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Remote sensing of live and dead intertidal oyster reefs using aerial photo interpretation in Northeast Florida

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Abstract

The eastern oyster, *Crassostrea virginica*, has been classified as a keystone species as well as an ecosystem engineer because of the significant benefits that oysters and oyster reefs provide. Oyster reefs are being recognized as valuable for shoreline protection within coastal areas. The severe loss of oyster reef coverage has encouraged different types of conservation, mapping, monitoring and restoration efforts throughout its native range. Intertidal oyster reefs are an important habitat as well as an important industry in Florida, which makes accurate habitat monitoring a key element of resource management for this species. This project focused on creating a continuous intertidal oyster reef habitat map in northeast Florida. Existing aerial photography was used to identify oyster reef signatures, and map the distribution of intertidal oyster reefs throughout the study region using ArcGIS software. When accuracy assessment was completed, we found the number of observed agreements was 97% of the total observations. This mapping effort represents the first successful attempt at fine-scale oyster reef mapping across the entire northeast Florida region and resulted in a total of 17,953 individual reefs being mapped, with a total reef coverage of 651.86 ha. By using existing aerial photography, this methodology represents a low-cost method for reef mapping, compared to other methods such as drone imagery or field-based mapping. This baseline map of current oyster distribution will serve many functions for management this particular ecosystem. Future changes to reef distribution can be mapped and used to identify potential negative or positive impacts to the habitat.

Keywords Aerial photography · *Crassostrea virginica* · Habitat mapping · Oyster reefs · Dead reefs · Remote sensing

The eastern oyster, *Crassostrea virginica*, has been classified as a keystone species as well as an ecosystem engineer because of the significant benefits that oysters and oyster reefs provide. Oyster reefs are being recognized as valuable for shoreline protection within coastal areas. The severe loss of oyster reef coverage has encouraged different types of conservation, mapping, monitoring and restoration efforts throughout its native range. Intertidal oyster reefs are an important habitat as well as an important industry in Florida, which makes accurate habitat monitoring a key element of resource management for this species. This project focused on creating a continuous intertidal oyster reef habitat map in northeast Florida. Existing aerial photography was used to identify oyster reef signatures, and map the distribution of intertidal oyster reefs throughout the study region using ArcGIS software. When accuracy assessment was completed, we found the number of observed agreements was 97% of the total observations. This mapping effort represents the first successful attempt at fine-scale oyster reef mapping across the entire northeast Florida region and resulted in a total of 17,953 individual reefs being mapped, with a total reef coverage of 651.86 ha. By using existing aerial photography, this methodology represents a low-cost method for reef mapping, compared to other methods such as drone imagery or field-based mapping. This baseline map of current oyster distribution will serve many functions for management this particular ecosystem. Future changes to reef distribution can be mapped and used to identify potential negative or positive impacts to the habitat.

Introduction

Crassostrea virginica, also known as the eastern or American oyster, is a bivalve mollusk in the family Ostreiade. The eastern oyster has a range from the Gulf of Mexico coast up to the

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Gulf of St. Lawrence, Canada (Galtsoff 1964). Typical habitats for the eastern oyster include sounds, bays, and estuaries, ranging from brackish water to hypersaline lagoons (Kennedy et al. 1996). The eastern oyster has been classified as a keystone species as well as an ecosystem engineer because of the important benefits that oysters and oyster reefs provide (Coen et al. 2007). Due to their three-dimensional structure, oyster reefs maintain high levels of biodiversity (Coen and Luckenbach 2000). Oysters also influence the surrounding phytoplankton community via water filtration, which affects water clarity (Riisgård 1988). Oysters not only support species richness, but they act as soft-armor for shorelines (Piazza et al. 2005; Manis et al. 2015). Reefs can absorb wave energy which helps to preserve emergent vegetation and stabilize sediments along shorelines (Coen et al. 2007).

It has been estimated that 85% of shellfish reefs have been lost worldwide (Beck et al. 2011). Since the 1800s in the US, approximately 60% of the historical spatial extent and over 85% of total biomass of oysters have been lost (zu Ermgassen et al. 2012). Oyster coverage has decreased for several reasons: disease, habitat destruction, overharvesting and reduced water quality (Wenner et al. 1996; Kirby 2004; Johnson et al. 2009). Baseline information of the abundance and distribution of *C. virginica* is an important first step in better managing and conserving this species. Species distribution mapping serves several important purposes for environmental conservation, supervision of protected areas, and natural resource management. Firstly, these maps establish current distribution and extent of a particular species or habitat, which serves as baseline data for evaluating potential future impacts to that species. This information helps guide decision-making and facilitates better management of the species in question. Species distribution maps can also be useful for data analysis such as resource assessments and several different ecological analyses. Habitat maps (or species distribution based on these maps) can serve as input data for ecological forecast models that can be used to answer a variety of “what if” questions. Continuous habitat mapping can be used to investigate potential human impacts and offer solutions for future environmental mitigation.

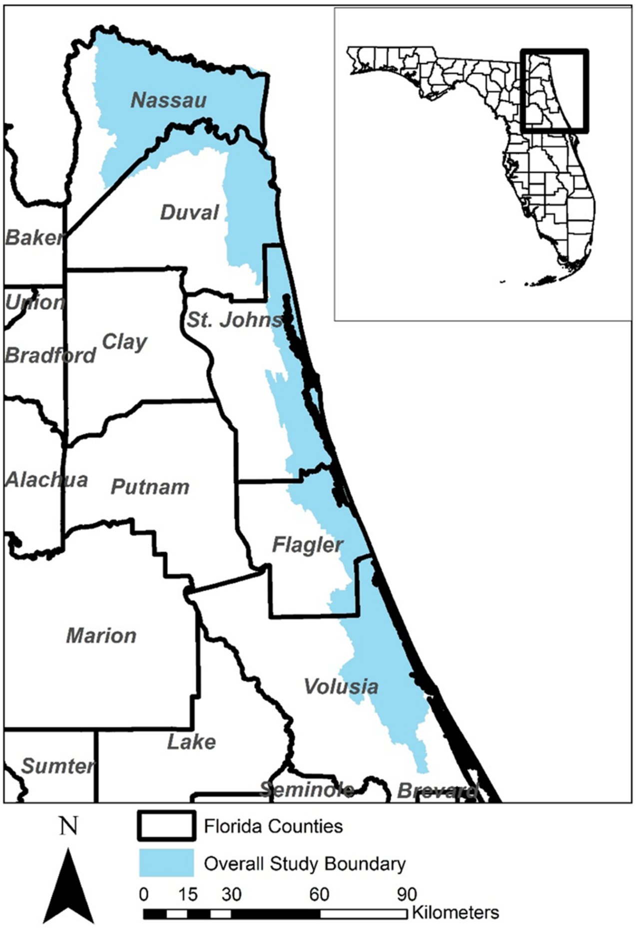

Fig. 1 Map of project study area

For this project, aerial photography was used to identify intertidal oyster reef signatures and map the distribution of intertidal oyster reefs throughout the northeast coastline of Florida (approximately 193 linear kilometers of coastline) (Fig. 1) (Saint Johns River Water Management District 2015). The main objective of this project is to assess the potential for available aerial imagery and existing aerial photography to be used to map oyster reefs at a high resolution and with high accuracy. This oyster reef habitat map will serve as baseline data for any future changes to oyster reef distribution, such as habitat loss/destruction, overharvesting, boating impacts, effects from climate change/sea level rise or issues with disease outbreaks. Maps such as these can also serve to establish critical habitat set aside for protected areas or fisheries recharge. Several important ecological questions can be asked using the current oyster distribution for the Northern Coastal Basins (NCB) study area.

Methods

Study location

This study took place in the NCB area, which is along the northeast coast of Florida (Fig. 4) from Ponce Inlet north to the Georgia border. This region encompasses five coastal counties: Nassau, Duval, St. Johns, Flagler and northern Volusia. The area south of Ponce Inlet within Volusia County was previously mapped in Garvis et al. (2015) using similar methodology. The northern most extent of the study area was −81.495396°, 30.714381° and the southernmost extent was −80.932145°, 29.044367°. The available imagery used in this project are listed in Table 1.

Table 1 Available Aerial Photography for northeast Florida

Coverage	Name	Year	Type	Flight dates	Scale
District wide	2009 Digital Orthophotography	2009			
Nassau, Duval, St. Johns, Flagler	3001_TAG	2009	True color	1/19–20/2009, 2/20/2009	1’
Volusia	FDOT	2009	True color	1/8–9/2009	1’
St. Johns, Flagler, Volusia	2006 TIFF files from first oyster mapping effort	2006	Infrared		
Volusia Co	*Volusia County Orthophotography*				
	Volusia County 2012, 1 ft. True color	2012	True Color	1/4–1/15/2012	1’
	Volusia County 2006, 1 ft. True color	2006	True Color		
	Volusia County 2006, 1 ft. CIR	2006	Infrared		
Flagler Co	*Flagler County Orthophotography*				
	Flagler_County_2014_RGB	2014	True color		
	Flagler County 2011, 1 ft. True Color	2011	True color		1’
	Flagler County 2011, 1 ft. CIR	2011	Infrared		1’
	Flagler County 2008, 1 ft. True Color	2008	True color		1’
	Flagler County 2008, 1 ft. CIR	2008	Infrared		1’
	Flagler County 2005, 1 ft. True Color	2005	True color		1’
	Flagler County 2005, 1 ft. CIR	2005	Infrared		1’
	Flagler County 2002, 1.5 ft. B&W	2002	B&W		1.5’
St. Johns Co	*St. Johns County Orthophotography*				
	St. Johns County 2013, 1 ft.	2013	True color		1’
	St. Johns County 2013, 1 ft. CIR	2013	Infrared		
	St. Johns County 2011, 1 ft.	2011	True color	12/27–28/2010	1’
	St. Johns County 2008, 1 ft.	2008	True color		1’
	St. Johns County 2008, 1 ft. CIR	2008	Infrared		1’
	St_Johns_2005_RGB	2005	True color		
Duval Co	*Duval County Orthophotography*				
	Duval County 2011, 1 ft. True Color	2011	True color		1’
	Duval County 2008, 1 ft. True Color	2008	True color		1’
	Duval County 2005, 1 ft. True Color	2005	True color		1’
Nassau Co	*Nassau County Orthophotography*				
	Nassau_County_2014_RGB	2014	True color		
	Nassau County 2011, 1 ft. True Color	2011	True color		1’
	Nassau County 2008, 1 ft. True Color	2008	True color		1’
	Nassau County 2005, 1 ft. True Color	2005	True color		1’
	Nassau County 2005, 1 ft. CIR	2005	Infrared		1’

Missing information in regard to scale and flight dates were due to lack of meta data. Assume the 2014 imagery is 1’

Aerial photography acquisition

Online aerial imagery from ESRI (2015) and Google Earth (2015) were available throughout the study area. Aerial photographs used in this study and associated metadata were obtained from St. Johns River Water Management District (SJRWMD) (Table 1). SJRWMD collaboratively acquired true color and color infrared orthophotography, in conjunction with county, state and federal agencies, to attain complete photographic coverage of the study area. The pixel or cell size for most of the imagery was 30.48 cm (1 ft); some sections have a 45.72 cm (1.5 ft) cell size. Image tile-level metadata defined the cell size for individual image tiles.

District imagery was collected with digital sensors and the project conforms to the Orthophotography Specifications as outlined by the statewide “Baseline Specifications for Orthophotography and LiDAR, v. 1.2.” as posted on the Florida Division of Emergency Management web page <http://floridadisaster.org/gis/lidar/>, with three general exceptions: 1) for this project, color infrared imagery was acquired (the statewide specifications state that color infrared imagery is optional); 2) if the image resolution will be

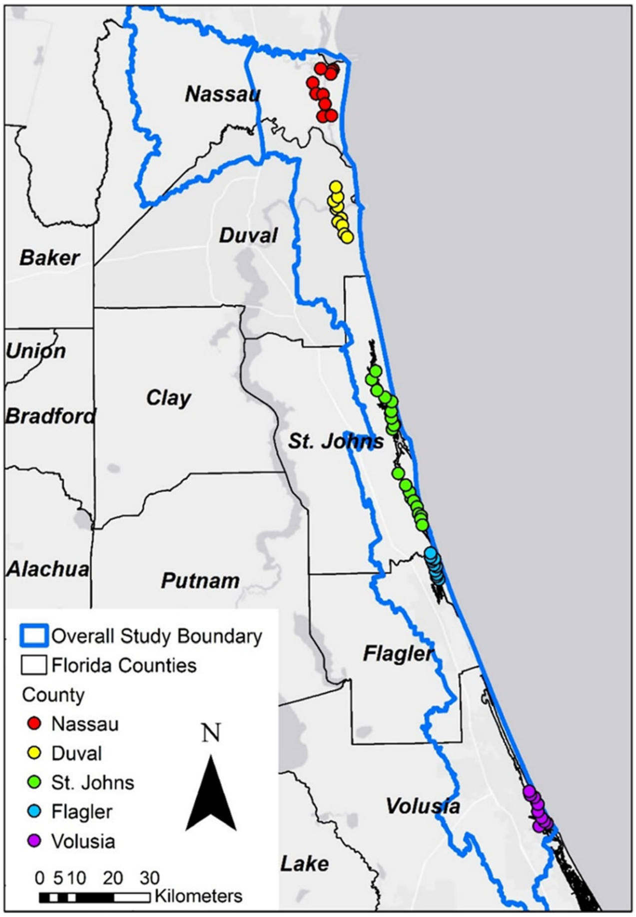

Fig. 2 Map of oyster mapping field checking points (60 in total), color coded by county. 10 points were selected randomly within areas that contained mapped reefs for each county. St. Johns County was given 20 field checking points due to the large size of the county

something other than one foot, exceptions to the specifications regarding accuracy requirements, imagery resolution, and deliverable tiling scheme may be made, as long as changes to the statewide specifications are documented by the Consultant and approved by the District; and 3) the number of independently surveyed image checkpoints required may differ from the number stated in the statewide specifications, due to differences in the size of the project area. The spatial reference was NAD 1983 HARN (units: meters), UTM, Zone 17 N. Aerial photographs were predominantly free of glare and had sufficient contrast to detect oyster reefs.

Preliminary field checking

Pre-photointerpretation fieldwork was conducted prior to screen digitization to assist with accurate photointerpretation (Fig. 2). This preliminary field checking was completed to refine signature identification in the images prior to digitization. Data collected for each field check site included: date, latitude and longitude of field check site, assumed classification based on aerial imagery, actual classification based on field identification, description of oyster community, and notes on the potential problems with aerial photointerpretation for that specific site.

Data classification

Oyster reefs were mapped using the unique signatures shown in Fig. 3 and were classified by the following conventions:

Classification Conventions:

CLASS NAME CLASS DESCRIPTION.

Oyster Reef: Oyster reefs were identified based on the following criteria (i.e. "signatures"): globular or irregular in shape, dark margins with a slightly lighter middle area, and with a smooth texture. Most reefs were located near wetland islands at a shallow bathymetry, due to the fact that oysters are intertidal throughout the Northern Coastal Basins area.

SUBCLASS: *Aggregated reefs*: Large areas of scattered oyster clusters and mud, not dense enough to be reliably mapped as continuous oyster reef based on aerial imagery.

Dead Reef: Dead reefs were identified based on the following criteria: bright white reflection due to bleached disarticulated shells that are continuously exposed, even at high tide. Dead reefs are found either adjacent to existing oyster reefs or standing alone, typically located on main boating channels.

Aerial photography interpretation

Aerial photography interpretation took place in 2015 and 2016, with a focus on 2015 imagery for consistency. During the mapping process, 2015 ESRI aerial imagery as well as 2015 Google Earth imagery was used and SJRWMD aerial photography (2005–2014) provided auxiliary information for areas that were difficult to photo-interpret (Table 1). Maps throughout this study were created using ArcGIS® software by ESRI. ArcGIS and ArcMap are the intellectual property of ESRI and are used herein under license (ESRI 2015).

A photointerpretation key was developed that contained examples of all oyster habitat classification types delineated for the study. Both descriptions of the classification types and aerial photo scenes depicted the different oyster signatures (Fig. 3). All oyster habitats were mapped to the level of detection (no minimum mapping unit). Oyster reefs were identified based on the following criteria (i.e. "signatures"): globular or irregular in shape, dark margins with a slightly lighter middle area, and a smooth texture (Fig. 3A). Natural reefs exhibited all three known reef morphologies: patch reefs which are small and compact, fringing reefs that are found parallel to the shoreline (excluding those obscured by

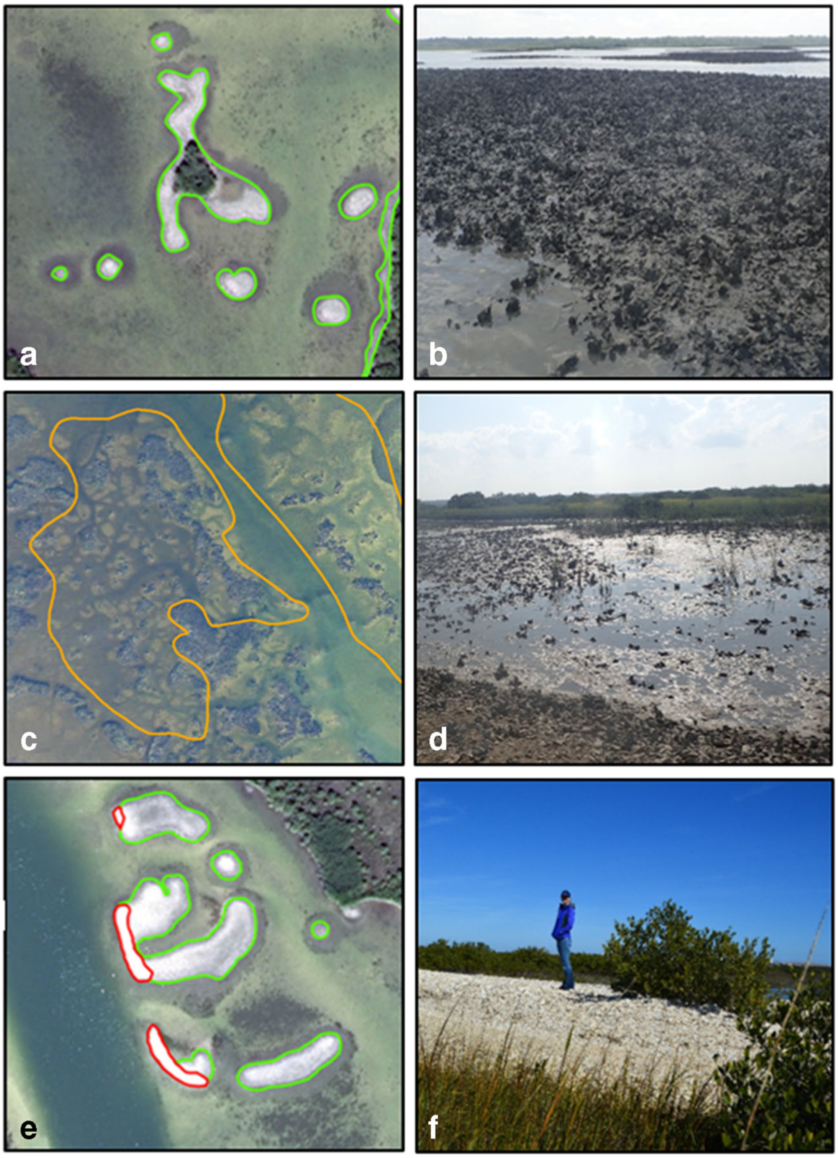

Fig. 3 Three unique reef signatures were used to identify reef types during photointerpretation. Live reefs are outlined in green (3A), aggregated live reefs (3C) and dead reefs are outlined in red (3E). Examples of how these signatures appeared in the field are live reefs (3B), aggregated live reefs (3D) and dead reefs (3F)

shoreline vegetation), and string reefs that are perpendicular to the shoreline (Kennedy and Sanford 1999). Most reefs were located near wetland islands at a shallow bathymetry, because oysters are intertidal throughout the study area. Narrow, fringing oyster reefs that were obscured by vegetation were not included in the study. Scattered live clusters were also not included. Only dense clusters of live oysters were included in the natural reef class. A subclass of live reef was created, called aggregate reef, to capture the large areas of scattered oyster clusters and mud that were not dense enough to be reliably mapped as continuous oyster reef based on aerial imagery (Fig. 3C). Dead reefs were identified based on the bright white reflection from bleached disarticulated shells that are continuously exposed, even at high tide (Fig. 3E). These are not true reefs in the sense that they do not contain live oyster clusters, but the term 'dead reef' or 'dead margin' is commonly used to describe them in oyster research (Dix et al. 2018). Dead reefs were found either adjacent to existing oyster reefs or standing alone, typically located on main boating channels.

Accuracy assessment

A set of spatially distributed accuracy assessment points were generated to test the map for mapping and classification accuracy. 200 original points and 200 backup points in case of inaccessibility of original points were spatially balanced across grid classes identified as live, dead and non-oyster areas. The random points were weighted by oyster area within mapped areas, as well as randomly distributed across intertidal areas where oyster reefs could be expected but no oysters had been mapped. A minimum distance of 200 m was enforced between points. Accuracy assessment was conducted by both University of Central Florida (UCF) and SJRWMD staff. During accuracy assessment, the reef type, GPS coordinates,

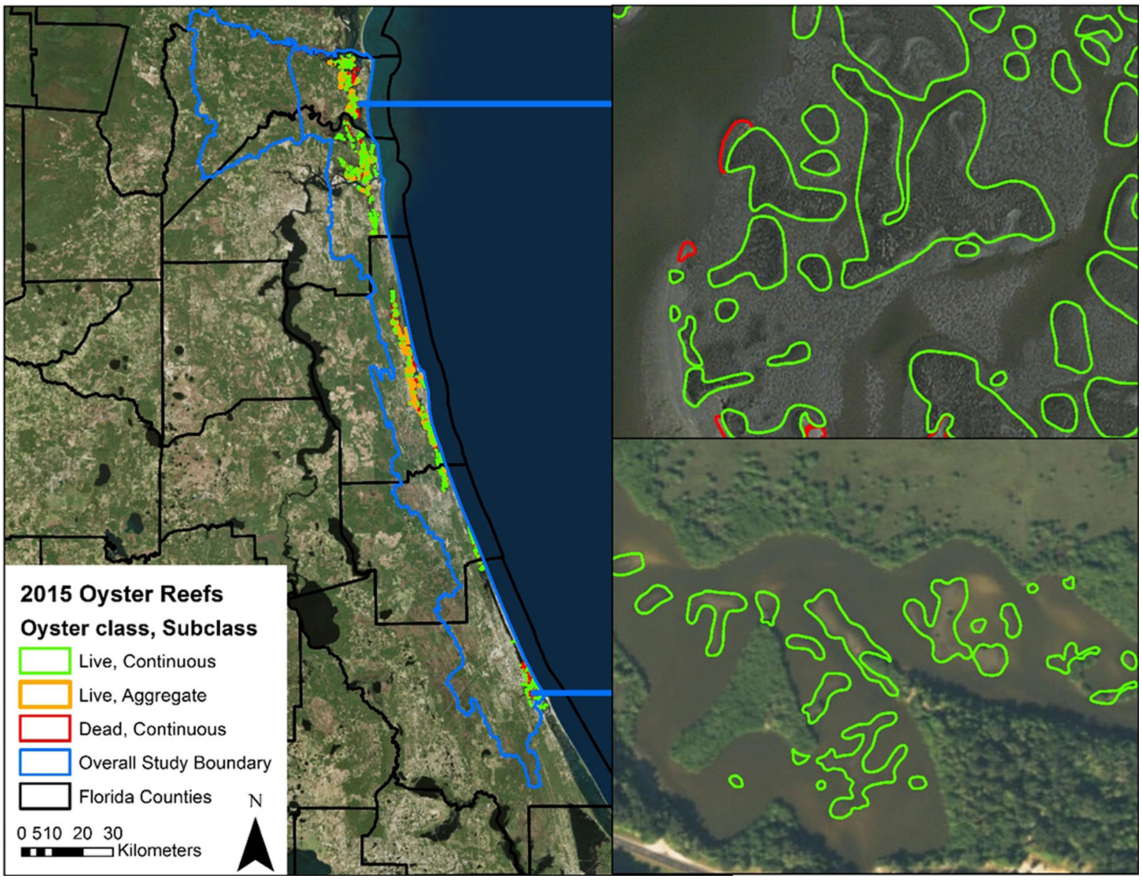

Fig. 4 Overall study area shown in blue. Examples of intertidal oyster reef polygons with live reefs in green and dead reef in red

and additional field photos were recorded. Accuracy was measured by calculating the kappa statistic (k) using the following formula:

$$k = \frac{p_o - p_e}{1 - p_e} = 1 - \frac{1 - p_o}{1 - p_e}$$

Where p_o was the relative observed agreement among observers, and p_e was the hypothetical probability of a coincidental agreement, using the observed data to calculate the probabilities of each observer randomly stating each category. If the raters were in complete agreement, then $k = 1$. If there was no agreement among the observers other than what would be expected by chance (as given by p_e), $k \leq 0$.

Results

Reef distribution patterns

The final reef count and hectares mapped by county is summarized in Table 2. There were 17,953 reefs mapped throughout the study area, with a total coverage of 651.86 ha. The southernmost boundary of this mapping effort was Sheephead Cut in the New Smyrna Beach area, which is in the northern half of Volusia County. Hundreds of small live reefs were mapped near or north of the Ponce Inlet. Once inside the Halifax River, the abundance of dead reefs increased substantially. The portion of the Halifax River within the Daytona and Ormond Beach area contains almost no live or dead reefs, most likely due to hard-armoring of the shoreline and channelization of the river. North Volusia County contained 1632 reefs that covered an area of 40.13 ha. North of this area, we have the Tomoka Marsh Aquatic Preserve, which contains many small intertidal reefs among the marsh areas. Dead reefs have formed near the mangrove islands that border the main boating channel in the northern half of Flagler County. Flagler County had the lowest amount of oyster habitat with a total of 1099 reefs that cover 18.13 ha. St. Johns County represents the largest amount of estuarine habitat of any county in this study. There were 4848 reefs mapped with an area of 331.81 ha. St. Johns County also has the largest amount of aggregate reef class, with large areas of scattered oyster clusters found among many intertidal reefs and marsh grass patches. This county has large dead reefs that follow along the main Intercoastal Waterway (ICW) that runs throughout the area. North of

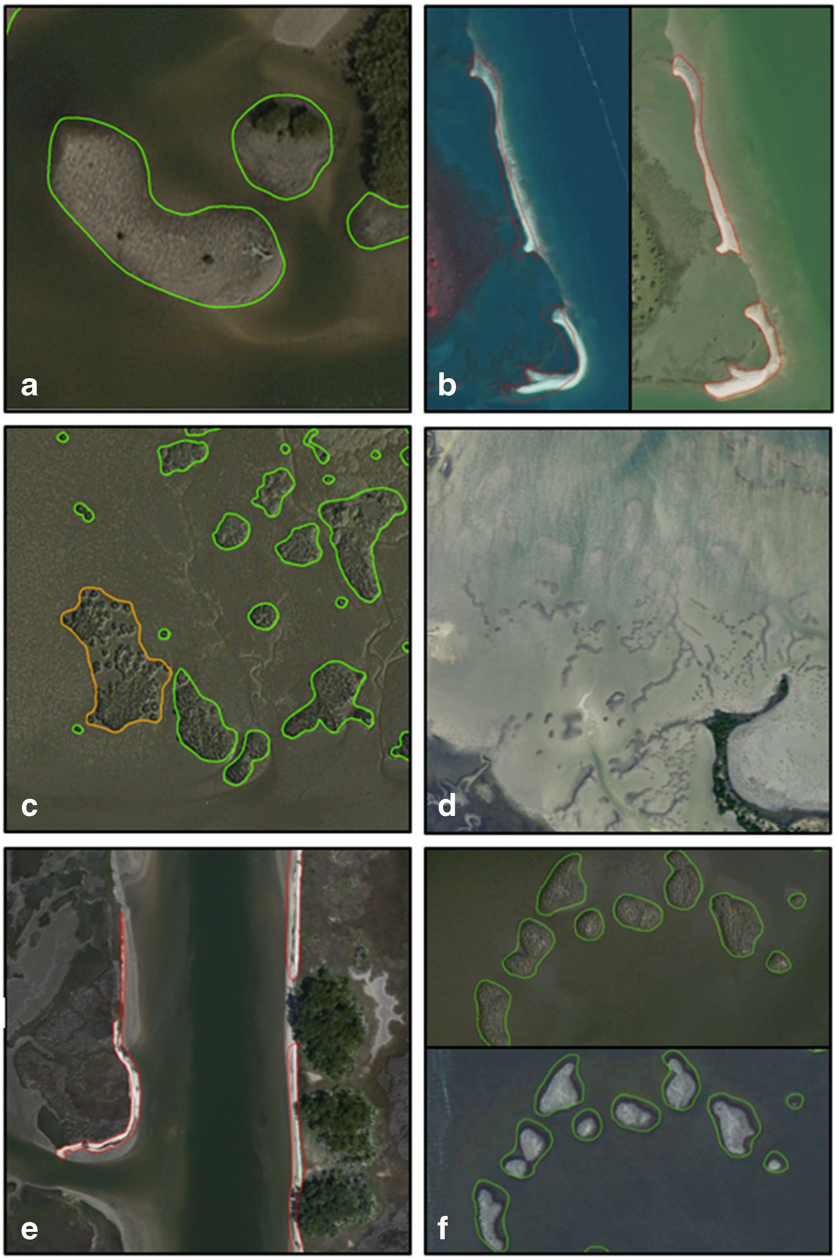

Fig. 5 Examples of issues encountered during the digitizing process. 5A: small patches of vegetation on reefs (typically mangroves and *Spartina* sp.), 5B: dead reef movement over time (2008–2014), 5C: small aggregated oyster clusters that are too small to map individually (outlined in orange), 5D: high tide obscuring reef signature, 5E: discerning between dead reefs and sandy shoals, and 5F: small differences in georeferencing between different sets of imagery

the Guana Tolomato Matanzas National Estuarine Research Reserve (GTMNERR), there are no more intertidal reefs found along ICW within St. Johns County, likely due to hard armoring of the waterway. The southern half of Duval County has very few intertidal reefs, and is dominated by saltmarsh patches. North of the St. Johns River in Duval County, the number of oyster reefs increased substantially within the Timucaun Ecological and Historical Preserve. Overall, Duval County contained 3561 mapped oyster reefs that covered an area of 103.67 ha. The highest density of reefs per unit of estuarine area is found in Nassau County, the northernmost county in this study. Nassau had a total of 6816 reefs mapped. This county has large amounts of intertidal areas that are difficult to navigate with a boat and restrictions on oyster harvesting, which may partially explain the large amount of reefs present in the county.

Accuracy assessment

Once accuracy assessment was completed, we found the number of observed agreements was 225 (97% of the observations) and the number of agreements expected by chance was 121 (52% of the observations). This resulted in a simple kappa coefficient of 0.929 (S.E. = 0.025, 95% CI = 0.880–0.977), which indicates a strength of agreement that is

Table 2 Summary of mapping count and area results by county

	Total Coverage (hectares)	Number of Reefs	Mean Reef Area (meters^2)	Minimum Reef Area (meters^2)	Maximum Reef Area (meters^2)	Mean Reef Perimeter (meters)
Volusia	40.13	1632				
Dead	4.52	113	400.04	20.43	4074.49	107.64
Live	35.61	1519				
Aggregate	1.81	6	3018.77	1060.60	7301.80	350.53
Continuous	33.80	1513	223.38	1.79	10,196.62	61.36
Flagler	18.13	1099				
Dead	1.61	23	702.15	16.18	3300.09	155.56
Live	16.52	1076				
Aggregate	1.35	5	2695.75	1091.86	4963.09	331.49
Continuous	15.17	1071	141.63	2.38	3637.41	47.05
St. Johns	331.81	4848				
Dead	36.21	423	856.06	17.66	5349.54	202.32
Live	295.60	4425				
Aggregate	192.85	273	7063.82	1053.59	97,502.52	416.49
Continuous	102.75	4152	247.47	0.04	8704.75	62.91
Duval	103.67	3561				
Dead	8.44	238	354.60	7.37	6741.04	102.50
Live	95.23	3323				
Aggregate	42.36	120	3529.57	966.09	22,475.07	357.85
Continuous	52.88	3203	165.09	1.71	6447.48	51.48
Nassau	158.11	6813				
Dead	11.84	252	470.02	9.03	8520.01	111.59
Live	146.27	6561				
Aggregate	46.11	121	3810.89	1041.11	25,582.19	349.52
Continuous	100.15	6440	155.52	2.17	4162.81	43.40
Grand Total	**651.86**	**17,953**				

considered to be 'very good' (Tables 3 and 4) (Viera and Garrett 2005). This mapping effort resulted in a total of 17,953 reefs being mapped, with a total reef coverage of 651.8 ha (Table 2). Overall, the resultant data were accurate and suitable for future trend analyses of oyster habitats within the northeast Florida area. The data produced should provide a valuable inventory of the oyster habitat existing within the project area during the 2015 time frame.

Mapping limitations and issues

During the project, we encountered a few issues that highlight the potential limitations of this dataset (Fig. 5). Vegetation growing adjacent to or on top of existing oyster reefs obscured detection in some imagery. After observing the phenomenon in the field, vegetation patches in mapped oyster reef interiors were often not removed from the mapped footprint because living oysters were often observed underneath the vegetation. Vegetation was not included in the oyster reef footprint if the oyster reef was a fringe reef surrounding a patch of mangroves or saltmarsh grass.

Another issue related to minimum mapping unit and definition of distinct small patch oyster reefs. Large expanses of scattered oyster clusters were not easily separated into distinct small patch reefs. An in-field review did not qualify these large areas as continuous reef because of low density between clusters and gaps in coverage. Instead, because these areas did contain a moderate amount of live oyster clusters, a new classification identified as aggregate subclass of live oyster reef was created, lumping these large areas of scattered clusters. Over time, some of these aggregated reef areas may be refined to show individual small patches and overall greater detail, by removing non-oyster area, with future mapping efforts and refinements.

Within the dead reef class, it was sometimes difficult to distinguish between dead reef area versus shoals or sandbars due to high reflectivity of these areas in the imagery. It should be noted that in spite of this difficulty, this inaccuracy only appears to a small portion of the total dataset. Contextual

Table 3 Summary of Accuracy Assessment results by county

County	Class	QA Points Generated	QA Points Completed	Percent Completed	No. Correct	No. Incorrect	Accuracy
Volusia	*Dead*	2	2	100.00	2	0	100.00
	Live	14	10	71.43	10	0	100.00
	Non-oyster	6	4	66.67	4	0	100.00
Flagler	*Dead*	1	1	100.00	1	0	100.00
	Live	7	5	71.43	5	0	100.00
	Non-oyster	7	6	85.71	6	0	100.00
St. Johns	*Dead*	22	11	50.00	10	1	90.91
	Live	103	55	53.40	55	0	100.00
	Non-oyster	86	46	53.49	43	3	93.48
Duval	*Dead*	9	7	77.78	7	0	100.00
	Live	37	21	56.76	21	0	100.00
	Non-oyster	27	16	59.26	16	0	100.00
Nassau	*Dead*	6	6	100.00	3	3	50.00
	Live	39	22	56.41	21	1	95.45
	Non-oyster	34	21	61.76	21	0	100.00
Total	–	400	233	–	225	8	–
						Overall Accuracy	96.50%

information was often used to classify dead reef or sandbar/shoal areas during mapping. If it was an area with a large amount of oyster reefs nearby, it was likely a dead reef. Also, if patches between the reef in question and the shoreline were either saltmarsh or live oysters, it was also likely a dead reef. However, areas with large trees adjacent to the shoreline tend to be sandbars/shoals. Additional field checking will be needed to increase the accuracy of the dead reef classification in future mapping updates. Comparing between aerial imagery years, we observed slight movement of dead reefs from the older sets of photos to the most current imagery. The left-hand photo is from 2008 and the right-hand photo is from 2014 (Fig. 5, panel B). In the photo, the red outline represents the 2014 location of the dead reef, and when this is overlaid on the 2008 imagery, we observed that the dead reef moved away from the channel and towards the mangrove island. This is consistent with previous research in Mosquito Lagoon that documented continuous movement of dead reefs over a 66-year period (Garvis et al. 2015). As a result of this change, we favored using the most currently available imagery to create the dead reef polygons.

Discussion

This product is the first of its kind to document coverage of intertidal oyster reefs in the estuarine region from New Smyrna Beach to the Florida-Georgia border. It represents the largest intertidal reef mapping effort in the state of Florida to date. This project was funded as part of the Northern Coastal Basins Initiative overseen by the Saint Johns River Water Management District (SJRWMD 2016). This mapping project feeds into better watershed management and improving water quality, which are two of the main objectives of the NCB Surface Water Improvement and Management (SWIM) plan. Additionally, the main objective of the present study was to assess the potential of freely available aerial imagery for fine-scale, high accuracy habitat mapping of intertidal oyster reefs. As such, this study adds to the ongoing efforts of the Oyster Integrated Mapping and Monitoring Program (OIMMP) of the Florida Fish and Wildlife Conservation Commission (FFWCC) that was created to encourage state-wide collaboration, communication and data sharing among anyone involved in oyster reef mapping,

Table 4 Kappa statistics for oyster reef accuracy assessment

		Mapped Class		
		Oyster	*Non-Oyster*	*Percent Accuracy*
Field Checked Class	*Oyster*	135	5	96%
	Non-Oyster	3	90	97%
	Total	**140**	**95**	

monitoring, and restoration (Dix et al. 2018). Many different stakeholders are interested in the effective management of oysters as a natural resource and as an industry within the state of Florida. The management needs of all stakeholders require better understanding of the spatial dimensions and distributions of oyster reefs. As a result, the present mapping effort focused on Northeast Florida, the methodology and results are potentially useful to other regional and state-wide management efforts.

The baseline map of current oyster distribution will mainly serve for management of the ecosystem. Maps can also help locate critical habitat for intertidal oyster reef protection. Results from an earlier mapping effort (Garvis et al. 2015) were integrated into outreach publications as well as a smartphone app designed to protect reef areas by promoting good boating behaviors in Mosquito Lagoon (Bowerman and DeLorme 2014). Given the geospatial distribution of oysters, ecological questions relating to environmental parameters and oyster dynamics can be addressed. Species distribution maps can also help inform decision-making that may impact oyster reef habitat (Beck et al. 2011). The analysis of oyster reef distribution and associated condition metrics can help identify which regions are either stressed and in need of management/restoration or which oyster habitats can serve as larval sources for nearby emerging reefs, and should be protected from harvesting.

Based on our findings and previous research, we recommend an updated mapping effort at least every 10 years for non-stressed areas, and a more frequent mapping update for stressed areas that may be impacted by boat wakes, disease or over-harvesting (Garvis et al. 2015). When managing oyster reefs as a natural resource, it is important to recognize and understand the causal mechanisms responsible for positive or negative impacts to the habitat to guide future conservation planning. Garvis et al. (2015) as well as Grizzle et al. (2002) provide correlative evidence that boat wakes are playing a major role in oyster reef declines in Mosquito Lagoon, Florida. Campbell (2014) demonstrated that boat wake heights as small as 2 cm are capable of dislodging and moving individual as well as clusters of oysters. Our study supports this research with the majority of dead margins or dead reefs appearing along major boating channels. Updated mapping efforts could help track these dead margins and provide opportunities for boat wake restrictions and other reef protection measurements to help mitigate these losses. Additionally, future mapping efforts could include a classification of oyster condition based on aerial or satellite imagery. Grizzle et al. (2018) were able to successfully identify areas of high, medium and low oyster density on intertidal oyster reefs in Apalachicola, with a thematic accuracy of 77%. The difference between our thematic accuracy and the thematic accuracy presented in Grizzle et al. (2018) is potentially due to differences in resolution of aerial and satellite image. As technologies improve, we can assume improvements to both types of imagery in terms of resolution. Given the global loss of 85% of historical reef coverage, oyster reef habitat protection needs to be the focus of conservation policy for estuaries, especially in protected waters or areas that depend on oysters as an industry (Beck et al. 2011).

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Compliance with ethical standards

User constraints The St. Johns River Water Management District prepares and uses information for its own purposes and this information may not be suitable for other purposes. This information is provided as is. Further documentation of this data can be obtained by contacting:

GIS_Support@sjrwmd.com or St. Johns River Water Management District, c/o GIS, PO Box 1429, Palatka, Florida, 32,178–1429, (386) 329–4500.

Complete liability disclaimer information available at: http://www.sjrwmd.com/disclaimer.html.

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