

**ESTIMATING SEA SCALLOP INCIDENTAL MORTALITY
FROM PHOTOGRAMMETRIC BEFORE-AFTER-CONTROL-IMPACT
SURVEYS**

by

Danielle Marie Ferraro

A thesis submitted to the Faculty of the University of Delaware in partial
fulfillment of the requirements for the degree of Master of Science in Marine Studies

Fall 2016

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ACKNOWLEDGMENTS

First and foremost, I would like to thank my advisor, Dr. Art Trembanis, for his guidance and support over the past several years. His intelligence, leadership, and enthusiasm pushed me to be a better scientist and I am so thankful that he believed in me through all parts of the process. I would also like to thank the rest of my committee for their contributions to this project and my graduate student experience. I would like to thank Dr. Doug Miller for his assistance with data analysis, the constructive discussions that paved the way for this project, and for always keeping my sanity in check. I would like to thank Dr. Dave Rudders for sharing his scallop-y wisdom, and for all of the thorough critique he provided during the data analysis and writing process. I would like to thank Dr. Matt Oliver for all of the thoughtful discussion and feedback that helped me improve this study. Additionally, I am indebted to several other individuals who contributed greatly to this work. My eternal thanks to Hunter Brown for always being patient and willing to teach, and whose data engineering prowess enabled this project to happen. I also thank Val Schmidt, whose MATLAB mastery rivals magic, and for all of his hard work with data manipulation. I must also thank Captains Art and Ken Ochse and the able-bodied crew of the F/V Christian and Alexa for hosting and enabling the data collection that led to this document, and for being flexible when we demanded vehicle deployments in the middle of the night. I am vastly grateful for the work done by the image annotation team, as the completion of the project truly hinged on their efforts.

I would also like to thank my many labmates, past and present, for all of the support, feedback, and friendship over the past few years. I am thankful for the immense support from the Lewes community of students, staff, and faculty that made my time here so meaningful. Lastly, I would like to thank my parents, Brooke, and Tom for all of the love and support that pushed me to reach my goals.

TABLE OF CONTENTS

LIST OF TABLES	vii
LIST OF FIGURES	ix
ABSTRACT	xiv
Chapter	
1 INTRODUCTION	1
2 METHODS	8
2.1 Study Areas	8
2.2 Autonomous Underwater Vehicle	10
2.3 Surface Vessel and Commercial Dredge	12
2.4 Multiple-Before-After-Control-Impact (MBACI) Experimental Design	14
2.5 Image Processing	18
2.6 Image Annotation	23
2.7 Incidental Mortality Calculation	29
2.8 Side-scan Sonar Processing	32
3 RESULTS	34
3.1 The AUV Platform	34
3.2 Incidental Mortality	37
3.3 Substrate Analysis and Dredge Scars	43
4 DISCUSSION	56
4.1 Incidental Mortality	56
4.2 Physical Impact of Dredge	59
4.3 The AUV Platform	59
4.4 Image Processing and Annotation	60
4.5 Conclusion	63
REFERENCES	65

Appendix

A	INCIDENTAL MORTALITY – FULL AUV MISSION	70
B	INCIDENTAL MORTALITY – BUFFERED DREDGE SCARS	74
C	SCALLOP SAMPLE SIZES	78
D	SIDE-SCAN SONAR MOSAICS	80

LIST OF TABLES

Table 1. Intrinsic parameters of the AUV camera at the time of the study generated by the camera calibration toolbox. All values in pixels.	21
Table 2. Number of images annotated and percent of total (%) by individual annotator.	28
Table 3. Change in compromised scallops (%) within the dredge path following treatment in the ETCA. Errors are standard deviation.	42
Table 4. Change in compromised scallops (%) within the dredge path following treatment in the NLCA. Errors are standard deviation.	43
Table 5. Comparison of maximum and mean incidental mortality values within the dredge path found in this study (indicated with *) to those in the literature and used currently by the fishery.	57
Table 6. Change in compromised scallops (%) over the full AUV mission following treatment in the ETCA. Errors are standard deviation.	72
Table 7. Change in compromised scallops (%) over the full AUV mission following treatment in the NLCA. Errors are standard deviation.	73
Table 8. Change in compromised scallops (%) within the dredge path with a 3 m buffer following treatment in the ETCA. Errors are standard deviation.	76
Table 9. Change in compromised scallops (%) within the dredge path with a 3 m buffer following treatment in the NLCA. Errors are standard deviation.	77
Table 10. Incidental mortality values (%) within the dredge path in the ETCA along with the number of total, healthy, and compromised scallops annotated. One-tow, five-tow, and zero-tow (control) dredge treatments are denoted A, B, and C, respectively. At Site 3, B and C are switched. A 1 indicates a pre-treatment survey and a 2 indicates a post-treatment survey.	78

Table 11. Incidental mortality values (%) within the dredge path in the NLCA along with the number of total, healthy, and compromised scallops annotated. One-tow, five-tow, and zero-tow (control) dredge treatments are denoted A, B, and C, respectively. A 1 indicates a before-treatment survey and a 2 indicates an after-treatment survey..... 79

LIST OF FIGURES

Figure 1. Map of rotational closed areas at the time of the study highlighting the three sites within the ETCA and NLCA, respectively.	10
Figure 2. The Gavia AUV assembled for acoustic and optical habitat mapping. The lever arm distance between the INS and the camera was 0.86 m.....	12
Figure 3. The New Bedford style scallop dredge used in this study aboard the F/V Christian and Alexa.	13
Figure 4. The spatial layout of the three nested treatments within each site at both the ETCA and NLCA. In the ETCA, the position and nomenclature of the five-tow treatment (B) and zero tow treatment (C) at Site 3 were switched.....	16
Figure 5. Standard AUV mission plan consisting of ten parallel lines of 750 m in length at 2 m intervals. In the NLCA, line length was decreased to 550 m and the number of lines was increased to 14. Dashed red lines indicate the intended dredge path through the center of the mission.	17
Figure 6. Example filmstrip of sequential seabed images collected during an AUV mission.....	17
Figure 7. Histogram of elapsed time between the recovery of the dredge and deployment of the AUV (h). Mean (dashed line) was 8.02 ± 4.37 h. NLCA Site 1 A2 was excluded from the plot and mean because it had an interval time of 65.7 hours.....	18
Figure 8. Example images before and after enhancement with Fred's ImageMagick retinex script or the Stretch Contrast function in GIMP.	22
Figure 9. Complete distortion model of the Gavia AUV camera at the time of this study. Contour lines are in pixels.	23
Figure 10. Sample screenshot of SIAS with the pop up window of detailed annotation fields that appears following a mouse click on a scallop.	24
Figure 11. Examples of healthy, undamaged scallops (A-C) and damaged scallops from the dataset. Compromised annotations included scallops that were punctured (D), crushed (E), broken (F-H), or inverted (I).....	27

Figure 12. Sample section of ETCA Site 1 C1 (before control) AUV mission showing total imaged area overlaid with imaged area from every fourth photo.	29
Figure 13. Sample map from a post one-tow dredge treatment AUV mission from (NLCA Site 1 A2) depicting centroids of annotated photos in the full AUV mission, the bounds of a dredge scar, and the 3 m buffer drawn around the scar bounds. Here 14 parallel lines are depicted, but at the ETCA only 10 parallel lines made up the AUV mission. Results in the main text refer to the data within the dredge scar only. Incidental mortality results from the full AUV mission are reported in Appendix A, and results from within the scar plus a 3 m buffer are reported in Appendix B.....	31
Figure 14. Histogram of altitude frequency and means with standard deviation for photos taken during two replicate AUV missions, NLCA Site 2 B1 (before five tows) and B2 (after five tows).	35
Figure 15. Photo centroids of two replicate missions, NLCA Site 2 C1 (before zero tows) and C2 (after zero tows) depicting sub-meter precision. Extent rectangle depicting the area mapped in this figure is on the left, overlaid onto the full trackline for NLCA Site 2 C1.	36
Figure 16. Percent compromised scallops within the dredge path before and after the three dredge treatments in the ETCA and NLCA.	41
Figure 17. Mean change in compromised scallops within the dredge path following one, five, or zero tows on a hard substrate (NLCA) and sandy substrate (ETCA). Error bars are standard deviation (n=3).	42
Figure 18. Representative side-scan sonar image from Sonar Facies 1 (A), depicting a generally smooth sandy seafloor with interspersed pockmark-like features. Optical calibration of Sonar Facies 1 includes a flat seafloor with seabed depressions created by sea scallops (B-C) and shell hash that is not resolved in the side-scan sonar (D).....	45
Figure 19. Representative side-scan sonar image from Sonar Facies 2 (A), illustrating the generally smooth texture. Optical calibration of Sonar Facies 2, showing a sandy, featureless seabed (B-D).....	46
Figure 20. Representative side-scan image from Sonar Facies 3 (A), depicting a flat, textured seafloor. Optical calibration of Sonar Facies 3, showing gravel and coarser debris (B, D) as well as an example of a large rock often found within gravelly areas in the NLCA (C).....	47

Figure 21. Representative side-scan sonar image of Sonar Facies 4a (A) showing large bedform features. Optical calibration of Sonar Facies 4a depicting the current-driven bedforms (B-D).....	48
Figure 22. Representative side-scan sonar image of Sonar Facies 4b (A), illustrating large bedform features with superposed current ripples. Optical calibration of Sonar Facies 4b reveals peaks and troughs characteristic of the ripples at this facies (B-D).	49
Figure 23. Representative side-scan sonar image of Sonar Facies 5 (A, box), showing shorter wavelength (10-30 cm) ripples that were difficult to resolve in side-scan sonar mosaics. Optical calibration of Sonar Facies 5 better distinguished the small ripple features (B-D).	50
Figure 24. Substrate composition in the dredge path in the ETCA and NLCA summed over all sites.	52
Figure 25. Example side-scan sonar mosaics with and without guides before and immediately after one dredge tow (A-D), and before and immediately after five dredge tows (E-H) at Sites 2 and 1 in the NLCA, respectively. One-tow treatments were distinguishable by a single dredge scar (D), while five-tow treatments were distinguishable by a group of overlapping dredge scars (H).....	54
Figure 26. Example side-scan sonar mosaics with and without guides immediately after (A, C) and eight weeks following (B, D) five dredge tows at ETCA Site 3. Dredge scars were still visible after eight weeks, particularly after five-tow treatments.	55
Figure 27. Percent compromised scallops before over the full AUV mission and after the three dredge treatments in the ETCA and NLCA.	71
Figure 28. Mean change in compromised scallops over the full AUV mission following one, five, or zero tows on a hard substrate (NLCA) and sandy substrate (ETCA). Error bars are standard deviation (n=3).	72
Figure 29. Percent compromised scallops within the dredge path with a 3 m buffer before and after the three dredge treatments in the ETCA and NLCA. ..	75
Figure 30. Mean change in compromised scallops within the dredge path with a 3 m buffer following one, five, or zero tows on a hard substrate (NLCA) and sandy substrate (ETCA). Error bars are standard deviation (n=3). ..	76

Figure 31. Side-scan sonar mosaics of ETCA one-tow treatment: Site 1 A1 (A) and A2 (B).....	81
Figure 32. Side-scan sonar mosaics of ETCA five-tow treatment: Site 1 B1 (A) and B2 (B).....	82
Figure 33. Side-scan sonar mosaics of ETCA zero-tow treatment (control): Site 1 C1 (A) and C2 (B).....	83
Figure 34. Side-scan sonar mosaics of ETCA zero-tow treatment (control): Site 2 C1 (A) and C2 (B).....	84
Figure 35. Side-scan sonar mosaics of ETCA one-tow treatment: Site 3 A1 (A) and A2 (B).....	85
Figure 36. Side-scan sonar mosaics of ETCA five-tow treatment: Site 3 B1 (A) and B2 (B).....	86
Figure 37. Side-scan sonar mosaics of ETCA one-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 3 A2 (A) and A3 (B).....	87
Figure 38. Side-scan sonar mosaics of ETCA five-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 3 B2 (A) and B3 (B).....	88
Figure 39. Side-scan sonar mosaics of ETCA zero-tow treatment (control) after eight weeks with initial post-dredge mosaic for comparison: Site 3 C2 (A) and C3 (B).....	89
Figure 40. Side-scan sonar mosaics of ETCA one-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 2 A2 (A) and A3 (B).....	90
Figure 41. Side-scan sonar mosaics of ETCA five-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 2 B2 (A) and B3 (B).....	91
Figure 42. Side-scan sonar mosaics of ETCA zero-tow treatment (control) after eight weeks with initial post-dredge mosaic for comparison: Site 2 C2 (A) and C3 (B).....	92

Figure 43. Side-scan sonar mosaics of ETCA one-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 1 A2 (A) and A3 (B).....	93
Figure 44. Side-scan sonar mosaics of ETCA five-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 1 B2 (A) and 13 (B).....	94
Figure 45. Side-scan sonar mosaics of ETCA zero-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 1 C2 (A) and C3 (B).....	95
Figure 46. Side-scan sonar mosaics of NLCA one-tow treatment: Site 1 A1 (A) and A2 (B).....	96
Figure 47. Side-scan sonar mosaics of NLCA five-tow treatment: Site 1 B1 (A) and B2 (B).....	97
Figure 48. Side-scan sonar mosaics of NLCA zero-tow treatment (control): Site 1 C1 (A) and C2 (B).....	98
Figure 49. Side-scan sonar mosaics of NLCA one-tow treatment: Site 2 A1 (A) and A2 (B).....	99
Figure 50. Side-scan sonar mosaics of NLCA five-tow treatment: Site 2 B1 (A) and B2 (B).....	100
Figure 51. Side-scan sonar mosaics of NLCA zero-tow treatment (control): Site 2 C1 (A) and C2 (B).....	101
Figure 52. Side-scan sonar mosaics of NLCA one-tow treatment: Site 3 A1 (A) and A2 (B).....	102
Figure 53. Side-scan sonar mosaics of NLCA five-tow treatment: Site 1 B1 (A) and B2 (B).....	103

ABSTRACT

After several decades of stock decline, the Atlantic sea scallop (*Placopecten magellanicus*) fishery is one of the most valuable in the United States due in part to the implementation of new management measures in 1994. The continued sustainability of the fishery is dependent on catch limits determined by yearly stock projection models. Incidental mortality is an important term in sea scallop stock projection models, but is historically difficult to measure. Current estimates are derived from experiments that relied heavily on qualitative observations and as a result lack precision. To better estimate incidental mortality, I used a Multiple-Before-After-Control-Impact (MBACI) experimental design to measure the effect of scallop dredging on the disposition of sea scallops that remain on the seafloor following dredging. An autonomous underwater vehicle (AUV) was employed to collect color photos and side-scan sonar images of the seafloor before and after controlled dredge treatments in the Mid-Atlantic and Georges Banks regions. Approximately 170,000 photos were annotated for instances of dredge-induced mortality. I found 2.5% and 8% incidental mortality for the Mid-Atlantic Bight and Georges Banks sites, respectively, a difference that is likely attributable to the relatively harder substrate of the scallop habitat on Georges Banks resulting in greater physical trauma. This study provides a quantitative estimate of incidental mortality using a precise and noninvasive platform. The spatial scale and distribution of the study sites are broader relative to past studies and represent the two principal stocks of the sea scallop resource. These results are lower than the incidental mortality values currently used in

fishery stock models and suggest the existing values are conservative, but appropriate estimates.

Chapter 1

INTRODUCTION

The Atlantic sea scallop (*Placopecten magellanicus*) along the coastal northwestern Atlantic Ocean is one of the most valuable single species fisheries in the United States, worth about half a billion dollars annually over the last decade (NMFS, 2006-2014). The fishery is considered a management success after the scallop fishery management plan (FMP) was overhauled following near crashes in the 1970s and 1990s. The new FMP enacted many measures still in place today, including gear adjustments (e.g. 4 in rings and sea turtle chain mat) and a moratorium on fishing vessel permits, as well as rotational area management (Hart and Rago, 2006). Due in large part to these changes, overfishing has not occurred in the sea scallop fishery since 2003 (NEFSC, 2004) and recent stock projections are optimistic (NEFSC, 2014). Routine monitoring and annual stock assessments are carried out so predictive models can be used to forecast the future of the stock and current fishing effort limits can be established. To accurately project the sea scallop stock, models must accommodate a suite of spatially dependent factors such as natural mortality, fishing mortality, and incidental fishing mortality.

Incidental mortality is the death of scallops that encounter the dredge but are not landed, primarily resulting from shell damage due to interaction with the gear. The term is defined as:

$$F_I = \frac{F_L c (1-e)}{e} \quad (1)$$

where F_L is landed fishing mortality, c is the fraction of scallops that suffer mortality in the path of the dredge but are not caught, and e is the efficiency of the dredge. The Atlantic sea scallop fishery currently estimates c to be 10% in the Mid-Atlantic (soft substrate) and 20% on Georges Bank in the waters off New England (hard substrate) (NEFSC, 2014). It is an important term of stock models for many commercially important fish species, but is historically difficult to measure and understudied (Broadhurst *et al.*, 2006; Myers *et al.*, 2000). Estimates for sea scallops in the literature are conservative and are not consistent in technique or result. Caddy (1973) estimated c to be 15-20% on a gravelly substrate in the Gulf of St. Lawrence, Canada by observing tracks from single dredge tows from a submersible. A similar submersible-based study suggested dredge-induced damage and mortality in uncaught scallops was <5% on sandy substrate in the Mid-Atlantic (Murawski and Serchuk, 1989). Hart and Rago (2006) concluded incidental mortality in sea scallops was relatively low after finding no differences between closed and open areas in the increases of survival rates of pre-recruit scallops. Evidence from other scallop species suggests dredge-induced mortality is significantly higher than natural mortality (McLoughlin, 1991; Naidu, 1988).

More than one pathway of events can result in incidental mortality. Specifically, these pathways include the death of post-release discards as well as scallops that are not retained by the dredge. A scallop that is retained and harvested by the dredge may be discarded and die prior to or after its return to the seafloor. The decision to discard can result from visible shell damage that has compromised meat quality, or because the individual is undersized and must be thrown back during the sorting process (Stokesbury *et al.*, 2011). Mortality of discards can be largely

attributed to the exposure to warmer water and air temperatures during collection that surpass the lethal limit for scallops (20-24 deg C) (Bremec *et al.*, 2004; Dickie and Medcof, 1963; Dickie, 1958). Alternatively, scallops not retained by the dredge may pass through the ring or inter-ring spaces, or be passed over by the dredge and die as a result of related injuries (Caddy, 1989). The fraction of non-landed and non-discarded scallops is the focus of this study. Non-landed scallops can be directly compromised by the physical impact of the dredge by being crushed or buried in the sediments (Naidu, 1988; Caddy, 1973). Additionally, scallops may be fatally damaged by indirect consequences of a dredge pass. Dumping of processed waste may increase scavenger populations (Britton and Morton, 1994) and localized fishing efforts can attract or increase susceptibility to predators (Jenkins and Brand, 2001; Caddy, 1973) and disease (McLoughlin *et al.*, 1991).

The goals of this study were to advance the understanding of sea scallop incidental mortality using a robust, quantitative method, and present a precise estimate of the parameter to fishery managers. The primary research objectives were:

1. To quantify incidental mortality of the sea scallops that remain on the seafloor immediately after dredging at two different sea scallop fishing access areas.
2. To investigate variability in incidental mortality across soft and hard bottom substrates.
3. To investigate variability in incidental mortality across a range of dredge intensities (0 - control, 1, or 5 dredge tows).
4. To characterize and quantify the physical impact and spatial extent of the dredge tows.

To accomplish these objectives, I used an autonomous underwater vehicle (AUV) to image the seafloor photographically and acoustically before and after dredge

treatments. To my knowledge, this is the first study to quantify incidental mortality of sea scallops using systematic photogrammetric surveys, in addition to being the first to utilize an AUV. Therefore, this research also serves as a proof of concept for this and similar platforms for use in further mortality analyses.

AUVs are tools well-suited for habitat mapping and benthic surveys (Seiler *et al.*, 2012; Armstrong *et al.*, 2006; Grasmuek *et al.*, 2006). Equipped with digital and acoustic imagery payloads, untethered and unmanned vehicles can enable research at depths too deep or hazardous for boat-mounted instruments or divers. Propelled vehicles are effective at surveying long distances (i.e. kilometers to tens of kilometers) on the time scale of hours, allowing for relatively efficient collection of data for high-resolution maps. An internal inertial navigation system (INS) aided with a Doppler velocity log (DVL), such as the one on the AUV used in this study, can produce sub-meter positioning accuracies, enabling high precision and repeatability in replicate surveys. Bottom tracking enables AUVs to maintain a constant altitude off the seafloor, which is desired in most benthic mapping studies (Clark, 2016). Additionally, autonomous systems do not appear to startle fauna as much as towed or dropped systems do (Fernandes *et al.*, 2003; Fernandes *et al.* 2000), which is important when attempting to observe environments as they would be when undisturbed. Recent examples include the use of integrated downward-facing cameras to measure the distribution and abundances of benthic species (e.g. Forrest *et al.*, 2012) and create biogeographic catalogs of benthic communities (e.g. Bewley *et al.*, 2015). As a useful supplement to digital imagery, high-resolution acoustic imagery illuminates the texture of the seafloor, revealing sonar facies that indicate bottom features and relative sediment types (e.g. Raineault *et al.*, 2012; Rankey and Doolittle,

2012). The use of autonomous systems for fisheries stock assessments is in early development, but recent studies highlight the use of AUV-derived imagery in the sea scallop fishery to quantify scallop abundance and distribution (Walker *et al.*, 2016; Singh *et al.*, 2014), shell height distributions (Singh *et al.*, 2013), and visualize dredge scars (Walker *et al.*, 2016).

In order to assess the ecological impact of scallop dredging, I used a Before-After-Control-Impact (BACI) experimental design. As described by Stewart-Oaten *et al.* (1986), detection of the treatment effect is achieved by testing whether the difference in the desired parameter at a control site and an impacted site changes once the impact begins. To do so, replicate samples are collected before and after an impact at both an impacted and control site. The specific BACI design used here is termed Multiple-Before-After-Impact-Control (MBACI) because there were multiple replications in space (Downes *et al.*, 2002). A major assumption of BACI experiments is that the disturbance affects the environment enough to differentiate it from its prior state and concurrent changes occurring at control sites (Underwood, 1993). The BACI model incorporates the variability between replicate sampling locations over time in the error term of the analysis, together with the change after the impact. The impact is statistically significant when the variance due to the interaction between location and condition (impacted vs. non-impacted) is large compared to the variability at a location over time, plus residual error (Bernstein *et al.*, 2004). In order to successfully detect an effect, if present, it is advantageous to have control sites as similar to impact sites as possible, including water depth, substrate type, and benthic assemblages (Collie *et al.*, 1997; Smith *et al.*, 1993). BACI sampling designs have been used to assess the impact of prawn trawling on seabed biota (Pitcher *et al.*, 2009) and in other

environmental impact assessments including the effect of point source pollution (Roberts *et al.*, 1998), localized removal of marine invertebrates (e.g. Martin *et al.*, 2012), and spillover from marine protected areas (Francini-Filho and Moura, 2008).

This study offers a quantitative estimate of sea scallop incidental mortality in important scallop fishing access areas in the coastal Northwest Atlantic Ocean. Many studies have documented the types of damage imparted on uncaptured scallops, but most existing incidental mortality estimates are based on qualitative observations and are difficult to reproduce. These observations were visual inspections or images captured from within submersibles traveling along dredge scars, limited to what can be physically seen by the vehicle's occupants (Murawski and Serchuk, 1989; Caddy, 1973). This study expands previous incidental mortality survey scales from ~1 km long transects to tracklines of several kilometers over an area of tens of thousands of square meters, resulting in an increase of several orders of magnitude of ground coverage and scallop counts from which to derive impact statistics. The value of seafloor images is also improved relative to past studies due to precise georeferencing and subsequent spatial relation to the dredge path where it was not previously possible. Additionally, it is well known that the impact of fishing gear on benthic organisms is highly dependent on substrate (Link *et al.*, 2005; Collie *et al.*, 1977; deGroot, 1984). I conducted field experiments in the Elephant Trunk Closed Area (ETCA) and Nantucket Lightship Closed Area (NLCA), allowing me to examine the impact of dredging on two major bottom types experienced in the sea scallop fishery both in terms of direct physical impact on the seafloor and on resultant incidental mortality. Because the study was carried out on the Mid-Atlantic and Georges Banks fishing grounds with nested sites spaced kilometers to tens of kilometers apart, my

results are representative of the spatial scale of the fishery and have direct application in fisheries management. The current management system has resulted in noticeable positive effects on scallop abundance, but in order to continue effectively implementing the management strategies, precise and up-to-date monitoring of all sources of fishing mortality is needed. The uncertainty associated with current estimates of incidental mortality has wide implications for projections of stock and determination of annual catch limits. My findings corroborate and provide a more robust statistical basis for the values used by the fishery and indicate that they should continue to be included in current stock models.

Chapter 2

METHODS

2.1 Study Areas

This study took place in two distinct locations along the east coast of the United States: the Elephant Trunk Closed Area (ETCA) and Nantucket Lightship Closed Area (NLCA) (Fig. 1). The ETCA and NLCA are two federally defined scallop fishing access areas within the area rotational management system implemented by the National Marine Fisheries Service (NMFS). These areas are rotationally opened and closed to scallop fishing vessels in response to annual stock surveys. The ETCA and NLCA encompass sand and mixed sand, gravel, and rock, respectively, and represent contrasting bottom types typically encountered by the fishery. The range of substrates within these two closed areas enabled us to test the effect of substrate on incidental mortality. Additionally, I chose closed areas in order to isolate the dredge treatments in this study from concurrent fishing efforts in open areas. Each area was sampled at three distinct sites within the bounds of the closed region. Sites were chosen based on prior knowledge of relatively high abundance from previous NOAA and VIMS scallop surveys (Rudders, personal communication) and feasibility of dredging.

The Elephant Trunk is a region of sandy substrate in the Mid-Atlantic Bight 65 km east of Fenwick Island, Delaware. In June of 2003, there was a high abundance of small scallops in the Mid-Atlantic (Stokesbury *et al.*, 2004). The ETCA was established in July 2004 to protect this sea scallop recruitment event (USA Federal

Regulations 2004). The NMFS last closed the Elephant Trunk in 2012 to protect a new population of juvenile scallops after a low abundance of recruits in 2011. The sites within the ETCA were within a depth range of 50-60 m.

The Nantucket Lightship Closed Area is located 19 km from the southeastern extent of the Nantucket Shoals, a series of shallow, broken shoals approximately 60 km off of Nantucket Island, Massachusetts. The substrate in NLCA is dominated by gravel and coarse sand with interspersed boulder piles and deposits. NLCA is located within the greater Georges Bank region, which contains a counterclockwise summer gyre (Bigelow, 1927). The gyre hydrographically retains planktonic scallop larvae, favoring reproduction and survival and forming dense scallop beds on Georges Bank that support the largest single scallop resource in the world (Caddy, 1989; Larsen and Lee, 1978). Scallops there may be slightly more crowded than those in the Mid-Atlantic Bight, which may also aggregate spawning adults and increase reproductive potential (Carey and Stokesbury, 2011). The sites within the NLCA were within a depth range of 60-70 m.

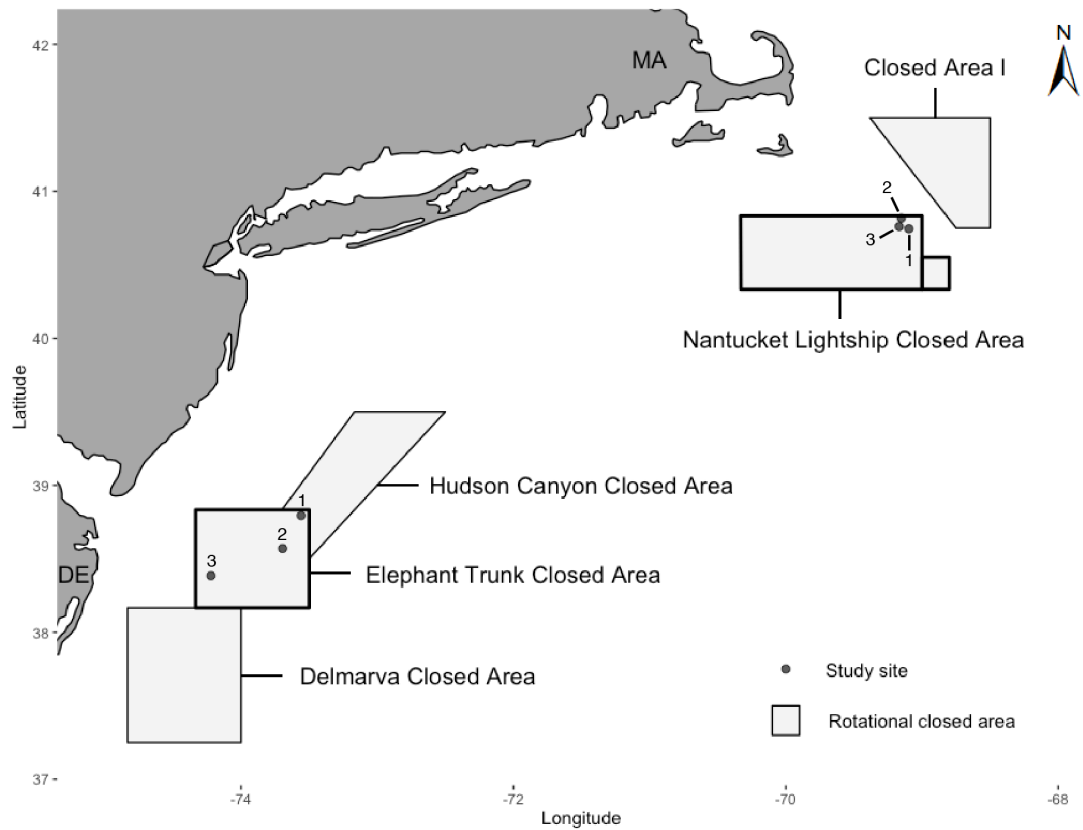


Figure 1. Map of rotational closed areas at the time of the study highlighting the three sites within the ETCA and NLCA, respectively.

2.2 Autonomous Underwater Vehicle

The autonomous underwater vehicle (AUV) used in this study was manufactured by Teledyne-Gavia. The modular design of this vehicle allows it to be configured for specific research goals. For all missions in this study, the configuration was as follows: nose cone, battery, inertial navigation system and Doppler velocity log (INS/DVL), control module, and propulsion (Fig. 2). The nose cone contains a forward-looking obstacle avoidance sonar, as well as the downward-facing, digital, color camera used to collect still imagery of the seafloor. The camera is a Point Grey

Grasshopper 14S5C/M-C model that takes georeferenced photos with a Sony ICZ285AL CCD at a resolution of 1280 x 960 pixels (1.2 mega pixels). The camera is also paired with a flash strobe on the control module for illumination. All photos were collected in portable pixmap (ppm) format, a non-compressed RGB image file type. The photos were stored with embedded vehicle metadata including capture time, location, altitude, depth, pitch, roll, and individual image properties such as brightness, white balance, and exposure. The INS/DVL module is responsible for the sub-meter precision in the navigation of the AUV. When the DVL has bottom lock, it measures altimetry as well as velocity in relation to the seafloor. This allows the AUV to maintain a pre-determined constant altitude throughout its mission. Post-processing of the AUV missions showed the vehicle remained within 7-8 cm of its commanded altitude of 2.5 m during the surveys in this study, which is similar to the variation reported by studies using the same vehicle (Walker *et al.* 2016; Raineault *et al.*, 2012; Forrest *et al.* 2012). When the AUV is not near enough to the seafloor, the DVL measures the velocity of the water current below the vehicle. A constant depth can also be commanded, as depth is continuously calculated through the internal pressure sensor located in the control module. The control module also houses a GPS that records position while the AUV is at the surface. The INS gets inputs from the DVL, pressure sensor, and GPS, and total position drift rate is 0.5 m/h (Patterson *et al.*, 2008), or 0.1% of distance traveled (Rankey and Doolittle, 2012). The AUV also has user-selectable frequency (900 kHz/1800 kHz) side-scan sonar located on the control module. Side-scan sonar is used to acoustically image the texture and relative hardness of the seabed. In this study, it was used specifically to observe the physical impact of the dredge on the seafloor by illuminating dredge scars. Only the starboard transducer

was operational during this study, but the 2 m line spacing and 10 m range setting resulted in extensive overlap with no sonar gaps.

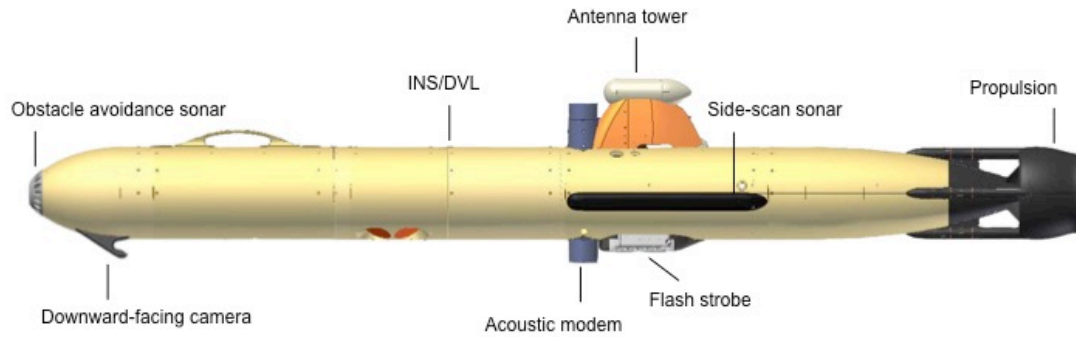


Figure 2. The Gavia AUV assembled for acoustic and optical habitat mapping. The lever arm distance between the INS and the camera was 0.86 m.

2.3 Surface Vessel and Commercial Dredge

Dredging is the primary way sea scallops are commercially harvested, with nearly 350 registered full time dredge vessels active (NEFSC, 2014). The 30 m F/V Christian and Alexa was the platform for all dredge treatments in this study. Dredge tows were carried out with the vessel's starboard New Bedford style commercial scallop dredge, which is the standard type for the fishery. The dredge is composed of a rigid, triangular frame with a 3.5 m wide cutting bar and ring bag of 4 inch (~10 cm) linked rings, engineered to allow undersized juvenile scallops pass through the ring bag and avoid capture (Fig 3). During a deployment, the dredge is towed along the

seafloor by the vessel, collecting in the ring bag scallops and other benthic fauna in the path of the dredge. Tows were conducted at the standard commercial fishing speed of 2.0-2.5 m/s and the point locations of dredge deployment and recovery were recorded. After each individual tow, the catch was emptied on deck and sorted into bushels. One bushel of scallops was measured into 5 mm length bins as a representative sample of the total catch. Skates and finfish were counted, measured, and logged separately. After processing, all of the catch was discarded at a distance of no less than one kilometer from the tow location to ensure we did not return captured scallops to the AUV mission area.



Figure 3. The New Bedford style scallop dredge used in this study aboard the F/V Christian and Alexa.

2.4 Multiple-Before-After-Control-Impact (MBACI) Experimental Design

This study was conducted using a Multiple-Before-After-Control-Impact (MBACI) experimental design, enabling the characterization of the scallop beds before and after dredge impacts. According to the MBACI design, I compared selected areas of seabed before and after a treatment (dredging) as well as comparing the change at control areas (no dredging) to impacted areas. Within each closed area, three sites were chosen that were distanced from each other by approximately 6 km in the ETCA and 30-50 km in the NLCA. Three treatments with a distance of 500 m between each were designated within each site corresponding to the three dredge treatments: one, five, or zero tows (Fig 4.). The one and five-tow treatments represented light and heavy dredging and were denoted A and B, respectively, and the zero tow treatment was the control, denoted as C. At a five-tow treatment, the five tows were intended to be made over the same trackline to simulate an open fishing area where many fishing vessels dredge simultaneously and have intersecting tracks (Walker *et al.*, 2016). Replicate treatments ($n = 3$) enabled us to measure not only significant differences between locations, but significant effects of the treatments (Hurlbert, 1984).

At each treatment I ran an AUV mission (A1, B1, or C1), conducted a dredge treatment, and re-ran the same AUV mission following the treatment (A2, B2, or C2). AUV missions were of standard boustrophedon, or “lawnmower,” design, composed of 10 parallel lines of 750 m in length spaced apart by two meters (Fig. 5). I used the AUV’s terrain-following behavior to command a constant altitude of 2.5 m and

collected photos at 3.75 frames per second (fps). Every other photo was removed, resulting in an effective frame rate of 1.875 fps. With an image footprint of approximately 2.72 m^2 , this ensured overlap between sequential photos as well as between lines to result in near 100% photographic coverage of the $13,500 \text{ m}^2$ area per mission. Sequential images overlapped by approximately 45%, depending on how bottom currents affected the AUV propulsion setting of 600 rpm (Fig. 6). During the second field season in the NLCA, lines were shortened to 550 m and increased in number to 14 to provide the ship's captains a wider swath in which to center their dredge tow. During all AUV missions, the downward-facing camera collected photos at 3.75 fps and the 1800 kHz high-frequency side-scan sonar acoustically imaged the seabed.

Following the initial AUV survey, one, five, or zero 15-minute dredge tows were made through the center of the mapped region. Dredging began approximately a quarter mile before reaching the treatment in order to maintain constant speed (2.0-2.5 m/s) through the treatment area. The dredge catch was sorted on deck and discarded. Immediately following the dredge treatment, the same AUV mission was repeated. The follow-up survey was executed as soon as possible after dredging, on average 8 hrs post-treatment (Fig. 7). The mean of elapsed time excludes NLCA Site 1 A2 which had an atypically large interval of 65.7 hours because the mission had to be re-run at the end of the cruise due to navigation error. I returned to the sites in the ETCA eight weeks after the initial cruise and re-ran the AUV missions again with the intent to observe community recovery over time, if any. I did not have an equivalent cruise in the NLCA, so I report only the results of acoustic seabed imaging and dredge scar persistence from these later missions.

A linear mixed effects model was applied to investigate the effects of the two dredge treatments on any difference in incidental mortality between the replicate sites.

The model was defined in R statistical software as:

$$lmer(percentComp \sim Treatment + Period + Treatment * Period + (1|Site)) \quad (2)$$

where *percentComp* represented the outcome variable, percent compromised scallops. Explanatory variables were *Treatment*, representing the effect of the one or five-tow dredge treatments, *Period*, representing the effect of the interval between the before and after surveys, *Treatment * Period*, representing the interaction term, and *(1|Site)* representing the random site effect. All statistical analyses were carried out in R statistical software.

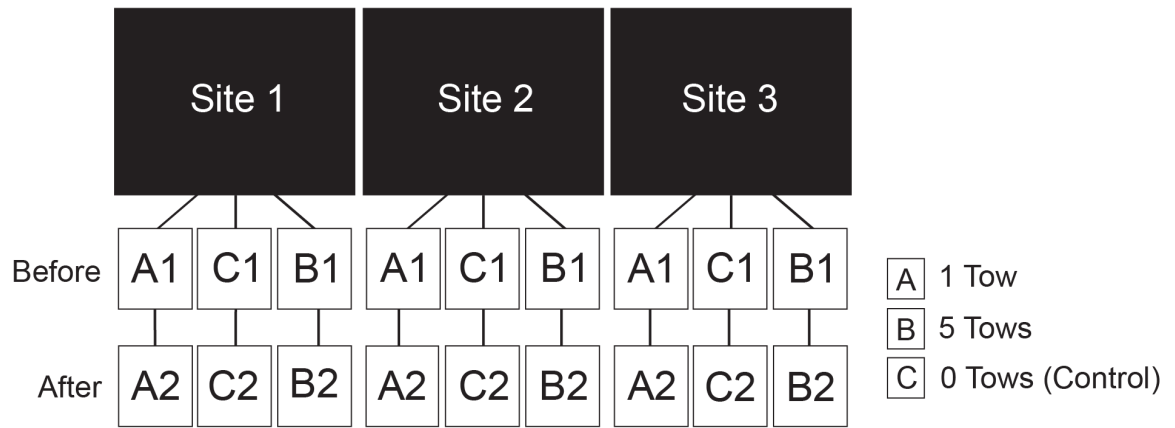


Figure 4. The spatial layout of the three nested treatments within each site at both the ETCA and NLCA. In the ETCA, the position and nomenclature of the five-tow treatment (B) and zero tow treatment (C) at Site 3 were switched.

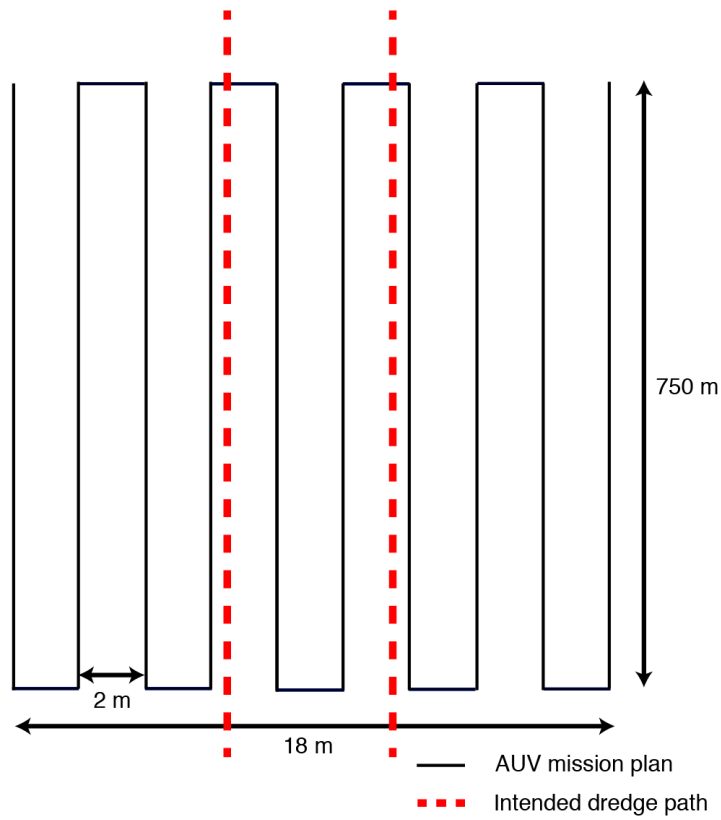


Figure 5. Standard AUV mission plan consisting of ten parallel lines of 750 m in length at 2 m intervals. In the NLCA, line length was decreased to 550 m and the number of lines was increased to 14. Dashed red lines indicate the intended dredge path through the center of the mission.

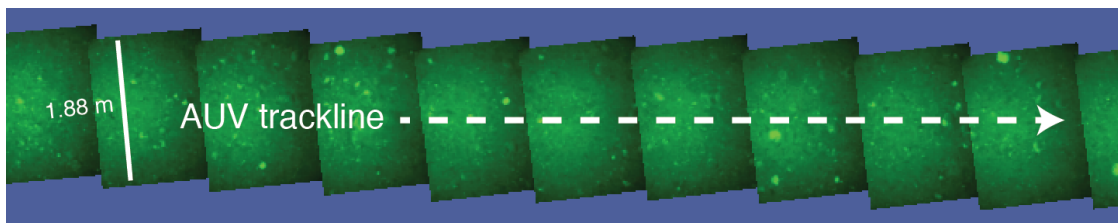


Figure 6. Example filmstrip of sequential seabed images collected during an AUV mission.

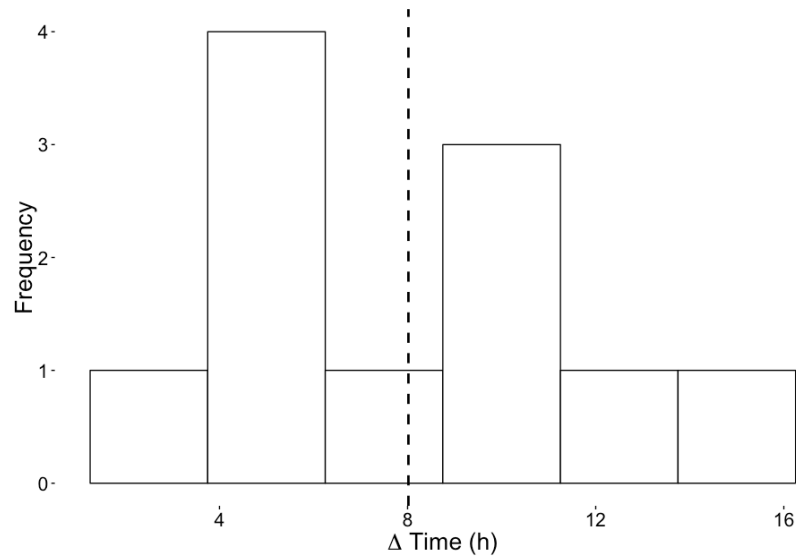


Figure 7. Histogram of elapsed time between the recovery of the dredge and deployment of the AUV (h). Mean (dashed line) was 8.02 ± 4.37 h. NLCA Site 1 A2 was excluded from the plot and mean because it had an interval time of 65.7 hours.

2.5 Image Processing

Following the collection of imagery, images were post-processed and enhanced so that the each photo taken at depth was clear enough for a human to visually resolve its contents. Because the AUV collected raw images during both day and night, brightness, white balance, contrast, and overall image quality varied throughout the photos. Each photo had one of two batch enhancement schemes applied (Fig. 8). The first was the retinex algorithm from Fred's ImageMagick Scripts (<http://www.fmwconcepts.com/imagemagick/retinex/>), which applied a color model and brightness gain that best clarified the seabed over the variety of conditions

observed. If that scheme produced sub-optimal results, the Stretch Contrast function in GIMP was applied to the raw photo. This stretched the RGB histogram values in each individual photo to the respective full contrast range. Following enhancement, the photos were converted to jpg format so that they were compatible with the online annotation system.

The footprint of an image at a given altitude can be calculated by first determining the horizontal field of view in air:

$$HFOV_{air} = 2 \tan^{-1} \left(\frac{W_{CCD}}{2f} \right) \quad (3)$$

where W_{CCD} is the width of the camera's charge coupled device (CCD), and f is the focal length (mm). The product is then used to calculate the horizontal field of view in water:

$$HFOV_{water} = 2 \sin^{-1} \left[\frac{\sin\left(\frac{HFOV_{air}}{2}\right)}{n} \right] \quad (4)$$

where n is the refractive index of water, ranging from 1.33-1.37. At 2.5 m altitude, the camera has a horizontal field of view of 41.19°. For this calculation, an n value of 1.37 was used to account for maximum possible refraction.

Next, image width over an assumed flat surface is defined as:

$$Image\ Width = 2 \cdot H \cdot \tan \left(\frac{HFOV_{water}}{2} \right) \quad (5)$$

where H is the distance of the AUV from the seafloor (m). Finally, the width to height dimension ratio of 4:3 allows the image height to be defined as:

$$Image\ Height(m) = 0.75 * Image\ Width \quad (6)$$

At 2.5 m AUV altitude, the camera has a horizontal field of view of 41.19° and an image footprint of 1.88 x 1.45 m (2.72 m²). The camera's resolution is 1280 x 960 pixels, or 8.26 x 6.19 mm, resulting in the ability to resolve objects no smaller than

0.51 cm. These footprint calculations do not include roll, pitch, or distortion corrections, which did not introduce a significant effect. The effect of roll and pitch on image footprint was calculated with a trigonometric method used by Singh *et al.* (2014) for a similar Gavia AUV. The angle, in deg, between the outside horizontal or vertical field of view and a straight line (θ) is given by:

$$\theta = \frac{FOV_{water}}{2} \quad (7)$$

A new dimension that includes the changes (if any) in the vertical or horizontal dimension (D_n) caused by pitch or roll can then be calculated by:

$$D_n = H * \tan\left((\theta \pm \phi) * \frac{\pi}{180}\right) \quad (8)$$

where ϕ is pitch or roll. Roll and pitch in the dataset were approximately 0.7 and 3.5 deg, respectively, resulting in < 3% error in both dimensions. Other studies using the same AUV reported similar error in image size due to exclusion of these parameters (Walker *et al.*, 2016; Singh *et al.*, 2014; Singh *et al.*, 2013). These effects were considered negligible particularly since this study did not include length measurements that may have been affected by these sources of error.

Additionally, I utilized the Camera Calibration Toolbox for MATLAB to compute the intrinsic parameters of the camera including focal length, principal point, skew coefficient, and the radial tangential distortion coefficients (Bouguet, 2002; Jeikkilä and Silvén, 1997). To use the toolbox, a series of photo were taken by the AUV of a planar checkerboard held at a variety of angles and distances from the camera. The checkerboard and AUV were submerged in a saltwater ballast tank. The toolbox extracted the grid corners of each checkerboard square from each photo, and based on a user-input distortion factor, re-projected the corners onto the images. A single set of intrinsic parameters with uncertainty and output radial, tangential, and

complete distortion models were output (Table 1) (Fig 9.). When converted to mm, the focal length output from the toolbox matches that of the above calculations (8 mm). The toolbox also calculated the extrinsic parameters for each individual photo consisting of a rotation matrix and translation vector. The results of the calibration indicated that the photos taken by the AUV's Grasshopper camera had a barrel distortion that is only noticeable around the margins of the frame, resulting in a slight pixel loss when undistorted. Approximately 68% of the frame exhibited a distortion of less than 4 pixels, or 6 mm of ground distance. The upper right and lower left corners of the frame had 8 or more pixels of displacement, or 12 mm. These results allow for correction of slightly distorted object measurements near the margins of the frame, but had no effect on counts of individuals as used in this study.

Table 1. Intrinsic parameters of the AUV camera at the time of the study generated by the camera calibration toolbox. All values in pixels.

Focal length	[1664.35820 1663.73357] $\pm$ [8.95456 8.71202]
Principal point	[619.58446 527.04711] $\pm$ [13.04627 10.56703]
Skew	[0.00000] $\pm$ [0.00000]
Distortion	[-0.01736 0.08675 0.00709 -0.00932 0.00000] $\pm$ [0.02405 0.12569 0.00219 0.00291 0.00000]

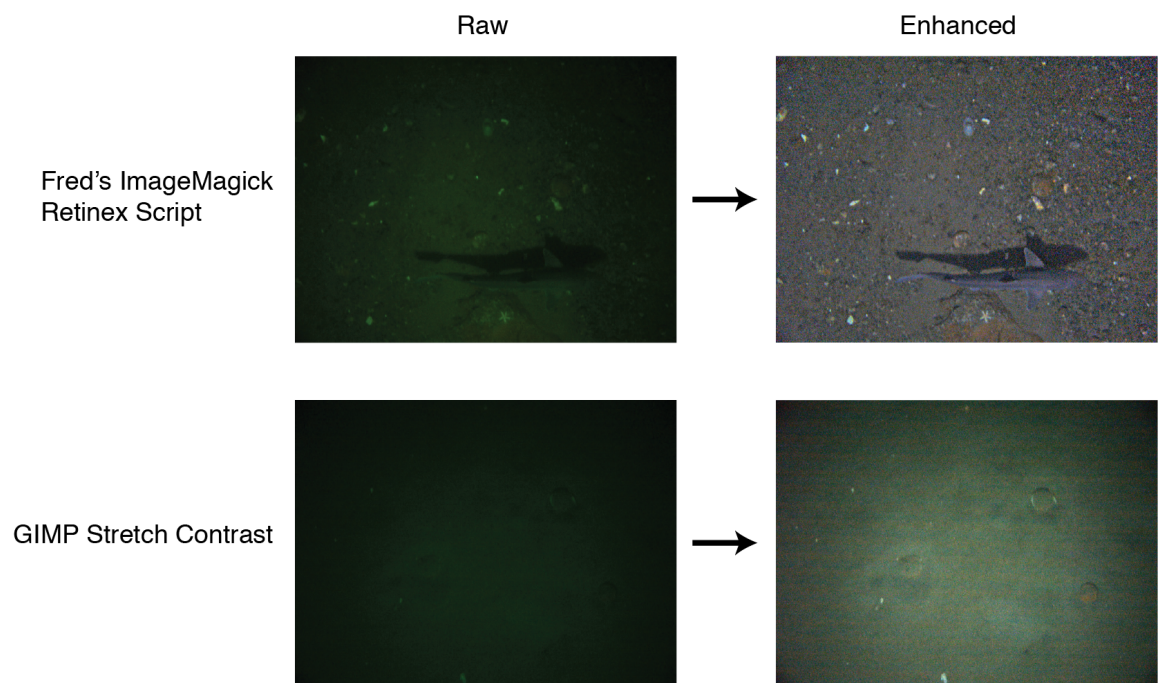


Figure 8. Example images before and after enhancement with Fred's ImageMagick retinex script or the Stretch Contrast function in GIMP.

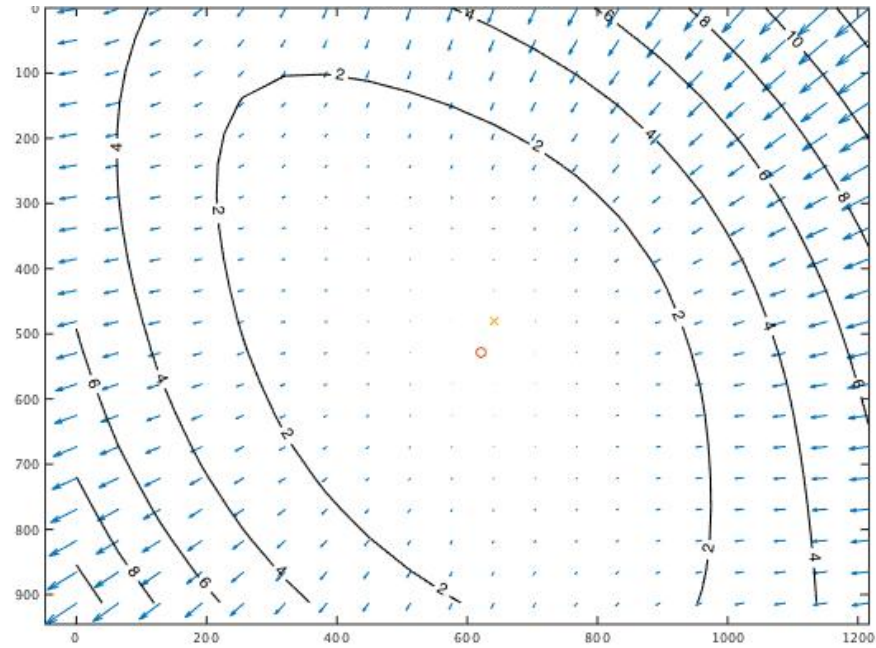


Figure 9. Complete distortion model of the Gavia AUV camera at the time of this study. Contour lines are in pixels.

2.6 Image Annotation

Because of the sheer abundance of photos taken, it was necessary to create a streamlined photogrammetric image analysis process. All images were absorbed into a custom online Scallop Image Annotation System (SIAS) that allowed us to load the color and brightness adjusted images into a user-friendly, click-driven GUI (Fig. 10). SIAS loads each photo sequentially by AUV mission and a trained image annotator identified each scallop in the photo, as well as designating each scallop counted as healthy or compromised. Annotators could also select “Unsure” to denote scallops

with an unresolvable or uncertain health status, but only 147 scallops were marked as such, making the proportion negligible within the complete AUV mission photoset (0.05%). Several image-scale characteristics were also recorded, including presence or absence of scallops, bed type, and image clarity. All annotations were stored in a MySQL relational database with associated image and AUV mission metadata.

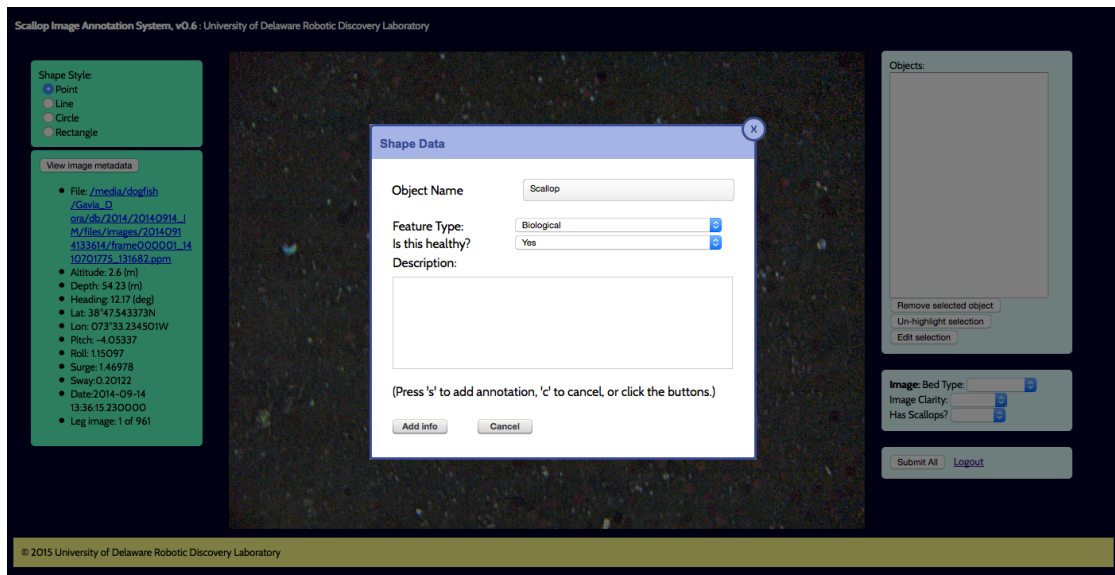


Figure 10. Sample screenshot of SIAS with the pop up window of detailed annotation fields that appears following a mouse click on a scallop.

Healthy scallops have non-damaged shells and hinges and typically sit in a slight depression on the seabed. They sit with their left valve flush to the seafloor, and their orange or brown right valve facing into the water column. Mantle tissue was sometimes discernible on the shell margin. Often, a crescent-shaped shadow, cast by a scallop with valves normally open for feeding, could be seen near the margin. Compromised or damaged scallops were distinguished from live, healthy scallops as a

shell fitting one of the health indicator groups potentially leading to mortality (Fig. 11) (Medcof and Bourne, 1964). They possessed disarticulated shells and were often whitish due to pigment loss. Scallops that were severely damaged at the hinge or had large holes or breaks through the middle of either the right or left valve were also noted as compromised. Additionally, inverted scallops were marked as compromised. Healthy scallops typically had their left valve flush to the seafloor, and their right valve facing upwards into the water column. Minchin *et al.* (2000) demonstrated the ability of healthy scallop individuals to right themselves within ten minutes when inverted. Dredging is likely to cause inversion and may leave the animal stressed and unable to normally right itself, potentially increasing vulnerability to predation (Minchin *et al.*, 2000; Caddy, 1989). Because 5-10% of sea scallops are albino and have white right valves (Hart, personal communication), righted albino scallops were differentiated from inverted scallops by the presence of biological growth on the right valve exposed to the water column.

Fifteen student or professional annotators were trained to accurately identify scallops in photos and assign each individual a healthy or compromised rating (Table 1). An annotation guide provided to each annotator contained examples of healthy and compromised scallops and the guidelines for using SIAS. Following an initial training meeting, each trainee was required to annotate a test set of 60 photos and count within 5% of the correct number of scallops and number of healthy scallops. If an annotator did not fall within those bounds initially, a second meeting and training set was assigned. Upon successful completion, annotators were granted access to SIAS. While most photos were annotated only once by a single annotator, all trained annotators were required to annotate the same mission leg (Leg 1 of ETCA Site 1 A1) containing

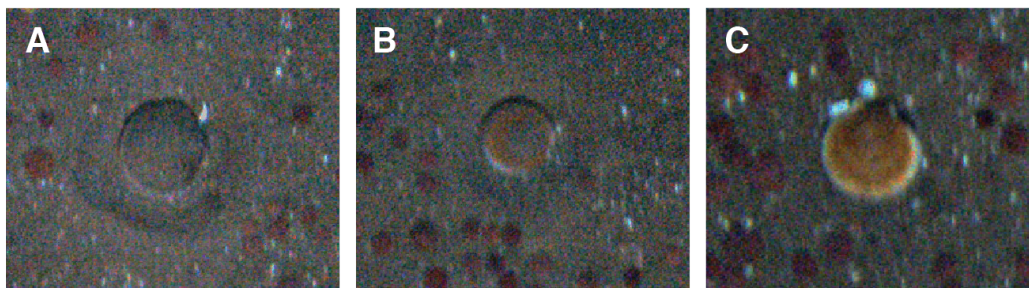
928 photos in order to analyze user error. Averaged over all fifteen annotators, the standard deviation of percent compromised scallops in this mission leg was 2.3%.

Guidelines for annotation in SIAS were as follows:

1. Every scallop will be annotated (counted) and given a healthy, compromised, or unsure rating.
2. A scallop will only be annotated if it is over 50% within the image frame.
3. Empty shells will not be annotated.
4. Every photo containing scallops will be marked as having scallops.
5. Every photo will be annotated with the dominant substrate and an indicator of image quality.

At ETCA Sites 1 and 2, 100% of the image set was annotated. ETCA Site 3 and all NLCA sites were downsampled to one of every four photos in order to reduce time spent annotating. Because photos collected at 1.875 fps had sufficient overlap, downsampling only reduced the total area imaged by 43% (Fig. 12).

Healthy scallops



Compromised scallops

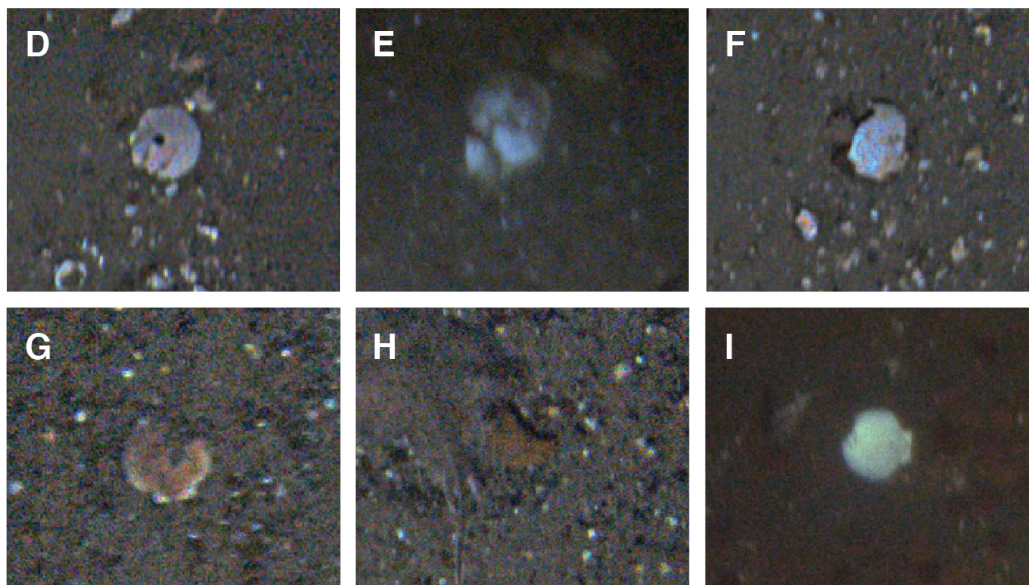


Figure 11. Examples of healthy, undamaged scallops (A-C) and damaged scallops from the dataset. Compromised annotations included scallops that were punctured (D), crushed (E), broken (F-H), or inverted (I).

Table 2. Number of images annotated and percent of total (%) by individual annotator.

Annotator	Num. images	Percent of total
Annotator 1	37651	21.54
Annotator 2	26055	14.91
Annotator 3	20813	11.91
Annotator 4	14096	8.06
Annotator 5	13659	7.81
Annotator 6	12016	6.87
Annotator 7	10466	5.99
Annotator 8	10031	5.74
Annotator 9	8305	4.75
Annotator 10	7275	4.16
Annotator 11	3879	2.22
Annotator 12	2553	1.46
Annotator 13	2293	1.31
Annotator 14	2175	1.24
Annotator 15	1425	0.82

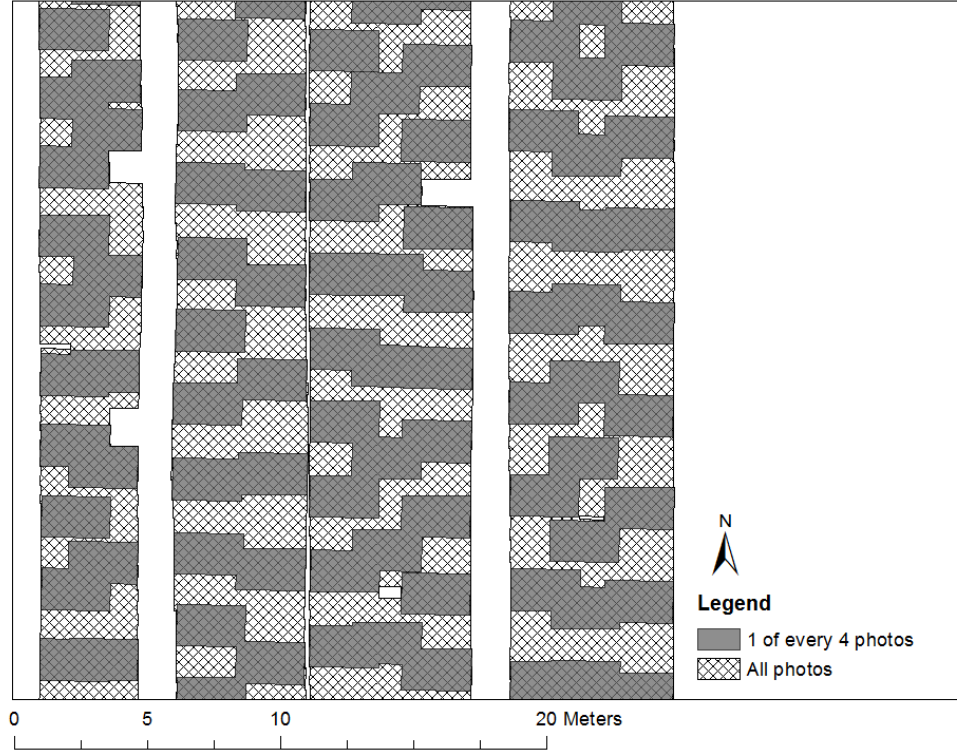


Figure 12. Sample section of ETCA Site 1 C1 (before control) AUV mission showing total imaged area overlaid with imaged area from every fourth photo.

2.7 Incidental Mortality Calculation

The image annotation data was stored in a MySQL relational database linking annotations to their associated image metadata and AUV state parameters during the time of capture. SQL queries were crafted to request information from the database with a variety of desired parameter definitions. Incidental fishing mortality for each before-after AUV mission pair was defined as:

$$c = \left(\frac{unhealthy_t}{total_t} - \frac{unhealthy_0}{total_0} \right) * 100 \quad (9)$$

where $unhealthy_t$ and $unhealthy_0$ are the numbers of unhealthy scallops at time t (after) and time 0 (before), respectively, and $total_t$ and $total_0$ are the numbers of total scallops at time t and time 0, respectively. Scallops with health annotations of “Unsure” made up approximately 0.05% of the total and were removed from the dataset prior to analysis. Mortality values were calculated from the fraction of photos in each mission that were within the path of the dredge. A photo was defined as being within the dredge path if its centroid fell within the scar polygon. Calculations were also made from the complete set of photos in each mission, which added a majority amount of untreated photos (Appendix A). I also calculated incidental mortality values from the photos within the dredge scars with a 3 m buffer around the perimeter to test the hypothesis that a significant amount of damaged scallops displaced by the dredge landed adjacent to the dredge scar following a tow (Appendix B) (Fig. 13). This distance was chosen because of anecdotal evidence seen in video footage from a GoPro camera mounted on the dredge during tows, and because it extended the width of the scar perimeter by a length of one to two more photos on all sides. A shorter distance may not have included a significant amount of additional photos.

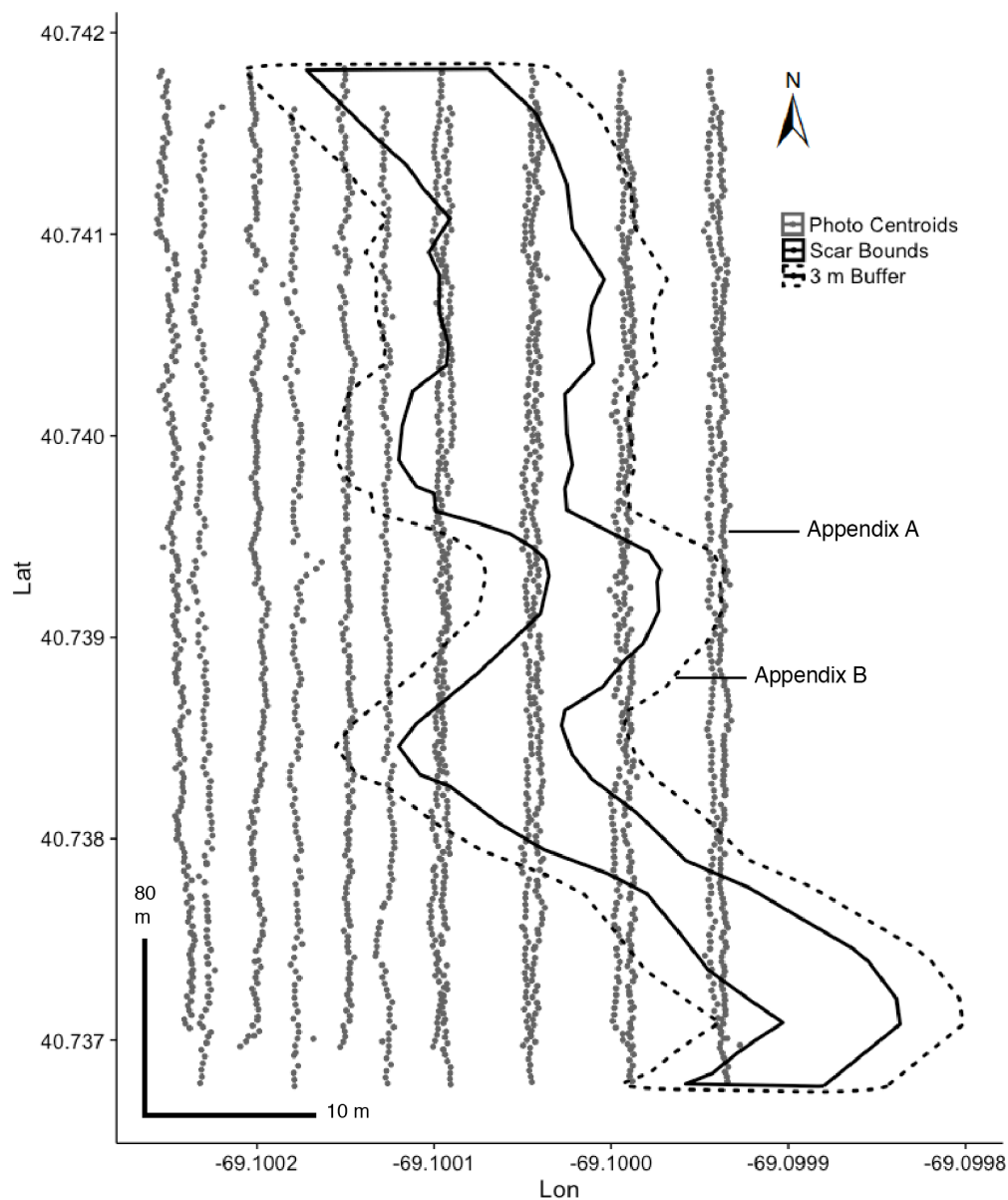


Figure 13. Sample map from a post one-tow dredge treatment AUV mission from (NLCA Site 1 A2) depicting centroids of annotated photos in the full AUV mission, the bounds of a dredge scar, and the 3 m buffer drawn around the scar bounds. Here 14 parallel lines are depicted, but at the ETCA only 10 parallel lines made up the AUV mission. Results in the main text refer to the data within the dredge scar only. Incidental mortality results from the full AUV mission are reported in Appendix A, and results from within the scar plus a 3 m buffer are reported in Appendix B.

2.8 Side-scan Sonar Processing

Side-scan sonar was collected during all AUV missions in order to acoustically image the texture of the seafloor. Primarily, it enabled us to visualize the physical impact of the dredge. Raw side-scan sonar files were made into mosaics with Sonarwiz 6 using standard operating procedures including gain adjustment and nadir gap removal. The mosaics created from post dredge missions were visually searched for dredge scars. Scars were detected by looking for a linear path roughly 4.5 m wide, smoother than the surrounding seabed, and lacking the pockmark features formed by scallops settling into the seabed. Additionally, the dredge often created sharply defined linear trails of mounded sediment on the peripheral edges of the tow path. When scars were located, the bounds were manually digitized using the polyline feature tool in Sonarwiz. Where five-tow treatments were applied, 1-2 digitizations were drawn around the group or groups of dredge scars. The side-scan sonar mosaics and digitizations were exported as georeferenced shapefiles (.shp) and Google Earth layers (.kmz). Scar digitizations were also exported as text files (.csv). The digitization of dredge scars was the only means by which to recognize the exact location of dredge treatments, since the dredge is not equipped with a means to log underway position. Digitizing the exact bounds enabled us to spatially relate the dredge treatments to the photos taken during the mission. I used the scar bounds to constrain my SQL queries and calculate incidental mortality within just the path of the dredge, the dredge scar with a 3m buffer, and over the entire imaged area. Side-scan sonar data was also used to reveal facies that described the major bottom types at the locations in this study. Each facies was visually detected by the patterns and relative reflective intensity in

side-scan mosaics and optically calibrated with photos taken by the AUV at the same location.

Chapter 3

RESULTS

3.1 The AUV Platform

The AUV missions to investigate incidental mortality of sea scallops on a sandy substrate were completed in the ETCA from July 8-16 and September 11-14, 2014. The hard substrate survey was carried out in the NLCA from July 8-14, 2015, in order to keep the two initial cruises in each closed area seasonally consistent. During each cruise, approximately 170,000 photos were collected with concurrent side-scan sonar over 18 AUV missions resulting in a summed trackline length of 135 km. Each individual AUV mission imaged an area of approximately 13,500 m² over 3 hours. Very little spread in altitude was observed within a single mission or over a pair of replicate missions. Altitude was kept within 7-8 cm over the duration of a single mission, and the means of replicate missions varied by about 1 cm (Fig. 14). Additionally, vehicle-estimated positioning between tracklines of replicate missions varied at sub-meter precision (Fig. 15).

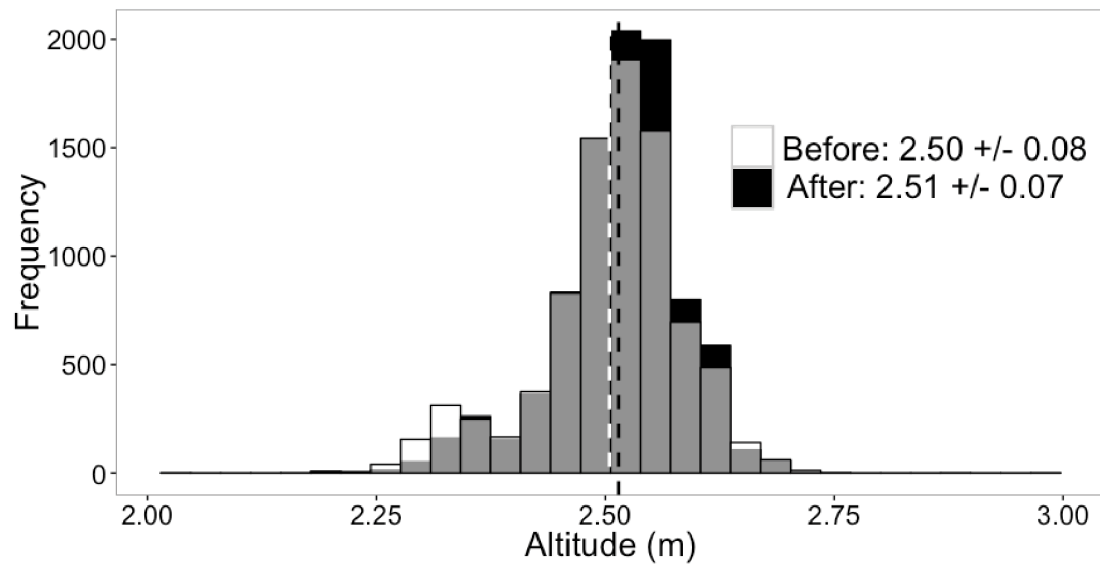


Figure 14. Histogram of altitude frequency and means with standard deviation for photos taken during two replicate AUV missions, NLCA Site 2 B1 (before five tows) and B2 (after five tows).

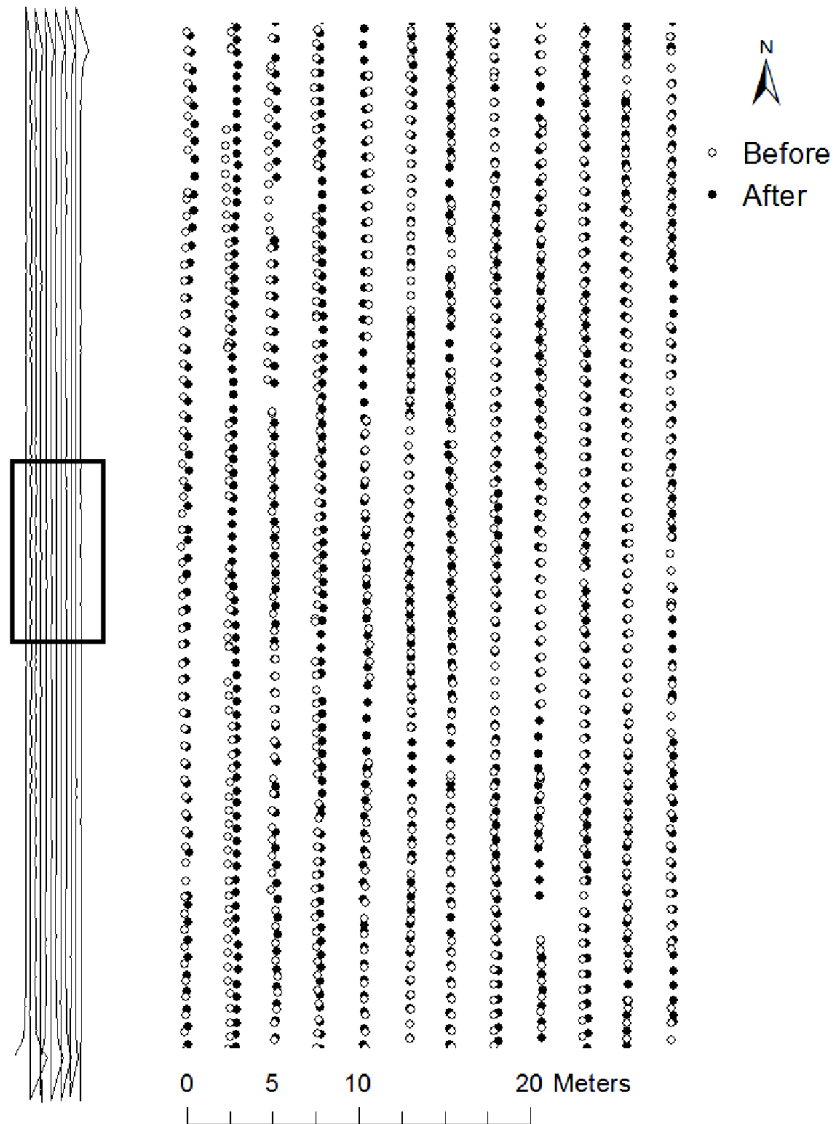


Figure 15. Photo centroids of two replicate missions, NLCA Site 2 C1 (before zero tows) and C2 (after zero tows) depicting sub-meter precision. Extent rectangle depicting the area mapped in this figure is on the left, overlaid onto the full trackline for NLCA Site 2 C1.

3.2 Incidental Mortality

In the ETCA, a total of 133,246 photos were annotated for scallop presence and instances of mortality. The baseline percent compromised scallops was fairly consistent across sites, with compromised scallops comprising approximately 3% of the sample prior to treatment (Fig. 16). Resultant incidental mortality values were low overall for all dredge treatments, reaching a maximum of 5.40% after a one-tow treatment (Fig. 17). Following the one-tow treatments, mean change in percent compromised scallops following dredge treatments was $0.66\% \pm 4.24$ (sd). Following the five-tow treatments incidental mortality was still low, but slightly higher than at the one-tow treatment with a mean change in compromised scallops of $2.46\% \pm 3.74$. The three control treatments showed little change following treatment as expected, with a mean change of $-0.28\% \pm 0.39$. Standard deviations were relatively high because means were calculated from three values with considerable spread (Table 3). A two factor ANOVA on the data fit to a linear mixed effects model showed no significant difference in mortality as a result of one or five dredge tows. Results of the ANOVA test from R statistical software are as follows:

```
Linear mixed model fit by REML ['lmerMod']
Formula: percentComp ~ Treatment + Period + Treatment *
Period + (1 | Site)
REML criterion at convergence: 60.7408
Random effects:
Groups      Name      Std.Dev.
Site      (Intercept)    0.00
```

```

Residual                2.31
Number of obs: 18, groups: Site, 3
Fixed Effects:
(Intercept)      Treatment1 Tow      Treatment5 Tows
3.0000           0.5711                0.2222
PeriodAfter      Treatment1 Tow:PeriodAfter      Treatment5
Tows:PeriodAfter
-0.2818          0.9396                2.7369

```

Analysis of Variance Table

	Df	Sum Sq	Mean Sq	F value
Treatment	2	7.8316	3.9158	0.7338
Period	1	4.0078	4.0078	0.7510
Treatment:Period	2	5.8021	2.9010	0.5436

The annotation team annotated one in every four photos taken in the NLCA, resulting in the annotation of 38,614 photos. The baseline percent compromised scallops was distinctly higher and more variable than in the ETCA, with values ranging from approximately 3-20% prior to treatment (Fig. 16). Overall incidental mortality values were slightly higher than in the ETCA, but had larger spread within treatments (Fig. 17). The maximum percent compromised scallops observed after dredging was 14.19%, following a five-tow treatment. At the one-tow treatments, mean change in percent compromised scallops was $-1.20\% \pm 7.03$. This was skewed negatively due to an outlier at Site 1, where I observed an apparent 9.29% decrease in

compromised scallops following dredging. This may be attributed to an abnormally small sample size at that particular treatment due to only 11% of the mapped area being within the dredge scar. Only 696 scallops were found in the dredge path before dredging and 553 scallops were found after, with just nine annotated as compromised following treatment. This was the second smallest sample size in the NLCA, where a typical sample mean was around 3000-4000 scallops. All scallop sample sizes for this study are reported in Appendix C. Sites 2 and 3 had more predictable results after the one-tow treatment, with increases of 2.33% and 3.37%, respectively. At the five-tow treatments, incidental mortality was $7.93\% \pm 6.82$. The five-tow treatments in the NLCA had substantially higher incidental mortality than those of the ETCA, particularly at Site 3 where an increase in percent compromised scallops of nearly 15% was observed (Table 4). The three control sites had a mean change of $0.84\% \pm 2.21$, and had a larger standard deviation than the mean change of the control sites at ETCA. A two factor ANOVA on the data fit to a linear mixed effects model showed no significant difference as a result of either treatment, but showed a larger effect of the interaction between sampling period (before or after) and treatment than in the ETCA. The linear mixed model and results of the ANOVA test from R statistical software are as follows:

```
Linear mixed model fit by REML ['lmerMod']  
Formula: percentComp ~ Treatment + Period + Treatment *  
Period + (1 | Site)  
REML criterion at convergence: 86.2349  
Random effects:
```

Groups	Name	Std.Dev.
Site	(Intercept)	2.459
Residual		6.333

Number of obs: 18, groups: Site, 3

Fixed Effects:

(Intercept)	Treatment1 Tow	Treatment5 Tows
10.0169	-3.4375	-6.2479
PeriodAfter	Treatment1 Tow:PeriodAfter	Treatment5 Tows:PeriodAfter
0.8447	-2.0440	7.0825

Analysis of Variance Table

	Df	Sum Sq	Mean Sq	F value
Treatment	2	60.572	30.286	0.7550
Period	1	28.672	28.672	0.7148
Treatment:Period	2	68.815	34.408	0.8578

Calculating incidental mortality within the dredge path removed some of the dilution that may have been caused by the relatively high abundance of untreated photos in each AUV mission. This is because on average, only 17% of the total AUV mission area was dredged during a one-tow treatment (83% untreated), and 56% of the mission area was dredged during a five-tow treatment (44% untreated). Incidental mortality values calculated over the entire AUV mission tended to be smaller, likely due to the noise introduced by the larger set of photos that included a large proportion

of photos outside of the dredge path (Appendix A). Adding a 3 m buffer around the dredge scar did not appear to increase incidental mortality relative to the calculations just within the dredge scar, suggesting the amount of scallops that had been displaced outside of the dredge path does not contribute significantly to incidental mortality. In fact, the addition of the buffer slightly reduced the proportion of compromised scallops observed after dredging (Appendix B).

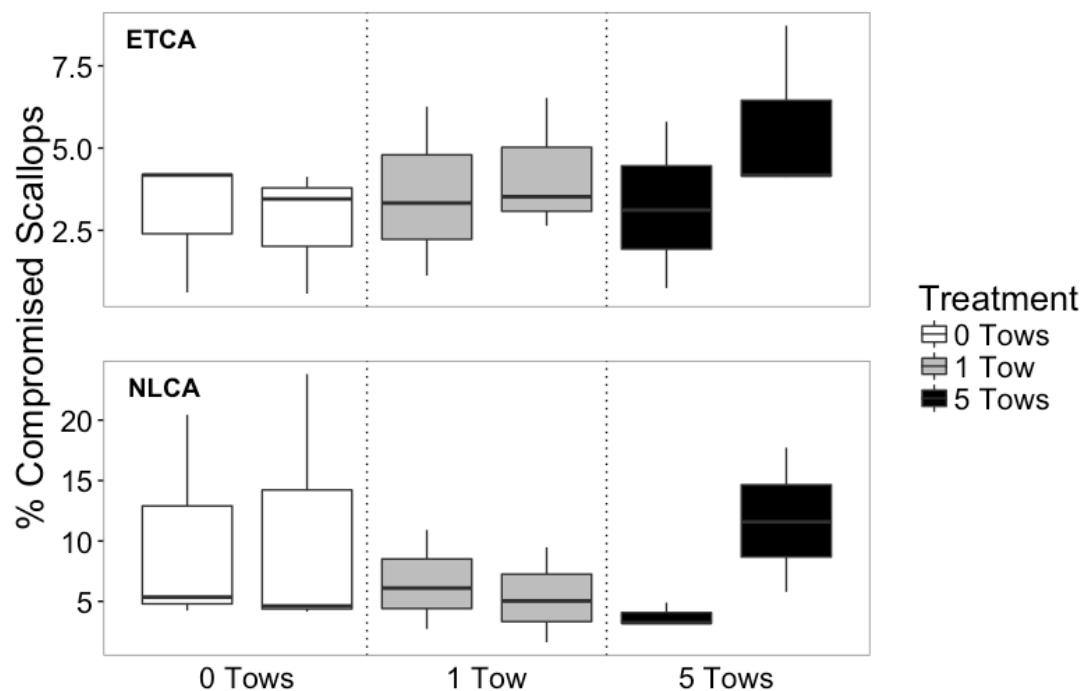


Figure 16. Percent compromised scallops within the dredge path before and after the three dredge treatments in the ETCA and NLCA.

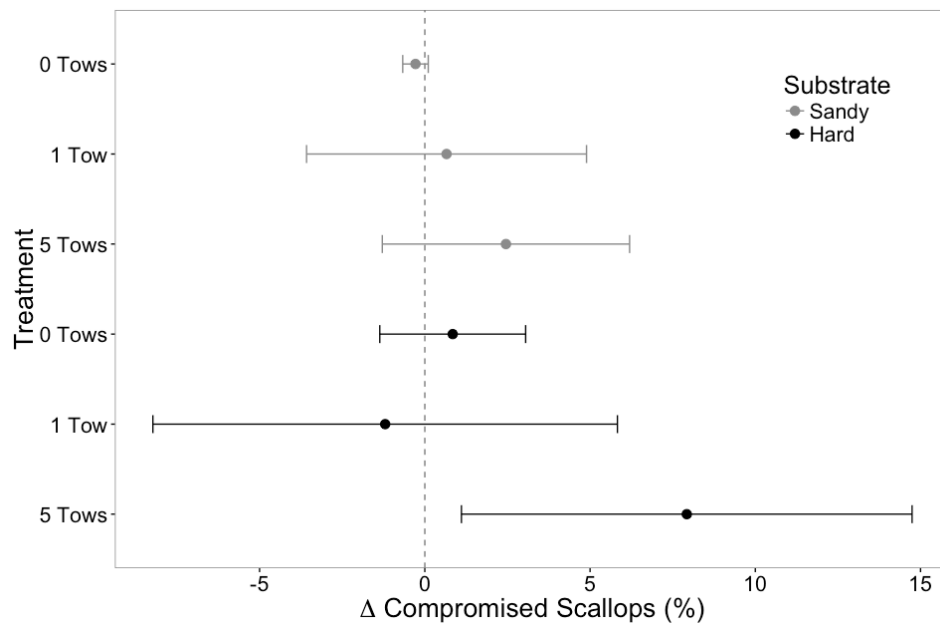


Figure 17. Mean change in compromised scallops within the dredge path following one, five, or zero tows on a hard substrate (NLCA) and sandy substrate (ETCA). Error bars are standard deviation (n=3).

Table 3. Change in compromised scallops (%) within the dredge path following treatment in the ETCA. Errors are standard deviation.

	0 Tows	1 Tow	5 Tows
Site 1	-0.08	-2.74	3.43
Site 2	-0.73	-0.69	2.09
Site 3	-0.04	5.40	-1.68
Mean	-0.28 ± 0.39	0.66 ± 4.24	2.46 ± 3.74

Table 4. Change in compromised scallops (%) within the dredge path following treatment in the NLCA. Errors are standard deviation.

	0 Tows	1 Tow	5 Tows
Site 1	3.37	2.33	14.49
Site 2	-0.73	-9.29	8.41
Site 3	-0.10	3.37	0.88
Mean	0.84 ± 2.21	-1.20 ± 7.03	7.93 ± 6.82

3.3 Substrate Analysis and Dredge Scars

Analysis of the substrate in the ETCA and NLCA revealed a range of anticipated bottom types, diverging primarily between the soft, sandy substrate that makes up most of the Mid-Atlantic Bight and the coarse sand, gravel, and rocky substrates that are prevalent in the Georges Bank region. Seven major facies were identified in the side-scan sonar data collected at all sites and calibrated to seafloor images (Figs 18-23). The most common bottom type was a sandy, mostly flat seabed with or without interspersed pockmark-like features (Sonar Facies 1 and 2). This seabed type was observed at all depth ranges encountered in this study (50-70 m). Much of the sandy seabed was near large areas of shell hash, which were not distinguishable in side-scan sonar mosaics but were marked as a separate substrate type during image annotation due to its relative hardness compared to sand (Figure 18, panel D). Gravelly seabeds were found mostly in the NLCA, distinguished by localized areas of small rocks and coarser debris (Sonar Facies 3). These bottom types had more complex terrain, with small sub-meter changes in relief and an accompanying benthic community more diverse than that within Facies 1. Some areas of sandy seafloor also had large bedform features of 0.5 to 1 m in length (Sonar Facies

4a), often with superposed current ripples on the crest (Sonar Facies 4b). Shorter wavelength ripples (10-30 cm) were visible in photos over all study sites, but were difficult to distinguish in side-scan sonar due to their small size (Sonar Facies 5). The facies were translated to the three bed type image annotations: Sandy (Sonar Facies 1, 2, 4a, 4b, 5), Shell Hash (Sonar Facies 1, 2, 4a, 4b, 5 where images showed shell hash) and Gravel (Sonar Facies 3).

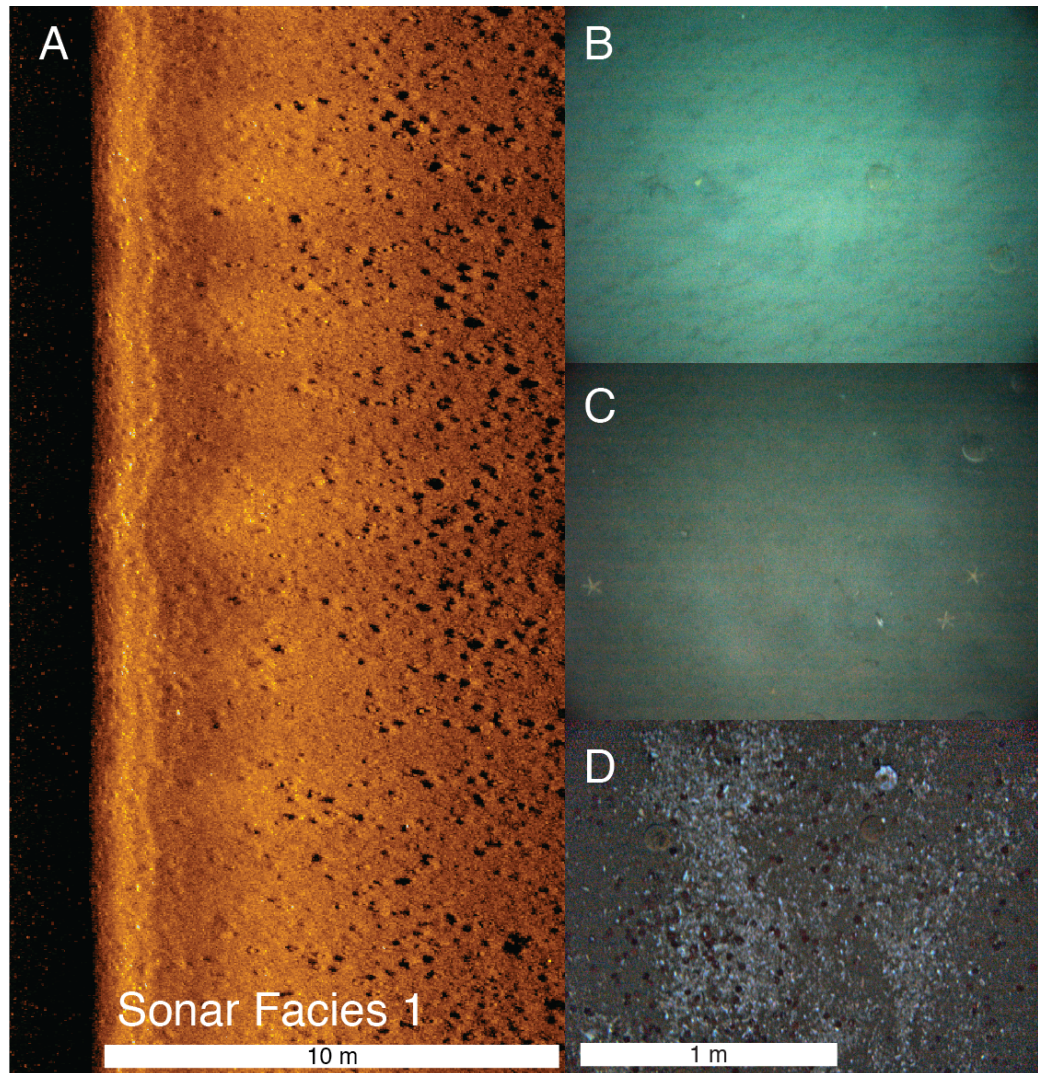


Figure 18. Representative side-scan sonar image from Sonar Facies 1 (A), depicting a generally smooth sandy seafloor with interspersed pockmark-like features. Optical calibration of Sonar Facies 1 includes a flat seafloor with seabed depressions created by sea scallops (B-C) and shell hash that is not resolved in the side-scan sonar (D).

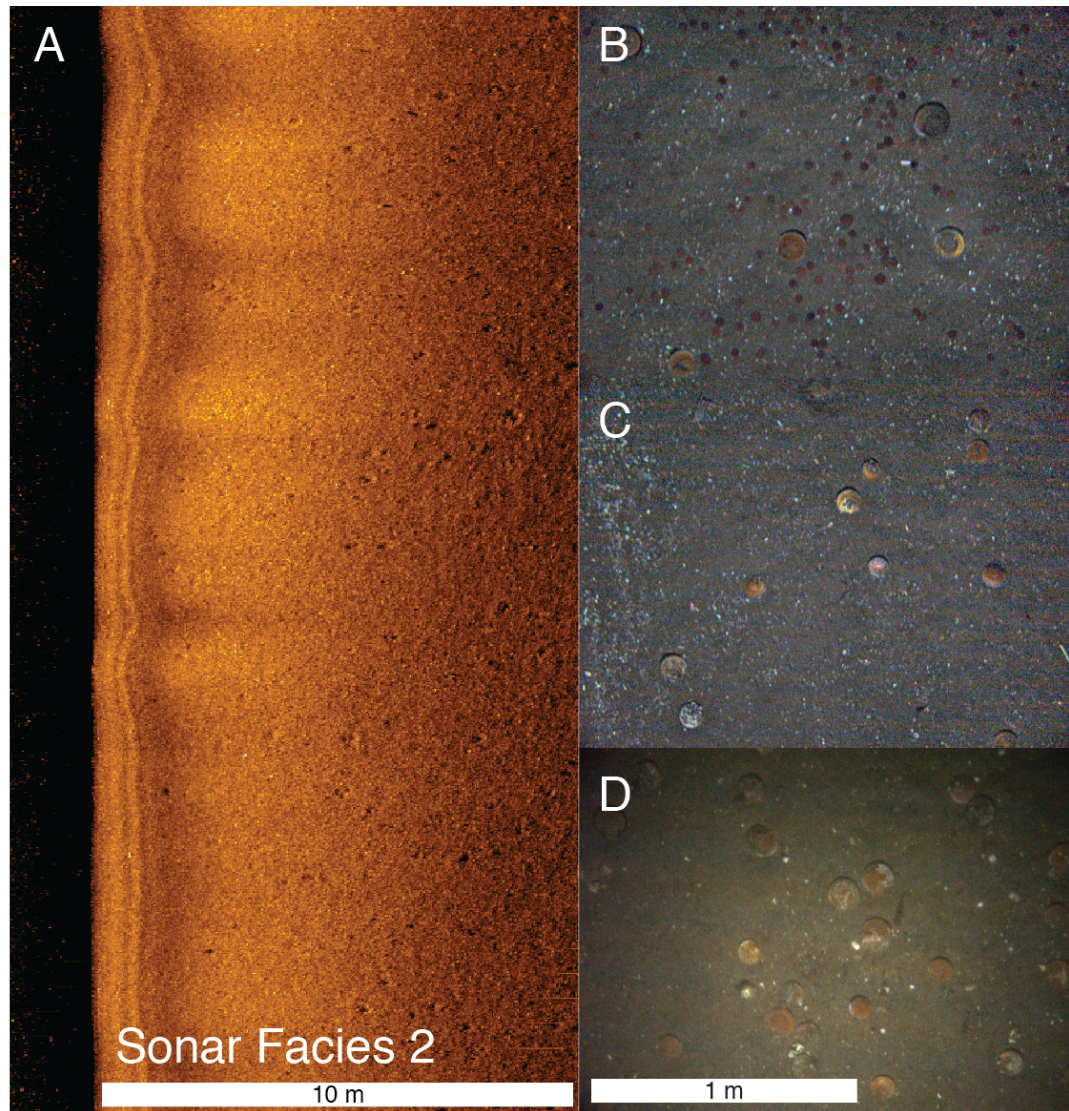


Figure 19. Representative side-scan sonar image from Sonar Facies 2 (A), illustrating the generally smooth texture. Optical calibration of Sonar Facies 2, showing a sandy, featureless seabed (B-D).

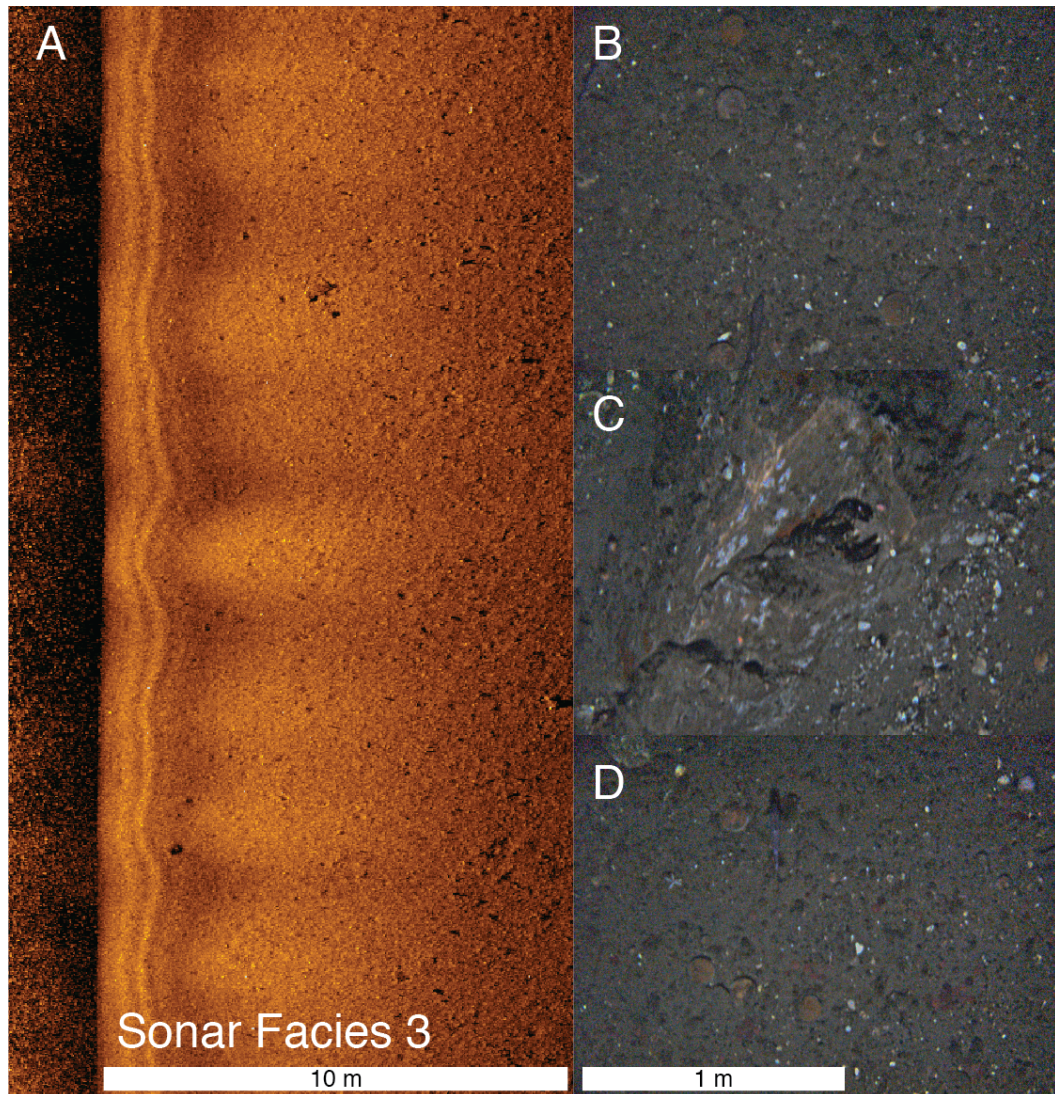


Figure 20. Representative side-scan image from Sonar Facies 3 (A), depicting a flat, textured seafloor. Optical calibration of Sonar Facies 3, showing gravel and coarser debris (B, D) as well as an example of a large rock often found within gravelly areas in the NLCA (C).

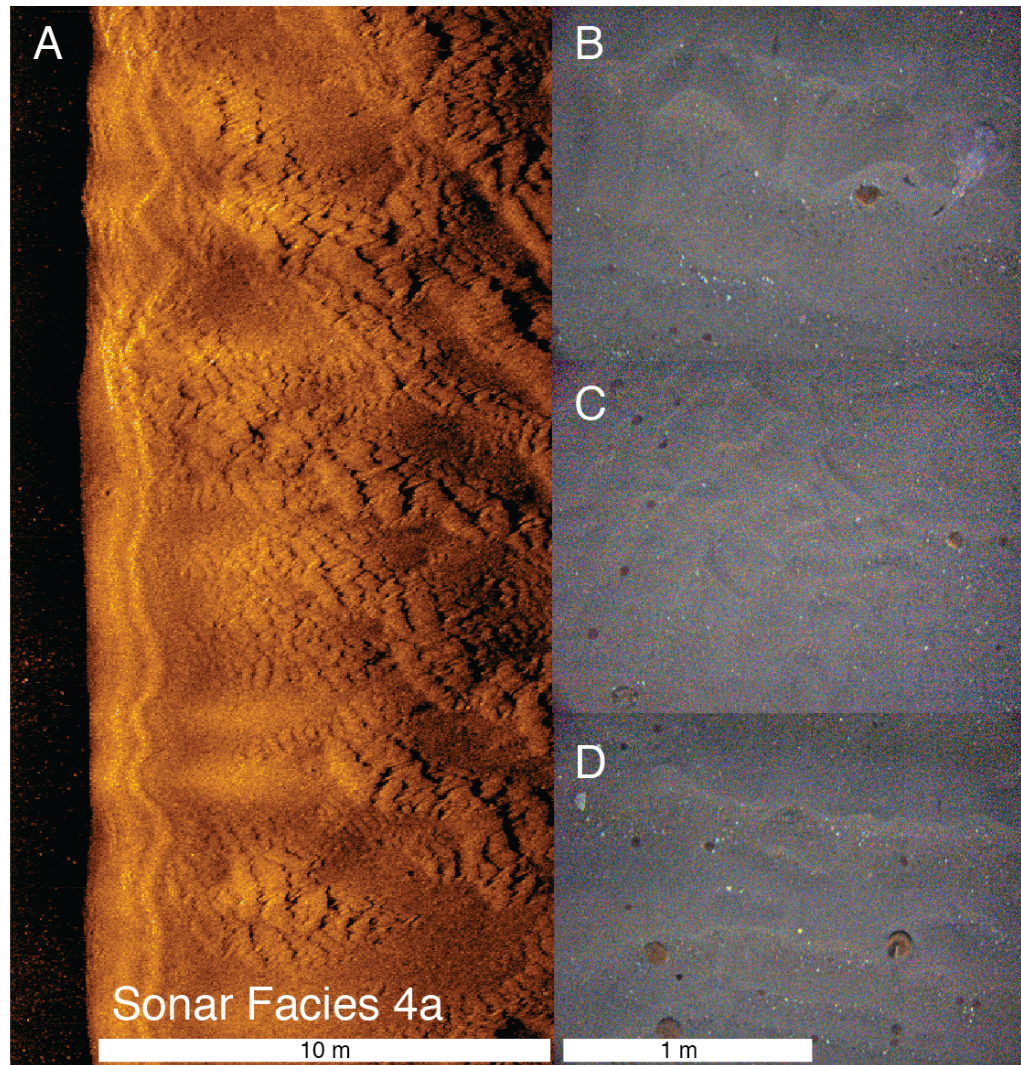


Figure 21. Representative side-scan sonar image of Sonar Facies 4a (A) showing large bedform features. Optical calibration of Sonar Facies 4a depicting the current-driven bedforms (B-D).

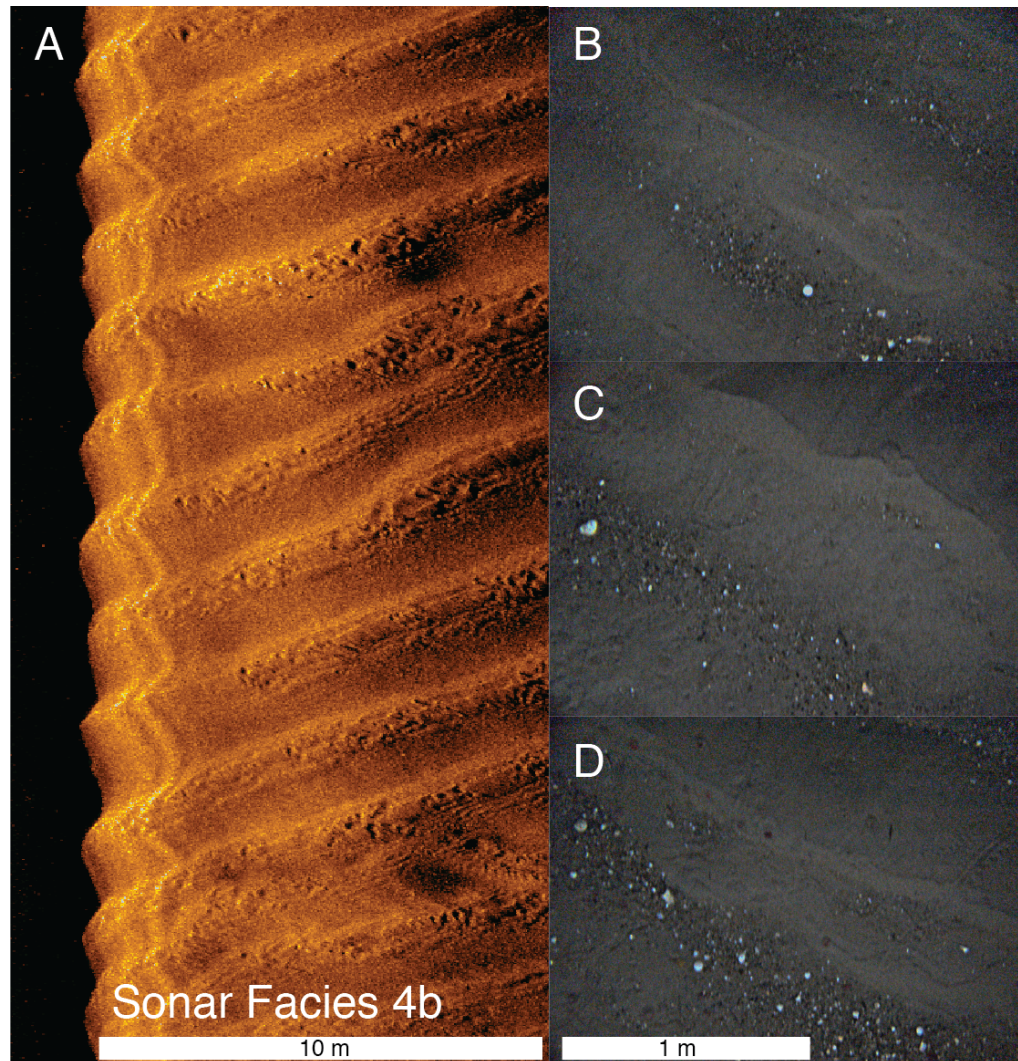


Figure 22. Representative side-scan sonar image of Sonar Facies 4b (A), illustrating large bedform features with superposed current ripples. Optical calibration of Sonar Facies 4b reveals peaks and troughs characteristic of the ripples at this facies (B-D).

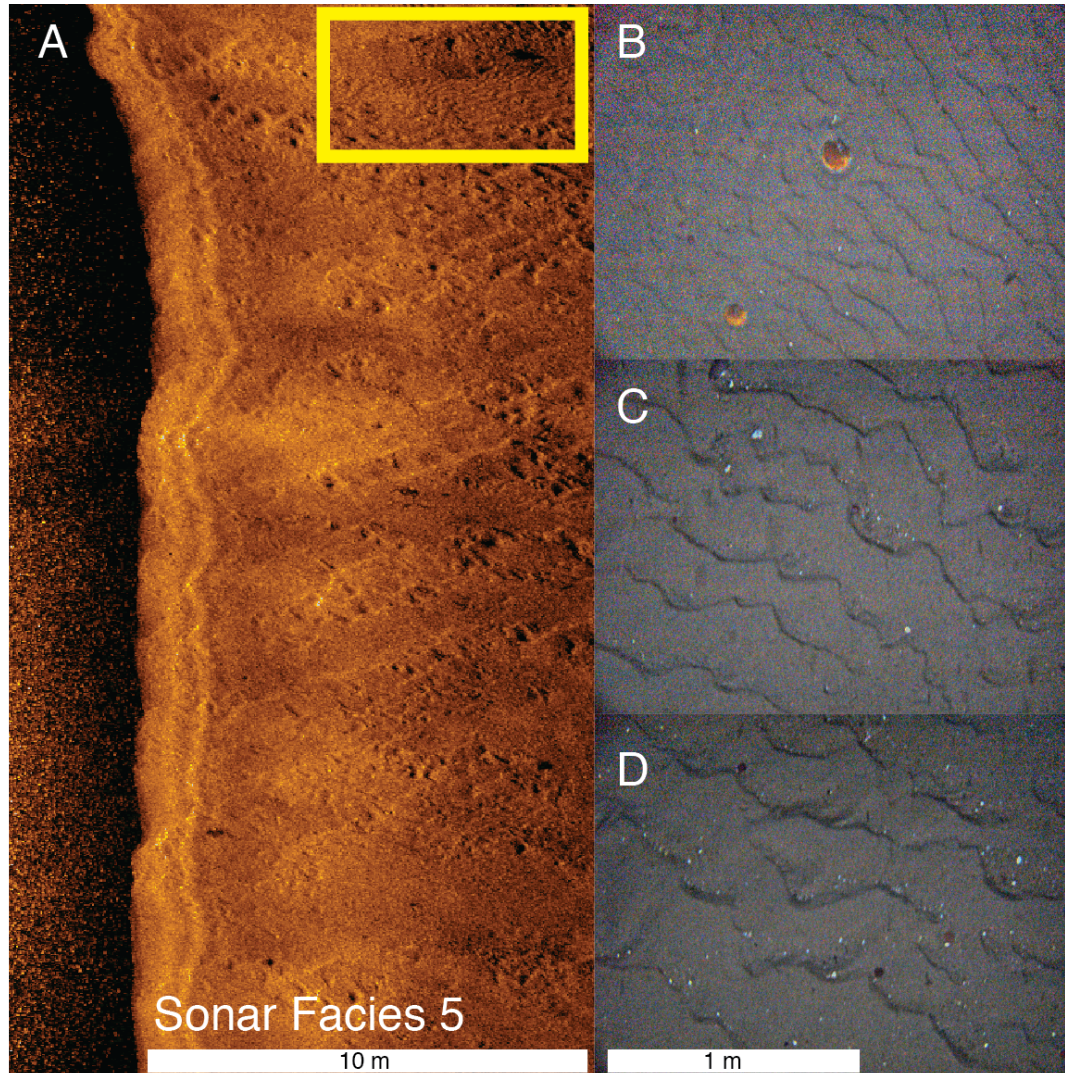


Figure 23. Representative side-scan sonar image of Sonar Facies 5 (A, box), showing shorter wavelength (10-30 cm) ripples that were difficult to resolve in side-scan sonar mosaics. Optical calibration of Sonar Facies 5 better distinguished the small ripple features (B-D).

According to manual seabed classification by image annotators, the dominant substrate in the ETCA was mostly sand with areas of overlaid shell hash across all sites (Fig. 18). Shell hash made up 15-38% of the total at each treatment where it was

present. 100% of photos at Site 3 were annotated as sandy, except for the control treatment, which had areas of shell hash and a small proportion of gravel. The substrate classification was corroborated by the side-scan sonar mosaics in the ETCA, which showed flat, featureless areas of seabed with little diversity in acoustic texture at all sites (Appendix D). In contrast, the substrate in the NLCA was variable across sites as well as treatments. While the seabed was generally uniformly sandy in the ETCA, the substrate in the NLCA had striking variability on small spatial scales of meters to tens of meters. Manual classification of the images indicated that the majority of the seafloor at the sites was sandy, but contained patches of shell hash, gravel, and rocks (Fig. 18). Shell hash and gravel made up no more than 16% of the total seabed at treatments where either was present. Many large rocks and some boulders were also observed interspersed among sandy or gravelly areas in photos, but were not denoted in image annotations. These large features were clearly observed in the side-scan sonar mosaics (Appendix D).

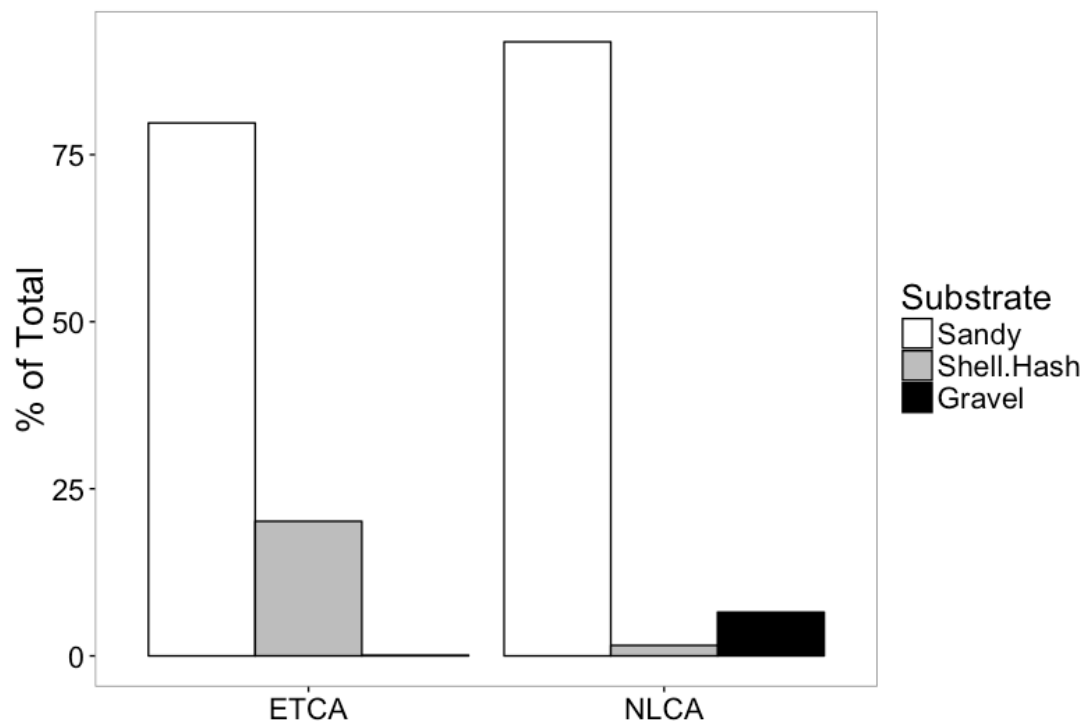


Figure 24. Substrate composition in the dredge path in the ETCA and NLCA summed over all sites.

I treated site as a random variable to incorporate the local variability of substrate in the statistical model, but found no significant effect on incidental mortality in either closed area. The introduction of the exact proportion of harder substrates, gravel and shell hash, into the model as additional factors also did not reveal statistical significance. The lack of significance may be due to the relatively low level of harder substrates at both the ETCA and NLCA, or the small sampling size ($n=3$) of replicate. Regardless, larger increases in damaged scallops were found on areas of seafloor with higher proportions of hard substrate. At the five-tow treatment of NLCA Site 1, gravel and shell hash made up 9.79% and 6.44% of the total area imaged with the AUV respectively, the largest proportions of non-sandy substrate annotations of all

treatments in the dataset. Following five dredge tows I observed 14.49% incidental mortality, the maximum observed after any treatment in either closed area.

Dredge scars were easily detected in the ETCA, distinguishable by a smoothed area of seabed bordered by linear ridges of sediment. Dredge scars were less easily delineated in the NLCA due to the heterogeneity of the seabed, however, scars were clearly revealed upon close inspection of each individual side-scan sonar file in SonarWiz's Digitizer View. Some large rocks in the path of the dredge were evidently displaced as the dredge passed over them, leaving short trails of scour. One-tow treatments were digitized by drawing a polygon around the perimeter of the single scar. While the objective of the five-tow treatment was to precisely dredge over the same line five times, the tows often intersected each other or were slightly spatially separated (Fig. 19). In some cases, more than one polygon was drawn around separate clusters of intersecting scar paths in order to capture the dredged area without including area outside of the scar. In the AUV missions in the ETCA eight weeks following the initial tow treatment, the original dredge scars could still be seen on the seabed, albeit degraded and less prominent on the seabed (Fig. 20). Scars from a single tow were barely ascertainable; scars from five-tow treatments were more easily recognized.

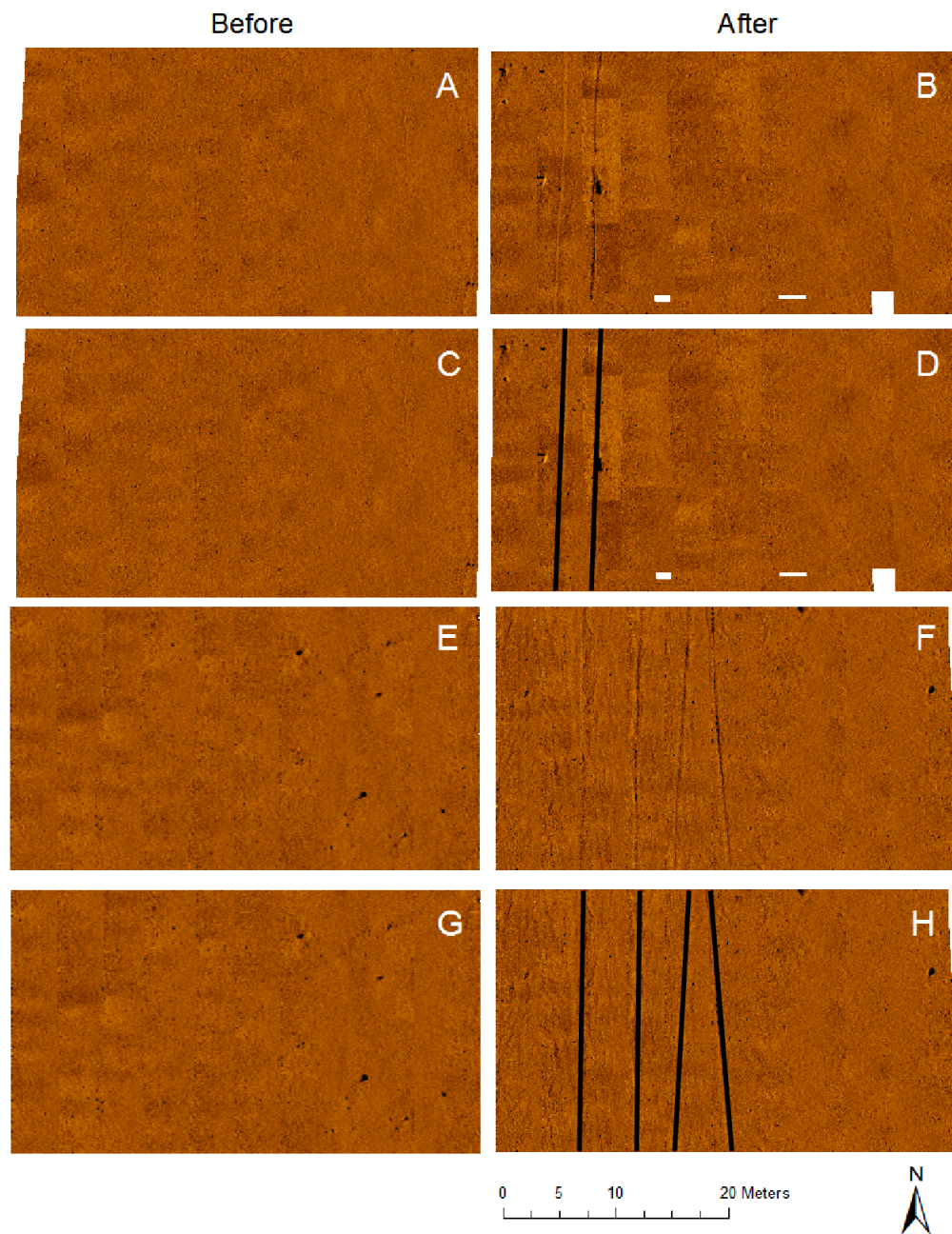


Figure 25. Example side-scan sonar mosaics with and without guides before and immediately after one dredge tow (A-D), and before and immediately after five dredge tows (E-H) at Sites 2 and 1 in the NLCA, respectively. One-tow treatments were distinguishable by a single dredge scar (D), while five-tow treatments were distinguishable by a group of overlapping dredge scars (H).

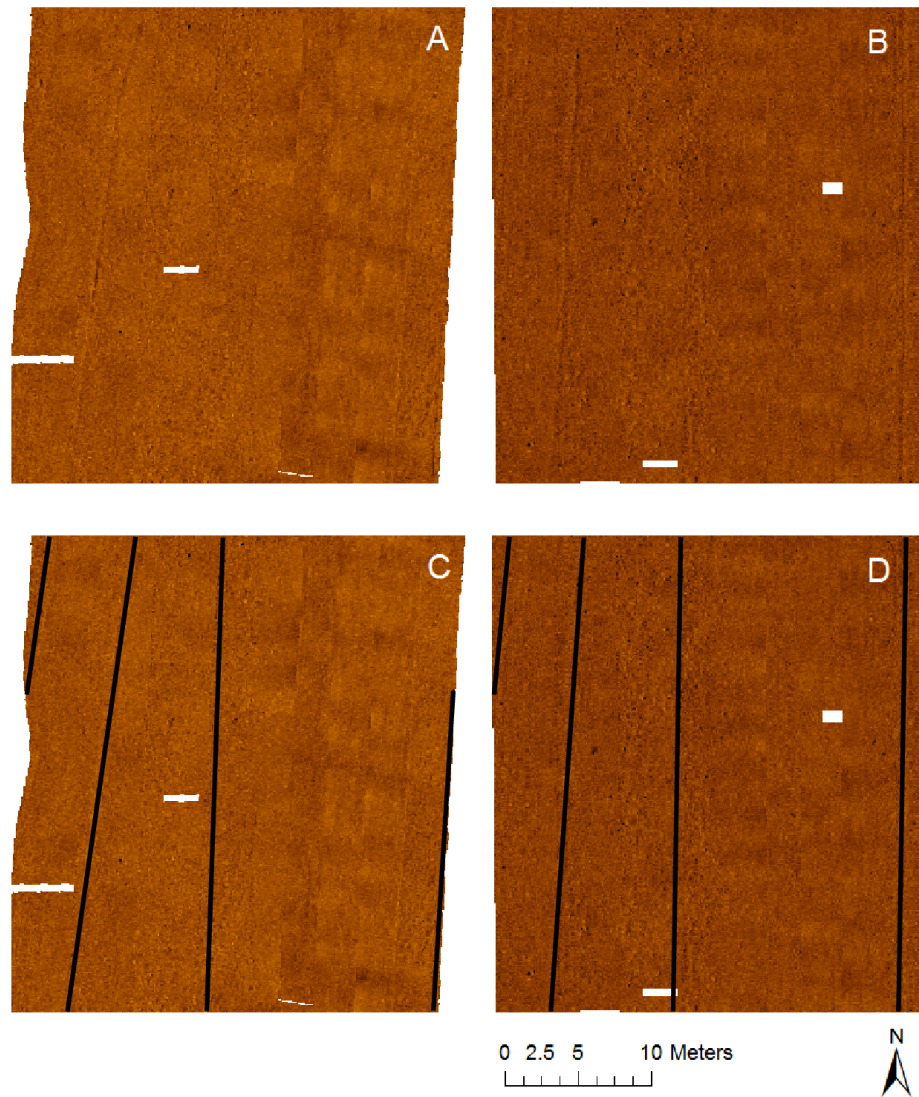


Figure 26. Example side-scan sonar mosaics with and without guides immediately after (A, C) and eight weeks following (B, D) five dredge tows at ETCA Site 3. Dredge scars were still visible after eight weeks, particularly after five-tow treatments.

Chapter 4

DISCUSSION

4.1 Incidental Mortality

My calculations of incidental mortality of sea scallops left on the seafloor after dredging corroborated the values currently used in fishery models. I consider the maximum and 5 tow treatment mean values in this study the most significant because they represent the worst-case scenario, and directly compared them to values used in the fishery and found in the literature (Table 4). While not representative of the entire data set, the maximum values aligned well with those found in the literature. In the ETCA, I observed a maximum increase in compromised scallops of 5.40%, which complements the estimations of Murawski and Serchuk (1989) of up to 5% mortality on sandy substrate in the Mid-Atlantic. The mean value of the five-tow treatments, 2.46%, matched the evidence that suggests the level of incidental mortality in sea scallops is relatively small (Hart and Rago, 2006). The fishery currently uses 10% as the value for incidental mortality on sandy substrate. This is slightly higher than the amount of incidental mortality observed in the study in the ETCA, but it is a conservative estimation that is appropriate in the context of fisheries management. It is practical to use conservative values of parameters that have moderate uncertainty, like incidental mortality, in fisheries models to avoid overfishing resulting from miscalculation of reference points. In the NLCA, I observed a maximum incidental mortality value of 14.19%. This approaches the lower bounds of the 15-20% range estimated by Caddy (1973) on a gravel substrate significantly north of Georges Bank,

in the Gulf of St. Lawrence, Canada. The mean value of the five-tow treatments was 7.93%, which is lower than reported by Caddy (1973) but again supports the evidence that scallop incidental mortality may be low overall (Hart and Rago, 2007). The sites in the NLCA were mostly sand (>84%) interspersed with gravel and shell hash, so it is reasonable to believe more damage may have been observed if gravel made up a higher proportion of the substrate. Assessment models currently use 20% to represent the incidental mortality rate on hard substrates of Georges Bank. Again, this value is higher than those in the study and in the literature, but it is a reasonable conservative estimate for this parameter particularly on a hard substrate that is likely to result in higher levels of damage imparted by the dredge (Murawski and Serchuk, 1989).

Table 5. Comparison of maximum and mean incidental mortality values within the dredge path found in this study (indicated with *) to those in the literature and used currently by the fishery.

	Sandy	Hard
Fishery Model	10%	20%
Literature	<5% (Murawski and Serchuk, 1989)	15-20% (Caddy, 1973)
Mean (5-Tow)*	2.46%	7.93%
Maximum*	5.40%	14.19%

I chose dredge treatments of relatively light and assumed heavy dredge intensity to better understand the compounding effect repeated dredge tows may have on incidental mortality, particularly in the context of a heavily fished open access area. Vining (1978) acknowledged that seabed disturbance as a result of mobile benthic fishing gear is highly variable as some parts of the seafloor may be fished a single time, while others are fished multiple times by one or several vessels. While I

attempted to control for this by dredging over the same path each time, the tows intersected and crossed each other multiple times, consistent with other observations of commercial fishing efforts in open areas (Walker, 2013). As a result, the five-tow treatments are not necessarily five times the intensity of a single tow, but may fall anywhere on the spectrum of one to five tows. I observed higher values of incidental mortality following the five-tow treatments regardless of this overlap variability, particularly in the NLCA. Therefore, it is likely that many scallops interacted with the gear several times throughout the duration of the treatment, especially since the efficiency of New Bedford dredges is known to be low (Yochum and Dupaul, 2008). The inability of the one-tow treatments to result in an observable change in the amount of compromised scallops suggests that a single tow may not be sufficient for this method. More treatment replicates may have revealed a trend, but the effect was muted in this study by a small sample size with standard deviation that fell well within the random error of this dataset.

In this study, sampling in two closed areas known to have contrasting substrate compositions enabled us to measure the difference of dredge impact between a sandy and hard seabed. I observed higher values of incidental mortality in the NLCA compared to the ETCA, but the difference between the results at the two closed areas was not statistically significant. Results suggest incidental mortality was higher in the NLCA particularly at the five-tow treatments, where an increase in the amount of compromised scallops was seen at all three replicate sites and was the sole example of such in the entire dataset. These results support previous hypotheses that dredging on hard substrate may lead to scallops being crushed between the dredge and dislodged rocks (Murawski and Serchuk, 1989).

4.2 Physical Impact of Dredge

The acoustic imaging method used to visualize fishing impacts on the seabed clearly revealed dredge scars at every post treatment AUV mission. The acoustic signatures of scars were consistent with descriptions of visual observations and acoustic images from the literature (DeAlteris *et al.*, 2000; deGroot, 1984; Caddy, 1973). On sandy substrate, the dredge flattened ripples and other small-scale features. The dredge had a scraping effect on harder substrate in the NLCA, disturbing the substrate but not completely removing relief. Scars in the NLCA did not always have clear linear accumulations of sediment on the outer sides of the scar, likely due to the presence of larger-grained sediment such as gravel. The presence of scars on the seabed eight weeks following dredging indicated that dredge marks are likely to persist especially in low energy areas (Jones, 1992). While I showed the persistence of physical impacts from fishing in the ETCA, dredging on hard bottom areas is likely to have longer effects on benthic habitat than mobile soft bottom areas, where sediments are periodically resuspended by storms (Collie, 1998). On hard bottoms, benthic communities are less adapted to frequent disturbance and the effects of gear may persist longer.

4.3 The AUV Platform

The AUV is an efficient acoustic and digital imaging platform for use in benthic fisheries surveys. I demonstrated the ability to collect large amounts of photos (>10,000) over the duration of a single battery life, resulting in image coverage of

13,500 m² on a trackline of 7.5 km. The total distance surveyed by the AUV was one to two orders of magnitude larger than the studies on which current incidental mortality estimates are based (Murawski and Serchuk, 1989; Caddy, 1973). The highly precise navigation of the AUV enabled us to repeatedly survey an area, which was integral to the goals of this study. Image footprint areas for individual photos can be calculated from the AUV's continuous collection of vehicle state data, taking into consideration parameters like altitude, pitch, and roll. This study builds off of recent work that highlights AUVs as a non-invasive way to measure scallop abundance, distribution, and size (Walker *et al.*, 2016; Singh *et al.*, 2014; Singh *et al.*, 2013). Additionally, the ability to capture the precise spatial extent of the dredge tows in a post processing and mapping software like SonarWiz was an improvement from past studies that required divers or submersibles to make observations within dredge tracks over limited spatial distances and for much shorter time intervals (Murawski and Serchuk, 1989; Collie *et al.*, 1977; Caddy, 1973). This method accurately calculates area towed and digitizes the dredge's path, exporting the dredge scar in a variety of georeferenced file formats for other uses.

4.4 Image Processing and Annotation

While the large amount of photos used in this study was a scientific advantage, it introduced logistical challenges to the image analysis process. Images were collected in raw ppm format, and virtually every image had to be enhanced before scallops could be distinguished. Most often, the photos looked black or very dark green. They were inherently lighter in the NLCA, which is likely due to the camera

adjusting to the contribution of the flash strobe without much ambient light at depth. No single post-processing scheme was successful at brightening the entire set of photos, and over half of the images had to be re-enhanced with a second method. The retinex scheme worked best on photos that were not excessively dark, and produced images with the most true to life white balance. The GIMP Stretch Contrast scheme worked on photos that were not clarified by the retinex, but did not always properly adjust the white balance, causing the color of scallops to blend into the substrate in some cases. While the best scheme was applied to all photos, some missions were left slightly overexposed, causing light colors to be blown out. It was impossible to manually grade the success of an enhancement scheme at a scale any smaller than a random sample from a single AUV mission because of the sheer amount of photos. Each raw ppm file was nearly 4 MB and the collective image set was well over 1 TB of data, so transfer, conversion to jpeg format, and subsequent enhancement took several weeks. The value of collecting photos in raw format should be discussed, since similar studies collected and annotated georeferenced photos in jpeg format that required less or no image enhancement (Walker *et al.*, 2016; Singh *et al.*, 2013). However, the benefit of collecting raw, lossless images over compressed, lossy images is the preservation of all data, allowing for more post-processing options. In the future, it may be beneficial to collect both raw and compressed photos during a patch test to determine which format favors image quality in those particular environmental conditions.

In addition to image size and quality, manual image annotation was the major bottleneck in this study. The time needed to annotate scallops in a photo set of several hundred thousand photos was estimated based on the results of Walker *et al.*, (2016)

who used the same AUV to collect photos for manual annotation of scallops. However, the time required to annotate my images grossly differed. Walker *et al.* (2016) annotated over 200,000 images (100% of the data set) in 98 person hours, at a rate of roughly 2,000 images per hour. In this study, the annotation team and I annotated nearly 172,000 images in 1,150 person hours, which took a full year even after downsampling to one of every four images in the NLCA. A single image annotator worked at an average rate of 150 images per hour, over 13 times slower than the rate reported by Walker *et al.* (2016). This divergence can likely be attributed to the difference between the annotation interfaces, since SIAS was created just prior to this study and a more rudimentary system was used in the former. SIAS requires typing of words into several fields, and may require more mouse clicks per photo than the prior system. Additionally, it sometimes took several seconds to load the image on the page in SIAS, undoubtedly contributing to slower annotation rates. Despite these drawbacks, the MySQL database that stored the annotations enabled analyses not easily feasible by Walker *et al.* (2016) and was a significant benefit to this study. If future groups are to use SIAS there are ways to decrease the amount of clicks and typing required per photo that may reduce annotation time, such as autofilling fields with the entries from the previous image. The most effective way to decrease overall processing time is to downsample, which has been shown in this study to drastically reduce annotation effort without sacrificing significant image coverage. Even a smaller fraction of photos would likely still be a relatively robust sample, since benthic habitat mapping image analyses typically only a small of the total set of images (Bewley *et al.*, 2015). However, it is important to note that immoderate downsampling reduces effort at the expense of precision, as uncertainty has been

shown to scale inversely with sample size (Walker *et al.*, 2016). In this study, the outlier at NLCA Site 2 A was likely attributable to a low sample size ($n = 553$ scallops). The relatively low abundance at this treatment was exacerbated by the downsampled annotation scheme, further reducing the sample size of scallops from which to calculate mortality estimates. Two other treatments (NLCA Site 1 A, ETCA Site 3 A) also had a sample size under 600 scallops (Appendix C). The precision of future scallop image annotation efforts may be aided by constraining annotation to those photos only within the dredge path, and annotating 50-100% of the total photoset.

4.5 Conclusion

This study provided estimates of sea scallop incidental mortality that support the values currently used by fishery managers. My findings suggest that dredging can result in the loss of up to 15% of the scallops that interact with the dredge but are not harvested, depending on the composition of the substrate. The AUV platform reduced some of the common sources of uncertainty in past calculations of incidental mortality, such as the inability to determine whether photos were taken inside or outside of the dredge scar, but reaffirmed the need for automated image segmentation processes in the age of big data (Gallagher, 2014). This work has demonstrated that AUVs can successfully capture organism damage in photos and lays foundations for future investigations of scallop incidental mortality. Specifically, this dataset can be processed further to relate shell height to mortality since size is already known to be a factor (Yochum and Dupaul, 2008). It could also be mined for abundances of sea stars

and crabs in order to contribute to existing knowledge about post-dredging predator aggregations (Jenkins and Brand, 2001; Caddy, 1973; Caddy, 1968). In the future, returning to the study area for continued replicate surveys over weeks or months will provide a time series that can inform on the recovery of local scallop communities following fishing disturbance. I acknowledge the uncertainty inherent in my calculations due to a low sampling size, and posit that more treatment replicates within each site may have improved precision.

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Appendix A

INCIDENTAL MORTALITY – FULL AUV MISSION

Incidental mortality was first calculated by using 100% of the photos in each AUV mission, including those outside of the dredge path. Resultant incidental mortality values were lower than those within the dredge scar only, as expected. In the ETCA, there was very little change in the amount of compromised scallops after dredge treatments (Fig. 21). Incidental mortality was below 3% across all treatments and no significant difference as a result of treatment was observed (Fig. 22). The average increase in compromised scallops following the five-tow treatment was 0.81%, lower than the equivalent value calculated for the photos within the dredge path by 1.65%. The maximum increase in compromised scallops following the five-tow treatment was 2.94%, 0.49% lower than that of the same value calculated for photos within the scar only. The average change in compromised scallops following the one-tow treatments was negative and had a spread over three times its absolute value (Table 6). In the NLCA, there was also a very small change in the amount of compromised scallops after dredge treatments (Fig. 21). However, incidental mortality was slightly higher following the five-tow treatments, matching the trend observed in mortality values within the dredge path described in the main text above (Fig. 22). The maximum value following a five-tow treatment was 10.67%, down from 14.49% observed within the dredge path (Table 7). This indicates a loss of nearly 25% of the signal due to noise introduced by including photos outside of the dredge path. Using the full set of photos for each treatment distinctly diluted the results because of the

large proportion of untreated photos included in the analysis. The amount of photos outside of the dredge scar ranged from 77.5% to 89% at one-tow treatments to 30% to 69% at five-tow treatments.

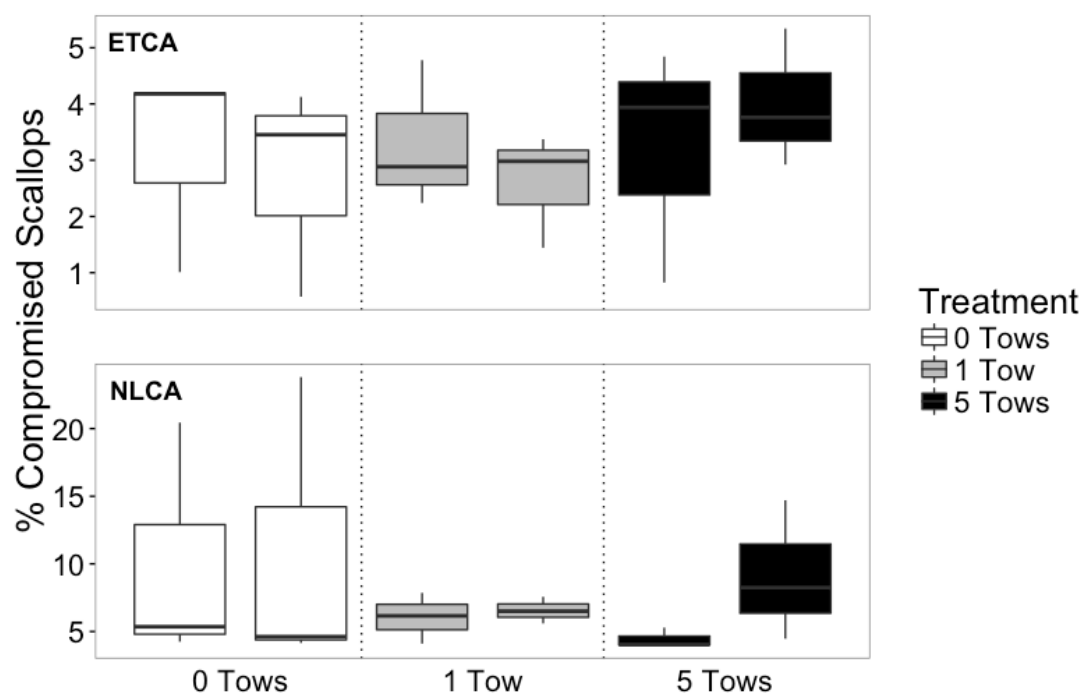


Figure 27. Percent compromised scallops before over the full AUV mission and after the three dredge treatments in the ETCA and NLCA.

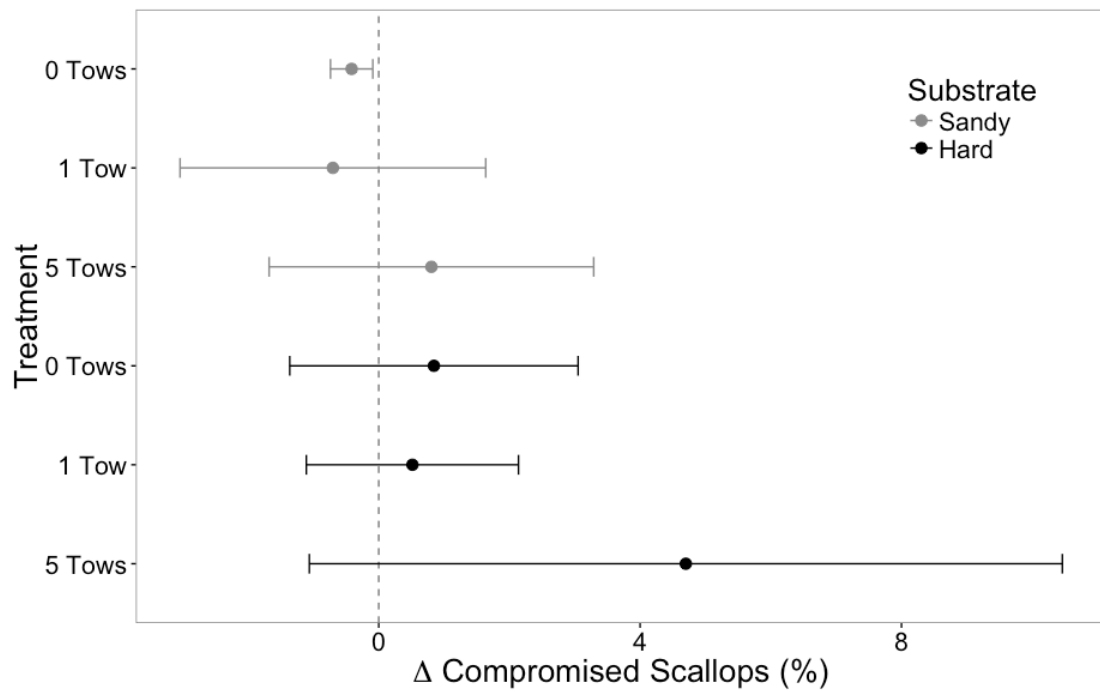


Figure 28. Mean change in compromised scallops over the full AUV mission following one, five, or zero tows on a hard substrate (NLCA) and sandy substrate (ETCA). Error bars are standard deviation (n=3).

Table 6. Change in compromised scallops (%) over the full AUV mission following treatment in the ETCA. Errors are standard deviation.

	0 Tows	1 Tow	5 Tows
Site 1	-0.08	-3.34	2.94
Site 2	-0.73	1.13	1.40
Site 3	-0.44	0.10	-1.92
Mean	-0.41 ± 0.32	-0.70 ± 2.34	0.81 ± 2.48

Table 7. Change in compromised scallops (%) over the full AUV mission following treatment in the NLCA. Errors are standard deviation.

	0 Tows	1 Tow	5 Tows
Site 1	3.37	1.49	10.67
Site 2	-0.73	1.36	4.25
Site 3	-0.10	1.41	-0.83
Mean	0.84 ± 2.20	0.52 ± 1.62	4.70 ± 5.76

Appendix B

INCIDENTAL MORTALITY – BUFFERED DREDGE SCARS

To account for scallops that encounter the dredge but land outside of the dredge path, I added a 3 m buffer around the perimeter of the dredge scar and calculated incidental mortality with this addition. This distance was chosen because of video footage obtained from a GoPro camera that depicted the dredge displacing scallops within a few meters alongside the dredge path. While 3 m is likely an overestimate (Rudders, personal communication), I chose to use that distance to ensure that the width of the buffer was at least one but no more than two photos around the perimeter. Generally, incidental mortality within the scar with the 3 m buffer was higher than that of the full AUV mission, but lower than that of the scar path only. The results were not statistically significant from either of the other two conventions (Student's t-test). In the ETCA, there was still very little change in the amount of compromised scallops after dredge treatments (Fig. 23). Incidental mortality was below 3% across all treatments and no significant difference as a result of treatment was observed (Fig. 24). The maximum increase in compromised scallops following the five-tow treatment was almost identical to the same value calculated for the entire AUV mission but the mean increased by nearly half a percent. The average change in compromised scallops following the one-tow treatments was negative and had a spread almost four times its absolute value (Table 8). In the NLCA, a larger change can be seen following dredge treatments than in the ETCA (Fig. 23). The results in the NLCA more closely match those from within the scar path only, with a

mean increase in compromised scallops following five-tow treatments of 6.91% (Fig. 24). The maximum incidental mortality value following a five-tow treatment was 12.52%, down from 14.49% observed within the dredge path, but larger than the 10.67% increase seen over the full AUV mission (Table 9). The results from the buffered scar calculations suggest that there is not a significant proportion of scallops outside of the direct dredge path that contribute to incidental mortality..

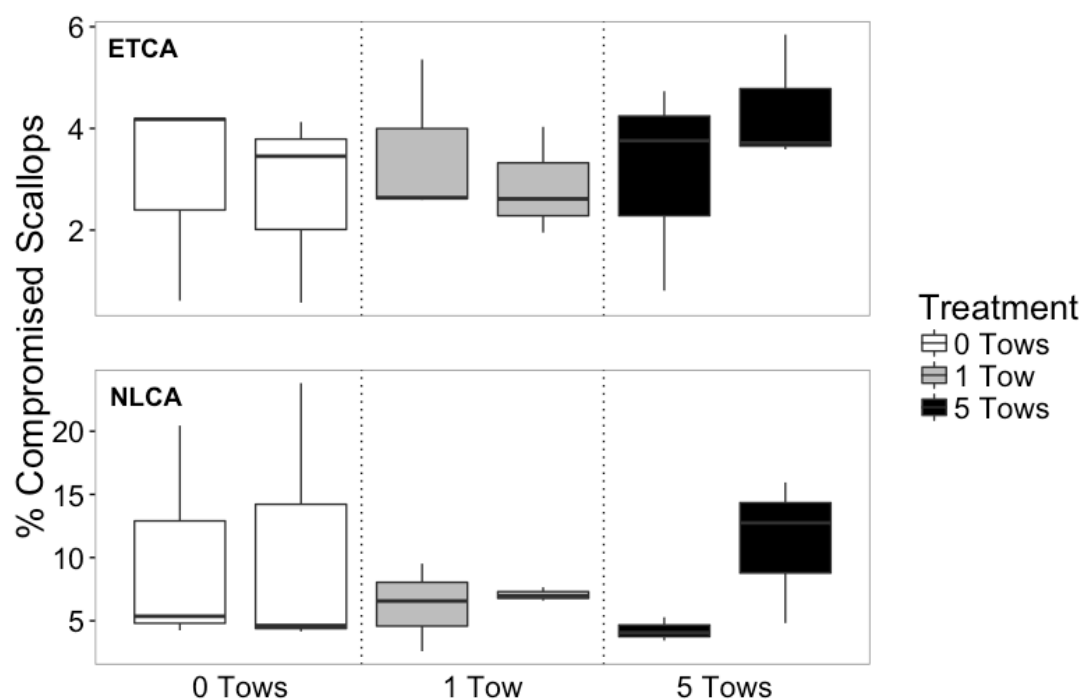


Figure 29. Percent compromised scallops within the dredge path with a 3 m buffer before and after the three dredge treatments in the ETCA and NLCA.

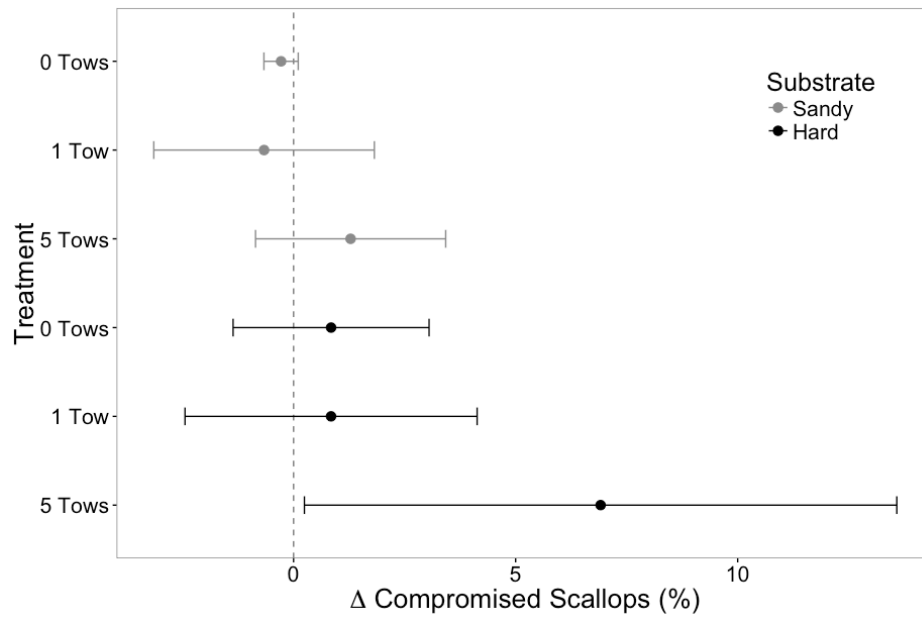


Figure 30. Mean change in compromised scallops within the dredge path with a 3 m buffer following one, five, or zero tows on a hard substrate (NLCA) and sandy substrate (ETCA). Error bars are standard deviation (n=3).

Table 8. Change in compromised scallops (%) within the dredge path with a 3 m buffer following treatment in the ETCA. Errors are standard deviation.

	0 Tows	1 Tow	5 Tows
Site 1	-0.08	-3.41	2.91
Site 2	-0.73	-0.02	2.09
Site 3	-0.04	1.44	-1.14
Mean	-0.28 ± 0.39	-0.66± 2.48	1.28 ± 2.14

Table 9. Change in compromised scallops (%) within the dredge path with a 3 m buffer following treatment in the NLCA. Errors are standard deviation.

	0 Tows	1 Tow	5 Tows
Site 1	3.37	4.00	12.52
Site 2	-0.73	-2.56	8.69
Site 3	-0.10	1.10	-0.46
Mean	0.84 ± 2.06	0.84 ± 3.29	6.91 ± 6.67

Appendix C

SCALLOP SAMPLE SIZES

Table 10. Incidental mortality values (%) within the dredge path in the ETCA along with the number of total, healthy, and compromised scallops annotated. One-tow, five-tow, and zero-tow (control) dredge treatments are denoted A, B, and C, respectively. At Site 3, B and C are switched. A 1 indicates a pre-treatment survey and a 2 indicates a post-treatment survey.

ETCA	Treatment	Num. scallops	Num. healthy	Num. compromised	Percent healthy	Percent compromised
	Site 1 A1	1677	1571	105	93.68	6.26
	Site 1 A2	852	821	30	96.36	3.52
	Site 1 B1	11532	11438	86	99.18	0.75
	Site 1 B2	7970	7631	333	95.75	4.18
	Site 1 C1	8010	7670	337	95.76	4.21
	Site 1 C2	8941	8569	369	95.84	4.13
	Site 2 A1	2824	2720	94	96.32	3.33
	Site 2 B1	7191	6964	224	96.84	3.12
	Site 2 B2	1994	1816	174	91.07	8.73
	Site 2 A2	2729	2656	72	97.33	2.64
	Site 2 C1	7009	6710	293	95.73	4.18
	Site 2 C2	7702	7436	266	96.55	3.45
	Site 3 A1	534	527	6	98.69	1.12
	Site 3 C1	2532	2385	147	94.19	5.81
	Site 3 A2	383	357	25	93.21	6.53
	Site 3 C2	533	509	22	95.50	4.13
	Site 3 B1	4245	4219	26	99.39	0.61
	Site 3 B2	4878	4850	28	99.43	0.57

Table 11. Incidental mortality values (%) within the dredge path in the NLCA along with the number of total, healthy, and compromised scallops annotated. One-tow, five-tow, and zero-tow (control) dredge treatments are denoted A, B, and C, respectively. A 1 indicates a before-treatment survey and a 2 indicates an after-treatment survey.

NLCA	Treatment	Num. scallops	Num. healthy	Num. compromised	Percent healthy	Percent compromised
	Site 1 A1	553	538	15	97.2875	2.7125
	Site 1 B1	2595	2505	84	96.5318	3.2370
	Site 1 C1	978	777	200	79.4479	20.4499
	Site 1 B2	1303	1072	231	82.2717	17.7283
	Site 1 C2	823	626	196	76.0632	23.8153
	Site 2 A1	696	618	76	88.7931	10.9195
	Site 2 C1	4613	4362	247	94.5589	5.3544
	Site 2 B1	1392	1346	44	96.6954	3.1609
	Site 2 A2	553	544	9	98.3725	1.6275
	Site 2 C2	4849	4624	224	95.3599	4.6195
	Site 2 B2	1305	1154	151	88.4291	11.5709
	Site 3 A1	868	814	53	93.7788	6.1060
	Site 3 C1	9420	9014	400	95.6900	4.2463
	Site 3 B1	8250	7841	405	95.0424	4.9091
	Site 3 A2	876	793	83	90.5251	9.4749
	Site 3 C2	11711	11224	486	95.8415	4.1499
	Site 3 B2	10433	9820	604	94.1244	5.7893
	Site 1 A2	397	377	20	94.9622	5.0378

Appendix D

SIDE-SCAN SONAR MOSAICS

Following are the side-scan sonar mosaics created for all scallop incidental mortality AUV missions. All mosaics have a resolution of 0.10 m.

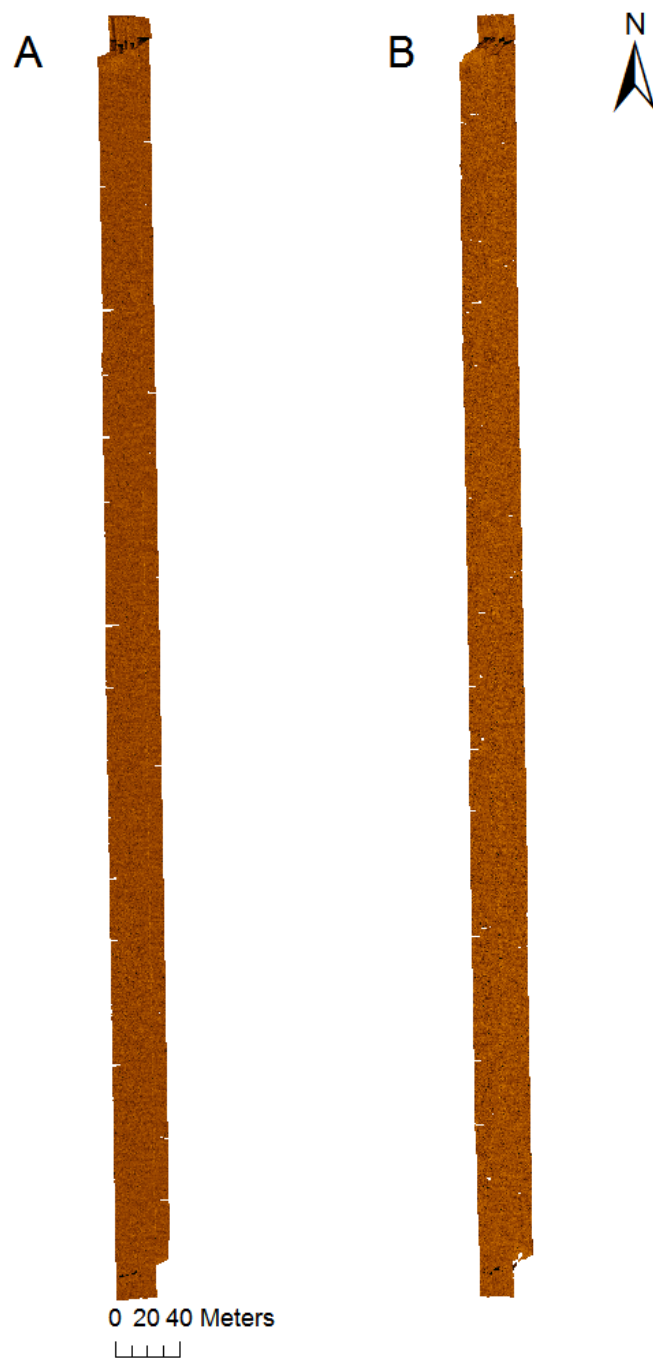


Figure 31. Side-scan sonar mosaics of ETCA one-tow treatment: Site 1 A1 (A) and A2 (B).

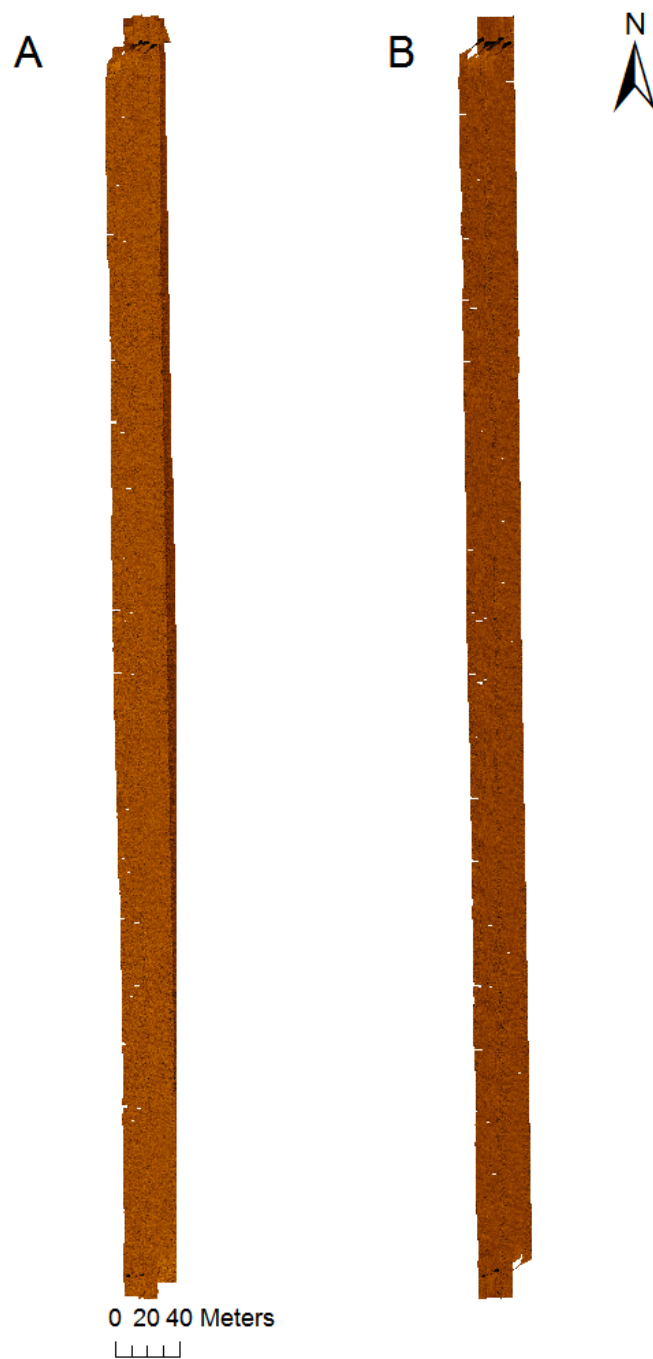


Figure 32. Side-scan sonar mosaics of ETCA five-tow treatment: Site 1 B1 (A) and B2 (B).

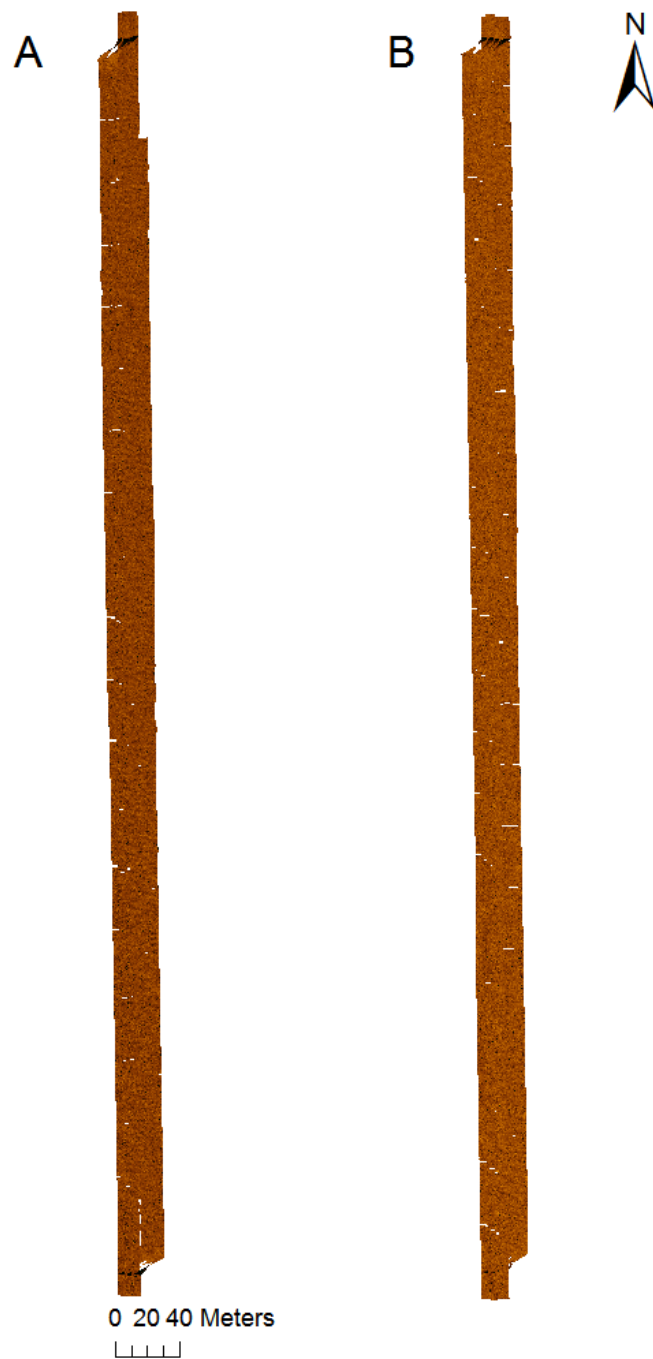


Figure 33. Side-scan sonar mosaics of ETCA zero-tow treatment (control): Site 1 C1 (A) and C2 (B).

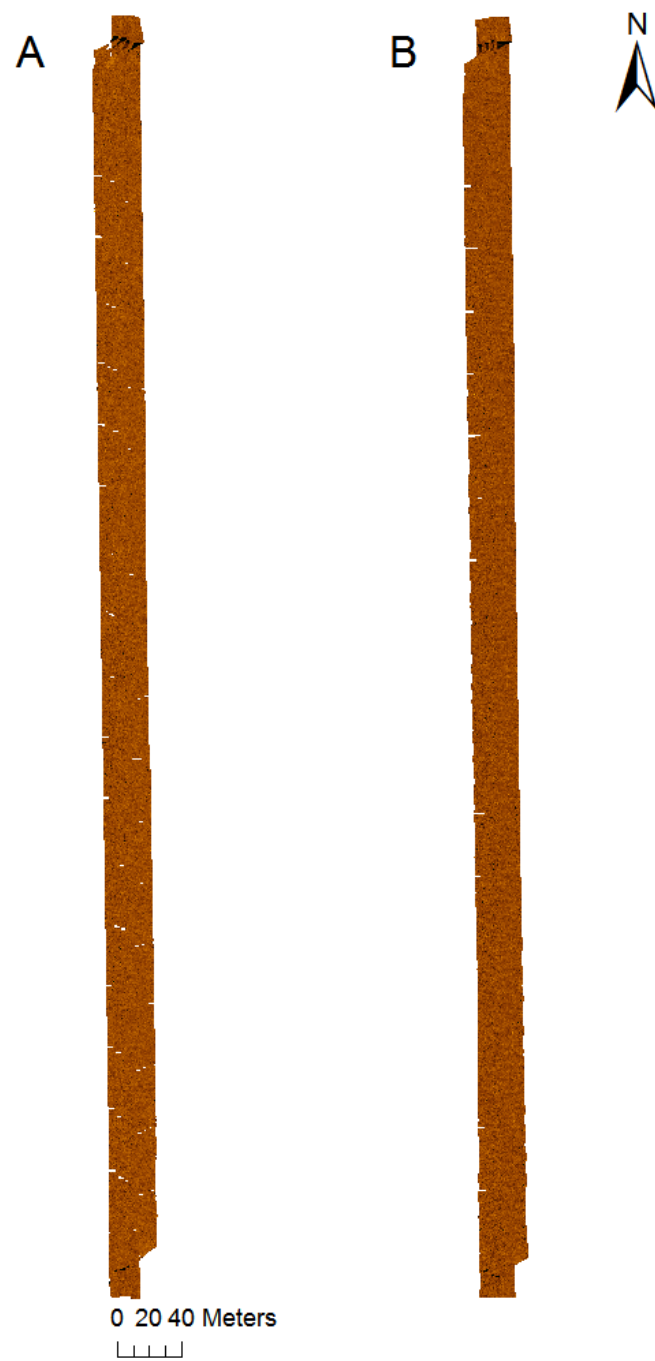


Figure 34. Side-scan sonar mosaics of ETCA zero-tow treatment (control): Site 2 C1 (A) and C2 (B).

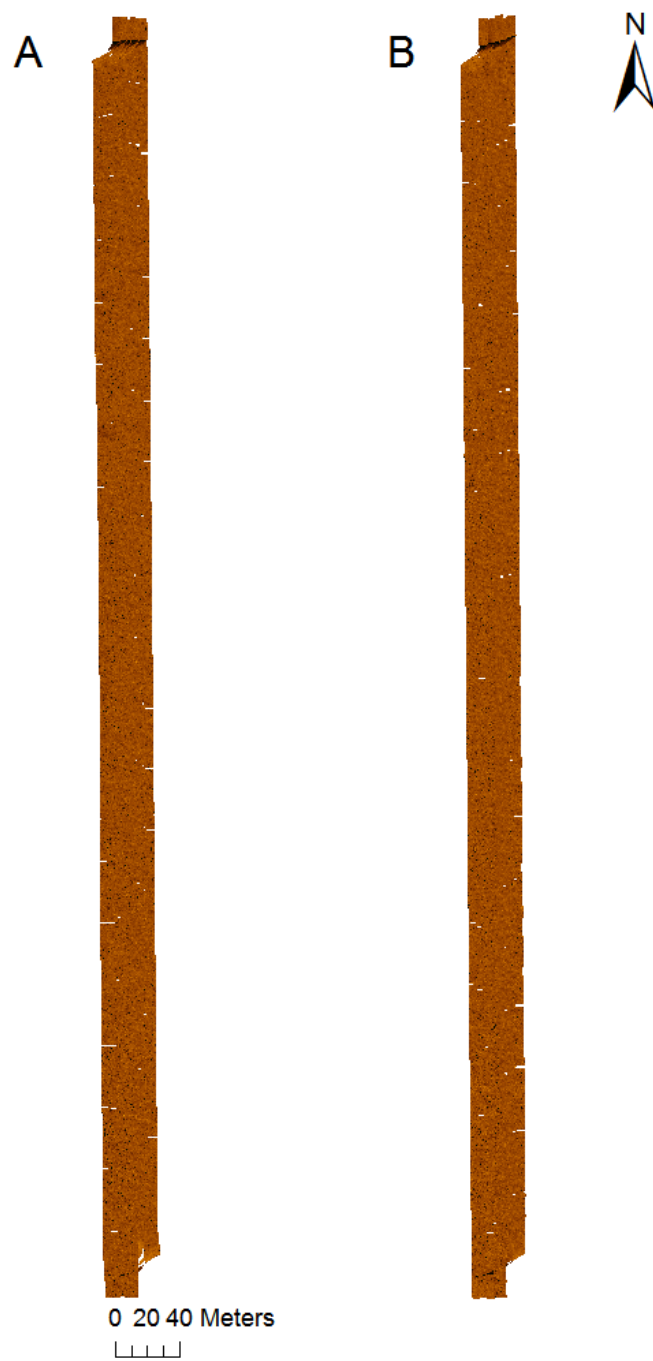


Figure 35. Side-scan sonar mosaics of ETCA one-tow treatment: Site 3 A1 (A) and A2 (B).

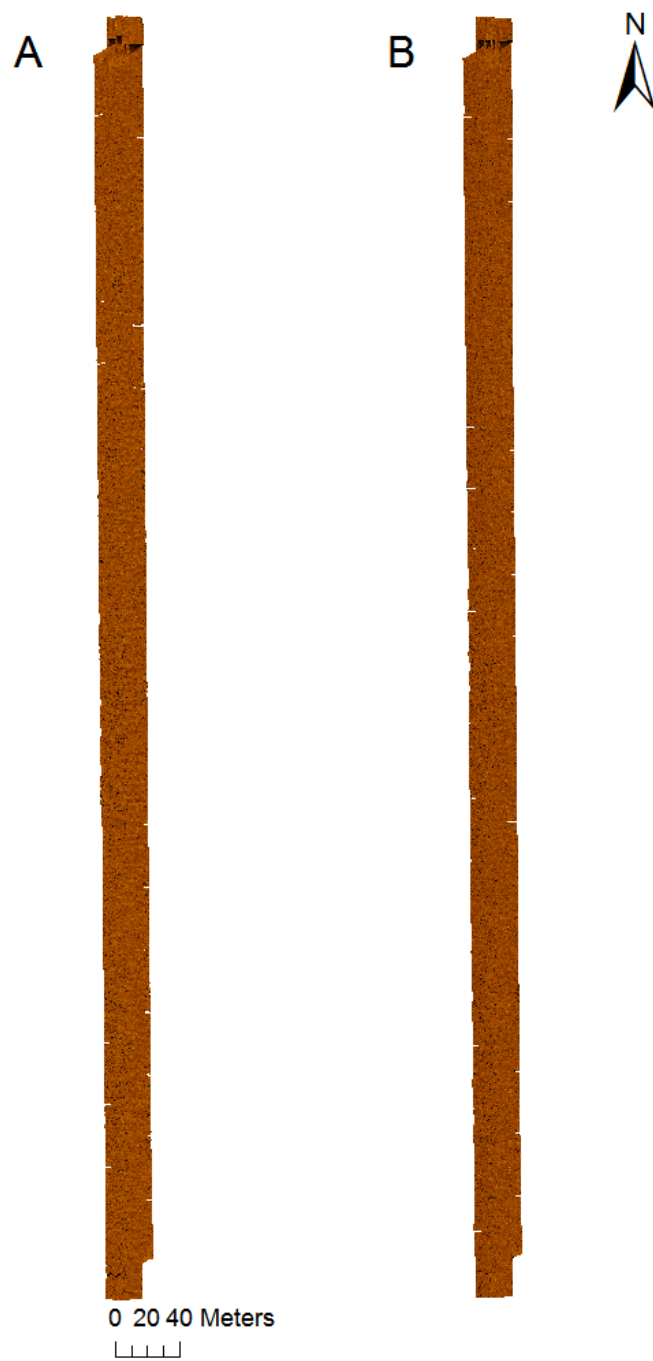


Figure 36. Side-scan sonar mosaics of ETCA five-tow treatment: Site 3 B1 (A) and B2 (B).

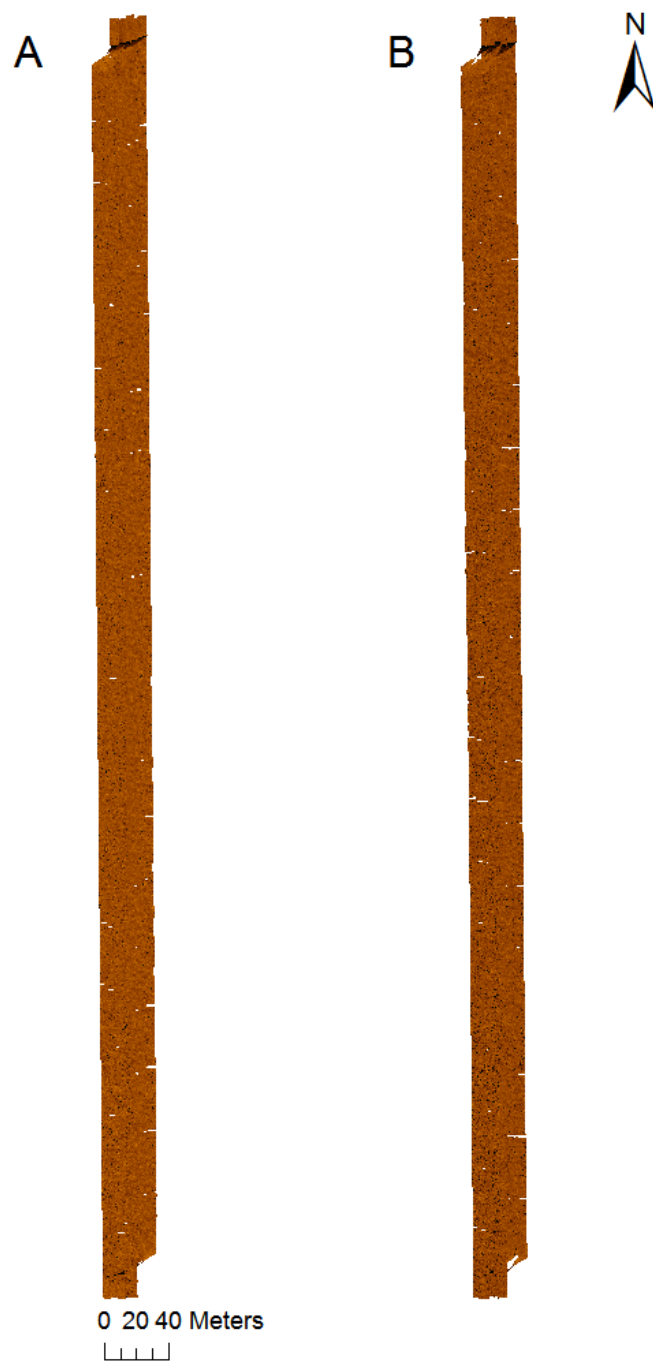


Figure 37. Side-scan sonar mosaics of ETCA one-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 3 A2 (A) and A3 (B).

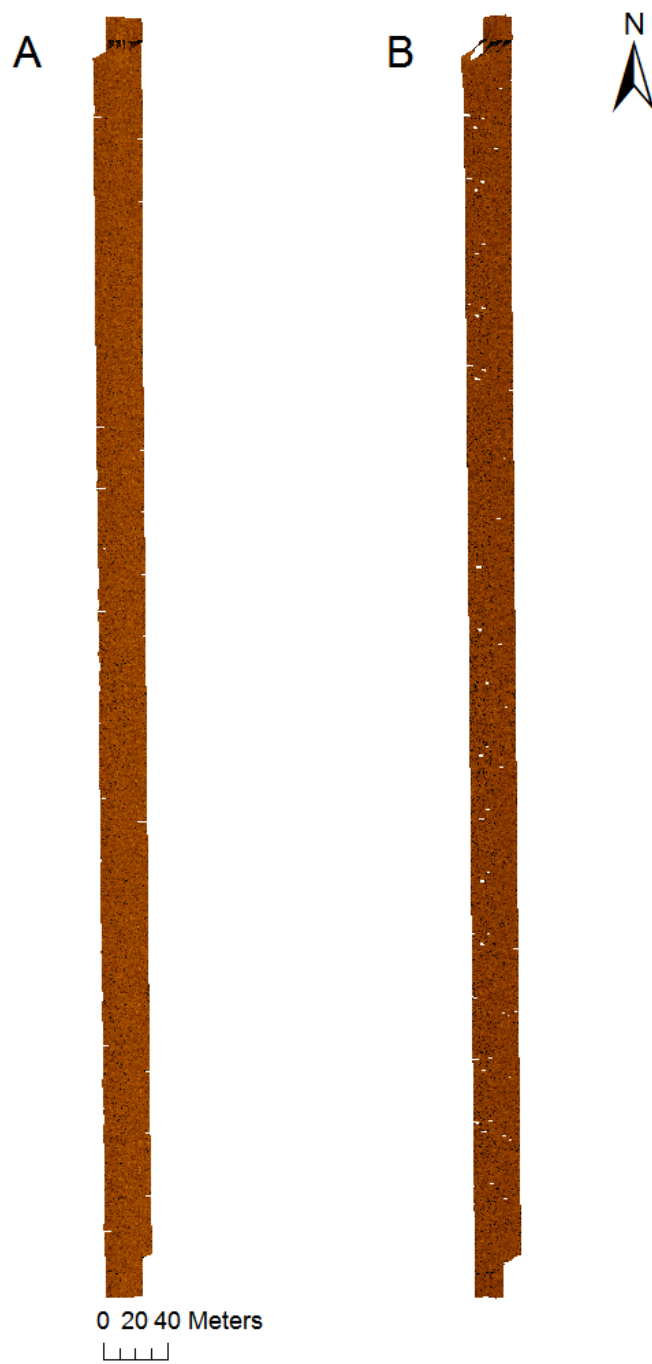


Figure 38. Side-scan sonar mosaics of ETCA five-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 3 B2 (A) and B3 (B).

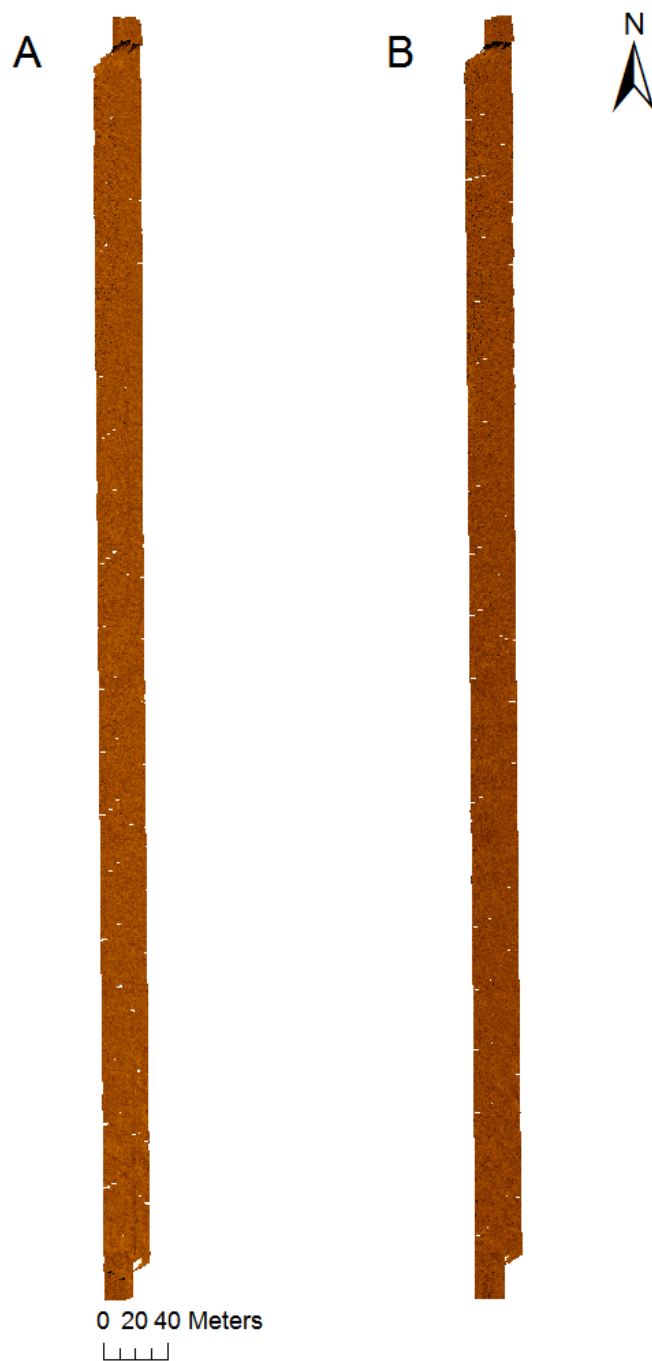


Figure 39. Side-scan sonar mosaics of ETCA zero-tow treatment (control) after eight weeks with initial post-dredge mosaic for comparison: Site 3 C2 (A) and C3 (B).

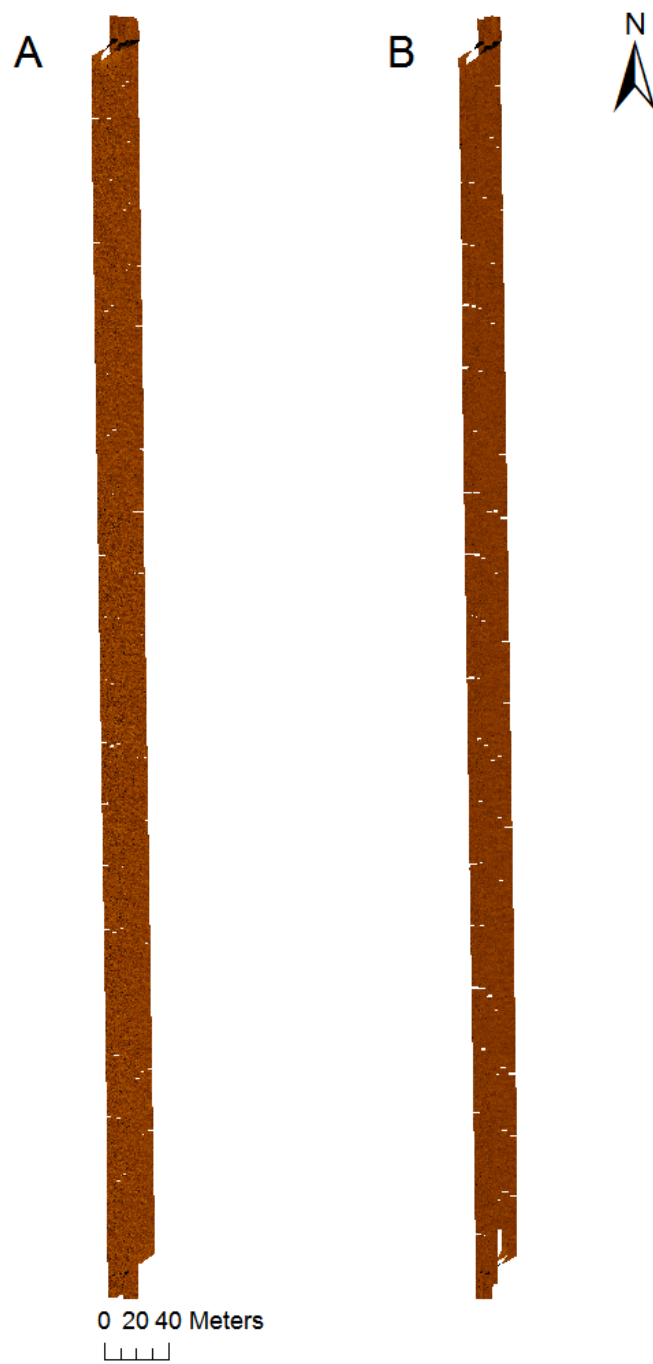


Figure 40. Side-scan sonar mosaics of ETCA one-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 2 A2 (A) and A3 (B).

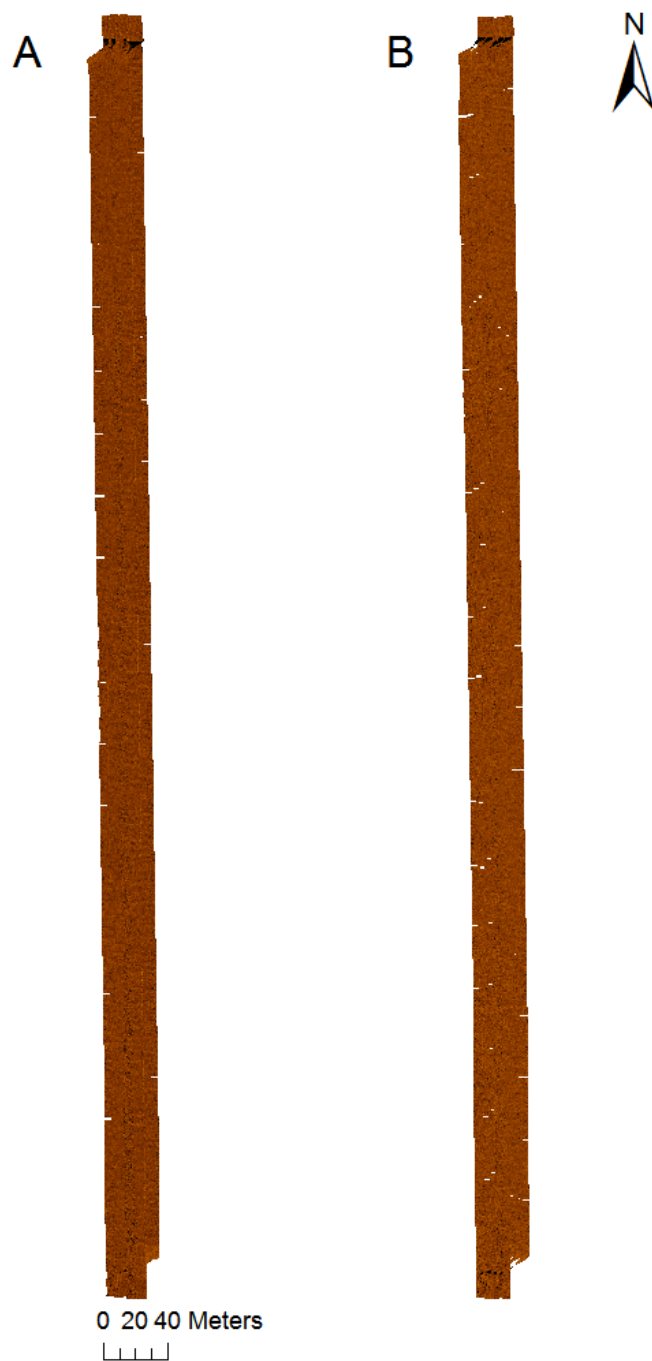


Figure 41. Side-scan sonar mosaics of ETCA five-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 2 B2 (A) and B3 (B).

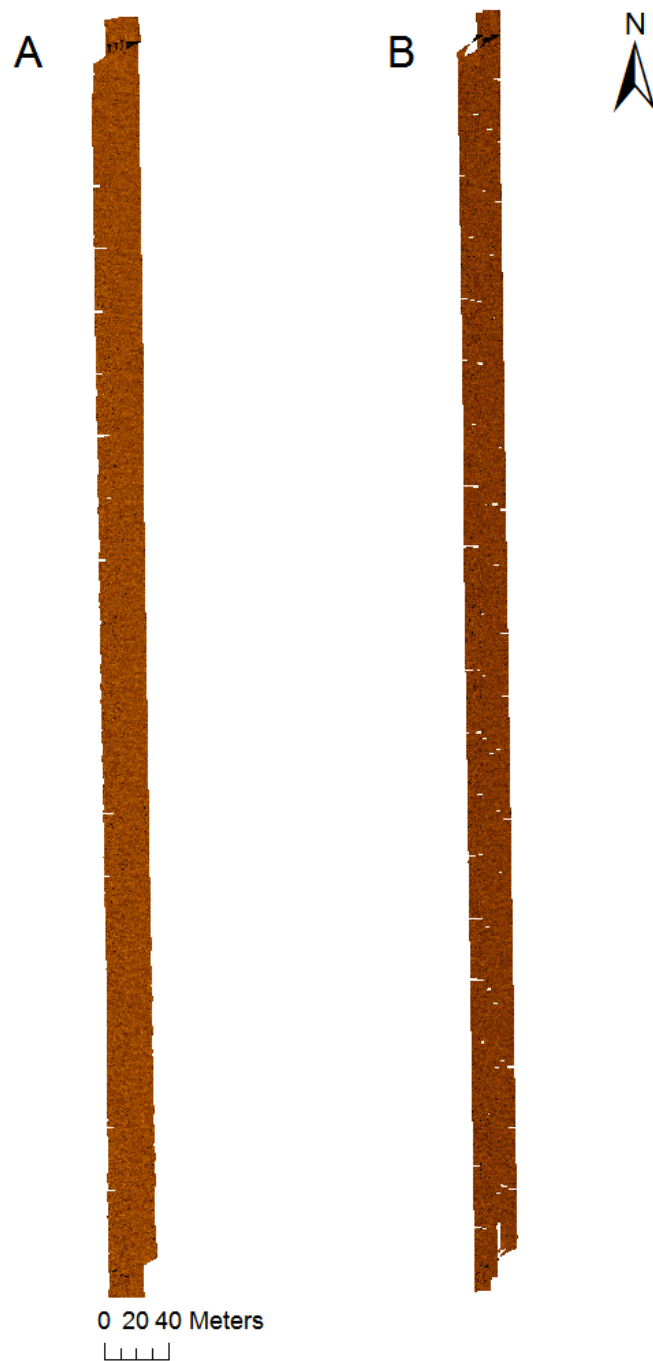


Figure 42. Side-scan sonar mosaics of ETCA zero-tow treatment (control) after eight weeks with initial post-dredge mosaic for comparison: Site 2 C2 (A) and C3 (B).

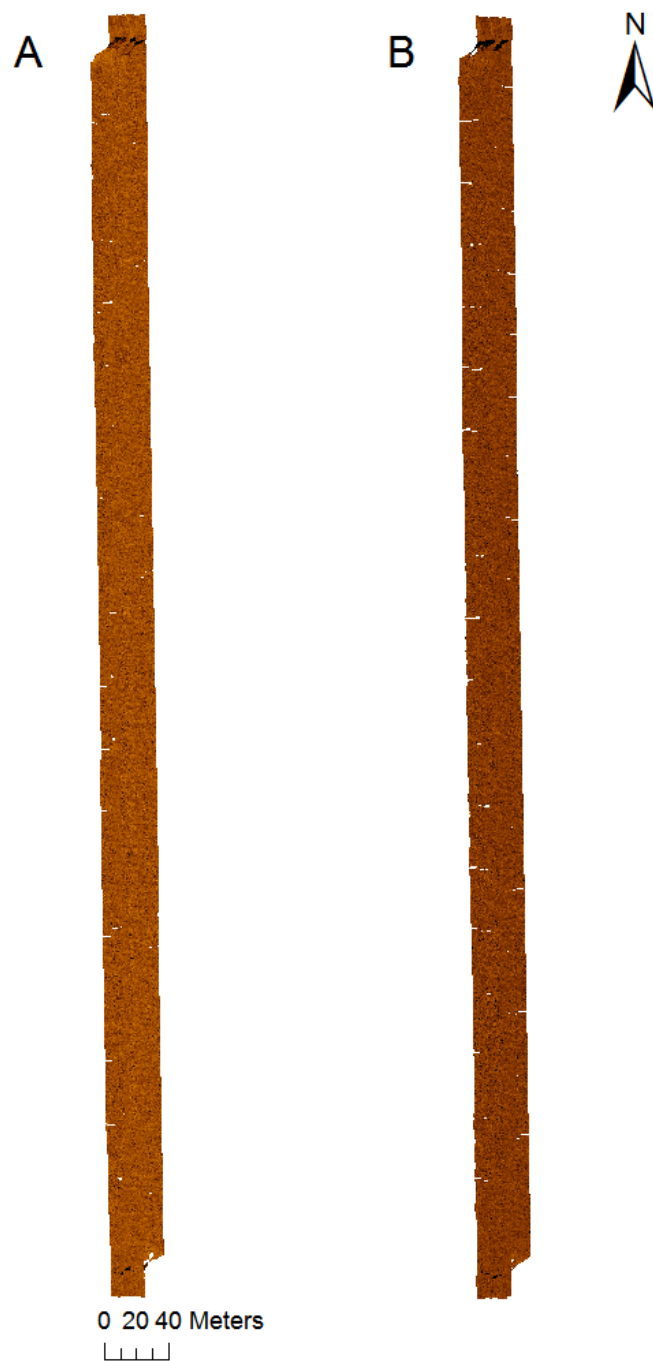


Figure 43. Side-scan sonar mosaics of ETCA one-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 1 A2 (A) and A3 (B).

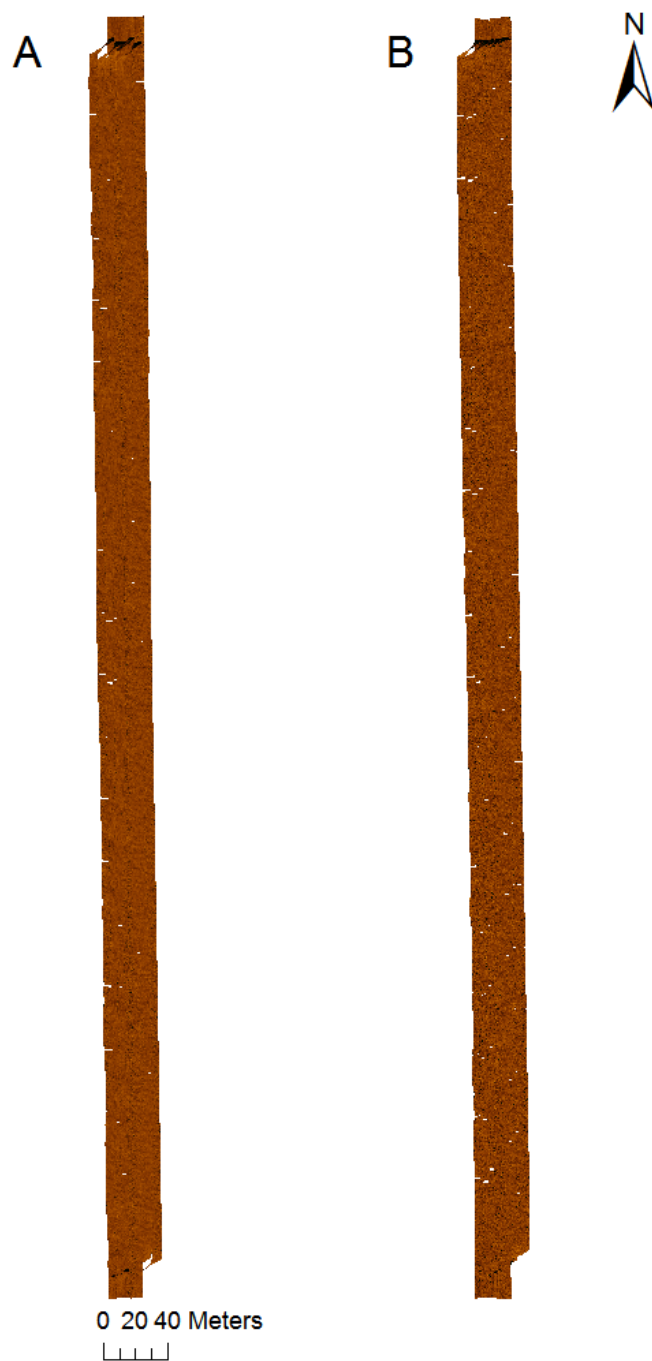


Figure 44. Side-scan sonar mosaics of ETCA five-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 1 B2 (A) and 13 (B).

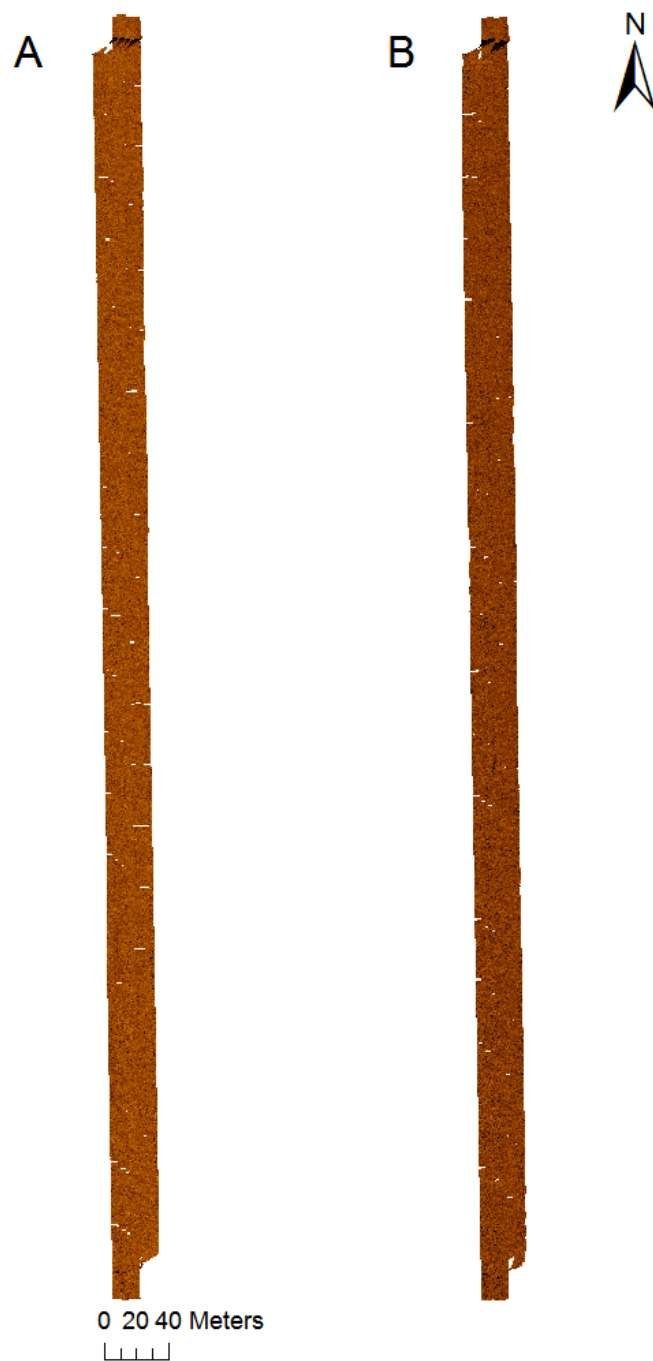


Figure 45. Side-scan sonar mosaics of ETCA zero-tow treatment after eight weeks with initial post-dredge mosaic for comparison: Site 1 C2 (A) and C3 (B).



Figure 46. Side-scan sonar mosaics of NLCA one-tow treatment: Site 1 A1 (A) and A2 (B).

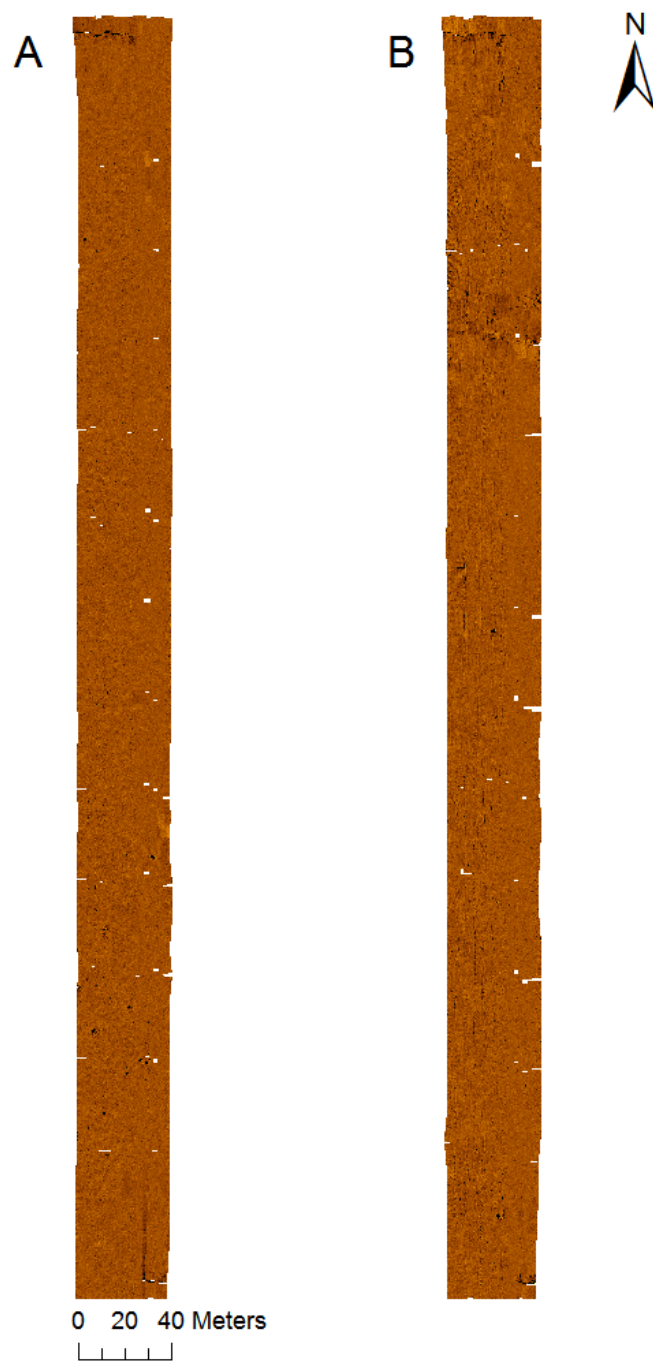


Figure 47. Side-scan sonar mosaics of NLCA five-tow treatment: Site 1 B1 (A) and B2 (B).



Figure 48. Side-scan sonar mosaics of NLCA zero-tow treatment (control): Site 1 C1 (A) and C2 (B).

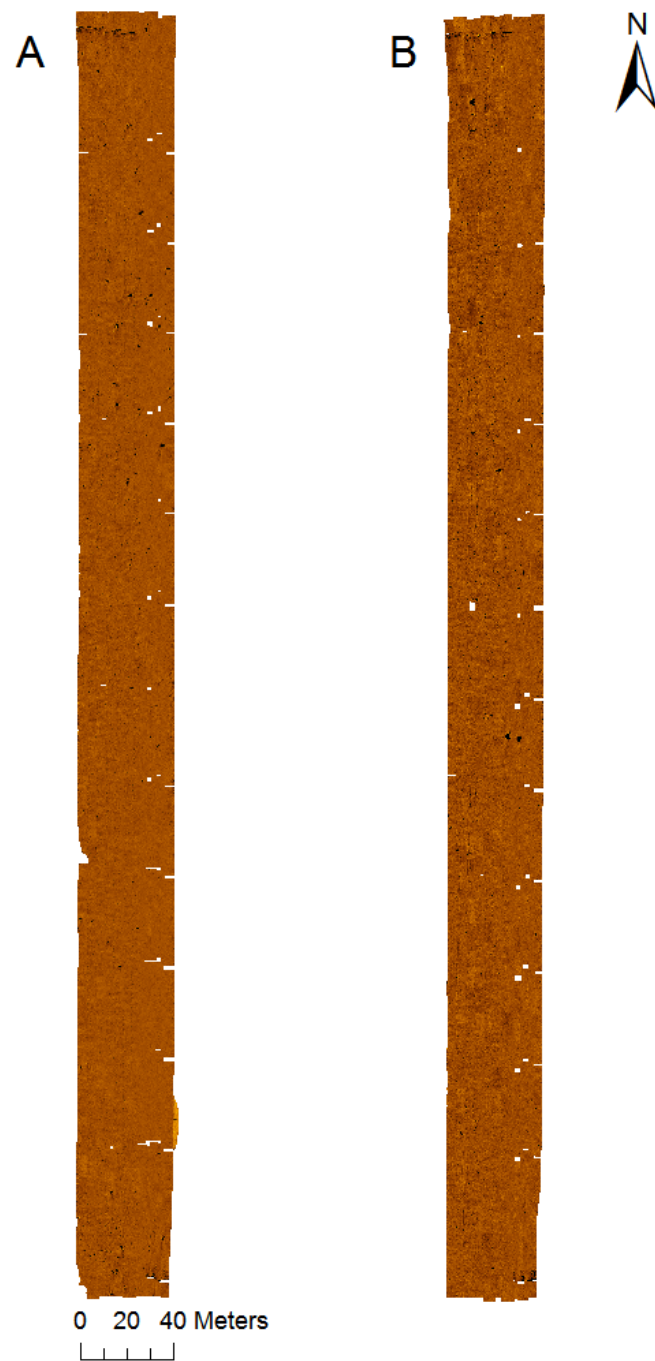


Figure 49. Side-scan sonar mosaics of NLCA one-tow treatment: Site 2 A1 (A) and A2 (B).

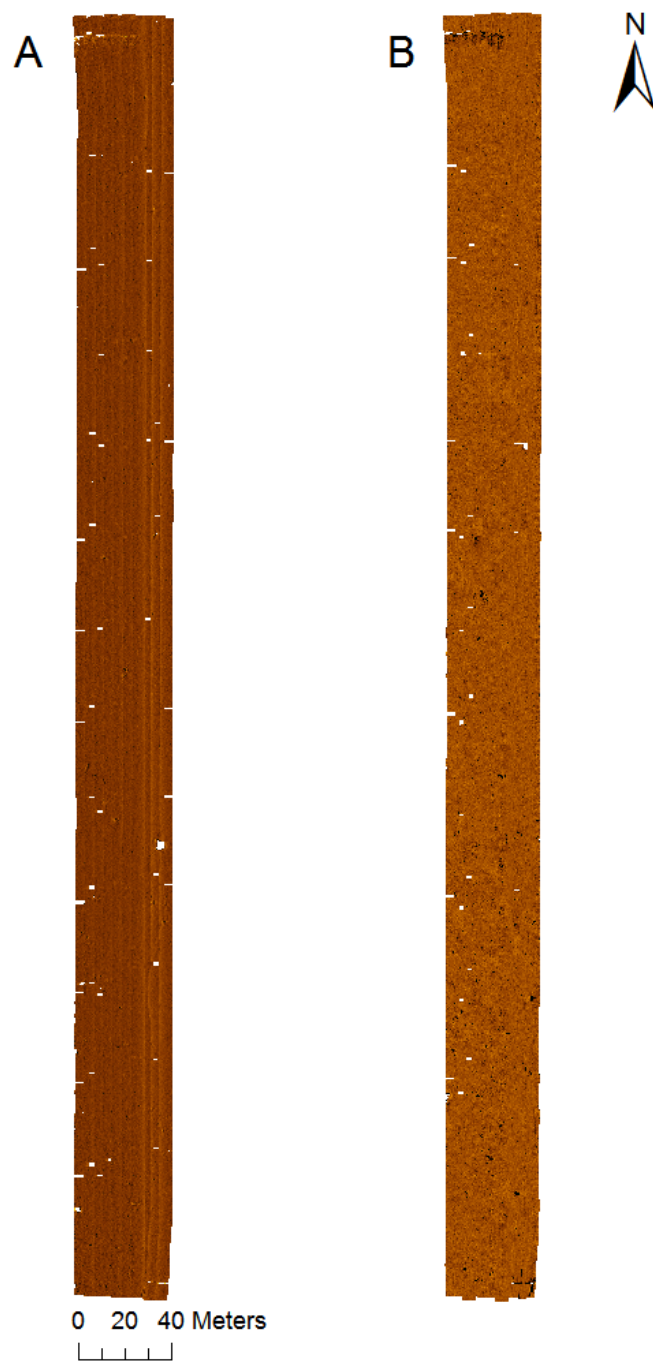


Figure 50. Side-scan sonar mosaics of NLCA five-tow treatment: Site 2 B1 (A) and B2 (B).

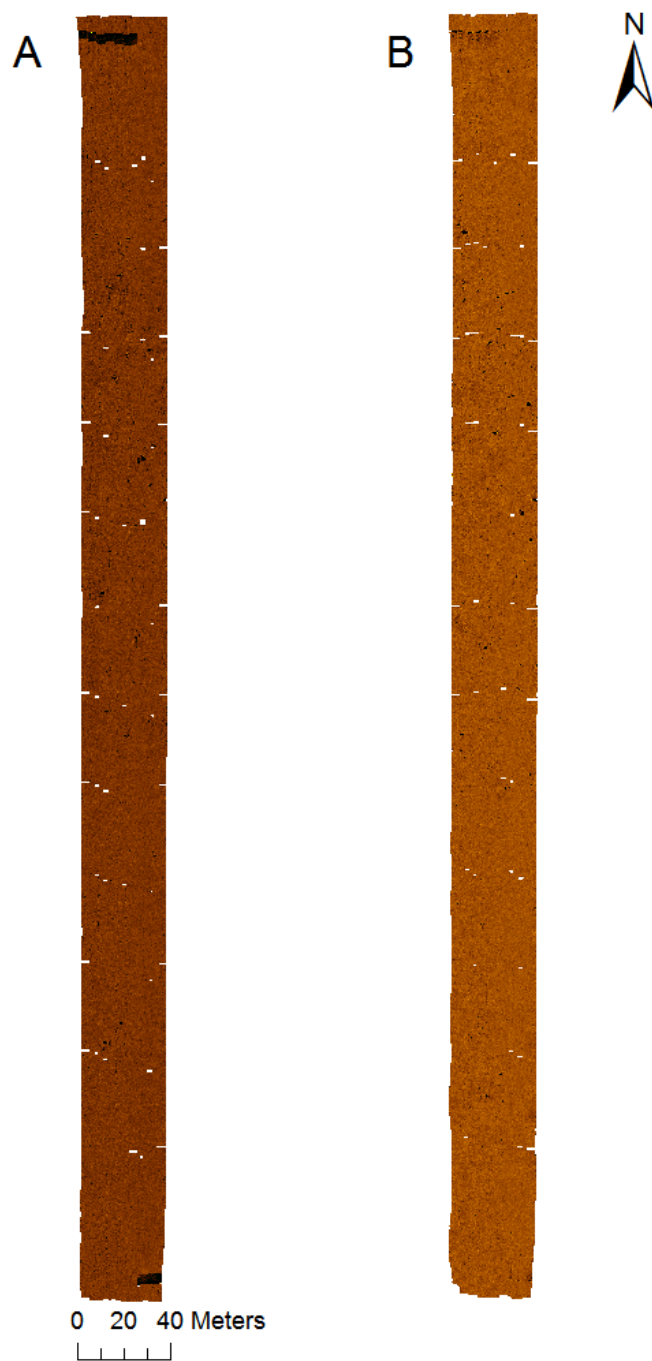


Figure 51. Side-scan sonar mosaics of NLCA zero-tow treatment (control): Site 2 C1 (A) and C2 (B).

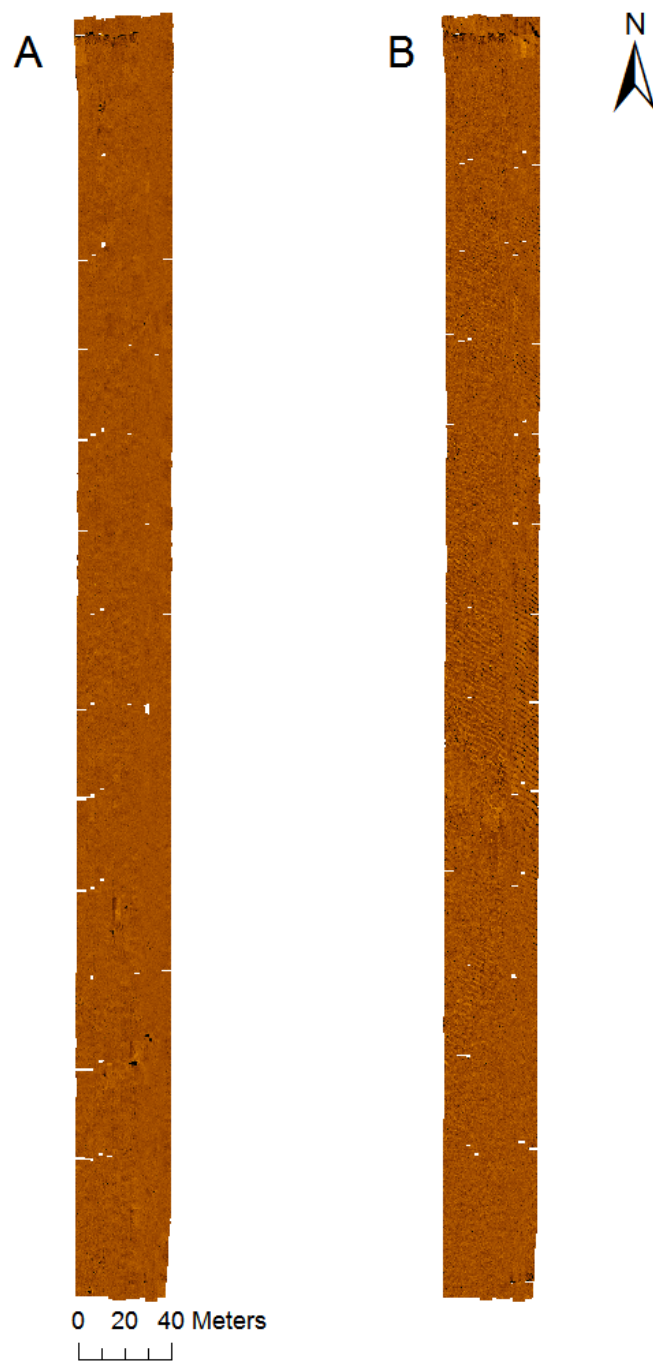


Figure 52. Side-scan sonar mosaics of NLCA one-tow treatment: Site 3 A1 (A) and A2 (B).

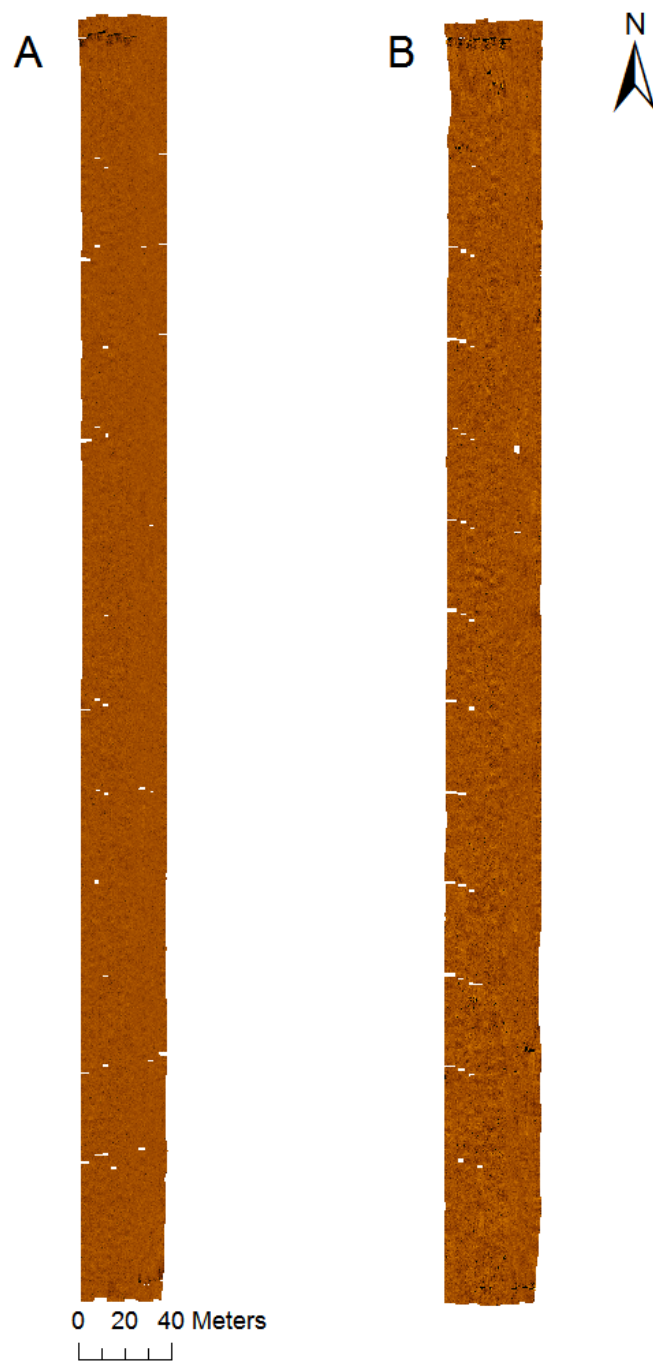


Figure 53. Side-scan sonar mosaics of NLCA five-tow treatment: Site 1 B1 (A) and B2 (B).