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Effects of Hydraulic Dredging and Vessel Operation on Atlantic Sturgeon Behavior in a Large Coastal River

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EFFECTS OF HYDRAULIC DREDGING AND VESSEL OPERATION ON ATLANTIC STURGEON BEHAVIOR IN A LARGE COASTAL RIVER

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Biology at Virginia Commonwealth University.

by

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Abstract

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The tidal James River, a focus of VCU's Atlantic Sturgeon program, supports both commercial shipping and hydraulic dredging. These anthropogenic threats present documented but preventable sources of mortality to the endangered species. Using three separate VEMCO Positioning System (VPS) receiver arrays, spatial data of previously-tagged fish were collected. ArcGIS and Programita software were used to analyze fish spatial distributions in the presence and absence of potential threats, using additional data including automatic identification system (AIS) vessel locations, vessel passages compiled using camera footage, and dredge records provided by the US Army Corps of Engineers. The data showed a change in distribution associated with vessels that varied according to river width but not vessel type. Dredging was associated with differences in spatial distribution, but more clearly for adults than sub-adults. The responses of Atlantic Sturgeon provide information necessary to propose potential threat mitigations, including seasonal restrictions for both vessels and dredging.

Introduction

Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) is a large, long-lived, anadromous fish that ranges from Labrador to the St. Johns River in Florida (Smith and Clugston 1997). Historically, Atlantic Sturgeon were culturally significant to Native Americans and represented a valuable food source to early European colonists (Barbour 1986). However, the species was exploited with improved fishery technology and increased effort for valuable meat and roe, causing harvesting to peak in the late 19th century before dropping sharply (Smith and Clugston 1997). The James River population was legally protected from fishing in Virginia after a harvest moratorium in 1974 (Balazik et al. 2012a). Atlantic Sturgeon were protected coastwide when the Atlantic States Marine Fisheries Commission instituted a moratorium in 1998 (ASMFC 1998). Atlantic Sturgeon numbers remained low and were listed under the federal Endangered Species Act (ESA) as threatened or endangered for all distinct population segments (DPS) of the United States in 2012, and the Chesapeake Bay DPS, which includes James River Atlantic Sturgeon, continues to be listed as endangered (Balazik and Musick 2015).

Age of maturation of Atlantic Sturgeon varies according to latitude, with females maturing later than males. In South Carolina, males reach maturity at an average of 8.1 y. and females at 10.9 y. (Smith 1985). In the Chesapeake Bay DPS, males mature as early as age-11 (Balazik et al. 2012a) and then typically return to riverine habitats annually (Balazik and Musick 2015). Females, however, may have long intervals of marine residence, up to 5 y. (Smith 1985). Because Atlantic Sturgeon may require a decade or more to mature, they are slow to recover from low population numbers like other long-lived species. Considering years at sea not spawning as well, the overall reproductive rate of the species is low (Beamesderfer and Farr 1997). Therefore, reducing mortality should be a priority to increase the potential for populations to recover. Doing so requires identifying sources of mortality within the different habitats the species uses and mitigating those threats.

Although Atlantic Sturgeon can no longer be legally harvested in the United States, they may still be threatened by vessel strikes (Brown and Murphy 2010, Balazik et al. 2012b), habitat degradation and loss (Smith and Clugston 1997, Armstrong and Hightower 2002), dredging (Hoover et al. 2011), and other anthropogenic (and therefore preventable) hazards. Identifying such threats, estimating potential impacts, and creating solutions to minimize such impacts are necessary to protect the species. The two threats specifically considered in this study were vessel strikes and hydraulic dredging.

Vessels may harm aquatic life in multiple ways including noise, forces generated in the water, and direct hits from propellers (Whitfield and Becker 2014). Whale mortalities from direct strikes are well-documented because the likelihood of reports is high based on the sizes of resulting carcasses (Conn and Silber 2013). However, for aquatic animals with smaller body sizes, the frequency of vessel strikes is more difficult to quantify (Whitfield and Becker 2014). Atlantic Sturgeon adults are large enough that carcasses of fish struck by vessels have been regularly reported, but these reports are mainly in areas where researchers are likely to be looking and therefore a significant number of strikes may remain unknown (Balazik et al. 2012b).

The potential threat of vessel strikes to Atlantic Sturgeon in the James River has been previously addressed using data from depth sensors in tagged *A. oxyrinchus* (Balazik et al.

2012b). As a benthic species, Atlantic Sturgeon are especially threatened by the passage of deep-draft vessels whose propellers would more likely be at the same depth as the fish. In addition, when individuals are travelling up or down the river they may swim higher in the water column and be threatened by more shallow propellers. However, the behavioral response (i.e. avoidance or attraction) of Atlantic Sturgeon to operating vessels is not well-understood, and that response would affect the likelihood of vessel strikes.

The operation of hydraulic dredges may cause injury and mortality in benthic fishes through entrainment, including sturgeons (Drabble 2012, Boysen and Hoover 2009). Both an adult Atlantic Sturgeon and a juvenile were killed by a dredge operating in Delaware according to a recent report (Murray 2014). Also, like propellers, dredges create noise and hydrodynamic forces that may disrupt fish behavior. Behavioral responses of fishes to noise are well-documented but are generally species-specific (Whitfield and Becker 2014, Myrberg 1990). Past research has shown noise may increase stress in aquatic animals as well as cause energy to be wasted avoiding the source of the noise (Becker et al. 2013). The behavioral responses of Atlantic Sturgeon to dredges is not well-known, and further research will aid in assessing the species' vulnerability.

The main objective of this study was to test for evidence of avoidance in Atlantic Sturgeon to vessels and dredge operation, in order to better understand their vulnerability to the two threats in riverine habitats for the purpose of management. Major research questions were whether or not Atlantic Sturgeon avoid the two threats by changing spatial distribution, whether any such response to vessels depends on propeller depth, and whether sub-adults exhibit a different response to dredging than adults. In addition, the use of VEMCO Positioning Systems (VPS) to track and quantify aquatic animal behavior is a relatively new technology and has been used successfully to study Atlantic Sturgeon (Espinoza et al. 2011, McLean et al. 2014), but the methods of analysis used in this study were somewhat novel. Therefore, a secondary objective of this study was to develop such methods of analysis for future uses of VPS to study Atlantic Sturgeon.

Methods

VEMCO Positioning Systems (VPS)

The tags and receivers used for this study were made by VEMCO. For years, multiple research groups have surgically implanted intracoelomic tags in hundreds of Atlantic Sturgeon, captured both at sea and in rivers, which then regularly transmit coded sound to identify the tagged fish. Receivers off the Atlantic coast and within tributary river systems record the transmissions they receive to provide research groups with coarse movement data, but receivers can also be placed in relatively close proximity to create a VEMCO Positioning System (VPS). Using the time difference of arrival of tag audio bursts between receivers, array data can be used to calculate latitude and longitude positions, with corresponding time and date, of identified tagged individuals. That data processing is a service performed by VEMCO.

Three VPS arrays were set in three consecutive years at different areas of interest along the James River (Figure 1). The three study areas were: 1. The navigation channel just downstream of VCU's Rice Rivers Center 2. In the channel cut-through at the oxbow near Presquile National Wildlife Refuge, upstream from Hopewell, Virginia and 3. A dredge site at the mouth of the Chickahominy River and upstream of Jamestown (Figure 2). Sites 1 and 2 were where vessel passage was considered the potential threat of interest, and at site 3 dredging was the potential threat of interest.

Rice Rivers Center

The VCU Rice Rivers Center is in Charles City, Virginia. The width of the river at that point is approximately 2 km. with a channel 250 m. wide, of which 300 ft. of width is officially navigation channel. The channel ranges between approximately 8 and 10 m. deep. For fall-spawning Atlantic Sturgeon, the channel at that point along the James is a migration corridor to the staging grounds upstream at Presquile National Wildlife Refuge. Vessel passages were quantified using camera data from the fall of 2013, concurrent with the operation of the VPS array. Vessels were classified as either recreational, tugs, or ships to reflect differences in draft depth. Each passage was recorded by vessel type, its direction of travel, and the time and date it passed.

Presquile National Wildlife Refuge

Presquile NWR is an island created by a narrow artificial channel, and within that channel fall-spawning adult Atlantic Sturgeon stage, spending days to weeks in the general area before heading further upstream to spawn. The artificial 7.6 m. (25 ft.) channel was created in 1933 for commercial vessels to have a shorter path to Richmond upstream, rather than the ox-bow surrounding Presquile (Figure 3). The width of the cut-through is approximately 150 m. at its most narrow. The depth of the navigation channel is often the minimum required at 25 ft., but at the downstream end of the cut-through there is a hole with a depth of approximately 20 m. Evidence shows the narrow width and relatively shallow depth of this section of the river presents a threat to Atlantic Sturgeon as vessels pass at that site (Balazik et al. 2012b). Vessel passages were quantified using camera data from the island in the late summer and early fall of 2014, in a manner similar to the Rice Rivers Center site (Figure 4).

Chickahominy Mouth Dredge

The James River just downstream of the Chickahominy River is approximately 4 km. wide with a channel over 200 m. wide, of which 300 ft. of width is officially navigation channel. The channel is approximately 25 ft. deep at its most shallow, the minimum required for commercial traffic. The US Army Corps of Engineers (USACE) conducts annual channel maintenance dredging to remove accumulated sediment. Depending on the timing, this dredging may occur when fall-spawning Atlantic Sturgeon are migrating upstream. Like the Rice Rivers Center site, the Chickahominy location is a corridor for migrating adults, but differs in that it is also an area frequented by feeding sub-adults as it is further downstream where the salinity is greater. During dredging, adult Atlantic Sturgeon travelling upstream to spawn were considered to be threatened because past research has shown adults tend to travel through the channel of the James River (Balazik et al. 2012b). However, the distribution of sub-adults and level of risk was predicted to differ from adults because their behavior in general varies from the adult life stage. The VPS array at the dredge site operated in the fall of 2015, and a record of the dredge progress from USACE was used to determine when the dredge was operating in the area of the array.

VPS Coverage

Both the Rice Rivers Center and Presquile arrays had continuous spatial coverage because receivers were placed relatively evenly. However because of possible interference with the dredge, receivers at the dredge site were unable to be placed in a large central area in which the pipe that transported spoil was dragged. Therefore, rather than the VPS array being evenly distributed through the dredge site, it constituted more of a U-shape surrounding the area of interest (Figure 5). The gap between receivers likely resulted in a loss of ability to detect tags and determine positions, but it appears that the loss was far from total because many positions in the dataset occurred within the gap, including the navigation channel itself where fish point density was high. A receiver at the Presquile site, near the middle of the cut-through, was lost as well during retrieval of the array. It appears that there were fewer points in its vicinity compared to the rest of the channel, but it is unclear if that decrease is accurate or a result of lack of coverage (Figure 6).

Definition of Points During Potential Threats

For both Rice Rivers Center and Presquile NWR, instances of tugs or ships passing through the array were considered events which may change behavior. Atlantic Sturgeon positions that were during or within 10 minutes after such passages were marked separately from all other points as representing potential stress and therefore potentially different behavior. At Presquile NWR, which is a much narrower and more shallow section of the river than Rice, a behavioral response associated with high recreational traffic was considered to be possible but less likely than a response associated with tugs and ships.

Large vessels, tugs and deep-draft ships, were treated as individual events, but the large amount of recreational traffic was summarized by boats per hour. Of the Presquile dataset, fish positions during hours where more than 50 boats passed (during fishing tournaments) were marked separately from all other points, excluding points that had already been marked as within 10 minutes of a tug/ship passage. Because of the greater width and depth of the river at the Rice Rivers Center site, the response to recreational traffic was not analyzed due to the greater variability in pathways of small vessels, unlike larger vessels which travel along the navigation channel.

USACE maintained a record of the dredge operation, indicating the sections of the river dredged and on which days. The dredge was active near continuously for the month of September 2015, but only from the 10^{th} through the 29^{th} was the dredge active in the area of the array. Prior to the 10^{th} the dredge was operating hundreds of meters upstream. Outside of the period when the dredge was active within the area of the array, it was assumed all position data would represent baseline behavior and points during the dredge operation would indicate any possible behavioral changes as a result of the dredge.

Point Pattern Analysis

In the field of plant ecology, testing for evidence of interaction among plants of the same species or between species can be performed with point pattern analysis (Wiegand and Moloney 2004, Andersen 1992). Although animal movement data differ from plant location data in certain fundamental ways, testing for similarity between point distributions can be done using the bivariate pair correlation function and Monte Carlo simulations in a manner similar to past analysis on plants (Andersen 1992). However, some assumptions are required for this to be appropriate.

One key assumption is stationarity, i.e. timing is not a factor. No matter the method of analysis used for these datasets, this would need to be assumed to evaluate data from late August with data from late October. It was therefore assumed that behavior generally did not change seasonally at each site. Behavior does vary between the sites (feeding vs. travelling vs. staging), but each site should have relatively stable behavior over the course of the migratory season for fall-spawning adults and for sub-adults. Another assumption is that the consecutive, time-dependent nature of points from individuals moving in pathways leads to negligible spatial autocorrelation, meaning that individuals are able to move quickly enough that the placement of points reflects choices in behavior and not simply reflect on their past positions. The larger a study area, the more spatial autocorrelation would be a factor. The datasets of this study also only represent individuals which have been captured and implanted with VEMCO telemetry tags, and therefore it is assumed that the location data derived from those tags are accurate and representative of behavior of the general population of James River Atlantic Sturgeon.

The bivariate pair correlation function, known by $g_{12}(r)$, is used to quantify the co-occurrence of two types of points, in this case baseline positions vs. positions during possible threats. The function works by measuring the density of type 2 points within concentric rings of varying radii around type 1 points, relative to the overall density of type 2 points (Wiegand and Moloney 2014, Figure 7). Therefore, values above 1 indicate at a particular radius that the density of type 2 points is greater than their average density, and values below 1 indicate the density of type 2 points is less than their average density. $g_{12}(r)$ values greater than 1 indicate type 2 points more closely follow the spatial distribution of type 1 points than would be expected by chance, and values less than 1 indicate that the two types tend to disperse from each other more than would be expected by chance. Programita® software was used to test if the observed $g_{12}(r)$ curve of each comparison between points during potential threats and baseline points was significantly different than expected, that is if the two types of points followed the same spatial distribution, through the use of Monte Carlo simulations (Wiegand and Moloney 2014).

For each comparison, 500 simulations were calculated, each retaining the baseline point distributions and generating a new placement of points during potential threats according to a kernel estimate of the baseline. Kernels were calculated within Programita® using the Epanechnikov method with a smoothing radius of 30 m. The points during potential threats in each simulation were placed according to a heterogeneous Poisson process according to the baseline kernel (Wiegand and Moloney 2014). For each simulation, a resulting $g_{12}(r)$ curve was calculated and the final 5 lowest and 5 highest (top and bottom 1%) values were recorded to create simulation envelopes. Comparing the actual $g_{12}(r)$ distribution for a dataset to its simulation envelopes allows the similarity between point spatial distributions to be quantified relative to random chance, i.e. that positions during potential threats are a random sampling of positions from the baseline spatial distribution of tagged fish.

Estimated Swimming Velocity Distributions

In addition to comparing spatial similarity between baseline points and points during possible threats, swimming velocity distributions were compared as well. Velocities were calculated through the extension in ESRI ArcMap, Tracking Analyst, using the Track Intervals to Features function. Velocities were based on the difference in distance and time between consecutive points by the same tagged individual. Telemetry tags produced audio bursts on varying intervals at an average of 120 seconds, so point pairs that had a time difference greater than 250 seconds were removed from calculation to eliminate individuals leaving the array for long periods and returning, as well as any other interruptions that were considered too long for average velocity to be an appropriate measure. It was unknown what pathways, with varying speeds, individuals would have taken between points, so swimming velocity estimates were simply raw averages. Welch two sample t-tests in R statistical software was used to determine significance between velocity estimate means.

Results

Rice Rivers Center

The Rice array collected 8,031 total points attributed to 102 tagged individuals, of which 148 points (from 39 individuals) were within 10 minutes of a tug or ship passage (Table 1, Figures 8 and 9). The overall spatial distribution tended to follow the navigation channel which crossed through the middle of the array, with fewer points distributed along the shallower areas at the edges. Visually the points occurring within 10 minutes of a tug/ship passage were distributed more evenly throughout the range where points were detected (Figure 10). This was reflected in the observed $g_{12}(r)$ distribution and simulation envelopes. The observed curve was located below the values of the middle 98% of simulations until a radius of 183 m. (Figure 11). Therefore, the difference between the baseline and during potential threats spatial distributions represents a probability less than 0.02 under the null hypothesis that the two distributions follow the same kernel. The mean swimming velocity of tagged fish in the absence of tugs or ships was 0.507 m/s while the mean velocity within 10 minutes of a tug/ship passage was 0.51 m/s, an insignificant difference (p=0.99) (Figure 12).

Presquile NWR

35,188 total points were recorded by the Presquile array from 92 individuals, of which 347 points (from 62 individuals) occurred within 10 minutes of a tug passage (Table 1, Figures 13 and 14). Of the remaining positions outside of a tug passage, 34,640 were during hours where less than 50 recreational boats passed and 201 (from 38 individuals) where more than 50 boats passed. For both comparisons, the spatial distributions of collected points followed the navigation channel through the cut-through and shortly downstream of it. Point density was higher closer to the ends of the cut-through, particularly at the downstream end. There was a relatively reduced density of points near the middle of the cut-through, which may have been due to a lost receiver.

Both the recreational boat comparison and the tug/ship comparison appeared to have similar results visually. The points during each possible stressor followed the hotspots of the baseline but were decreased elsewhere at the edges (Figures 15 and 16). For both comparisons, the observed $g_{12}(r)$ distributions began above the corresponding upper simulation envelopes, merging back between the simulation envelopes at 478.5 m. for the tug/ship distribution and 348.5 m. for the recreational boat distribution (Figures 17 and 18). The mean swimming velocity estimate in the absence of large vessels was 0.445 m/s and in their presence was 0.44 m/s, an insignificant difference (p=0.78) (Figure 19). The mean velocity outside of high recreational traffic hours was 0.445 m/s and the mean velocity during those hours was 0.47 m/s (p=0.64) (Figure 20).

<u>Chickahominy Mouth Dredge</u>

There were 2,625 points recorded from 85 adults at the dredge site, of which 121 points from 20 individuals occurred during the period when the dredge was active in the array vicinity (Table 1, Figures 21, 22, and 23). Likewise, there were 3,329 total points recorded from 41 sub-adults, of which 388 points occurred during active dredging (also from 20 individuals). There are two channels at the site, the main navigation channel maintained by USACE and a natural channel resulting from the outflow of the Chickahominy River, and both channels contained a relatively higher density of points. Beyond the channels, many points were scattered in more shallow areas from both life stages but especially in regard to the sub-adults.

The adult positions during the active dredge were visibly more evenly spread than the corresponding baseline, and that was reflected in the difference between the observed $g_{12}(r)$ distribution and the corresponding simulation envelopes (Figure 24). The observed distribution was below the values of the middle 98% of simulations until 930.5 m. (Figure 25). The sub-adults however appeared to have more closely followed their baseline spatial distribution during the dredge (Figure 26). The observed $g_{12}(r)$ distribution of the sub-adults began below the lower simulation envelope, fell within the middle 98% range at 33.5 m., went back below the simulation envelope at 597.5 m., and returned at 1400.5 m. (Figure 27). The mean velocity for the adults increased during the dredge from 0.55 m/s to 0.69 m/s which was a statistically significant increase ($p<0.01$) (Figure 28). However, the mean velocity for sub-adults significantly decreased from 0.415 m/s to 0.32 m/s ($p<0.01$) (Figure 29).

Discussion

<u>Point Pattern Analysis Mathematical Similarities</u>

For all bivariate pair correlation functions calculated, the actual distributions and their corresponding simulation envelopes began greatly above 1. This is to be expected based on the nature of this study as compared to applications of similar statistics in plant ecology. In a study plot of a forest, a plant may occur potentially anywhere in the plot. However when applying these spatial statistics to a fish species, the locations of tagged individuals depend heavily on their available environment. For example, at the Presquile site the shoreline is a rigid boundary beyond which individuals will not occur. In addition, for benthic species like Atlantic Sturgeon water depth will weigh heavily in where individuals prefer to spend their time. It was clear from all sites that Atlantic Sturgeon tended to occur in the deepest part of the river detected by the array. Pair correlation values above 1 indicated that the density of points during potential threats near baseline points was higher than their overall density, meaning that the two types of points co-occur more than random. However, because the points during potential threats were governed by basic factors also controlling the baseline distribution that is not a surprising result. The $g_{12}(r)$ values beginning above 1 at low radii for all comparisons is simply a result of the geometry of the river and habitat preferences of the Atlantic Sturgeon not resulting in a rectangular range of points.

Similarly, the convergence of all bivariate pair correlation functions to 1 over long radii, of both the observed values and their simulation envelopes, is a geometric inevitability. At each radius of the function, every baseline point has a ring of that radius surrounding it within which the density of points during potential threats is calculated, and these densities are averaged. As the rings around every baseline point increase in radius, more of the study area is included and the density of points during potential threats in the rings approaches their overall density within the study area, resulting in a ratio of 1. Because all bivariate pair correlation functions will approach 1 at long radii, functions representing the observed data will always converge toward their simulation envelopes eventually.

Therefore if a pair correlation function began outside of the simulation envelopes, interpreting the radius at which it eventually crossed into the band between those envelopes is difficult and may not necessarily be meaningful. In a relatively homogeneous distribution of points, as in plant ecology, that radius can be easier to interpret. For example, a similar method was recently used to compare the spatial point distributions of two tree species. The resulting observed bivariate pair correlation function was above its upper simulation envelope until approximately 2 m., indicating that the two species tend to attract each other by some mechanism until 2 m., beyond which whatever mechanism causing the co-occurrence becomes negligible (Erfanifard and Stereńczak 2017). For this study however, baseline points were not interacting in any way with points during potential threats; the two types occurred at different times and conceivably have no direct causal effects on each other. The radii at which observed pair correlation functions cross their simulation envelopes therefore likely reflect merely on the relative geometry of spatial distributions.

Significance of Hotspots in Baseline Distributions

For all baseline distributions, the deepest portions of the river (channels) tended to have the highest density of points, as expected for a benthic species of fish (Figures 10, 15, 16, 24, and 26). However at Presquile for instance, the downstream portion of the cut-through had the highest density of points, but a deeper hole is present shortly more downstream. Possible explanations for deviations from purely following bathymetry could be individuals avoiding the need to fight strong water currents by preferring the inside edge of curves. Adult spatial distribution would not be explained by food abundance because adults are known not to feed while on spawning migrations (Smith 1985). Distribution of food sources may explain the habitat preference of sub-adults which feed in the estuary, but sub-adult positions were noted only at the dredge site. Interestingly dredge spoil may negatively impact benthic macroinvertebrates who are food sources for juveniles and sub-adults (Nellis et al. 2007). However the dredge is annual at that site, so any changes the spoil may have induced may already be the norm.

Response to Tug and Ship Passages

The bivariate pair correlation distributions of the Presquile NWR and Rice Rivers Center datasets appear to show opposite responses to tugs and ships. The values observed at the Rice Rivers Center site began below the values expected by the simulations, while the Presquile NWR values began above their expected values (Figures 11 and 17). For the Rice site, it appeared Atlantic Sturgeon did not follow their baseline spatial distribution in the presence of tugs/ships and instead were generally more dispersed, not following the usual hotspot within the channel in the center of the array. This would appear to indicate avoidance behavior because tugs and ships followed the navigation channel.

It also appeared at Presquile that Atlantic Sturgeon did not follow their baseline distribution in the presence of large vessels, but in a manner opposite to the Rice site. The observed $g_{12}(r)$ values occurring above the values expected by the simulations indicates the points during potential threats occurred more frequently at the hotspots of the baseline distributions and less frequently along the fringes, meaning the fish occurred relatively more often in the channel/cut-through. This appears to indicate attraction to the potential threat. The lack of positions in areas outside the channel following tug and ship passages may suggest that Atlantic Sturgeon who were outside of the cut-through and navigation channel may have left the array, while individuals in the cut-through did not have that option and remained. An alternative explanation would be that in response to ships and tugs that the individuals gathered towards the deepest waters nearby, but that would be an opposite response to what was seen at the Rice site. Both explanations could therefore indicate avoidance behavior that was nevertheless ineffective at actually avoiding the potential threat.

Another possibility is that the stimuli associated with passing vessels may vary between the two sites. The differences in channel and overall river width and depth between the two sites may have created differences in the length of time sound and pressure waves were detectable to Atlantic Sturgeon in the study areas, affecting habituation to stimuli and therefore readiness to react. There may also have been different volumes and directionality of the noise and pressure waves, resulting from reflection and collimation within the cut-through at Presquile vs. the more open channel at Rice Rivers Center. These differences in acoustics could be associated with different responses, i.e. evasion at Rice versus a more catatonic response at Presquile.

It is also possible however that the different roles of the sites to migrating adults could explain the difference in response between sites. Perhaps when adults were actively travelling through the channel at the Rice Rivers Center site they were more likely to divert their path when they sensed a large propeller in the water, but at the staging ground at Presquile they were less active and less likely to evade a tug/ship completely. The baseline swimming velocity mean at Presquile was slightly lower than the corresponding mean velocity at Rice Rivers Center, 0.445 m/s as compared to 0.507 m/s, so relatively lower responsiveness at the staging grounds may partly explain the difference. Previous data also show that adults in travel tend to move higher in the water column, but staging adults may try to stay as close to the bottom as possible otherwise (Balazik 2012b).

For both sites, the difference in mean velocity in the absence vs. the presence of large vessels was statistically insignificant, p=0.78 for Presquile and p=0.99 for Rice (Figures 12 and 19). The fact that the mean swimming velocity for either site was not different between a tug/ship passage and the baseline suggests that changes in spatial distribution were not results of drastic movements under stress. In fact, at both sites it was the group of points that occurred outside of tug/ship passages that had instances of speeds higher than 2 m/s while the points within 10 minutes of a tug or ship did not, likely a result of much higher sample size (Table 1). The lack of change in movement speed between times of tug and ship passage and their absence also suggests that although there appears to be avoidance behavior, particularly obvious at the Rice site, this would have occurred through either anticipation through stimuli and simple directional change in their normal movements.

Response to Recreational Traffic

The response at Presquile to hours of high recreational boat traffic was nearly identical to the response at that site to larger vessels. Although the draft depths of speed boats are less likely to cause physical harm to bottom-dwelling Atlantic Sturgeon, the spatial distribution of the fish appeared to change regardless. The most likely explanation is noise, as the underwater wake and turbulence produced by smaller vessels is far less than that produced by more deep-draft vessels. The similarity between results at Presquile is also notable because the recreational traffic comparison was based on busy hours, while the tug and ship comparison was based on individual passages. The data appear to imply that even if the stimuli of passing vessels are prolonged Atlantic Sturgeon remain in the channel of the cut-through where they are more vulnerable as compared to outside of the cut-through.

This implies that a speed limit for tugs and ships as a possible solution to vessel strikes at Presquile NWR may not be effective. If Atlantic Sturgeon are aware of propeller noise and respond by moving away from the channel where possible, outside of the cut-through, but remain in the channel if already there even during hours of sustained high traffic, larger vessels moving more slowly may not induce individuals remaining in the cut-through to flee. However, that may be a faulty assumption. An alternative explanation is that even though it may appear individuals have more time to react during hours of high recreational traffic because the propeller noise is somewhat sustained, the direction of stimuli is constantly changing as boats pass over the surface. The hours where more than 50 boats passed through were before and after fishing tournaments, so nearly every boat was moving as quickly as possible to reach favorable fishing spots or return to the dock to prevent disqualification. In the case of a tug or deep draft vessel, a slow-moving consistent noise from one end of the cut-through may induce fleeing if the noise approaches slowly and comes consistently from one direction relative to the fish. Further research which directly measures noise underwater through the use of a hydrophone could provide more useful evidence.

Adult vs. Sub-Adult Behavior at Dredge Site

The two life stages present at the dredge site, adults and sub-adults, were expected to have different general behavior and therefore possibly different response behavior to threats. For sub-adults, the dredge site is part of the estuary where they feed but for adults it is a migration corridor to the staging area upstream. Therefore, it was expected that the sub-adults would venture more often into the shallows outside of the navigation channel while the adults would mainly travel directly through the channel. Those general patterns appear to be true based on the baseline distributions (Figures 24 and 26). It also appears that responses to the dredge operation were different between adults and sub-adults.

For both life stages, the observed pair correlation functions began below their expected values, but the sub-adult function more closely followed the values expected by the associated simulations. Although both comparisons were different with statistical significance, the evidence is stronger that the adults exhibited an avoidance response than the sub-adults. Oddly enough dredging was associated with adults occurring more often outside of the channels, where they would normally travel, but that was not true for sub-adults which had been expected to spend much of their time feeding outside the channels during normal behavior.

These results are concerning because sub-adults are presumably more at risk of entrainment than adults, due both to their smaller size and their reduced swimming velocity (Boysen and Hoover 2009). The mean swimming velocity of adults was 0.55 m/s when the dredge was not operating in the area but was significantly higher ($p<0.01$) at 0.69 m/s when the dredge was active nearby. The mean velocity for sub-adults was 0.415 m/s in absence of the dredge and 0.32 m/s during the dredge, a significant decrease ($p<0.01$). Not only do those velocity estimates portray slower movements from sub-adults in general, but that in the presence of a threat they may move even more slowly, which would presumably put them at greater risk. The adults on the other hand appear to travel through the area more quickly than their baseline movements through the area. However, this comparison may break the stationarity assumption of this study because the dredge occurred over a continuous period (9/10 through 9/29) in the middle of the study, rather than discrete instances like ship/tug passages. At the time of the dredge, the fall spawn was occurring upstream, so it is possible that latecomers may have been moving more quickly to join or adults who had already spawned were moving quickly out to sea (Balazik and Musick 2015).

The results of the dredge site appear to show that the adults were less threatened by dredging as compared to sub-adults. The spatial distribution of the adults varied from largely following the navigation channel and natural adjacent channel to travelling outside the channels. Nevertheless, it is certainly possible for adults to be killed by dredges (Murray 2014). The sub-adults however appeared to be notably at risk. Although sub-adults moved more slowly, perhaps indicating that they were aware of the threat and made more deliberate movements, there were instances where they passed through the area of the cutterhead (Figure 30). There have not been any reports of Atlantic Sturgeon found dead in the spoil of a James River dredge or any telemetry data indicating so (such as a tag remaining at the same position near a dredge indefinitely), but it may be prudent to reduce the risk of entrainment to sub-adults. One solution is to reduce the diameter of the pipe through which sediment is collected (Hoover et al. 2011).

VPS Future Use for Small-Scale Behavior

Although many studies have used VPS and many have used Programita®, this study is the first of its kind in regard to measuring small-scale avoidance behaviors with VPS using point pattern analysis. The use of bivariate pair correlation functions with Monte Carlo simulations for context appears to be a viable method for analyzing spatial data from fish, although there are alternative perspectives to analyzing movement patterns that more explicitly recognize time through uses of pathways and vectors (McLean et al. 2014, Kelly and Klimley 2012). However as long as basic assumptions are reasonably met, particularly stationarity, animal point data can be analyzed in a manner similar to plant location data. One aspect upon which this kind of analysis can be improved however is to recognize the dimension of depth. For the most part Atlantic Sturgeon tend to remain near the bottom of the water column, but especially during travel they may move to a shallower depth (Balazik et al. 2012b). Conclusions were drawn based on differences in latitude and longitude location, but depth differences between individuals and threats may have made threats appear closer to the fish than they really were. Depth tags are available from VEMCO, and they may be incorporated in future studies.

Management Implications

It does not appear that propeller strikes are a particularly important threat at Rice Rivers Center, as compared to Presquile NWR, as well as at presumably similar areas along the river where the channel is deep and the river is wide. However strikes are still possible anywhere, and the results do support previous findings that the cut-through at Presquile NWR puts adults Atlantic Sturgeon at a substantial risk of strikes (Balazik et al. 2012b). The data collected represent the fall-spawning adults of the James River population, but the spring-spawning adults also use that site as spawning grounds and potentially exhibit similar behavior. Therefore, preventing strikes at that site may be a seasonal management challenge.

As discussed earlier, a speed limit for commercial traffic may not be a viable solution because it may or may not make a difference in eliciting adults to leave the cut-through. Other more extreme solutions could include widening the cut-through or preventing all large vessel traffic seasonally and transporting cargo by rail and by interstate as an alternative. A somewhat small number of tug vessels (n=16) passed through the cut-through during the fall of 2014, so applying propeller guards to vessels which pass through is a possible solution (Perry et al. 2014). All of these options would require careful consideration for costs in effort and money but because Atlantic Sturgeon are a federally protected species an unpleasant solution may be necessary.

Recreational traffic may also produce negative behavioral effects rather than propeller strikes (Whitfield and Becker 2014). The data from this study far from answer any questions about whether or not spawning or migratory behavior overall can be disrupted, but that is a question that is worth pursuing, especially because it is hypothesized the spring-spawning adults in the James River use Presquile NWR as a spawning ground.

In regard to the dredge it would be sensible for the USACE to sample their spoil for any signs of entrainment however possible, including looking for scutes or other Atlantic Sturgeon remains. Although an Atlantic Sturgeon has not yet been found to have been killed or injured by a dredge in the James River, it is possible as has happened elsewhere. The results of this study could be used to inform management of populations of sturgeon in other commercially important rivers, whether Atlantic Sturgeon, Shortnose Sturgeon, or otherwise. Broadly speaking these results also may support further management of vessel traffic and dredge operations to support aquatic life in general.

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Literature Cited

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Appendix

Table 1. Summary table of comparisons using the bivariate pair correlation function for point pattern analysis and the Welch two sample t-test for velocity distributions. Velocities are presented with standard error values.

Comparison	Rice Rivers Center Tugs/Ships	Presquile NWR Tugs/Ships	Presquile NWR Recreational Traffic	Dredge Site Adults	Dredge Site Sub-Adults
Baseline Points/ Points During Threats	7,883/148	34,841/347	34,640/201	2,504/121	2,941/388
Total Individuals/ Individuals During Threats	102/39	92/62	92/38	85/20	41/20
Baseline Velocity (m/s)	0.507 ± 0.007	0.445 ± 0.002	0.445 ± 0.002	0.55 ± 0.01	0.415 ± 0.007
Velocity During Threats (m/s)	0.51 ± 0.06	0.44 ± 0.03	0.47 ± 0.05	0.69 ± 0.03	0.32 ± 0.02
Significance (p-value)	0.99	0.78	0.64	<0.01	<0.01
Radius Converging to Expected (m)	183.5	478.5	348.5	930.5	33.5

Figure 1. Retrieved receiver mount from the dredge site array. A concrete base with steel rebar keeps the receiver at the bottom of the river oriented vertically. The long vertical piece of rebar has a synchronization tag at the top to allow the array to detect drifts of receivers for accuracy.

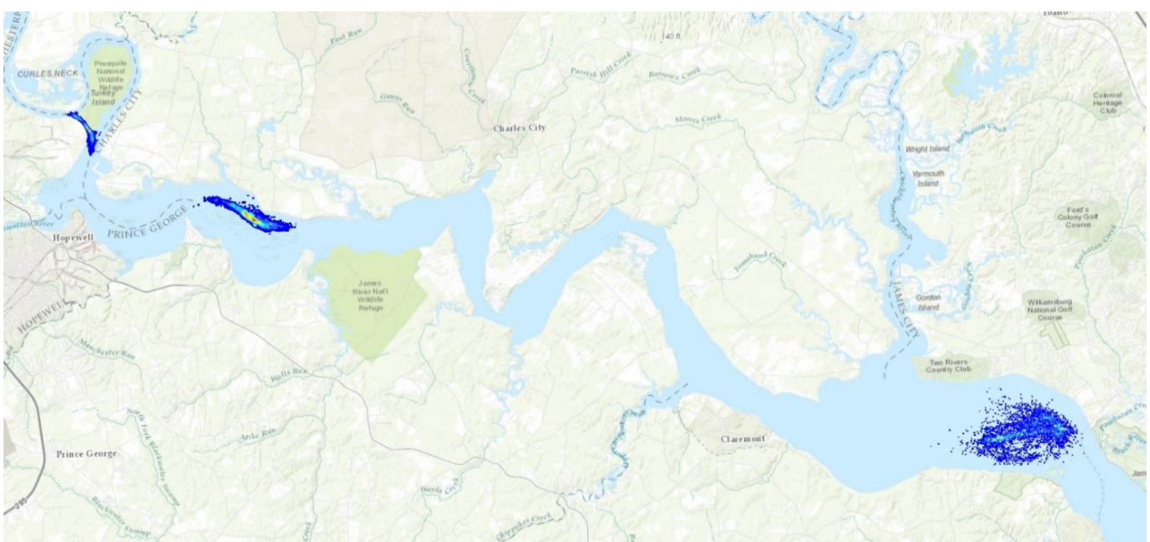

Figure 2. All three study sites with point density rasters indicating the extent of the array ranges. The most westward (upstream) is Presquile NWR, the middle is Rice Rivers Center, and the most downstream is the dredge site.

Figure 3. Presquile National Wildlife Refuge at Turkey Island on which the camera recording vessel traffic was placed on the southern tip.

Figure 4. Example image of footage from the Presquile site with a tug passing downstream.

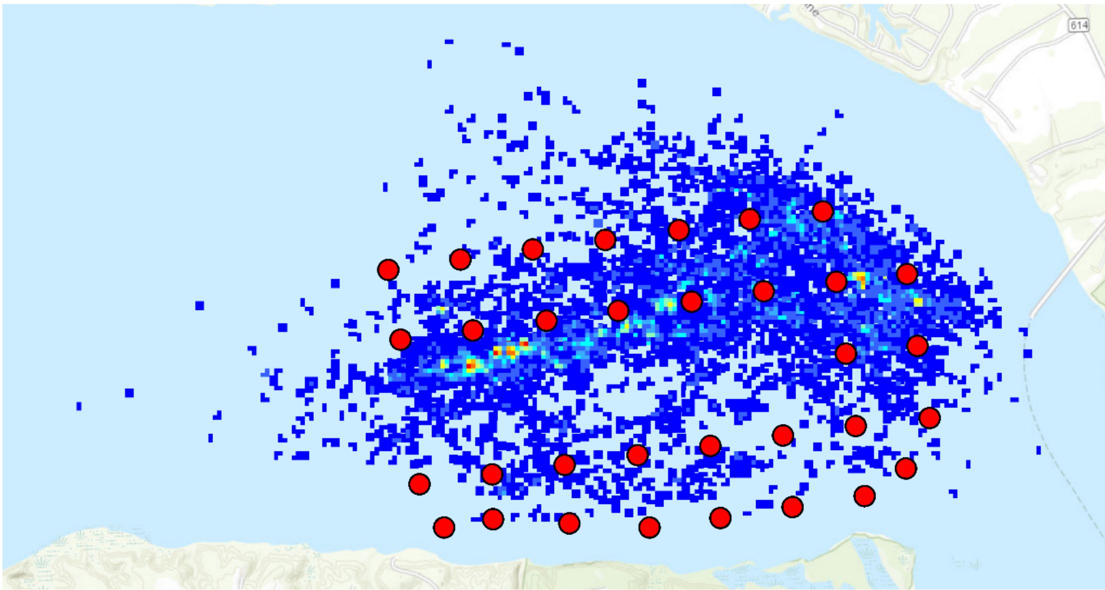

Figure 5. Array at the Chickahominy dredge site, the red icons depict receivers and the point density raster shows where points were detected throughout the study period. The gap between receivers may have had a reduced detection ability.

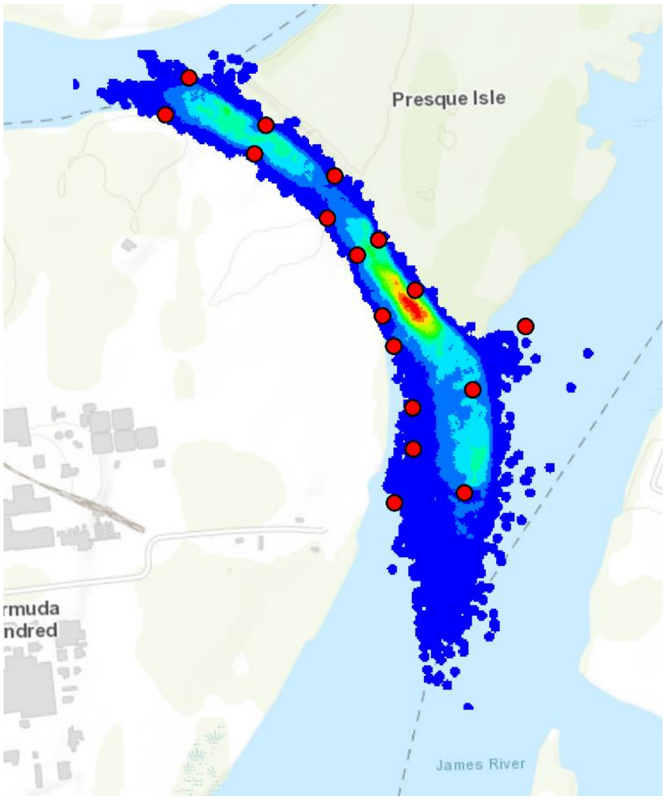

Figure 6. Array at the Presquile NWR site with red icons representing receivers. A receiver in the middle of the cut-through was not able to be retrieved, which may explain the lower density of points recorded in the nearby area.

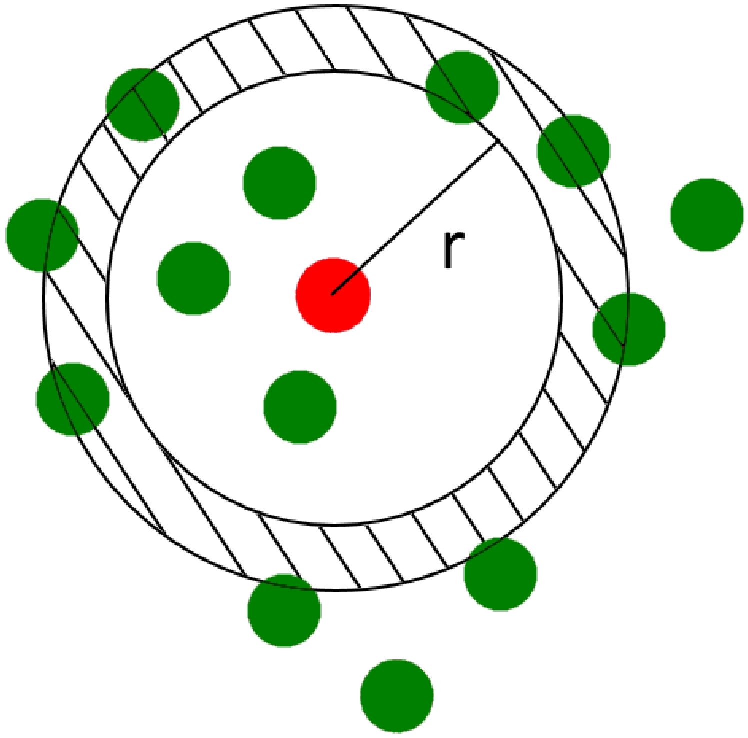

Figure 7. Ring of radius r through which $g_{12}(r)$, the bivariate pair correlation function, is calculated. For the univariate pair correlation function all points would be of the same type.

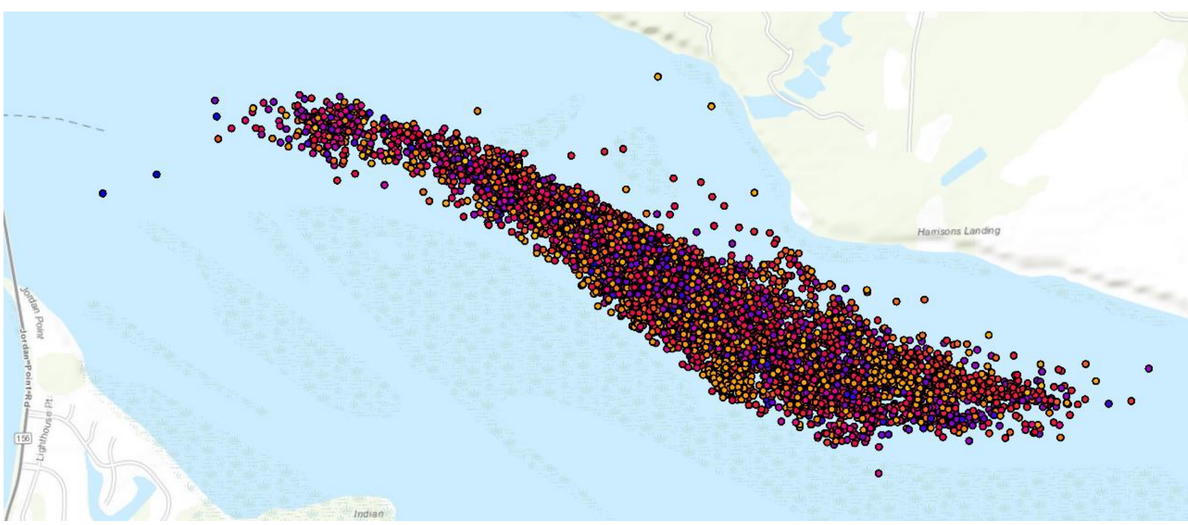

Figure 8. All recorded points of the array at Rice Rivers Center, color-coded by transmitter (individual).

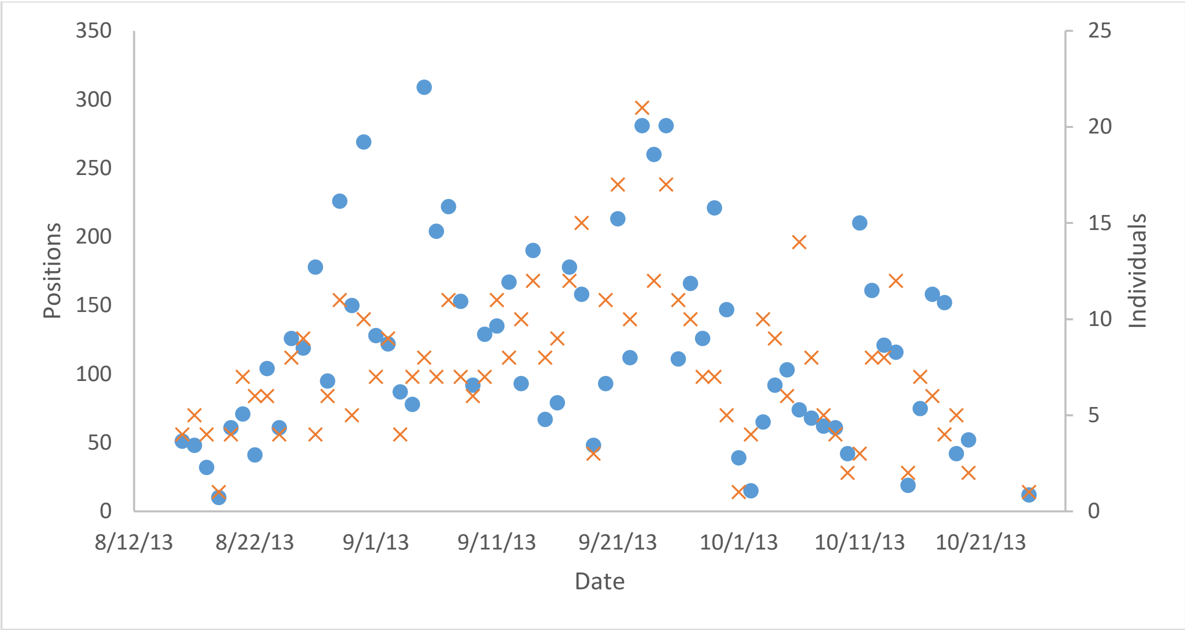

Figure 9. Number of positions collected (circles) and individuals present (x's) at the Rice Rivers Center site array by date.

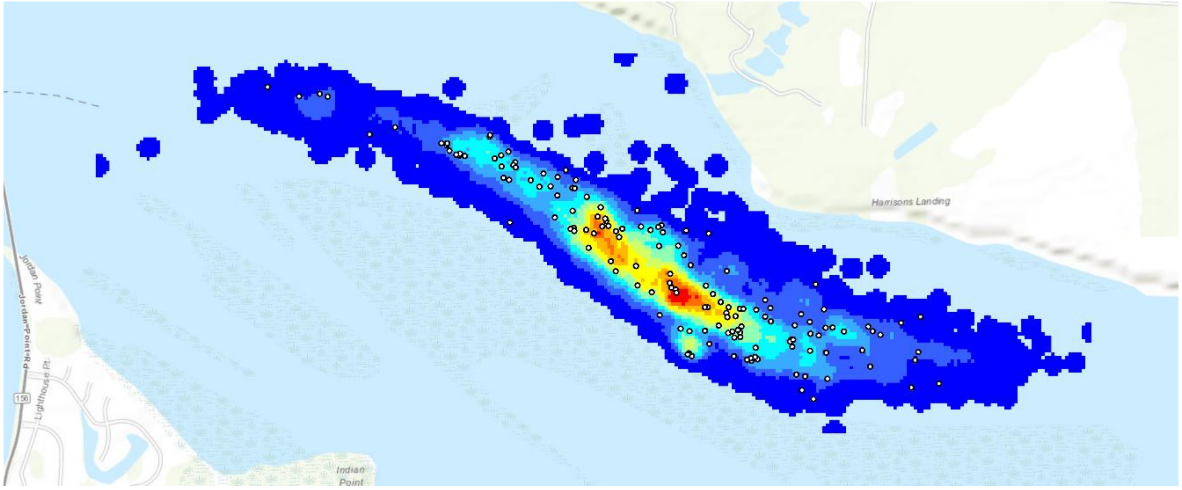

Figure 10. Distribution of points collected at the Rice Rivers Center site. The point density raster represents the baseline distribution outside of a tug or ship passage. The points over the raster were at the time of or within 10 minutes of a tug/ship passage.

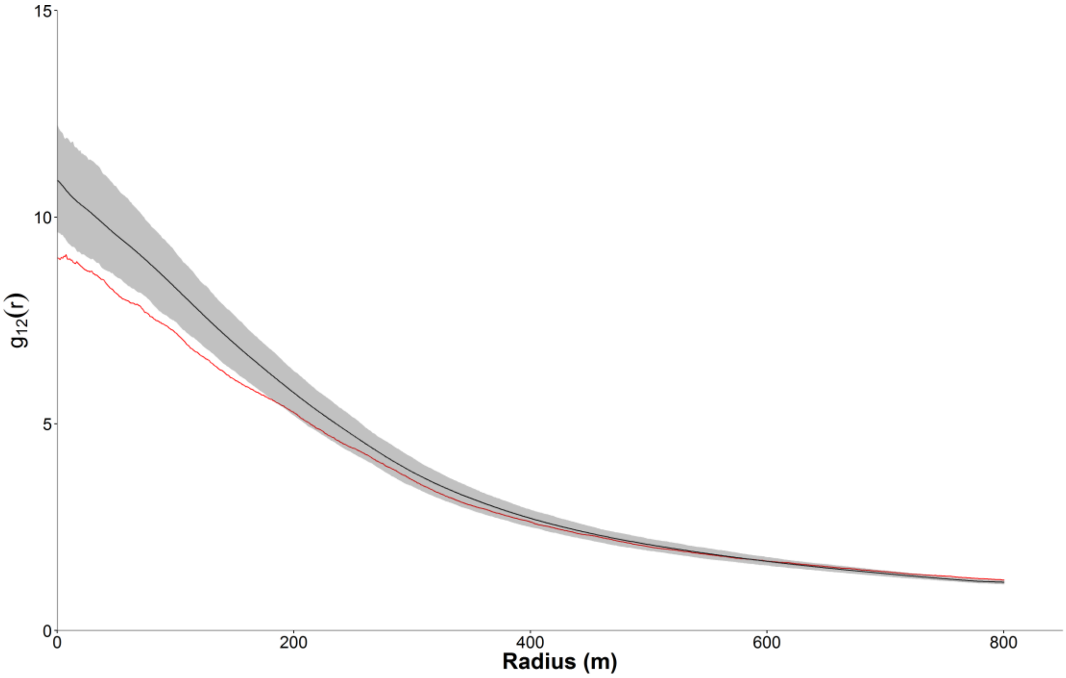

Figure 11. Resulting $g_{12}(r)$ distribution from the Rice site data comparing the baseline spatial distribution to the points during potential threats spatial distribution. The red line represents the actual data, and the gray band represents the values of the middle 98% of 500 simulations. The red line crosses between the simulation envelopes at 183.5 m.

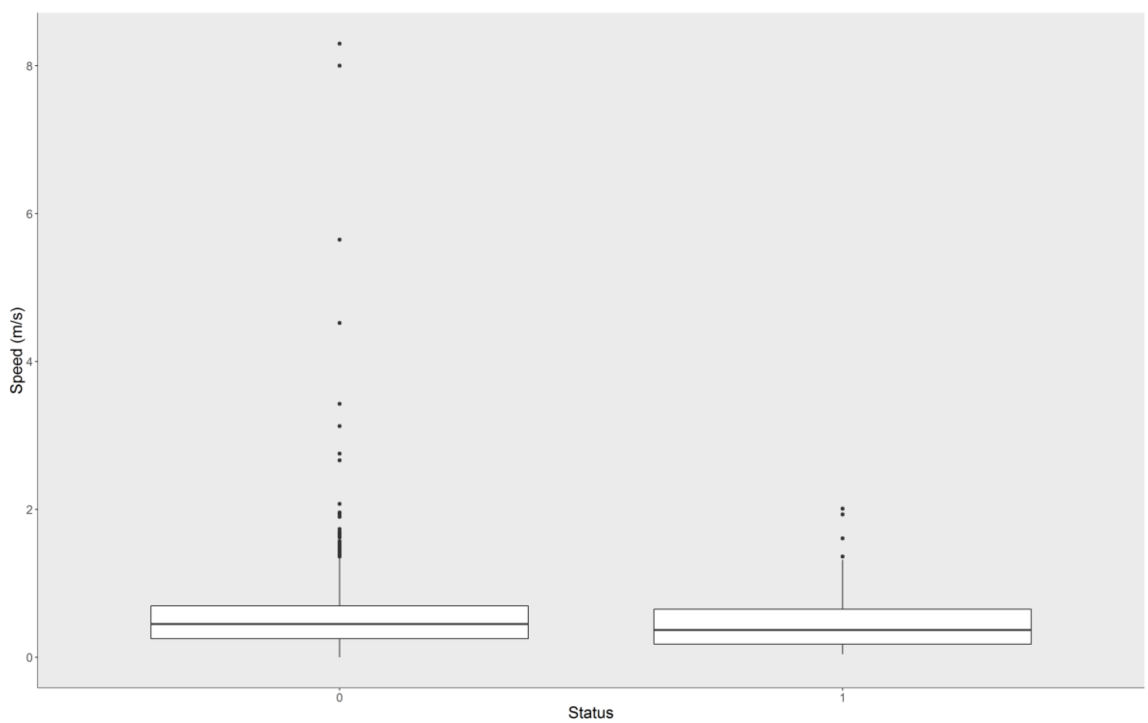

Figure 12. Boxplots of swimming velocity estimates at the Rice Rivers Center site. The mean swimming velocity outside of tug/ship passages (left) was 0.507 ± 0.007 m/s (± 1 SE), and the mean velocity within 10 minutes of a tug/ship passage (right) was 0.51 ± 0.06 m/s. This difference was insignificant (p=0.99).

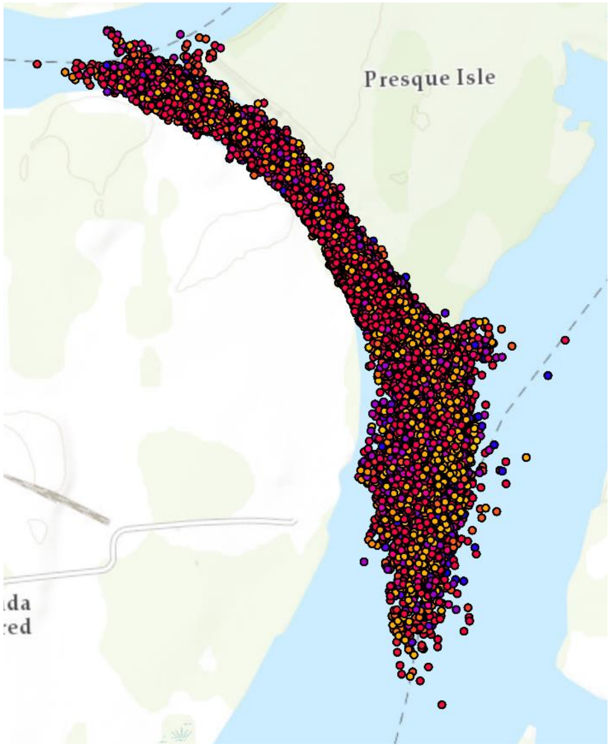

Figure 13. All recorded points of the array at Presquile NWR, color-coded by transmitter (individual).

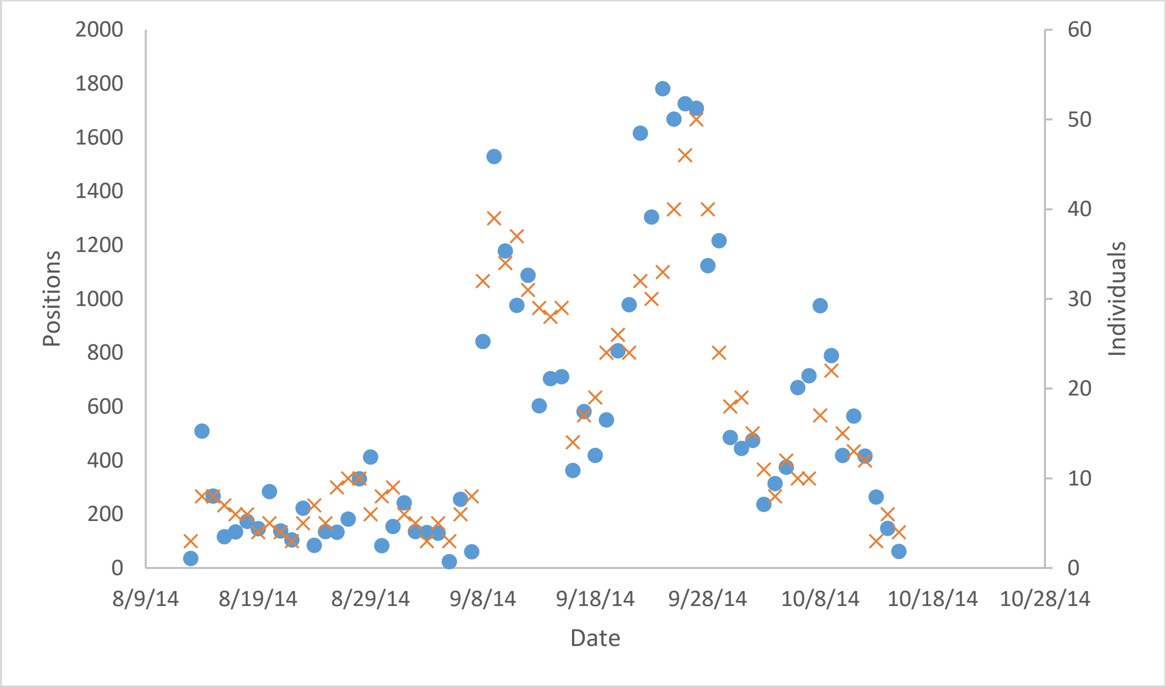

Figure 14. Number of positions collected (circles) and individuals present (x's) at the Presquile NWR site array by date.

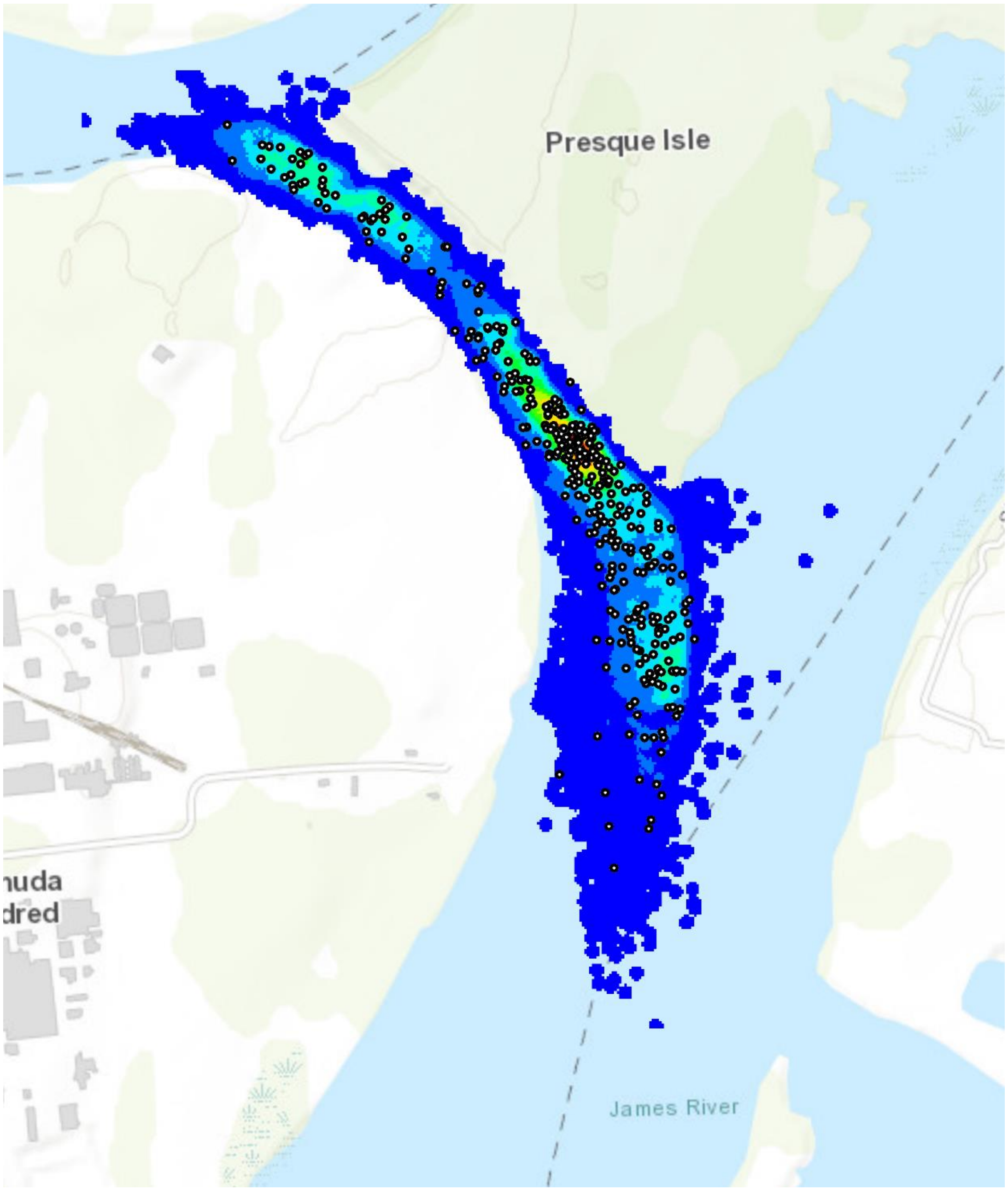

Figure 15. Distribution of points collected at Presquile NWR. The point density raster represents the baseline distribution outside of a tug or ship passage. The points over the raster were at the time of or within 10 minutes of a tug/ship passage.

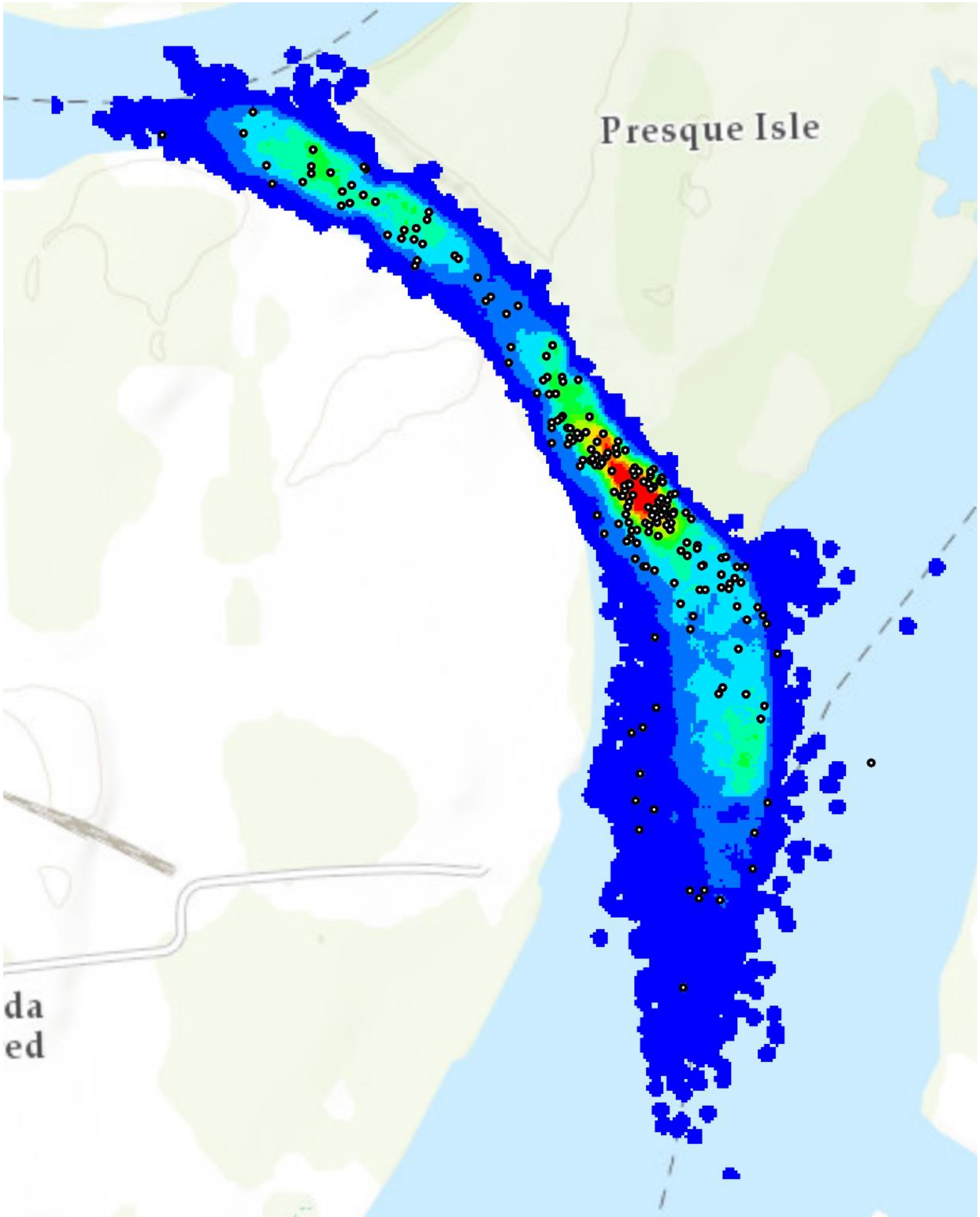

Figure 16. Distribution of points collected at Presquile NWR, excluding points within 10 minutes of a tug/ship passage. The point density raster represents the baseline distribution during hours where less than 50 recreational boats passed through the cut-through, while the points over the raster were during such busy hours (fishing tournaments).

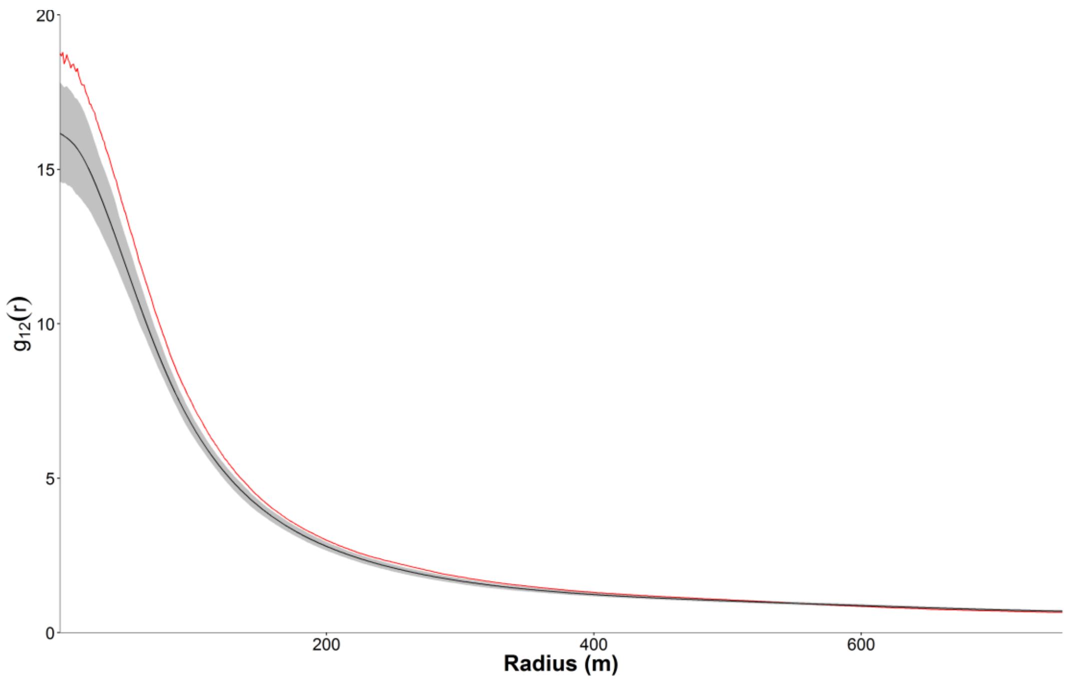

Figure 17. Resulting $g_{12}(r)$ distribution from the Presquile tug/ship passage comparison comparing the baseline spatial distribution to the points during potential threats spatial distribution. The red line represents the actual data, and the gray band represents the values of the middle 98% of 500 simulations. The red line crosses between the simulation envelopes at 478.5 m.

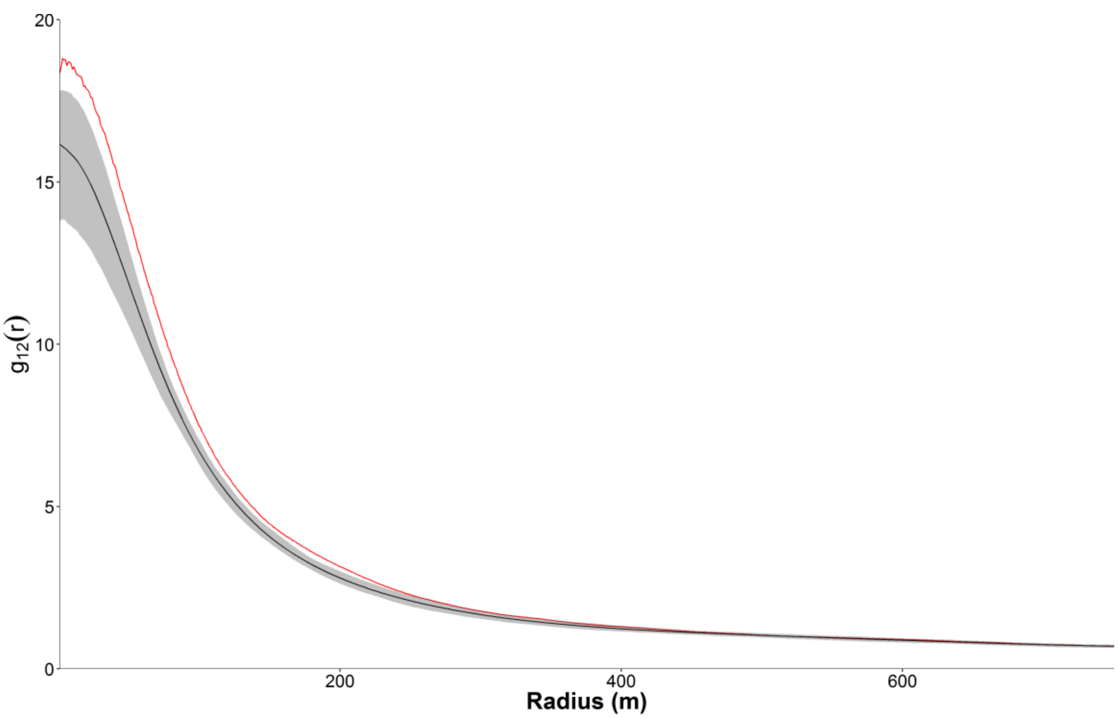

Figure 18. Resulting $g_{12}(r)$ distribution from the Presquile recreational traffic comparison comparing the baseline spatial distribution to the points during potential threats spatial distribution. The red line represents the actual data, and the gray band represents the values of the middle 98% of 500 simulations. The red line crosses between the simulation envelopes at 478.5 m.

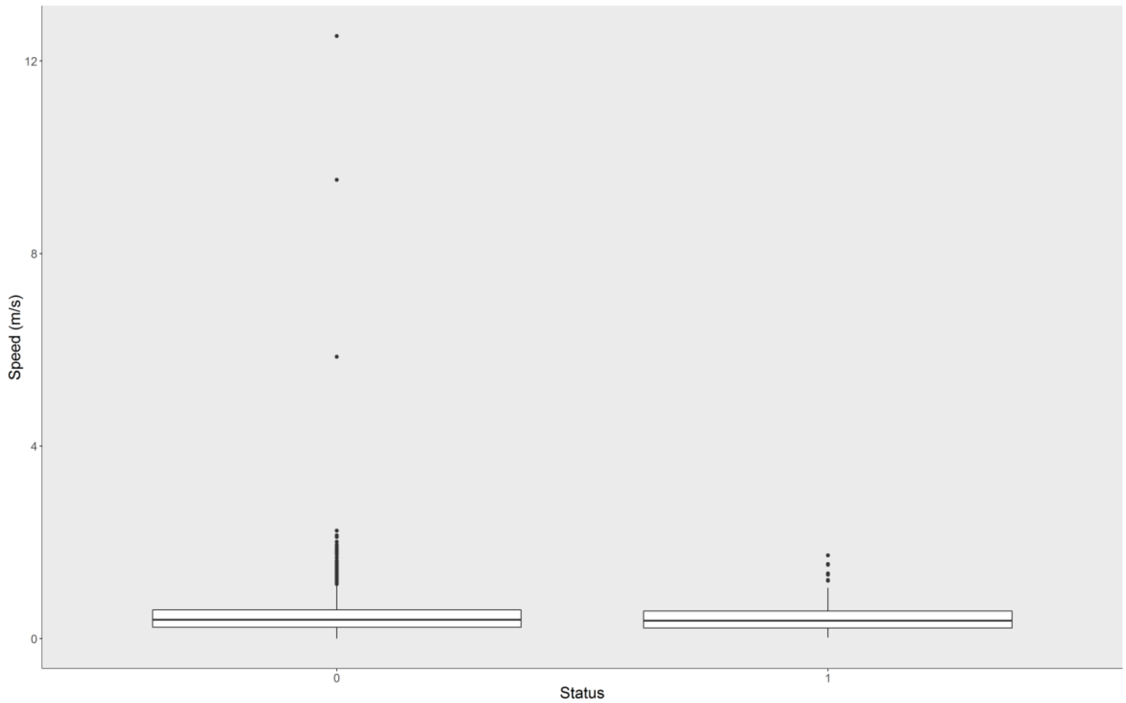

Figure 19. Boxplots of swimming velocity estimates for the Presquile tug/ship comparison. The mean swimming velocity outside of tug/ship passages (left) was 0.445 ± 0.002 m/s (± 1 SE), and the mean velocity within 10 minutes of a tug/ship passage (right) was 0.44 ± 0.03 m/s. This difference was insignificant (p=0.78).

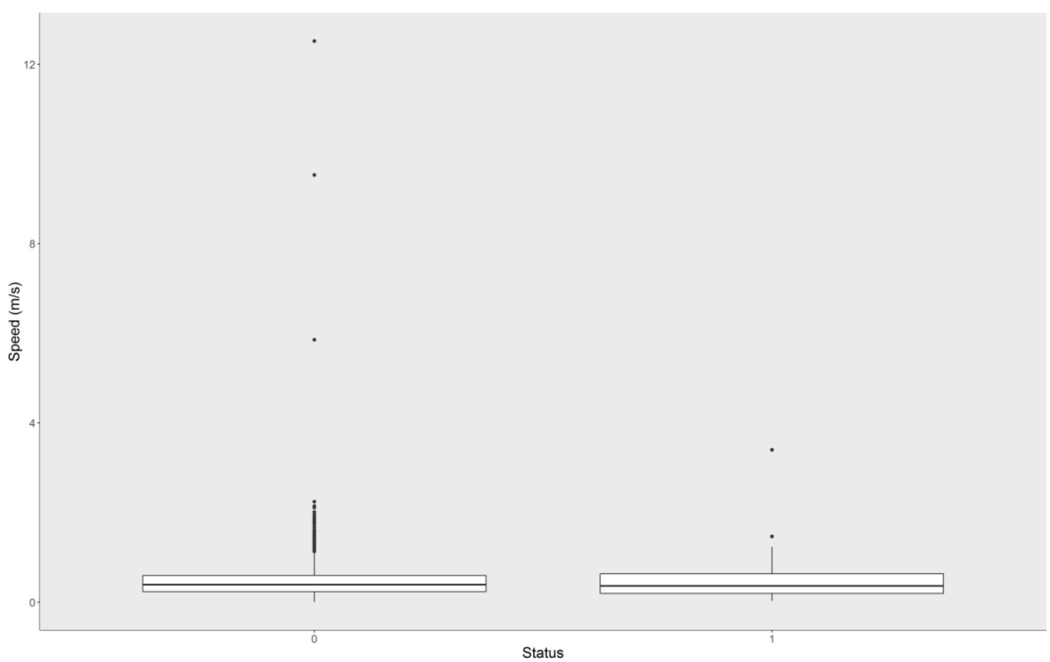

Figure 20. Boxplots of swimming velocity estimates for the Presquile recreational traffic comparison. The mean swimming velocity outside of busy hours (left) was 0.445 ± 0.002 m/s (± 1 SE), and the mean velocity during busy hours (right) was 0.47 ± 0.05 m/s. This difference was insignificant (p=0.64).

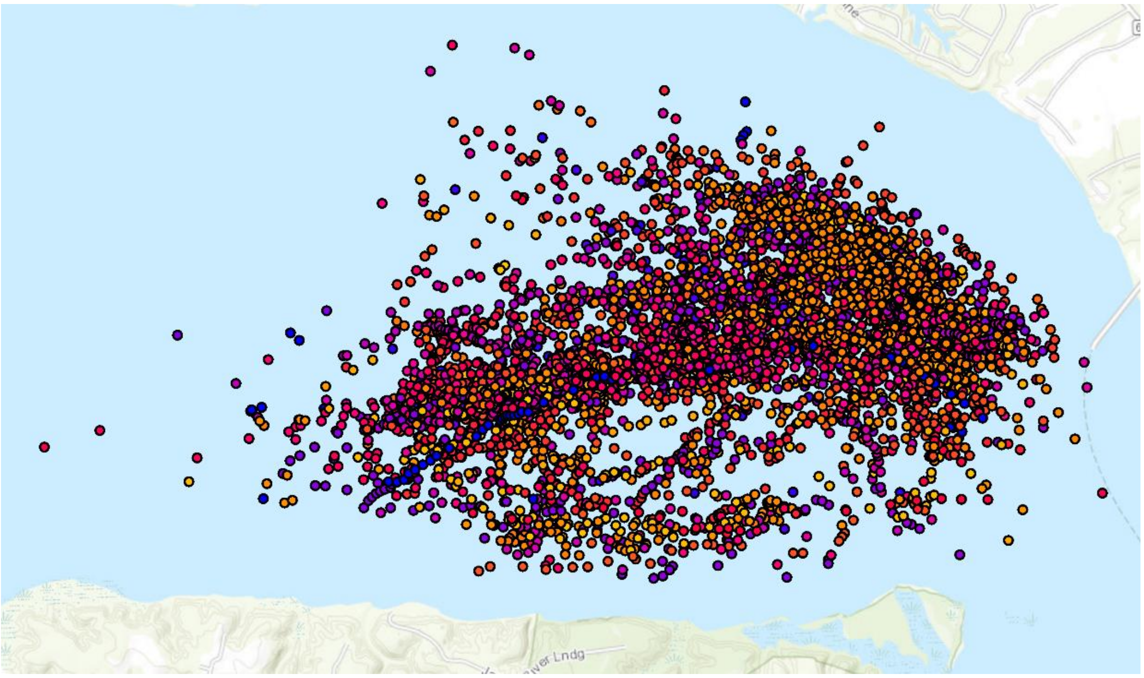

Figure 21. All recorded points of the array at the dredge site, color-coded by transmitter (individual).

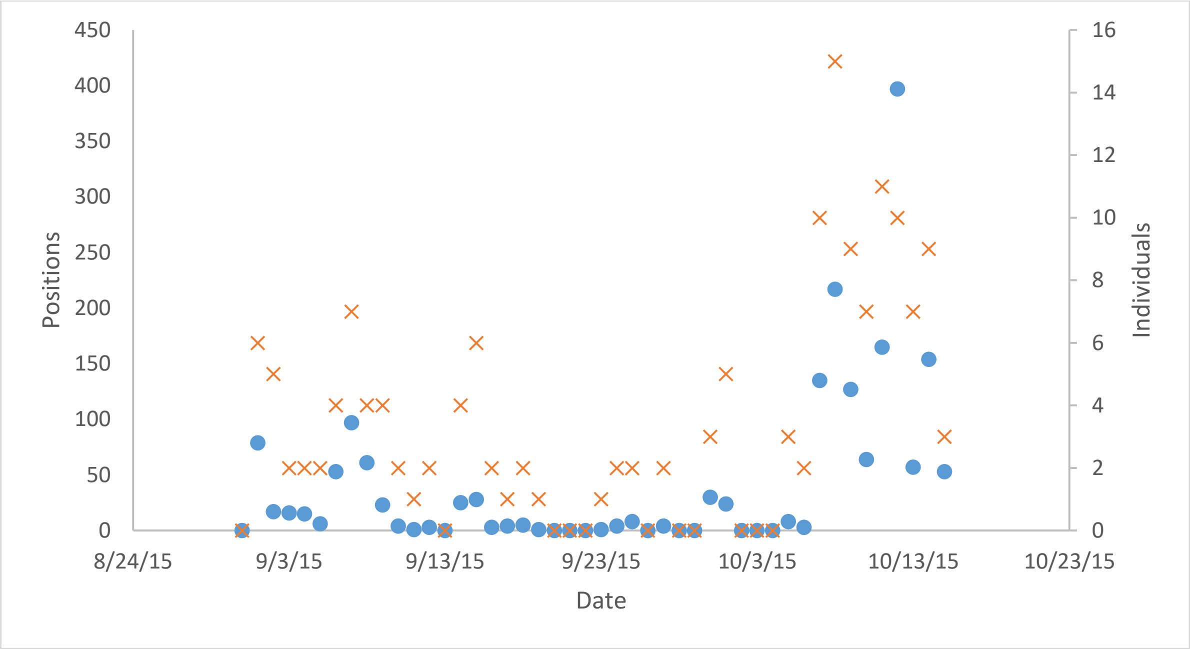

Figure 22. Number of adult positions collected (circles) and individuals (x's) present at the dredge site array by date.

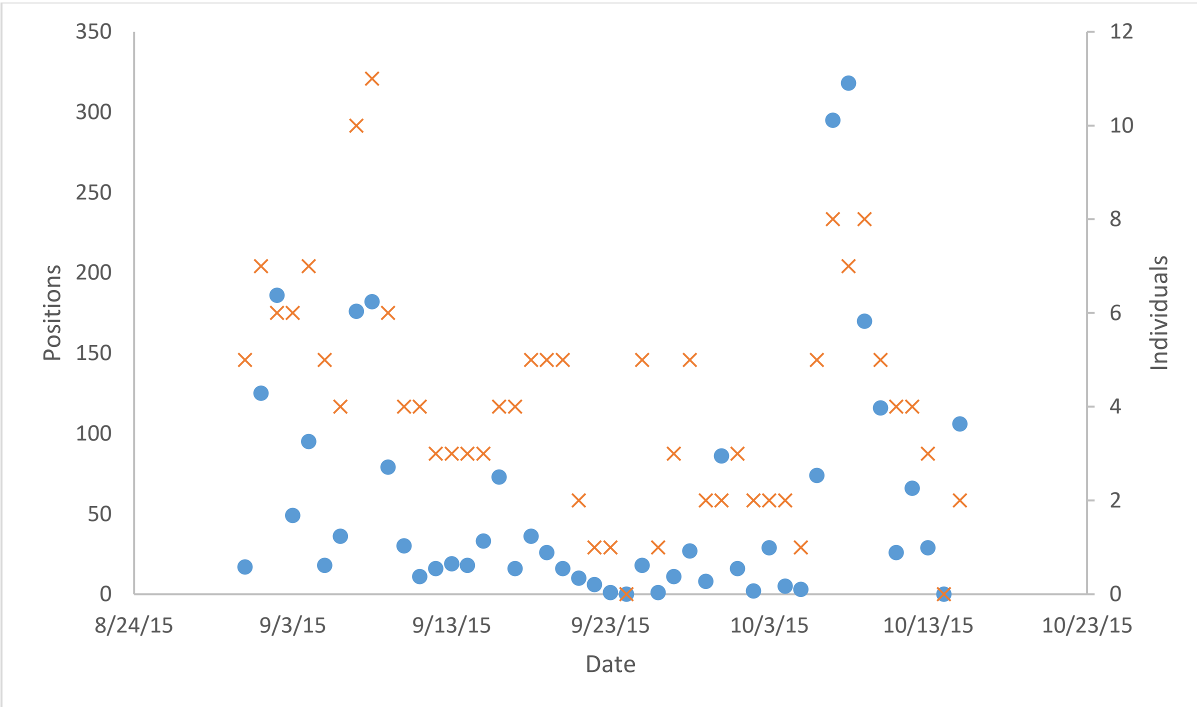

Figure 23. Number of sub-adult positions collected (circles) and individuals (x's) present at the dredge site array by date.

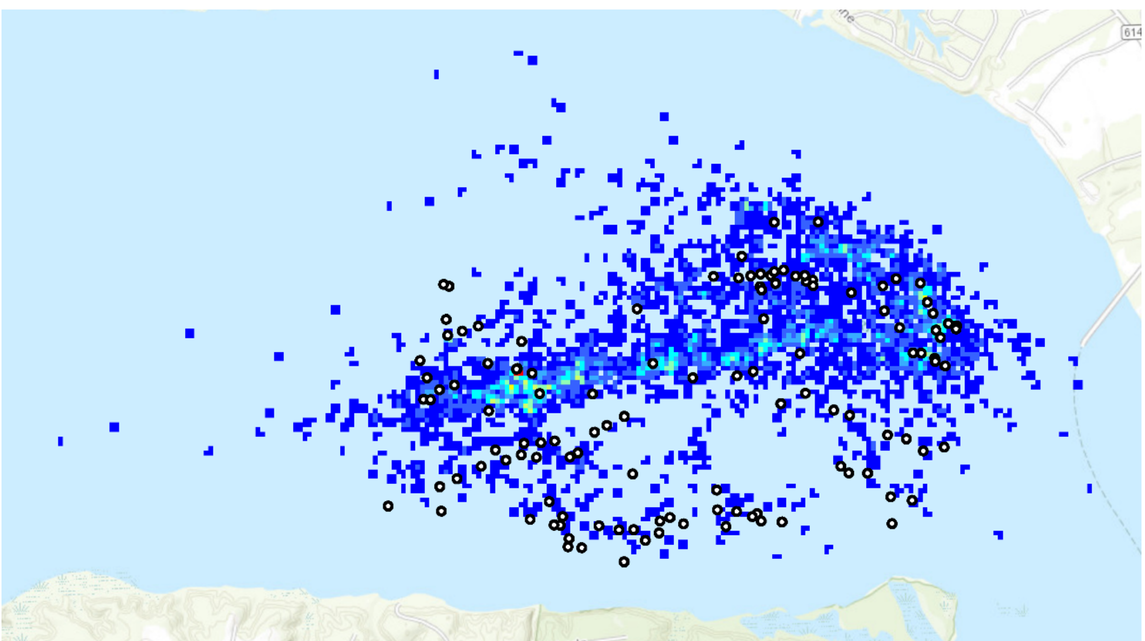

Figure 24. Distribution of adult points collected at the dredge site. The point density raster represents the baseline distribution when the dredge was not operating in the area, while the points over the raster were during the dredge (9/10 through 9/29).

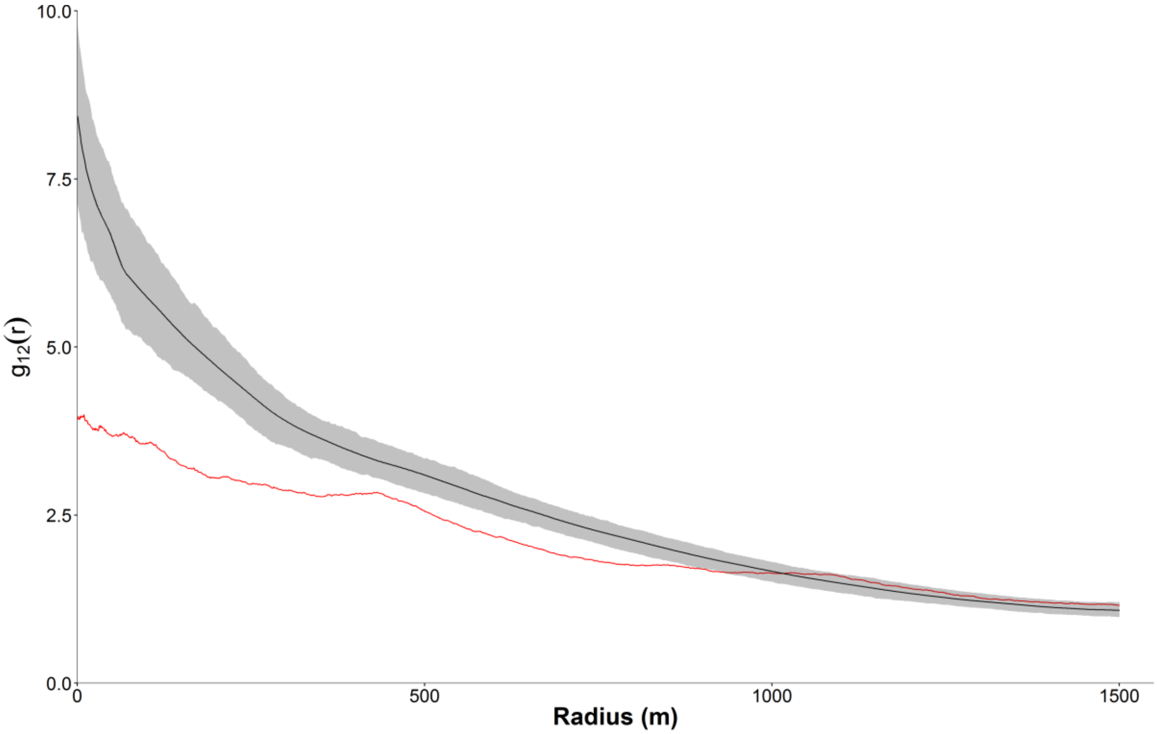

Figure 25. Resulting $g_{12}(r)$ distribution from the dredge site adults comparing the baseline spatial distribution to the points during potential threats spatial distribution. The red line represents the actual data, and the gray band represents the values of the middle 98% of 500 simulations. The red line crosses between the simulation envelopes at 930.5 m.

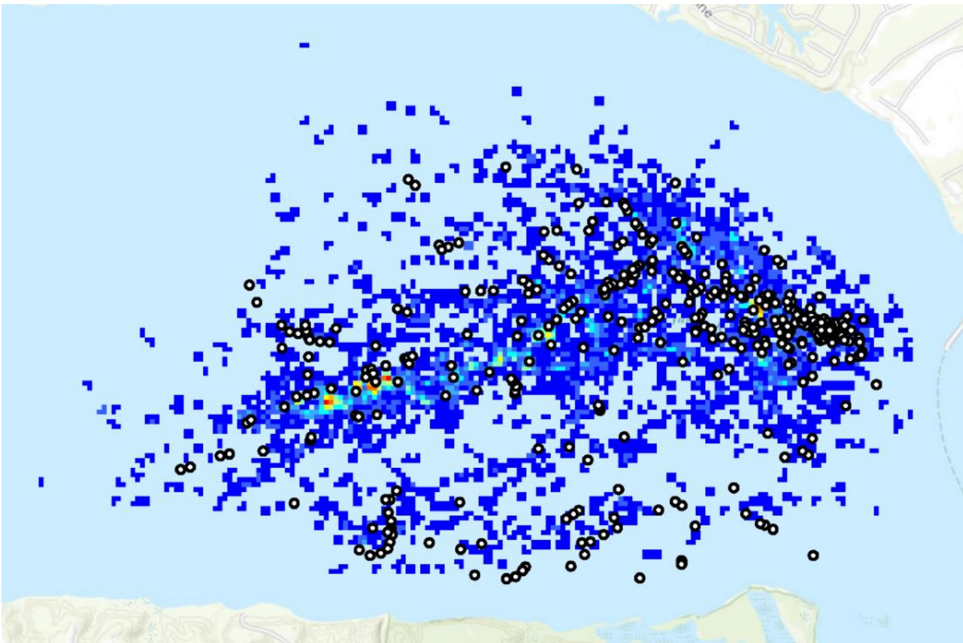

Figure 26. Distribution of sub-adult points collected at the dredge site. The point density raster represents the baseline distribution when the dredge was not operating in the area, while the points over the raster were during the dredge (9/10 through 9/29).

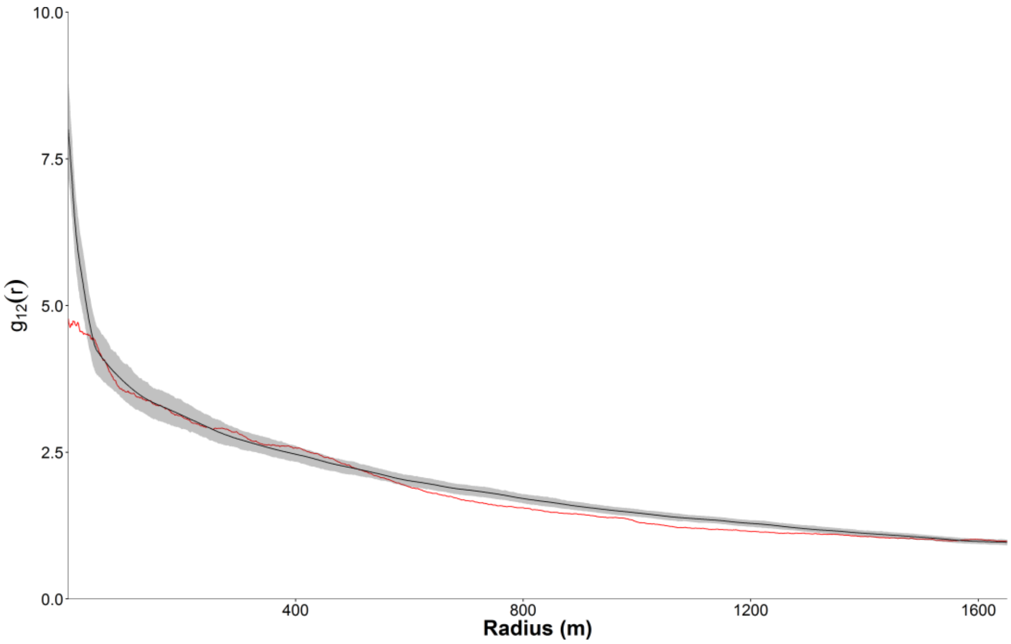

Figure 27. Resulting $g_{12}(r)$ distribution from the dredge site sub-adults comparing the baseline spatial distribution to the points during potential threats spatial distribution. The red line represents the actual data, and the gray band represents the values of the middle 98% of 500 simulations. The red line crosses between the simulation envelopes at 33.5 m, crosses back below at 597.5 m, then returns between simulation envelopes at 1400.5 m.

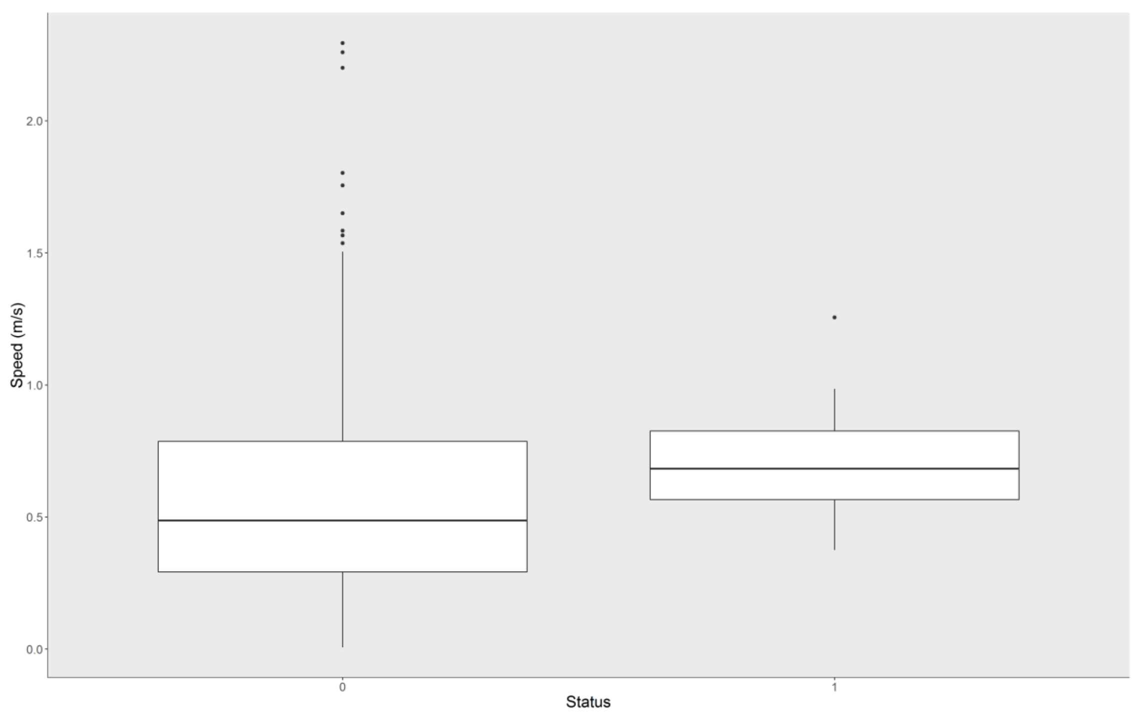

Figure 28. Boxplots of swimming velocity estimates for the dredge site adults comparison. The mean swimming velocity outside of the dredge (left) was 0.55 ± 0.01 m/s (± 1 SE), and the mean velocity during the dredge (right) was 0.69 ± 0.03 m/s. This difference was significant (p<0.01).

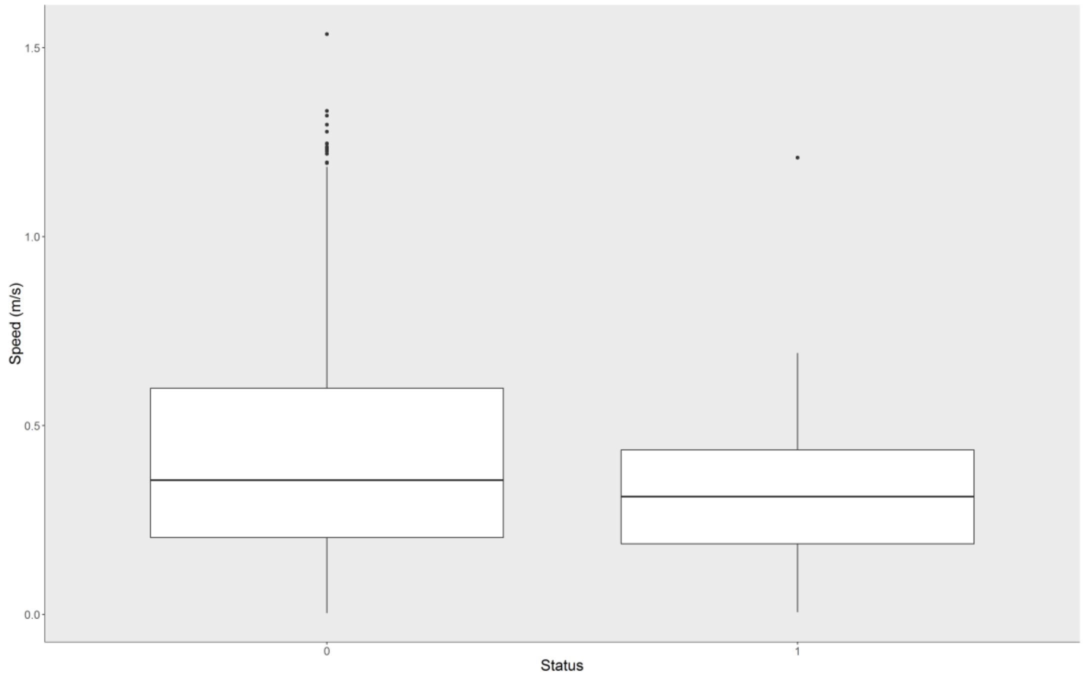

Figure 29. Boxplots of swimming velocity estimates for the dredge site sub-adults comparison. The mean swimming velocity outside of the dredge (left) was 0.415 ± 0.007 m/s (± 1 SE), and the mean velocity during the dredge (right) was 0.32 ± 0.02 m/s. This difference was significant (p<0.01).

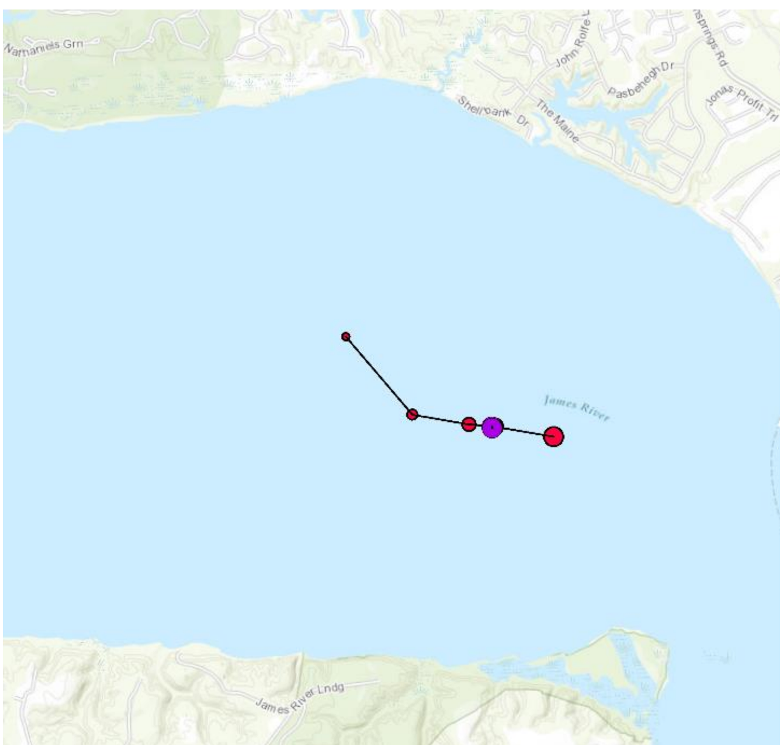

Figure 30. Pathway of a sub-adult that passed through the section of the channel at which the dredge was active at the time. The red icons and pathway represents the sub-adult's locations and the purple was the location of the dredge as determined by AIS.

Vita

Michael Ross Barber was born on March 18th, 1993 in Monroe County, Indiana and is an American citizen. He graduated Ocean Lakes High School, Math and Science Academy, in Virginia Beach in 2011, and later Virginia Commonwealth University in 2015 with B.S. degrees in both Biology and Chemistry. During undergraduate study, he volunteered with Dr. Jonathan Moore for VCU's long-term data collection on Prothonotary Warblers. During graduate study as a Master's student in Biology, he worked with Dr. Balazik and Dr. Garman on VCU's Atlantic Sturgeon project including sampling for adults with gill-netting, sampling for juveniles with trawling and gill-netting, and analyzing spatial data collected through VEMCO acoustic telemetry. He also assisted with other research work in the Fish Ecology lab at VCU when available. For three semesters, he worked as a teaching assistant for the Department of Biology, teaching two semesters of Introduction to Biology Lab, I and II, and one semester of Vertebrate Natural History Lab.