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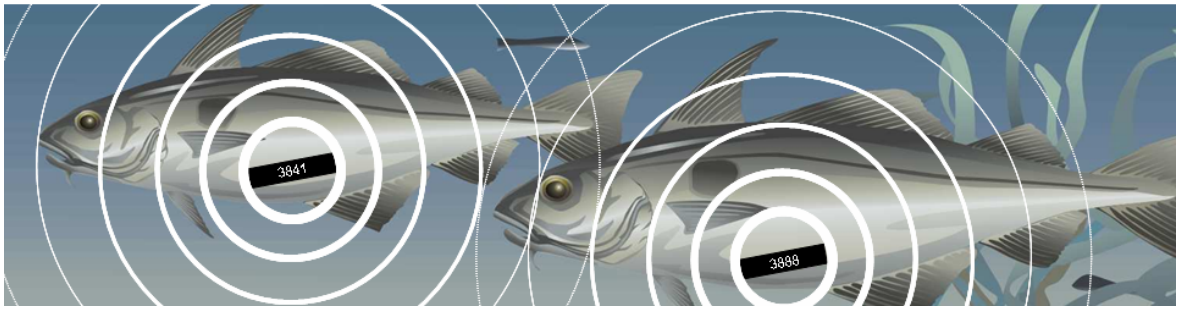
Is Closed Area I serving as a refuge for haddock? A study of fine-scale behavior through the use of ultrasonic tagging techniques



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I. Executive Summary

- According to the fishing community, Closed Area I (CAI) on Georges Bank is beneficial for haddock and may have been an important contributor to the recent recovery of New England haddock stocks. However, very little data exists to assess whether haddock actually reside in CAI.
- An extensive literature review revealed that a non-overlapping acoustic receiver array would be the best way to observe residency and fine-scale movements of acoustically tagged haddock in CAI.
- Prior to deployment, laboratory and field experiments were conducted to verify that haddock are robust to surgical acoustic tag placement protocols; survival rates for long-term (6 week) laboratory and short-term (3 day) field (caging) trials were 58% and 83%, respectively. A significant sub-lethal effect of tagging on fish condition factor was detected but attributed to the combined effect of tagging and holding (i.e., tank effects). Overall, the trials were deemed successful enough to move forward with the full-scale field tracking experiment.
- Two months (August-September 2007) of acoustic detection data from the full array of 18 receivers (before all but 3 were lost to a hurricane) revealed a high degree of residency for a group of haddock representing about one third of the 78 tag releases (after correcting for 11 known deaths). Another third were considered transient (having left the area shortly after tagging) and the final third were never detected.
- Supplementary data was available from the 3 remaining receivers (until December 2007), 2 others found and returned by industry members in 2008, and from mobile (boat-based) telemetry in August of 2008, and confirmed a pattern of residency.
- Additional information on haddock behavior and preferences was generated: 1) Haddock preferred deeper depths (> 150 m) in the northwest portion of CAI which kept them away from the western boundary; 2) haddock moved primarily along a “haddock highway” in a north-south direction in the central portion of CAI (likely moving with the tides, thereby explaining high swimming speeds); and 3) haddock were more active at night than during daytime hours.
- Overall, results support the hypothesis that at least a portion of haddock are resident to CAI. Therefore closed areas may indeed be beneficial to rebuilding haddock stocks.

II. General Introduction[1]

Haddock (*melanogrammus aeglefinus*) were once the mainstay of the New England groundfishing fleet with landings from Georges Bank averaging 46 kt between 1931-1960 (Brodziak et al. 2008). However, as was the case for most groundfish stocks in this region, overfishing during the latter half of the 20th century took it's toll such that haddock landings had declined more than 100-fold by the 1990's from mid-century highs (Brodziak et al. 2008). In an effort to end overfishing and rebuild haddock and other groundfish stocks, the National Marine Fisheries Service (NMFS) introduced a range of regulatory actions including the establishment of year-round offshore area closures (closed to bottom-tending mobile gear; Figure 1, pg. 65). As a result of these measures, fishing mortality dropped from over 0.5 in 1993 to below 0.2 in 1995 and haddock stocks have been rebuilding ever since (Brodziak et al. 2008). In particular, spawner biomass increased from 15 kt in 1993 to 117 kt in 2004 and a series of high recruitment years have occurred since 2000 with an outstanding year class in 2003, the highest on record (Brodziak et al. 2006).

In addition to stock increases, there is compelling spatial evidence to suggest that closed areas may be favoring the ongoing recovery of haddock. In an analysis of fishing patterns adjacent to Gulf of Maine and Georges Bank closed areas, Murawski et al. (2005) identified haddock as the species which may benefit most from this management tool. 73% of the haddock catch (2001-2003) was within 5km of closed areas despite less than 25% of the groundfishing effort within this range. Only yellowtail flounder (*Pleuronectes ferrugineus*) came close to this type of catch distribution with 50% of the catch within 5km. In contrast, only 20% of the cod (*Gadus morhua*) catch was within 5km of closed areas. These data suggest that haddock biomass may be building up in closed areas, and less so in adjacent open areas. In other words, closed areas in the NE US appear to be benefiting haddock more than any other groundfish species.

In order for haddock to benefit from closed areas, to the point where they appear to be "spilling over" into the fishery, they would have to display some degree of residency within (i.e., closed areas should be the center of their aggregation). While regular trawl

[1] This introduction is repeated in manuscript 2.

surveys conducted by the NMFS provide a broad-scale and random sampling of groundfish distribution throughout the entire Gulf of Maine and Georges Bank region, the spatial and temporal resolution is not sufficient to address specific questions of habitat use and movement of haddock on fine scales as, for instance, inside a closed area. On the other hand, questions of habitat associations, movement and residency behavior have been addressed in other species at various scales using acoustic monitoring technologies but never with haddock. For instance, Lindholm et al. (2007) were able to infer site fidelity in a subset of cod tagged with acoustic transmitters in the western Gulf of Maine (tagged cod were detected on an array of 4 acoustic receivers fixed near the sea floor). Similarly, acoustic arrays of different configurations have been applied to monitor large-scale migration in cod (Comeau et al. 2002), spawning behavior in cod (Howell 2009), foraging behavior in great white sharks around seal colonies (Klimley et al. 2001) and use of marine reserves in Caribbean sharks (Chapman et al. 2005). Residency of marine fish to particular areas may also be examined by large-scale conventional tagging operations (e.g., Howell et al. 2008). However, in this case, movement data is dependent on fishery returns which may not be suitable for closed area research.

Aside from the fine-scale offshore work undertaken by Lindholm et al. (2007), and to the author's knowledge, no other study has ever applied automated acoustic monitoring to track residency and movement behavior of fish in a large-scale offshore area closure. The purpose of the present study was therefore to apply acoustic tracking to test the hypothesis that haddock show a degree of residency in Closed Area I, an area 30 miles from shore, measuring ~ 4,000 km^2, and known to overlap significantly with preferred haddock habitat (Brodziak 2005). Given the strengths of acoustic tracking technology (i.e., presence/absence of tagged fish within detection range of receivers in near real time), this study also aims to provide additional data on haddock biology including swimming speed, habitat utilization and diel activity patterns.

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III. Notes on Report Structure and Project Objectives

This project report is presented as two separate manuscripts that have been prepared in standard format for submission to the primary literature. The overall goal of this project was to apply automated acoustic monitoring to examine haddock residency and fine-scale movement behavior inside of Closed Area I. Before the method could be applied, it was imperative to conduct trials to verify that haddock can withstand the stress of surgical tag placement. Some concern about their robustness to the stresses of handling and tagging was raised by a previous NEC funded tagging study (Rudolph 2009). The first manuscript, *Effects of intraperitoneal acoustic tag implantation on haddock (*Melanogrammus aeglefinus*) survival and condition*, addresses this concern and sets the stage for the main part of this project outlined in the second manuscript, *Monitoring haddock (*Melanogrammus aeglefinus*) residency and movement behavior in an extensive offshore closed area with a non-overlapping acoustic receiver array*. Figure and tables are arranged by manuscript and all data have been presented in summary form to allow for an objective appraisal of the results. The full dataset from receiver log files totaling over 170,000 data points will be made available to the NEC in database format.

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Effects of intraperitoneal acoustic tag implantation on haddock (*Melanogrammus aeglefinus*) survival and condition

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Abstract

The effects of intraperitoneal acoustic tag implantation were examined on long-term (6 week) haddock survival and condition (Fulton's condition factor and liver-somatic index) in the laboratory, and on short-term (3 day) survival in the field. Haddock responded well to clove oil anaesthesia (40 mg $\cdot$ L^{-1}; mean ± SD time to induction was 249 ± 23 seconds, and mean time to full recovery was 1055 ± 40 seconds). Six-week survival rates for haddock that underwent surgical tag implantation and control haddock were 50% and 86%, respectively; survival rate of implanted haddock corrected for control mortality was 58% and 30 day survival was 62.5%. Fulton's condition factor (FCF) was significantly lower for haddock that underwent surgery and survived the duration of the experiment compared to control haddock that also survived 6 weeks; FCF did not differ among implanted and control haddock that died prematurely. Liver-somatic index (LSI), on the other hand, did not differ among treatment groups (i.e., implanted versus control haddock) but was lower in haddock that died prematurely compared to haddock that survived the entire experiment. These condition index results suggest that haddock suffered increased stress associated with tag insertion (which was likely compounded by tank effects, most notably increased infection) and that mortality was associated with cessation of feeding which was most likely due to infection (a tank effect). Field trials showed that haddock can survive the capture, surgery, release experience under realistic field conditions (i.e, 90 m depth); survival rate at this depth after 3 days for implanted and control haddock was 83% and 75%, respectively. Results from this experiment support further use of intraperitoneal acoustic tag implantation as a means of acoustic tracking of haddock in the wild with the acknowledgement that some mortality and sublethal effects may be unavoidable.

1. Introduction

Acoustic tagging, or telemetry, is becoming a popular method for tracking fish in their natural environments. A great deal can be learned about fish migration (Welch et al. 2002), population structure (Comeau et al. 2002), foraging behaviors (Klimley et al. 2001) and habitat associations (Lindholm et al. 2007) using this method which does not rely on recapturing the tagged fish, an important constraint for conventional tagging studies (Bolle et al. 2005). Although powerful for inferring fishery-independent movement patterns, limitations to acoustic tagging technology include high unit costs, field logistics (i.e., being able to locate tagged fish either on fixed receivers or with mobile telemetry units) and the potential for these larger tags to cause adverse effects on survival and physiology of the fish being studied. Thus, prior to commencing any acoustic telemetry study, great care should be given to choosing the proper tag placement protocol and, whenever possible, ensuring that the tags themselves have minimal impact on fish movement and biology.

Bridger and Booth (2003) reviewed three methods of electronic tag placement on/in fish – external attachment, intragastric insertion, and surgical implantation – and concluded that the choice of method depends on a variety of factors including species, fish and transmitter size, and duration of study. Based on a range of possible tag induced effects, including reductions in swimming performance (e.g., Counihan and Frost 1999) and growth (e.g., Greenstreet and Morgan 1989), and increases in abrasion related injuries (e.g., Thorstad et al. 2000), Bridger and Booth (2003) concluded that external tagging may be most suitable for short-term research in environments that lack high velocities and physical obstructions (due to the potential for snagging). Similarly, intragastric insertion, although with minimal effects on swimming (e.g., McCleave and Stred 1975), should be considered mostly for short-term studies (Bridger and Booth 2003) due to possible effects on feeding (e.g., Jepsen et al. 2001) and concerns regarding tag expulsion; for cod, 50% regurgitation may take place between 5 (Lucas and Johnstone 1990) and 32 days (Winger and Walsh 2001). Finally, surgical implantation, while much more involved in terms of deeper anaesthesia and longer handling times (Bridger and Booth 2003), may be the only method suitable for studies where long-term tag deployments are required. Effects on growth and survival of surgically implanted tags in

salmonids and Atlantic cod have been observed to be minimal (Adams et al. 1998, Cote et al. 1999, respectively). Furthermore, there is very little evidence of effects of surgical implantation on swimming performance in a variety of species (see Bridger and Booth 2003).

This study is part of a larger project to examine haddock residency and movement behavior in an offshore closed area (Closed Area I, ~ 30 miles southeast of Cape Cod, Massachusetts; see Sherwood, accompanying manuscript, for details). Thus, given the goals of the study for which this tagging trial was initiated (i.e., long-term monitoring) and the fact that the majority of telemetry studies on cod (closely related to haddock) have used surgical implantation as a means of tag attachment (e.g., Cote et al. 1999, Robichaud and Rose 2001, Windle and Rose 2005), the purpose of this study was therefore to examine the possible effects of surgical tag implantation (including anaesthesia) on haddock survival and physiological condition. This study represents the first such trial with haddock which are expected to tolerate surgical implantation of acoustic tags as readily as cod.

2. Methods

2.1. Field sampling and laboratory facilities

A total of 18 haddock ranging in size from 46 to 62 cm were captured by hook and line in April of 2007 at the southern end of Jeffreys Ledge in the Gulf of Maine (approximately 42° 50’N, 70° 15’W) and brought back to holding facilities at the University of New England’s Marine Science Education and Research Center. Haddock were divided among two circular tanks each 2 m in diameter and 1.5 m deep and supplied with flowing seawater. Opaque covers were fitted to each tank to minimize stress from overhead lights. Haddock were allowed to acclimate to their new surroundings for a period of two weeks prior to commencing anaesthesia and surgery trials. Haddock were considered fully acclimated when normal feeding and swimming behavior resumed, which for the majority of individuals took place within one week. During this initial acclimation period, 2 haddock died. Haddock were fed a mixture of clam and herring cut up into bite size pieces. Water temperature for the duration of the experiment ranged from 8°C to 12°C.

2.2. Anaesthesia trials

A number of different anaesthetic agents are available for use in fish surgery (see Bowser 2001 for a review). Given that the purpose of this study was to explore acoustic tag implantation techniques for haddock to be released in the wild, MS222 (3-aminobenzoic acid ethyl ester methanesulphate, for which the U.S. Food and Drug Administration, or FDA, mandates a 21 day withdrawal period) was ruled out in favor of clove oil (active ingredient eugenol) which is considered non-mutagenic and a safe substance by the FDA (Woody et al. 2002). Anaesthesia trials using clove oil were conducted on haddock following protocols outlined in Woody et al. (2002). Specifically, haddock were introduced to an anaesthetic bath (in a 50 L cooler) containing 40 mg $\cdot$ L^{-1} of clove oil. This concentration was at the low end of the range of concentrations tested by Woody et al. (2002) for adult sockeye salmon and was chosen to ensure both short induction and recovery times for haddock. Since clove oil does not completely dissolve in water below 15°C, and water temperatures for the field component of this study were expected to be around 7°C, clove oil was mixed with ethanol in a 1:9 ratio (Anderson et al. 1997) to facilitate mixing (Woody et al. 2002). Thus, to achieve 40 mg $\cdot$ L^{-1} of clove oil in a 50 L bath, 1.86 ml of clove oil was added to 16.7 ml of ethanol, which was added to the bath. Anaesthesia trials were conducted on 4 haddock where time to 4 stages of anaesthesia (Woody et al. 2002) were measured: stage 2 (sporadic loss of equilibrium and difficulty maintaining position); stage 3 (complete loss of equilibrium and inability to regain upright position); stage 4 (no reaction to handling or a sharp prod to peduncle); and recovery (ability to remain upright, normal swimming behavior). A stopwatch was started at the moment haddock were introduced to the anaesthetic bath.

2.3. Surgery trials (laboratory)

Surgeries to implant “dummy” V16 acoustic tags (Vemco Inc.) were conducted on 9 haddock and the remaining 7 haddock were left as controls. The study for which these trials were conducted (Sherwood, accompanying manuscript) required long battery life and high detection range. V16 tags are the second largest tag produced by Vemco (and hence fulfill these requirements since battery life and detection range are related to tag size among other factors), measure 68 mm long, and weigh 11 g in water and 25 g in air.

Dummy V16s are designed to replicate the real tag in every way including weight, which, in water for the V16, represented 1.3% of the body weight of the smallest sized haddock (46 cm and 829 g) used in this experiment (i.e., well within the "2% rule"; Brown et al. 1999). The standard operating procedure for tag implantation was adapted from Fabrizio et al. (2005) and is described as follows: Prior to commencing surgery, the entire surgical area (top of cart and cradle, Figure 1) was disinfected with Wavecide ® spray and wiped dry with clean paper towels. All surgical instruments were cold sterilized for at least 10 minutes in a stainless steel tray containing Envirocide ® (glutaraldehyde), removed, rinsed with distilled water and placed on sterile guaze pads in an easily accessible area. Haddock were placed in the anaesthetic bath (see above) and were transferred dorsal side down to the surgery cradle (Figure 2) after stage 4 anaesthesia set in (Woody et al. 2002); a flow system (small submersible pump with ¾" tubing) was turned on to ensure proper irrigation of the gills. The incision site (ventral, about 2 cm anterior to the anus and slightly off to the side; Figure 2) was dabbed dry with sterile gauze and scales were removed. A small incision (~ 2 cm) was made with a fresh #12 scalpel blade cutting from front to back. Care was taken when making the incision to not puncture the intestinal tract which underlies the incision site. Once the incision was made, a dummy tag, sterilized (by immersion in the glutaraldehyde solution for at least 1 hour) and coated in triple antibiotic ointment, was inserted into the body cavity and massaged into place so that it lay lengthwise and did not cause any outward pressure under the incision. The incision was closed in a simple interrupted pattern (Wagner et al. 2000) with 2-3 non-absorbable nylon sutures (Ethilon ® 3-0, fs-1 cutting) and 3 surgeons knots per suture. A thin layer of Vetbond ® was applied to the incision to ensure full closure and the entire incision area was covered with a layer of triple antibiotic ointment. Finally, a numbered T-bar tag (Hallprint Pty Ltd.) was inserted into the dorsal musculature for identification purposes before returning the haddock back to the water for recovery (control haddock were also tagged with T-bar tags). Haddock (both dummy tagged and control) were left alone for a period of 6 weeks (42 days) during which time they were fed to satiation once per day and monitored for any infections and abnormalities. Haddock deemed to be in failing condition (e.g., fin rot and/or abnormal swimming) were euthanized by an overdose with MS-222. At the end of 6 weeks, all haddock were euthanized by an overdose with MS-

222, weighed (nearest g), measured (nearest mm), gutted and weighed again (nearest g) and liver weight was also measured (nearest g). All protocols for this study were reviewed and approved by the University of Southern Maine's and the University of New England's Institutional Animal Care and Use Committees (IACUC # 031207-01 and UNE09-2007, respectively)

2.4. Sub-lethal effects monitoring (laboratory)

In addition to survival, which was monitored over the course of the six week experiment, potential indicators of sub-lethal effects were also considered in the form of biological condition indices. Specifically, Fulton's condition factor (*K*) and the liver-somatic index (LSI), both indicators of energetic fitness and energy reserves (Lambert and Dutil 1997), were measured and are given as follows:

$$FCF = \frac{W_{gutted}}{L^3} \cdot 100$$

where W_{gutted} is gutted weight (g) and L is total length (cm), and

$$LSI = \frac{W_{liver}}{W_{gutted}} \cdot 100$$

Where W_{liver} is liver weight (g) and W_{gutted} is gutted weight (g). Effects monitoring for tag insertion trials typically considers growth either in terms of length or weight gain (e.g., Cooke et al. 2003). The duration of this experiment and small sample size limited the ability to use growth in this way since very little growth in length occurred (although FCF is analogous to weight gain, or loss, in the absence of length gains). To the author's knowledge, no other study has considered liver index as an endpoint in this type of study. Liver index, in addition to FCF, may provide useful information on energy stores which should be related to recent feeding levels (Adams and McLean 1985) as well as stress. Fulton's condition factor and liver-somatic index were compared among haddock from surgery and control groups and survivors versus non-survivors by analysis of variance (ANOVA).

2.5. Surgery trial (field)

In addition to conducting surgery trials with dummy acoustic tags in the laboratory, it was also important to investigate whether haddock can survive the entire capture/ surgery/release experience in the wild. Specifically, this project is part of larger study to examine haddock movements and behavior in Closed Area I (CAI, western Georges Bank) about 30 miles southeast of Cape Cod, Massachusetts. Haddock tend to select depths of about 90-150m in this area (Cape Cod Commercial Hook Fishermen's Association, CCCHFA, personal communication). Therefore capture/surgery/release trials took place within this depth range on a total 30 haddock (16 surgery and 14 control) in July of 2007. Haddock were captured by hook and line and transferred to holding tanks which were cooled to 7°C (to approximate bottom temperature) with ice (seawater). Surgery to implant dummy acoustic tags was conducted on haddock that were deemed in good condition (responsive and swimming near bottom of holding tank) following the same protocol as used in the laboratory (see previous sections). Following surgery, haddock were held for ~ 1 hour to monitor recovery and, if in good condition, were transferred to a holding cage (1.5 m diameter × 1 m high; Figure 3) which was slowly lowered to the bottom. Two such trials, each with 4 cages (trial 1: 8 surgery and 8 control; trial 2: 6 surgery and 8 control), were conducted for a duration of 5 and 3 days in the western portion of CAI, respectively at 150 and 90 m depth (haddock were divided equally among cages). The intention was for both trials to last only 3 days, however, weather impeded returning to the first trial until day 5. At the end of each trial, cages were lifted off the bottom and survival of surgery and control haddock was recorded and compared.

3. Results

3.1. Anaesthesia trials

Anaesthesia trials, using clove oil, were conducted on four haddock prior to commencing surgery trials to ensure that haddock could be immobilized during surgery and to ensure that they recover fully from anaesthesia. Figure 4 shows the results of these trials. Mean (± 1 SD) time to stage 2 anaesthesia (sporadic loss of equilibrium) was 125 ± 22 seconds,

mean time to stage 3 anaesthesia (complete loss of equilibrium) was 178 ± 33 seconds, mean time to stage 4 anaesthesia (not reactive) was 277 ± 60 seconds, and mean time to full recovery was 1166 ± 225 seconds. An increasing trend in time to all stages of anaesthesia was apparent by order of haddock in the experiment (i.e., haddock 4 took the longest to be induced and to recover). If haddock 4 is removed, mean times to the 4 stages of anaesthesia for the remaining 3 haddock become 117 ± 20, 165 ± 26, 249 ± 23, and 1055 ± 40 seconds. Mean time from full induction (stage 4) to full recovery for the first 3 haddock was 806 ± 26 seconds or about 13 minutes. Recovery, despite taking 13 minutes, was very rapid once it set in and haddock resumed normal activity almost immediately when they "came to".

3.2. Surgery trials (laboratory)

Survival results of the laboratory surgery trials are shown in Figure 5. Four of the 9 haddock that underwent surgery survived the duration of the experiment (6 weeks). One haddock had to be euthanized immediately following surgery due to complications; the remaining 4 had to be euthanized at later dates following surgery as a result of failing condition (erratic swimming and/or cessation of feeding) due primarily to infection by fin rot; 3 of these 4 succumbed in a 3 day window at about 2 weeks following surgery. There was no significant difference in size of haddock that survived (mean ± 1 SD length = 51.4 ± 3.6 cm) and those that died (54.5 ± 6.2 cm). In contrast, 6 of the 7 control haddock survived. Associated survival rates for surgery versus control haddock were therefore 50% (when haddock that died due to complication during surgery is removed) and 86%, respectively. Sample sizes were too small to test for significance. Survival rates for surgery haddock, corrected for control survival (86%) may have been 58%. Similarly, if only the first 30 days are considered, survival rate for surgery haddock increases to 62.5%.

Sub-lethal endpoints (Fulton's condition factor and liver somatic index) were also measured at the end of the experiment and are shown in figures 6 and 7. FCF (figure 6) was significantly lower for haddock that underwent surgery than for controls (Table 1). There was also a significant interaction effect between treatment group (surgery vs. control) and whether fish survived the duration of the experiment or not (Table 1). In

other words, FCF was significantly lower for haddock that underwent surgery and survived the duration of the experiment (mean ± 1 SD FCF = 0.67 ± 0.08) compared to control haddock that also survived the entire experiment (mean FCF = 0.85 ± 0.05), but there was no difference in FCF between haddock of either treatment group that died prematurely (the 2 haddock that died during the acclimation period were included in the control group for this analysis). LSI (figure 7) was not significantly different among treatment groups, but did differ significantly among haddock that survived the duration of the experiment and those that did not (Table 1). In contrast to the situation with FCF, there was no significant interaction effect for LSI as a function of treatment group and survival to the end of the experiment.

3.3. Surgery trials (field)

To test whether haddock could survive the entire capture/surgery/release experience, surgery trials were conducted in the field. An initial trial with 8 surgery haddock and 8 control haddock (captured and released to cages without surgery) resulted in 100% mortality for both treatment groups. This first trial was conducted at 150 m depth and lasted 5 days; the plan to return in 3 days was hampered by bad weather (the site was about 30 miles offshore). Haddock in this trial were not only dead but completely scavenged suggesting that they may have succumbed to a sand flea infestation. A second trial, conducted at 90 m depth and lasting only 3 days, yielded much better results (figure 8). Five of the 6 surgery haddock and 6 of the 8 control haddock survived for survival rates of 83% and 75%, respectively. The 3 dead haddock were not completely scavenged suggesting an absence of sand fleas in this location.

4. Discussion

The purpose of this study was to determine whether haddock can survive intraperitoneal acoustic tag implantation, similar to Atlantic cod (Cote et al. 1999, Robichaud and Rose 2001, Windle and Rose 2005), and whether there are any sub-lethal effects associated with this procedure. While there was certainly mortality associated with the surgery protocol, the 6 week-long experiment did indeed reveal that haddock can survive acoustic tag implantation in the laboratory at a rate of 58% (corrected for control mortality; 30 day

survival was 62.5%). This rate compares well with 20-day survival rates for transmitter implantation in juvenile largemouth bass (between 42 and 65%; Cooke et al. 2003). Although the mortality rate for surgery haddock is already corrected for mortality in control haddock, there remains the possibility that mortality in surgery haddock may have been magnified as a result of multiple stressors (i.e., the combined stress of holding and surgery). In other words, surgery in the absence of tank effects (e.g., when fish are released back to nature) may not have led to as high as 42% mortality. Indeed, field estimates of long-term survival for Atlantic cod implanted with acoustic tags, based on telemetry tracking over a year, have been as high as 84% (Windle and Rose 2005). As such, the level of mortality observed in the lab here (potentially artificially magnified) was deemed to be acceptable for further testing in the field through long-term telemetry tracking (see Sherwood, accompanying manuscript).

Further reason to pursue long-term tracking studies of haddock in the field came from a successful short-term caging trial. Although the first cage trial was a failure (100% mortality), the second trial showed that haddock can have very high short-term (3 day) survival rates following capture, surgery and release (83%). This short-term survival rate compares very well to short-term (5-10 days) survival rates for Atlantic cod tagged with external t-bar tags (88%; Brattey and Cadigan 2004) suggesting that in the short-term, at least, surgery is no more invasive for haddock than t-bar tags are for cod. Total mortality in the first trial may have been due to multiple factors: 1) the location may have been too deep (150 m); 2) the trial may have been too long (5 days); and 3) due to the length of the trial and the location, the caged haddock may have succumbed to a sand flea (parasitic amphipods) infestation, which can be a common cause of mortality in caging studies of this kind (e.g., Tallack and Slifka 2007). The success of the second trial may have been due to attempts to mitigate one or all of these factors: 1) the trial was moved to a shallower depth (90 m); 2) the trial lasted only 3 days; and 3) the new location may have been far enough away from sand fleas which tend to be located in patches (CCCHFA, personal communication). The fact that implanted haddock were not only living, but thriving, when they were brought back to the surface in the second trial, suggests that they had overcome the initial stress of capture, surgery and release. For this reason, the experiment was considered a success.

In addition to survival, this study also considered sub-lethal effects of acoustic tag implantation in haddock. The two endpoints, Fulton's condition factor (FCF) and liver somatic index (LSI) were included to provide information on the energetic well-being of haddock over the course of the 6 week-long laboratory holding experiment. These indices provided interesting results on their own (figures 6 and 7) and may also be useful for interpreting survival results in the lab. Growth has been observed to both decrease for fish tagged in various ways with electronic devices (Bégout Anras et al. 2003, Jepsen et al. 2008, Thorstad et al. 2009) or to be relatively unaffected (Adams et al. 1998, Cote et al. 1999). Whether or not fish growth is affected likely has something to do with relative tag size (Thorstad et al. 2009). While growth may provide insights on energetic well-being of a fish, perhaps better measures of this are condition factor and liver index. This is because, unless one examines otoliths or other hard parts, determining growth requires size information at the beginning and end of a time interval (i.e., at the time of tagging and at the time of recapture). This information may either be lacking in many studies or error prone. Condition indices (like FCF and LSI), on the other hand, require measurements only at the end of an experiment or at the time of recapture. Additionally, the relative size of different organs versus the whole body in relation to length can provide information on different physiological processes which may respond to different environmental conditions on different time frames. For example, LSI may respond more quickly to starvation than FCF (Arndt et al. 2005). Thus, FCF could conceivably be an indicator of long-term stress and LSI an indicator of a short-term energy deficit. In this light, it is interesting to speculate how haddock may have responded to the stresses of surgery and holding in the laboratory trials. The fact that there was a significant interaction effect between treatment (surgery vs. control) and survival to the end of the experiment on FCF suggests that it took the entire duration of the experiment for the stress of tag implantation, perhaps compounded by the stress of holding, to affect FCF. The haddock that died early did not appear to die from low condition (e.g., Dutil and Lambert 2000). To the contrary, it appears that haddock can handle lower levels of FCF (Figure 6). On the other hand, LSI was not related to treatment but was significantly lower in haddock that died prematurely in both treatment groups. This difference likely reflects starvation and lack of acclimation to the holding environment. Indeed, haddock

that succumbed early were observed to cease feeding and these haddock were also afflicted with fin rot infections. Overall then, it is hypothesized that haddock in the laboratory experiment died mostly from infection and stress related causes (that led to starvation and low LSI; not expected to be a problem in natural settings), and that by the end of the experiment, tag implantation may have led to lower energetic fitness (i.e., lower FCF; could be a problem in natural settings).

This is the first study to examine the potential effects of intraperitoneal acoustic tag implantation on haddock survival and condition. Numerous acoustic tagging studies have been conducted on closely related Atlantic cod with great success (Cote et al. 1999, Robichaud and Rose 2001, Windle and Rose 2005). However, before applying the same protocols to haddock, which some considered to be less hardy and robust for tagging purposes than cod (CCCHFA, personal communication; also, tag return rates from a conventional tagging study on Georges Bank haddock are alarmingly low [2.2%; Rudolph 2009] suggesting high tagging mortality), it was imperative to verify that haddock could withstand the surgery and the tags. Overall, haddock tolerated the experimental procedures quite well. They were responsive to clove oil anaesthesia, they survived both long-term laboratory and short-term field surgery trials at acceptable rates (it is argued that lab mortality was due mostly to infection), however, they exhibited decreased body condition (FCF) at the end of the six week laboratory trial. Based on these results, it was decided to continue with the longer term field study (tagging of 78 haddock and monitoring by an array of 18 receivers) for which this study was initiated, and where further information on haddock survival and behavior, following acoustic tagging, would become available (see Sherwood, accompanying manuscript).

5. Acknowledgements

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Table 1. Results of analysis of variance (ANOVA) for effects of treatment (surgery vs. control), survival, and their interaction on haddock FCF and LSI.

	FCF		LSI	
Effect	*F*	*p*	*F*	*p*
Treatment (T)	10.415	0.007	0.047	0.831
Survival (S)	0.002	0.962	4.743	0.048
T×S	7.130	0.019	0.854	0.372
N	17		17	
R^2	0.57		0.17	

Figure 1. Surgery cradle.

Figure 2. Incision site on anaesthetized haddock.

Figure 3. Cage being deployed for field surgery trials.

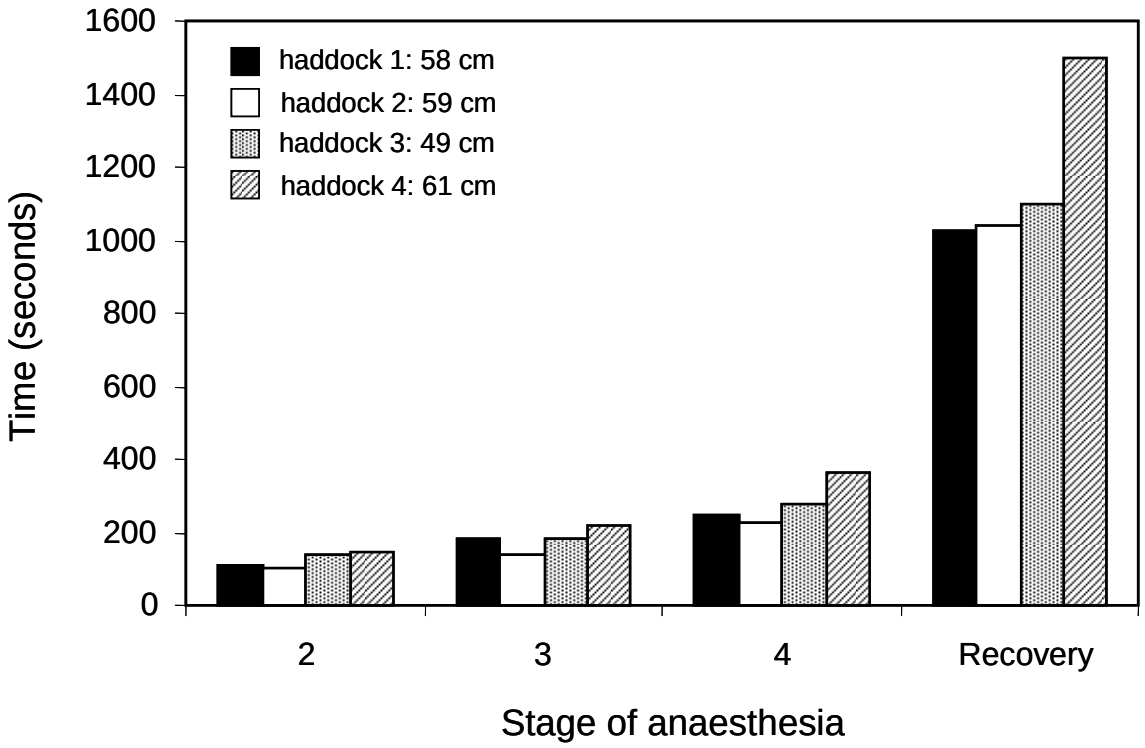

Figure 4. Time to 4 stages of anaesthesia (see methods) for 4 different haddock of varying sizes (lengths indicated in legend).

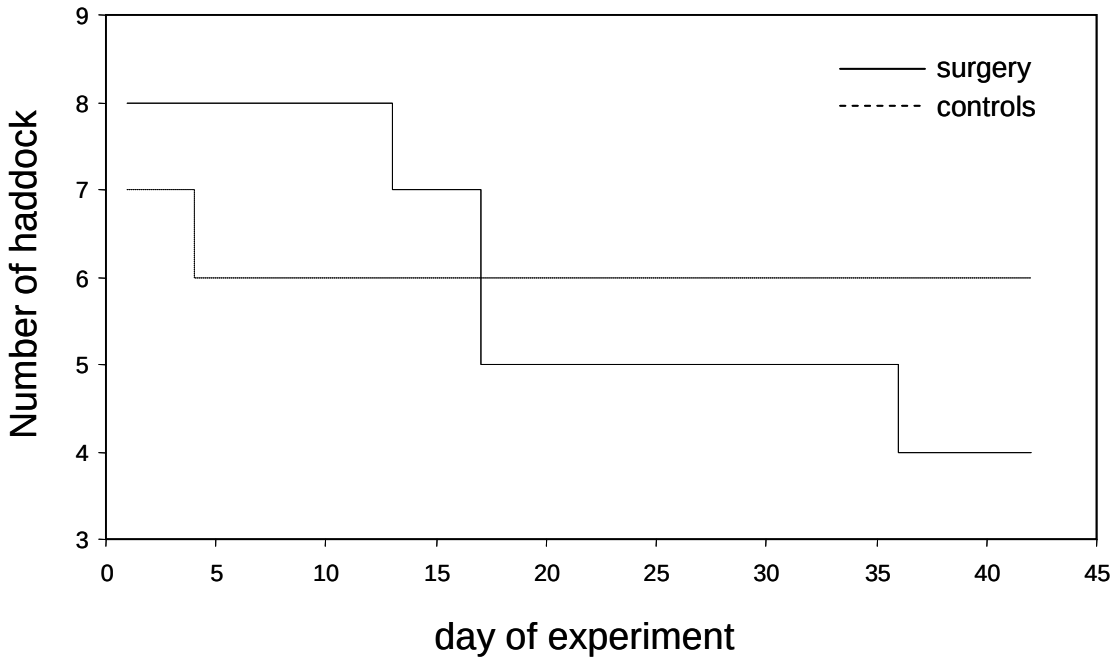

Figure 5. Number of surgery and control haddock remaining each day over the course of the 6 week experiment.

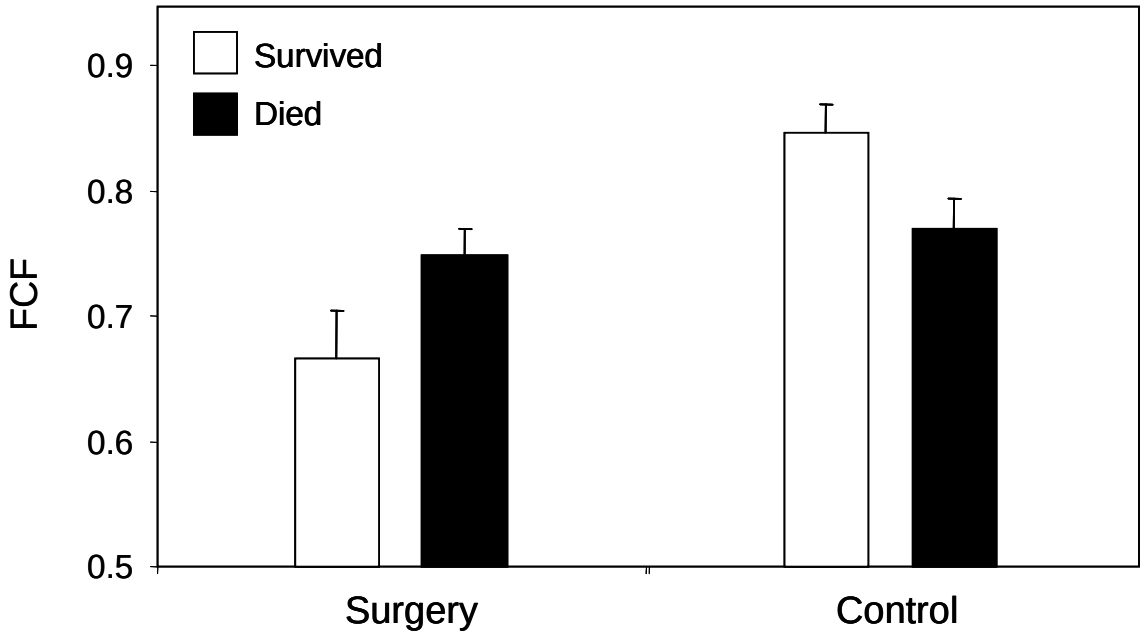

Figure 6. Fulton's condition factor (FCF) of haddock that underwent surgery versus control haddock, and by haddock that survived the duration of the experiment (6 weeks) and those that died prematurely (control haddock that died prematurely includes haddock that died during acclimation period). Error bars represent standard error.

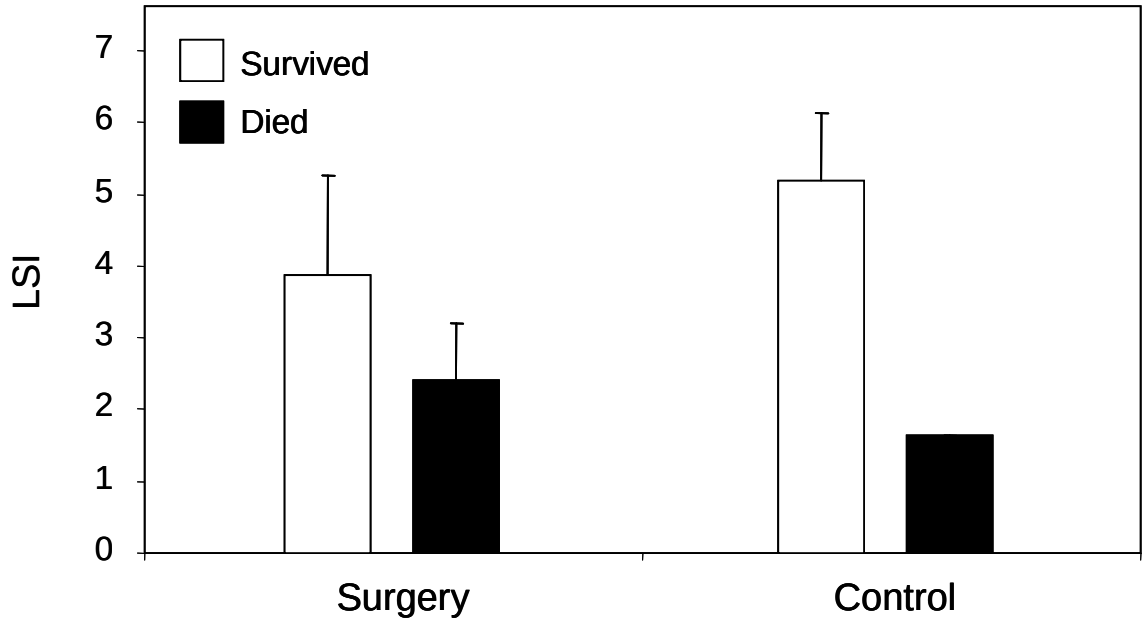

Figure 7. Liver somatic index (LSI) of haddock that underwent surgery versus control haddock, and by haddock that survived the duration of the experiment (6 weeks) and those that died prematurely (control haddock that died prematurely includes haddock that died during acclimation period). Error bars represent standard error.

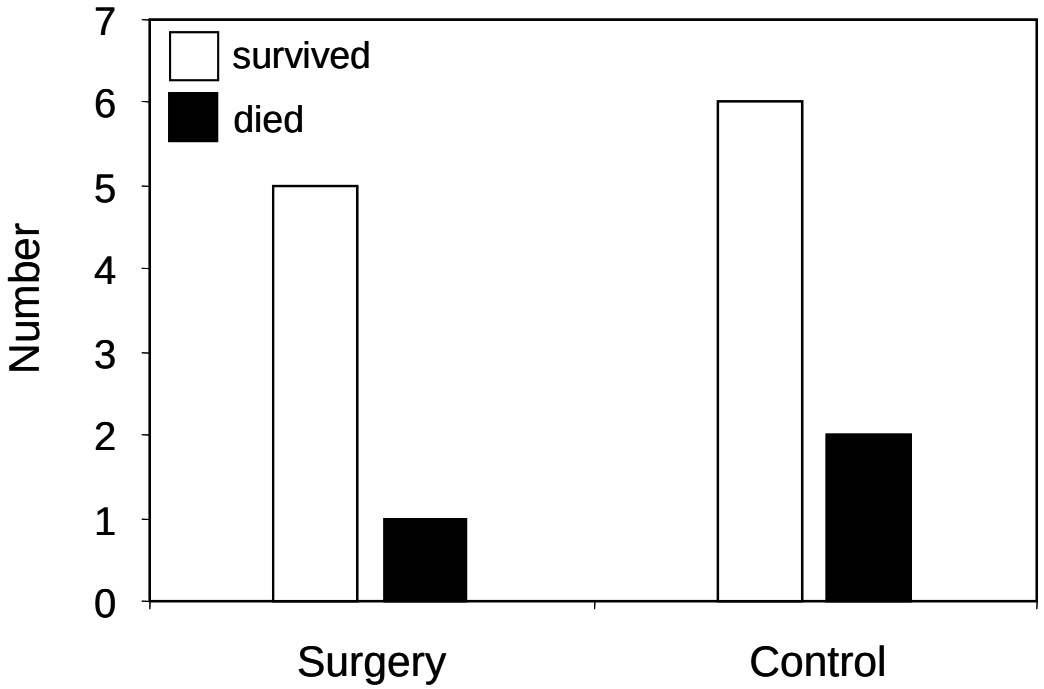

Figure 8. Number of haddock that survived field capture/surgery/release and capture/release (controls) versus the number that died. Note that release means being held for 3 days in cage on bottom at 90 m depth.

Monitoring haddock (*Melanogrammus aeglefinus*) residency and movement behavior in an extensive offshore closed area with a non-overlapping acoustic receiver array

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Abstract

The Georges Bank haddock stock has increased 10-fold over the last decade possibly due to effective management practices including the establishment of four year-round area closures on Georges Bank and in the Gulf of Maine. While closed areas in this region were intended to reduce fishing mortality on groundfish species including haddock, there is currently no data to support the claim that haddock use closed areas to their advantage and hence no data to objectively assess whether closed areas have played a role in the nascent recovery of haddock (Brodziak et al. 2008). To address this uncertainty, a monitoring array of 18 acoustic receivers was set up in the northwest corner of Closed Area I (CAI) in 2007 to observe residency and fine-scale movement behavior of haddock within this area. Roughly one third (after correcting for 11 known deaths) of the 78 acoustically tagged haddock showed a high degree of residency within the array (up to one year). Another third appeared to leave the array shortly (< 10 days) following release (transients) and the final third were never detected. The majority of detections for resident fish over the first two months were near the center of the array (in deeper water) as opposed to near the boundaries of CAI. Mobile (boat-based) telemetry in 2008, which allowed for monitoring outside of the closed area, agreed with these results and showed that 91% of detections were within the closed area, some of which were further east than the original array coverage. Discrete, short-term (< 48 hrs) movements between adjacent receivers, some of which were 2-3 faster than the maximum sustained swimming speed for haddock, were primarily in the north-south direction (along a “haddock highway”) which matches the prevailing tidal currents in this area, suggesting that haddock use tides to their advantage. Finally, data on arrivals and departures to and from detection range of receivers revealed that haddock are more active at night than during daylight hours. Overall, results of this study support the notion that closed areas may be contributing to the rebuilding of Georges Bank haddock.

1. Introduction

Haddock (*melanogrammus aeglefinus*) were once the mainstay of the New England groundfishing fleet with landings from Georges Bank averaging 46 kt between 1931-1960 (Brodziak et al. 2008). However, as was the case for most groundfish stocks in this region, overfishing during the latter half of the 20th century took it's toll such that haddock landings had declined more than 100-fold by the 1990's from mid-century highs (Brodziak et al. 2008). In an effort to end overfishing and rebuild haddock and other groundfish stocks, the National Marine Fisheries Service (NMFS) introduced a range of regulatory actions including the establishment of year-round offshore area closures (closed to bottom-tending mobile gear; Figure 1). As a result of these measures, fishing mortality dropped from over 0.5 in 1993 to below 0.2 in 1995 and haddock stocks have been rebuilding ever since (Brodziak et al. 2008). In particular, spawner biomass increased from 15 kt in 1993 to 117 kt in 2004 and a series of high recruitment years have occurred since 2000 with an outstanding year class in 2003, the highest on record (Brodziak et al. 2006).

In addition to stock increases, there is compelling spatial evidence to suggest that closed areas may be favoring the ongoing recovery of haddock. In an analysis of fishing patterns adjacent to Gulf of Maine and Georges Bank closed areas, Murawski et al. (2005) identified haddock as the species which may benefit most from this management tool. 73% of the haddock catch (2001-2003) was within 5km of closed areas despite less than 25% of the groundfishing effort within this range. Only yellowtail flounder (*Pleuronectes ferrugineus*) came close to this type of catch distribution with 50% of the catch within 5km. In contrast, only 20% of the cod (*Gadus morhua*) catch was within 5km of closed areas. These data suggest that haddock biomass may be building up in closed areas, and less so in adjacent open areas. In other words, closed areas in the NE US appear to be benefiting haddock more than any other groundfish species.

In order for haddock to benefit from closed areas, to the point where they appear to be "spilling over" into the fishery, they would have to display some degree of residency within (i.e., closed areas should be the center of their aggregation). While regular trawl surveys conducted by the NMFS provide a broad-scale and random sampling of

groundfish distribution throughout the entire Gulf of Maine and Georges Bank region, the spatial and temporal resolution is not sufficient to address specific questions of habitat use and movement of haddock on fine scales as, for instance, inside a closed area. On the other hand, questions of habitat associations, movement and residency behavior have been addressed in other species at various scales using acoustic monitoring technologies but never with haddock. For instance, Lindholm et al. (2007) were able to infer site fidelity in a subset of cod tagged with acoustic transmitters in the western Gulf of Maine (tagged cod were detected on an array of 4 acoustic receivers fixed near the sea floor). Similarly, acoustic arrays of different configurations have been applied to monitor large-scale migration in cod (Comeau et al. 2002), spawning behavior in cod (Howell 2009), foraging behavior in great white sharks around seal colonies (Klimley et al. 2001) and use of marine reserves in Caribbean sharks (Chapman et al. 2005). Residency of marine fish to particular areas may also be examined by large-scale conventional tagging operations (e.g., Howell et al. 2008). However, in this case, movement data is dependent on fishery returns which may not be suitable for closed area research.

Aside from the fine-scale offshore work undertaken by Lindholm et al. (2007), and to the author's knowledge, no other study has ever applied automated acoustic monitoring to track residency and movement behavior of fish in a large-scale offshore area closure. The purpose of the present study was therefore to apply acoustic tracking to test the hypothesis that haddock show a degree of residency in Closed Area I, an area 30 miles from shore, measuring ~ 4,000 km^2, and known to overlap significantly with preferred haddock habitat (Brodziak 2005). Given the strengths of acoustic tracking technology (i.e., presence/absence of tagged fish within detection range of receivers in near real time), this study also aims to provide additional data on haddock biology including swimming speed, habitat utilization and diel activity patterns.

2. Methods

2.1. Array design

Acoustic arrays can be arranged as listening lines (sometimes referred to as "curtains") to infer timing and direction of migrations (e.g., Welch et al. 2003), as overlapping grids to

explore fine-scale habitat use in confined areas (e.g., Heupel et al. 2004), or as non-overlapping grids to "sample" habitat use and residency on a more diffuse scale (see Heupel et al. 2006 for a review of acoustic array design considerations). In order to address a pressing question that industry members and managers have regarding spillover rates of haddock from Closed Area I to the fishery, this study would ideally have employed a curtain design to close off the entire area or a significant portion of it. In this case, acoustically tagged haddock could have been monitored leaving and possibly reentering the closed area in absolute terms (assuming perfect array coverage). However, due to funding and logistical constraints (this design would have required ~ 200 receivers and an enormous amount of vessel time), a non-overlapping array design was chosen instead to *sample* haddock presence within the closed area at discrete locations. While this design could not evaluate spillover *per se*, it had the advantage of sampling haddock presence and inferring movement (between adjacent receivers) over a broad area (500 km^2) with a relatively small number of receivers (n = 18). After consultations with fishermen from the Cape Cod Commercial Hook Fishermen's Association who fish inside CAI under a special access program (SAP), it was decided to locate the array in the northwestern corner of CAI (Figure 2). No equipment was placed outside of the closed area due to the likelihood that it would be lost to trawling activity, which can be heavy near the edges of CAI.

2.2. Equipment and range testing

This study made use of Vemco VR2W acoustic receivers moored near the sea floor as shown in Figure 3. The manufacturer's maximum reported detection range for these units is 800 m. And although detection range is a critical parameter when designing and deploying curtain and overlapping grid arrays, it becomes less important to estimate accurately when dealing with non-overlapping arrays when presence/absence around discrete locations is all that is required for data collection (i.e., relative versus absolute presence data). Nonetheless, detection range for tags (see next section) suspended near the bottom was estimated by drifting away from VR2W units moored near the seafloor (at a depth of ~ 155 m). In this case, detection range was found to be at or near the maximum distance of 800 m.

A total of 18 receivers were deployed over two dates at the beginning of the experiment (see Table 1 for details). Note that receiver losses did take place and that one receiver was replaced midway through the deployment (Figure 4). The most significant loss was likely due to Hurricane Noel passing over the area on November 3, 2007. Other losses near the beginning of the deployment could have been due to entanglement in passing vessels. Losses at later dates were likely due to mooring failures. All moorings were fitted with whale-safe weak links as per National Environmental Policy Act (NEPA) regulations.

2.3. Fish capture and tagging

A total of 78 haddock were tagged and released within the array at the end of July/beginning of August 2007. Vemco V16-4H-R64 coded pingers (68 x 16 mm, 11 g in water) were surgically implanted in haddock following procedures developed in the lab and during sea trials (see accompanying manuscript by Sherwood). Fish were captured by hook-and-line from depths of about 90 m near the western boundary of CAI and released at various locations within the array (Figure 2). Haddock were also tagged with external T-bar tags (Hallprint, green) which included contact information if tagged haddock were recaptured. None were reported which is not surprising given the low return rates (2.2 %) found in a conventional haddock tagging project in the same area (Rudolph 2009). Length of tagged haddock ranged from 49-71 cm (Table 2). Sex was not determined. All fishing was sanctioned by a Letter of Authorization (LOA) from the National Marine Fisheries Service (NMFS). All surgery/tagging protocols were reviewed by the University of Southern Maine's Institutional Animal Care and Use Committee (USM IACUC protocol # 031207-01).

2.4. Data acquisition and analysis

Data from the array of 18 initial receivers was downloaded on 3 occasions following deployment. Downloads required full retrieval and redeployment of moorings. Table 1 outlines dates of deployment and dates of downloading for each receiver. Note that data was available from the full array (minus two losses) up until the second download on September 27th, 2007. Thereafter, data is available only from 3 receivers up until

December 11th (the final download, at which time it was discovered that most receivers had been lost likely due to Hurricane Noel) and from an additional 2 receivers found and returned in 2008 by industry members. Figure 4A is a summary of activities over the course of one year including deployments and downloads. During downloads, data were transferred via a Bluetooth connection to Vemco's VUE software installed on a portable laptop. This data was subsequently exported to SPSS version 16.0 for manipulation and analyses.

2.5. Mobile tracking

In addition to acoustic monitoring, mobile boat-based tracking was conducted in July and August of 2008. A total of 60 stations were plotted on a course covering an area about 2 times larger than the area of the fixed array (Figure 14); mobile tracking had the advantage of allowing for data collection outside of the closed area. Each station was visited on 6 separate dates. A hydrophone was lowered into the water at each station and the area was monitored for 5 minutes with a Vemco VR100 mobile tracking unit for the presence of tag signals.

3. Results

3.1. Summary of detections and fate of tagged haddock

A total of 172,281 detections were recorded on the array over the course of the deployment from July 31st, 2007 to August 11th, 2008 or slightly more than one year. Roughly one half of these (89,602) covered the 2 month period for which the array was mostly intact (i.e., up until the second download on September 27th, 2007). Not every detection represented a live haddock. In some cases, haddock appeared to have succumbed to the tagging experience and died in the vicinity of a receiver which resulted in a large number of detections for that tag and receiver (ping rate for tags was 60 seconds on average). There was no way to tell definitively which tags were dead versus alive, however, it was assumed that tags detected consistently near a receiver where the tag was released, and on no other receiver, were dead. The assumed fate of each haddock is listed in Table 2. In this way, it was estimated that 97,582 detections were from live

haddock with 46,824 of these in the first two months. Finally, in terms of numbers of detections, live haddock were further subdivided into “residents” versus “transients” (see fate in Table 2). Residents were haddock that were detected longer than 10 days following release on at least 2 receivers (only one of these “resided” in the array for less than 30 days). Transients were haddock detected no longer than 10 days on one or more receivers. Appendix I aids in visualizing the fate of haddock both spatially and temporally: tag 3827 (pg. 87) is a classic DOA (dead on arrival); tag 3838 (pg. 90) represents well a transient; and tag 3844 (pg. 91) is a good example of a resident. Residents accounted for 96,007 detections (45,249 of these in first 2 months on full array) and transients for 1,575 (all within 2 months). Overall, 11 haddock were deemed to have died, 25 were assumed transients, 22 were considered residents and an additional 20 were never detected following release (missing in action or MIA). Thus, one third (33%, or 22 of the 67 haddock not known to have died) of the haddock released in the array in CAI appeared to be resident to the area. Figure 4C helps to visualize the fate of all haddock over the entire deployment.

Figure 5 shows the loss of haddock from the array initially from transients at very high rates (17-35% day^{-1}; see Figure 5 caption for exponential rate loss equations), and then from residents at much lower rates (0.5% day^{-1} for the full array and 1.2% day^{-1} for the reduced array). The rate of loss from the reduced array may not be very meaningful since it only represents a handful of sampling locations (nonetheless, it agrees well with the loss rate from the full array). On the other hand, the loss rate from the full array in the first two months may represent quite well the loss of haddock from the northwest corner of CAI. And while this loss rate may seem low, if it continued over a whole year, 22 resident haddock initially would become only 4. This does not mean that they would have left the closed area. To the contrary they could also have moved to the east within CAI. The increase in number of haddock detected per day despite a dramatic decrease in number of receivers at day 58 (Figure 4 and Figure 5) was likely due to the addition of receiver 434 in an area of high haddock concentration (Figure 8).

3.2. Distribution of residents

The majority (98%) of live detections were from haddock considered to be residents. While these residents were present in the array throughout much of the deployment, there was some spatial variation in where they occurred (see Table 3 for a summary of detections by receiver). Figure 6 shows the distribution of assumed resident haddock in the first two months of the full array. These haddock tended to concentrate near the eastern side of the array (middle of the closed area) and the largest numbers of haddock were found right near the center/bottom of the array. Very few haddock were detected in the northwest corner of the array and closed area. Furthermore, there were significantly more haddock detected on center receivers than edge receivers (6.6 ± 0.9 vs. 3.5 ± 2.2; student's *t*-test: $p < 0.05$). This was likely due to depth preferences with more resident haddock appearing on receivers at greater depths (Figure 7; linear regression: $R^2 = 0.32$, $p < 0.05$). Haddock appear to have preferred depths > 150 m over the first 2 months of deployment. Resident haddock distribution following 2 months looked similar to the first 2 months with the exception that some haddock used the NW corner of the array and possibly shallower depths (Figure 8). Too few receivers remained after 2 months to evaluate depth preferences over longer time periods.

3.3. Haddock movements, swimming speed and diurnal variations

Based on time stamps for each detection and known location of receivers, it was possible to construct movement histories for each haddock. While live haddock logged nearly 100,000 detections, these represented only 179 discrete movements between receivers. Only 117 of these were within 48 hrs (a length of time arbitrarily chosen to reflect directed movements); 108 of these were within the first 2 months (Figure 9). Figure 10 shows 13 short-term (< 48 hrs) movements after 2 months. Not surprisingly, the majority of short-term movements occurred along the eastern edge of the array which agrees well with distributions (Figure 6). What was interesting was how most short-term movements occurred along a north-south axis (Figure 11, top). This may represent movement within preferred depth contours or movement with the tides. Indeed, the prevailing tidal direction in this area of the Great South Channel is north-south (SMAST/UmassD 2005). There was even some indication that haddock may turn around at the closed area

boundary given that lateral movements (east-west) were rare except at the northern edge of CAI (Figure 9). Further evidence for tidal "surfing" comes from examination of swimming speeds which was possible to calculate for each discrete movement given known distances between receivers and known start and end times (Table 4). Maximum sustainable swimming speed (U_{ms}) for haddock has been examined in the lab and determined to be about 0.6 $m \cdot s^{-1}$ (Breen et al. 2004). The majority of short-term movements from this study fell within this range, however, 17 movements were greater than 0.6 $m \cdot s^{-1}$ and 7 of these were double the maximum sustainable swimming speed of haddock. The majority of movements greater than 0.6 $m \cdot s^{-1}$ were also in the north-south direction (Figure 11, bottom). There was no relationship between swimming speed and body size for haddock (Figure 12) which is not very meaningful given that not all movements within 48 hours were likely to be strictly directed (i.e., from one receiver to the next).

Time information stored on the receivers also allowed for a determination of when haddock are most active (i.e., diurnal variations). In cases where haddock moved between receivers, the time of departure from one receiver to the time of arrival on the next was noted. The sum of departures and arrivals (an indication of when haddock are on the move) was significantly greater (Student's *t*-test; $p < 0.01$) at night than during the day (Figure 13).

3.4. Mobile telemetry

A total of 11 haddock were detected by mobile telemetry (Figure 14). Only one of these appeared to be alive (tag number 3852) based on the observation that it was detected at two locations on two different dates (Table 5). The distance between detection locations in this case was 3.5 km, which should be well beyond the detection range of the hydrophone (~ 800 m) indicating that the tag must have moved. Three of the detected haddock were almost certainly dead (tag numbers 3855, 3866 and 3877) based on the observation that they were detected at the same location on 5 different dates. The other 7 tags could have been from dead or live haddock. While every effort was made to resample each station as precisely as possible, it is conceivable that minor variations in location and/or sea state (ambient noise) could have led to false negatives (i.e., missed

signals). In any case, the data show that haddock, dead or alive, were located primarily near the center of the closed area (n = 9) as opposed to the edge (n = 1) or outside (n = 1). Interestingly, 3 of the tags detected by mobile telemetry were tags previously undetected by the receiver array (see Table 2). Four of the 11 tags were to the east of the array suggesting that losses (Figure 5) could have been due to movements in this direction within the closed area.

4. Discussion

4.1. Haddock residency and survival in CAI

The primary objective of this study was to apply acoustic monitoring to assess residency of haddock in Closed Area I (CAI). In other words, is CAI serving as a refuge for haddock? An analysis of fishing patterns and landings around closed areas in the Gulf of Maine and Georges Bank (Murawski et al. 2005) suggest that haddock are associated with area closures more so than any other fishery species in the northeast United States. Results from the present study show that at least one third (33%) of tagged haddock were highly resident to CAI. Long residence times for this group (up to one year) suggest that CAI supports all of their feeding requirements and perhaps even their spawning needs (although no actual data on feeding and spawning were generated).

While one third of the tagged haddock remained highly resident in CAI, another two thirds were never detected or left the acoustic array early on and their fate is unknown. Possibilities include natural mortality, tag-induced mortality (in addition to the 11 inferred to have died near receivers), fishing mortality (particularly around the edges; i.e., spillover), movement within the closed area to a portion not covered by the array, or emigration from the closed area (i.e., migrations). There is no way to assess natural, tag-induced and fishing mortality (there were no fishery returns). In terms of small-scale shifts in distribution (either outside or within CAI), mobile telemetry conducted in 2008 revealed that 3 of the 11 detected tags were east of the area covered by the array but still in CAI (Figure 14). One of these tags was located at two stations on two different dates suggesting that this fish was sill alive. Thus, there is reason to believe that more haddock may have resided east of the array (still in CAI) in 2007. Only one of the 11 tags detected

by mobile telemetry was outside of the closed area suggesting that most tagged haddock either lived or died within the boundaries. Alternatively, haddock may have moved out of the vicinity of the closed area altogether (e.g., to other regions of Georges Bank). Results from a conventional tagging study (Rudolph 2009), despite low return rates, found that larger-scale movements from CAI were primarily to the east; only one haddock tagged in CAI was recaptured in the western Gulf of Maine (Rudolph 2009). The ratio of residents to assumed transients (1:2) in this study is strikingly similar to acoustic monitoring results for cod residency in the western Gulf of Maine closed area (Lindholm et al. 2007). In fact, movement type differentiation (i.e., residents versus transients) may be a common phenomenon in fish populations (e.g., Morinville and Rasmussen 2003, Kerr et al. 2009, Sherwood et al. submitted). An ongoing Northeast Consortium funded study is examining the hypothesis that closed areas may be favoring the resident types in cod (Sherwood and Grabowski 2009).

Results from this study may shed some light on findings from previous tagging efforts. Return rates for haddock conventionally tagged in CAI (Rudolph 2009) were extremely low (0.7%). This, in turn, was only about one third of the return rate for the whole project (2.2%; Rudolph 2009), which is still much lower than return rates for cod (6.7%) in a similar study (Tallack, in review). This low rate of return for haddock in CAI may reflect high tagging mortality or a low availability of these fish to open areas and the Special Access Program area inside CAI (SAP, for hook fishermen; dashed box in Figures 2,6,8-10). Reporting rates inside the SAP should not have been low given the fact that the group that fishes this box are the same that administered the conventional tagging project (i.e., the Cape Cod Commercial Hook Fishermen's Association). Figure 6 shows how a good number of haddock were detected to the east of the SAP. Figure 14 (mobile telemetry results) shows that a proportion of tagged haddock moved even further east still. Thus, it is suggested here that the extremely low return rates of haddock tagged inside of CAI (Rudolph 2009) may have been due partly to their unavailability to the open fishery (via residency in CAI) and partially to their unavailability to the SAP. The expansion of the SAP in 2009 should ensure that hook fishermen participating in this program have fuller access to the areas frequented by haddock in CAI as revealed by this study.

The alternative explanation for low return rates in the conventional tagging study (Rudolph 2009) is high tag-induced mortality. This study provides some insight into survival rates for haddock that underwent a much more invasive procedure than simple T-bar tag placement (i.e., surgical transmitter implantation). Surgical survival rates from long-term (6 week) laboratory and short-term (3 day) caging trials were 58% and 83%, respectively (Sherwood, accompanying manuscript). Survival rate here, up to 30 days was at least 27% (21 of 78 haddock "resided" in the array up to 30 days); survival to 60 days was at least 22%, a small drop potentially due to other factors than mortality. There is no way to know how many fish categorized as MIA or transient actually died. In reality, a significant proportion of them likely lived such that the survival rates should have been higher than 27 and 22% for 30 and 60 days, respectively. Long-term survival rates in other instances of surgical tag placement in fish have been as high as 84% (Windle and Rose 2005; for cod); in this case, the fact that cod were aggregating on a spawning ground likely led to a higher relocation rate. Conversely, the mortality rate for the entire experiment was at least 14%, based on 11 haddock which appeared to die near receivers mostly early in the deployment. Mortality rates for this study likely would have been much higher if precautions were not taken to ensure the survival of tagged haddock. These included tagging haddock caught mostly on jigs (rod-and-reel) as opposed to long-lines (less time on hook), fishing in relatively shallow water (see Figure 2), and holding haddock in water cooled to bottom temperature (~ 7 °C) prior to surgeries.

4.2. Additional insights into haddock behavior

In addition to information on haddock residency inside of a closed area, this study provides new information on haddock biology, some of it never before observed in nature. This includes data on depth preferences, foraging behavior (via tidal "surfing"), swimming speed, and diurnal behavior. With respect to depth preferences, haddock were shown to prefer deeper depths within CAI (Figure 7). This suggests that, although the extent of the acoustic array covered only about 500 km^2 compared to about 4,000 km^2 for the entire closed area, the experiment likely is valid for more than one eighth of the closed area. In other words, haddock seem to avoid depths of less than 100 m or 60 fathoms (Figure 2). And, given the fact that depths towards the east side of CAI and to

the south are less than 100 m, the array may have represented almost one half of the preferred depth for haddock in CAI (Figure 2).

An interesting finding, possibly related to foraging behavior, was revealed when directions of haddock movements and swimming speeds were examined (i.e., movements between receivers in the array within 48 hours). In particular, the majority of movements were in the north-south direction (Figures 9 and 11, top). This could reflect movement along depth contours or movement with the prevailing tides which are strongest in the north-south direction in the great south channel (SMAST/UMassD 2005). In addition, it is tempting to conclude that haddock actively turned around at the edge of CAI given that lateral movements (east-west) were quite rare except at the northern extent of what looks like a "haddock highway" within CAI (Figure 9). Such active avoidance may not be far-fetched. Possible reasons for haddock to recognize a boundary include noise disturbance from fishing vessels (fishing activity can be intense at the boundaries of closed areas; Murawski et al. 2005) or physical disturbances to the seafloor and benthic communities outside versus inside the closed area (e.g., Collie et al. 2009). The fact that swimming speeds in some cases exceeded the maximum sustainable value (0.6 $m \cdot s^{-1}$; Figure 12) established in laboratory trials (Breen et al. 2004), and that most of these were in the north-south direction as well (Figure 11, bottom), suggests that haddock use tides to move around in CAI. Tidal transport has been observed in adult cod (Arnold et al. 1994) but, to the author's knowledge, never in adult haddock. Demersal fish like cod and haddock can likely forage independently of tides by staying near the bottom (i.e., in the boundary layer). They likely use tides to minimize the cost of searching for prey over larger distances. In fact, tides may be one of the reasons that haddock reside in CAI given their intensity in this region (SMAST/UmassD 2005) and the possibility that haddock can use them to maximize foraging efficiency. Finally, this study finds evidence of nocturnal behavior in haddock. Arrivals and departures to and from detection range of receivers were significantly higher at night than during daylight hours (Figure 13). A similar, smaller-scale study by Lindholm et al. (2007) found no such evidence of diel activity in cod.

4.3. Conclusions

The "great haddock revival" (Weir 2009) is emerging as one of the bright spots in contemporary fisheries management. While the majority of the world's assessed fish stocks require rebuilding (Worm et al. 2009), Georges Bank haddock have achieved a comeback that wouldn't have been thought possible a decade ago. The salient question for this study was to what extent did closed areas contribute to this dramatic turnaround? The approach taken was to assess whether haddock actually use one of the closed areas that appears to overlap with haddock essential fish habitat. Specifically, do haddock reside in CAI on Georges Bank? This is slightly different than a question motivated by catch trends around closed areas (e.g., Murawski et al. 2005). That is, what is the rate of spillover from the closed area to the fishery? It was argued that it would be highly impractical to answer this question using acoustic monitoring equipment (section 2.1). However, to have spillover, there must be some degree of residency (a center of aggregation) in the closed area. Therefore, this study addresses the root of the problem by employing an acoustic array design (non-overlapping grid) capable of sampling movement and site fidelity on a scale representative of a large portion of CAI. In this way it was shown that at least one third of tagged haddock were indeed resident to CAI. Further data on movements and depth preferences suggest that the array portion of CAI may coincide with essential haddock habitat (for adults). The overall recommendation of this study is that CAI likely has a positive impact on haddock biology on Georges Bank and closed areas, in general, may have had an important role to play in the recent recovery of haddock.

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Table 1. Receiver details including coordinates and dates of deployment and downloading.

Receiver #	Longitude	Latitude	Date	Action
432	69.0054	41.3932	07/31/07	Deployment
432	69.0054	41.3932	08/02/07	Download
432	69.0054	41.3932	08/29/07	Download
432	69.0005	41.3971	09/27/07	Download
432	69.0040	41.3932	12/09/07	Download
433	69.1509	41.2854	07/31/07	Deployment
433			08/02/07	Lost
434	69.1509	41.2918	09/27/07	Deployment
434	69.1522	41.2901	12/09/07	Download
435	69.2819	41.4028	07/31/07	Deployment
435	69.2819	41.4028	08/02/07	Download
435	69.2819	41.4028	08/29/07	Download
435	69.2809	41.4049	09/27/07	Download
435			12/09/07	Lost
436	68.9701	41.4566	07/31/07	Deployment
436	68.9701	41.4566	08/02/07	Download
436	68.9701	41.4566	08/29/07	Download
436	68.9695	41.4539	09/27/07	Download
436			12/09/07	Lost
437	69.1511	41.3333	07/31/07	Deployment
437	69.1511	41.3333	08/02/07	Download
437	69.1511	41.3333	08/29/07	Download
437	69.1445	41.3422	09/27/07	Download
437			12/09/07	Lost
438	69.1566	41.4173	08/02/07	Deployment
438	69.1566	41.4173	08/29/07	Download
438			09/27/07	Lost
439	69.1550	41.4483	08/02/07	Deployment
439	69.1550	41.4483	08/29/07	Download
439	69.1512	41.4413	09/27/07	Download
439			12/09/07	Lost
440	69.2773	41.4599	08/02/07	Deployment
440	69.2773	41.4599	08/29/07	Download
440	69.2748	41.4561	09/27/07	Download
440			12/09/07	Lost
440	69.3080	41.3650	08/11/08	Found
441	69.0858	41.4010	08/02/07	Deployment
441	69.0858	41.4010	08/29/07	Download
441			09/27/07	Lost
442	69.0162	41.4548	08/02/07	Deployment
442	69.0162	41.4548	08/29/07	Download
442	69.0139	41.4542	09/27/07	Download
442			12/09/07	Lost

Receiver #	Longitude	Latitude	Date	Action
443	69.2120	41.3366	07/31/07	Deployment
443	69.2120	41.3366	08/02/07	Download
443	69.2120	41.3366	08/29/07	Download
443	69.2050	41.3418	09/27/07	Download
443	69.2056	41.3455	12/09/07	Download
444	69.0974	41.3283	07/31/07	Deployment
444	69.0974	41.3283	08/02/07	Download
444	69.0974	41.3283	08/29/07	Download
444	69.0965	41.3332	09/27/07	Download
444			12/09/07	Lost
445	69.0915	41.4566	08/02/07	Deployment
445	69.0915	41.4566	08/29/07	Download
445	69.0906	41.4530	09/27/07	Download
445			12/09/07	Lost
446	69.0923	41.2720	07/31/07	Deployment
446	69.0923	41.2720	08/02/07	Download
446	69.0923	41.2720	08/29/07	Download
446	69.0923	41.2720	09/27/07	Download
446			12/09/07	Lost
447	69.2103	41.3943	07/31/07	Deployment
447	69.2103	41.3943	08/02/07	Download
447	69.2103	41.3943	08/29/07	Download
447	69.2101	41.3975	09/27/07	Download
447			12/09/07	Lost
448	69.1095	41.2246	07/31/07	Deployment
448	69.1095	41.2246	08/02/07	Download
448	69.1095	41.2246	08/29/07	Download
448	69.1078	41.2324	09/27/07	Download
448			12/09/07	Lost
449	69.2164	41.4517	08/02/07	Deployment
449	69.2164	41.4517	08/29/07	Download
449	69.2143	41.4485	09/27/07	Download
449			12/09/07	Lost
450	69.0415	41.3461	08/02/07	Deployment
450	69.0415	41.3461	08/29/07	Download
450	69.0343	41.3504	09/27/07	Download
450			12/09/07	Lost
450	69.1853	41.2138	03/23/08	Found

Table 2 (next page). Haddock details including tag number, total length, release location, and release date. A summary of tracking data is also shown including number of receivers each haddock visited, the number of times each haddock was detected and the number of discrete movements made by each haddock in < 2 months (full array) and > 2 months (reduced array). Duration refers to the length of time that each haddock remained within detection. Fate is described in section 3.1. Mobile tracking results are also shown.

Tag ID Code	Total Length (cm)	Release Date	Release Location		# Receivers		# Detections		# Movements		Duration (days)	Presumed fate	Mobile tracking # detections
			Long	Lat	< 2 mo	> 2 mo	< 2 mo	> 2 mo	< 2 mo	> 2 mo			
3818	54	8/15/2007	69.146	41.284	2	2	2	32,297	0	0	300	Resident	0
3819	56	8/15/2007	69.146	41.284	0	0	0	0	0	0	NA	MIA	0
3820	55	8/15/2007	69.146	41.284	0	0	0	0	0	0	NA	MIA	0
3821	66	8/15/2007	69.143	41.292	0	1	0	1,778	0	0	116	DOA	0
3822	56	8/15/2007	69.143	41.292	0	0	0	0	0	0	NA	MIA	0
3823	53	8/15/2007	69.143	41.292	0	0	0	0	0	0	NA	MIA	0
3824	64	8/15/2007	69.143	41.292	2	0	66	0	0	0	1	Transient	0
3825	49	8/15/2007	69.143	41.292	1	0	4	0	0	0	42	Resident	0
3826	61	8/15/2007	69.143	41.292	3	0	53	0	2	0	6	Transient	0
3827	57	8/15/2007	69.141	41.333	1	1	18,872	49	0	0	45	DOA	0
3828	68	8/15/2007	69.141	41.333	3	0	82	0	2	0	2	Transient	0
3829	59	8/15/2007	69.141	41.333	1	0	5,291	0	0	0	24	DOA	0
3830	51	8/15/2007	69.141	41.333	5	2	1,309	52	2	1	87	Resident	0
3831	53	8/15/2007	69.141	41.333	1	0	30	0	0	0	2	Transient	0
3832	54	8/15/2007	69.141	41.333	4	2	1,866	1,294	0	1	181	Resident	0
3833	54	8/15/2007	69.141	41.333	6	5	1,251	792	9	7	300	Resident	1
3834	51	8/15/2007	69.141	41.333	1	1	2,241	23	0	0	45	DOA	0
3835	57	8/15/2007	69.141	41.333	1	0	7,319	0	0	0	33	DOA	0
3836	52	8/2/2007	69.005	41.399	2	0	28	0	1	0	1	Transient	0
3837	54	8/2/2007	69.005	41.399	1	0	7	0	0	0	1	Transient	0
3838	51	8/2/2007	69.248	41.445	1	0	1	0	0	0	0	Transient	0
3839	53	8/2/2007	69.005	41.399	1	1	44	8	0	0	89	DOA	3
3840	56	8/2/2007	69.005	41.399	1	1	19	422	0	0	96	DOA	2
3841	52	8/2/2007	69.005	41.399	3	0	445	0	1	0	15	Resident	0
3842	54	8/2/2007	69.005	41.399	5	0	102	0	5	0	2	Transient	0
3843	54	8/2/2007	69.120	41.270	1	0	2	0	0	0	0	Transient	0
3844	52	8/2/2007	69.046	41.438	10	2	1,093	388	7	1	194	Resident	0
3845	51	8/2/2007	69.120	41.270	1	2	7	762	0	2	234	Resident	1
3846	54	8/2/2007	69.120	41.270	0	0	0	0	0	0	NA	MIA	0
3847	52	8/2/2007	69.120	41.270	0	0	0	0	0	0	NA	MIA	0
3848	52	8/2/2007	69.120	41.270	2	0	35	0	1	0	2	Transient	0
3849	51	8/2/2007	69.120	41.270	1	0	5	0	0	0	1	Transient	0
3850	56	8/2/2007	69.120	41.270	2	0	87	0	2	0	44	Resident	0
3851	58	8/2/2007	69.153	41.297	0	1	0	394	0	0	87	DOA	0
3852	55	8/2/2007	69.153	41.297	9	0	1,481	1	9	0	65	Resident	4
3853	68	8/2/2007	69.153	41.297	0	1	0	28,345	0	0	130	DOA	0
3854	50	8/15/2007	69.122	41.257	0	0	0	0	0	0	NA	MIA	0
3855	55	8/15/2007	69.122	41.257	0	0	0	0	0	0	NA	MIA	5
3856	54	8/15/2007	69.122	41.257	0	0	0	0	0	0	NA	MIA	0
3857	58	8/15/2007	69.146	41.284	0	0	0	0	0	0	NA	MIA	0
3858	51	8/15/2007	69.146	41.284	1	0	1	0	0	0	0	Transient	0
3859	50	8/15/2007	69.146	41.284	1	1	3	1	0	0	181	Resident	0
3860	50	8/2/2007	69.248	41.445	0	0	0	0	0	0	NA	MIA	0
3861	50	8/2/2007	69.248	41.445	8	0	765	0	6	0	33	Resident	0
3862	54	8/2/2007	69.248	41.445	0	0	0	0	0	0	NA	MIA	1
3863	51	8/2/2007	69.248	41.445	5	2	538	310	4	1	95	Resident	2
3864	54	8/2/2007	69.248	41.445	0	0	0	0	0	0	NA	MIA	0
3865	57	8/2/2007	69.248	41.445	0	0	0	0	0	0	NA	MIA	0
3866	52	8/2/2007	69.046	41.438	0	0	0	0	0	0	NA	MIA	5
3867	53	8/2/2007	69.248	41.445	1	0	1	0	0	0	6	Transient	0
3868	53	8/2/2007	69.248	41.445	1	1	32,673	4	0	0	123	Resident	0
3869	57	8/2/2007	69.046	41.438	0	0	0	0	0	0	NA	MIA	0
3870	53	8/2/2007	69.046	41.438	0	0	0	0	0	0	NA	MIA	0
3871	52	8/2/2007	69.046	41.438	2	0	89	0	5	0	3	Transient	0
3872	50	7/31/2007	69.149	41.289	1	1	16	6,117	0	0	90	Resident	0
3873	55	7/31/2007	69.149	41.289	2	0	71	0	0	0	4	Transient	0
3874	51	7/31/2007	69.121	41.232	1	0	14	0	0	0	2	Transient	0
3875	52	7/31/2007	69.140	41.295	2	0	48	0	1	0	3	Transient	0
3876	53	7/31/2007	69.121	41.232	1	0	9	0	0	0	2	Transient	0
3877	52	7/31/2007	69.121	41.232	2	0	20	0	1	0	4	Transient	5
3878	53	7/31/2007	69.121	41.232	2	0	41	0	2	0	5	Transient	0
3879	58	7/31/2007	69.121	41.232	1	0	8,992	0	0	0	15	DOA	0
3880	71	7/31/2007	69.121	41.232	2	0	593	0	1	0	3	Transient	0
3881	50	7/31/2007	69.121	41.232	2	0	37	0	3	0	3	Transient	0
3882	53	8/2/2007	69.153	41.297	7	0	470	0	10	0	30	Resident	0
3883	57	7/31/2007	69.140	41.295	3	0	18	0	1	0	6	Transient	0
3884	59	7/31/2007	69.140	41.295	2	0	29	0	2	0	4	Transient	0
3885	57	7/31/2007	69.140	41.295	0	0	0	0	0	0	NA	MIA	0
3886	49	7/31/2007	69.140	41.295	7	4	954	64	10	0	299	Resident	0
3887	49	7/31/2007	69.140	41.295	0	1	20	1	5	0	64	Resident	0
3888	59	8/2/2007	69.153	41.297	6	3	2,226	12	4	0	310	Resident	0
3889	56	8/2/2007	69.153	41.297	0	0	0	0	0	0	NA	MIA	0
3891	53	7/31/2007	69.157	41.282	0	1	0	265	0	0	121	DOA	0
3892	55	7/31/2007	69.145	41.286	1	1	27	4,329	0	0	133	Resident	0
3894	53	7/31/2007	69.157	41.282	0	0	0	0	0	0	NA	MIA	0
3895	54	7/31/2007	69.149	41.289	2	1	3	21	1	0	73	Resident	0
3896	59	7/31/2007	69.149	41.289	8	0	193	0	11	0	7	Transient	0
3897	55	7/31/2007	69.149	41.289	2	1	9	4,313	0	0	95	Resident	2

Table 3. Summary of detections by receiver.

			# Detections				# Haddock			
Receiver	Edge	Depth	Total	Dead	Transient	Resident	Total	Dead	Transient	Resident
First 2 months (full array)										
432	In	80	844	63	99	682	12	2	3	7
434	Edge	60	12	0	11	1	2	0	1	1
435	Edge	59	1040	0	103	937	8	0	3	5
436	Edge	78	1498	0	73	1425	13	0	6	7
437	In	81	35847	33723	115	2009	19	4	5	10
438	In	82	136	0	14	122	4	0	1	3
439	Edge	82	137	0	30	107	4	0	1	3
440	Edge	52	0	0	0	0	0	0	0	0
441	In	83	1157	0	16	1141	8	0	2	6
442	Edge	80	2059	0	53	2006	7	0	2	5
443	Edge	65	280	0	65	215	4	0	2	2
444	In	86	1851	0	69	1782	13	0	3	10
445	Edge	76	359	0	0	359	5	0	0	5
446	In	82	796	0	178	618	14	0	8	6
447	In	77	32735	0	6	32729	7	0	3	4
448	Edge	60	9814	8992	697	125	15	0	10	5
449	Edge	83	165	0	0	165	2	0	0	2
450	In	83	872	0	46	826	11	0	4	7
Reduced array (> 2 months)										
432	In	80	1103	429	0	674	10	2	0	8
434	Edge	60	78049	30580	0	47469	14	3	0	11
440	Edge	52	70	0	0	70	4	0	0	4
443	Edge	65	113	0	0	113	1	0	0	1
450	In	83	2738	0	0	2738	8	0	0	8

Table 4. Detection data for distance, speed and heading calculations. Time 1 is when a given haddock left receiver 1 and time 2 is when it arrived at receiver 2.

Tag	Length (cm)	Receiver1	Receiver2	Array	Time1 (days)	Time2 (days)	Δt (days)	Distance (km)	Heading (degrees)	Speed (m/s)
3818	54	100434	100440	reduced	132.57	314.70	182.14			
3826	61	100438	100437	full	19.98	21.05	1.07	9.341	177.2	0.101
3826	61	100439	100438	full	19.92	19.97	0.06	3.451	182.2	0.717
3828	68	100435	100437	full	16.20	16.71	0.51	13.399	125.3	0.305
3828	68	100443	100435	full	15.90	16.18	0.27	9.71	319.8	0.413
3830	51	100437	100441	full	19.04	19.26	0.22	9.298	35.9	0.495
3830	51	100441	100445	full	20.17	20.37	0.21	6.196	355.6	0.344
3830	51	100450	100432	reduced	101.83	102.12	0.29	6.042	29.9	0.242
3830	51	100445	100435	full	21.02	23.37	2.35			
3830	51	100435	100450	full	54.74	101.78	47.04			
3832	54	100450	100432	reduced	86.23	87.01	0.78	6.042	29.9	0.089
3832	54	100444	100450	full	58.95	61.28	2.33			
3832	54	100437	100446	full	20.10	23.46	3.37			
3832	54	100448	100444	full	53.90	58.47	4.57			
3832	54	100446	100448	full	29.21	53.46	24.25			
3832	54	100432	100450	reduced	88.35	195.90	107.55			
3833	54	100432	100436	full	41.33	41.97	0.64	7.641	22.6	0.138
3833	54	100432	100442	full	43.46	45.10	1.64	6.902	352.5	0.049
3833	54	100436	100432	full	42.30	43.46	1.17	7.641	202.6	0.076
3833	54	100436	100442	full	56.20	57.96	1.76	3.853	266.9	0.025
3833	54	100436	100442	full	51.01	51.96	0.95	3.853	266.9	0.047
3833	54	100441	100442	full	27.30	29.23	1.92	8.339	44.1	0.050
3833	54	100442	100432	full	58.25	58.92	0.66	6.902	172.5	0.121
3833	54	100442	100436	full	46.37	47.17	0.79	3.853	86.9	0.056
3833	54	100450	100432	full	40.34	40.62	0.28	6.042	29.9	0.254
3833	54	100432	100450	reduced	60.37	60.93	0.56	6.042	209.9	0.125
3833	54	100434	100443	reduced	118.17	118.98	0.81	7.328	320.4	0.105
3833	54	100434	100450	reduced	80.67	81.43	0.76	11.364	53.5	0.173
3833	54	100443	100434	reduced	116.55	118.17	1.62	7.328	140.4	0.052
3833	54	100443	100434	reduced	128.56	130.31	1.75	7.328	140.4	0.048
3833	54	100450	100432	reduced	81.96	83.99	2.03	6.042	29.9	0.034
3833	54	100450	100434	reduced	61.76	63.33	1.57	11.363	233.6	0.084
3833	54	100442	100436	full	52.00	55.01	3.01			
3833	54	100442	100450	full	33.18	40.32	7.14			
3833	54	100437	100441	full	17.23	27.27	10.04			
3833	54	100434	100443	reduced	114.18	116.30	2.12			
3833	54	100440	100450	reduced	163.73	167.46	3.73			
3833	54	100434	100440	reduced	63.89	68.46	4.57			
3833	54	100440	100434	reduced	68.80	76.80	7.99			
3833	54	100432	100434	reduced	87.43	100.60	13.17			
3833	54	100434	100440	reduced	130.44	163.72	33.27			
3833	54	100450	100440	reduced	171.35	314.70	143.34			
3836	52	100450	100432	full	3.07	3.50	0.44	6.042	29.9	0.159
3841	52	100436	100442	full	13.33	14.04	0.71	3.853	266.9	0.063
3841	52	100432	100436	full	2.70	8.91	6.21			
3842	54	100432	100450	full	2.70	3.05	0.35	6.042	209.9	0.201
3842	54	100436	100444	full	0.97	1.19	0.22	17.791	216.7	0.928
3842	54	100442	100432	full	1.96	2.28	0.32	6.902	172.5	0.253
3842	54	100444	100442	full	1.19	1.95	0.76	15.606	25.7	0.239
3842	54	100450	100432	full	3.07	3.51	0.44	6.042	29.9	0.159
3844	52	100436	100442	full	55.83	56.15	0.32	3.853	266.9	0.138
3844	52	100441	100438	full	7.13	7.34	0.21	6.189	287	0.337
3844	52	100442	100450	full	57.43	59.37	1.94	12.259	189.9	0.073
3844	52	100442	100450	full	35.66	37.24	1.58	12.259	189.9	0.090
3844	52	100444	100450	full	39.56	40.08	0.52	5.074	67	0.112
3844	52	100445	100442	full	33.32	35.34	2.01	6.3	91.9	0.036
3844	52	100450	100432	full	40.46	41.02	0.57	6.042	29.9	0.123
3844	52	100432	100450	reduced	118.33	118.79	0.45	6.042	209.9	0.154
3844	52	100450	100444	full	37.31	39.49	2.19			

Table 4 (continued).

Tag	Length (cm)	Receiver1	Receiver2	Array	Time1 (days)	Time2 (days)	Δt (days)	Distance (km)	Heading (degrees)	Speed (m/s)
3844	52	100437	100441	full	24.71	27.55	2.84			
3844	52	100432	100441	full	3.13	6.06	2.93			
3844	52	100441	100445	full	27.75	31.09	3.34			
3844	52	100438	100443	full	7.40	14.21	6.82			
3844	52	100443	100437	full	14.44	24.29	9.85			
3844	52	100432	100436	full	41.18	55.43	14.24			
3844	52	100450	100432	reduced	81.02	98.83	17.81			
3845	51	100432	100450	reduced	104.24	105.30	1.05	6.042	209.9	0.066
3845	51	100450	100432	reduced	103.66	104.19	0.54	6.042	29.9	0.130
3845	51	100432	100450	reduced	92.09	103.46	11.36			
3845	51	100450	100432	reduced	72.27	92.03	19.76			
3848	52	100436	100444	full	2.87	3.72	0.85	17.791	216.7	0.242
3850	56	100444	100446	full	4.43	4.45	0.02	6.267	176.2	3.077
3850	56	100446	100444	full	5.03	5.18	0.15	6.267	356.2	0.478
3852	55	100432	100436	full	41.48	42.26	0.77	7.641	22.6	0.115
3852	55	100436	100442	full	45.75	45.78	0.03	3.853	266.9	1.722
3852	55	100437	100444	full	7.08	8.04	0.96	4.531	97	0.054
3852	55	100441	100445	full	26.46	27.51	1.05	6.196	355.6	0.068
3852	55	100442	100445	full	45.79	46.53	0.74	6.3	271.9	0.098
3852	55	100444	100441	full	25.08	25.52	0.44	8.137	6.8	0.214
3852	55	100445	100444	full	46.84	47.97	1.13	14.265	182	0.146
3852	55	100446	100444	full	18.12	18.25	0.12	6.267	356.2	0.587
3852	55	100450	100432	full	40.48	41.24	0.76	6.042	29.9	0.091
3852	55	100444	100450	full	35.22	40.19	4.98			
3852	55	100444	100446	full	8.06	14.22	6.15			
3852	55	100445	100444	full	27.56	35.16	7.60			
3852	55	100444	100434	full	47.98	67.43	19.45			
3859	50	100444	100450	full	16.62	196.61	179.99			
3861	50	100432	100436	full	29.42	29.92	0.51	7.641	22.6	0.174
3861	50	100439	100449	full	4.21	5.11	0.90	5.149	274.2	0.066
3861	50	100444	100447	full	1.21	1.27	0.07	11.963	308	2.101
3861	50	100444	100448	full	34.31	34.96	0.66	11.553	185.1	0.204
3861	50	100447	100439	full	1.28	3.17	1.90	7.571	37.5	0.046
3861	50	100450	100444	full	32.83	34.22	1.38	5.074	247	0.042
3861	50	100436	100450	full	30.00	32.83	2.83			
3861	50	100449	100432	full	5.34	28.56	23.23			
3863	51	100437	100444	full	4.53	5.30	0.77	4.531	97	0.068
3863	51	100444	100446	full	5.62	6.05	0.43	6.267	176.2	0.168
3863	51	100447	100437	full	4.41	4.50	0.08	8.398	143.9	1.198
3863	51	100448	100446	full	16.02	16.10	0.08	5.449	15.3	0.784
3863	51	100432	100450	reduced	90.41	90.94	0.52	6.042	209.9	0.133
3863	51	100446	100448	full	27.04	32.06	5.02			
3863	51	100446	100448	full	6.08	15.44	9.35			
3863	51	100448	100444	full	32.37	44.12	11.75			
3863	51	100444	100432	full	44.23	90.36	46.13			
3863	51	100450	100432	reduced	91.07	97.18	6.11			
3868	53	100447	100434	full	30.43	60.40	29.97			
3871	52	100436	100442	full	3.10	3.49	0.39	3.853	266.9	0.113
3871	52	100436	100442	full	4.32	4.46	0.14	3.853	266.9	0.311
3871	52	100442	100436	full	3.50	4.31	0.81	3.853	86.9	0.055
3871	52	100442	100436	full	4.47	4.55	0.08	3.853	86.9	0.542
3871	52	100442	100436	full	2.93	2.97	0.04	3.853	86.9	1.233
3872	50	100435	100434	full	0.75	59.59	58.83			
3873	55	100435	100446	full	0.73	3.83	3.10			
3875	52	100446	100448	full	2.17	2.52	0.35	5.449	195.3	0.179
3877	52	100448	100446	full	1.63	3.04	1.41	5.449	15.3	0.045
3878	53	100437	100448	full	4.73	4.91	0.18	12.555	164	0.799
3878	53	100448	100437	full	4.44	4.72	0.27	12.555	344	0.529
3880	71	100448	100446	full	2.43	2.74	0.31	5.449	15.3	0.206
3881	50	100446	100448	full	2.24	2.48	0.24	5.449	195.3	0.264

Table 4 (continued).

Tag	Length (cm)	Receiver1	Receiver2	Array	Time1 (days)	Time2 (days)	Δt (days)	Distance (km)	Heading (degrees)	Speed (m/s)
3881	50	100448	100446	full	1.63	2.21	0.57	5.449	15.3	0.110
3881	50	100448	100446	full	2.52	2.66	0.14	5.449	15.3	0.449
3882	53	100432	100450	full	10.13	11.20	1.07	6.042	209.9	0.065
3882	53	100438	100441	full	6.16	6.35	0.20	6.189	107	0.363
3882	53	100444	100446	full	30.05	30.35	0.30	6.267	176.2	0.242
3882	53	100444	100450	full	31.03	31.37	0.34	5.074	67	0.172
3882	53	100446	100444	full	16.37	17.22	0.85	6.267	356.2	0.085
3882	53	100446	100444	full	30.51	30.97	0.47	6.267	356.2	0.155
3882	53	100441	100432	full	7.08	10.13	3.05			
3882	53	100450	100446	full	12.08	16.11	4.03			
3883	57	100446	100447	full	5.30	5.68	0.38	16.798	324.1	0.510
3883	57	100448	100446	full	1.62	4.51	2.89			
3884	59	100446	100448	full	2.84	2.97	0.13	5.449	195.3	0.490
3884	59	100448	100446	full	2.97	3.45	0.47	5.449	15.3	0.133
3886	49	100432	100450	full	52.96	53.36	0.39	6.042	209.9	0.178
3886	49	100437	100444	full	40.18	41.28	1.10	4.531	97	0.048
3886	49	100437	100444	full	58.29	59.26	0.98	4.531	97	0.054
3886	49	100439	100449	full	44.34	46.01	1.67	5.149	274.2	0.036
3886	49	100444	100437	full	55.97	57.17	1.20	4.531	277.1	0.044
3886	49	100444	100445	full	41.38	43.13	1.75	14.265	2	0.094
3886	49	100445	100439	full	43.24	44.30	1.06	5.382	260.1	0.059
3886	49	100449	100439	full	46.05	47.31	1.26	5.149	94.2	0.047
3886	49	100450	100432	full	52.15	52.43	0.28	6.042	29.9	0.248
3886	49	100450	100444	full	54.11	55.37	1.26	5.074	247	0.047
3886	49	100439	100450	full	47.36	50.17	2.81			
3886	49	100444	100434	full	59.28	64.00	4.72			
3886	49	100434	100432	reduced	64.03	70.00	5.97			
3886	49	100432	100440	reduced	70.02	298.92	228.90			
3887	49	100443	100448	full	1.61	3.17	1.56	14.828	146.7	0.110
3887	49	100446	100444	full	3.59	3.68	0.08	6.267	356.2	0.873
3887	49	100446	100448	full	3.33	3.36	0.03	5.449	195.3	2.116
3887	49	100448	100446	full	3.36	3.59	0.23	5.449	15.3	0.276
3887	49	100448	100446	full	3.17	3.33	0.16	5.449	15.3	0.397
3887	49	100444	100434	full	3.68	64.51	60.83			
3888	59	100436	100442	full	53.02	53.75	0.73	3.853	266.9	0.061
3888	59	100437	100438	full	6.59	8.29	1.70	9.341	357.2	0.064
3888	59	100438	100442	full	8.30	10.06	1.76	12.455	70.3	0.082
3888	59	100442	100436	full	50.99	52.01	1.02	3.853	86.9	0.044
3888	59	100441	100445	full	27.22	30.48	3.26			
3888	59	100445	100442	full	45.35	49.26	3.91			
3888	59	100442	100441	full	10.19	25.87	15.67			
3888	59	100442	100432	full	58.03	86.34	28.31			
3888	59	100432	100450	reduced	86.37	102.29	15.92			
3888	59	100450	100440	reduced	102.30	311.89	209.59			
3892	55	100435	100434	full	0.72	92.04	91.32			
3895	54	100435	100448	full	0.56	1.88	1.33	24.494	143.9	0.214
3895	54	100448	100434	full	1.88	59.86	57.98			
3896	59	100435	100444	full	0.57	1.74	1.17	17.523	118.2	0.173
3896	59	100436	100437	full	5.79	6.53	0.73	20.415	227.8	0.323
3896	59	100436	100450	full	4.79	5.00	0.21	13.655	205.9	0.750
3896	59	100441	100436	full	5.71	5.78	0.08	11.474	57.3	1.691
3896	59	100444	100441	full	5.60	5.70	0.10	8.137	6.8	0.926
3896	59	100444	100446	full	1.75	1.82	0.07	6.267	176.2	1.076
3896	59	100444	100447	full	2.63	2.78	0.15	11.963	308	0.954
3896	59	100446	100436	full	3.51	4.76	1.24	22.917	26.4	0.213
3896	59	100446	100444	full	2.52	2.61	0.09	6.267	356.2	0.789
3896	59	100447	100446	full	2.78	3.21	0.43	16.798	144.1	0.454
3896	59	100450	100444	full	5.03	5.59	0.56	5.074	247	0.105
3897	55	100436	100434	full	42.90	59.65	16.75			
3897	55	100435	100436	full	0.75	42.90	42.15			

Table 5. Summary of mobile tracking results

Tag ID	Date	Station	Longitude	Latitude
3833	7/16/2008	46	69.211	41.295
3833	8/13/2008	46	69.211	41.295
3839	7/2/2008	37	69.016	41.408
3839	7/16/2008	37	69.016	41.408
3839	8/13/2008	37	69.016	41.408
3840	8/13/2008	37	69.016	41.408
3840	8/30/2008	37	69.016	41.408
3845	8/13/2008	33	69.098	41.291
3852	7/16/2008	18	68.915	41.389
3852	8/30/2008	18	68.915	41.389
3852	7/31/2008	19	68.935	41.361
3855	7/2/2008	32	69.117	41.261
3855	8/13/2008	32	69.117	41.261
3855	8/21/2008	32	69.117	41.261
3855	8/30/2008	32	69.117	41.261
3855	7/16/2008	32	69.149	41.277
3862	8/30/2008	52	69.224	41.441
3863	8/21/2008	30	69.163	41.199
3863	8/30/2008	30	69.163	41.199
3866	7/2/2008	17	68.894	41.420
3866	7/31/2008	17	68.894	41.420
3866	8/21/2008	17	68.894	41.420
3866	8/30/2008	17	68.894	41.420
3866	7/16/2008	17	68.900	41.423
3877	7/16/2008	33	69.098	41.290
3877	7/2/2008	33	69.098	41.291
3877	8/13/2008	33	69.098	41.291
3877	8/21/2008	33	69.098	41.291
3877	8/30/2008	33	69.098	41.291
3896	7/16/2008	21	68.977	41.302
3896	8/21/2008	21	68.977	41.302

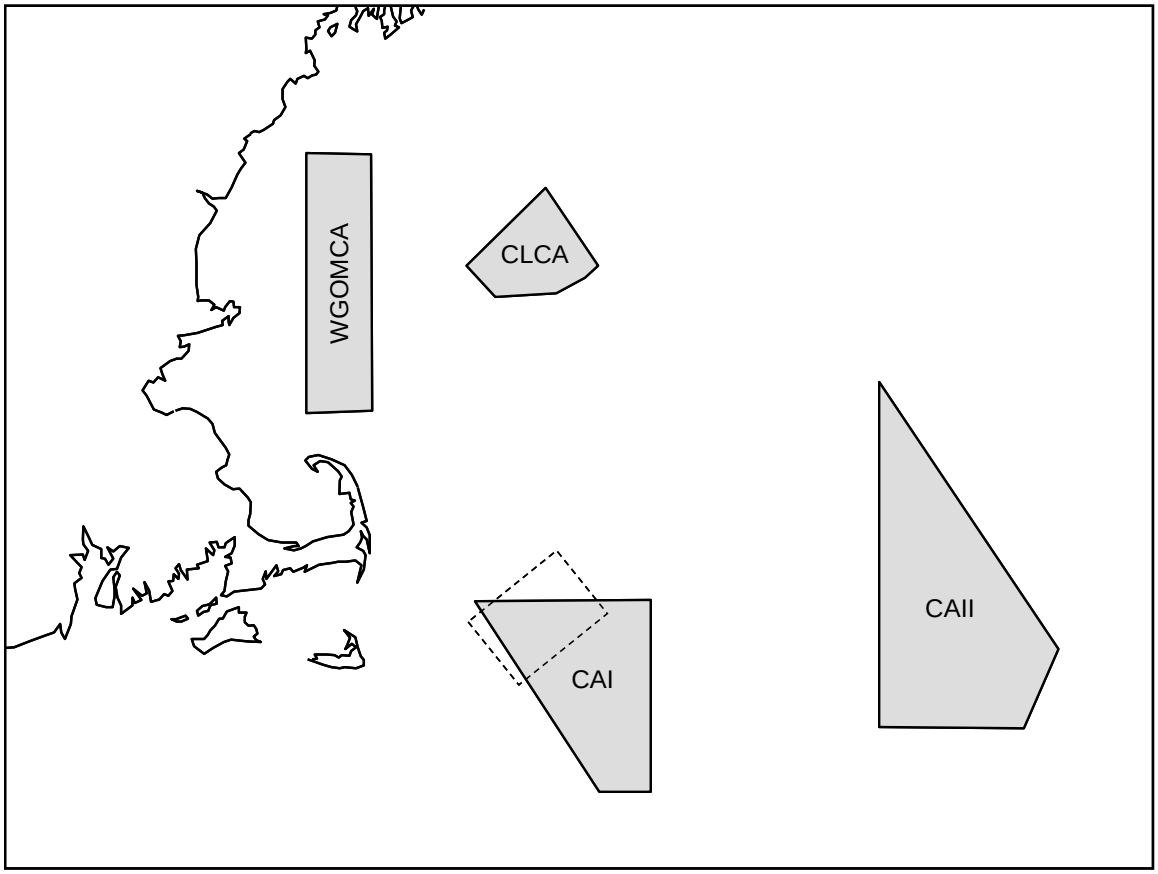


Figure 1. Map of Gulf of Maine and Georges Bank showing location of 4 year-round closed areas: 1) WGOMCA, Western Gulf of Maine Closure Area; 2) CLCA, Cashes Ledge Closed Area; 3) CAI, Closed Area I; and 4) CAII, Closed Area II. A fifth year-round closed area, Nantucket Lightship Closed Area (NLCA), in southern New England, is not shown. CAI and CAII (as well as NLCA) were established in 1994. WGOMCA was added in 1996 and CLCA was added in 1998. Dashed rectangle shows area of coverage for figures 2, 6, 8-10 (i.e., array location).

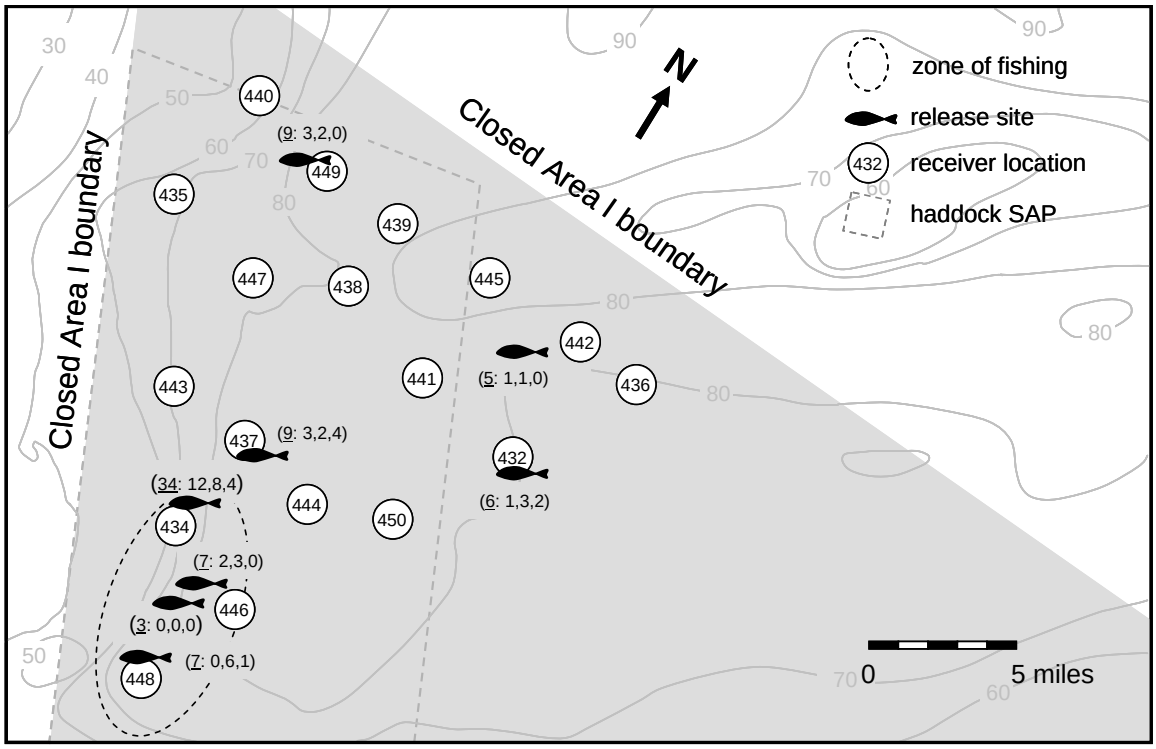


Figure 2. Map of northwest corner of CAI showing array configuration, fishing area and release sites. Numbers in parentheses are number of tagged haddock released per site followed by numbers of those haddock which were subsequently deemed to be resident, transient or dead (see section 3.1). Depth contours are shown in fathoms. Dashed line represents extent of haddock SAP.

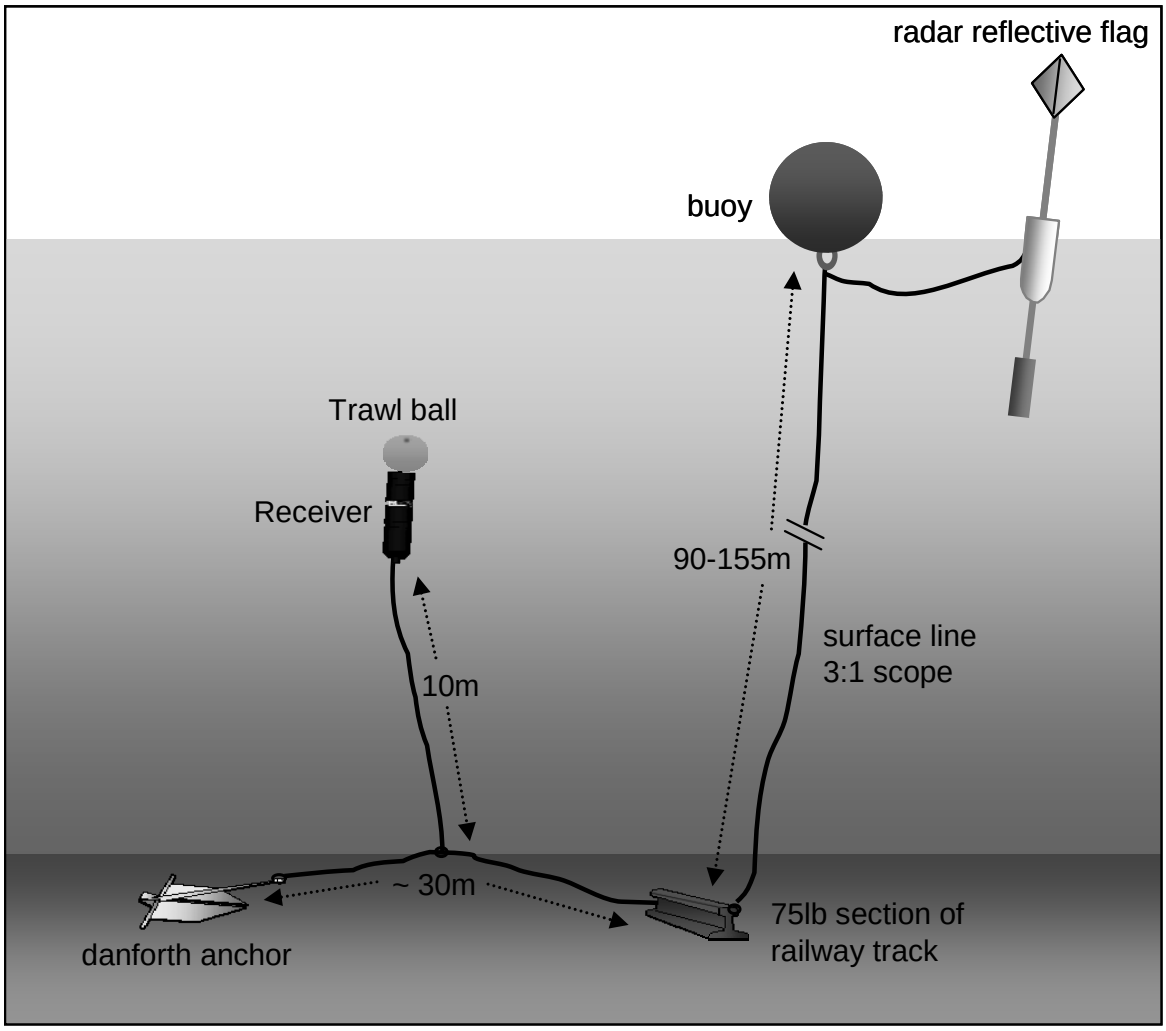


Figure 3. Schematic of mooring configuration. Note the break in the depth scale for the surface line.

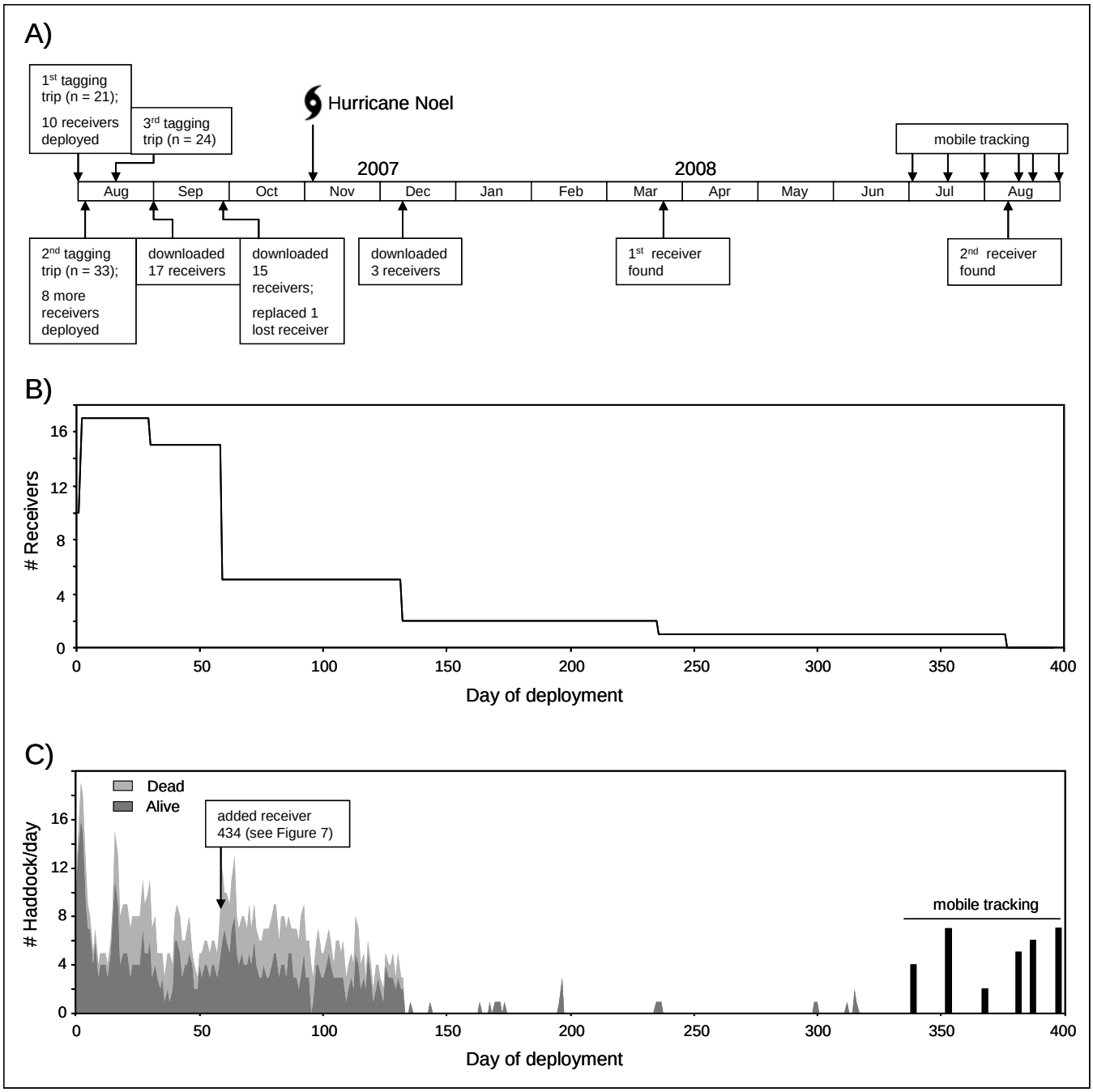


Figure 4. Timeline of activities and events in 2007 and 2008.

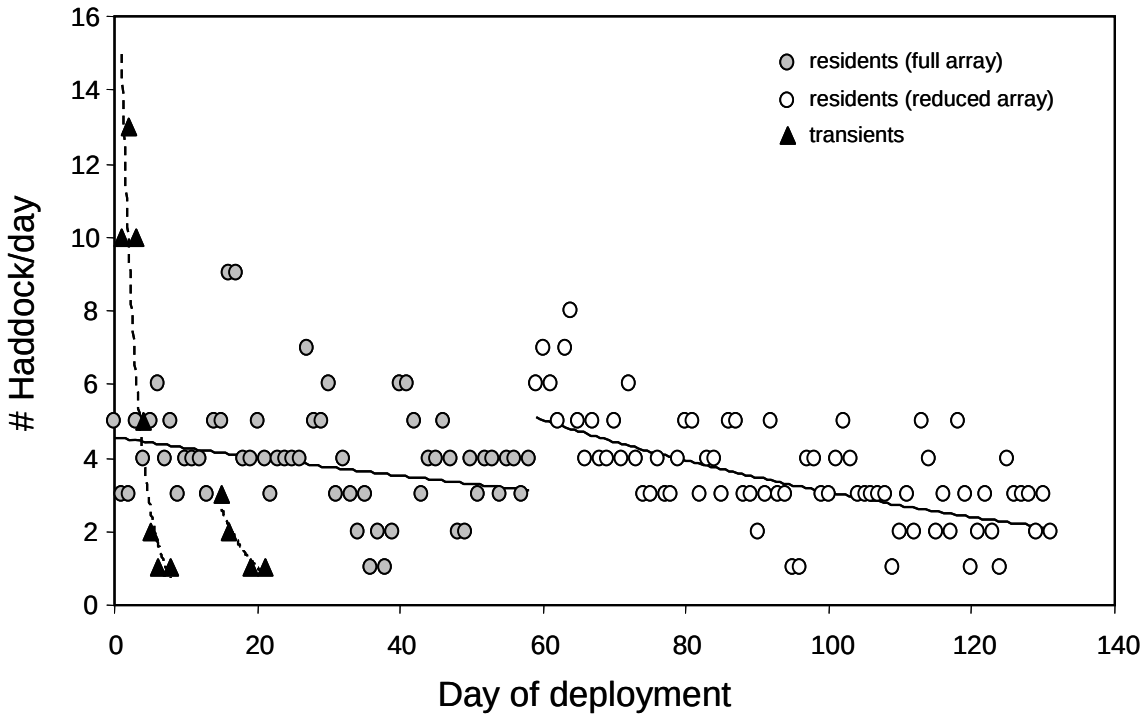


Figure 5. Exponential decay (loss) curves of haddock from the full (first 2 months) and reduced (after 2 months) arrays. First transient curve: # haddock = $23.01e^{-0.430\times day}$; R^2 = 0.86, $p < 0.05$ (35% day^{-1}). Second transient curve: # haddock = $42.59e^{-0.186\times day}$; R^2 = 0.89, $p < 0.05$ (17% day^{-1}). Full resident curve: # haddock = $4.56e^{-0.006\times day}$; R^2 = 0.07, $p <$ 0.05 (0.5% day^{-1}). Reduced resident curve: # haddock = $10.51e^{-0.012\times day}$; R^2 = 0.32, $p <$ 0.0001 (1.2% day^{-1}).

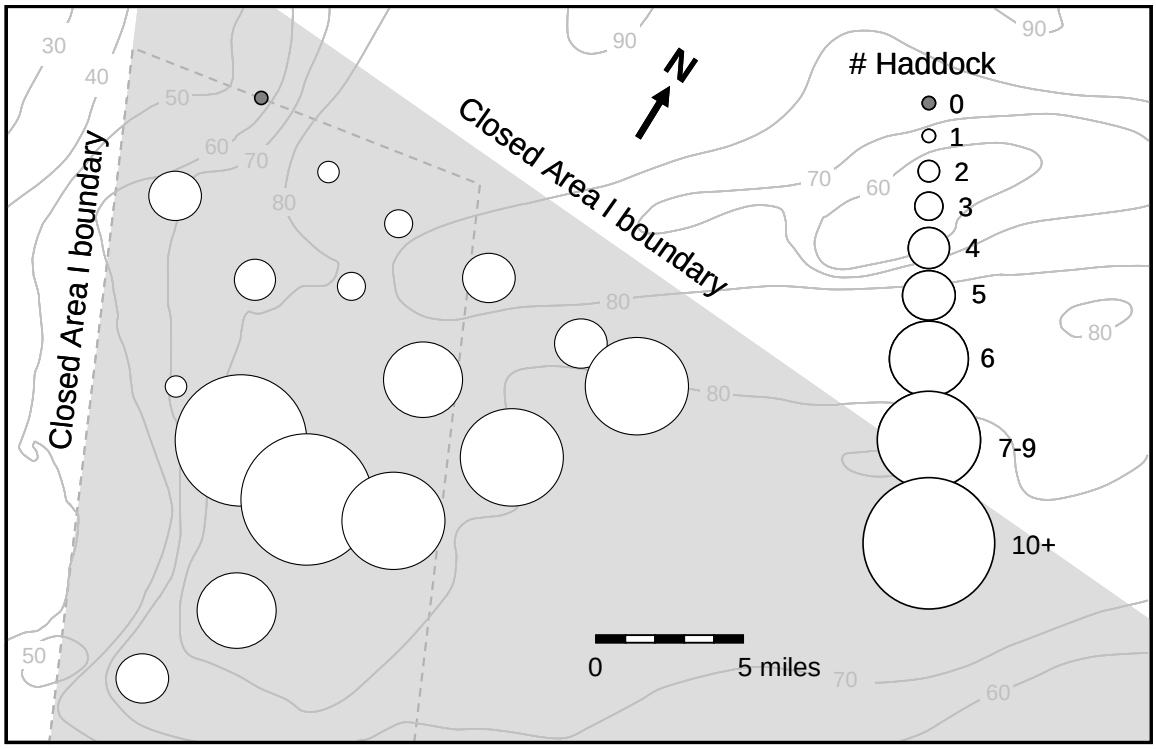


Figure 6. Number of haddock detected by receiver for the full array (i.e., within 2 months; before major receiver losses). Depth contours are in fathoms. Dashed line represents extent of haddock SAP.

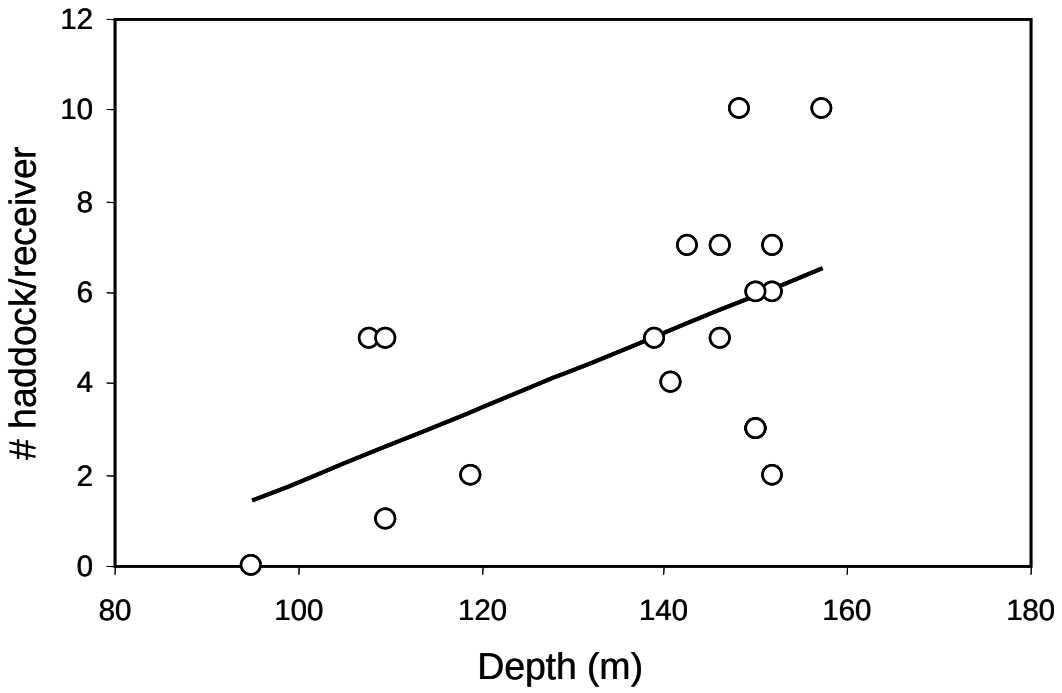


Figure 7. Relationship between number of haddock per receiver and depth of receiver ($R^2 = 0.32$, $p < 0.05$).

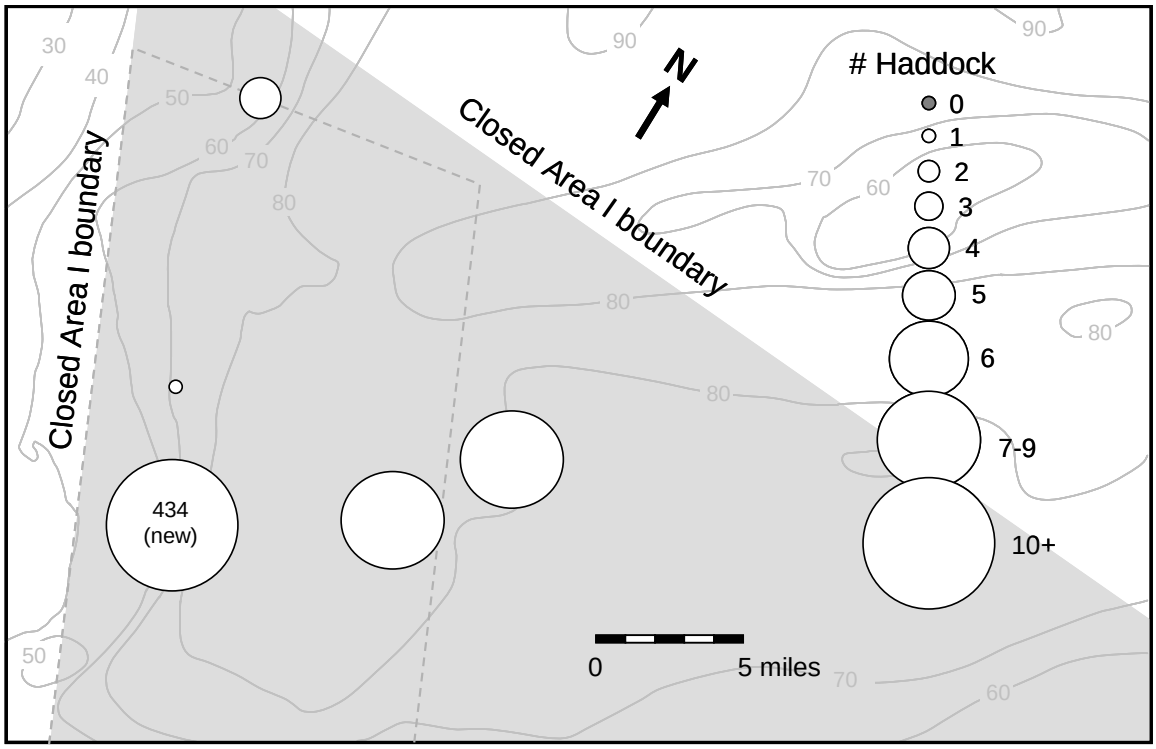


Figure 8. Number of haddock detected by receiver for the reduced array (i.e., after 2 months). Note how one receiver (434) was added on 9/27/09 to replace one lost at the beginning of deployment (433, Table 1). Depth contours are in fathoms. Dashed line represents extent of haddock SAP.

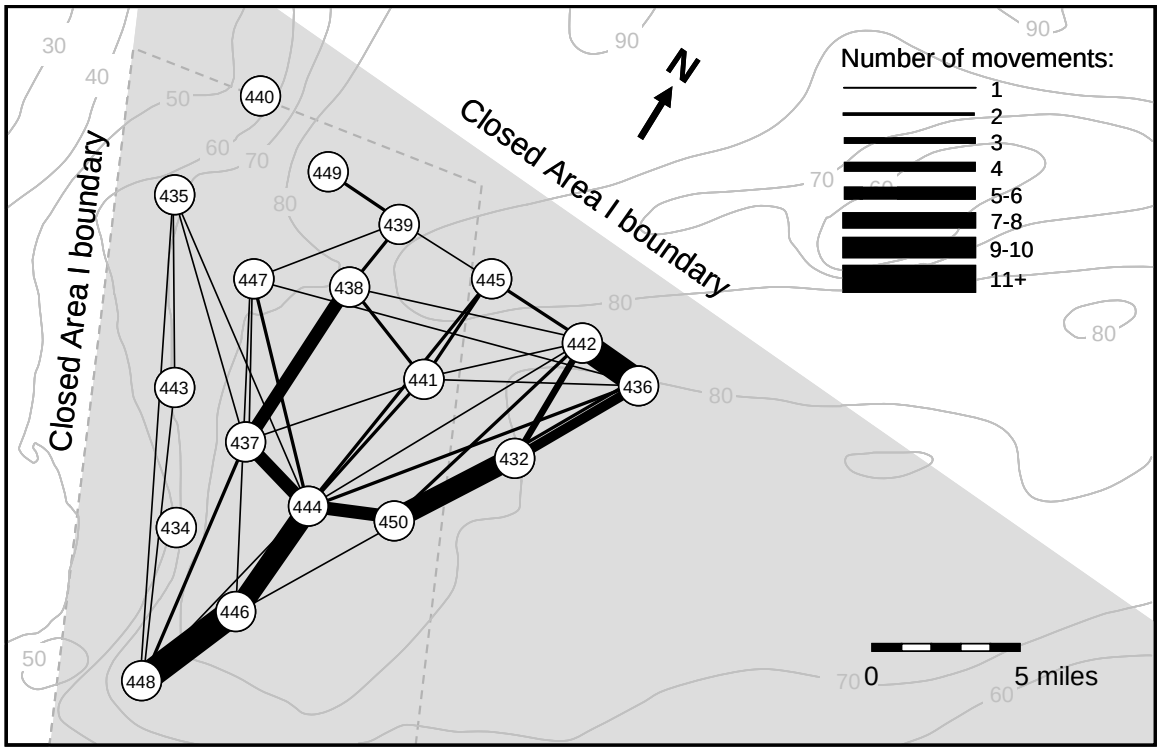


Figure 9. Connectivity diagram showing the number of discrete short-term (< 48 hrs) movements between each receiver for the full array (i.e., within 2 months). Depth contours are in fathoms. Dashed line represents extent of haddock SAP.

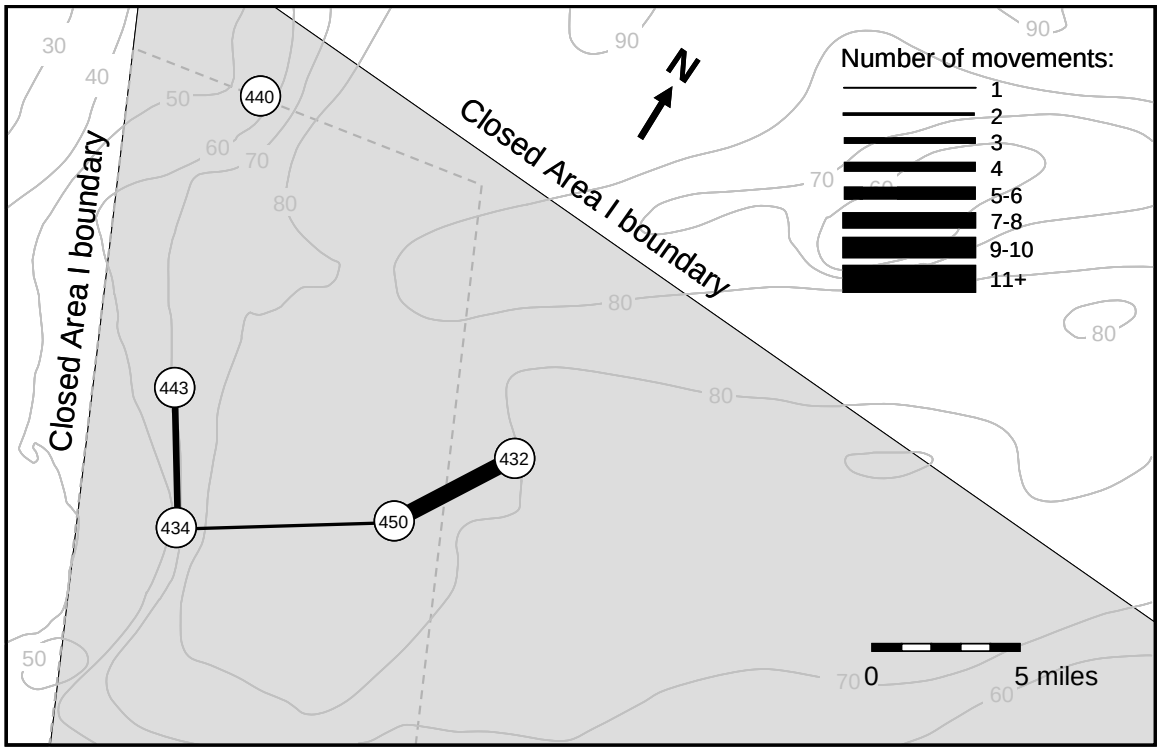


Figure 10. Connectivity diagram showing the number of discrete short-term (< 48 hrs) movements between each receiver for the reduced array (i.e., after 2 months). Depth contours are in fathoms. Dashed line represents extent of haddock SAP.

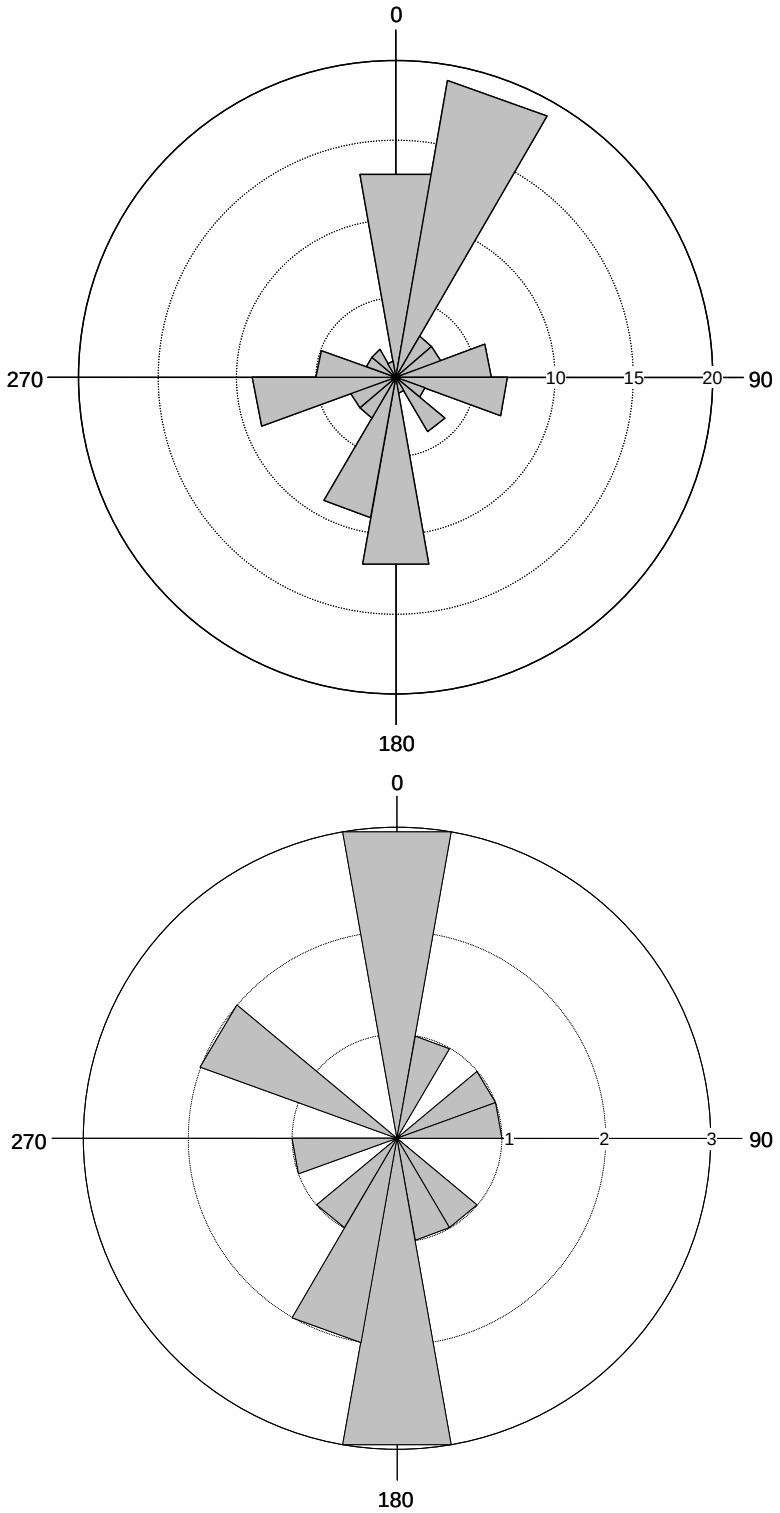


Figure 11. Rose histograms showing dominant direction of short-term (< 48 hrs) movements for all movements (top panel) and movements faster than maximum sustainable swimming speed (U_{ms} = 0.6 m/s) (bottom panel).

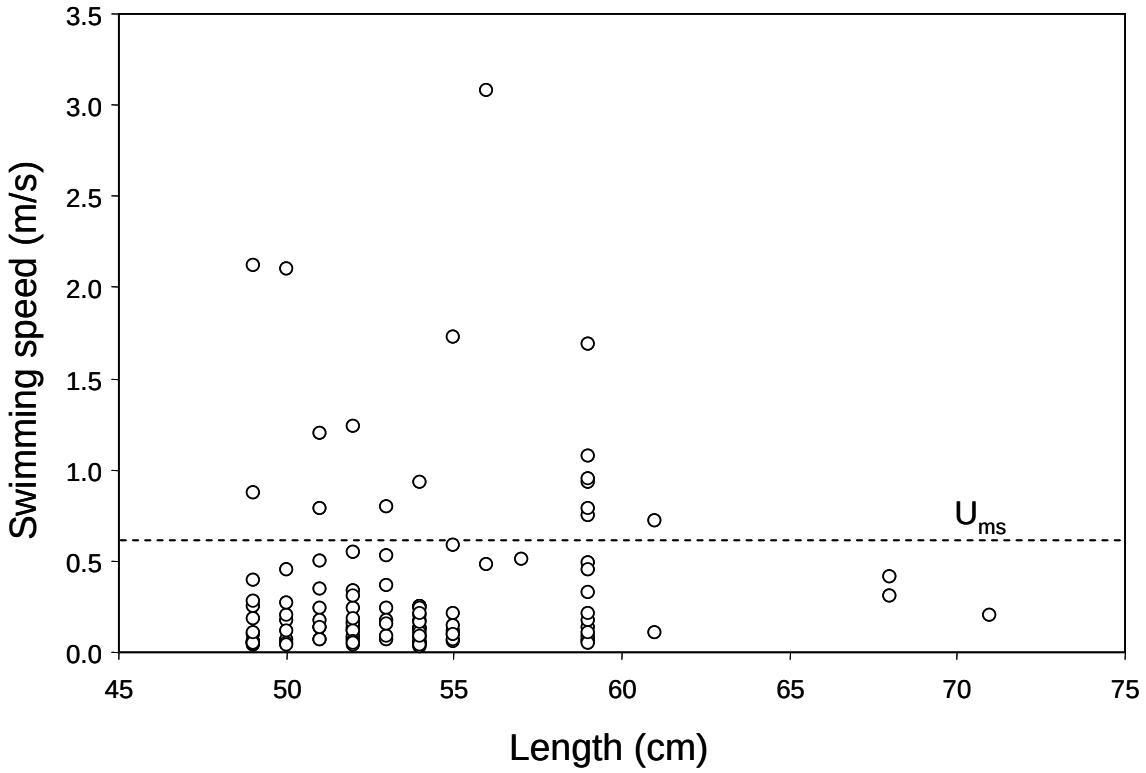


Figure 12. Swimming speed between receivers versus body length. No significant relationship was found. Maximum sustainable swimming speed for haddock (U_{ms}) is shown as dashed line (from Breen et al. 2004).

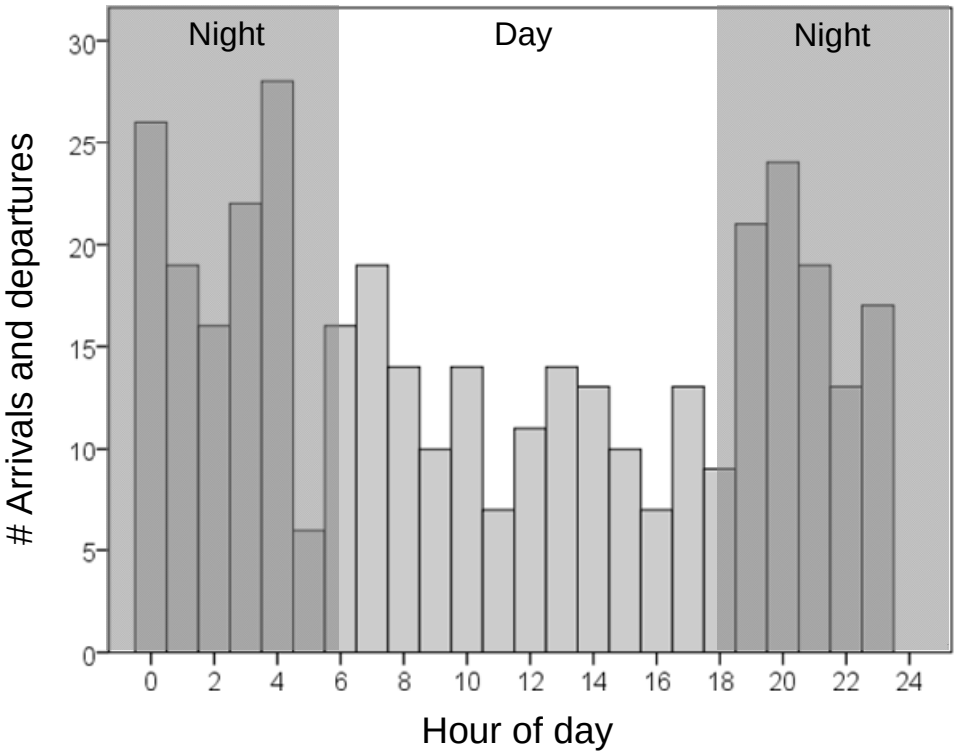


Figure 13. Number of arrivals and departures to and from receivers by hour. There were significantly more arrivals and departures at night than during the day (Student's *t*-test, $p < 0.01$).

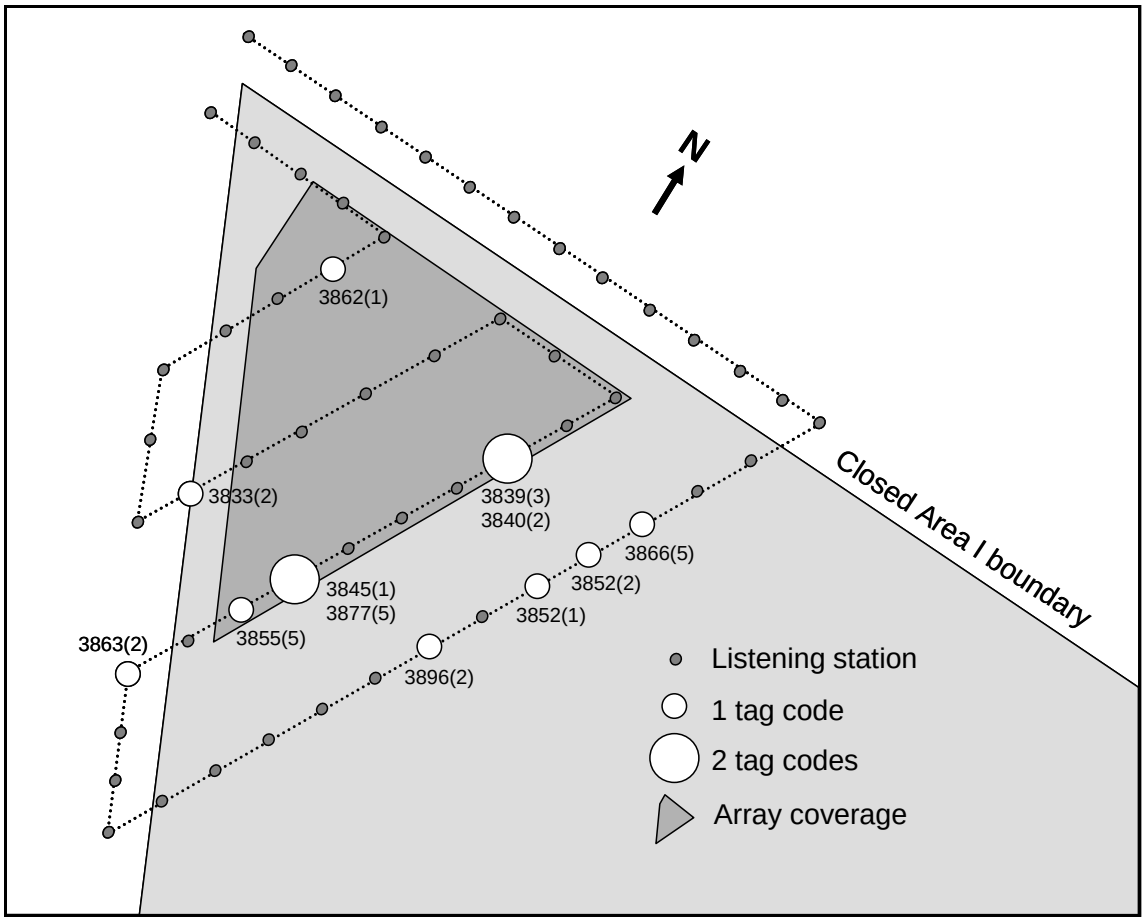


Figure 14. Results of mobile tracking in 2008 showing sampling stations and stations where tags were detected. Numbers in brackets after tag codes are number of times that tag was detected at that location.

VII. Partnerships

This project involved a fruitful collaboration between the Gulf of Maine Research Institute (GMRI) and the Cape Cod Commercial Hook Fishermen's Association (CCCHFA). CCCHFA staff (particularly Tom Rudolph) were very helpful in providing advice and logistical support out of Chatham and for putting Sherwood in touch with three very capable and dedicated fishing partners. Bruce Kaminski (F/V Never Enough), Peter Taylor (F/V Sea Hound) and Eric Hesse (F/V Tenacious) of the CCCHFA were involved from the very start in project design, array configuration, mooring construction, equipment testing, at-sea surgery trials, tagging and downloading data. If it were not for their intimate knowledge of the haddock fishery and Closed Area I, this project would not have gotten off the ground. Two other fishing partners from Maine were involved in earlier fish captures for laboratory trials: John Shusta (F/V Special J) and Robert Odlin (F/V Maine Lady). Relationships that developed as a result of this project have spilled over to other projects. For instance, John Shusta and Bruce Kaminski have been involved in cod collections for another NEC funded study. Phil Yund, Mike Dunnington and Tim Arienti of the University of New England offered valuable assistance in setting up the laboratory trials portion of this project.

VIII. Impacts/Applications

This project should contribute to informed evaluations of the impact of Gulf of Maine and Georges Bank area closures on rebuilding groundfish. Very little information exists to properly assess whether closed areas are achieving their goals of reducing groundfish mortality. In this case, it appears that Closed Area I is indeed serving as a refuge for haddock on western Georges Bank. Is this the case for other closed areas and species? A larger picture is emerging to suggest that closed areas are most beneficial to more sedentary species (which appears to include haddock).

Technically speaking, this project has demonstrated quite successfully that acoustic arrays are a very powerful means to assess habitat associations and residency in marine fish, even at offshore locations. Only one other study, to this author's knowledge, has attempted to monitor residency offshore (Lindholm et al. 2007) and not on the scale

represented here. A great deal could be learned about sub-population structure, life-history variation and species interactions in other target species at other locations around the Gulf of Maine and Georges Bank and elsewhere using non-overlapping arrays. Acoustic monitoring, as an application, is much more than a means to monitor large-scale ocean migrations with line arrays in highly migratory species (e.g., the Ocean Tracking Network; http://oceantrackingnetwork.org/).

IX. Related Projects

Sherwood, G.D., and Grabowski, J.H. Exploring the potential inadvertent effects of Gulf of Maine and Georges Bank area closures on cod life-history variation. Northeast Consortium 2006. Results from this cod project are often presented together with results from the haddock acoustics project to provide a broad comparative perspective of the impact of closed areas on groundfish recovery in the Gulf of Maine and Georges Bank.

Sherwood, G.D., and Grabowski, J.H. Passive acoustic monitoring of red cod residency at Cashes Ledge. Proposal submitted to the 2009 NEC RFP. This study, if funded, will build from the approach and expertise developed as a result of the haddock acoustics project.

Rudolph, T. 2009. Haddock Migration in New England Waters: Analysis of Movements between Stocks and Closed Areas. Final Report to the Northeast Consortium, 142 Morse Hall, 8 College Road, Durham NH 03824. This tagging project, was helpful in interpreting some of the results of this acoustic study. Acoustically tagged haddock were tagged with (green) tags from this larger tagging study in the event of recaptures and this acoustic project therefore benefited from existing outreach and reporting infrastructure.

X. Presentations

Results from this project have been presented at multiple forums. Focused presentations include:

- Sherwood, G.D. Automated acoustic monitoring of haddock in closed area I, Georges Bank. Northeast Consortium 7th Annual Project Participant's Meeting. Portsmouth NH. December 6, 2007 (oral).

- Sherwood, G.D. Automated acoustic monitoring of haddock in closed area I, Georges Bank. Haddock 2007: International Symposium on Haddock Conservation, Harvesting and Management. Portsmouth NH. October 25-26, 2007 (oral).
- Sherwood, G.D. Is Closed Area I serving as a refuge for haddock? Coast of Maine Passive Acoustic Sensor System (*CoM-PASS*) Annual Collaborators Meeting. Hallowell ME. December 18, 2007.
- Sherwood, G.D. Automated Acoustic Monitoring to Assess Movement Behavior and Residency of Haddock in Closed Area I (Georges Bank). Northeast Regional Tagging Symposium. Durham NH. October 18, 2008 (oral).
- Sherwood, G.D. Is Closed Area I serving as a refuge for haddock. Northeast Consortium 9th Annual Project Participant's Meeting. Portsmouth NH. March 25, 2009 (poster).

In addition to these, results have been incorporated into other presentations, particularly when discussing life-history impacts on stock rebuilding in relation to closed areas. The point that is usually made is that haddock, being more resident than other gadid species, may benefit more from closed areas. Presentations where haddock acoustic array results have been incorporated include:

- Sherwood, G.D. Can ecotype/foodweb interactions explain the state of cod in the northwest Atlantic? Canadian Society of Zoologists Annual Meeting. Halifax NS, Canada. May 19-23, 2008.
- Sherwood, G.D. Can ecotype/foodweb interactions explain the state of cod in the northwest Atlantic? University of Maine, School of Marine Sciences Seminar Series. Orono ME. October 31, 2008.
- Sherwood, G.D. Can ecotype/foodweb interactions explain the state of cod in the northwest Atlantic? University of Southern Maine, Department of Biology Seminar Series. Portland ME. March 13, 2009.

- Sherwood, G.D., and Grabowski, J.H. Monitoring the impact of closed areas on groundfish ecology in the Gulf of Maine and Georges Bank. Gulf of Maine Symposium. St. Andrew's, NB, Canada. October 4-9, 2009.

Overall, results from this project have been presented at a total of 9 symposiums, conferences, and seminar series. Three of these were international meetings. Finally, haddock acoustic findings are presented on a regular basis at GMRI to the interested public and potential donors. An animation of the results helps enormously in this regard and can be seen on YouTube at http://www.youtube.com/watch?v=9VUmUQfyIvE. Alternatively, search for "haddock survey" on YouTube.

XI. Student Participation

This project provided a unique learning experience for three summer interns who took part in both the laboratory and field components of the research. These included Jane Johnson and Nicole Condon, both undergraduate students from the University of New England (UNE), and Aaron Lyons an undergraduate from from the University of Southern Maine (USM). Nicole has gone on to a Master's degree program at the University of Hawaii and Aaron is now with the Fisheries Observer program in New England. Students were introduced to various concepts in fisheries ecology including stock rebuilding, and the importance of marine protected areas. In addition, Nicole Condon used some of the acoustic data as subject matter for a GIS class at UNE. Students were also introduced to practical aspects of fisheries ecology including methods in fish capture, fish holding (in tanks for the laboratory portion of this study), fish surgical techniques and fisheries acoustics (i.e. telemetry). This project is currently, directly benefiting a Master's student at GMRI (Marissa McMahon). As part of her M.Sc. thesis (jointly with the University of Maine) she is exploring the impact of large predators on lobster behavior (e.g., sheltering and foraging behavior). One of the tools that she is employing is acoustic tracking. The acoustic expertise accumulated during the course of this study by G. Sherwood is being transferred to Marissa who has completed the first phase of an acoustic array deployment.

XII. Published Reports/Papers

No published material has resulted from this work yet. However, this report was prepared as two manuscripts that are now ready to submit to the primary literature. A short description of this work has been published in proceedings of the Northeast Regional Tagging Symposium.

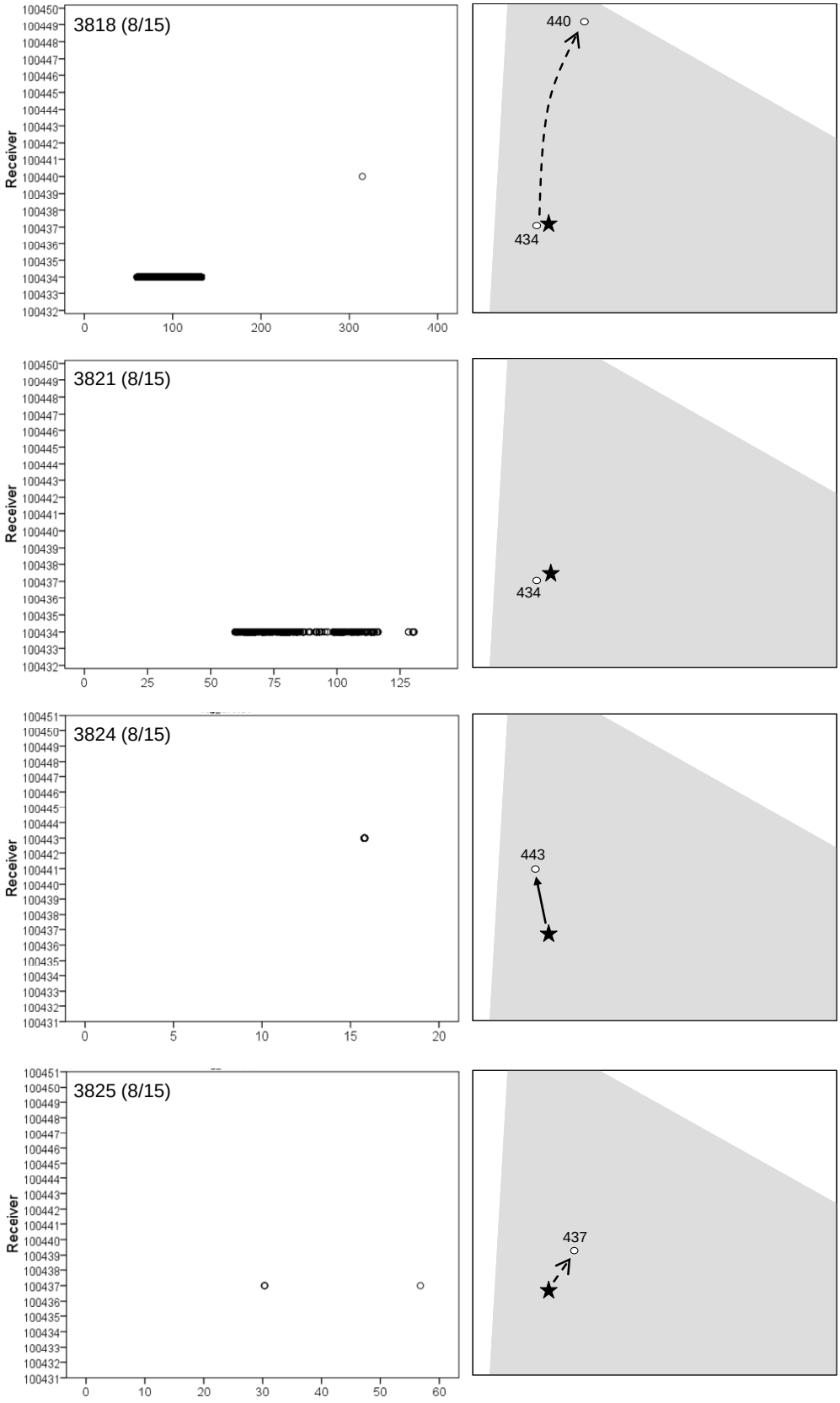
XIII. Future Research

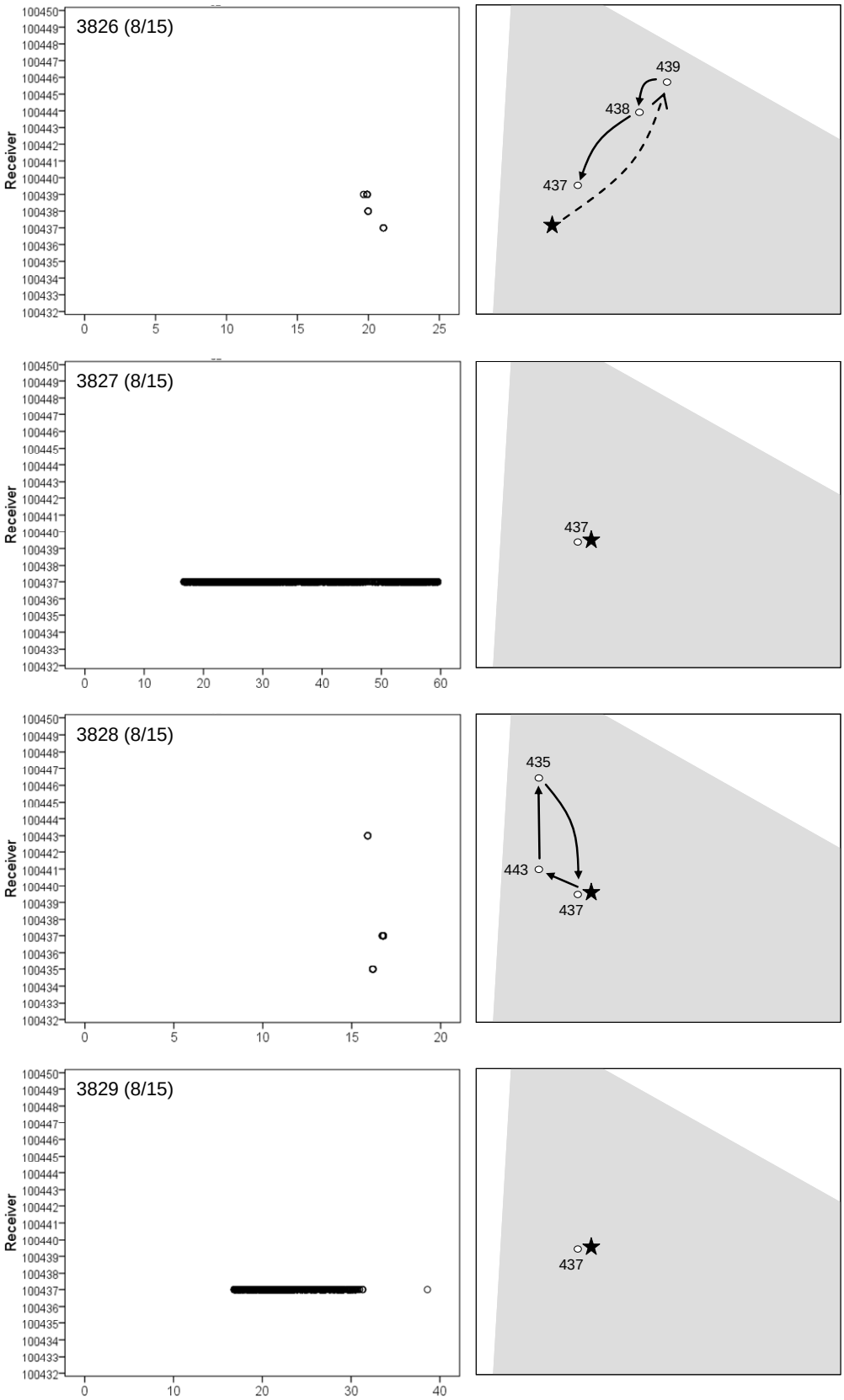
A number of different acoustic monitoring studies, stemming from the demonstration of this project's success, can be envisioned. Future acoustic studies could be smaller in scale to address specific questions of residency and species interactions (e.g., red cod residency at Cashes Ledge, or cod – herring interactions in the nearshore Gulf of Maine) or large in scale (e.g., to verify mixing rates of cod between the western Gulf of Maine and western Georges Bank, as revealed by the Northeast Regional Cod Tagging Study). Additionally, this study was not equipped to examine spillover rates of haddock from CAI into the adjacent fishery (a lingering question). Now that we know that the majority of movements occur in the north-south direction along a confined "highway" somewhere near the center of CAI, a follow-up study with a listening line array configuration (overlapping detection ranges) to observe spillover across the northern boundary of CAI could be designed for relatively little cost. This listening line could feasibly be made up of 10 or fewer receivers. Regardless of what the next study to use this technology in this region is, it is clear that it will benefit from the findings shown here. Particularly, that acoustic monitoring of non-highly migratory fish is possible in offshore settings. In parting, here are three points of advice: 1) make sure that there is some *a priori* evidence of residency before establishing a non-overlapping array in an offshore location (otherwise, one could end up monitoring nothing); 2) Make sure to download receivers often so that equipment loss does not result in data loss (this study was very fortunate to have downloaded data before Hurricane Noel wiped out most of the array – on this note, design experiments well in advance of hurricane season); and 3) consider a mooring system that would allow for grappling in the event that surface connections are lost. Gilles Lacroix (DFO, personal communication) described a mooring system deployed in

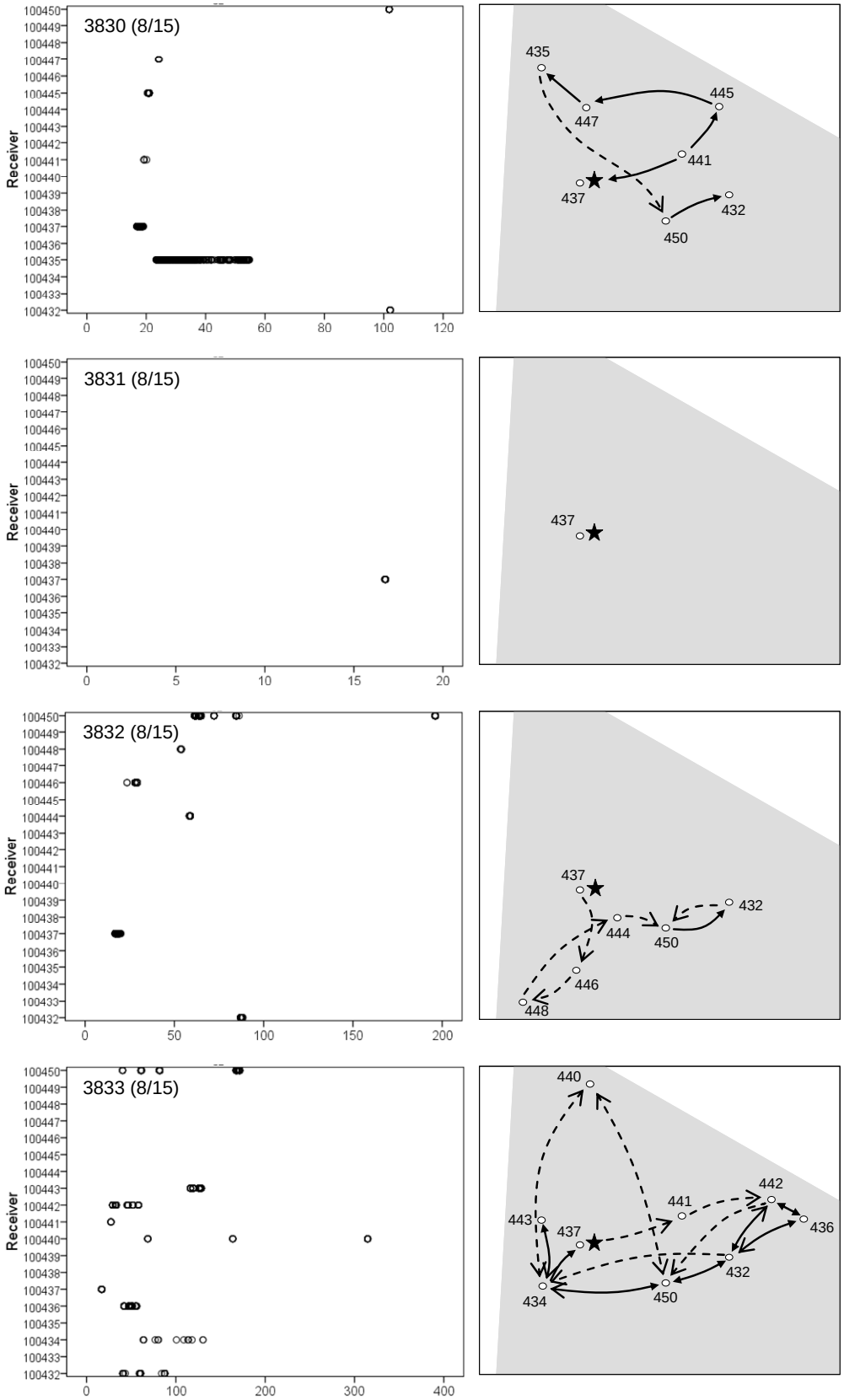
the Bay of Fundy that used no surface gear (receivers were retrieved by grappling a long bottom line connected to two anchors).

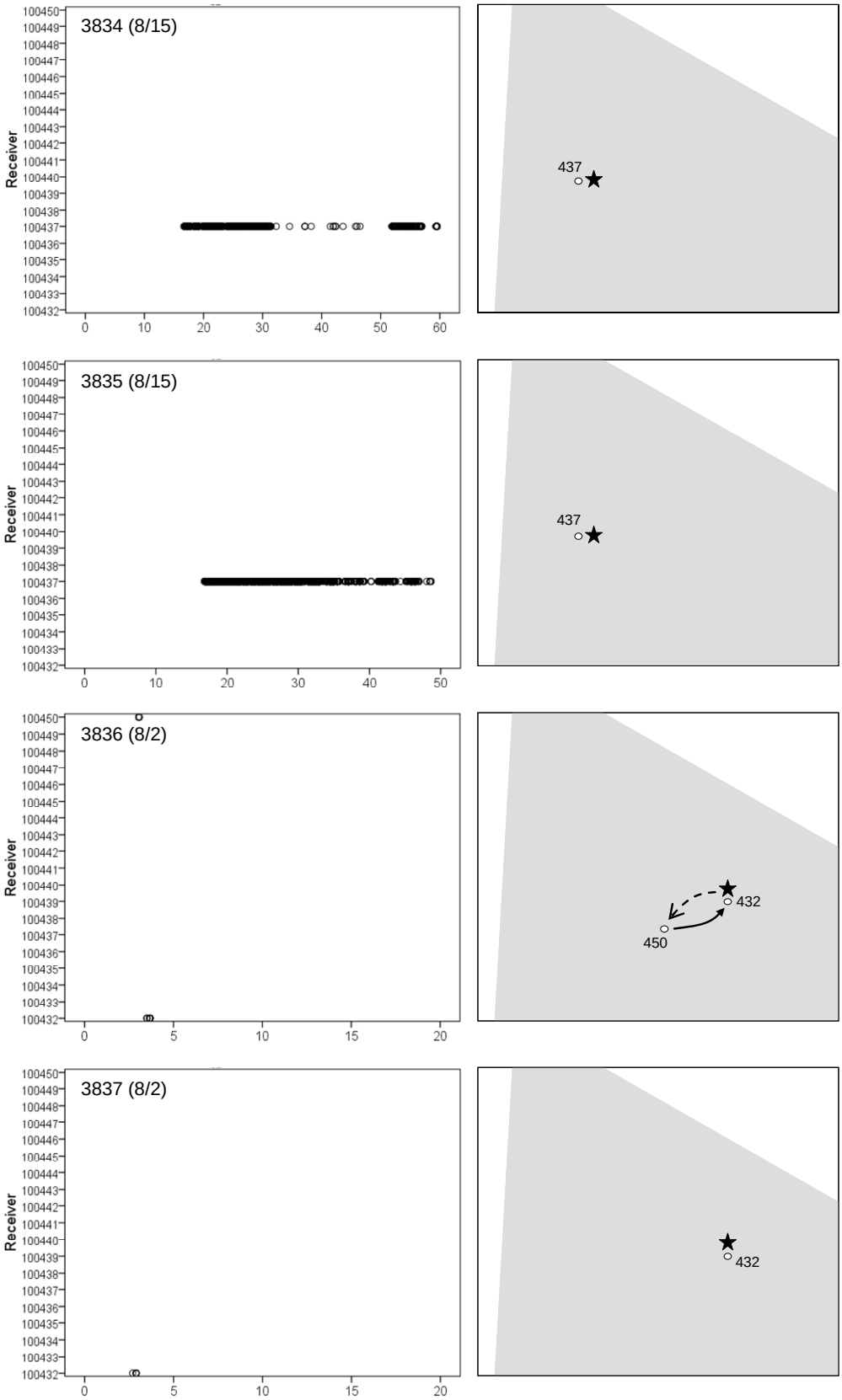
XIV. Appendix

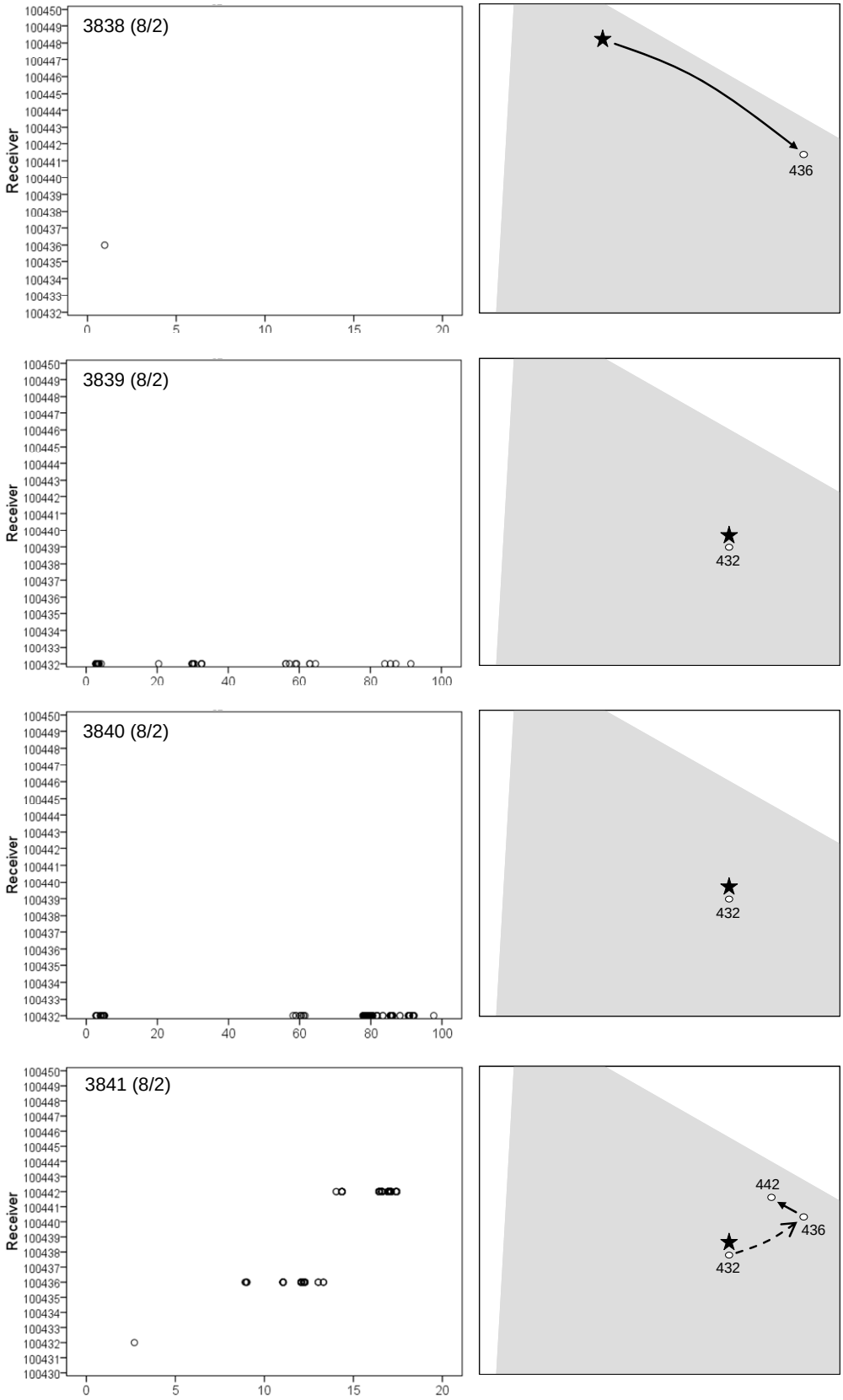
Time and space plots of tag detections and movements in the array by tag number. Release date is shown in brackets (left panels) and release site is indicated by a star (right panels). Dashed lines and open arrow heads represent movements that occurred over longer than 1 day; solid lines and solid arrow heads represent movements occurring over less than 1 day. To see an animation of these movement tracks, search for "haddock survey" on YouTube: http://www.youtube.com/watch?v=9VUmUQfyIvE.

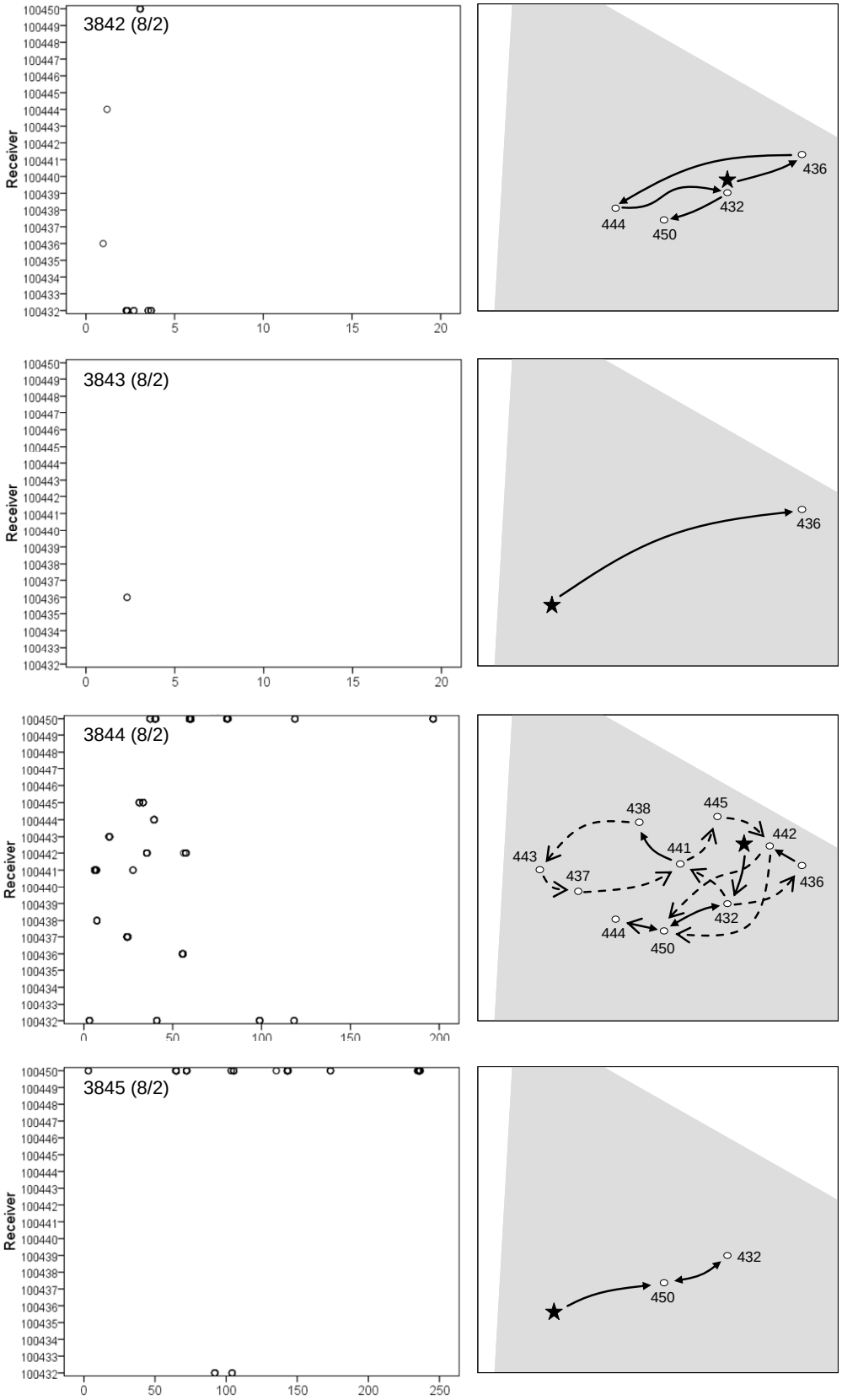

3818 (8/15)
Receiver
440
434
3821 (8/15)
Receiver
434
3824 (8/15)
Receiver
443
3825 (8/15)
Receiver
437

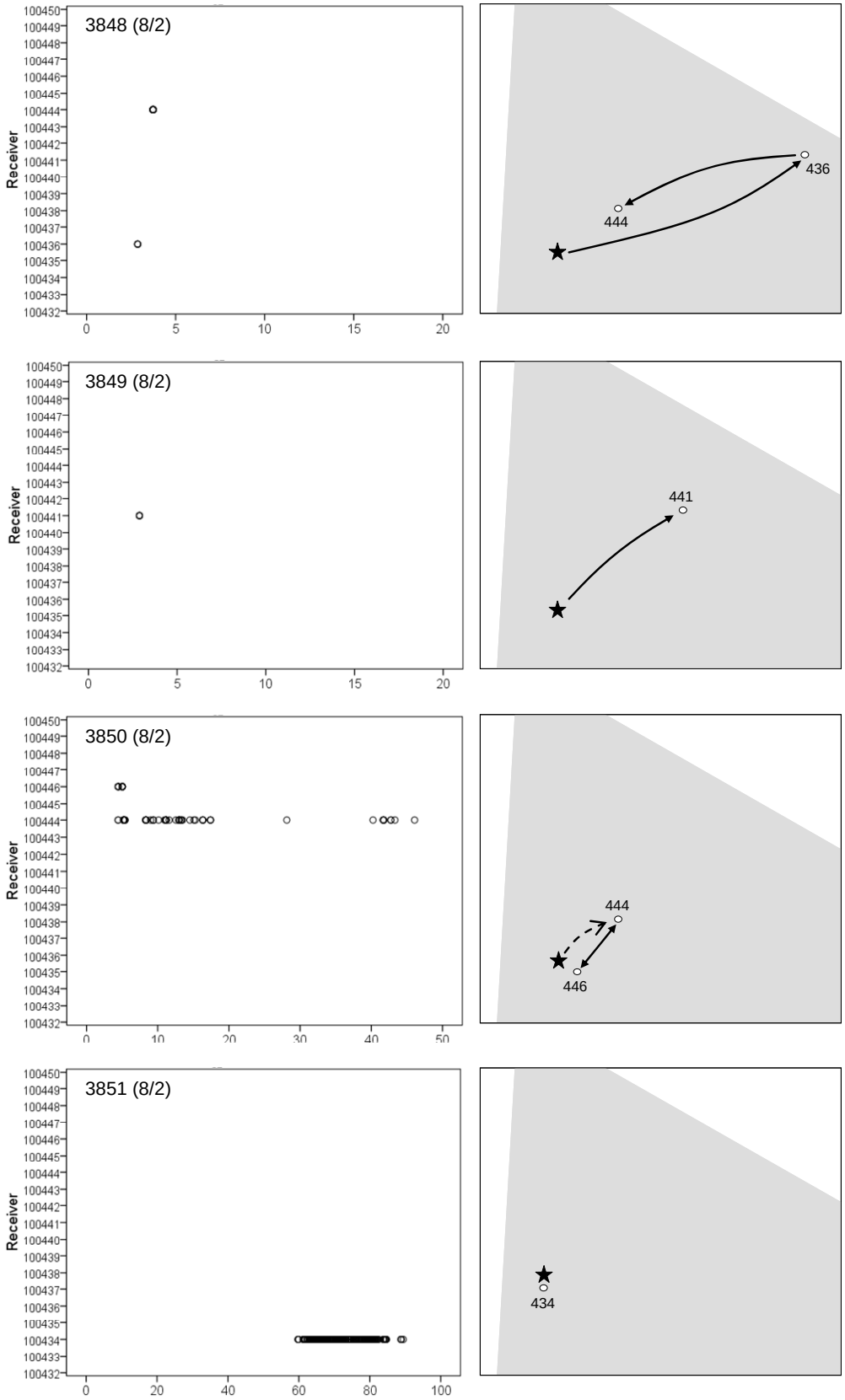

3826 (8/15)
Receiver
439
438
437
3827 (8/15)
Receiver
437
3828 (8/15)
Receiver
435
443
437
3829 (8/15)
Receiver
437

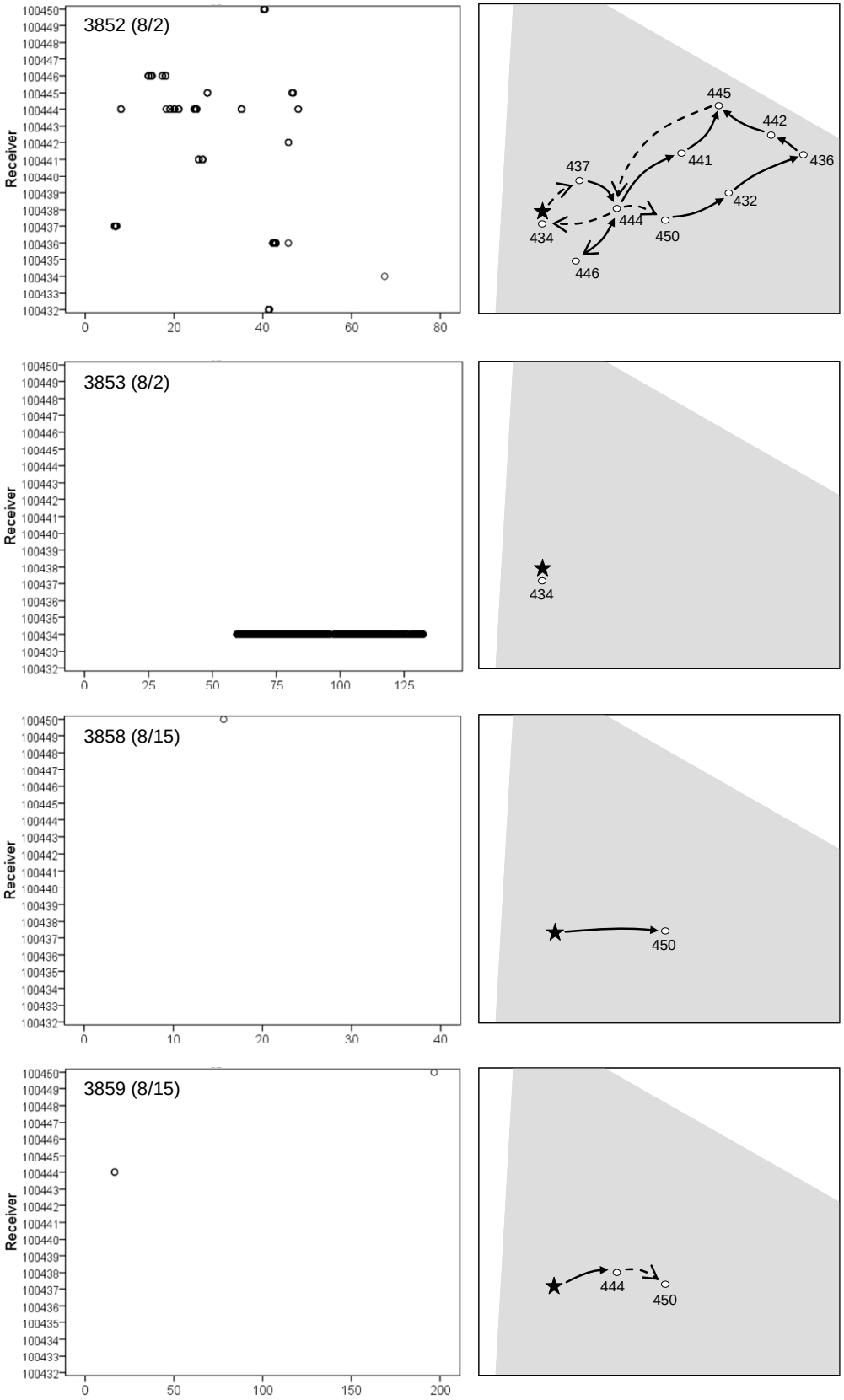

3830 (8/15)
Receiver
435
445
447
441
437
432
450
3831 (8/15)
Receiver
437
3832 (8/15)
Receiver
437
432
444
450
446
448
3833 (8/15)
Receiver
440
442
441
443
437
436
432
434
450


3834 (8/15)
Receiver
437
3835 (8/15)
Receiver
437
3836 (8/2)
Receiver
432
450
3837 (8/2)
Receiver
432


3838 (8/2)
Receiver
436
3839 (8/2)
Receiver
432
3840 (8/2)
Receiver
432
3841 (8/2)
Receiver
442
436
432


3842 (8/2)
Receiver
436
432
444
450
3843 (8/2)
Receiver
436
3844 (8/2)
Receiver
438
445
442
443
441
437
436
432
444
450
3845 (8/2)
Receiver
432
450


3848 (8/2)
Receiver
436
444
3849 (8/2)
Receiver
441
3850 (8/2)
Receiver
444
446
3851 (8/2)
Receiver
434


3852 (8/2)
Receiver
445
442
441
436
437
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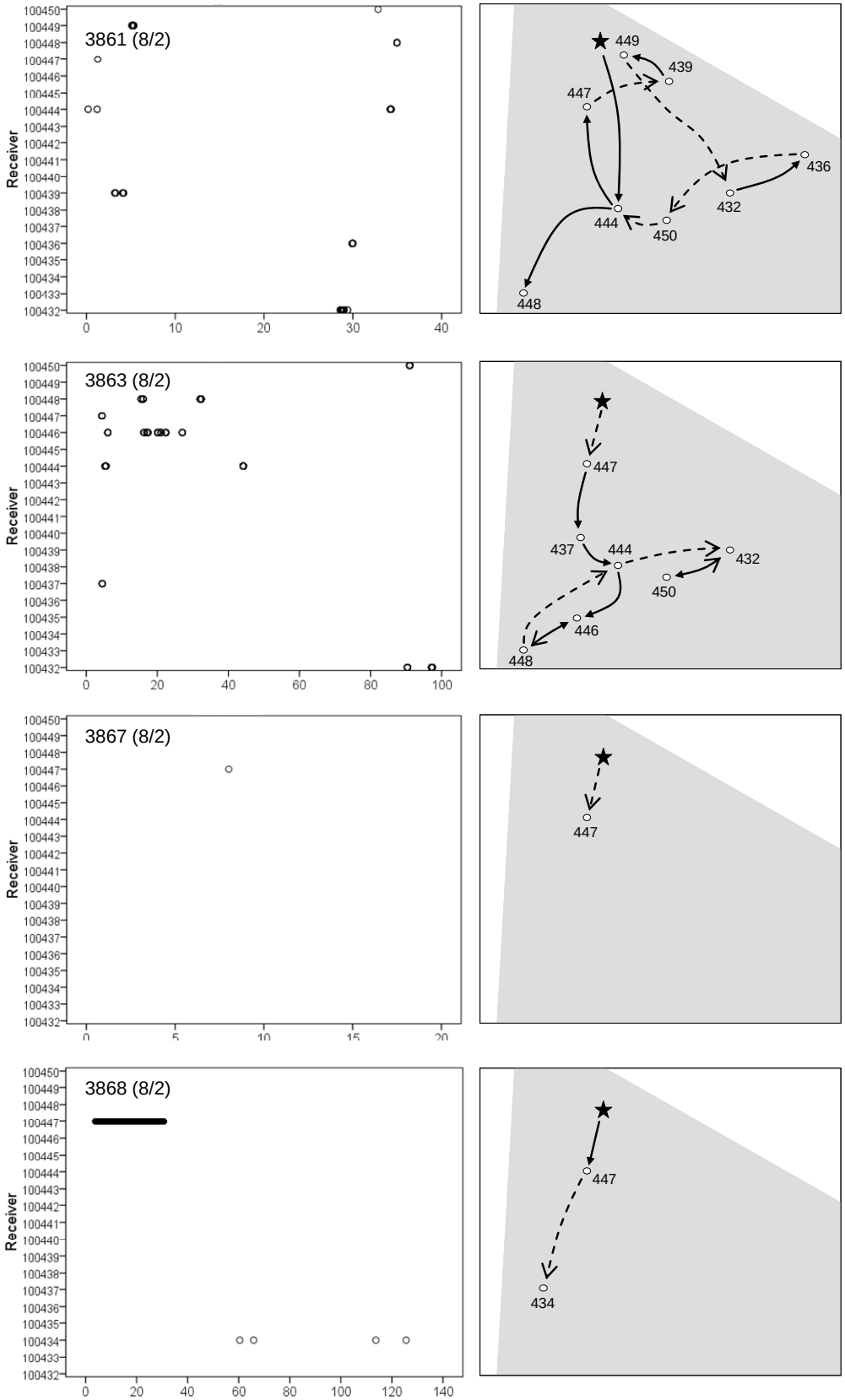
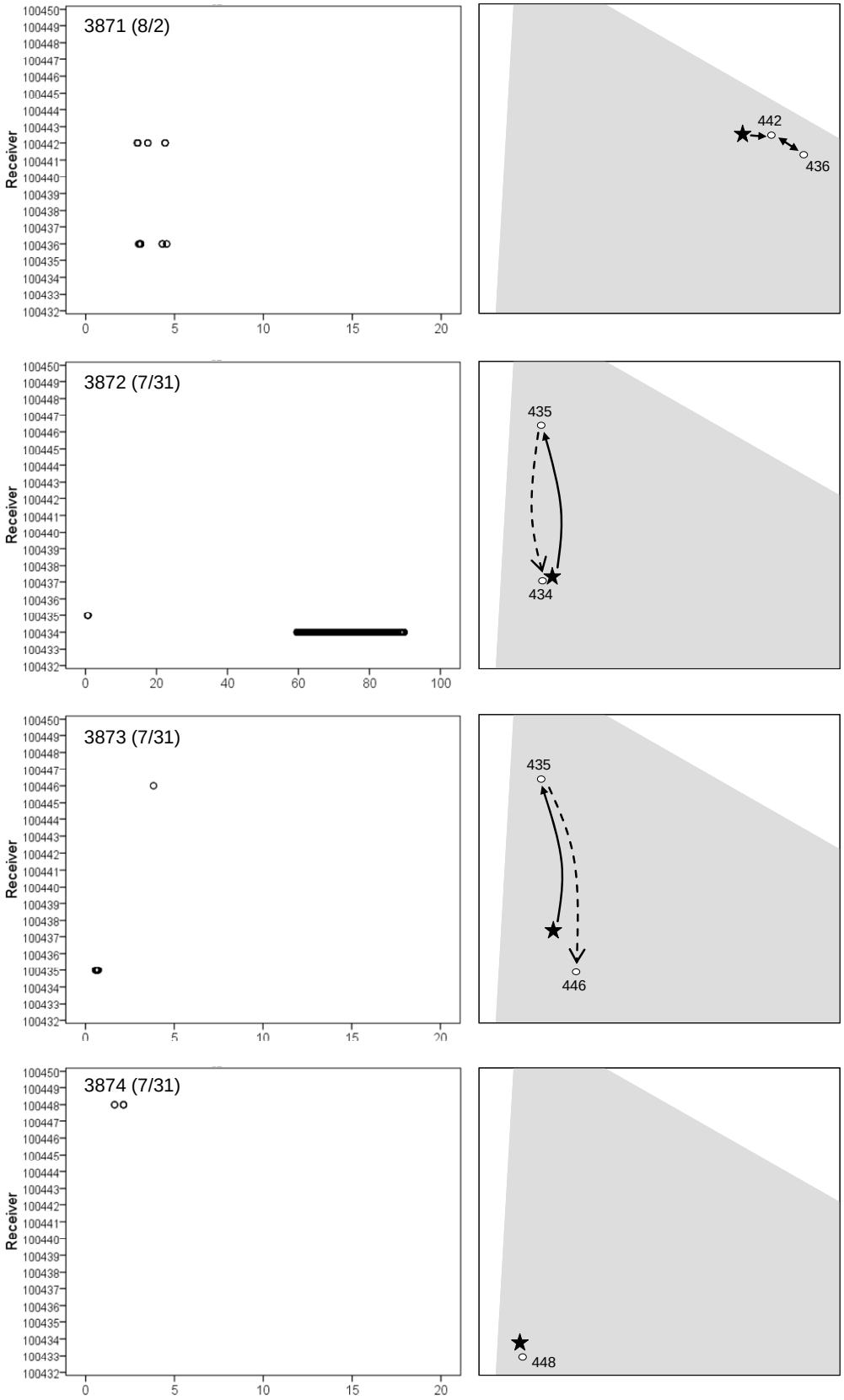
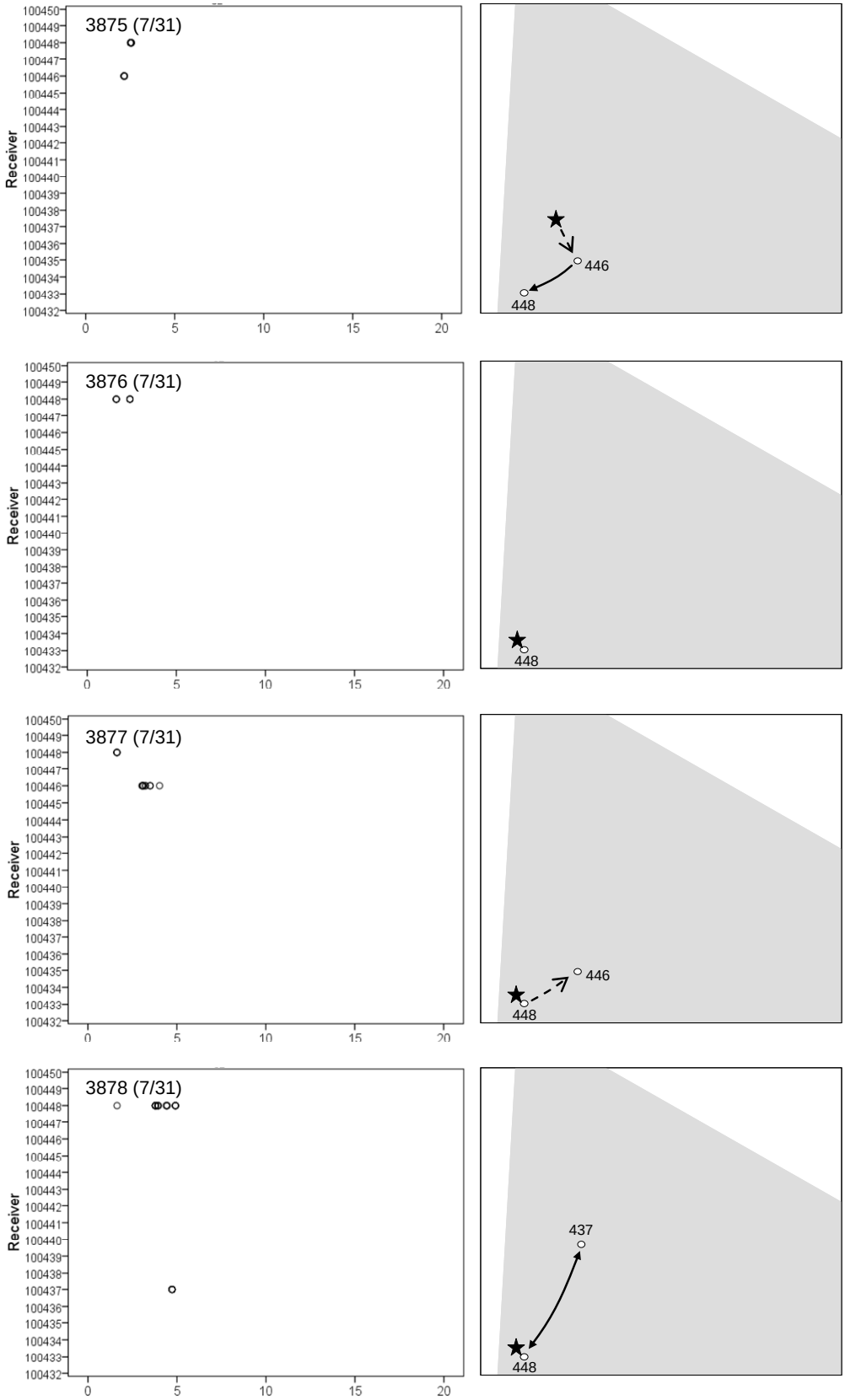
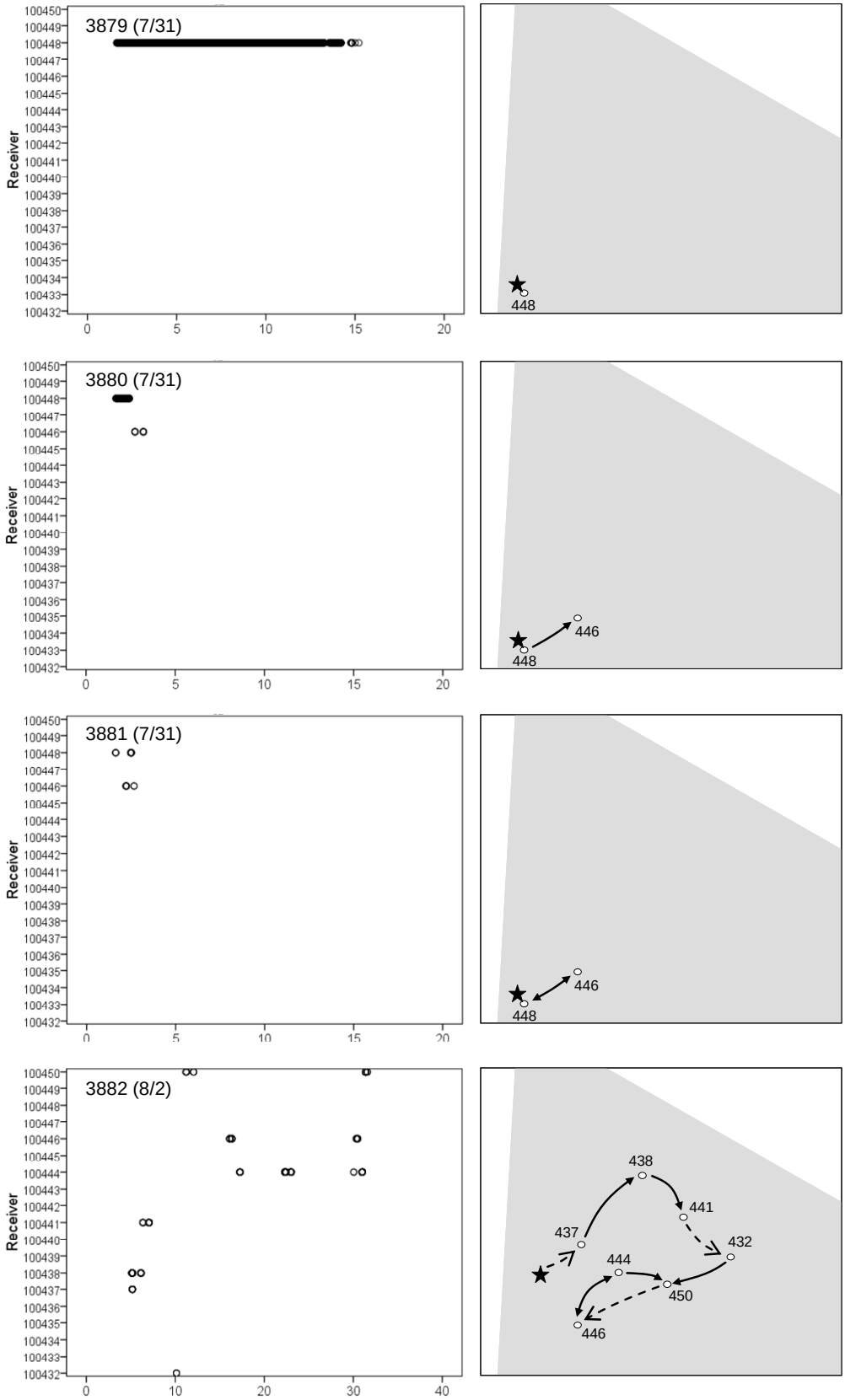
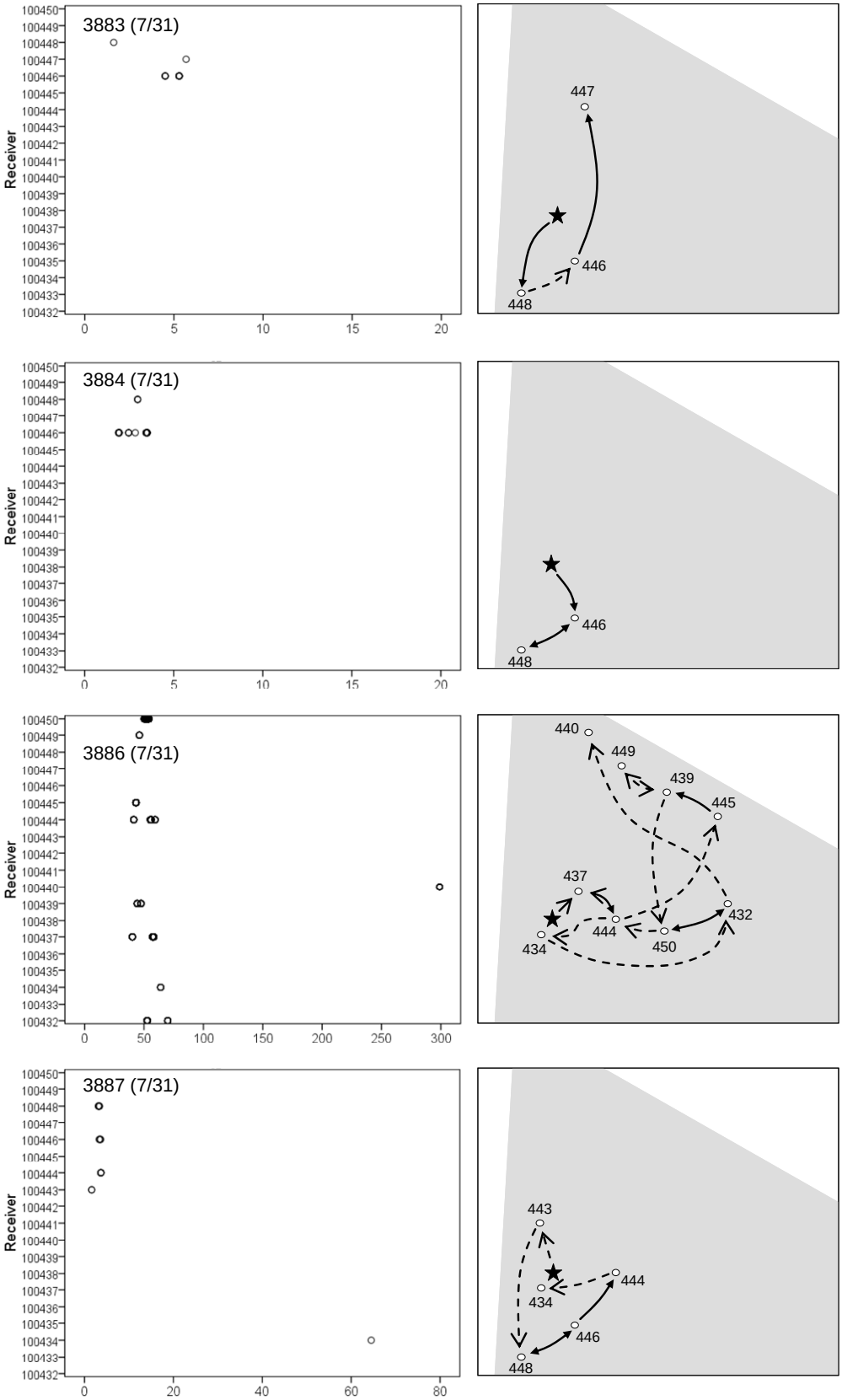
444
450
446
3853 (8/2)
Receiver
434
3858 (8/15)
Receiver
450
3859 (8/15)
Receiver
444
450


3861 (8/2)
Receiver
449
439
447
436
432
444
450
448
3863 (8/2)
Receiver
447
437
444
432
450
446
448
3867 (8/2)
Receiver
447
3868 (8/2)
Receiver
447
434


3871 (8/2)
Receiver
442
436
3872 (7/31)
Receiver
435
434
3873 (7/31)
Receiver
435
446
3874 (7/31)
Receiver
448


3875 (7/31)
3876 (7/31)
3877 (7/31)
3878 (7/31)
Receiver
446
448
437


3879 (7/31)
3880 (7/31)
3881 (7/31)
3882 (8/2)
Receiver
448
446
438
441
437
432
444
450


3883 (7/31)
Receiver
447
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448
3884 (7/31)
Receiver
446
448
3886 (7/31)
Receiver
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449
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445
437
432
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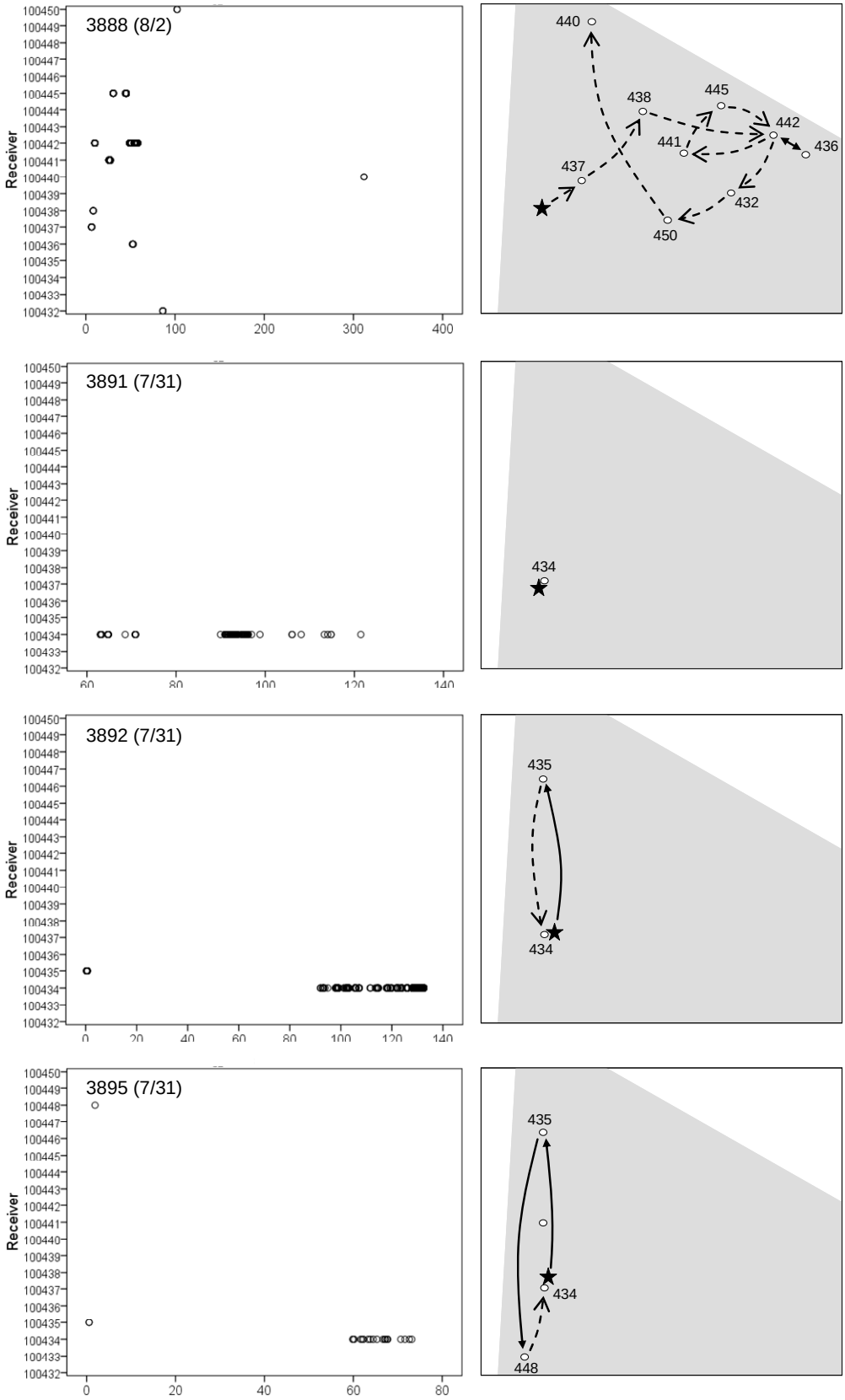
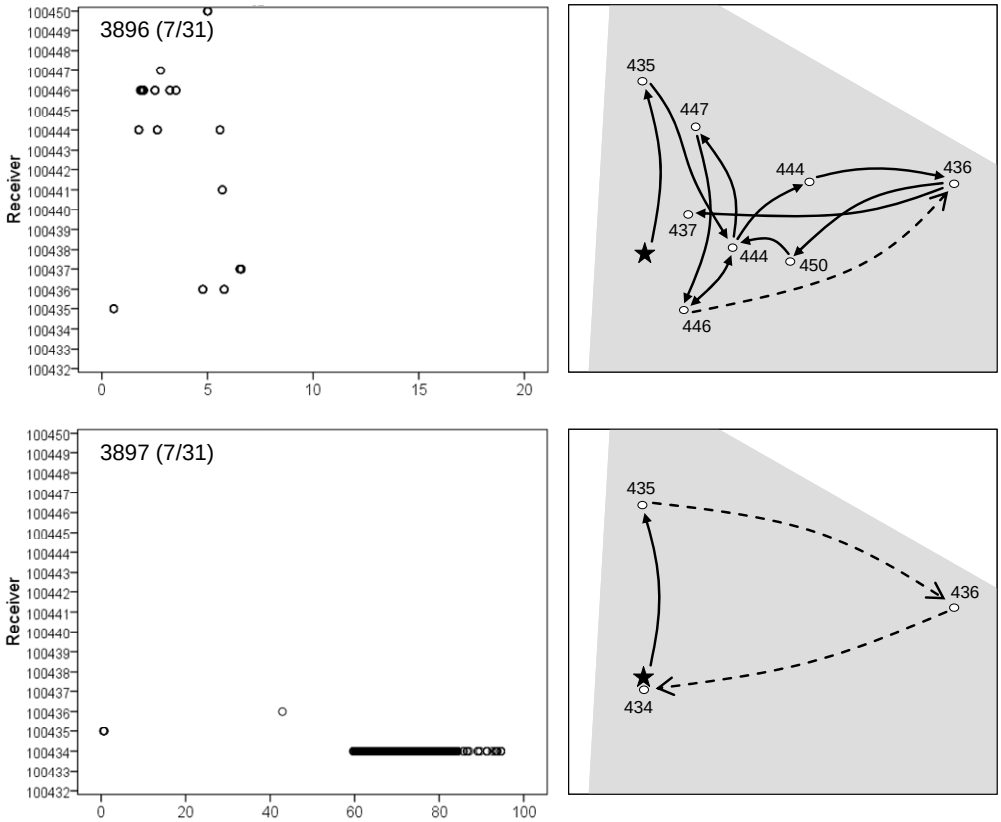
434
450
3887 (7/31)
Receiver
443
444
434
446
448


3888 (8/2)
Receiver
440
438
445
442
441
436
437
432
450
3891 (7/31)
Receiver
434
3892 (7/31)
Receiver
435
434
3895 (7/31)
Receiver
435
434
448


3896 (7/31)
Receiver
100450
100449
100448
100447
100446
100445
100444
100443
100442
100441
100440
100439
100438
100437
100436
100435
100434
100433
100432
0
5
10
15
20
435
447
444
436
437
444
450
446
3897 (7/31)
Receiver
100450
100449
100448
100447
100446
100445
100444
100443
100442
100441
100440
100439
100438
100437
100436
100435
100434
100433
100432
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60
80
100
435
436
434