group) could be calculated from the coefficient by simply multiplying by 100\%. In contrast, when the variable was a dummy variable with binary coding, the estimated coefficient required conversion using the antilog function to determine the proportion of the response observed by a given member group (when the dummy variable was one) to its reference group (when the dummy variable was zero) (Halvorsen and Palmquist
1980). Then, if \( \beta_i \) indicated the \( i^{th} \) coefficient of a dummy variable, the percent change in catch-weight experienced by the member group relative to the overall reference group was:

\[
\text{%change} = 100(\exp(\beta_i) - 1).
\qquad \text{(Eqn. 4)}
\]

**Percent-Changes in Mean Catch-Weight**

Examining treatment effects on the mean catch-weights of either yellowtail flounder or sea scallops does not address the industry’s constraint that yellowtail bycatch be reduced without causing scallop losses sufficient enough to make harvest unprofitable. Therefore, for each cruise, the catch-weights were used to determine the percentage change in mean catch-weights as shown in Equation 5:

\[
\hat{P}_{ju} = \left( \frac{\sum_{t=1}^{n} W_{j60t} - \sum_{t=1}^{n} W_{j90t}}{W_{j90t}} \right) \cdot 100\% 
\qquad \text{(Eqn. 5)}
\]

where

- \( j \) denotes either yellowtail flounder (if \( j \) equals one) or sea scallop (if \( j \) equals two),
- \( \hat{P}_{ju} \) is the estimated percentage change in mean catch-weight of species \( j \) during cruise \( u \) when gear is modified from a 90:34 ratio to a 60:34 ratio,
- \( W_{j60t} \) signifies the summed weight of the \( j^{th} \) species caught with a 60:34 configuration in the \( t^{th} \) tow,
- \( W_{j90t} \) signifies the summed weight of the \( j^{th} \) species caught with 90:34 configuration in the \( t^{th} \) tow, and
- \( n \) is the number of tows within cruise \( u \).
Because two dredges were towed simultaneously, a correlation between dredges was expected. Given this correlation, the fallacy of averages stated that \( \hat{\rho}_{ju} \) was not equivalent to the mean value of \( \Phi \), over all tows within the same combination of cruise and species (Welsh et al. 1988). Nonetheless, the use of \( \hat{\rho}_{ju} \) minimized the influence of outliers that had no justification for discard. This was particularly evident in tows with small yellowtail catches where a difference of a handful of fish resulted in large values of \( \Phi \), for yellowtail flounder.

By assuming a minimal change in relative prices and plotting percent change in mean yellowtail catch-weight (\( \hat{\rho}_{ju} \)) against percent change in mean scallop catch-weight (\( \hat{\rho} \)), the potential impact of implementing a large-scale change from the standard hanging ratio to a 60:34 hanging ratio was examined (Figure 3). Along the 45° line, the ratio of percent changes in yellowtail to scallop is one, and the difference in percent changes is zero. Accordingly, more or less fishing time may be required to catch a given scallop quota, but the relative amount of yellowtail bycatch would remain constant. For example, if the mean catch-weights of both scallop meats and yellowtail flounder were increased by 100%, half the tow time would be required to catch a given amount of scallops. However, because the yellowtail bycatch rate also doubled, half the tow time would result in the same amount of yellowtail-flounder bycatch.

In reality, the neutral line is expected to curve due to economic considerations (see dashed line in Figure 3). Large, negative values of \( \hat{\rho}_{ju} \) would decrease scallop catch.
enough to render fishing too costly so, at some unknown point, the line’s left side would bend sharply down. No data are available to evaluate this curve; therefore, the neutral line is assumed to be the 45° line.

Observations below the 45° line represent cruises where the modification from a standard hanging ratio to a 60:34 hanging ratio is thought to be beneficial to the industry; those above the line represent cruises where the tested modification is thought to be detrimental. A reduction in yellowtail-flounder bycatch accompanied by an increase in scallop catch (region IV) would benefit the industry because the yellowtail TAC would take longer to reach. Conversely, an increase in yellowtail-flounder bycatch accompanied by a decrease in scallop catch (region I) would harm the industry because the yellowtail TAC would be achieved more quickly, resulting in a shorter fishing season and a reduced achievement of the scallop TAC. If a mix of such gains or losses occurred, the outcome will be more complicated.

If both yellowtail bycatch and scallop catch increase, then the relationship between the percent changes in mean catch-weights of both species determines the potential effect on the scallop industry. If the scallop increase is greater than the yellowtail increase (region IIb), then less fishing time would be needed to catch a given amount of scallops while still resulting in less yellowtail bycatch. This would be beneficial for the industry. On the other hand, if the scallop increase is less than the yellowtail increase (region IIa), the yellowtail TAC would be reached faster than the increase in scallops could justify, which would be detrimental for the industry.

If both yellowtail bycatch and scallop catch decrease, then the relationship between the percent changes in mean catch-weights of both species again determines the
effect on the scallop industry. If the percentage change in mean scallop catch-weight is
greater than the percentage change in mean yellowtail catch-weight (region IIIb),
e.g., -5% scallop catch is greater than -25% yellowtail bycatch, then less yellowtail would
be caught overall even though some additional tow time would be required to offset the
loss of scallops. This would be good for the industry if other economic considerations
were absent and/or inconsequential. On the other hand, if scallop catch decreases more
than yellowtail bycatch (region IIIa), e.g., -25% scallop catch-weight is greater than -5%
yellowtail bycatch, then it would be detrimental to the industry because the additional
tow time needed to offset scallop loss would surpass the additional time justified by the
reduction in yellowtail-bycatch. More yellowtail bycatch would be caught as a result.

The addition of two elements, confidence intervals and a mean $\hat{P}_{ju}$, aided
interpretation of the modification’s impact to the scallop industry. First, 95% confidence
intervals in yellowtail percent changes ($\hat{P}_{ju}$) and scallop percent changes ($\hat{P}_{2n}$) (discussed
in Appendix I) were graphed as vertical and horizontal bars, respectively. These bars
depict within-cruise variances (Cumming et al. 2007). Second, mean $\hat{P}_{ju}$ was calculated
by averaging $\hat{P}_{ju}$ over all cruises by species, using only those tows where both species
were caught and measured. When mean $\hat{P}_{ju}$ was plotted with $\hat{P}_{1u}$ and $\hat{P}_{2n}$, mean $\hat{P}_{ju}$ was the
centric point. Assuming little sampling error and bias, mean $\hat{P}_{ju}$ illustrates the average,
observed impact of switching from a 90:34 ratio to a 60:34 ratio.
Financial Impact

Two access areas, CA2 and NLCA, closed early in 2006 when their respective yellowtail TACs were achieved before their respective scallop TACs were fully landed. To estimate the economic impact of a large-scale change in hanging ratio from 90:34 to 60:34, the 2006 yellowtail-flounder bycatch and sea-scallop landings within these areas were examined. In both areas, the Northeast Regional Office (NERO) of NMFS extrapolated observer data to obtain weekly, cumulative catch data for the fleet (Figure 4) (NOAA 2007b, 2007a; K. Wilhelm, NOAA, personal communication). For this analysis, I converted landings data from U.S. standard units, i.e., pounds, into metric units and assumed that these catch quantities were caught on the weekly report date.

Although the proportion of the fleet, $Q$, capable and willing to modify its gear from the standard to the modified configuration was unknown, a range of proportions was utilized to examine how $Q$ might affect different aspects of the assessment. To distinguish between these values, a subscript, $v$, was added so $Q_v$ indicated the following:

- $0\%$ of the fleet when $v$ was 0,
- $10\%$ of the fleet when $v$ was 1,
- $50\%$ of the fleet when $v$ was 2, and
- $100\%$ of the fleet when $v$ was 3.

When $Q_v$ equaled zero, no portion of the fleet was assumed to alter the gear; thus, it was equivalent to the bycatch estimated and reported by NERO ($\lambda_b$ in Equation 6).

To adjust 2006 catch quantities with experimental results, two more assumptions were made: 1) results observed during the three experimental cruises aboard a single vessel were assumed to be representative of all cruises taken by all vessels within the fleet and 2) percent change in mean catch-weight was assumed to be unaffected by
fishing area. To see how historical catch might have been altered through time, the reported cumulative catches within CA2 (if the $b$-subscript equaled one) or NLCA (if the $b$-subscript equaled two) were adjusted by observed values of percent change in mean catch-weight of yellowtail flounder. This was done to each week’s reported, cumulative catch until the area in question closed and data reporting stopped. The following equation was used:

$$ Y_{buv} = \lambda_b + \lambda_b \hat{P}_{1u} Q_v \quad \text{(Eqn. 6)} $$

where

- $Y_{buv}$ is the weekly, cumulative catch of yellowtail flounder, which was adjusted with results found on the $u^{th}$ cruise and the $v^{th}$ value of $Q$, caught by the fleet in either CA2 (if $b = 1$) or NLCA (if $b = 2$);
- $\lambda_b$ is the weekly, cumulative weight of yellowtail-flounder bycatch, which NERO estimated and reported (NOAA 2007a, 2007b) within the closed area designated by the $b$-subscript;
- $\hat{P}_{1u}$ is the percentage change in mean catch-weight of yellowtail flounder in cruise $u$;
- $Q_v$ designates the proportion of the fleet assumed to change from a 90:34 configuration to a 60:34 configuration; and
- $v$ indicates the value of $Q$ such that $Q_v = 0$ when $v = 0$, $Q_v = 0.1$ when $v = 1$, $Q_v = 0.5$ when $v = 2$, and $Q_v = 1.0$ when $v = 3$.

Two functions were assumed to determine the rate at which yellowtail flounder were caught and/or could have been caught once catch was adjusted using Equation 6. The first function is a simple linear relationship between catch and time given by:

$$ Y_{buv} = Y_0 + m'_{buv} D_{buv} \quad \text{(Eqn. 7)} $$

where

- $Y_{buv}$ is the weekly, cumulative catch of yellowtail flounder, which was adjusted (using Equation 6) with results found on the $u^{th}$ cruise with the $v^{th}$ value of $Q$, caught by the fleet in closed area $b$ (CA2 if $b = 1$ or NLCA if $b = 2$);
• $Y_0$ is the y-intercept;
• $m_{buv}$ is the slope of the function, given the $u^{th}$ cruise, $v^{th}$ value of $Q$, and yellowtail catch within closed area $b$;
• $D_{buv}$ is the number of days since the opening of closed area $b$, given cruise $u$ and $Q_v$.

This simple relationship was based on data from the last three weeks as reported by NERO and adjusted with Equation 6. It was assumed that, regardless of previous fluctuations, catch rate would remain constant if the fishing season were extended.

The second function was a sigmoid relationship given by:

$$Y_{buv} = \frac{\alpha_{buv}}{1 + e^{-\left(\frac{D_{buv} - X_{o\cdot buv}}{\beta_{buv}}\right)}}$$  \hspace{1cm} (Eqn. 8)

where

• $Y_{buv}$ is the weekly, cumulative catch of yellowtail flounder, which was adjusted (using Equation 6) with results found on the $u^{th}$ cruise with the $v^{th}$ value of $Q$, caught by the fleet in closed area $b$ (CA2 if $b = 1$ or NLCA if $b = 2$);
• $\alpha_{buv}$ signifies the constant equal to the maximum estimated yellowtail harvest in closed area $b$ that was calculated from the $u^{th}$ cruise and the $v^{th}$ value of $Q$;
• $X_{o\cdot buv}$ is a constant that is equal to the number of days at which 50% of $\alpha_{buv}$ is caught;
• $\beta_{buv}$ is the slope constant, particular to closed area $b$, cruise $u$ and the $v^{th}$ value of $Q$, whereby smaller values of $\beta_{buv}$ result in steeper slopes.

The parameters of this function were estimated using non-linear regression with PROC NLIN.

Similarly, the fleet’s cumulative catch of sea-scallop meats within these two areas (NOAA 2007a; K. Wilhelm, NOAA, personal communication) were adjusted using:

$$S_{buv} = \Gamma_b + \Gamma_b \hat{P}_{2u} Q_v$$  \hspace{1cm} (Eqn. 9)
where

- $S_{buv}$ is the adjusted, cumulative weight of sea-scallop meats caught by the fleet in closed area $b$, based on results calculated from cruise $u$ and the $v^{th}$ value of $Q$;
- $\Gamma_b$ represents the cumulative weight of sea-scallop meats caught by the fleet in closed area $b$, which was originally estimated by NERO (NOAA 2007a; K. Wilhelm, NOAA, personal communication);
- $\hat{P}_u$ is the percentage change in mean catch-weight of sea-scallop meats during cruise $u$;
- $Q_v$ is the proportion of the fleet assumed to change twine-top hanging ratio from 90:34 to 60:34, where $v = 0$ indicates $Q_v = 0$, $v = 1$ indicates $Q_v = 0.1$, $v = 2$ indicates $Q_v = 0.5$, and $v = 3$ indicates $Q_v = 1.0$.

Again, when $Q_v$ equaled zero, no portion of the fleet was assumed to alter the gear; thus, it was equivalent to the catch estimated by NERO, $\Gamma_b$. Because weekly scallop landings of 2006 were unavailable, sea-scallop catch was assumed to be a simple, linear function of time as shown in Equation 10:

$$S_{buv} = m_{buv} D_{buv} \quad \text{(Eqn. 10)}$$

where

- $S_{buv}$ is the total adjusted landings of sea-scallop meats caught by the fleet in closed area $b$, based on results calculated from cruise $u$ and the $v^{th}$ value of $Q$;
- $m_{buv}$ designates the function’s slope (given closed area $b$, cruise $u$ and $Q_v$), which is equal to the adjusted, cumulative scallop weight, on the original closure day (NOAA 2007a, 2007b) divided by the number of days in which closed area $b$ originally remained open;
- $D_{buv}$ is the number of days since the opening of closed area $b$, given cruise $u$ and $Q_v$.

These relationships determined how much longer CA2 and NLCA could have stayed open in 2006 and how much more scallop meat could have been caught if 1) some portion of the fleet ($Q$) altered gear and 2) percent changes similar to any of the three
cruises (designated by the subscript, \( u \)) were experienced. For each combination of closed area, value of \( Q_v \), and cruise, the following procedures were performed:

1. NERO’s final amount of cumulative yellowtail bycatch, i.e., the last week’s value of \( Y_{bu0} \), was used to determine (Equation 7) the reported yellowtail bycatch rate, \( m_{bu0} \).

2. The last week’s value of \( Y_{bu0} \) was adjusted (Equation 6) by either an observed value of \( \hat{P}_u \) or mean value of \( \hat{P}_u \). This adjusted value represents the amount of yellowtail that might have been caught during the length of time that the examined area was open. It was hypothesized that this adjusted value would be significantly less than the original.

3. Step 2 was repeated for the reported amounts of cumulative yellowtail bycatch in all weeks.

4. Using either the linear or sigmoid relationship (Equation 7 or 8, respectively), a new value of \( D_{buv} \) was calculated.
   i) If the linear relationship was used, a new catch rate (\( m'_{buv} \)) was found by fitting Equation 7 to the last three weeks of adjusted yellowtail catch data and associated catch/report dates. Then, using the new value of \( m'_{buv} \) and the last week’s unadjusted amount of yellowtail bycatch (\( Y_{bu0} \)), Equation 7 was rearranged to solve for \( D_{buv} \).
   ii) If the sigmoid relationship was used, each week’s cumulative yellowtail bycatch was adjusted (Equation 6). A sigmoid curve (Equation 8) was fit to the data using PROC NLIN, which estimated values for \( a_{buv} \), \( X_{\alpha_{bu}} \), and \( \beta_{bu} \). Then, Equation 8 was rearranged to solve for \( D_{buv} \).
This new value of $D_{bu}$ represents the number of days that the fleet could have taken to catch an equivalent amount of yellowtail bycatch using the adjusted yellowtail bycatch rate. In other words, it represents the amount of time that the area could have stayed open given $Q_v$ and percent changes similar to the $u^{th}$ cruise.

5. A historical scallop catch rate, $m_{bu0}$, was obtained (Equation 10) from historical scallop landings and the area’s reported fishing time (in days).

6. Historical scallop landings were adjusted (Equation 9) to find $S_{bu0}$, or the amount of scallops which might have been caught within the reported fishing time if results were similar to the given combination of closed area, $Q_v$ and cruise.

7. A new catch rate, $m_{bu}$, was then calculated (Equation 10) from adjusted scallop landings ($S_{bu0}$ from step 6) and the reported number of fishing days within the area.

8. Finally, the calculated time that the area could have stayed open ($D_{bu}$ from step 4) and the adjusted scallop catch rate ($m_{bu}$ from step 7) were used to determine (Equation 10) a new value of $S_{bu}$. This signifies the scallop catch that might have been landed in this new timeframe.

9. Steps 1 through 8 were repeated with the average percent changes (rather than observed values) in mean yellowtail and scallop catch-weights (mean value of $\hat{P}_{lw}$ and mean value $\hat{P}_{sw}$, respectively) for all three cruises. Again, this was done for every combination of closed area, value of $Q_v$, and mean percentage change.
The difference in scallop landings between the fleet’s reported landings on the observed closure day and predicted landings on the adjusted closure day, was multiplied by the 2006 value of $14.42 per kg ($6.54 per pound) (NMFS 2007b). The resulting revenue difference indicates the possible financial impact of modifying the hanging ratio from 90:34 to 60:34. These results are discussed in the next section.
RESULTS

Catch data were collected from 93 of 190 tows undertaken during three commercial trips. Some tows were discarded to avoid failed distribution assumptions caused by tows where no yellowtail flounders were caught in either dredge. In doing so I assumed that such tows took place where the species did not occur, not that all individuals escaped. In addition, some tows were discarded because they lacked length-frequency data; thus, catch-weights could not be determined. Still other tows were discarded to decrease sampling error. Usable tows met the following criteria:

- catch within each dredge included at least one yellowtail flounder and one basket of sea scallops;
- data from each dredge included length frequencies from all yellowtail flounder and shell-height frequencies from two baskets of sea scallops;
- both dredges were set and retrieved simultaneously; and
- no signs of tow disruption, such as a flip (where the dredge was overturned), hang (where any portion of the dredge was caught on something), or rider (where one dredge came to rest on top of the other dredge), were observed.

Fifty-five tows (17 tows in the first cruise, 20 tows in the second cruise, and 18 tows in the third cruise) were analyzed. Depth ranged from 30 to 40 fathoms, vessel speed ranged from four to five knots, and tow duration ranged from 20 minutes to one hour and 44 minutes. I examined 3,558 yellowtails and an estimated 142,725 scallops.

Compared to the standard hanging ratio, the 60:34 hanging ratio repeatedly caught smaller average catch-weights per cruise of yellowtail bycatch and usually caught larger average catch-weights per cruise of scallop meats (Figure 5). This pattern was also
observed in the frequency distributions of $\phi_n$, which illustrated a tendency for the 60:34 hanging ratio to catch smaller catch-weights per tow of yellowtail flounder and similar catch-weights per tow of sea-scallop meats (Figure 6).

Kolmogorov-Smirnov tests compared the distributions of size frequencies between dredges (Figure 7). The null hypothesis, stating that both dredges caught the same distribution, could not be rejected with respect to yellowtail flounders ($\text{KS}_a = 0.849863$, $p = 0.4655$), but was rejected with respect to sea scallops ($\text{KS}_a = 2.488280$, $p < 0.0001$). These results are reflected in the mean values of percent change in counts between gears at each size class, $E_1$ (Figure 7). Although no pattern was seen over any large range of yellowtail-flounder sizes, mean values of $E_1$ were usually greater than zero for scallops with shell heights greater than 60 mm and less than zero for scallops with shell heights less than 60 mm.

**ANOVA**

Average catch-weights were analyzed via ANOVA using hanging ratio as a fixed treatment and two random blocking factors (cruise and tow-within-cruise). Using the 60:34 hanging ratio resulted in a significant ($F_{1,54} = 4.27$, $p = 0.0435$) reduction in the expected value of the transformed catch-weight of yellowtail. Although the transformed scallop catch-weight was increased when using the 60:34 configuration rather than the standard, this difference was not significant ($F_{1,54} = 2.57$, $p = 0.1148$). The difference in the retransformed adjusted means of yellowtail and scallop catch-weights indicate that over the course of 100 tows, yellowtail bycatch would be reduced by 50 kg and scallop
catch would be increased by 210 kg if the modified hanging ratio were used rather than the standard (Figure 8; Table 2).

**Linear Regression with Dummy Variables**

To examine group differences in average catch and efficiency, multiple linear regression analysis was conducted with dummy variables and the covariate *Towtime*. Additive dummy variables identified group differences in average catches; multiplicative dummy variables identified group differences in catch per unit time.

After the correction of autocorrelation, homoscedasticity between groups was tested via one-way ANOVAs on the absolute values of the deviations from the group medians. With respect to yellowtail data, the null hypothesis of equal variance between cruises ($F = 0.61, p = 0.5459$) and hanging ratios ($F = 0.13, p = 0.7142$) was not rejected. While homoscedasticity was also observed in scallop data between hanging ratios ($F = 1.91, p = 0.1700$), heteroscedasticity was shown between cruises ($F = 3.70, p = 0.0279$) and could not be corrected.

The yellowtail catch was shown to be significantly ($p < 0.05$) different during the first cruise and dependant on tow time (Table 3). When using the 90:34 hanging ratio, the $y$-intercept of the yellowtail model was 367 times larger during cruise A than during other cruises (Figure 5 and Table 3). When using 90:34 during the reference cruise (cruise C), the change in catch increased significantly by 198% for each additional hour of towing. When using 90:34 during cruise A, however, the slope was reduced significantly by 235% relative to the other two cruises. No significant impact was seen on either the $y$-intercept or the slope in any cruise if a 60:34 configuration was used rather than a 90:34 configuration.
The assumption of homoscedasticity of residuals between cruises was violated with respect to the scallop model. This violation initially called the validity of the T-tests within the scallop model (Table 4) into question because such tests assumed an equal variance between observations where the dummy variable is one and where the dummy variable is zero (Hardy 1993). However, regression analysis was shown to be robust to heteroscedasticity if the heterogeneity among variances was not prominent (Bohrnstedt and Carter 1971). Such a lack of marked heterogeneity was seen in the scallop data (Figure 9). Given the subjective nature of this criterion, I also examined the robustness of ANCOVA, which is analogous to linear regression analysis with dummy variables (Hardy 1993), and ANOVA, which exhibits a robustness to heteroscedasticity that is extended to ANCOVA (Glass et al. 1972). Although this robustness is most applicable when sample size is equal, the most serious repercussions of unequal error variances were shown to occur when sample size was negatively correlated with variance (Horsnell 1953; Weerahandi 1995). This was not the case as the number of tows per cruise and variance within cruise were not correlated (Pearson $\rho = 0.9537$, p = 0.1944). Robustness notwithstanding, the model still offered reliable coefficient estimates (Hardy 1993).

As modeled, the squared catch-weight of scallops was significantly ($p < 0.05$) affected by $\text{CruiseA}$ and marginally ($p < 0.10$) affected by hanging ratio. For each hour of towing, the expected change in squared catch of the overall reference group, which used 90:34 during cruise C, increased by 7099.8 kg$^2$. In comparison to cruises B and C, the y-intercept of cruise A increased by 6948.6 kg$^2$ even as the slope decreased by 6584.7 kg$^2$/h. The lower hanging ratio had a marginally significant ($p < 0.10$) effect during the reference cruise, when the expected slope was reduced by 3416.2 kg$^2$/h.
In both models, the treatment effect between hanging ratios was overpowered by the cruise effect. Although additional cruises might have decreased this variation, it was not logistically possible.

**Percent-Changes in Mean Catch-Weight**

To visualize whether switching hanging ratios from 90:34 to 60:34 would reduce yellowtail bycatch without substantial losses in scallop catch, a graphical format was used (Figure 10) to compare percent change in mean yellowtail bycatch ($\hat{P}_{1w}$) to percent change in mean scallop catch ($\hat{P}_{2w}$). For a given amount of sea scallops, less yellowtail would be caught if $\hat{P}_{1w}$ was less than $\hat{P}_{2w}$; more yellowtail would be caught if $\hat{P}_{1w}$ was greater than $\hat{P}_{2w}$.

Cruises A and B resulted in greater percent changes in scallop catch than yellowtail bycatch. While this was not the case for cruise C, the magnitude of the difference between $\hat{P}_{1w}$ and $\hat{P}_{2w}$ was much smaller than the other two cruises and cruise C’s 95% confidence intervals straddled the beneficial and detrimental zones. Along the horizontal (scallop) axis, the confidence intervals of cruises B and C overlapped and cruise A stood alone. Along the vertical (yellowtail) axis, the confidence intervals of all three cruises overlapped. The mean scallop percent change was larger than the mean yellowtail percent change. As a result, a single vessel might not see the advantage of switching from the standard hanging ratio to the 60:34 hanging ratio in any one fishing trip given the cruise-to-cruise variation, but the average impact of such a modification would likely be beneficial to the industry in the long run.
Financial Impact

Early area closures in 2006 were examined to estimate the impact of modifying the hanging ratio from 90:34 to 60:34. Percent changes from each cruise, their mean, and three values of $Q$ (the proportion of the fleet assumed to modify its gear), were examined with both linear and sigmoid relationships (Equations 7 and 8, respectively) between cumulative catch and number of fishing days within each area.

Given a linear relationship and the mean value of $\hat{P}_{ju}$, CA2 could have remained open an additional 0.3, 2.6, or 5.8 days if $Q$ was assumed to be 10%, 50% or 100% respectively (Figure 11). Meanwhile, differences of -0.1, 1.1 and 2.8 days were calculated for NLCA (Figure 11). In comparison, the use of a sigmoid relationship indicated that CA2 could have remained open an additional 0.6, 3.7, or 8.7 days and NLCA could have remained open an additional 0.4, 1.8, or 3.7 days (Figure 12).

Consequently, when mean $\hat{P}_{ju}$ was applied to the observed catches of either area, an increased scallop catch resulted regardless of the value of $Q$ or relationship used.

That being said, $Q$ greatly affected within-cruise and between-cruise variance. As $Q$ increased, so did any one cruise’s estimated differences in fishing time and scallop landings as well as the variation between cruises within any one value of $Q$ (Figure 11 and Figure 12).

Catch adjustments based on the last cruise were estimated to be less than those reported by NERO. The greatest reduction in estimated scallop catch (-229.2 metric tons) was estimated in the analysis of CA2 using a linear yellowtail catch rate and value of $Q$ equal to 100% of the fleet. This estimated difference in scallop catch would have
resulted in a 0.89% decrease in landed ex-vessel value, which was reported to be $385,971,000 in 2006 (NMFS 2007b).

Given the mean value of $\hat{P}_{ju}$ and a ex-vessel price of $14.42$ per kg ($6.54$ per pound), revenues were calculated for adjusted scallop landings made within both areas. In CA2, revenue was either increased by $833$ thousand to $11.6$ million if a linear relationship between yellowtail catch and fishing time was applied or by $1.1$ million to $14.9$ million if a sigmoid relationship was applied. Meanwhile, revenues for adjusted scallop landings within NLCA would have been increased by $216$ thousand to $7.1$ million using a linear relationship or by $796$ thousand to $8.5$ million using a sigmoid relationship.
DISCUSSION

This study examined whether a hanging-ratio modification on New Bedford style sea-scallop dredges would reduce yellowtail-flounder bycatch without significantly reducing sea-scallop catch. Although Färe et al. (2006) employed econometric methods to determine technical efficiency (a measure of outputs relative to the utilization of inputs) in a multiproduct fishery by penalizing good outputs, i.e., target catch, for bad outputs, i.e., bycatch, such an analysis was beyond the scope of this study. Instead, I examined the effect of hanging ratio on each species separately and conceptualized the extent of simultaneous changes required in yellowtail-flounder bycatch and sea-scallop catch to justify implementation of the tested modification. Analyses indicated that, compared to the standard ratio, the modified hanging ratio (60:34) significantly reduced the estimated catch of yellowtail flounder but maintained a similar estimated sea-scallop catch. Although the potential exists for such a modification to appear unfavorable during any given cruise, the modification is expected to be beneficial to the industry by affecting an average outcome whereby the reduction in yellowtail bycatch exceeds that of scallop catch.

Field experiments were conducted on a commercial vessel involved in making commercial landings. Vessels engaged in commercial fishing search for high densities of the target species and avoid areas with high quantities of bycatch. As a result, bias was introduced as few locations with high densities of yellowtail flounder were sampled.
Still, use of a fishery-dependent experimental design enabled a better assessment of how the gear modification would work in those areas normally exploited by scallopers. Moreover, the setting garnered collaboration between science and industry, which is vital if gear-modification research and the resulting recommendations are to be readily accepted by scallopers.

Percentage changes in the catch of one species were examined with respect to either catch-weight per tow ($\Phi_t$) or count within each size class ($E_t$). These metrics served as simplified measures of relative harvest efficiency (Rudders et al. 1998), where positive values implied that the 60:34 ratio was more efficient (or better able to catch and retain the species in question) than the 90:34 ratio and negative values implied that the 60:34 ratio was less efficient.

For each species, values of $\Phi_t$ were calculated to determine the frequency with which the 60:34 hanging ratio caught larger catch-weights per tow than the standard hanging ratio. Values of $\Phi_t$ that occurred with the highest frequencies indicated that the 60:34 ratio tended to be less efficient at catching yellowtails and equally efficient at catching sea scallops on a tow to tow basis. These tendencies are reflected in the differences in mean catch-weights of both species, which were examined with ANOVAs. After accounting for the variation caused by cruise and tow-within-cruise, analyses indicated that the lower hanging ratio (60:34) corresponded with a significant decrease in mean yellowtail catch-weight and an insignificant increase in mean catch-weight of sea-scallop meats.
Swimming endurance, ability and swimming speeds in fish are associated with fish length (He 1993; Winger et al. 1999; Winger et al. 2004). Of fishes large enough to have difficulty passing through the rings yet small enough to fit through twine-top meshes, longer fishes are thought more capable of maintaining position in the gear long enough to increase their probability of escape compared to shorter fishes. Accordingly, the configuration associated with smaller mean catch-weights per tow, i.e., the 60:34 ratio, was expected to have fewer large yellowtail flounders than the other dredge configuration. This was not the case. A Kolmogorov-Smirnov test revealed no significant difference in the size-frequency distributions of yellowtail flounder in dredges fitted with the two hanging ratios and no pattern was seen in the mean values of estimated percent changes in yellowtail count at each size class (E). These results imply that yellowtail escapement might not be related to size. However, inter-cruise variance in E was such that additional cruises are necessary to either confirm or deny the lack of relationship.

Despite the high frequency with which the 60:34 ratio caught similar scallop catch-weights per tow as the standard hanging ratio (when Φ, equaled zero), the 60:34 ratio corresponded with more large scallops and fewer small scallops than the 90:34 ratio. Although inter-cruise variance in E was considerable, the slight increase in mean scallop catch-weight associated with the 60:34 hanging ratio may have been a result of this apparent shift in the relative efficiency within each size class. Additional cruises are necessary, however, to increase the precision of the expected value of E.
To determine whether the tested modification was beneficial to the scallop industry, I compared $\hat{p}_{1u}$ (percent change in mean catch-weight of yellowtail bycatch) to $\hat{p}_{2u}$ (percent change in mean catch-weight of scallop meats). Because the mean value of $\hat{p}_{1u}$ was less than the mean value of $\hat{p}_{2u}$, less yellowtail bycatch occurred on average for a given amount of scallop catch; thus, a modification in hanging ratio from 90:34 to 60:34 was considered beneficial to the industry overall.

Ultimately, hanging ratios may affect yellowtail-flounder catch-weights because of the physical characteristics of twine tops in use. Using a higher hanging ratio involves a bigger twine top (with more meshes) within a given space, which results in less available room for the net to spread out. Consequently, meshes would produce smaller openings and theoretically counteract any benefit gained by additional meshes. Exceptions might result during tows where the twine top ballooned out and allowed each mesh to spread fully open. Then, additional meshes within a wider twine top might magnify the opposing effect of the ballooning action and increase the chance of opportunistic escapes. An underwater camera could be employed in future experiments to monitor the twine top's movement while the gear is in use.

Alternatively, yellowtail-flounder catch-weights may have been affected by the hanging-ratio modification because of behavioral responses exhibited by the fish. While little, if any, work has been done to examine responses of flatfish to sea-scallop dredges, there has been work on their escape response to trawls (Bublitz 1996; Winger et al. 2004; Ryer 2008). The limited number of such studies is likely due to the difficulty of seeing into mobile fishing gears as turbidity in the surrounding water is increased (Caddy 1973).
Flatfishes were noted to react to approaching trawls as they would any other predator, by swimming away and resettling to the sea-floor some distance later (Winger et al. 2004; Ryer 2008). After trawl entry, three responses were noted: 1) flatfishes sunk to the bottom of the net as if resettling, and then fell back into it (Ryer 2008), 2) flatfishes made sporadic attempts to swim either out of or farther into the net (Ryer 2008) or 3) flatfishes made a hasty 180° turn while flipping onto either their eyed or dorsal sides (Bublitz 1996). Although the first two actions offered no aid in escaping, the last action explained how a laterally compressed fish that usually swims with its dorsal-ventral axis parallel to the sea floor (Gibson 2005) might escape through a diamond-shaped hole. Other research indicates that flow within prawn-trawl codends decreases as water is displaced forwards by the catch (Broadhurst et al. 1999). According to Broadhurst et al. (1999), this reduction might improve a fish’s chance of escaping the trawl by aiding forward motion or by using less energy to maintain its position within the codend. Again, more work is necessary to examine both flatfish behavior and flow dynamics within sea-scallop dredges to definitely determine how these aspects affect finfish escapement.

In the current study, sea-scallop catch may not have been adversely affected by the hanging-ratio modification due to an alteration in water flow through the gear and the limited swimming ability of scallops. A modification that resulted in a reduction of bycatch, such as that seen by using a 60:34 ratio rather than a 90:34 ratio, would allow for greater water flow as fewer yellowtails blocked mesh openings. Because advection was shown to influence sea-scallop movement (Carsen et al. 1996), an increase in water flow would have improved scallop retention within the modified gear by pushing scallops into the bag. However, vessel speeds experienced during the study (four to five knots)
far exceeded known swimming speeds of *P. magellanicus*, which range from 0.37 knots (Carsen et al. 1996) to 1.4 knots (Chapman et al. 1979). Such speed differences likely overwhelmed any additional advection effect in dredges rigged with a lower hanging ratio.

The first cruise (cruise A) diverged in many respects from the other two cruises. Using additive and multiplicative dummy variables in multiple linear regressions between tow time and transformed catch-weights of each species, cruise A was shown to have significantly larger intercepts and significantly reduced increases in catch-weights per hour compared to the other two cruises. When values of $\hat{P}_{lu}$ were plotted against values of $\hat{P}_{2u}$, cruise A was shown to have a percent change in mean scallop catch-weights that was visibly greater than those of the other cruises and surrounded by a 95% confidence interval that did not overlap with other confidence intervals. During the first cruise, Hurricane Florence generated high wind speeds and high seas, which eventually caused the vessel to cease fishing for 35 hours. The effect of worsening sea conditions on the dredges and their contents is unknown. If the two dredges did not maintain equal contact with the sea floor or catch was washed out of the gear as the dredges were hauled up, then the catch in one or both dredges may have been underestimated. Although weather might have contributed to the differences observed in the first cruise, additional research is necessary to better understand the effects.

The last cruise also broke from patterns seen in the study. Using the 60:34 ratio during cruise C resulted in a reduced increase in scallop catch-weight per hour. Cruise C also resulted in an increased value of $\hat{P}_{lu}$ and decreased value of $\hat{P}_{2u}$ relative to the other
two cruises. These differences caused a unique situation where $\hat{P}_1$ exceeded $\hat{P}_2$ and the theoretical impact of the modification was no longer regarded as beneficial to the scallop industry. The last cruise took place in mid-August and coincided with the major annual spawning period (between August and October) of the Atlantic sea-scallop (Parsons et al. 1992; Hart and Chute 2004). Possibly, the reduced relative scallop-catch efficiency of the lower hanging ratio seen in cruise C might have been due to a seasonal effect associated with reproductive activities.

While studies conducted on modified hanging ratios on sea-scallop dredges are limited, studies have been conducted on gill nets (Acosta and Appeldoorn 1995; Samaranayaka et al. 1997) and trammel nets (Acosta and Appeldoorn 1995). Hanging ratio on these fishing gears is defined (Fridman 1986) as either the ratio (HR) between the floatline’s length and the stretched net’s length or the associated decimal number (E). For example, if the floatline measures 200 m in length and the stretched net measures 400 m in length, then HR equals 1:2 and E equals 0.5. A higher HR, such as 1:3, represents a shorter floatline and/or longer net, but a higher E, such as 0.6, represents a longer floatline and/or shorter net. In contrast, the hanging ratio used on sea-scallop dredges (D) is defined as the ratio between the number of meshes within the net’s width and the number of rings on which these meshes hang. In other words, D is analogous to the ratio of the length of the net to the length of the floatline, or 1/E.

In comparing these hanging-ratio studies, one must also compare the gears. Gill nets and trammel nets are stationary fishing gears that are held vertically in the water to entangle passing fish. Commercial fishermen commonly use mesh sizes of 12.5, 15 and 18 cm in these gears (Samaranayaka et al. 1997). In contrast, sea-scallop dredges are
mobile fishing gears; their purpose is to bag scallops off the sea floor as the dredge passes. Current regulations dictate that a minimum mesh size of 10 inches (25.4 cm) is used on sea-scallop dredges. Regardless of these gear differences, escapement requires that organisms pass fully from one side of the net to the other.

Because Acosta and Appeldoorn (1995) noted opposing interactions between hanging ratio and mesh size in trammel nets, a comparison of results of their study to the current study is flawed. While large catches were seen in gill nets with either high HR (1:3) and large mesh (12.7 cm) or low HR (1:1) and small mesh (7.6 cm), large catches were seen in trammel nets with either low HR (1:1) and large mesh (12.7 cm) or high HR (1:3) and small mesh (7.6 cm). Because the current study did not utilize multiple mesh sizes, this interaction was not examined in sea-scallop dredges.

Samaranayaka et al. (1997) examined fish catch within gill nets using a single mesh size and two hanging ratios. They found catch-weight per unit netting area to be 40% higher within nets with E = 0.5 than nets with E = 0.6, i.e., shorter floatlines and/or longer nets produced larger catch-weights. This was similar to the results of the current experiment, where wider twine tops (90:34 hanging ratio) caught larger mean yellowtail catch-weights than narrower twine tops (60:34 hanging ratio).

In the current study, a cursory examination was made of the potential economic impact indicated by the observed values of $\hat{p}_u$. Adjusted catch was likely biased because applied results were taken from a small range of years, in only two closed areas, and aboard a single vessel, yet they were applied to the entire fleet regardless of fishing grounds. This could not be avoided without additional sampling on a variety of ships and over a variety of conditions. Such an extensive sampling regime was logistically beyond
the scope of this study. Instead, the percent changes in mean catch-weights seen in this study, aboard a single vessel, were assumed to represent changes seen in all closed areas where yellowtail flounder is prevalent and all vessels throughout the fleet. Moreover, the estimated financial impact might have been exaggerated due to the compensation of days at sea in open areas. When access areas closed early, days-at-sea compensation displaced fishing effort rather than reduced it. However, financial loss to the industry still occurred because it took longer to fish for a given amount of scallops in open areas, where catches contained lower scallop meats per pound (NEFMC 2006).

This financial analysis indicated that, on average, the tested hanging-ratio modification would result in increased fishing time and increased scallop catch for the fleet in either access area regardless of both the portion of the fleet assumed to modify its gear \((Q)\) and the utilized relationship between cumulative catch and fleet fishing days. Results based on observations of the last cruise indicated that a reduction in sea-scallop catch is possible even when the number of fleet fishing days is increased. However, the largest potential gains overshadow any potential losses in magnitude.

Eventually, a gear modification that reduces yellowtail bycatch without loss of scallop catch could be implemented on a large scale. The current study, however, compared two hanging ratios out of numerous possible hanging-ratio combinations. Further experimentation is needed to determine which hanging ratio is best and if its effect is specific to certain conditions. Additional hanging ratios could be tested and additional cruises could be made using multiple vessels within multiple areas and multiple seasons. A balanced incomplete block design would allow the configuration of the two dredges to change randomly after each tow. If variation within each cruise is
assumed to be zero, such a design would allow for multiple comparisons within each cruise. Moreover, the financial-impact analysis could be improved by more detail in future studies. One might consider items such the cost of materials, fuel, labor, market flooding, or even the ecological impacts of dredging. Quantification of such costs would allow researchers to better determine when a gear modification resulted in a neutral impact to the industry.

As in any gear-modification experiments meant to increase escapement, this study assumed that animals either escaped through the twine top unharmed or, once free, could recover quickly enough that survivability was not affected. If this were not the case, improved escapement only served to increase the unseen mortality rate (Broadhurst et al. 2006). Research is needed on the survival of flatfishes that escape from sea-scallop dredges to better understand how interaction with these fishing gears may be affecting their populations.
APPENDIX I:
Using the Delta Method
to Find 95% Confidence Intervals for \( \hat{P}_{ju} \)

By utilizing a second-order Taylor series expansion, the delta method approximates the variance of some function, \( g \), using the following equation (see Seber 1982):

\[
V[g(\cdot)] = \sum_{i=1}^{n} V[x_i] \left( \frac{\partial g}{\partial x_i} \right)^2 + 2 \sum \sum_{i<j} \text{cov} [x_i, x_j] \left( \frac{\partial g}{\partial x_i} \right) \left( \frac{\partial g}{\partial x_j} \right)
\]  
(Eqn. 12)

where \( g(\mathbf{x}) \) indicates the function of some vector \( \mathbf{x} = [x_1, x_2, \ldots x_n] \). To determine the variance of the estimated percentage change in mean catch-weight, \( \hat{P}_{ju} \) (Equation 5), I substituted the function, \( \hat{P} \), into Equation 12 and designated \( Z_{60} \) as the random variable for mean catch-weight caught while using the lower hanging ratio and \( Z_{90} \) as the random variable for mean catch-weight caught while using the higher hanging ratio. Thus, Equation 12 was restated as:
\[ V(\hat{P}_{ju}) = V(Z_{60}) \left( \frac{\partial P}{\partial Z_{60}} \right)^2 + V(Z_{90}) \left( \frac{\partial P}{\partial Z_{90}} \right)^2 + 2 \text{cov}(Z_{60}, Z_{90}) \left( \frac{\partial P}{\partial Z_{60}} \right) \left( \frac{\partial P}{\partial Z_{90}} \right) \]  \hspace{1cm} \text{(Eqn. 13)}

Therefore, it was necessary to find two derivatives of \( P \):

\[ \frac{\partial P}{\partial Z_{60}} = 100(Z_{90})^{-1} \]  \hspace{1cm} \text{(Eqn. 14)}

\[ \frac{\partial P}{\partial Z_{90}} = (-100)(Z_{60})(Z_{90})^{-2} \]  \hspace{1cm} \text{(Eqn. 15)}

These derivatives were substituted into Equation 13. The resulting equation was simplified as follows:

\[ V(\hat{P}_{ju}) = V(Z_{60}) \left( 10,000(Z_{90})^{-2} \right) + V(Z_{90}) \left( 10,000(Z_{60})^2(Z_{90})^{-4} \right) - 2 \text{cov}(Z_{60}, Z_{90}) \left( 10,000(Z_{90})^{-3}(Z_{60}) \right) \]  \hspace{1cm} \text{(Eqn. 16)}

An estimate of the variance of \( \hat{P}_{ju} \) was obtained by inserting estimates for parameters in Equation 16. Thus,

\[ \hat{V}(\hat{P}_{ju}) = \hat{V}(Z_{60}) \left( 10,000(Z_{90})^{-2} \right) + \hat{V}(Z_{90}) \left( 10,000(Z_{60})^2(Z_{90})^{-4} \right) - 2 \hat{\text{cov}}(Z_{60}, Z_{90}) \left( 10,000(Z_{90})^{-3}(Z_{60}) \right) \]  \hspace{1cm} \text{(Eqn. 17)}
Finally, a 95% confidence interval (CI) surrounding \( \hat{P}_{ju} \) was approximated using the following equation:

\[
95\% \text{CI} \approx \hat{P}_{ju} \pm 2\sqrt{\hat{V}(\hat{P}_{ju})}.
\]  
(\text{Eqn. 18})
APPENDIX II:
Other Flatfish Species

Flatfishes besides yellowtail flounder were caught while examining the effect of modifying the twine-top hanging ratio from 90:34 to 60:34 (Table 5). A preliminary analysis was made to determine the effect of the hanging-ratio modification on the catch rate of each of the additional flatfish species.

The methodology was similar to that used in the yellowtail assessment. Although different parameters were used (Table 5), individual lengths were converted to weights using Equation 1. Then, Equation 2 was used to calculate approximate catch-weights of each species within each combination of hanging ratio and tow. Finally, to determine which tows would be included in the analysis, the following criterion were utilized:

- catch within each dredge included at least one flatfish of the specified species and one basket of sea scallops;
- data from each dredge included length frequencies from all flatfish of the specified species and shell-height frequencies from two baskets of sea scallops;
- both dredges were set and retrieved simultaneously; and
- no signs of tow disruption, such as a flip, hang, or rider, were observed.

Because other flatfishes were caught with less frequency than yellowtail flounder, this selection process resulted in the utilization of fewer tows than in the yellowtail analysis. The reduced sample sizes may have biased the results if the sampled tows did not represent the gear’s ability to catch each of the flatfish species. A larger number of
tows, particularly if taken in fishing grounds where these species were prevalent, would have served to reduce this bias.

Although none of the additional flatfish species showed a significant difference in mean catch-weights during any one cruise, mean catch-weights were usually decreased with the use of a 60:34 ratio rather than a 90:34 ratio (Figure 13). However, winterflounder results were different in that the mean catch-weight of this species increased with the use of the 60:34 configuration during both cruises where winter flounders were caught.

The percent changes in mean catch-weights of these additional flatfish species were also examined in relation to the percent changes in mean catch-weights of sea-scallop meats that were caught during the same tows (Figure 14). This comparison allowed me to determine how the hanging-ratio modification from 90:34 to 60:34 might affect the scallop industry if the species of interest were any of the other captured flatfish species. With the use of additional values of the *j*-subscript (Table 5), Equation 5 was used to calculate the percentage change in mean catch-weight of each species.

Superficial similarities were seen between the results of four-spot flounder and yellowtail flounder. Like yellowtail, the observed values of $\hat{P}_{ju}$ for cruises A and B were plotted within the beneficial zone but the observed value of cruise C was just outside this zone. In addition, the confidence intervals of cruise A overlapped with respect to four-spot flounder but did not overlap with respect to scallop meats. Unlike yellowtail, however, the vertical confidence intervals of all three cruises crossed the neutral line, which indicated that the true value of $\hat{P}_{2u}$ might be greater than $\hat{P}_{3u}$. If so, the hanging-
ratio modification would instead have a negative financial impact on the scallop industry. Therefore, more cruises are needed to determine the impact with respect to four-spot flounder.

Observations of gray sole, summer flounder and windowpane flounder were made during only one cruise. In all cases, the percent changes in flatfish catches were negative, meaning that the 60:34 ratio caught smaller mean catch-weights than the 90:34 ratio. Although the observed data points for gray sole and summer flounder were plotted either in the beneficial zone or on the neutral line, the observed data point for windowpane flounder was plotted just outside the beneficial zone. These data points indicate that the financial impact of the hanging-ratio modification to the scallop industry might be beneficial, neutral and detrimental, respectively. However, because each plot reflects the results of only a single cruise, observations are needed from additional cruises to ensure that the results are not due to chance or untested variables.

Finally, data with respect to winter-flounder are unique compared to the other flatfish species. First, the percentage change in mean winter-flounder catch-weights was positive during both cruises where the species was caught. These positive values indicated that the 60:34 ratio caught greater mean catch-weights than the 90:34 ratio. Additionally, both plotted data points were situated outside of the beneficial zone. Although the confidence intervals cross into the beneficial zone, the placement of the observed values indicates that a hanging-ratio modification from 90:34 to 60:34 could be detrimental to the scallop industry if managers are attempting to reduce winter-flounder bycatch.
The unique situation shown by the winter-flounder analysis might result from differences in size or behavior. Winter flounder are notably thicker than most flatfish species in the area (Klein-MacPhee 2002) and, at some body length, a winter flounder may have a reduced ability to fit through twine-top meshes compared to other flatfish species of similar length. Pulled taut by external factors such as hydrodynamic forces, line tension generated by the catch, and gravity (Fridman 1986), little flexibility would be available in the meshes to enable a fish with added girth to escape. Alternatively, winter flounder may differ in their behavioral response to the gear. Research comparing the swimming abilities and escape responses of flatfishes within sea-scallop dredges is necessary to better understand the varying effects of altering hanging ratio from 90:34 to 60:34 on the assortment of flatfish species observed in the course of this experiment.
APPENDIX III:
Modifying Twine-Top Length
to Reduce Flatfish Bycatch

A common practice among scallopers was to add a row of rings to lengthen a
dredge’s bag and shorten the twine top (Smolowitz and DuPaul 1999). This practice was
thought to increase the amount of scallops that the bag could hold. This modification was
said to be accompanied by an increase in fish bycatch, but researchers had yet to examine
this effect. In August of 2006, a supplemental study was performed in which twine-top
length was modified to test its effect on both flatfish bycatch and sea-scallop catch.

Scientists observed one cruise aboard the F/V Celtic while it underwent
commercial fishing in CA2. The sampling methodology utilized a paired design
comparable to that used in the hanging-ratio comparison. Two dredges were deployed
and towed simultaneously, one on each side of the vessel. Both dredges were configured
with 4-inch (10.16-cm) rings, a 10-inch (25.4-cm) mesh size, and a 60:34 hanging ratio.
While one dredge held a twine top that was 8½ meshes long, the other dredge held a
twine top that was 5½ meshes long. In reducing twine-top length, the twine-top’s
position relative to the sweep chain was altered. Although the center of the sweep chain
was more anterior (farther from the club stick) than one edge of the longer twine top, the
center of the sweep chain was more posterior (closer to the club stick) than the shorter
twine top. Regardless of this additional change, the shorter twine top provided fewer
meshes for escape; thus, I hypothesized that the shorter twine top would catch significantly more flatfishes without increasing scallop catch enough to compensate for the increased bycatch.

Catch was monitored in a manner equivalent to the hanging-ratio comparison. As before, all flatfishes were measured to the nearest cm and the contents of two randomly sampled baskets of sea scallops were collected from each dredge for shell-height frequencies (in five-millimeter increments). As in the hanging-ratio comparison, these data were converted to weights using Equation 1. To determine catch-weights (Equation 2) without weighing samples at sea, these converted weights were summed for every combination of species, gear configuration, and tow.

Only a preliminary analysis was conducted because the observation of a single cruise probably increased the influence of chance or sampling bias. First, paired t-tests were used to compare the mean catch-weights associated with each dredge configuration. Then, the relationship between percentage changes in mean catch-weights of scallop meats and flatfish bycatch was examined. These percentage changes were calculated with a formula similar to Equation 5 except that the mean catch-weight of the longer twine top replaced that of the 90:34 hanging ratio, and the mean catch-weight of the shorter twine top replaced that of the 60:34 hanging ratio. In other words, during this supplemental study, the percentage changes in mean catch-weights were calculated with respect to the longer hanging ratio.

Of 51 tows undertaken during this cruise, scientists observed and recorded catch data during 23 tows. Each flatfish species was analyzed individually. Tows that contained none of the flatfish species of interest in either dredge, lacked length-frequency
data used to estimate catch-weight, or showed signs of tow disruption, were considered unusable and discarded. Therefore, analyses of four-spot flounder, gray sole, and yellowtail were based on 17, 11, and 17 tows, respectively.

Compared to the longer twine top (8½ meshes), the use of a shorter twine top (5½ meshes) did not significantly change the mean catch-weight of either four-spot flounder (two-tailed p = 0.117) or gray sole (two-tailed p = 0.452). The shorter twine top did result in a significantly (one-tailed p = 0.005) larger mean catch-weight of yellowtail (Figure 15). Using those 17 tows where yellowtail flounders were caught and measured, analysis indicated that using the shorter twine top resulted in a significantly larger (one-tailed p = 0.048) mean catch-weight of sea-scallop meats (Figure 16).

By examining the relationship between the percentage changes in the mean catch-weights of scallop meats and a given flatfish species, we theorized the type of impact that the studied modification might have on the scallop industry (Figure 17). The observed percent change in yellowtail bycatch exceeded that of the scallop meats caught in the same tows. In contrast, the observed percent changes in both gray sole and four-spot flounder were less than those of scallop meats. These relationships implied that the modification of twine-top length from 8½ meshes to 5½ meshes might have a detrimental impact on the scallop industry if yellowtail bycatch was the primary concern, but a beneficial impact if attempting to reduce bycatch of either gray sole or four-spot flounder.

These conclusions must be viewed with caution. By crossing the neutral line, the vertical 95% confidence intervals of both gray sole and yellowtail indicate that the true values of percentage change in flatfish might be found along the neutral line or even in the opposite zone. Because between-cruise variation was significant in the hanging-ratio
comparison, uncertainty is increased by a lack of cruise replicates. Untested factors, including season or weather, might have influenced the results. Ultimately, additional cruises are necessary to strengthen any conclusions drawn from this supplemental study.
APPENDIX IV: Management of Atlantic Sea Scallops in the Context of Rebuilding Yellowtail-Flounder Stocks

When a species is caught as bycatch in one fishery and harvested as a target species in another fishery, its incidental removal can adversely affect the target fishery and cause economic loss. Indeed, management decisions made for either species can have severe ramifications for the other. Because yellowtail flounders are frequently caught in some areas as bycatch in sea-scallop dredges, the sea-scallop fishery was affected by management decisions made to protect yellowtail flounders.

The Atlantic sea scallop is a semi-mobile bivalve found along the continental shelf of the Northwest Atlantic Ocean between the Gulf of St. Lawrence and Cape Hatteras, North Carolina (Posgay 1957). Sea scallops are generally found on firm sand or gravel substrates (Hart and Chute 2004). Confined to water temperatures below 20°C (Naidu and Robert 2006), aggregations are found at depths less than 20 m in the northern regions and greater than 55 m in the southern regions of their distributions (Bourne 1964).

The yellowtail flounder is a small-mouthed right-eyed pleuronectid that lives in the Northwest Atlantic Ocean between Newfoundland and the Chesapeake Bay. Yellowtail flounders, also called yellowtails, prefer sandy bottoms and cold temperatures (8° to 14 °C) (Klein-MacPhee 2002). Although yellowtail flounders can be found in
water as shallow as 9 m, they are commonly caught between depths of 37 and 64 m (Lux 1964).

While a limited inshore sea-scallop fishery has existed since 1880, commercial exploitation of the species was trivial until the discovery and harvest of dense offshore beds in the late 19\textsuperscript{th} and early 20\textsuperscript{th} centuries (Peters 1978). According to Naidu and Robert (2006), the scallop fishery was characterized by high fishing effort and overcapacity until national jurisdictions were established and new management regimes were implemented. In 1977, the creation of the American and Canadian 200-mile exclusive economic zones prevented other countries from commercial harvest of sea scallops. Then, in 1984, the World Court established a jurisdictional boundary between the American and Canadian waters of Georges Bank. Afterwards, global production remained high as \textit{P. magellanicus} accounted for more than a quarter of the mean annual global production of all scallop species between 1990 and 1999 (Naidu and Robert 2006).

In the United States, management of sea scallops evolved through a series of amendments to the Sea-Scallop Fishery Management Plan (FMP), which was adopted by the New England Fishery Management Council (NEFMC) and the Assistant Administrator for Fisheries of the National Oceanic and Atmospheric Administration (NOAA) in 1982. In 1994, Amendment 4 (NEFMC 1993) categorized vessels based on time spent fishing to allocate annual allowable fishing time, called days at sea, and established a days-at-sea reduction schedule to reduce fishing mortality. In addition, Amendment 4 replaced meat-count restrictions with an incremental increase in ring size. Several studies (Bourne 1965; DuPaul and Kirkley 1995; Goff 2002) found that dredges rigged with larger rings caught more market-size scallops, fewer small scallops and less
trash (meaning both bycatch and non-biological materials) than dredges rigged with smaller rings. The use of larger rings also delayed recruitment to the fishery and increased both yield-per-recruit and spawning stock biomass (Brust et al. 1996).

Yellowtail flounder is harvested as a target species using primarily otter-trawls. The practice began in the mid-1930s and grew so rapidly that, at its peak, 31,000 metric tons of yellowtail flounder were caught in 1942 (Lux 1964). By the late 1960’s, catch levels were thought unsustainable (Stone et al. 2004). The International Commission for the Northwest Atlantic Fisheries made many failed attempts to decrease fishing effort (Murawski et al. 2000; Stone et al. 2004). In 1985, NEFMC and NOAA adopted the Northeast Multi-Species FMP, which managed approximately a dozen groundfish species, including yellowtail flounder. In 1994, NEFMC made one more desperate attempt to prevent collapse of the fisheries and closed three areas of Georges Bank (Figure 2) via emergency action. Subsequently, Framework Adjustment 9 to the Northeast Multi-species FMP was written. All commercial fishing gears capable of catching groundfishes, including sea-scallop dredges, were prohibited from fishing in those areas (NEFMC 1999). Combined with a reduction in fishing effort and a formal rebuilding plan, these regulations played key roles in the recovery of the yellowtail flounder of Georges Bank (Stone et al. 2004) even if the species was once again declared both overfished and subject to overfishing in 2005 (Hogarth).

These closed areas, which contained historically important scallop fishing grounds, considerably affected the scallop fishery. Covering 17,000 km² (Murawski et al. 2000), the closures prevented the harvest of an estimated 2,300 metric tons of scallop meats per year (NEFMC 1999) and displaced scallop fishing effort from Georges Bank to
Mid-Atlantic regions. Then, to comply with the Sustainable Fisheries Act of 1996 and protect aggregations of juvenile scallops, NEFMC (1998) passed Amendment 7 to the Sea-Scallop FMP, which scheduled days-at-sea allotment reductions for a 10-year rebuilding period, from 1998-2008.

The scallop industry lobbied NEFMC to gain access to the original closed areas based on survey results that reported a 15 to 20-fold increase in scallop biomass within the closed areas (NEFMC 1999). As a result, Framework Adjustment 11 (NEFMC 1999) allowed limited access to a portion of CA2, but established a TAC on yellowtail flounder to protect the approved yellowtail rebuilding schedule. Additional restrictions included a TAC on scallop meats, scallop possession limits per trip, and open access days-at-sea tradeoffs. To monitor compliance, regulations established a TAC set-aside program to fund observers on vessels making trips into the access area. With Amendment 10 to the Sea-Scallop FMP, NEFMC (2003) established a schedule that allowed periodic access to other closed areas on a rotating basis under similar restrictions.
TABLES
Table 1: Cruise Summary

<table>
<thead>
<tr>
<th>Cruise</th>
<th>Start Date</th>
<th>End Date</th>
<th>Fishing Grounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8 September 2006</td>
<td>13 September 2006</td>
<td>Closed Area I</td>
</tr>
<tr>
<td>B</td>
<td>28 July 2007</td>
<td>31 July 31 2007</td>
<td>Closed Area II</td>
</tr>
<tr>
<td>C</td>
<td>19 August 2007</td>
<td>24 August 2007</td>
<td>Closed Area II</td>
</tr>
</tbody>
</table>

Dates refer to those dates when fishing activity started and stopped.
Table 2: ANOVA Adjusted Means of Transformed and Retransformed Weight per Tow

<table>
<thead>
<tr>
<th></th>
<th>60:34</th>
<th>90:34</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellowtail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSMean</td>
<td>3.99</td>
<td>4.27</td>
<td></td>
</tr>
<tr>
<td>Retransformed Mean (kg)</td>
<td>7.37</td>
<td>7.90</td>
<td>-0.5</td>
</tr>
<tr>
<td>Scallop</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSMean</td>
<td>4.00</td>
<td>3.96</td>
<td></td>
</tr>
<tr>
<td>Retransformed Mean (kg)</td>
<td>54.43</td>
<td>52.37</td>
<td>2.1</td>
</tr>
</tbody>
</table>

LSMean indicates the adjusted means of the species. Retransformed means (bold) were back-calculated with either the square-root of the exponential of the yellowtail LSMeans or the exponential of the scallop LSMeans. Fifty-five tows were included.
### Table 3:
Yellowtail Parameter Estimates of Model Three

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\beta_i$</th>
<th>SE($\beta_i$)</th>
<th>t-value</th>
<th>p-value</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept ($\beta_0$)</td>
<td>2.45</td>
<td>1.35</td>
<td>-1.81</td>
<td>0.074</td>
<td></td>
</tr>
<tr>
<td>Gear60 ($\beta_1$)</td>
<td>1.17</td>
<td>1.86</td>
<td>0.63</td>
<td>0.530</td>
<td>222.9</td>
</tr>
<tr>
<td>CruiseA ($\beta_2$)</td>
<td>5.91</td>
<td>1.68</td>
<td>3.51</td>
<td>0.001</td>
<td>36,720.4</td>
</tr>
<tr>
<td>CruiseB ($\beta_3$)</td>
<td>2.55</td>
<td>1.66</td>
<td>1.54</td>
<td>0.127</td>
<td>1,184.3</td>
</tr>
<tr>
<td>Gear60_x_CruiseA ($\beta_4$)</td>
<td>1.76</td>
<td>2.27</td>
<td>-0.77</td>
<td>0.441</td>
<td>-82.7</td>
</tr>
<tr>
<td>Gear60_x_CruiseB ($\beta_5$)</td>
<td>2.48</td>
<td>2.35</td>
<td>-1.06</td>
<td>0.294</td>
<td>-91.6</td>
</tr>
<tr>
<td>Towtime ($\beta_6$)</td>
<td>1.98</td>
<td>0.99</td>
<td>2.01</td>
<td>0.048</td>
<td>197.9</td>
</tr>
<tr>
<td>Gear60_x_Time ($\beta_7$)</td>
<td>-0.7</td>
<td>1.35</td>
<td>-0.52</td>
<td>0.603</td>
<td>-70.3</td>
</tr>
<tr>
<td>CruiseA_x_Time ($\beta_8$)</td>
<td>2.35</td>
<td>1.25</td>
<td>-1.88</td>
<td>0.064</td>
<td>-235.4</td>
</tr>
<tr>
<td>CruiseB_x_Time ($\beta_9$)</td>
<td>-0.8</td>
<td>1.32</td>
<td>-0.61</td>
<td>0.546</td>
<td>-79.8</td>
</tr>
<tr>
<td>Gear60_A_x_Time ($\beta_{10}$)</td>
<td>1.12</td>
<td>1.7</td>
<td>0.66</td>
<td>0.511</td>
<td>112.1</td>
</tr>
<tr>
<td>Gear60_B_x_Time ($\beta_{11}$)</td>
<td>1.58</td>
<td>1.89</td>
<td>0.84</td>
<td>0.403</td>
<td>158.4</td>
</tr>
<tr>
<td>AR1</td>
<td>0.46</td>
<td>0.09</td>
<td>-4.88</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

Each variable is listed with an estimate of its partial coefficient ($\beta_i$), standard error of the estimate (SE($\beta_i$)), t-value, and p-value. Significance (p<0.05) is indicated by two asterisks (**); marginal significance (p<0.10) is indicated by a single asterisk (*). Each variable has one degree of freedom. AR1 identifies the correction of a first-order autocorrelation. Where applicable, the table includes the percentage change in either the expected yellowtail catch-weight (for discrete variables) or the expected change in catch-weight per hour (for continuous variables with a time component) with respect to the overall reference group (data collected during cruise C from dredges with the standard 90:34 hanging ratio).
Table 4:  
Scallop Parameter Estimates of Model Three

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\beta_i$</th>
<th>SE($\beta_i$)</th>
<th>t-value</th>
<th>p-value</th>
<th>y-int</th>
<th>slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>** Intercept ((\beta_0))</td>
<td>-5525.2</td>
<td>1972.1</td>
<td>-2.80</td>
<td>0.006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gear60 ((\beta_1))</td>
<td>3903.7</td>
<td>2689.4</td>
<td>1.45</td>
<td>0.150</td>
<td>-1621.5</td>
<td></td>
</tr>
<tr>
<td>** CruiseA ((\beta_2))</td>
<td>6948.6</td>
<td>2526.4</td>
<td>2.75</td>
<td>0.007</td>
<td>1423.4</td>
<td></td>
</tr>
<tr>
<td>CruiseB ((\beta_3))</td>
<td>1005.0</td>
<td>2434.3</td>
<td>0.41</td>
<td>0.681</td>
<td>-4520.2</td>
<td></td>
</tr>
<tr>
<td>Gear60_x_CruiseA ((\beta_4))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gear60_x_CruiseB ((\beta_5))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>** Towtime ((\beta_6))</td>
<td>7099.8</td>
<td>1480.2</td>
<td>4.80</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Gear60_x_Time ((\beta_7))</td>
<td>-3416.2</td>
<td>2003.0</td>
<td>-1.71</td>
<td>0.091</td>
<td>3683.6</td>
<td></td>
</tr>
<tr>
<td>** CruiseA_x_Time ((\beta_8))</td>
<td>-6584.7</td>
<td>1926.5</td>
<td>-3.42</td>
<td>0.001</td>
<td>515.1</td>
<td></td>
</tr>
<tr>
<td>CruiseB_x_Time ((\beta_9))</td>
<td>1119.1</td>
<td>1972.8</td>
<td>0.57</td>
<td>0.572</td>
<td>8219.0</td>
<td></td>
</tr>
<tr>
<td>Gear60_A_x_Towtime ((\beta_{10}))</td>
<td>3097.7</td>
<td>2554.3</td>
<td>1.21</td>
<td>0.228</td>
<td>196.6</td>
<td></td>
</tr>
<tr>
<td>Gear60_B_x_Towtime ((\beta_{11}))</td>
<td>3944.5</td>
<td>2776.8</td>
<td>1.42</td>
<td>0.159</td>
<td>8747.2</td>
<td></td>
</tr>
<tr>
<td>** AR1</td>
<td>-0.3</td>
<td>0.1</td>
<td>-3.43</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>** AR2</td>
<td>0.3</td>
<td>0.1</td>
<td>2.65</td>
<td>0.009</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Each variable has an estimate of its partial coefficient ($\beta_i$), standard error of the estimate (SE($\beta_i$)), t-value, and p-value. Significance (p<0.05) is indicated by two asterisks (**) ; marginal significance (p<0.10) is indicated by a single asterisk (*). Each variable has one degree of freedom. Corrections for first-order and second-order autocorrelations are indicated by variables called AR1 and AR2, respectively. The right-most columns specify y-intercept values (y-int) and slopes associated with a particular group. The expected intercepts were calculated from the sum of $\beta_0$, $\beta_1$, $\beta_2$, $\beta_3$, $\beta_4$, and $\beta_5$; the expected slope was calculated from the sum of $\beta_6$, $\beta_7$, $\beta_8$, $\beta_9$, $\beta_{10}$ and $\beta_{11}$. 

65
Table 5:  
Other Flatfish Species

<table>
<thead>
<tr>
<th>j-subscript</th>
<th>Common Name</th>
<th>Scientific Name</th>
<th>$a_j$</th>
<th>$b_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Four-spot flounder</td>
<td><em>Paralichthys oblongus</em></td>
<td>-12.3202</td>
<td>3.1463</td>
</tr>
<tr>
<td></td>
<td>Gray sole</td>
<td><em>Glyptocephalus</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Summer flounder</td>
<td><em>Paralichthys dentatus</em></td>
<td>-12.2841</td>
<td>3.2156</td>
</tr>
<tr>
<td>6</td>
<td>Windowpane</td>
<td><em>Scophthalmus aquosus</em></td>
<td>-11.0093</td>
<td>2.8721</td>
</tr>
<tr>
<td></td>
<td>Winter flounder</td>
<td><em>Pseudopleuronectes</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>(blackback)</td>
<td><em>americanus</em></td>
<td>-11.6356</td>
<td>3.1091</td>
</tr>
</tbody>
</table>

Flatfish species, other than yellowtail flounder (*Limanda ferruginea*), were caught and analyzed during the comparison between a 90:34 hanging ratio and a 60:34 hanging-ratio. The assigned j-subscripts distinguish between species. Values of 1 and 2 are not used here for this subscript because they identify yellowtail flounder and sea scallops, respectively. The parameters, $a_j$ and $b_j$ (Wigley et al., 2003), were used in the conversion of individual lengths to weights (Equation 1).
FIGURES
Figure 1:
New Bedford Style Scallop Dredge

The dorsal surface of the dredge is raised for illustration (Diagram of a scallop dredge).
Gray areas indicate land; white areas indicate water. While a thin line represents the 50-fathom isobath, bold lines demarcate sea-scallop closed areas. Closed areas are labeled: Nantucket Lightship Closed Area (NLCA), Closed Area I (CA1) and Closed Area II (CA2).
Percent changes are calculated for each cruise based on a modification in hanging ratio from 90:34 to 60:34. Positive values indicate that dredges with the 60:34 hanging ratio caught larger mean catch-weights than dredges with 90:34. Negative values indicate that dredges with the 60:34 hanging ratio caught smaller mean catch-weights than dredges with 90:34. When the percent changes of both species are plotted within the shaded area, the modification is thought to benefit the scallop industry. When these data are plotted within the white area, the modification is thought to be detrimental to the scallop industry. Data points on the $45^\circ$ line depict neutral results. Theoretically, the dashed line indicates a neutral line that is more realistic. Regions are numbered and, in some cases, lettered to aid explanation.
Figure 4:
Percent TAC Achieved in CA2 and NLCA During the 2006 Fishing Season

CA2 data are indicated with black circles. NLCA data are indicated with empty diamonds. Dashed lines indicate yellowtail bycatch rate. Solid lines indicate scallop catch rate (NOAA 2007a, 2007b; K. Wilhelm, NOAA, personal communication).
Figure 5:
Mean Catch-Weight per Cruise
Using 60:34 and 90:34 Hanging Ratios

Catch-weights of A) yellowtail flounder (left) and B) scallop meats (right) are depicted. Cruises A, B and C had sample sizes of 17, 20 and 18 tows, respectively. Black bars represent dredges with a 60:34 hanging-ratio; grey bars represent dredges with a 90:34 hanging-ratio.
Figure 6 (next page): Histograms of Percent Change in Catch-Weight per Tow, $\Phi_n$, of (A) Yellowtail and (B) Scallop Meats. Data were collected from 55 tows during three cruises. Negative values indicate the 60:34 hanging ratio was less efficient than the 90:34 hanging ratio at catching the species. Positive values indicate the 60:34 hanging ratio was more efficient than the 90:34 hanging ratio at catching the species.
Figure 6:
Histograms of Percent Change in Catch-Weight per Tow, $\varphi_t$

A. Yellowtail

B. Scallop Meats
Figure 7 (next page): Mean Percent Change in Summed Count at Each Size Class of (A) Yellowtail and (B) Scallops. A total of fifty-five tows were examined. Bars indicate the mean value of the percentage change in the summed count at each size class over all three cruises. Vertical lines denote one standard deviation above the mean. Each measurement on the horizontal axes represents the start of a size class. While negative values on the vertical axis indicate that the 60:34 hanging ratio was less efficient at catching a given size relative to the 90:34 hanging ratio, positive values indicate that the 60:34 hanging ratio was more efficient than the 90:34 hanging ratio.
Figure 7:
Mean Percent Changes in Summed Count at Each Size Class

A. Yellowtail

B. Scallop
For each species, ANOVA examined transformed catch-weights using hanging ratio as the main treatment and two random blocking factors (cruise and tow-within-cruise). LSMeans$_{60:34}$ refers to the adjusted mean of transformed catch-weights from dredges rigged with a 60:34 hanging ratio. LSMeans$_{90:34}$ refers to the adjusted mean of transformed catch-weights from dredges rigged with a 90:34 hanging ratio. The error bars indicate the 95% confidence interval in the difference of adjusted means.
Figure 9:
Sea-Scallop Residuals of Model Three by Cruise

Dots denote mean residual values. Center lines denote median residual values. Boxes signify the 25th and 75th percentile values. Whiskers represent extreme observations. The number of analyzed tows for cruises A, B and C were 17, 20, and 18, respectively.
Figure 10:
Observed Percent Changes in Mean Catch-Weights:
Scallop Meats vs. Yellowtail Flounder

Hanging ratio was modified from 90:34 to 60:34. Observed values of $\hat{p}_{ju}$ (Equation 5) are plotted with dots and labeled with their respective cruises. Error bars represent 95% confidence intervals (calculated by the delta method) in either $\hat{p}_{ju}$ (vertical) or $\hat{p}_{2u}$ (horizontal). A star designates the mean value of $\hat{p}_{ju}$.
The number of fishing days represents the estimated time until the adjusted amount of yellowtail equaled the final cumulative amount of yellowtail reported by NERO. Scallop landings represent the estimated amount of cumulative scallop catch at the adjusted time of closure. Analyses relied upon a linear relationship between cumulative yellowtail catch and time (Equation 7).
Figure 11:
Estimated Fishing Time vs. Scallop Landings
Based on Linear Relationship

A. CA2

B. NLCA
Figure 12 (next page): Estimated Fishing Time vs. Scallop Landings Based on a Sigmoid Relationship for (A) CA2 and (B) NLCA.
Stars depict unadjusted catch quantities reported by NERO. Circles denote catch adjustments made with cruise observations. Letters indicate the cruises on which adjustments were based; common cruises are connected by a solid line. Triangles, which are connected by a dashed line, illustrate the use of mean values of \( \hat{P}_{ju} \) to make catch adjustments. Data points are also labeled with the values of \( Q \) used to adjust catch.

The number of fishing days represents the estimated time until the adjusted amount of yellowtail equaled the final cumulative amount of yellowtail reported by NERO. Scallop landings represent the estimated amount of cumulative scallop catch at the adjusted time of closure. Analyses relied upon a sigmoid relationship between cumulative yellowtail catch and time (Equation 8).
Figure 12:
Estimated Fishing Time vs. Scallop Landings
Based on a Sigmoid Relationship

A. CA2

B. NLCA
Figure 13:
Mean Catch-Weights of Flatfishes and Paired T-Tests by Species, Cruise and Hanging Ratio

Black indicates the 60:34 hanging ratio; gray indicates 90:34 hanging ratio. The table includes information on species, cruise, total number of fish per cruise using the 60:34 and 90:34 hanging ratios, respectively, and the number of tows within each cruise. The last two rows include results of one-tailed paired t-tests, which tested alternate hypotheses that the 60:34 hanging ratio caught smaller catch-weights than the 90:34 hanging ratio.
Four-spot flounders were caught while comparing two modified hanging ratios: 90:34 and 60:34. Dots indicate values of $\hat{p}_{ju}$ (Equation 5). These observations are labeled with their respective cruises and include 95% confidence intervals (calculated by the delta method) in either $\hat{P}_{ju}$ (vertical) or $\hat{P}_{2u}$ (horizontal). A star designates mean values of $\hat{P}_{ju}$. 
Gray soles were caught while comparing two modified hanging ratios: 90:34 and 60:34. A dot indicates the observed values of $\hat{P}$, (Equation 5). The data point is labeled with its respective cruise and includes 95% confidence intervals (calculated by the delta method) in either $\hat{P}_v$ (vertical) or $\hat{P}_h$ (horizontal).
Summer flounders were caught while comparing two modified hanging ratios: 90:34 and 60:34. A dot indicates the observed values of \( \hat{P}_{ju} \) (Equation 5). The data point is labeled with its respective cruise and includes 95% confidence intervals (calculated by the delta method) in either \( \hat{P}_{ju} \) (vertical) or \( \hat{P}_{ju} \) (horizontal).
Windowpane flounders were caught while comparing two modified hanging ratios: 90:34 and 60:34. A dot indicates the observed values of $\hat{p}_u$ (Equation 5). The data point is labeled with its respective cruise and includes 95% confidence intervals (calculated by the delta method) in either $\hat{p}_u$ (vertical) or $\hat{p}_w$ (horizontal).
Winter flounders were caught while comparing two modified hanging ratios: 90:34 and 60:34. Dots indicate the observed values of $\hat{P}_{ju}$ (Equation 5). The observations are labeled with their respective cruises and include 95% confidence intervals (calculated by the delta method) in either $\hat{P}_{6u}$ (vertical) or $\hat{P}_{2u}$ (horizontal). A star designates mean $\hat{P}_{ju}$. 
Figure 15:  
Mean Catch-Weights of Flatfishes and Paired T-Tests by Species and Twine-Top Length

<table>
<thead>
<tr>
<th>Species</th>
<th>Four spot</th>
<th>Gray sole</th>
<th>Yellowtail</th>
</tr>
</thead>
<tbody>
<tr>
<td># Fish</td>
<td>301; 245</td>
<td>30; 29</td>
<td>1327; 1583</td>
</tr>
<tr>
<td># Tows</td>
<td>17</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td>T-value</td>
<td>-1.655</td>
<td>-0.782</td>
<td>2.887</td>
</tr>
<tr>
<td>p-value</td>
<td>0.941</td>
<td>0.774</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Black bars indicate twine tops 8½ meshes long; gray bars indicate twine tops 5½ meshes long. The table includes information on species, cruise, total number of fish per cruise using 8½ meshes and 5½ meshes, respectively, and the number of tows. The last two rows include results of one-tailed paired t-tests, which tested alternate hypotheses that using the shorter twine top resulted in larger mean catch-weights of the specified flatfish species.
Figure 16:  
Mean Catch-Weights of Scallop Meats  
Using Two Twine-Top Lengths

Black indicates the longer twine-top (8½ meshes); gray indicates the shorter twine-top (5½ meshes). Each error bar represents one standard deviation. Calculations involve only the 17 tows where both yellowtail flounder and sea scallops were caught and measured.
Figure 17 (next page): Observed Percent Changes in Mean Catch-Weights When Twine-Top Length is Modified. Flatfishes were caught while comparing two twine-top lengths (8½ meshes and 5½ meshes). White symbols depict the observed percent changes in mean catch-weights with respect to the longer twine top. Each point is labeled with its respective flatfish species and includes 95% confidence intervals (calculated by the delta method) in either the percentage change in the mean flatfish catch-weight (vertical) or percent change in the mean catch-weight of scallop meats (horizontal). Data points within the shaded region indicate that a length modification from 8½ meshes to 5½ meshes would be beneficial to the sea-scallop industry if the decision was based on the specified flatfish species. Data points within the unshaded region indicate that a length modification from 8½ meshes to 5½ meshes would be detrimental to the sea-scallop industry. A position on the dashed line indicates a neutral impact.
Figure 17: Observed Percent Changes in Mean Catch-Weights When Twine-Top Length is Modified


---. 2003. Final amendment 10 to the Atlantic Sea Scallop Fishery Management Plan with a supplemental environmental impact statement, regulatory impact review, and regulatory flexibility analysis. NEFMC, Newburyport, MA.


---. 2006. Framework Adjustment 18 to the Atlantic Sea Scallop FMP including a environmental assessment, regulatory impact review, and regulatory flexibility analysis and Stock Assessment and Fishery Evaluation (SAFE) report. NEFMC, Newburyport, MA.


---. 2007b. Fisheries of the United States - 2006. NMFS, Silver Spring, MD.


VITA

Kelli A. Milleville