Report on the status of restored oyster reefs in the Loxahatchee River Estuary, Florida: nine years post-construction

2019 Assessment

Prepared by:

Jerry L. Metz

January 2021

Loxahatchee River District (LRD)
WildPine Ecological Laboratory
(561) 747-5700
www.loxahatcheeriver.org

Table of Contents

List of Figures ………… 3

List of Tables ………… 3

List of Photos………… 4

Appendix, List of Maps………… 4

1.0 Introduction………… 5

1.1 Oyster Natural History………… 5

1.2 Oyster Reef Ecological Functions………… 5

1.3 Threats to Oyster Reefs… ………… 5

1.4 Loxahatchee River Estuary………… 5

1.5 Oyster Reef Restoration in the LRE………… 6

1.6 Monitoring the Progress of the Restored Reefs………… 7

2.0 Methods………… 8

2.1 Oyster Reef Sampling Sites………… 8

2.2 Random Sampling Point Selection………… 8

2.3 Field Data Collection………… 9

2.4 Data Processing and Calculations: Viability, Density, and Shell Length...... 10

3.0 Results………… 10

3.2 Oyster Density………… 10

3.3 Oyster Shell Length………… 11

4.0 Discussion………… 13

4.1 Oyster Reef Overview………… 13

4.2 What Have We Learned?………… 14

4.3 What Happened to Site 12 (N8)?………… 15

4.4 Restoration Reef Material Composition………… 15

4.5 An Historical Perspective………… 16

4.6 Conclusion………… 17

References………… 18

Appendix………… 19

List of Figures

Figure 1. *Map of the Loxahatchee River Estuary and its major components. Freshwater enters the estuary primarily through the Northwest Fork. Also shown are the North Fork, Southwest Fork, Indian River Lagoon, Lake Worth Creek, and the Jupiter Inlet, the estuary's connection to the Atlantic Ocean. Red arrow indicates region of oyster reef restoration work……………………………………………………………………….* 6

Figure 2. *Detailed section map of the Northwest Fork showing perimeter locations of the two NOAA oyster restoration reefs (Site 13 and Site 14) and the upstream and downstream Natural oyster reefs. Sampling data from the two Natural oyster reefs were combined and are treated as a single data set…….* 8

Figure 3. *Oyster viability as mean percentage of all oysters at each Reef that were alive. Error bars indicate 1 SE……* 10

Figure 4. *Mean density of live oysters (solid bars) and dead oysters (cross hatch bars) among the three oyster reefs. Error bars indicate 1 SE………………………………………………………………………………………………………* 11

Figure 5. *Mean oyster shell length (mm) for both live oysters (solid bars) and dead oysters (cross-hatch) at each Reef. Error bars indicate 1 SE……………………………………………..……………………………………* 11

Figure 6. *Histogram shows live oyster size class. Blue and red bars indicate Site 13 and 14 respectively and black line indicates Natural reefs. Size classes shown are inclusive of the size range below it; i.e. the size class 10 includes measurements between 5.1 and 10 mm. Box along the horizontal axis indicates size class range of average live oyster shell length among the three reefs. Natural reef n=996; Site 13 n=940; Site 14 n=631……………………………………………………………………………….……………………* 12

Figure 7. *Histogram shows shell length frequency distribution of dead oysters from the three reefs. Blue and red bars indicate Site 13 and 14 respectively and black line indicates Natural reefs. Box along the horizontal axis indicates size class range of average live oyster shell length among the three reefs. Size classes shown are inclusive of the size range below it; i.e. the size class 10 includes measurements between 5.1 and 10 mm. Natural reef n=124; Site 13 n=197; Site 14 n=170…………..* 13

List of Tables

Table 1. *Part of the sampling procedure was sample point selection based on relative size of site. Table below show size, number of potential sampling points, and number of points sampled for the fall 2019 assessment...* 8

Table 2. *Aggregate summary statistics for live oysters for Sites 13 and 14 for each assessment. First three columns show average among the sample plots (quadrats) for Viability (%), Density (m^2), and oyster shell length (mm). The fourth column shows the plot with the maximum average shell length (mm). The fifth column shows the measurement of largest individual shell length. The sixth column shows the value of the sample plot (quadrat) with the highest density. The 2019 assessment is shown in bold…* 16

List of Photos

Photo 1. Image *shows barge equipped with a long-arm excavator used to deploy shell material onto the oyster restoration sites during summer of 2010*……………………………………………………………….. 7

Photo 2. *Diver demonstrating oyster sample collection. Image shows orange marker buoy, 25 cm X 25 cm weighted quadrat, and collection bucket. Image taken at a natural oyster reef*………………………… 9

Photo 3. *Aerial view of Site 14 oyster restoration reef superimposed with reef boundary (red outline) and sample points color-coded with density of live oysters*…………………………………………………… 14

Photo 4. *The NOAA restoration reefs were created using sandstone rock and various seashells that were undesired components of a local beach renourishment project. Photos show oysters attached to different size pieces of sandstone rock which appeared to exhibit the best results for recruiting oysters*……………………………………………………………………………………………. 15

List of Maps

Map 1a. Oyster Viability; Natural Reefs……………………………………………………………….. 19

Map 1b. Oyster Viability; Site 13……………………………………………………………………….. 20

Map 1c. Oyster Viability; Site 14……………………………………………………………………….. 21

Map 2a. Live Oyster Density; Natural Reefs……………………………………………………………. 22

Map 2b. Live Oyster Density; Site 13…………………………………………………………………… 23

Map 2c. Live Oyster Density; Site 14…………………………………………………………………… 24

Map 3a. Dead Oyster Density; Natural Reefs…………………………………………………………… 25

Map 3b. Dead Oyster Density; Site 13………………………………………………………………….. 26

Map 3c. Dead Oyster Density; Site 14………………………………………………………………….. 27

Map 4a. Live Oyster Shell Length; Natural Reefs……………………………………………………… 28

Map 4b. Live Oyster Shell Length; Site 13……………………………………………………………… 29

Map 4c. Live Oyster Shell Length; Site 14……………………………………………………………… 30

Map 5a. Dead Oyster Shell Length; Natural Reefs……………………………………………………… 31

Map 5b. Dead Oyster Shell Length; Site 13…………………………………………………………….. 32

Map 5c. Dead Oyster Shell Length; Site 14…………………………………………………………….. 33

1.0 Introduction

1.1 Oyster Natural History

Oysters are a sessile bivalve mollusk that occupy the littoral zone of coastal ecosystems and are a structural keystone organism in the environments in which they occur. The oyster *Crassostrea virginica* (eastern oyster) occupies a wide latitudinal range that extends from St Lawrence River in Canada to Brazil in South America (Buroker 1983). The eastern oyster is the most common oyster found in the waters of southeast region of North America including both the east coast and gulf coast of Florida.

Like many oyster species, *C. virginica* primarily prefers polyhaline, or brackish, conditions formed by the tidal mixing of riverine fresh water and seawater that make up estuarine habitats. Analogous to coral reefs, *C. virginica* forms aggregate reefs formed by larval oysters settling on an existing hard substrate, often the shell of other oysters, where it begins to grow, eventually growing over the substrate upon which it settled. This cycle continues indefinitely with each spawning season so long as there is favorable water conditions and suitable substrate upon which to attach.

1.2 Oyster Reef Ecological Functions

Healthy, thriving oyster reefs fulfill several important ecological and economical functions. Oysters are filter-feeders and thus expansive reefs are capable of filtering large volumes of water which improves water quality. Because oyster reefs occur within the shallow littoral zone, they mitigate wave energy created by storms or passing boats thus reducing shoreline erosion. As a reef-forming organism, oysters also create habitat for numerous other organisms including crabs, shrimp, finned fishes, and many families of invertebrates (Jud and Layman 2020). Many of these organisms in turn become a food source attracting many economically important fishes (Yeager and Layman 2011). Additionally, oysters are consumed by humans thus forming a basis for an entire aquaculture industry.

1.3 Threats to Oyster Reefs

However, oyster reefs face many threats due primarily to effects associated with rapidly growing human populations near coastal regions where it is estimated that over 85% of oyster habitat has been lost in the past two hundred years (TNC 2020). Some of these impacts include altered salinity and other water quality impairments, armored shorelines, and increased boat traffic. To mitigate the loss of oyster reef habitat, many regional, state, and federal agencies as well as non-governmental organizations (NGO's) are enacting programs to either rebuild or restore lost reefs or to expand existing reefs into areas of favorable water quality for oyster growth. For example, reef restoration is occurring along Florida's Gulf of Mexico region including Pensacola Bay and Apalachicola Bay to revitalize imperiled oyster habitats (TNC 2020, FWC 2020).

1.4 Loxahatchee River Estuary

The Loxahatchee River watershed encompasses an area of approximately 435 km^2 which drains into a comparatively small (approximately 500 ha) highly dynamic estuary that located along Florida's east coast in northern Palm Beach and southern Martin Counties (McPherson *et al*. 1982, VanArman *et al*. 2005; Figure 1). The estuary is formed by the confluence of both the north fork and northwest fork of the Loxahatchee River, the southwest fork through which excess stormwater flows during flood control releases, the southern reach of the Indian River Lagoon (Jupiter Sound), the northern reach of Lake Worth Creek, and the Jupiter Inlet which is the estuary's natural connection to the Atlantic Ocean. Like many populated watersheds in Florida, the LRE has experienced many hydrologic alterations through the years to accommodate growth in urban development and agriculture. Historical records indicate these alterations effectively shifted the salinity gradient westward and upstream thereby changing regions in the estuary that were able to support healthy oyster reefs (VanArman *et al*. 2005).

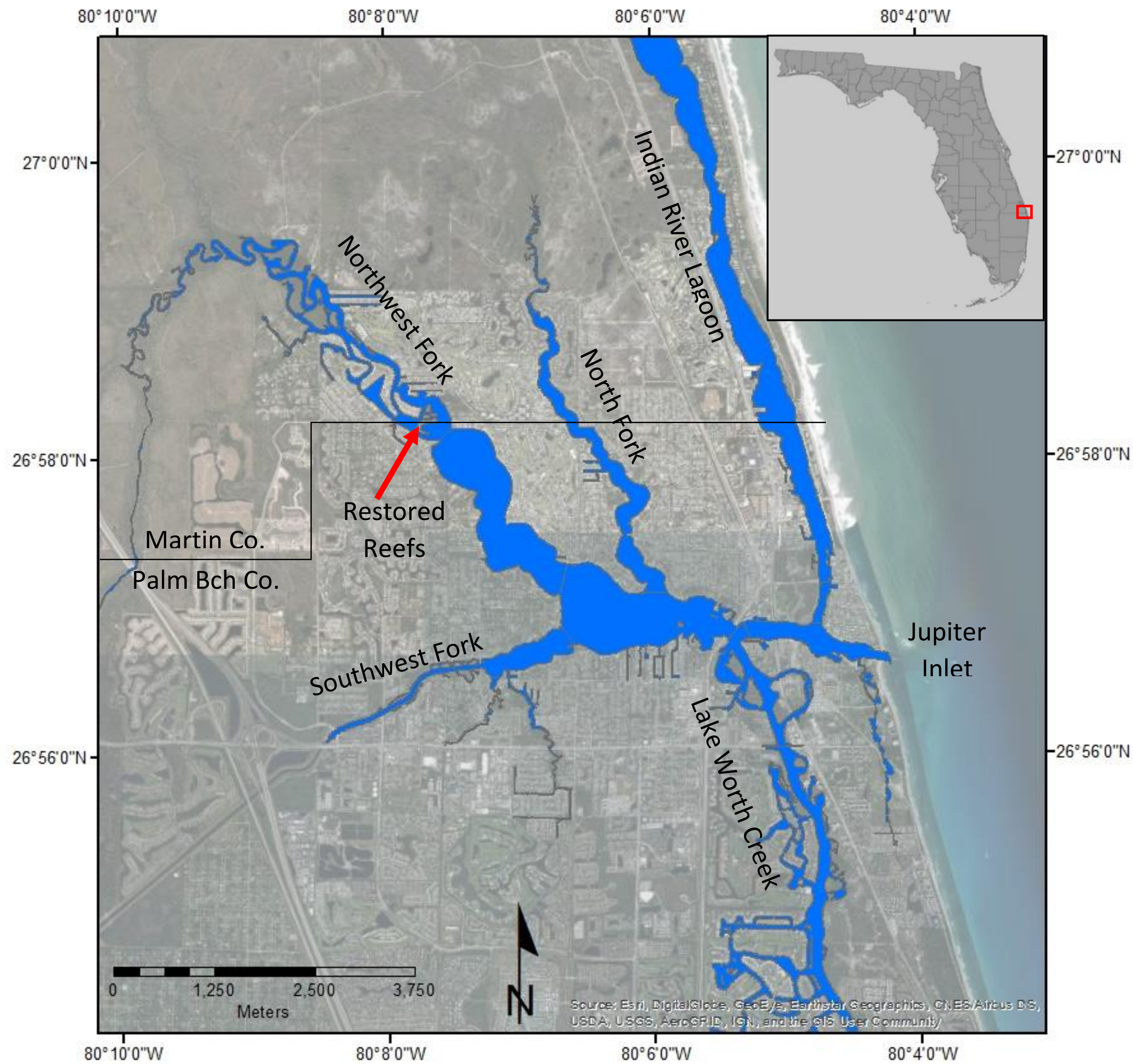


Figure 1. Map of the Loxahatchee River Estuary, Jupiter, Florida and its major components. Freshwater enters the estuary primarily through the Northwest Fork. Also shown are the North Fork, Southwest Fork, Indian River Lagoon, Lake Worth Creek, and the Jupiter Inlet, the estuary's connection to the Atlantic Ocean. Red arrow indicates region of oyster reef restoration work.

1.5 Oyster Reef Restoration in the LRE

Over the past century, the region of the river that once supported healthy oyster reefs has slowly shifted upstream in the northwest fork to its present location approximately 6.4 km (4 miles) from the inlet (region of red arrow shown in Figure 2). This short segment of the northwest fork is characterized as polyhaline (brackish water) with salinities ranging from near zero to marine depending on river flow and recent meteorological conditions. Some of the small islands in this region are composed of various mangrove species including red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), and white mangrove (*Laguncularia racemosa*), while other islands and nearby shorelines are characterized as residential homes with most accompanied by a dock extending from a mixture of hardened seawalls and mangrove shorelines. Despite the presence of extant oyster reefs in this region, there are large areas with no hard substrate suitable for oyster recruitment and growth.

Photo 1. Image *shows barge equipped with a long-arm excavator used to deploy shell material onto the oyster restoration sites during summer of 2010.*

During the late 2000's the Loxahatchee River District (LRD) and The Nature Conservancy (TNC) partnered on a pilot project to restore/create near-shore oyster reefs by deploying substrate consisting of bagged oyster shell beneath residential docks (Howard 2011). These reefs proved to be very successful and opened the way for broader oyster reef restoration projects. During the summer of 2010, the LRD in partnership with Martin County and other organizations collaborated to secure a grant from the National Oceanic and Atmospheric Administration (NOAA) through the American Recovery and Reinvestment Act of 2009. Through this funding, contractors used barges equipped with a long-arm excavator to deploy sandstone rock and shell material that was an unwanted by-product of a recent Palm Beach County beach nourishment project (see Howard 2011 for details). Once completed, the material created a total of 5.69 acres of new oyster reef substrate. The project resulted in two restoration reefs in the immediate vicinity of the healthiest naturally occurring oysters in the Northwest Fork, located approximately 6.4 km (4 miles) upstream from the Jupiter Inlet. Site 14 (26° 58.206'N, 80° 7.620'W), the larger of the two sites, was 4.75 acres (1.92 hectares) while the smaller Site 13 (26° 58.239'N, 80° 7.816'W) measured 0.94 acres (0.38 hectares). LRD conducted periodic assessments of the reefs to monitor the establishment and progress on a semiannual winter/summer schedule between 2011 to 2014, with single assessments conducted in 2016 and 2019.

1.6 Monitoring the Progress of the Restored Oyster Reefs

During the fall of 2019, researchers from the Loxahatchee River District revisited the restored reefs to assess the condition nine years after construction. The goal of this report is to assess key components of oyster presence such as presence, viability, density, and shell length and size class to gauge the current efficacy of the restoration efforts compared to nearby natural oyster reefs and examine changes that have been observed since construction. While there have been previous assessments of the reefs, the focus of this report is on the results of the assessment conducted during the fall of 2019. However, there is comparative references in the discussion to the prior assessments to put the results of this assessment into historical context. The data collection methods of all previous assessments are nearly identical to the 2019 assessment and provide valid historical reference for comparison.

2.0 Methods

2.1 Oyster Reef Sampling Sites

During the design and construction of the reef, a perimeter outlining the reef locations was developed (Figure 2). The same construction perimeter was used during assessments as a "soft" boundary for sampling. This report focuses on the two restoration reefs, Site 13 and Site 14 included in the NOAA funded reef construction project. Additionally, two smaller but healthy natural oyster reefs located nearby were selected to serve as background reference sites. The downstream natural reef (26° 58.373'N, 80° 7.687'W; "Natural DN" in Figure 1) is in close proximity to the two restored reefs while the upstream natural reef (26° 58.877'N, 80° 8.344'W; "Natural UP" in Figure 1), is located about 1.6 km (1 mile) upstream from the restored reefs. For the purposes of this report, the two natural reefs will be combined into a single dataset and referred to throughout text and figures as "Natural" reefs.

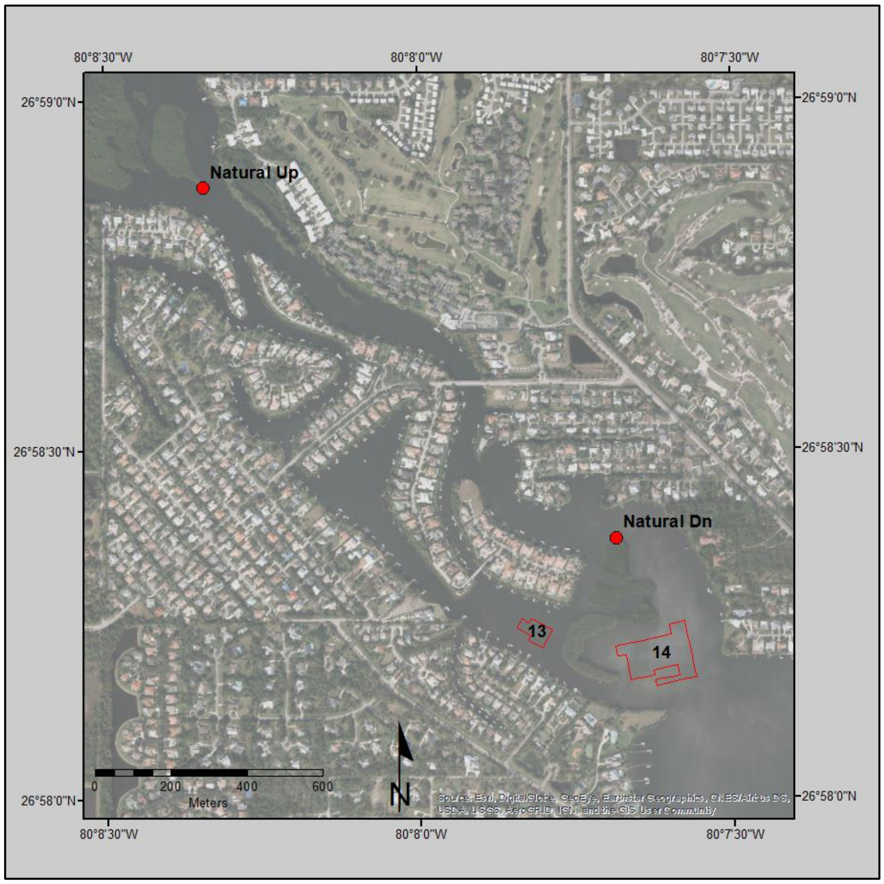


Figure 2. Detailed section map of the Northwest Fork showing perimeter locations of the two NOAA oyster restoration reefs (Site 13 and Site 14) and the upstream and downstream Natural oyster reefs. Sampling data from the two Natural oyster reefs were combined and are treated as a single data set.

2.2 Random Sampling Point Selection

Within each oyster reef, a point grid was created using the Fishnet feature of ESRI's ArcMap GIS software with points spaced 3.8 m (12.5 ft) apart and each point assigned a unique identification number. This resulted in an ample number of possible sample points from which to randomly choose. Table 1 below shows the sampling plan with the size of each reef and the number of randomly selected sample points.

The number of sample points chosen for each reef was based on the size (area) of the reef as well as available time and staff to conduct the sampling.

Table 1. *Part of the sampling procedure was sample point selection based on relative size of site. Table below show size, number of potential sampling points, and number of points sampled for the fall 2019 assessment.*

Site	Site 13	Site 14	Natural
Reef size (acres)	0.94	4.75	0.30
Total possible points	244	1336	89
Sampled Points	25	40	10

A web-based random sequence generator (www.random.org/sequences/) was used to randomly select the desired number of sample points from the pool of possible points shown in Table 1 that were to be assessed. Selected points were then uploaded to a handheld mapping-grade (sub-meter) GPS.

2.3 Field Data Collection

Sampling for the fall season was conducted during the month of September. This time period was chosen because our long-term oyster spat settlement data suggested that September occurs near the end of the peak annual oyster settlement season in the Loxahatchee and thus represent a high likelihood of encountering an abundant number of live oysters. For this assessment as well as previous assessments, the seasons were defined by the months in which the monitoring occurred. For example, “Winter” assessments included the months of February and March, while “Summer” assessments included the months of July and August. Because this assessment occurred in late September, later in the year than previous assessments, we labeled it “Fall” to avoid confusion.

Photo 2. D*iver demonstrating oyster sample collection. Image shows orange marker buoy, 25 cm X 25 cm weighted quadrat, and collection bucket. Image taken at a natural oyster reef.*

At the oyster sampling sites, the hand-held GPS was used to navigate to each sample point where a weighted buoy was deployed to mark the point’s location. Divers equipped with snorkeling gear placed a 25cm X 25cm weighted PVC quadrat over the marked location and excavated shell material inside the quadrat to a depth of 10 cm or until no reef material remained (Photo 2). Excavated material was returned to a nearby boat and examined by staff who measured and counted oysters that had settled on the material.

For an oyster to be measured and counted it had to either be alive (shell closed tightly) or dead with intact shell articulation (both halves present). Oysters shell length was measured (mm) from the shell hinge, to the most distal margin of the shell. Counts and measurements were recorded in the field on waterproof paper. For the two restored reefs, odd numbered sample points included shell length measurements for all live and all dead oysters while for even-numbered sample points, a sub-sample of the first ten live and first ten dead oysters were measured; the remaining oysters were simply counted as live or dead. This step was taken as a time saving measure. Shell length measurements were made for all intact oysters at the natural oyster reefs. Once assessed, all measured oysters and shell material were returned to their respective reef.

2.4 Data Processing and Calculations: Viability, Density, and Shell Length

This report examines three metrics of oyster presence and health including viability, density, and shell length. Viability is simply the fraction of oysters counted that were alive. Viability was calculated for each sample point by dividing the number of live oysters present by the total number of oysters collected at that sample point then multiplying by 100 to determine percentage. The viability reported for each oyster reef is the mean of all sample points that had oysters present. Sample points void of oysters were not included in the mean calculation.

Density is the number of oysters per m^2 and is determined by multiplying the count of both live and dead oysters from each 25cm x 25cm quadrat by 16 because the quadrat is $1/16^{th}$ of a square meter. This report presents the density of both live and dead oysters as an indicator of the overall health of the oyster reef. The reported density for each reef is the mean of all sample points and includes sample points that had no oysters present (i.e. zero).

The final metric examined in this report is oyster shell length of live and dead oysters. This report looks at two aspects of oyster shell length: mean oyster shell length and oyster shell length size class. The shell length (in mm) for live and dead oysters was averaged for each sample point. Then, the shell length for all sample points was averaged for each oyster reef and reported as the mean size for each reef. To examine shell length size class, a frequency distribution was determined at 5mm size intervals. Each 5mm interval is inclusive of the whole number and the oysters that fall into the increment below it; i.e. the 10mm size increment includes all oysters between 5.1 mm to 10 mm. A histogram for live and dead oysters shows visual representation of size class frequency distribution for each restoration site and for the Natural reefs.

In the appendix of this report are maps created in ESRI's ArcMap that show the locations of the individual sample points at each reef and are symbolized to reflect the viability, density, and shell length discussed in the text.

3.0 Results

3.1 General Observations and Viability

Oyster reef sampling occurred over three days between 9/19 to 9/27, 2019. A healthy population of live oysters was found at all oyster reefs, but live oysters were not found at all sample points. At Site 14, the largest of the restoration reefs, eight of the 40 sample points had no live oysters present, six of which completely devoid of substrate material (see Map 2c in Appendix), likely due to subsidence. All reefs had good viability (Figure 3) with Site 13 (82.9%; SD ± 12.9%) closely mirroring the Natural reef (85.8% SD ± 11.7%). Oyster viability at Site 14 was only slightly lower at 73.8% (SD ± 24.2%).

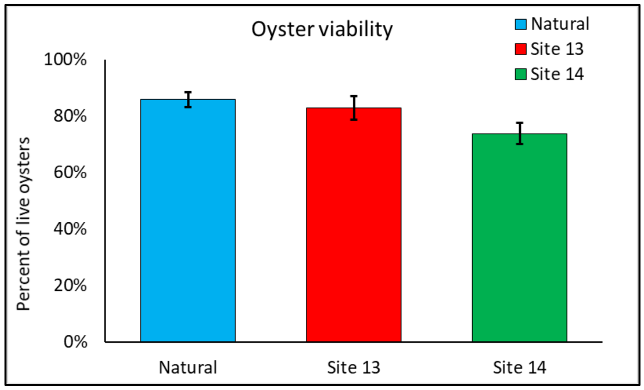


Figure 3. *Oyster viability as mean percentage of all oysters at each Reef that were alive. Error bars indicate 1 SE.*

3.2 Oyster Density

Oyster density was variable between the oyster reefs and among the sample points within each reef (Figure 4). The highest overall live oyster density was found at the Natural reefs where density was 1,517 oysters m^2 (SE ± 436, n=10). Live oyster density at Site 13 was also good and considerably less variable with 1,182 oysters m^2 (SE ± 97, n=25). Site 14 had the lowest live oyster density with 446 oysters m^2 (SE ± 108, n=40).

Density of dead oysters was substantially less than that of live oysters at all three oyster reefs (Figure 4). Mean density of dead oysters at the Natural reef was 198 oysters m^2 (SE ± 52, n=10) compared to the restoration reef Site 13 which had slightly more at 232 oysters m^2 (SE ± 41, n=25) and Site 14 which had the lowest dead oyster density of 79 oysters m^2 (SE ± 14, n=40).

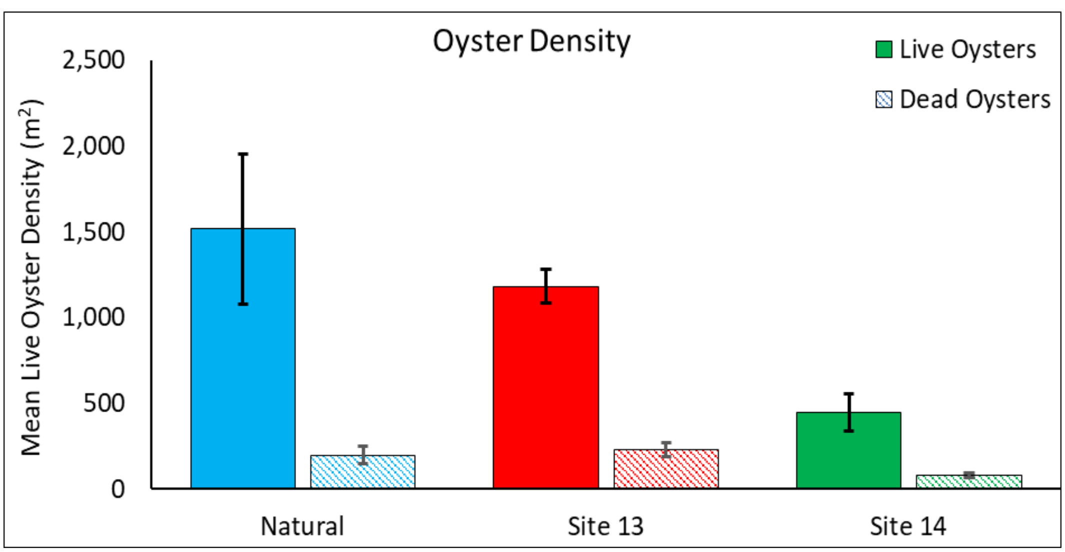


Figure 4. *Mean density of live oysters (solid bars) and dead oysters (cross hatch bars) among the three oyster reefs. Error bars indicate 1 SE.*

3.3 Oyster Shell Length

Live oyster shell length was somewhat uniform across the three oyster reefs (Figure 5). The Natural reef had a mean live oyster shell length of 25.7 mm (SEM ± 2.5, n=10) while the mean live oyster shell lengths of Site 13 and Site 14 were near identical at 30.9 (SEM ± 0.9, n=25) and 31.2 mm (SEM ± 1.7, n=40) respectively.

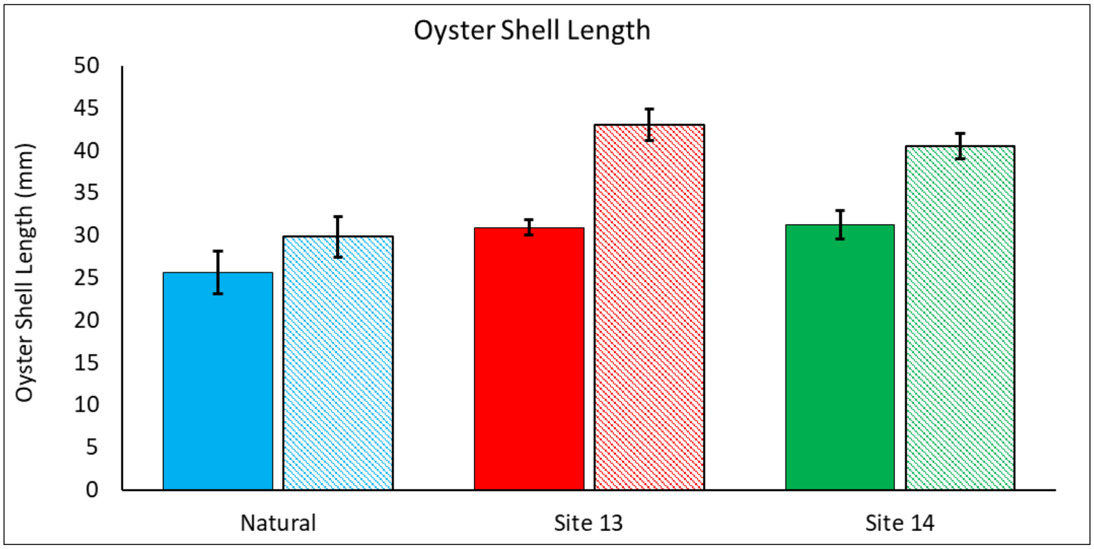


Figure 5. *Mean oyster shell length (mm) for both live oysters (solid bars) and dead oysters (cross-hatch) at each Reef. Error bars indicate 1 SE.*

A more interesting pattern in shell length emerges when the measurements of live oysters are examined by frequency distribution. There appears to be a bimodal frequency distribution of live oyster size classes representing at least two cohorts (Figure 6). The first group of most frequent size class includes oysters between 5 and 15 mm long and accounts for 31% of all measurements for each of the three reefs. The next frequency grouping is slightly less pronounced and includes oyster shell lengths between 35 and 45 mm and account for between 16% and 18% of all live oyster shell measurements. The range of mean live oyster shell lengths of all three reefs includes the size classes of 30 and 35 mm and accounts for between 12% and 18% of live oyster shell length measurements. Fewer than 1% of live oysters measured were larger than 75 mm; the generally recognized size of a "market" oyster. Incidentally, the largest live oyster measured at each reef was: Natural reef = 75 mm; Site 13 = 105 mm; and Site 14 112 mm.

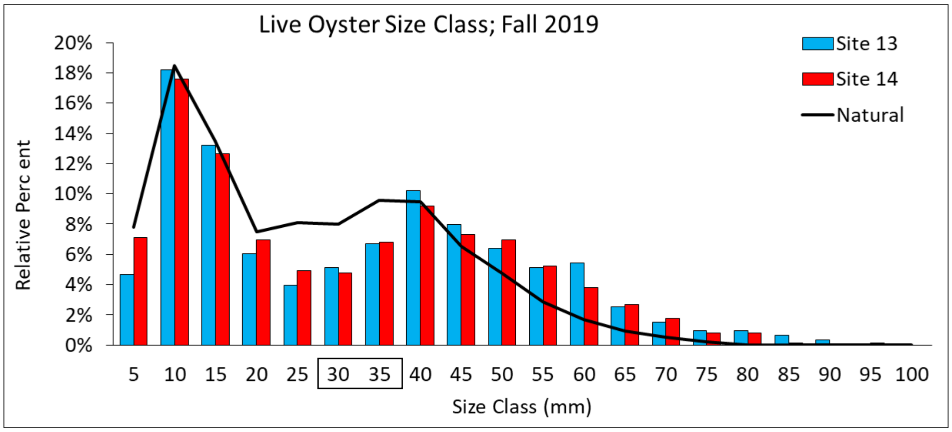


Figure 6. *Histogram shows live oyster size class. Blue and red bars indicate Site 13 and 14 respectively and black line indicates Natural reefs. Size classes shown are inclusive of the size range below it; i.e. the size class 10 includes measurements between 5.1 and 10 mm. Box along the horizontal axis indicates size class range of average live oyster shell length among the three reefs. . Natural reef n=996; Site 13 n=940: Site 14 n=631.*

The size frequency distribution for the dead shell length measurements differs considerably from that of the live oysters. There does not appear to be a well-defined bimodal distribution of shell length size classes as there was with the live oysters. This may be an artifact of the difference of measurements between live and dead oysters, or may be a function of the random size and age at death. The mean dead oyster shell length is very near the most frequently observed shell length (35 – 45 mm in figure 7). Also, there is a difference in the distribution between the Natural reef and the two restoration reefs. At the Natural reef, there tended to be greater number of smaller dead oysters than those measured at the restoration sites.

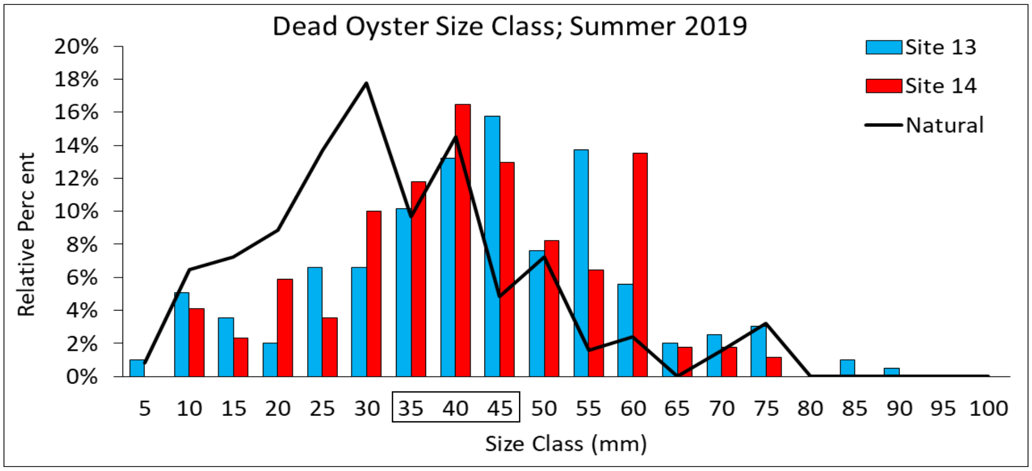


Figure 7. *Histogram shows shell length frequency distribution of dead oysters from the three reefs. Blue and red bars indicate Site 13 and 14 respectively and black line indicates Natural reefs. Box along the horizontal axis indicates size class range of average live oyster shell length among the three reefs. Size classes shown are inclusive of the size range below it; i.e. the size class 10 includes measurements between 5.1 and 10 mm. Natural reef n=124; Site 13 n=197; Site 14 n=170.*

4.0 Discussion

4.1 Oyster Reef Overview

Nine years after completion, the oyster restoration reefs continue to be productive. Both restored reefs support a healthy abundance of live oysters with a viability comparable to that of nearby natural oyster populations. Observations made at restoration Site 13 were especially encouraging where live oyster density was similar to that of the natural oyster reefs. The lower density observed at Site 14 was mostly due to lack of available shell material at several sample points. Since construction, some of the low-laying and thin layered substrate in portions of reef had either subsided, become buried, or a combination of both.

The observed difference in density between the two sites, and why some portions of Site 14 were bare, appears to be related to exposure to tidal currents and/or the thickness of the shell and rock layer deployed during construction. Site 14 is located in a region largely protected from direct tidal current except at the southern and eastern most edge of the reef which is adjacent to deeper channels subjected to tidal currents. It is possible that the decrease in tidal flow over the protected regions of this reef promotes sediment transport and deposition rates that outpaces upward growth of oyster recruitment, however more focused studies are needed. Site 13 on the other hand is located in a region of direct and swift tidal flow as noted by some of the divers who experienced difficulty working against the current. This was also the case at both natural oyster reef locations where the reef was exposed to direct tidal flow.

The size classes of the oysters observed at all sites was very encouraging. We saw two distinct shell length classes present at not only the restoration sites but also the natural reefs. Not only was this distribution pattern evident at all sites, the bimodal peaks at all sites represented identical size classes. This is indicative of continued oyster spawning and recruitment in this region of the Northwest fork of the river.

4.2 What Have We Learned?

As in any restoration effort, there are lessons learned through subsequent monitoring. One key observation made very early on was that substrate placed in proximity to naturally occurring oysters, and areas with good water quality, seemed to attract new oysters that settled and begin to grow rapidly following substrate deployment. During the 2011 assessment, six months following reef completion, the reported density for Site 13 and Site 14 was already 782 and 549 oysters m^2, with an average shell length of 31 mm and 25 mm respectively and several samples at each site had density over 1,000 oysters m^2. By 2019, 76% of sample points at Site 13 had density greater than 1,000 oysters m^2 with several over 2,000. By contrast, only 13% of samples at Site 14 had density greater than 1,000, but interestingly, half of those were also greater than 2,000 and, in fact, had the single densest sample between the two sites with 2,960, suggesting that regions within Site 14 where suitable substrate remained were still highly productive. Evidence of this can be seen in Photo 3 which is an aerial photograph of Site 14 taken during a period of exceptionally clear water in January 2019. From this image the regions less susceptible to sediment deposition can be identified as comparatively darker areas of oyster reef which are located near the channel where influence of tidal current is most prevalent. Conversely, sparce or bare areas may be a result of a thinner layer of substrate material placed during construction, combined with slower growing and lower productivity because of lower current velocity, causing subsidence/burial to outpace growth.

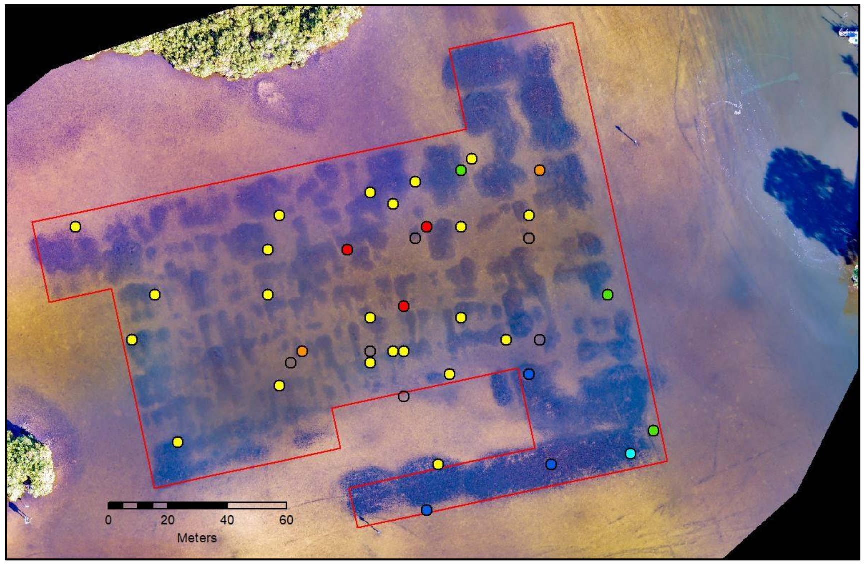


Photo 3. *Aerial view of Site 14 oyster restoration reef superimposed with reef boundary (red outline) and sample points color-coded with density of live oysters.*

Concurrent with early oyster reef monitoring conducted by the Loxahatchee River District, Jud and Layman (2020) investigated the colonization of macrofauna (crabs, shrimps, etc.) to the new substrate. Additionally, they compared the survival of macrofauna and oyster growth along a vertical gradient to determine if vertical relief had any effect on the community structure. In short, the study concluded that within 20 months following reef construction, macro faunal biomass was comparable to nearby natural reefs. Furthermore, the study demonstrated that vertical relief played a critical role in improved oyster growth and reduced sedimentation. Reef topography in the form of several piles or segmented rows offering greater vertical relief as opposed to a flat bed should be an important consideration in future oyster reef restoration efforts, especially when sedimentation is a concern.

4.3 What Happened to Site 12 (N8)?

During initial reef construction in 2010, a small experimental reef was constructed about 1 km southeast of Site 14 (26° 57.775’N, 80° 7.304’W). This small reef was designated Site 12; earlier referred to as “Site N8” due to its proximity to the green channel buoy marked as N8 located on the site’s eastern boundary. This site measured approximately 10 m x 40 m covering an area slightly more than 0.1 acres (0.05 hectares). The purpose of this small experimental reef was to explore the potential efficacy of future restoration efforts in this region of the river. During the early phases of the reef, oysters had in fact settled and began to grow on this reef as evidenced in previous monitoring. However, with time, this reef succumbed to fine sediment deposition or subsidence and by 2016 was nearly completely buried under several centimeters of fine sediment. For this reason, this location was considered unsuitable for future oyster reef restoration work and was not part of the 2019 assessment.

4.4 Restoration Reef Material Composition

The restoration reefs were constructed from shell and rock by product from a local beach renourishment project that was composed of different material types often associated with swash-zone rubble commonly found on Florida’s beaches. Most of the material consisted of various sized seashells that ranged in size from about 1 cm up to about 10 cm. Additionally, amongst the shells were many sandstone rocks ranging in size up to about 15 cm (see Photo 4).

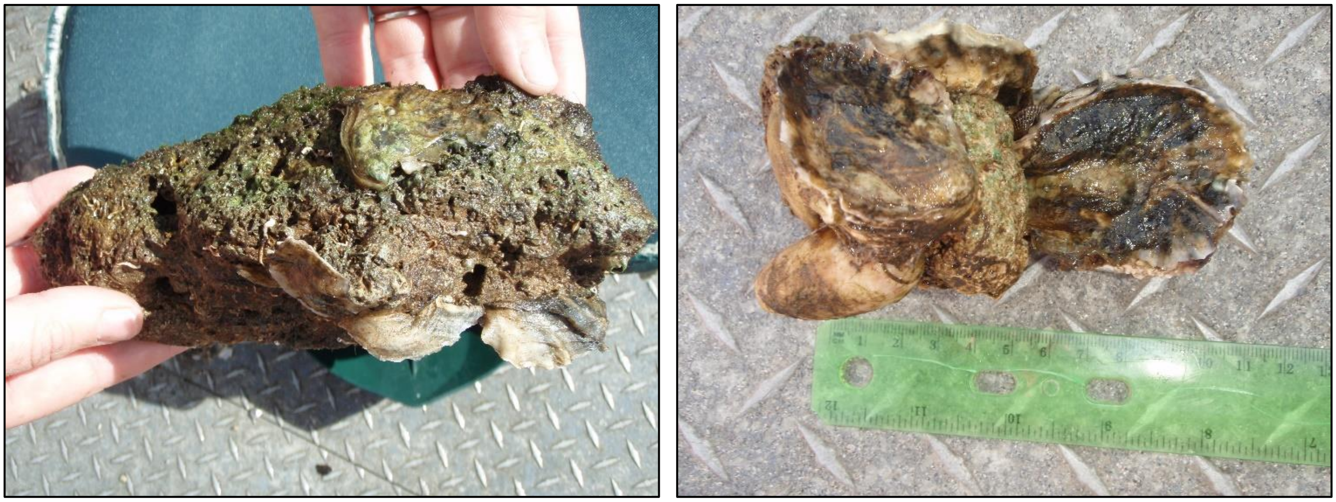


Photo 4. *The NOAA restoration reefs were created using sandstone rock and various seashells that were undesired components of a local beach renourishment project. Photos show oysters attached to different size pieces of sandstone rock which appeared to exhibit the best results for recruiting oysters.*

In the first reef assessments conducted during the early years following reef construction, it was noted that there was an apparent preference of material type that a disproportionate number of the oysters were settling and growing on. Most sandstone rocks of all sizes, especially the larger ones, seemed to have the highest number of oysters growing on them. Additionally, oysters were observed attached to the larger seashell material. However, oysters were seldom observed attached to seashells measuring smaller than about 2 cm.

4.5 An Historical Perspective

Prior to the assessment described in this report, there was periodic monitoring of these reefs. The restoration reefs were monitored semiannually during winter and summer beginning with the first assessment conducted during winter 2011 and continued through winter 2014 with a follow-up assessment during winter of 2016 (Table 2). During that time, the restoration reefs experienced changes in average viability, density, and shell length. For example, during the first assessment when the reef was only six months old, the reefs experienced the highest viability at 93.6%. Additionally, during the first assessment the reefs experienced among the highest average density at 650 oyster m^2 with not only the smallest average shell length (27.3mm) but also had the smallest maximum length individual shell length of all the assessments. These are expected characteristics of a newly constructed habitat. It appears that by one year following construction, the oyster reef had matured as the values for viability, density, and shell length fell within the range encountered throughout the nine years.

Table 2. *Aggregate summary statistics for live oysters for Sites 13 and 14 for each assessment. First three columns show average among the sample plots (quadrats) for Viability (%), Density (m^2), and oyster shell length (mm). The fourth column shows the plot with the maximum average shell length (mm). The fifth column shows the measurement of largest individual shell length. The sixth column shows the value of the sample plot (quadrat) with the highest density. The 2019 assessment is shown in bold.*

	Viability (%)	Avg Density (m^2)	Avg Shell Length (mm)	Max Avg Shell Length	Max Shell Length	Max Density
Winter 2011	93.6	650	27.3	37.1	70	1600
Summer 2011	92.5	641	35.6	47.6	80	1488
Winter 2012	53.4	258	39.4	52.5	83	736
Summer 2012	80.1	318	34.7	51.4	98	1264
Winter 2013	81.4	505	39.7	56.4	95	1648
Summer 2013	89.4	364	40.6	52.3	115	1248
Winter 2014	84.1	567	37.9	52.1	105	1968
Winter 2016	54.5	370	38.2	51.3	85	960
Fall 2019	**82.6**	**937**	**31.1**	**64.0**	**111**	**2960**

Data in Table 2 also shows the oyster reef's response to sudden mortality. The first example of this occurred sometime just prior to the winter 2012 assessment when average viability plummeted from 92.5% during summer 2011 to just 53.4%; the lowest viability we recorded. Additionally, the average density declined by 60% going from 641 oysters m^2 to just 258 oysters m^2; the lowest average recorded. However, by the next assessment 6 months later, viability had rebounded to 80.1% and average density began to increase thus demonstrating the reef's resiliency in rebounding following significant losses. This capability was demonstrated again when during the winter 2016 assessment viability had declined 34% to 54.5% and, once again, by this assessment had returned to 82.6% along with the highest average density and highest maximum density recorded. The value in these observations is that healthy oyster reefs, given optimal conditions and suitable substrate, can rapidly recover from substantial loss.

4.6 Conclusion

The results of this assessment indicate that the preparation and effort that went into restoring these oyster reefs was a worthwhile endeavor. We observed high density of oysters that were comparable to not only the natural oyster reefs, but also density observed in the initial assessment 6 months following construction. Also, the high number of new recruits to both reefs demonstrate the continued effectiveness of the reef. Based on the success of the NOAA funded reef restoration efforts discussed in this report and on the lessons learned through monitoring these reefs, it is our goal to explore future reef expansion into regions of the river where conditions are suitable for oyster settlement and growth. We offer this report as support for future oyster reef restoration and as guidance in materials and methods used in such construction. Constructing such reefs would certainly go a long way toward returning the valuable ecological services provided by such productive habitats.

References

Buroker, N.E. (1983). Population genetics of the American oyster *Crassostrea virginica* along the Atlantic coast and Gulf of Mexico. Marine Biology. 75: 99-112

Bachman, L.R., M.S. Ridler, and R.C. Dent. 2004. Distribution and viability of oyster communities in the loxahatchee River Estuary. Loxahatchee River District, 22 pp.

https://loxahatcheeriver.org/wp-content/uploads/2016/08/LRD_2003_OysterReport.pdf

Florida Fish and Wildlife Conservation Commission (FWC). (2020). FWC approves measures to support recovery and restoration of oysters in Apalachacola Bay.

https://content.govdelivery.com/accounts/FLFFWCC/bulletins/2b1695a

Howard, B. 2011. Loxahatchee River oyster reef restoration monitoring summary. Loxahatchee River District, 12pp.

https://loxahatcheeriver.org/pdf/LRD_OysterMonitSummary_2011.pdf

Jud, Zachary R., and Craig A. Layman. (2020). Changes in motile benthic faunal community structure following large-scale oyster reef restoration in a subtropical estuary. Food Webs 25 (2020) e00177

McPherson, Benjamin F., Maryanne Sabankas, and William A. Long. (1982). Physical, hydrological, and biological characteristics of the Loxahatchee River Estuary, Florida. US Geological Survey.

The Nature Conservancy (TNC). 2020. Oyster Reef Restoration.

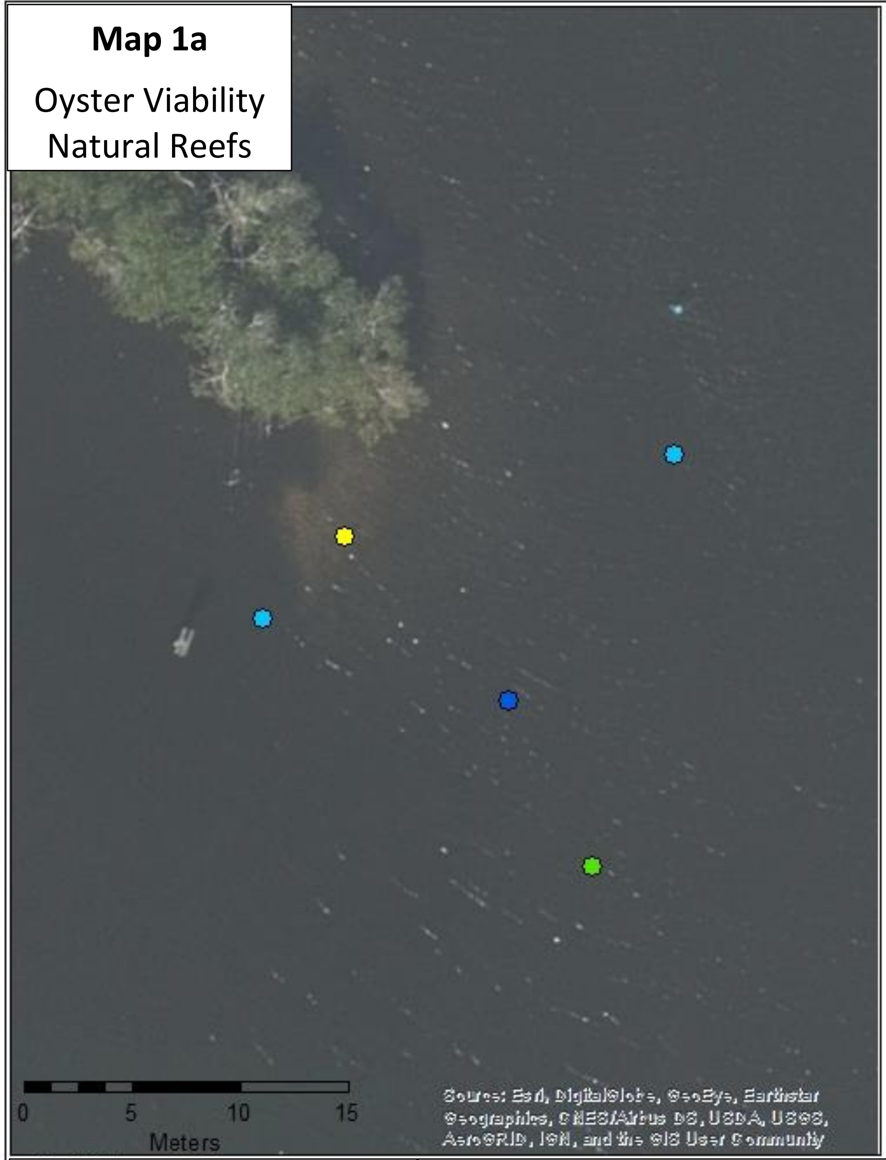
https://www.nature.org/en-us/about-us/where-we-work/united-states/florida/stories-in-florida/floridas-oyster-reef-restoration-program/

VanArman, Joel, Greg Graves, and Dana Fike. (2005). Loxahatchee watershed conceptual ecological model. Wetlands. 25 (4) 926-942

Yeager, Lauren A., Craig A. Layman. (2011). Energy flow to two abundant consumers in a sub tropical oyster reef food web. Aquatic Eco. 45 (2) 267-277

Map 1a

Oyster Viability
Natural Reefs



Viability of Live Oysters (% alive)

- 0
- 1 - 50
- 51 - 70
- 71 - 80
- 81 - 90
- 91 - 100

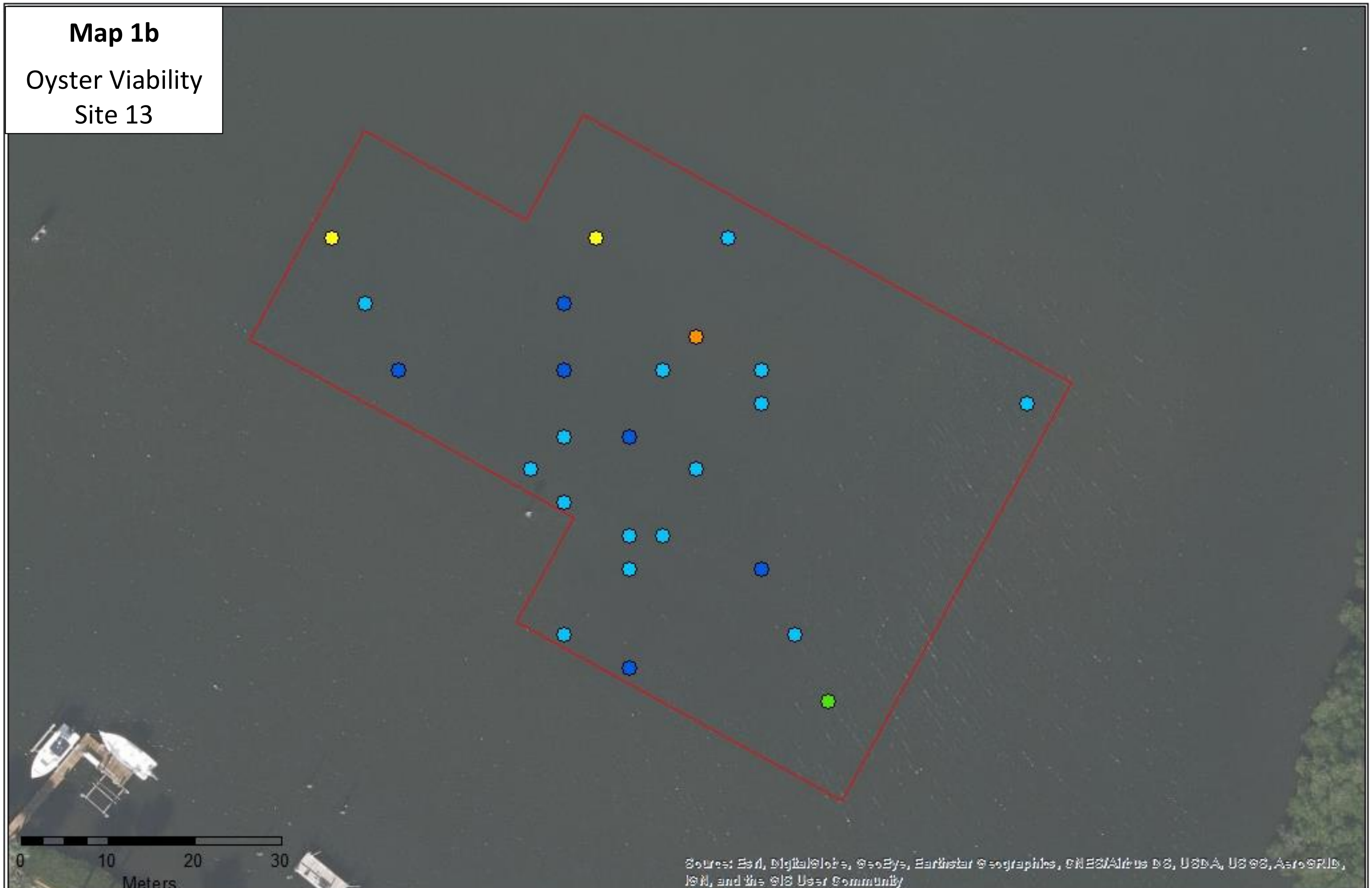
Oyster viability shown as the percentage of live oysters counted at each sample point at the upstream (left) and downstream (right) natural oyster reefs.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	(up) 26° 58.877'N, 80° 8.344'W (dn) 26° 58.373'N, 80° 7.687'W

N

Map 1b

Oyster Viability
Site 13



Viability of Live Oysters (% alive)

- 0
- 1 - 50
- 51 - 70
- 71 - 80
- 81 - 90
- 91 - 100

Oyster viability measured as the percentage of live oysters counted at each sample point at restoration reef Site 13. Red outline indicates approximate boundary of reef and sampling area.

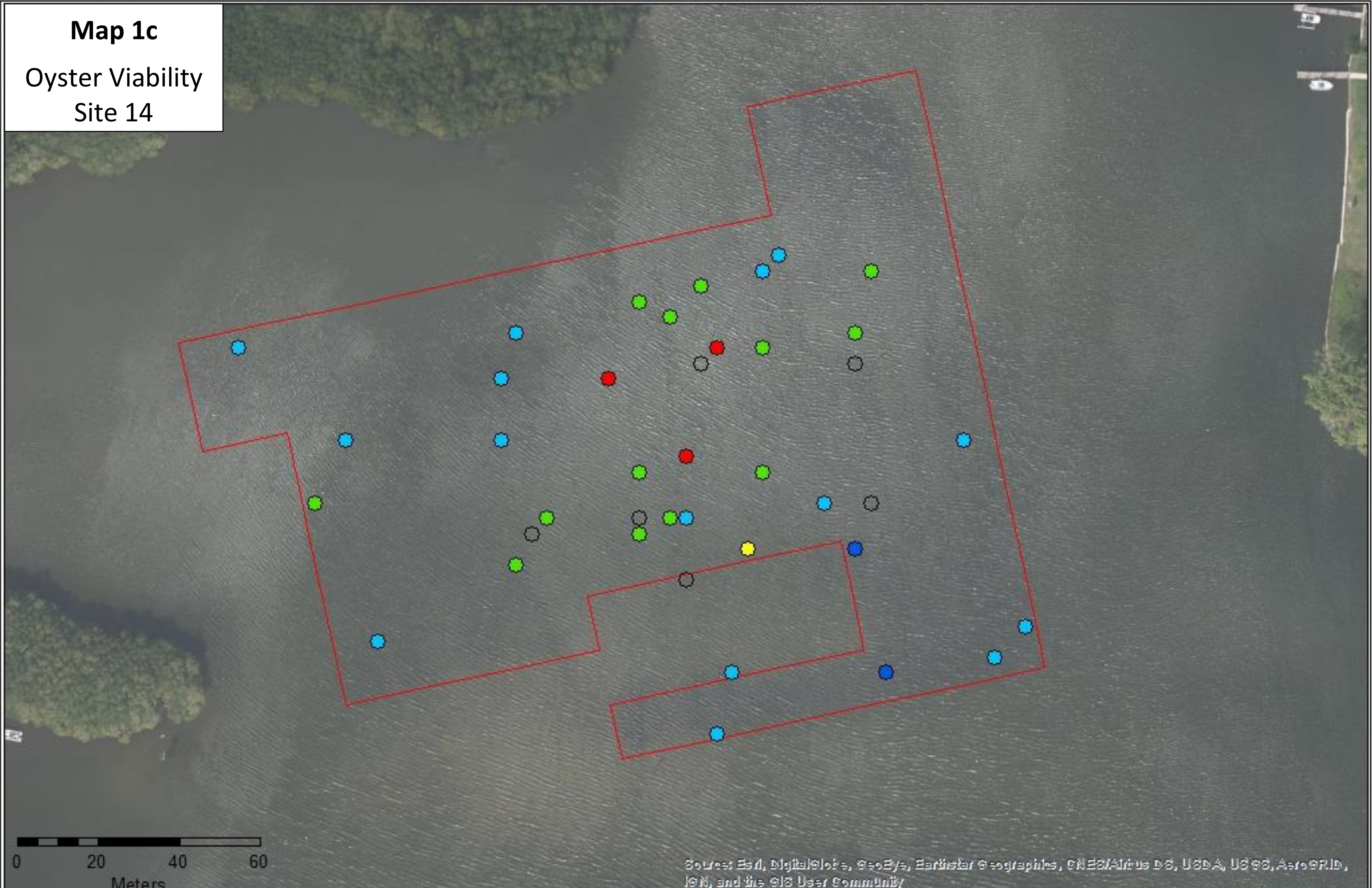
Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	26° 58.239'N, 80° 7.816'W

N

LOXAHATCHEE RIVER ENVIRONMENTAL CONTROL DISTRICT • 1971 •

Map 1c

Oyster Viability
Site 14



Viability of Live Oysters (% alive)

- 0
- 1 - 50
- 51 - 70
- 71 - 80
- 81 - 90
- 91 - 100

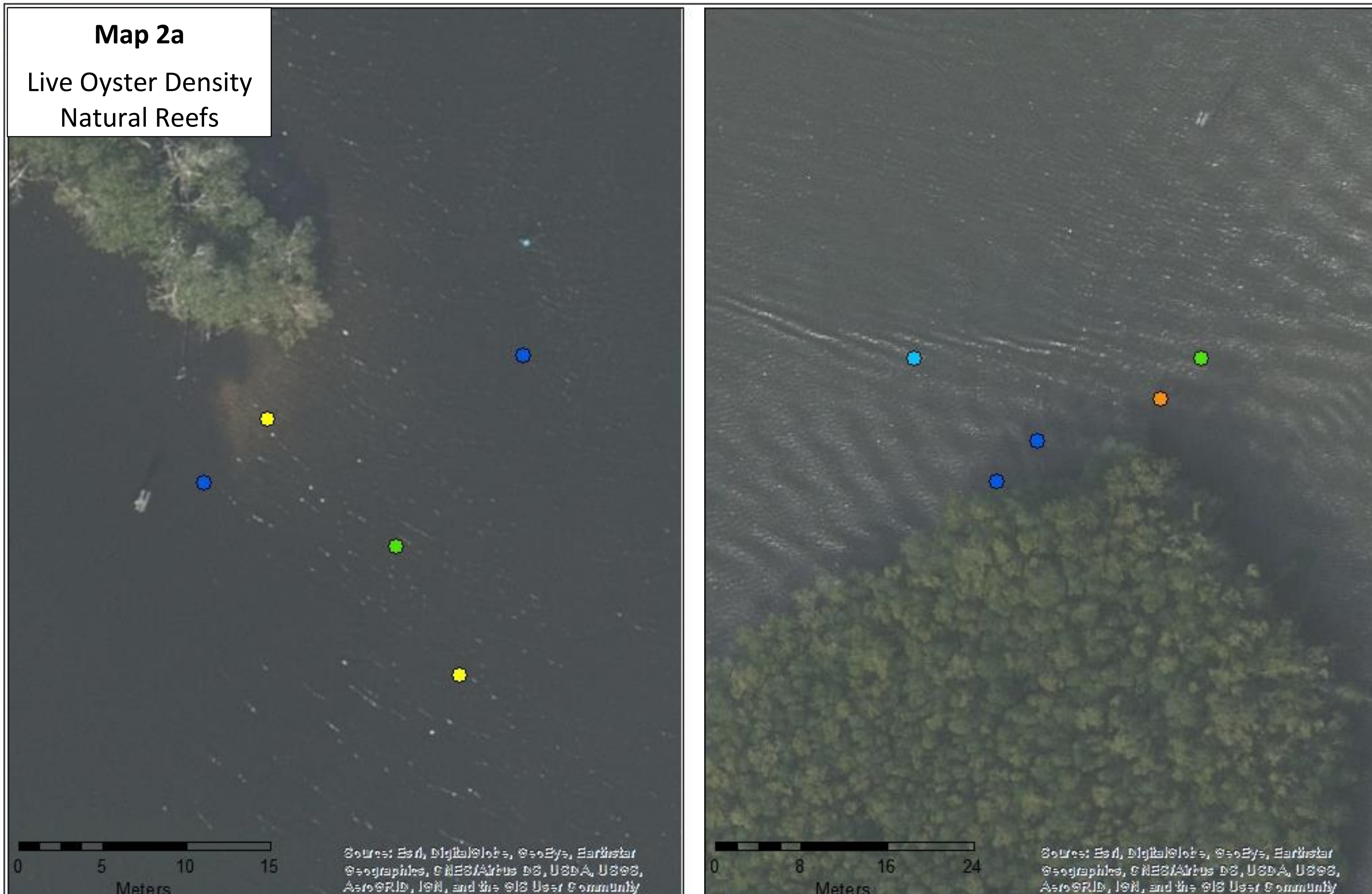
Oyster viability measured as the percentage of live oysters counted at each sample point at restoration reef Site 14. Red outline indicates approximate boundary of reef and sampling area. Empty circles indicate absence of substrate during sampling.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	26° 58.206’N, 80° 7.620’W

N

Map 2a

Live Oyster Density Natural Reefs



Mean Live Oyster Density (m2)

- 0
- 1 - 50
- 151 - 500
- 501 - 1,100
- 1,101 - 1,900
- > 1,900

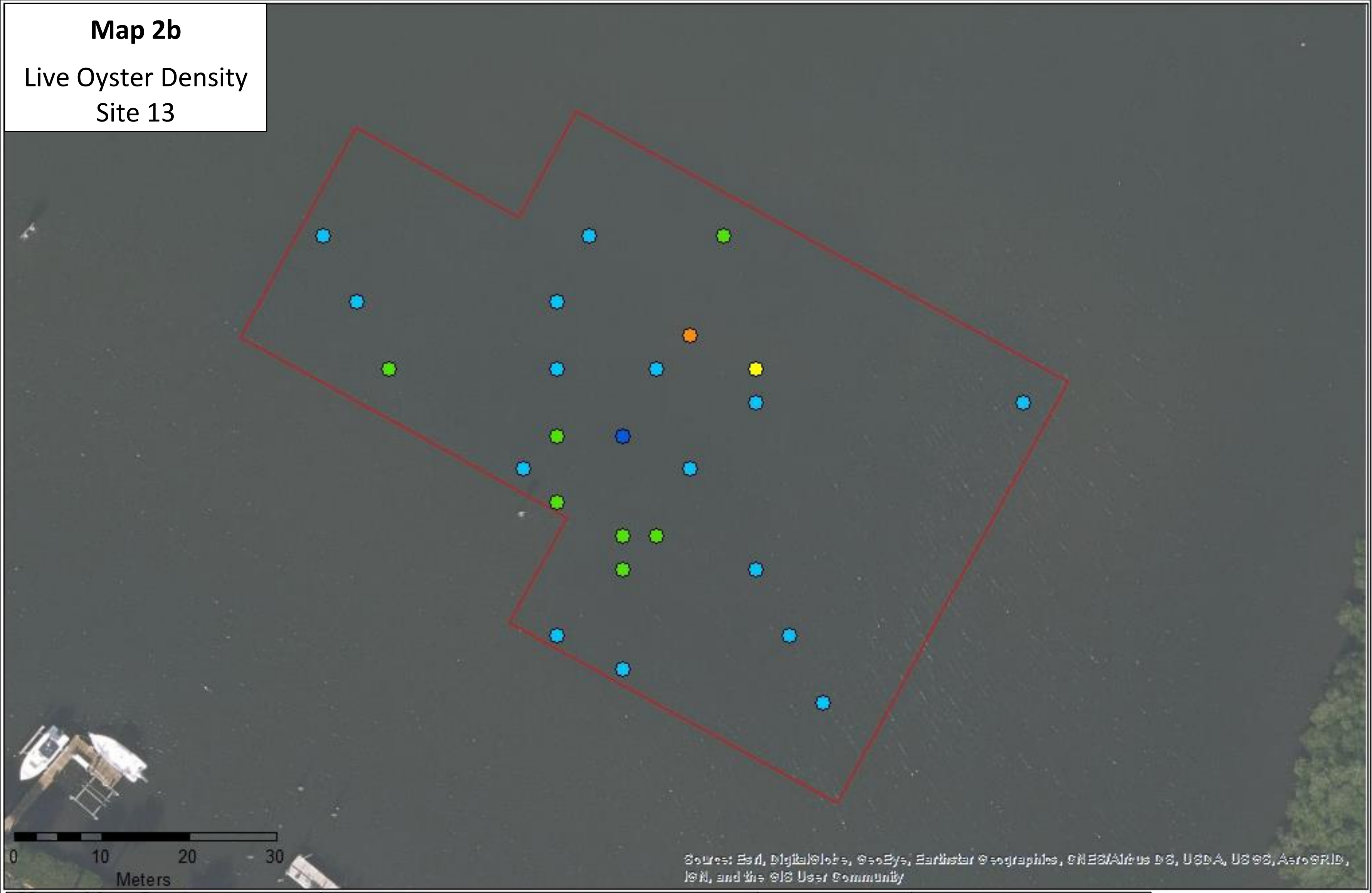
Mean live oyster density (per m^2) at the upstream (left) and downstream (right) natural oyster reefs.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	(up) 26° 58.877'N, 80° 8.344'W (dn) 26° 58.373'N, 80° 7.687'W

N

Map 2b

Live Oyster Density
Site 13



Mean Live Oyster Density (m2)

- 0
- 1 - 50
- 151 - 500
- 501 - 1,100
- 1,101 - 1,900
- > 1,900

Mean live oyster density (per m^2) at restoration reef Site 13. Red outline indicates approximate boundary of reef and sampling area.

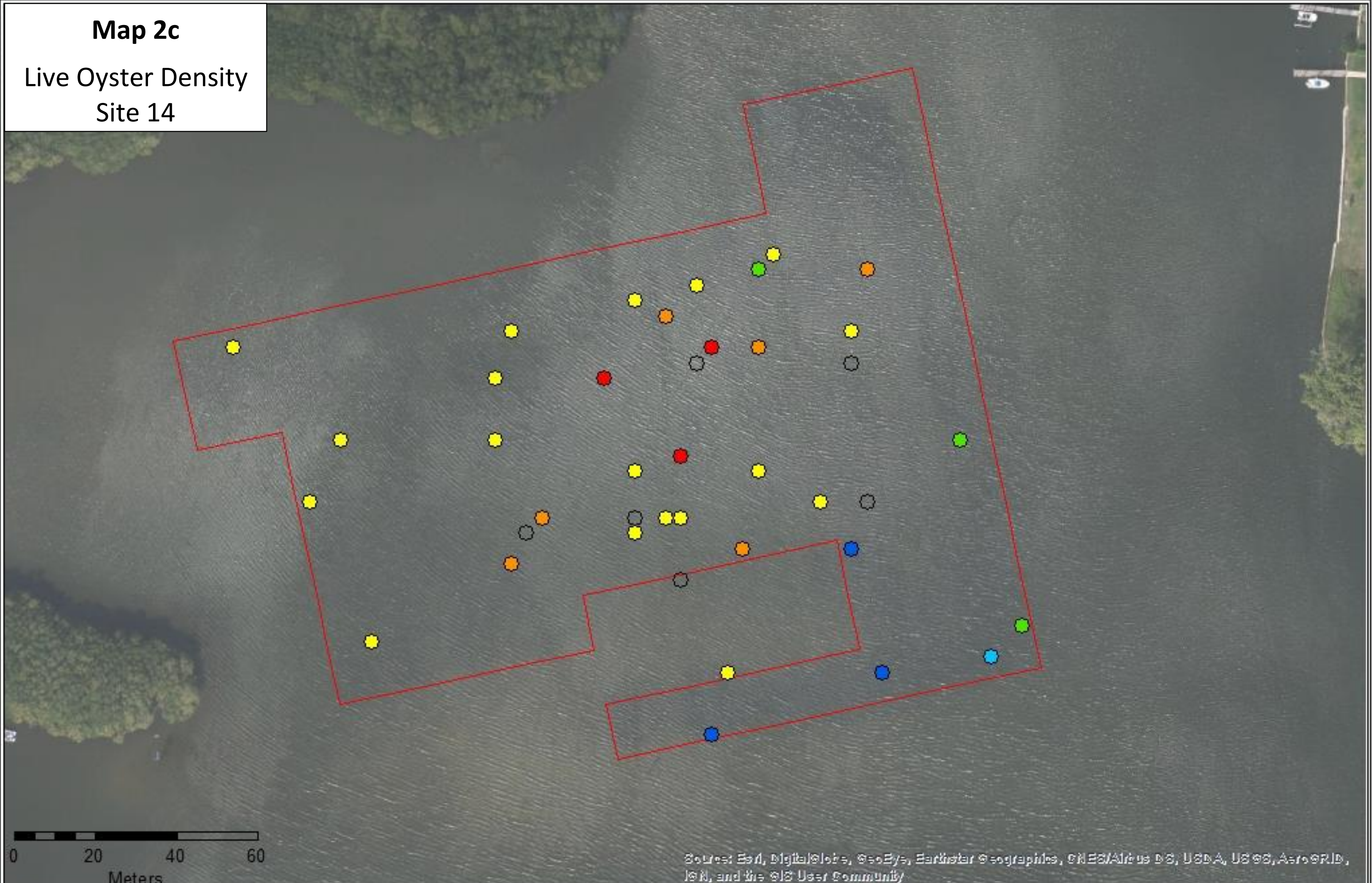
Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	26° 58.239'N, 80° 7.816'W

N

LOXAHATCHEE RIVER ENVIRONMENTAL CONTROL DISTRICT
1971

Map 2c

Live Oyster Density
Site 14



Mean Live Oyster Density (m2)

- 0
- 1 - 50
- 151 - 500
- 501 - 1,100
- 1,101 - 1,900
- > 1,900

Mean live oyster density (per m^2) at restoration reef Site 14. Red outline indicates approximate boundary of reef and sampling area. Empty circles indicate absence of substrate material during sampling.

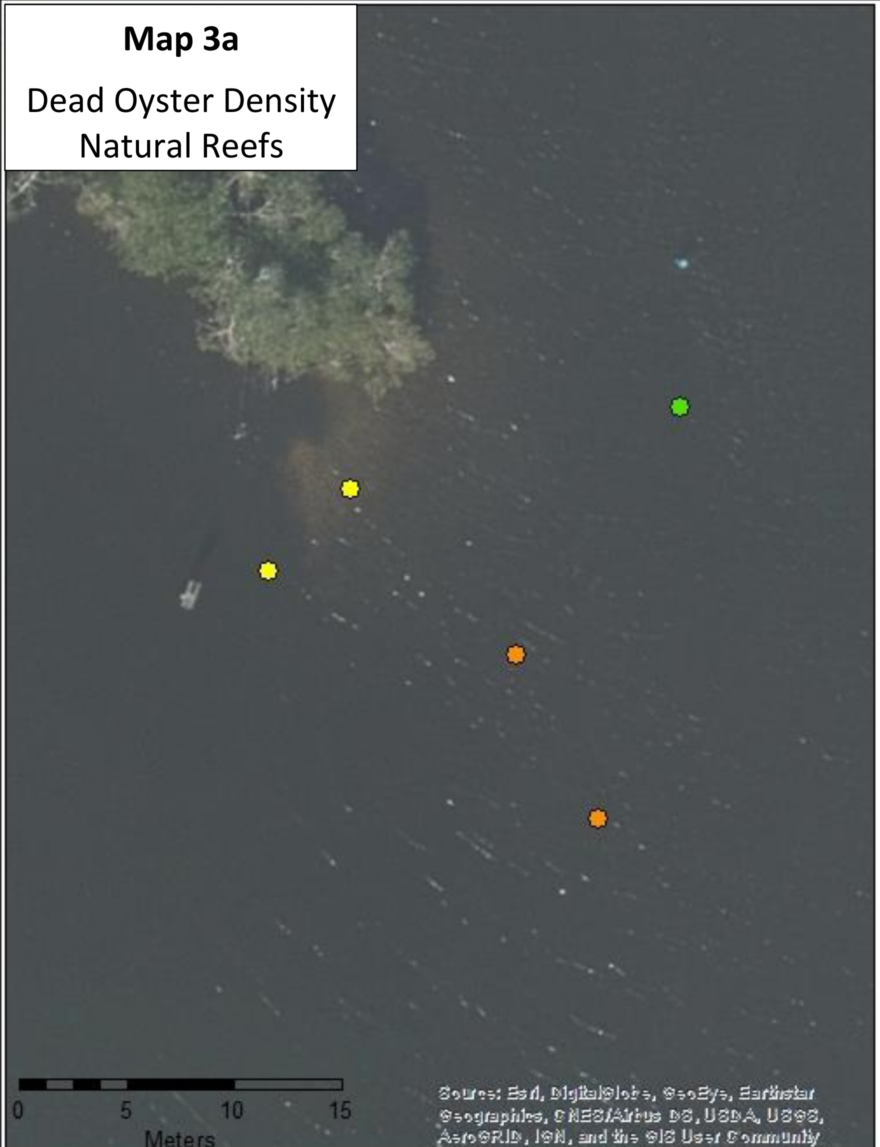
Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	26° 58.206’N, 80° 7.620’W

N

LOXAHATCHEE RIVER ENVIRONMENTAL CONTROL DISTRICT • 1971 •

Map 3a

Dead Oyster Density Natural Reefs



Mean Dead Oyster Density (m2)

- 0
- 1 - 50
- 151 - 500
- 501 - 1,100
- 1,101 - 1,900
- > 1,900

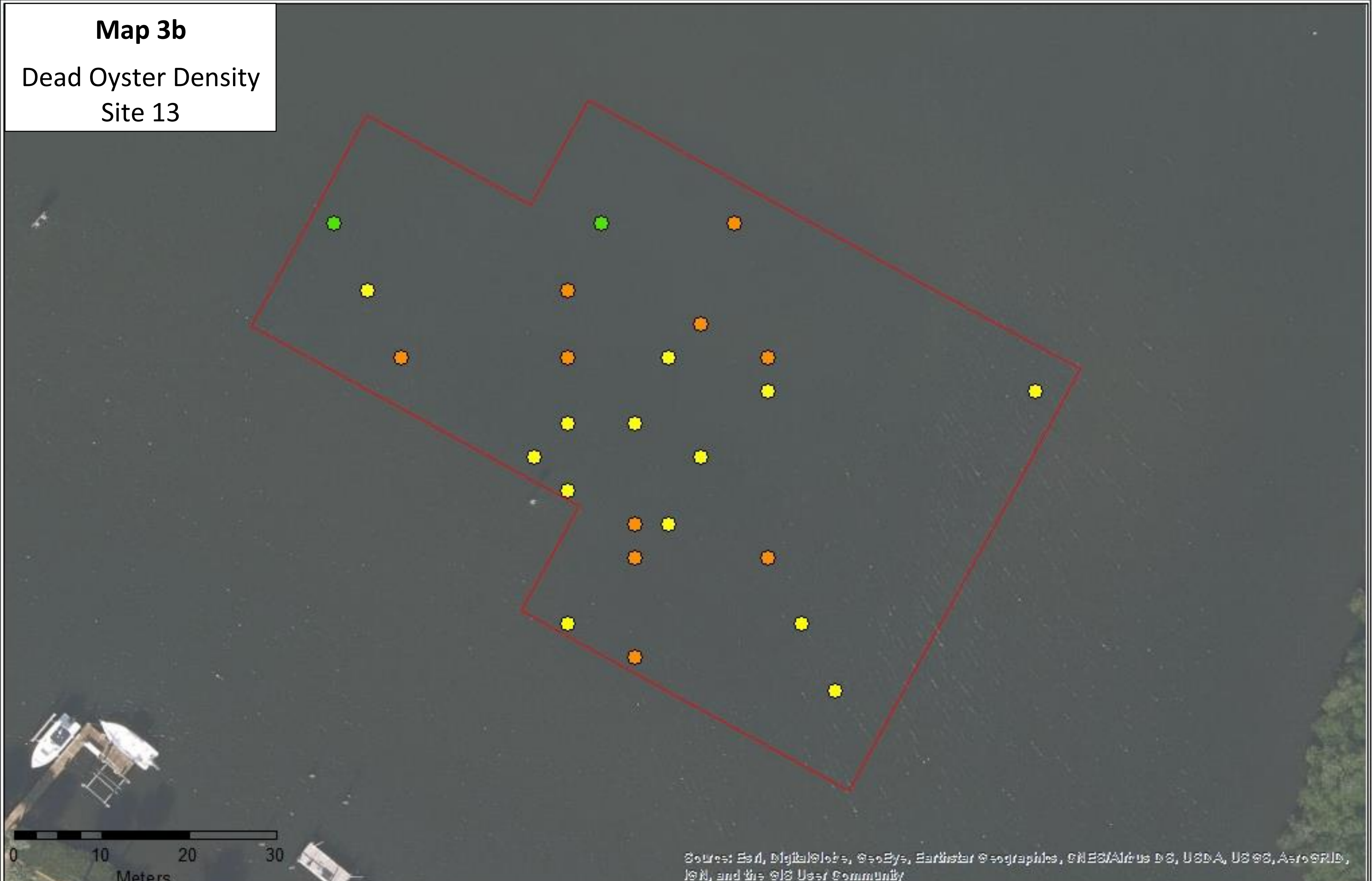
Mean dead oyster density (per m^2) at the upstream (left) and downstream (right) natural oyster reefs.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	(up) 26° 58.877'N, 80° 8.344'W (dn) 26° 58.373'N, 80° 7.687'W

N

Map 3b

Dead Oyster Density
Site 13



Mean Dead Oyster Density (m2)

- 0
- 1 - 50
- 151 - 500
- 501 - 1,100
- 1,101 - 1,900
- > 1,900

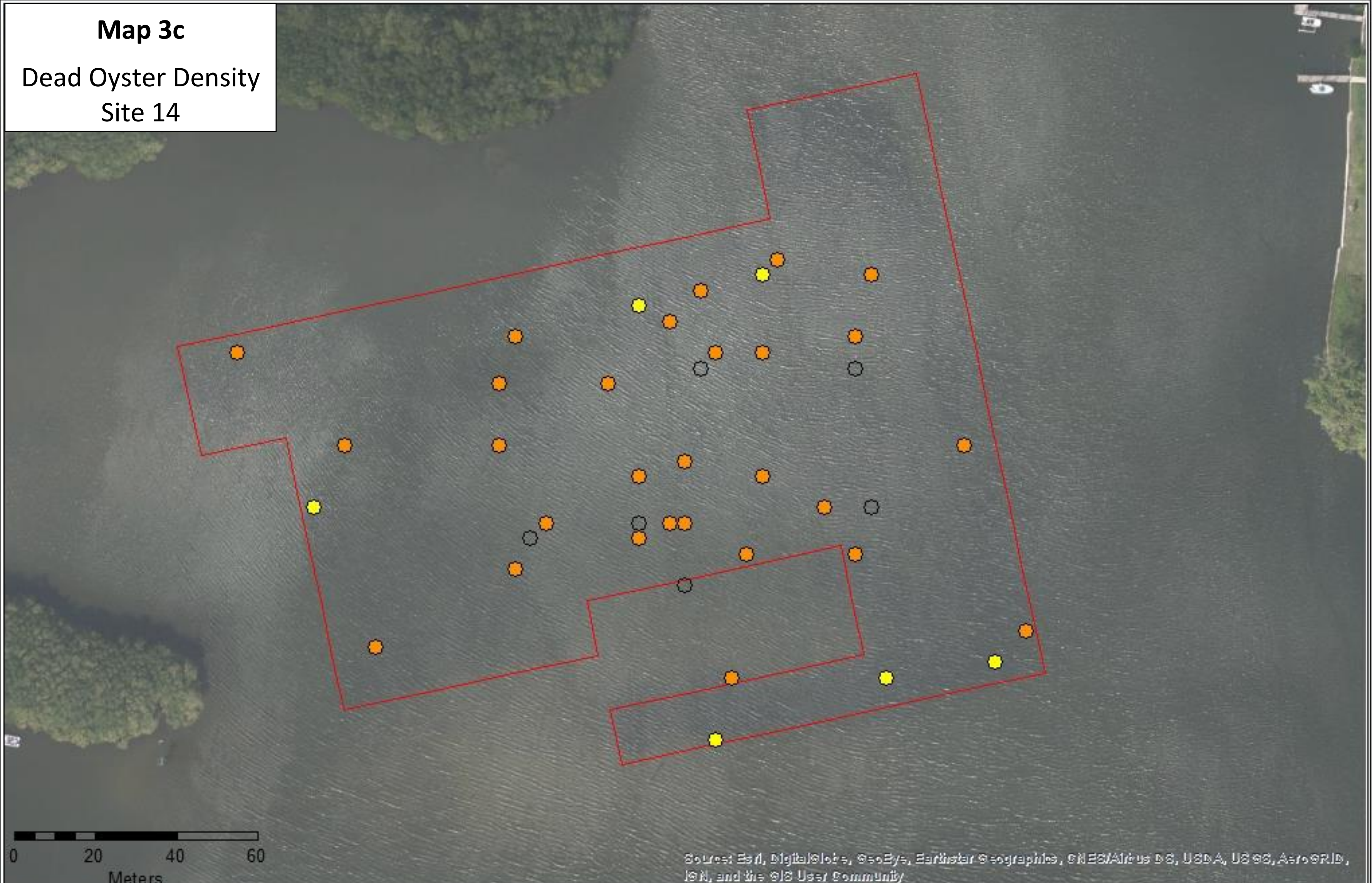
Mean dead oyster density (per m^2) at restoration reef Site 13. Red outline indicates approximate boundary of reef and sampling area.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	26° 58.239'N, 80° 7.816'W

N

Map 3c

Dead Oyster Density
Site 14



Mean Dead Oyster Density (m2)

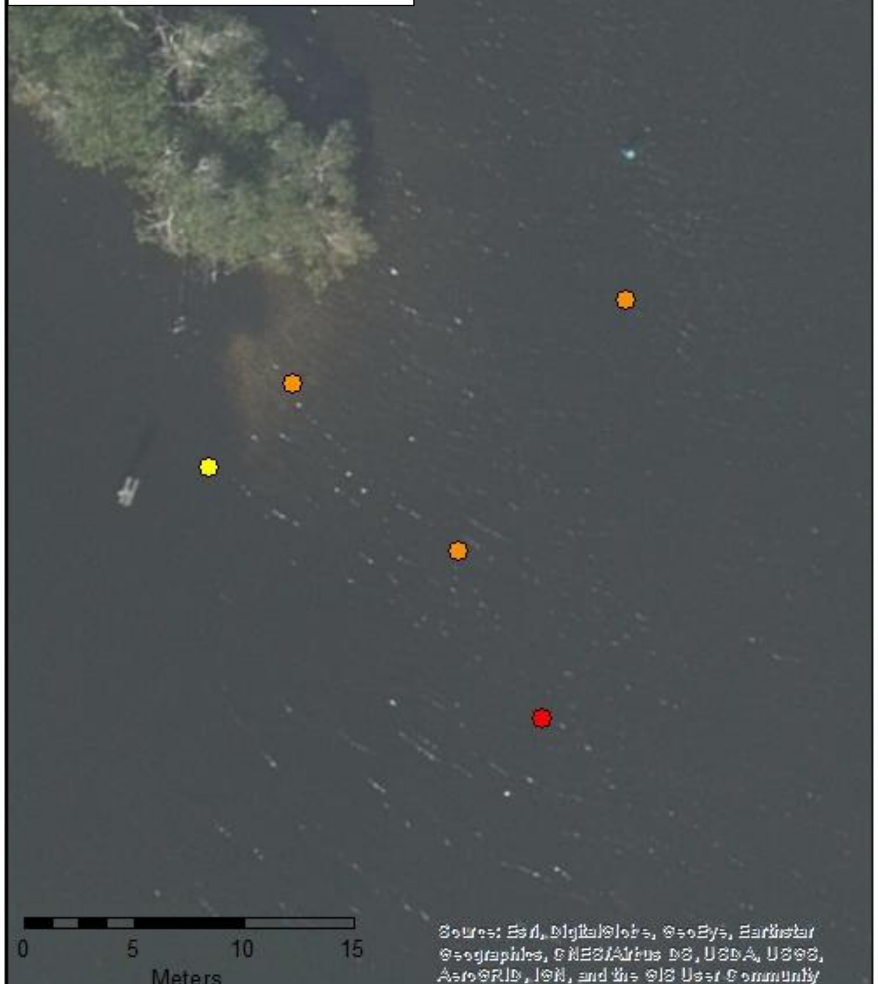
- 0
- 1 - 50
- 151 - 500
- 501 - 1,100
- 1,101 - 1,900
- > 1,900

Mean dead oyster density (per m^2) at restoration reef Site 14. Red outline indicates approximate boundary of reef and sampling area. Empty circles indicate absence of substrate material during sampling.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	26° 58.206'N, 80° 7.620'W

Map 4a

Live Oyster Shell Length
Natural Reefs



Mean Live Oyster Shell Length (mm)

- 13.9 - 20.0
- 20.1 - 25.0
- 25.1 - 30.0
- 30.1 - 35.0
- 35.1 - 40.0
- 40.1 - 64.0

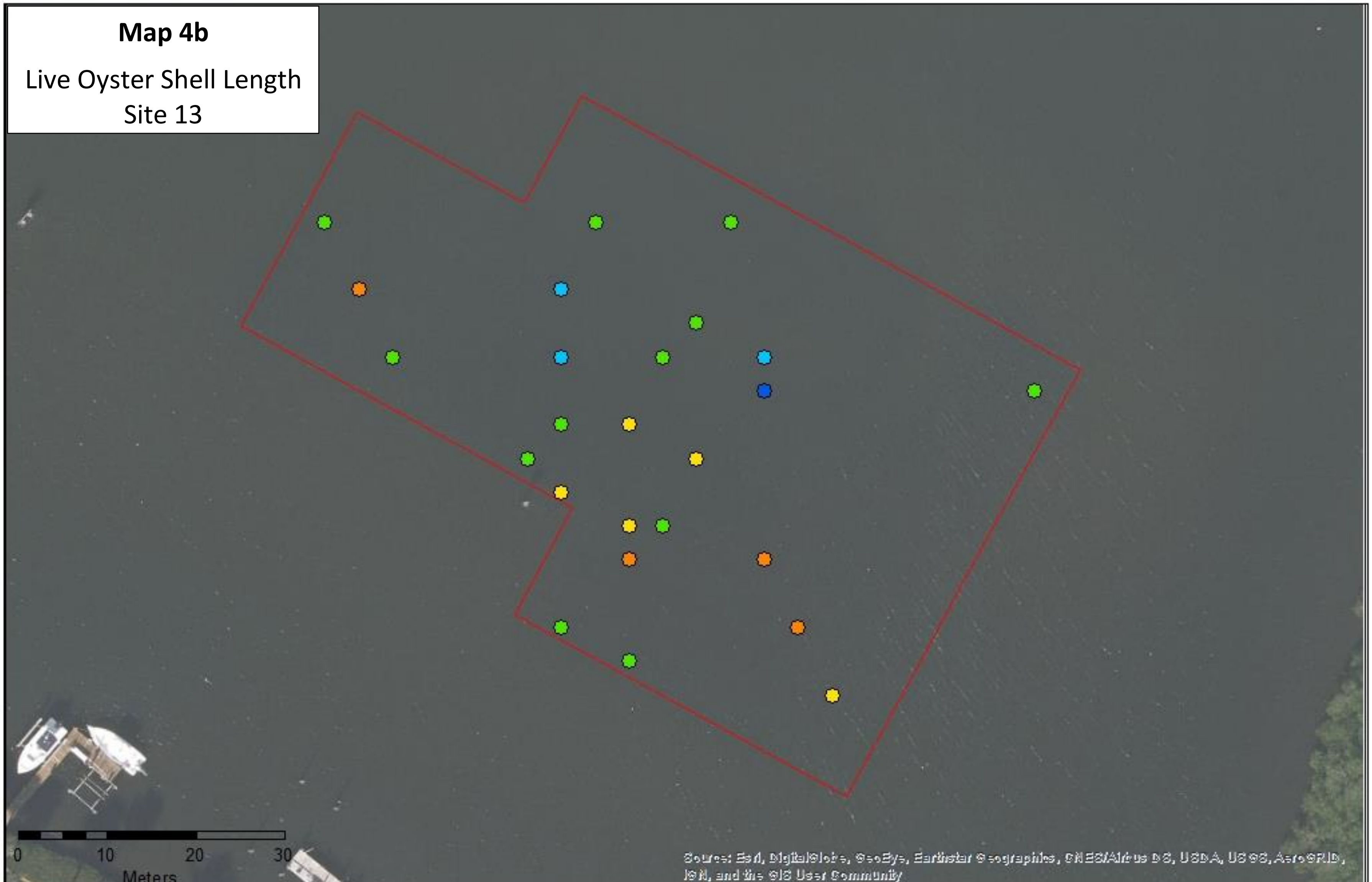
Mean live oyster shell length (mm) at each sample point at the upstream (left) and downstream (right) natural oyster reefs.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	(up) 26° 58.877'N, 80° 8.344'W (dn) 26° 58.373'N, 80° 7.687'W

N

Map 4b

Live Oyster Shell Length
Site 13



Mean Live Oyster Shell Length (mm)

- 13.9 - 20.0
- 20.1 - 25.0
- 25.1 - 30.0
- 30.1 - 35.0
- 35.1 - 40.0
- 40.1 - 64.0

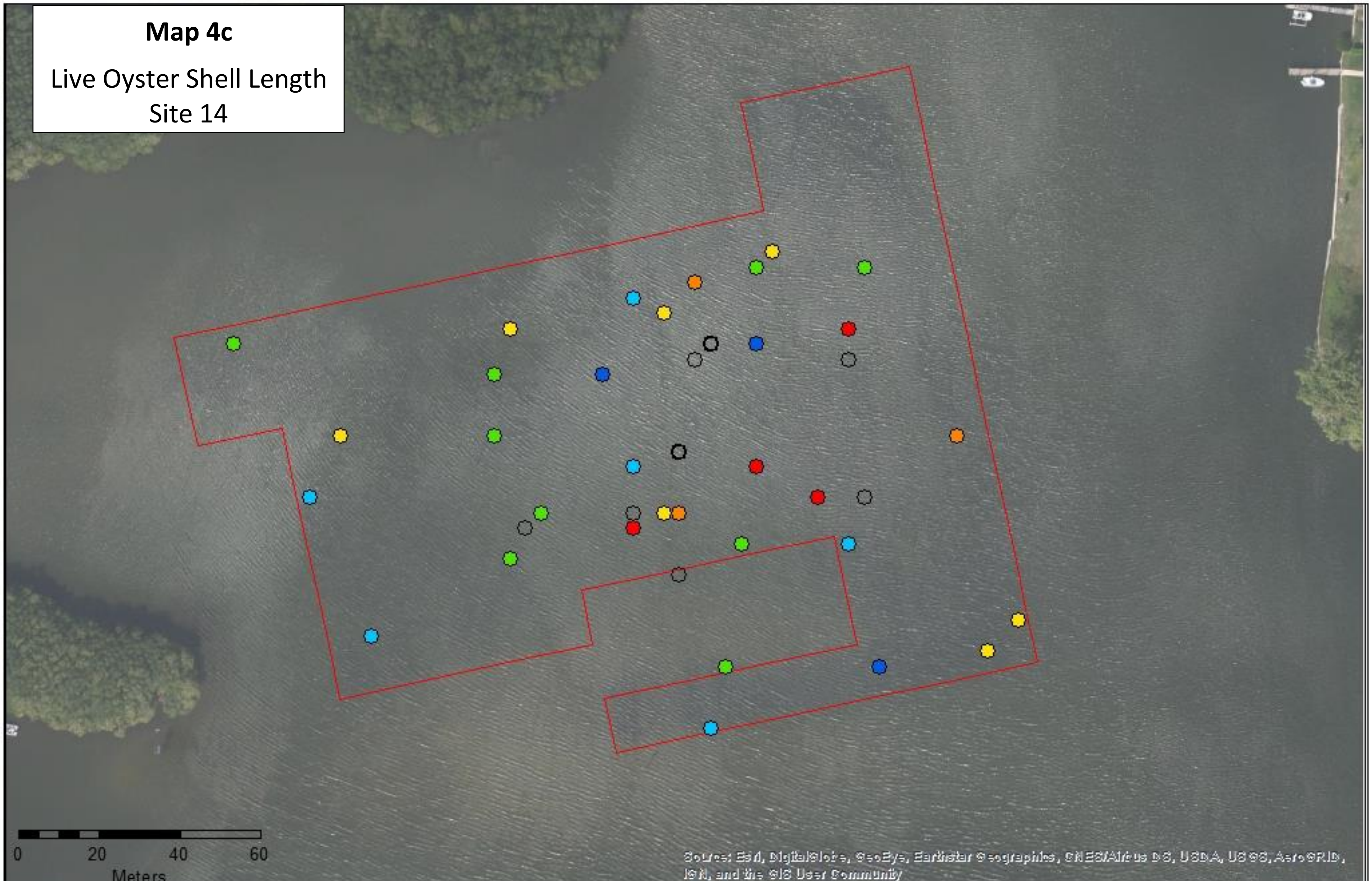
Mean live oyster shell length (mm) at restoration reef Site 13. Red outline indicates approximate boundary of reef and sampling area.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	26° 58.239′N, 80° 7.816′W

N

Map 4c

Live Oyster Shell Length
Site 14



Mean Live Oyster Shell Length (mm)

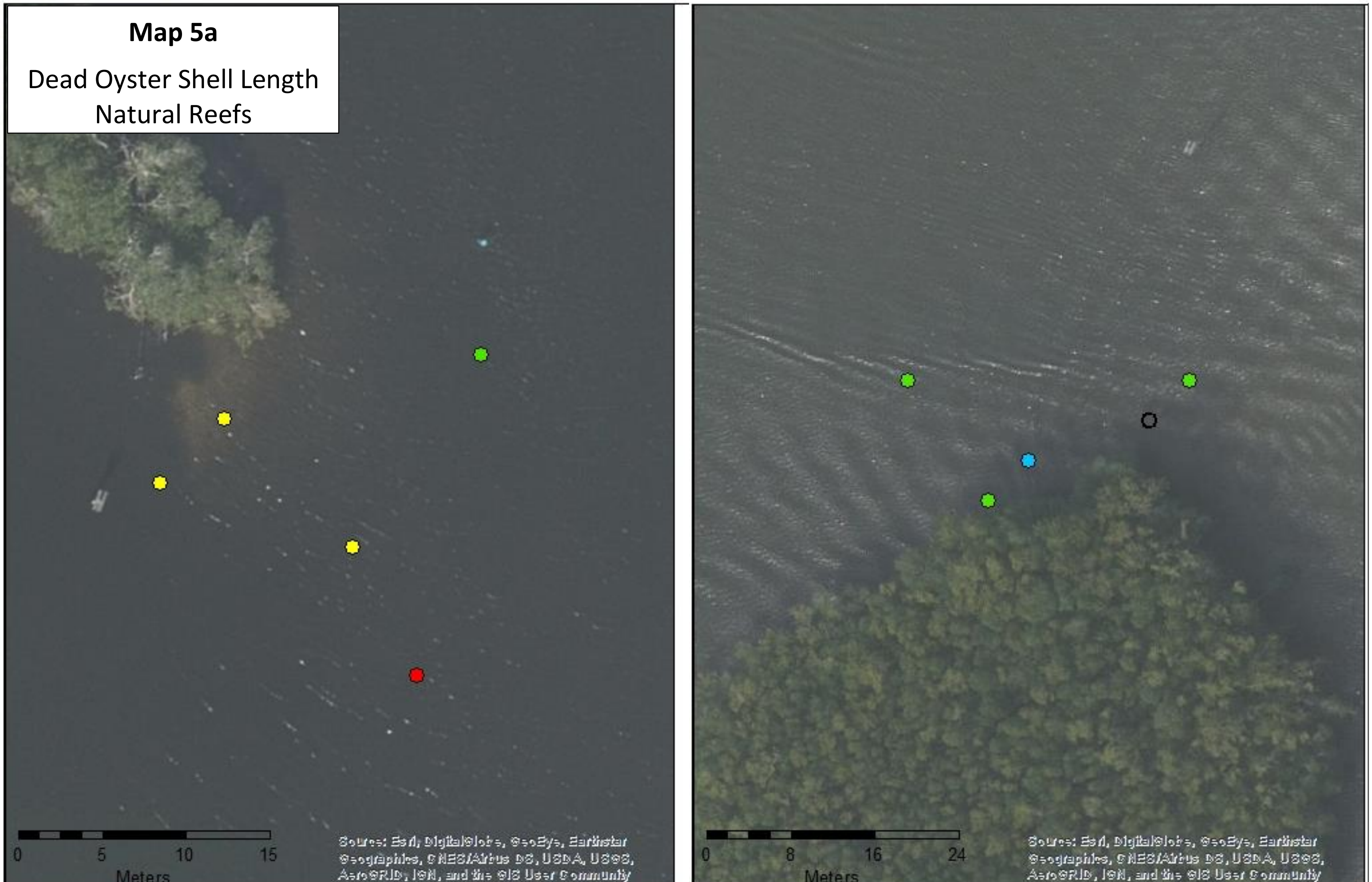
- 13.9 - 20.0
- 20.1 - 25.0
- 25.1 - 30.0
- 30.1 - 35.0
- 35.1 - 40.0
- 40.1 - 64.0

Mean live oyster shell length (mm) at restoration reef Site 14. Red outline indicates approximate boundary of reef and sampling area. Empty circles indicate absence of substrate material during sampling. Bold empty circles indicate presence of substrate material but no live oysters were present.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	26° 58.206’N, 80° 7.620’W

Map 5a

Dead Oyster Shell Length
Natural Reefs



Mean Dead Oyster Shell Length (mm)

- 13.9 - 20.0
- 20.1 - 25.0
- 25.1 - 30.0
- 30.1 - 35.0
- 35.1 - 40.0
- 40.1 - 64.0

Mean dead oyster shell length (mm) at each sample point at the upstream (left) and downstream (right) natural oyster reefs. Bold empty circle indicates presence of substrate material but no dead oysters were present.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	(up) 26° 58.877’N, 80° 8.344’W (dn) 26° 58.373’N, 80° 7.687’W

N

Map 5b

Dead Oyster Shell Length
Site 13

Mean Dead Oyster Shell Length (mm)

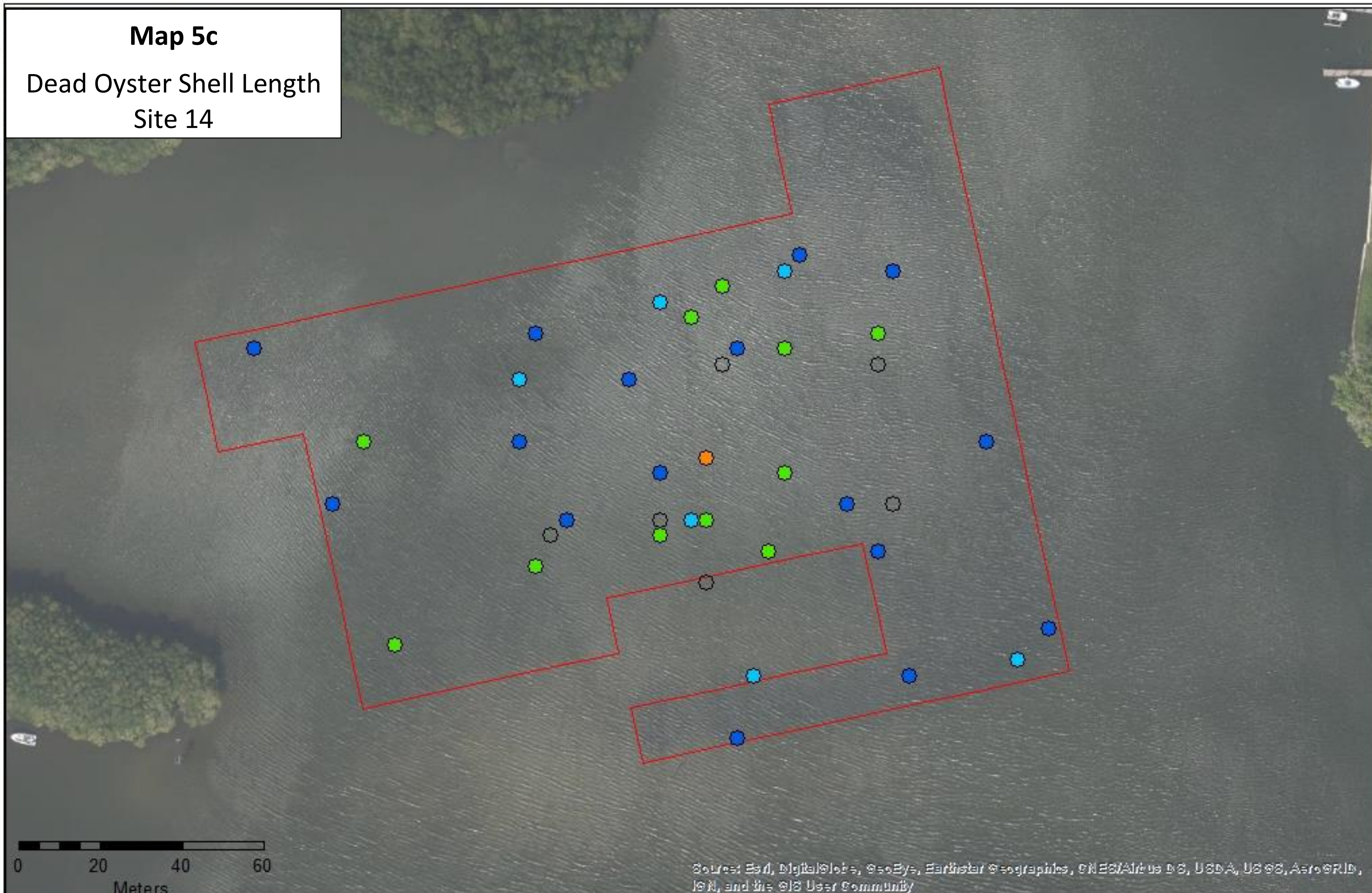
- 13.9 - 20.0
- 20.1 - 25.0
- 25.1 - 30.0
- 30.1 - 35.0
- 35.1 - 40.0
- 40.1 - 64.0

Mean dead oyster shell length (mm) at each sample point at restoration Site 13. Red outline indicates approximate boundary of reef and sampling area.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	26° 58.239'N, 80° 7.816'W

N

Map 5c
Dead Oyster Shell Length
Site 14



Mean Dead Oyster Shell Length (mm)

- 13.9 - 20.0
- 20.1 - 25.0
- 25.1 - 30.0
- 30.1 - 35.0
- 35.1 - 40.0
- 40.1 - 64.0

Mean dead oyster shell length (mm) at each sample point at restoration Site 14. Red outline indicates approximate boundary of reef and sampling area. Empty circles indicate absence of substrate material during sampling.

Map prepared by:	Jerry Metz
Date of Sampling:	9/19/19 to 9/27/19
Geographic Center of Reef:	26° 58.206'N, 80° 7.620'W

N