Extent and Distribution of Submerged Aquatic Vegetation

High-Salinity Estuarine Waters

2nd Edition Metric Report

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INTRODUCTION

Why Are the Extent and Distribution of Submerged Aquatic Vegetation Important Within the Albemarle-Pamlico Estuarine System?

Underwater vascular plants are key components of aquatic ecosystems. They play multiple roles in keeping Albemarle-Pamlico Estuarine System (APES) waters healthy by providing habitat, food, and shelter for aquatic life, sequestering carbon, protecting shorelines, absorbing and recycling nutrients, filtering sediment, and acting as a barometer of water quality. Commonly called "submerged aquatic vegetation" (SAV), these plants enrich shallow aquatic environments around the world, providing sanctuaries for mollusks, crustaceans, and finfish as well as sustenance for waterfowl and other herbivores.[1, 2]

SAV includes marine, estuarine, riverine and lacustrine vascular plants that are rooted in unconsolidated sediment and is one of five types of aquatic plants in APES waters, the others being floating aquatic vegetation, emergent aquatic vegetation, micro- and macroalgae, and blue-greens (cyanobacteria).[4] Because SAV are rooted in anaerobic sediments, they need to produce a large amount of oxygen to aerate the roots, and therefore have the highest light requirements of all aquatic plants.[5] SAV can become stressed by eutrophication and other environmental conditions that impair water transparency and/or diminish the oxygen content of water and sediments. The plant's response to these factors enables them to be sensitive bio-indicators of environmental health.[6]

While more than 500 species of SAV inhabit the world's rivers, lakes, estuaries, and oceans[7], APES and its tidal tributaries are home to about 14 common species.[8] High-salinity polyhaline (10-30 ppt) species, commonly referred to as seagrass, include three species; a temperate species growing at its' southern range limit, *Zostera marina* (eelgrass), a tropical species growing at its' northern limit, *Halodule wrightii* (shoalgrass) and the eurytolerant cosmopolitan species, *Ruppia maritima* (widgeongrass).[9] The co-occurrence of eelgrass and shoalgrass at their respective geographic range limits is a unique attribute of North Carolina coastal waters.[10] There are only four other locations in the world where temperate and tropical seagrasses overlap in their natural geographic range. To better understand the ecological implications of this unique circumstance and effectively manage this critical resource, APNEP needs detailed knowledge about the extent, distribution, and change in seagrass communities.

Seagrass meadow in northeastern Pamlico Sound. Photo by APNEP.

Seagrass meadows in North Carolina are found in subtidal waters less than two meters deep and in the intertidal areas of sheltered estuarine waters. These areas have loose sediment, adequate light, and moderate to low current velocities or wave turbulence.[11,12] Seagrass coverage ranges from small, isolated patches less than a meter in diameter to large continuous meadows covering hundreds of acres. The extent, distribution, and density of seagrass fluctuate seasonally and yearly due to environmental variability and human activity, leading to moderate and large-scale changes.[13]

Major threats to seagrass habitats include water quality degradation from excessive nutrient and sediment loading, channel dredging, and emerging threats such as accelerated sea level rise, increasing water temperatures, more frequent and intense tropical cyclones, barrier island instability, and the expansion of shellfish mariculture.[13,14] Given the high value of seagrass as the foundation of multiple ecosystem services, it is essential to regularly monitor this resource. This monitoring helps detect any dramatic declines or positive responses due to natural variability or APNEP-led and other protection and restoration activities.[15]

What type of ecosystem monitoring information is included in this metric report?

In 2021, APNEP adopted an integrated three-tiered monitoring plan as the first element of an estuarine ecosystem-wide monitoring strategy designed to generate data to enable more robust future assessments of APES seagrass distribution and abundance.[16,17] The hierarchical structure of the monitoring plan is described below.

Tier-1 Monitoring: This level characterizes the overall distribution and extent of seagrasses in APES using well-established remote sensing methods and analysis techniques (aerial imagery interpretation). Tier 1 focuses on specific properties such as presence/absence, distribution, and extent, ideally inventorying seagrasses across the entire system. This approach has been widely used for assessing seagrass status and trends over long periods and broad scales. APNEP has conducted Tier-1 monitoring since 2006.[18]

Tier-2 Monitoring: This level characterizes the ecological condition of seagrasses over relatively large areas by selecting statistically determined random and spatially balanced sample sites within the Tier-1 extent. Tier-2 surveys are generally restricted to subsections of the larger ecosystem, collected in the water and at a higher temporal frequency than Tier 1. Tier-2 data provide more detailed properties describing the spatial-temporal variation in seagrass structure (e.g., species composition) and abundance (e.g., percent cover, shoot density, biomass) to quantify stressor/response relationships and provide estimates of the ecological condition of the resource over a broad area. Since 2006, APNEP and its partners have been collecting a limited amount of Tier-2 data, mostly species composition, salinity, water depth, and temperature. With the formal adoption of a tiered monitoring plan in 2021, future metric reports will incorporate a wider scope of Tier-2 data (e.g., seagrass species composition, percent seagrass cover, macroalgal cover, water clarity, water depth, salinity, and temperature).

***Tier-3 M*onitoring:** This level is more intensive, drawing from a larger number of metrics sampled simultaneously and more frequently, and thus at a smaller number of sites. Tier-3 monitoring is typically driven by specific scientific hypotheses (e.g., measuring levels of uncertainty, evaluating multiple process-related responses, evaluating carbon sequestration rates). Tier-3 monitoring may also be driven by local and regional program objectives that directly address questions regarding the specific mechanisms responsible for explaining the changes detected in Tiers 1 and 2.

In this report we focus mainly on the acquisition and interpretation of Tier-1 seagrass monitoring data within APES. In the discussion of the results, we also integrate information from Tier-2 and Tier-3 data sources to supplement our assessment of the status and trends of seagrass in APES indicated by the Tier-1 data. Prior to the adoption of a tiered plan in 2021, APNEP has mostly relied on its partners and other external surveys for Tier-2 and Tier-3 data by drawing on information from past or ongoing surveys and research programs conducted in the region by local, state, and federal agencies, academic institutions, and NGOs. Future metric reports will include greater integration and analyses of Tier-2 and Tier-3 data and a more comprehensive assessment of the factors affecting the status and trends of this resource.

Tier-1 Survey Description: Location and Timing

Seagrass communities consisting of *Z. marina*, *H. wrightii* and *R. maritima* are found in polyhaline and mesohaline waters. Their distribution extends from the U.S. Highway 64 Bridge near Roanoke Island south to Ocracoke Inlet, including the back barrier shelves behind the Outer Banks and mainland shores of Core, Back, and Bogue Sounds, as well as the North River estuary (Figure 1). The seagrass meadows occur in various combinations of species, with some areas dominated by a single species while others contain mixed assemblages. This metric reports the extent and location of those seagrass communities by two spatial cover classes (continuous= > 70% cover and patchy = < 70% cover; see the *Data Manipulation* section in the appendix for further details) detected with digital aerial imagery during the following three survey periods:

- Survey 1 (2006-2007)
    - May/June 2006: Aerial surveys of Bogue and Back Sounds between Barden Inlet and Bogue Inlet, and the mainland side of Core Sound.
    - October 2007: Aerial surveys between Roanoke Island and Barden Inlet.
- Survey 2 (2013)
    - May 2013: Aerial surveys between Roanoke Island and Bogue Inlet.
- Survey 3 (2020)
    - May/June 2020: Aerial surveys between Roanoke Island and Bogue Inlet.

The initial report for this metric summarized data from 2006 and 2007 (Survey 1) and 2013 (Survey 2)[18]. As noted in that report, during Survey 2 interference by cloud cover rendered the imagery acquired for much of Core Sound unsuitable for seagrass mapping between Ophelia Inlet and Barden Inlet at Cape Lookout (see Appendix Figure A1); therefore, extent and location measures for seagrass in much of Core Sound were not included in the first metric report. For the subsequent Survey 3 data (2020), some of the imagery was also uninterpretable due to turbidity on the mainland side of Core Sound and several small areas of the North Zone (see Appendix Figure A1).

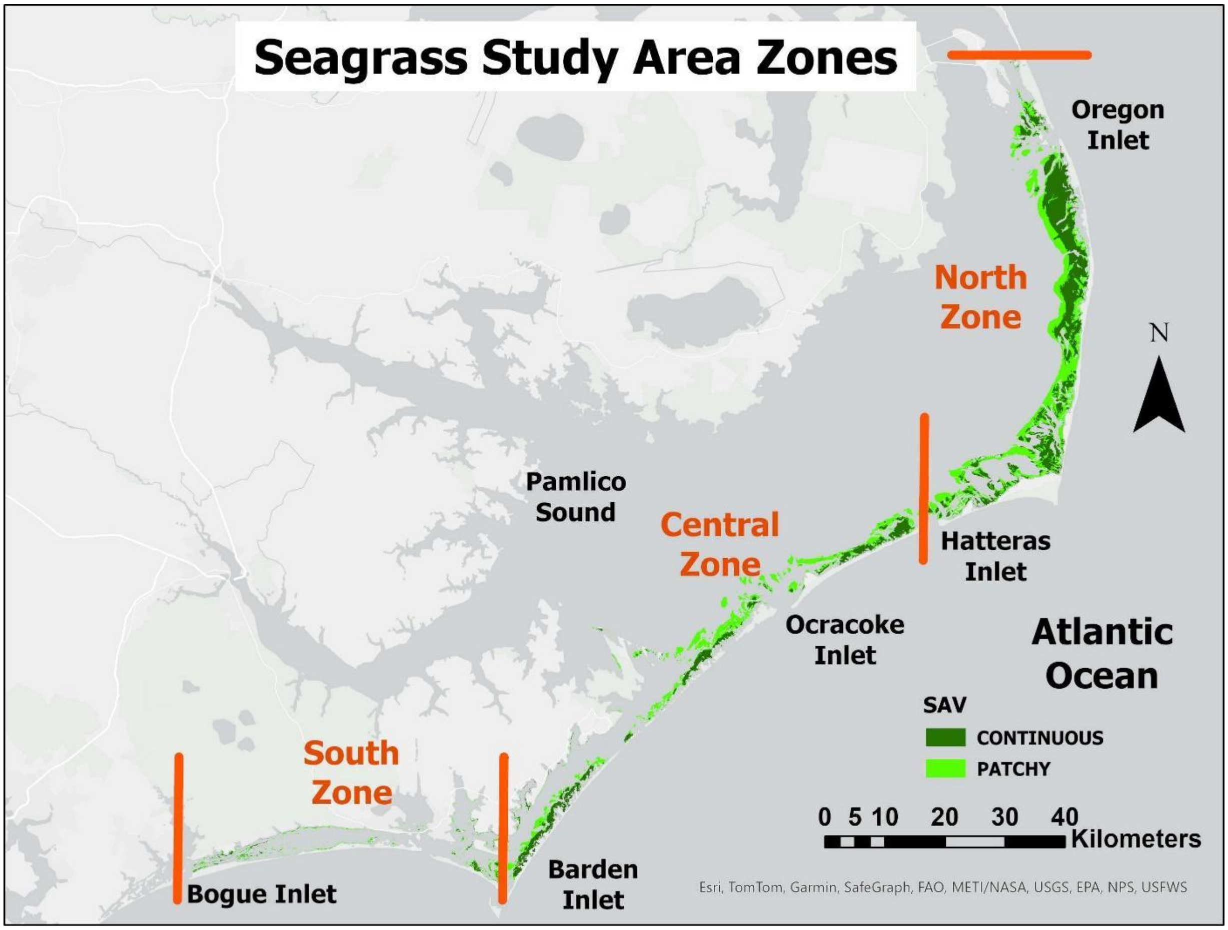

Figure 1. *The three zones for the seagrass Tier-1 monitoring effort: 1) the "North Zone" from the U.S. Highway 64 Bridge at Roanoke Island to Hatteras Inlet, 2) the "Central Zone" from Hatteras Inlet to Barden Inlet near Cape Lookout and, 3) the "South Zone" from Barden Inlet to Bogue Inlet. The seagrass map is from interpretation of the 2006/2007 imagery.*

RESULTS

What Do the Data Show?

Spatial Trends in Seagrass Extent

The areal extent of seagrass from Survey 1 was 109,607 acres, Survey 2 was 95,157 acres, and Survey 3 was 88,531 acres (Table 1).

Table 1. *Comparison of seagrass extent (acres) detected by aerial photography in two spatial cover classes and the total for all three surveys. Due to interference by cloud cover during Survey 2 and turbidity during Survey 3, those two surveys were incomplete.*

Spatial Cover Class	**Survey 1 2006-07**	**Survey 2 2013**	**Survey 3 2020**
Continuous	51,368	30,347	23,622
Patchy	58,239	64,810	64,909
Total	109,607	95,157	88,531

As described above, cloud cover and turbidity interfered with the detection of bottom signatures and limited our ability to obtain complete areal extent estimates for seagrasses in Surveys 2 and 3. To investigate changes in the three spatial cover classes relative to the total extent, the data for each of the three surveys were analyzed in two different ways: 1) regionally and 2) by categories of spatial cover class change.

Regionally, the data were divided into three zones: 1) the “North Zone” from the U.S. Highway 64 Bridge at Roanoke Island to Hatteras Inlet, 2) the “Central Zone” from Hatteras Inlet to Barden Inlet near Cape Lookout, and 3) the “South Zone” from Barden Inlet to Bogue Inlet (Figure 1). In addition to mapping the two cover class categories within each zone, we also quantified the transition of each category between surveys. For this analysis we assessed eight cover class changes between the surveys:

1) continuous SAV to no SAV,
2) patchy SAV to no SAV,
3) continuous SAV to patchy SAV,
4) patchy SAV both years of analysis,
5) no SAV to patchy SAV,
6) continuous SAV both years of analysis,
7) patchy SAV to continuous SAV, and
8) no SAV to continuous SAV.

Additional information on methodology for the category transitions can be found in the *Data Manipulation* section of the Appendix.

The change in seagrass distribution and areal extent for the entire study area and regional zones were based on seagrass habitat polygons generated from interpretation of digital multispectral imagery, whereas the data for the categorial transitions (Tables 3, 5, 8, and 10) could not be generated by comparing polygonal data from the three surveys due to software limitations and had to be rasterized (see the *Data Manipulation* section in the appendix for further details). Therefore, cross-comparisons between polygon-based (Tables 2, 4, 6, 7 and 9) and raster-based (Tables 3, 5, 8 and 10) calculations may cause minor inconsistencies in areal extent not exceeding 10 acres.

NORTH ZONE

As noted above, several North Zone areas in Survey 3 could not be interpreted due to turbidity (see Appendix Figure A1). These areas contained seagrass in the first two surveys. Therefore, the seagrass delineations (from the uninterpretable areas in Survey 3) were eliminated from Surveys 1 and 2 to perform the change detections and generate the data in Tables 2 and 3 and Figure 2. The removals led to 2,416 acres and 2,025 acres less than presented in the initial report of this metric for Surveys 1 and 2, respectively.

The North Zone contained most of the seagrass mapped in all zones, with 64.9% of the seagrass mapped in Survey 1, 69.2% in Survey 2 and 69.2% in Survey 3 (Figures 1 and 2). This zone experienced an overall loss of seagrass across the three surveys with 68,445 acres in Survey 1, 64,420 acres in Survey 2 and 61,294 acres in Survey 3 (Table 2). The annual rate of loss between Surveys 1 and 2 (0.98% y^{-1}) was higher than the rate of loss between Surveys 2 and 3 (0.7% y^{-1}). Over the entire 13-year period from Survey 1 to Survey 3, the rate of loss was 0.8% y^{-1}.

As was reported for changes between Surveys 1 and 2 in the first metric report[18], the largest change between the three surveys was in the continuous meadows: 38.8% loss between Surveys 1 and 2 and 37.3% loss between Surveys 2 and 3 (Table 2). Over the entire 13-year period from Survey 1 to Survey 3, the loss in continuous meadows, including conversion to patchy meadows, was 62.3%.

During the three surveys, patchy meadows became a larger proportion of the total seagrass extent (Table 2). The biggest seagrass conversion in the North Zone in Survey 3 was conversion of continuous to patchy seagrass (Table 3, Figure 2). The conversion of continuous to patchy seagrass from Survey 2 to 3 was 10,365 acres but not as large as the same conversion between Surveys 1 and 2 (14,999 acres). Over the entire 13-year period from Survey 1 to Survey 3, 21,886 acres transitioned from continuous to patchy seagrass, representing 61.7% of the continuous seagrass present in Survey 1.

In all survey periods, the conversions of patchy and continuous meadows to no seagrass exceeded the conversions of no seagrass to both categories of seagrass (Table 3). Between Surveys 1 and 3, approximately twice the amount of seagrass in both categories were converted to no seagrass and the biggest loss of seagrass across all surveys was conversion of patchy seagrass to no seagrass; 6,845 acres between Surveys 1 and 2, 7,902 acres between Surveys 2 and 3, and 9,531 acres between Surveys 1 and 3 (Table 3). Most of the loss occurred at the outer, western edges of the patchy beds on the back barrier shelf extending along the length of the North Zone (Figure 2).

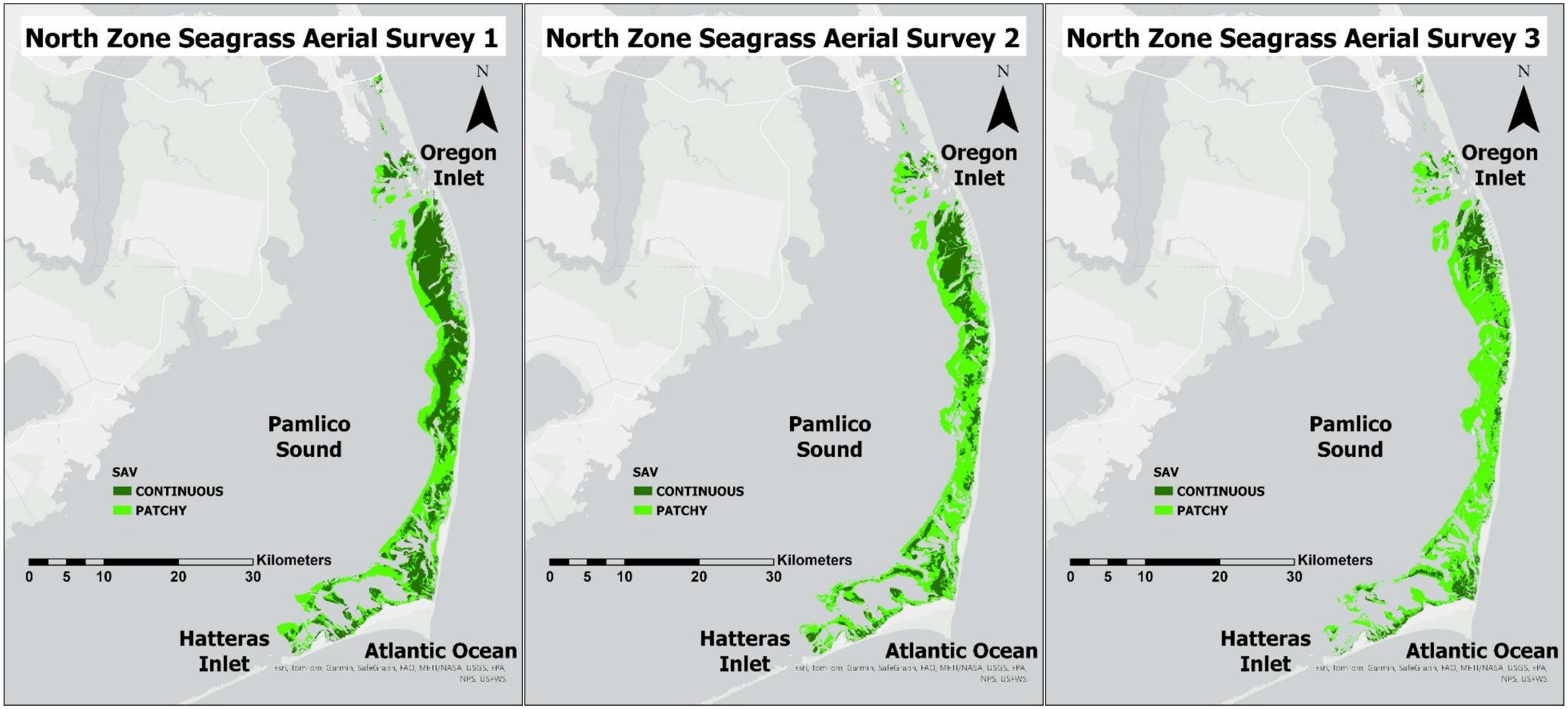

Figure 2. *Seagrass location and spatial cover classes (continuous and patchy) in the North Zone during Surveys 1 (2006-2007), 2 (2013) and 3 (2020).*

Table 2. *Comparison of seagrass extent (acres) in two spatial cover classes, the total extent, the change in acres between each survey, and the percent change in parentheses for the North Zone. Seagrass areas detected in Surveys 1 and 2 were clipped to exclude seagrass delineations from areas that could not be interpreted in Survey 3.*

Spatial Cover Class	Survey 1 2006-07	Survey 2 2013	Survey 3 2020	Change (%) Survey 1 to 2	Change (%) Survey 2 to 3	Change (%) Survey 1 to 3
Continuous	35,454	21,358	13,382	-14,096 (39.8)	-7,976 (37.3)	-22,072 (62.3)
Patchy	32,991	43,062	47,912	+10,071 (30.5)	+4,850 (11.3)	+14,921 (45.2)
Total	68,445	64,420	61,294	-4,025 (5.9)	-3,126 (4.9)	-7,151 (10.4)

Table 3. *All possible categories of spatial cover class change between three survey periods, or classes remaining the same for the North Zone. Seagrass areas detected in Surveys 1 and 2 were clipped to exclude seagrass delineations from areas that could not be interpreted in Survey 3.*

Spatial Cover Class Change Category	Acres 2007-2013	Acres 2013-2020	Acres 2007-2020
Continuous SAV to No SAV	1,981	1,346	3,199
Patchy SAV to No SAV	6,854	7,902	9,531
Continuous SAV to Patchy SAV	14,999	10,365	21,866
Patchy SAV Both Years of Analysis	23,510	31,700	21,066
No SAV to Patchy SAV	4,473	5,836	4,948
Continuous SAV Both Years of Analysis	18,467	9,647	10,360
Patchy SAV to Continuous SAV	2,627	3,378	2,394
No SAV to Continuous SAV	263	347	618

CENTRAL ZONE

As noted earlier, turbidity interfered with visualizing and interpreting the signatures of seagrass on the mainland side of Core Sound in Survey 3 (see Appendix, Figure A1). Furthermore, as explained in the first metric report[18], all of Core Sound from Barden Inlet to Ophelia Inlet in Survey 2 was uninterpretable due to cloud cover. Therefore, the data for the Central Zone was divided into two geographic subareas. The first subarea, for Surveys 1 and 3 only, was the Outer Banks area (the back barrier shelf) of the Central Zone from Barden Inlet, through to and including Hatteras Inlet with the mainland side of Core Sound excluded (Figure 3, Tables 4 and 5).

The second subarea encompassed the back barrier shelf from Ophelia Inlet (northern Core Sound) to Hatteras Inlet with data from Surveys 1, 2 and 3 (the mainland side of Core Sound excluded) (Figure 4, Tables 6 and 7). Therefore, the seagrass delineations in this area (from the uninterpretable mainland area in Survey 3) were eliminated from Surveys 1 and 2 to perform the change detections and generate the data in Tables 7 and 8 and Figure 4. The removals led to 816 acres and 1,300 acres less than presented in the initial report of this metric for Surveys 1 and 2, respectively.

The Outer Banks side of the Central Zone, from Barden to Hatteras Inlet (Subarea 1), had the second largest seagrass area out of the three zones with 29.8% of total seagrass area in Survey 1 and 25.6% in Survey 3 (Figure 3). Between Surveys 1 and 3, Subarea 1 had a net loss of 8,823 acres, or 28.1% of the seagrass resource recorded in this zone for 2007 (Table 4). Over the entire 14-year period the rate of loss was 2.0% y^{-1}. The biggest change category was the conversion of 10,334 acres of patchy seagrass to no seagrass. The conversion from both patchy and continuous categories to no seagrass (12,436 acres) was 3.5 times greater than the conversion of no seagrass to patchy and continuous seagrass (3,613 acres) (Table 5). Most of the conversion of patchy seagrass to no seagrass occurred at the deep-water edge of the beds on the back barrier shelf and on the flood tidal shoals inside and around Hatteras and Ocracoke Inlets (Figure 3). Between these surveys, the width of Ocracoke and Hatteras Inlets increased substantially (see Appendix, Figure A2) and was accompanied by the extensive loss of seagrass on the flood delta shoals on the sound-side of the inlets (Table 6).

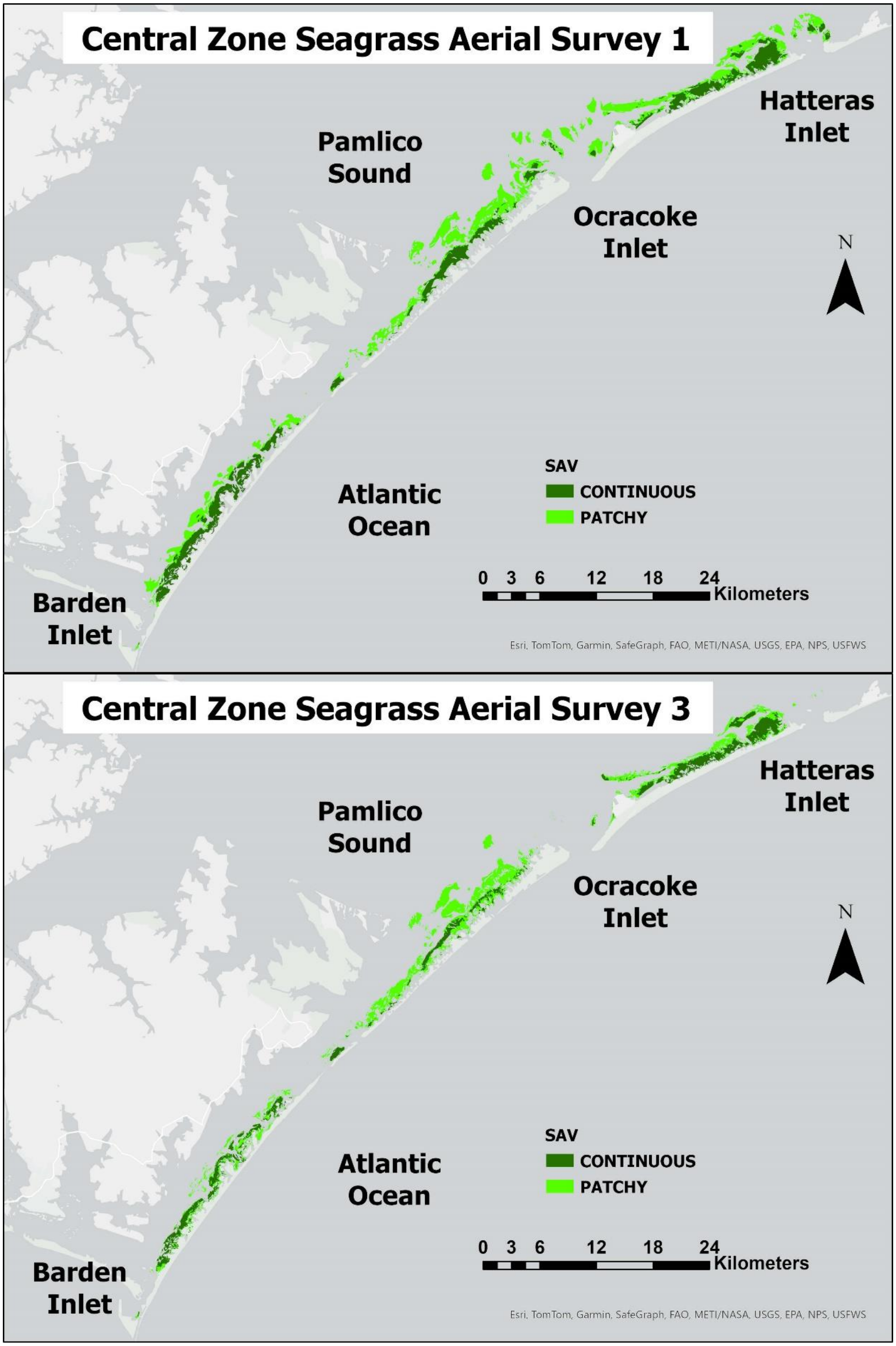

Figure 3. *Seagrass location and spatial cover classes (continuous and patchy) in the Central Zone Subarea 1 during Surveys 1 (2006-2007) and 3 (2020).*

Table 4. *Comparison of seagrass extent (acres) in two spatial cover classes, the total extent, the change in acres, and the percent change in parentheses between Surveys 1 (2006-2007) and 3 (2020) for the Central Zone Subarea 1, from Hatteras Inlet to Barden Inlet, not including the mainland side of Core Sound. Seagrass areas detected in Survey 1 were clipped to exclude seagrass delineations from areas that could not be interpreted in Survey 3.*

Spatial Cover Class	Survey 1 2007	Survey 3 2020	Change (%)
Continuous	12,440	8,415	-4,025 (32.4)
Patchy	19,006	14,208	-4,798 (25.2)
Total	31,446	22,623	-8,823 (28.1)

Table 5. *All possible categories of spatial cover class change between Surveys 1 (2006-2007) and 3 (2020), or classes remaining the same for Central Zone Subarea 1. Seagrass areas detected in Survey 1 were clipped to exclude seagrass delineations from areas that could not be interpreted in Survey 3.*

Spatial Cover Class Change Category	Acres
Continuous Seagrass to No Seagrass	2,102
Patchy Seagrass to No Seagrass	10,334
Continuous Seagrass to Patchy Seagrass	3,328
Patchy Seagrass Both Years of Analysis	7,738
No Seagrass to Patchy Seagrass	3,142
Continuous Seagrass Both Years of Analysis	7,010
Patchy Seagrass to Continuous Seagrass	933
No Seagrass to Continuous Seagrass	471

Table 6. *Increased width in meters (m) of Ocracoke and Hatteras Inlets and corresponding loss of seagrass acres (ac) on the flood tidal shoals on the sound side of the two inlets.*

<table>
<tr><th colspan="7">OCRACOKE INLET</th></tr>
<tr><th>Metric</th><th>Survey 1 2007</th><th>Survey 2 2013</th><th>Survey 3 2020</th><th>Change Survey 1-2</th><th>Change Survey 2-3</th><th>Change Survey 1-3</th></tr>
<tr><td>Width (m)</td><td>2,047</td><td>2,240</td><td>2,940</td><td>193</td><td>700</td><td>893</td></tr>
<tr><td>Seagrass (ac)</td><td>2,758</td><td>2,592</td><td>123</td><td>-166</td><td>-2,469</td><td>-2,635</td></tr>
<tr><th colspan="7">HATTERAS INLET</th></tr>
<tr><th>Metric</th><th>Survey 1 2007</th><th>Survey 2 2013</th><th>Survey 3 2020</th><th>Change Survey 1-2</th><th>Change Survey 2-3</th><th>Change Survey 1-3</th></tr>
<tr><td>Width (m)</td><td>1,774</td><td>2,398</td><td>3,750</td><td>624</td><td>1,352</td><td>1,976</td></tr>
<tr><td>Seagrass (ac)</td><td>1,416</td><td>468</td><td>40</td><td>-948</td><td>-428</td><td>-1,376</td></tr>
</table>

As was the case for Subarea 1 in the Central Zone, Subarea 2 also experienced a loss of seagrass across the three surveys with 23,316 acres in Survey 1, 22,147 acres in Survey 2 and 17,364 acres in Survey 3 (Table 7). As with the trend in Subarea 1 (Table 5), the change from patchy seagrass to no seagrass displayed the greatest loss with -4,782 acres from Surveys 1 to 2, -6,194 acres from Surveys 2 to 3 and -7,682 acres from Surveys 1 to 3. The annual loss rate was 0.83% yr^{-1} between Surveys 1 and 2 and increased to 3.08% y^{-1} between Surveys 2 and 3. Over the entire 14-year period the annual loss rate in Subarea 2 was 1.96% y^{-1} and the conversions from both seagrass categories to no seagrass exceeded the conversion to seagrass by a factor of 3.

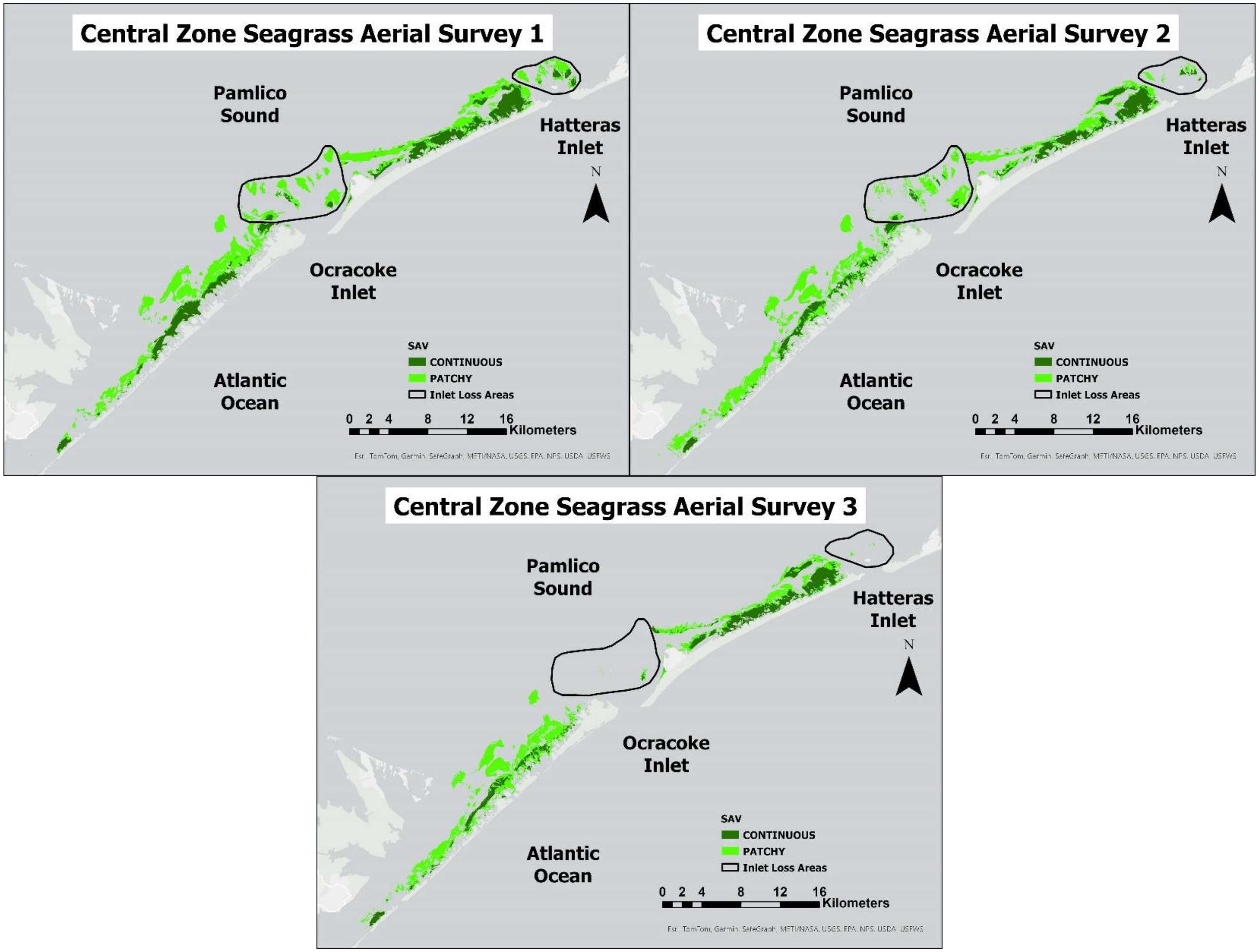

Figure 4. *Seagrass location and spatial cover classes (continuous and patchy) in the Central Zone Subarea 2 during Surveys 1 (2006-2007), 2 (2013) and 3 (2020), specifically for the subarea presented in the initial report of this metric.*[18] *The black polygons labeled "Inlet Loss Areas" in the legend designate the areas used to quantify the "Ocracoke Inlet Seagrass Acres" and "Hatteras Inlet Seagrass Acres" in Table 6.*

Table 7. *Comparison of seagrass extent (acres) in two spatial cover classes, the total extent, the change in acres between each survey, and the percent change in parentheses for the Central Zone Subarea 2, specifically for the subarea presented in the initial report of this metric.[18] Seagrass areas detected in Surveys 1 and 2 were clipped to exclude seagrass delineations from areas that could not be interpreted in Survey 3.*

Spatial Cover Class	Survey 1 2006-07	Survey 2 2013	Survey 3 2020	Change (%) Survey 1 to 2	Change (%) Survey 2 to 3	Change (%) Survey 1 to 3
Continuous	7,521	6,511	5,597	-1,010 (13.4)	-914 (14.0)	-1,924 (25.6)
Patchy	15,795	15,636	11,767	-159 (1.0)	-3,869 (24.7)	-4,028 (25.5)
Total	23,316	22,147	17,364	-1,169 (5.0)	-4,783 (21.6)	-5,952 (25.5)

Table 8. *All possible categories of spatial cover class change between the three survey periods, or classes remaining the same for the Central Zone Subarea 2. Seagrass areas detected in Surveys 1 and 2 were clipped to exclude seagrass delineations from areas that could not be interpreted in Survey 3.*

Spatial Cover Class Change Category	Acres 2007-2013	Acres 2013-2020	Acres 2007-2020
Continuous Seagrass to No Seagrass	401	866	1,218
Patchy Seagrass to No Seagrass	4,782	6,194	7,682
Continuous Seagrass to Patchy Seagrass	1,671	1,532	1,994
Patchy Seagrass Both Years of Analysis	10,186	8,239	7,226
No Seagrass to Patchy Seagrass	4,386	1,995	2,547
Continuous Seagrass Both Years of Analysis	5,423	4,113	4,310
Patchy Seagrass to Continuous Seagrass	1,112	1,203	888
No Seagrass to Continuous Seagrass	150	279	398

SOUTH ZONE

Turbidity was an issue along the mainland at the far eastern end of the South Zone in the 2020 imagery for Survey 3 and prevented a complete interpretation of areas that contained seagrass in Surveys 1 and 2 (see Appendix, Figure A1). Therefore, the seagrass delineations (from the uninterpretable areas in Survey 3) were eliminated from Surveys 1 and 2 to perform the change detections and generate the data in Tables 9 and 10 and Figure 5. The removals led to 213 acres and 268 acres less than presented in the initial report of this metric for Surveys 1 and 2, respectively[18].

The South Zone contained the least amount of seagrass of the three zones, accounting for 5.1% of the total seagrass area in Survey 1, 5.2% in Survey 2, and 5.2% in Survey 3 (Figure 5, Table 9). This zone experienced a loss of seagrass across the three surveys with 5,637 acres in Survey 1, 4,967 acres in Survey 2 and 4,611 acres in Survey 3 (Table 9). The highest annual loss rate occurred between Surveys 1 and 2 (1.98% y^{-1}) and was nearly twice the rate observed between Surveys 2 and 3 (1.02% y^{-1}). Over the entire 14-year period, seagrass in this region was lost at a rate of 1.4% y^{-1}. The largest conversion in all three surveys was patchy seagrass to no seagrass, with 1,495 acres between Surveys 1 and 2, 1,627 acres between Surveys 2 and 3 and 2,224 acres between Surveys 1 and 3 (Table 10).

The notable change in the annual loss rate between Surveys 2 and 3 compared to Surveys 1 and 2 was further examined by a closer spatial inspection of the aerial imagery which showed a substantial area of seagrass expansion in the western region of the South Zone in Bogue Sound (Figure 5). To isolate this area of change, Bogue Sound was divided into east and west subareas as shown in the Appendix (Figure A3). The west subarea showed a decrease from Survey 1 (1,433 acres) to Survey 2 (1,241 acres), but an increase in Survey 3 (2,183 acres). Over the entire 14-year period the west subarea gained seagrass at an annual rate of 3.73% y^{-1}. In contrast, the east subarea saw decreases across the three surveys, with 4,204 acres in Survey 1, 3,730 acres in Survey 2 and 2,429 acres in Survey 3. The annual loss rate over the entire 14-year period in the east subarea was 3.01% y^{-1}. As was the case for the other zones, the conversion of patchy seagrass to no seagrass was the largest change observed and was accompanied by a decrease in the extent of the continuous meadows over the entire 14-year period.

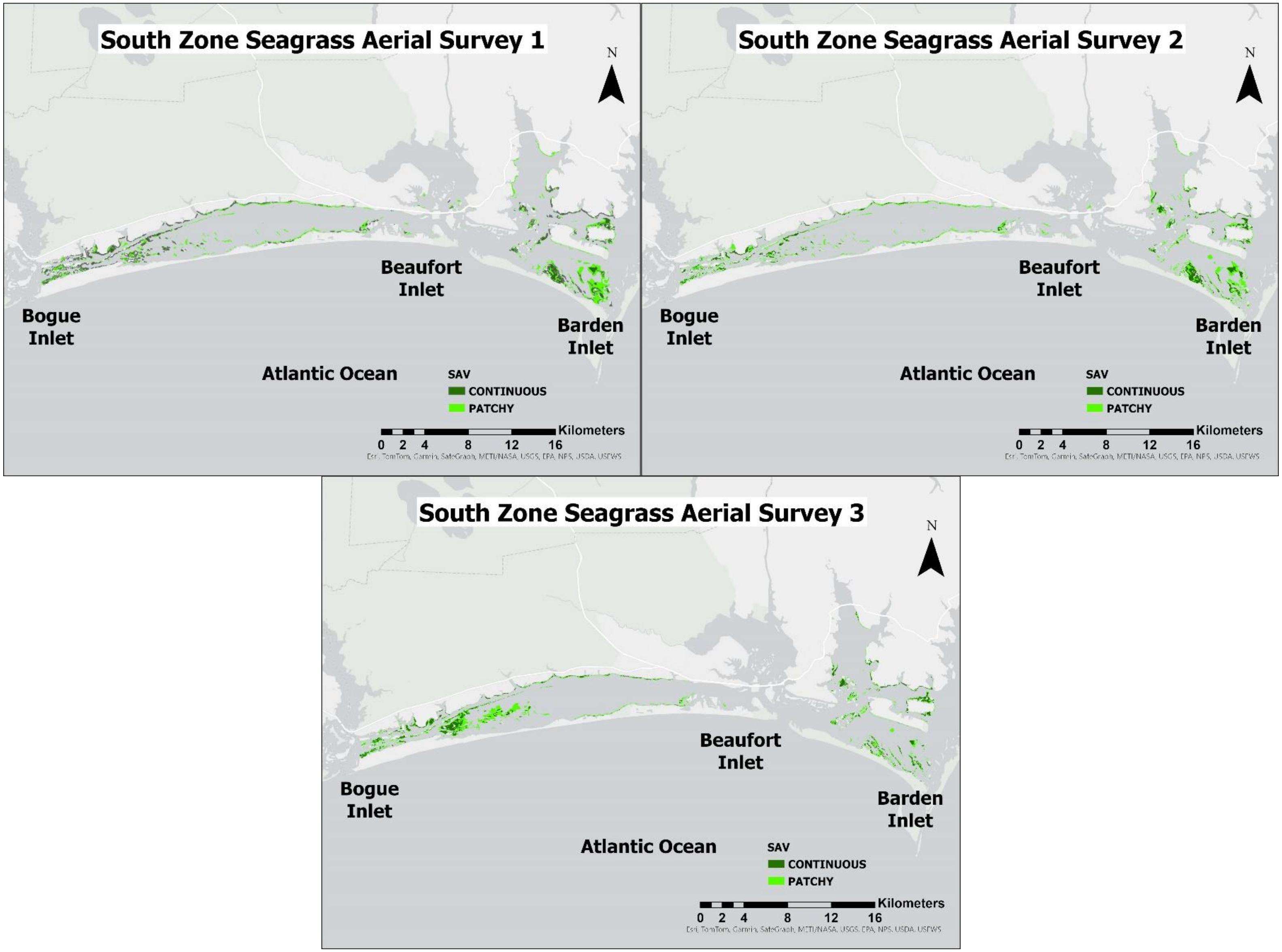

Figure 5. *Seagrass location and spatial cover classes (continuous and patchy) in the South Zone during Surveys 1 (2006-2007), 2 (2013) and 3 (2020).*

Table 9. *Comparison of seagrass extent (acres) in two spatial cover classes, the total extent, the change in acres between each survey, and the percent change in parentheses for the South Zone. Seagrass areas detected in Surveys 1 and 2 were clipped to exclude seagrass delineations from areas that could not be interpreted in Survey 3.*

Spatial Cover Class	Survey 1 2006-07	Survey 2 2013	Survey 3 2020	Change (%) Survey 1 to 2	Change (%) Survey 2 to 3	Change (%) Survey 1 to 3
Continuous	2,003	1,644	1,825	-359 (17.9)	181 (11.0)	-178 (8.9)
Patchy	3,634	3,323	2,786	-311(8.6)	-537 (16.2)	-848 (23.3)
Total	5,637	4,967	4,611	-670 (11.9)	-356 (7.2)	-1,026 (18.2)

Table 10. *All possible categories of spatial cover class change between the three surveys, or classes remaining the same for the South Zone. Seagrass areas detected in Surveys 1 and 2 were clipped to exclude seagrass delineations from areas that could not be interpreted in Survey 3.*

Spatial Cover Class Change Category	Acres 2007-2013	Acres 2013-2020	Acres 2007-2020
Continuous Seagrass to No Seagrass	163	341	515
Patchy Seagrass to No Seagrass	1,495	1,627	2,224
Continuous Seagrass to Patchy Seagrass]	589	416	547
Patchy Seagrass Both Years of Analysis	1,861	1,127	933
No Seagrass to Patchy Seagrass	870	1,243	1,306
Continuous Seagrass Both Years of Analysis	1,250	887	941
Patchy Seagrass to Continuous Seagrass	274	566	473
No Seagrass to Continuous Seagrass	120	371	410

APES COASTWIDE CHANGE ANALYSIS

To estimate changes in seagrass areal extent across the entire APES region for the three surveys, the data in each zone were collated for each survey. As indicated earlier, some portions of the zones in Surveys 1, 2 and 3 could not be interpreted due to turbidity. Therefore, to standardize the spatial footprint, the areas that could not be interpreted across all three surveys were removed (Figure A4). Most notably, some sizable areas in the North Zone in Survey 1, southern Core Sound in Survey 2, and all of mainland Core Sound in Survey 3 were removed from the footprint. To conduct the change analysis, we used Survey 1 as the baseline and removed the areas that could not be interpreted in Surveys 2 and 3 to compute an adjusted baseline for Survey 1 (Table 11). The adjusted baseline for total seagrass extent in Survey 1 (99,398 acres) was 12,309 acres less than the total originally documented (109,607; see Table 1). Likewise, areas that could not be interpreted in Survey 1 were removed from Surveys 2 and 3, and consequently, the areas used in the change analysis (the standardized spatial footprint) were less than the totals documented in Table 1 (Table 11).

Table 11. *Comparison of the adjusted seagrass extent (acres) in two spatial cover classes and the total extent (acres) in Surveys 1 (2006-2007), 2 (2013) and 3 (2020) in the APES region.*

Spatial Cover Class	Survey 1	Survey 2	Survey 3
Continuous	44,978	29,513	20,804
Patchy	54,420	62,021	62,465
Total	99,398	91,534	83,269

Using the adjusted coastwide baseline extent from Survey 1 and data from Survey 3, the total extent of seagrasses declined by 16,129 acres (16.2%) during the 14-year period. The rate of decline was 1.16% y^{-1}, or approximately 1,150 acres per year. As expected, based on the prior analyses of the three zones described earlier in the report, the extent of continuous meadows declined by approximately 50%, and the proportion of patchy meadows increased by 20% over the entire survey period.

DISCUSSION

The three coastwide Tier-1 surveys reported here confirm that the polyhaline waters of APES currently have the largest acreage of seagrass meadows on the Atlantic seaboard. During a comparable timespan in the mid- and south Atlantic regions, estuaries north (Chesapeake Bay) and south (Indian River Lagoon, FL) of APES experienced substantially larger seagrass declines than we documented. This is compelling evidence of the critically important functions and services seagrass habitats are providing to APES, as well as other coastal ocean ecosystems in the region. Despite this optimistic regional comparison, over a period of 14 years we identified three notable changes in the APES seagrass meadows:

1) The total area of seagrass meadows is declining,
2) The rates of change in extent vary spatially and temporally, and
3) The cover characteristics are shifting toward more patchy and fragmented meadows.

Coastwide, over the past 14 years APES has lost about 16,129 acres (16.2%) of its seagrass areal extent at an annual loss rate of about 1.16% y^{-1}. While the loss rate we observed is at the lower end of the global range reported for seagrasses[19, 20], these changes are not trivial. Since 1980 (four decades), it was estimated that 29% of the global seagrass area was lost [21]. By comparison, in just the recent 1.5 decades, seagrass loss in APES is on track to match the global pace of decline, though not at as fast a rate as recently reported for catastrophic losses in the United Kingdom[22]. Given the extent of recent seagrass losses in neighboring Atlantic coastal ecosystems over the past two decades, both north (Chesapeake Bay)[23] and south (Indian River Lagoon, FL)[24] of APES, the changes we are reporting should draw the attention of state and federal resource agencies responsible for managing this habitat.

We also documented evidence of spatial and temporal variability in changes in the extent of seagrass meadows. The Central Zone displayed the greatest rate of change (-1.9 to -2.0% y^{-1}), especially between Surveys 2 and 3 when loss rates in Subarea 2 (3.08%$^{-1}$) were three times the APES regionwide rate. The only evidence of noticeable expansion in acreage occurred between Surveys 2 and 3 in the west subarea of Bogue Sound in the South Zone, but barely offsetting loss in the east subarea. Also notable throughout the surveys were large areas of shallow water in all three zones (< 2.0 m deep) that appeared to be potential or suitable habitat that were unvegetated during the surveys.

Our three surveys also demonstrate that the cover characteristics of the meadows were in transition. Most notable was the widespread transition from continuous to patchy cover and patchy cover to no seagrass. These constituted the largest transitions in all three zones and coastwide, patchy cover increased over time. The fourteen-year record of change indicates that seagrass coverage is becoming more fragmented. The persistent loss in total extent combined with fragmentation of the seagrass meadows deserves notice, given that both metrics are known to affect the function, ecological services, and the resilience of seagrass meadows.[25] These metrics also serve as reliable indicators of potential environmental changes that may be occurring in APES which are directly impacting the growth, reproduction, abundance, and persistence of the meadows. [26]

Why Are These Changes Happening?

A common area of change was observed at the deep-water edge of the seagrass meadows, particularly for the patchy beds that extend from Oregon Inlet to Cape Hatteras in the North Zone. In general, the deepest portions of the beds are the meadow perimeter areas which are most exposed to wave energy originating from northerly wind fetches. Patchy meadows are typically found in relatively higher energy environments in North Carolina.[27] The deep edges of the meadows are also vulnerable to the effects of sea level rise. Typically, the deep edges of the meadows are located at or near the threshold of light limitation for seagrasses and increases in sea level rise further reduce the amount of light reaching the plants.

The three surveys were conducted during an especially active period for tropical cyclones in North Carolina which can physically disturb the meadows and estuarine water quality conditions.[28, 29] From 2010 to 2020, 10 tropical cyclones directly impacted APES.[30] Two storms were especially notable during this period. In 2018, the duration and excessive precipitation from Hurricane Florence had significant physical and water quality impacts in APES. Florence was followed by Hurricane Dorian in 2019, which produced a 2.5-m storm surge in southeastern Pamlico Sound and northern Core Sound. Some of the largest and most acute losses of seagrass extent we observed were in the direct path of the storm surge in the two subareas in the Central Zone between Surveys 2 (2013) and 3 (2020).[30] The storm associated changes were not confined to just the deep edges of the meadows; they were dispersed across the seascape and especially acute on the flood tidal deltas around Ocracoke and Hatteras Inlets where there were large losses of seagrass associated with the widening of the inlets and the shifting of shoals on the flood tidal deltas (Figure A2).[31]

The deeper areas of the meadows are also the most light-limited locations in the beds and thus most vulnerable to changes in water clarity (optical water quality).[32] While a recent compilation of water quality data indicated that water clarity in the polyhaline region of APES is generally suitable for seagrass growth to a depth of 1.7 m, there were a high proportion of locations where clarity was characterized as either fair or poor, meaning the percentage of incident light reaching the plants either did not meet the minimum required (22% incident photosynthetically active radiation (PAR) to 1.7m) or were near the threshold.[33] Given the high temperatures experienced in summer at this latitude, light is critical for seagrasses to maintain a positive carbon balance and oxygenate anaerobic sediments, especially for the temperate species *Z. marina*. A recent study of temperature trends in Back Sound (South Zone) showed that since 1962 extreme water temperatures (≥ 30 °C) have occurred more frequently and summer stressful temperature days for *Z. marina* (≥ 23 °C) have increased from 34 days to 156 days.[34] An analysis of Tier-2 data indicated that declines in meadow biomass in Back Sound since 1979 were primarily attributed to loss of the temperate species, eelgrass[34]. Another recent study has also shown that *Z. marina* populations in North Carolina are highly dependent on flowering, annual seed dispersal, and recruitment from a seed bank; a strategy that results in widely distributed areas of patchy and seasonally ephemeral seagrass meadows.[35] Jarvis et al. (2012) hypothesized that this life history strategy could be a response to avoid thermal stress and allow eelgrass to persist despite increasing summer stressful water temperatures. Therefore, a plausible explanation for some of the changes we have observed in the extent (loss from thermal stress) and cover characteristics (increased patchiness) of the meadows could be partially attributed to the response of *Z. marina* to increasingly higher summer water temperatures and marginal or fluctuating water clarity compounded by an increase in relative storminess.

The seasonal bi-modal abundance of the temperate and tropical seagrass species in North Carolina (monitored with the Tier-2 metric “Relative Abundance of Seagrass Species)” makes it difficult to acquire the peak signatures of both species in one time window. To optimize signature acquisition, we strived to obtain the Tier-1 imagery in late spring (mid-April to mid-June) with the expectation that we could capture the overlap of signatures for both species. For the preferred acquisition period we were able to map the South Zone in all three surveys and obtained nearly complete coastwide assessments in Surveys 2 and 3. As described earlier in this report, we periodically encountered challenges with weather, clouds, tides, aircraft availability, and turbidity that limited imagery acquisition and interpretation. Our initial survey was a hybrid of imagery acquired in May/June 2006 (South Zone) and October 2007 (Central and North Zones). Given that these two acquisition periods were more than a year apart and coincided with the different peak abundances of the species (*Zostera* in May/June, *Halodule* in October) we can’t completely rule out the potential influence of our imagery acquisition schedule in Survey 1 as a factor when interpreting the changes we observed in some of the later surveys conducted in fall. For example, all three zones were mapped in May 2013 during Survey 2, but only the South Zone was acquired in May during Survey 1. Some of the changes we observed between Surveys 1 and 2 in the Central and South Zones could be due to the seasonal shift in species abundance.

Based on the experience gained during these three surveys and our understanding of the ecology of the seagrass ecosystem in North Carolina, we revised our Tier 1 acquisition plan in 2021 to better address the bimodal seasonal abundance of seagrasses in APES. Beginning in 2021 we realigned the three original polyhaline zones into four smaller subregions. Annually, Tier-1 data are now being acquired in both spring and fall to capture the peak signatures of the two dominant species. Around the time of each acquisition, "in-water" Tier-2 data are also being collected at 150 randomly selected and spatially balanced stations by APNEP and partner field teams. To date, Tier-1 and Tier-2 data have been acquired in all of the newly established subregions: the original South Zone that extends from Bogue Inlet to Barden Inlet (2021, 2025); Core Sound, from Barden Inlet to Ocracoke Inlet (2022); Pamlico Sound South from Ocracoke Inlet to Avon (2023); and Pamlico Sound North from Avon to Manteo (2024). Interpretation of the Tier-1 imagery for all surveys as well as an analysis of the Tier-2 data will be included in the next edition of this metric report.

What Is Not Shown by This Metric?

The data presented here cannot be easily compared to earlier seagrass mapping efforts. While some pre-2000 efforts to map seagrass and low-salinity SAV in APES have been performed, they were limited in scope and used different techniques and classification schemes.[36,37,38,39] There are at least three older sources of mapping data under review for Core Sound and Bogue Sound that may provide an opportunity to assess longer-term changes in this important seagrass resource, including 1981, 1985, and 1988. Regarding more recent Tier-1 extent data, the entire geographic range of high-salinity seagrass in APES was flown in June 2019. Unfortunately, only portions of that imagery were interpretable. However, the usable imagery can be interpreted to help fill in some spatial and temporal gaps, especially in areas affected by tropical cyclone activity around that period.

What Are the Implications for Management?

The gravity of climate change is evident in the coastal waters of APES. Summer stressful water temperatures are increasing, sea level is rising, and the magnitude and frequency of storms is predicted to become an even larger component of the physical and chemical disturbances that alter hydrology and water quality in estuarine waters.[40] From a management perspective, this poses two distinct but closely related issues that we need to consider in a seagrass monitoring network.

The first question is how do we distinguish the effects of environmental factors attributed to climate change from the potentially manageable anthropogenic disturbances that impact seagrass (e.g., impaired water quality)? While the trends we report here are convincing indicators of both a sustained loss in extent and a change in structure of the seagrass meadows throughout APES, the Tier-1 data alone do not provide compelling explanations for why these changes are occurring and which factors are primarily driving the changes.[41] To provide managers with the evidence they need to make informed decisions, for example, implementation of a water clarity standard to protect seagrass[42], it is essential that a monitoring program collect and integrate Tier-2 and Tier-3 data with Tier-1 information. The recently adopted seagrass monitoring strategy addresses some of these needs and will be a critical component of both the short- and long-term management efforts in APES.

The second issue addresses a separate but related question. In lieu of climate change and the possibility that some of the factors affecting seagrass abundance are at a global scale and not directly manageable at the scale of APES, how can a monitoring program contribute to an understanding of the resilience of seagrasses in the APNEP region? We alluded to this earlier in the discussion regarding the importance of Tier-2 data for species composition and the differences in life history strategies between the dominant seagrass species. Based on the Tier-2 data for species composition we have compiled thus far, about 50% of the seagrass meadows in APES are comprised of mixed species dominated by *Zostera* and *Halodule*.[43] The remaining distribution is made up of nearly evenly divided monotypic meadows of each species. While we haven't yet thoroughly analyzed the temporal or spatial trends in the species composition data, the tiered and integrated monitoring program that APNEP has adopted is poised to assess whether increasing water temperatures are differentially affecting the species composition of the meadows and the resilience of the APES seagrass ecosystem to climate change. Integrating this information with Tier-2 water clarity data will contribute to a better understanding of the interaction of these factors and help explain changes in the distribution and abundance of seagrasses, as well as the effectiveness of a water clarity standard.[44]

Setting aside this uncertainty, the sustained trends in the Tier-1 data we observed over 14 years are unambiguous indicators of change in the extent and structure of the seagrass meadows. The loss of approximately 14,000 acres estimated in our APES coastwide change analysis is nearly 16% of the resource we documented in 2020, and a larger fraction of the resource is transitioning to a state of partial fragmentation. These changes are altering the functions and services of the seagrass meadows with implications that deserve the immediate attention of resource managers. While managing the factors we know affect seagrass condition (e.g., sediment and nutrient loading, water quality, watershed and coastal land use) is important, it will also be crucial to implement new approaches to mitigate the effects of climate change (e.g., increased storminess, rising temperatures, elevated sea level) to avoid large and lasting impacts to APES.

What are the Proposed Ultimate and Interim Targets for this Metric?

Several approaches have been taken to derive "assessment points" for a Tier-1 extent metric. One alternative has been to utilize potential/suitable habitat models to estimate spatial extent of seagrass based on parameters such as water depth, water quality, sediment type, and wind exposure[45]. In principle, a modelling approach is attractive, but in practice it is prone to error by data limitations, especially bathymetry and water quality data. Alternatively, stakeholders within estuarine systems such as Chesapeake Bay and Tampa Bay derived ultimate targets with reference to historical seagrass extent provided by both local knowledge, in-water surveys, and aerial images from decades past. For the limited number of APES water bodies where historical aerial images of adequate quality exist to detect seagrass extent, ultimate targets could be proposed in a similar manner. However, for many APES waterbodies no such historical data archive exists.

The North Carolina Department of Environmental Quality (NCDEQ) proposed using the "known historical maximum extent" as an interim SAV protection and restoration goal in the recently amended Coastal Habitat Protection Plan (CHPP).[46] The acreage estimates in the historical extent were obtained from 40+ years of studies and mapping efforts assembled into one composite layer for nine regions in North Carolina. The known historical extent of seagrass in APES comprised three of the nine regions for a total of 149,427 acres and included APNEP's first survey (2006-2007), which was the largest acreage documented of the three surveys the Partnership has conducted. The estimated historical maximum extent estimate is 41% larger than what we documented in Survey 1 (109,607 acres; see Table 1); a difference of approximately 39,820 acres. By Survey 3 in 2020, the difference in the documented extent (88,531 acres) and the historical extent was even larger. We suspect that this difference may indicate long-term declines in seagrass extent that managers should be aware of; however, we don't have reliable historical seagrass maps going back to 1980 to confirm the extent of these changes. Furthermore, APES has lost about 16,000 acres of seagrass since Survey 1, some of which we are confident is "potential habitat" that can be repopulated by seagrass, assuming our management practices preserve the environmental conditions that sustain persistent seagrass meadows and promote their reestablishment. Preliminary interpretations of recently acquired aerial imagery indicate that some areas have been repopulated with seagrass since 2020. Based on this information, we continue to recommend an interim goal for this metric be based on APNEP's Survey-1 extent. Given the headwinds of declines and changes in the structure of the meadows over the past 14 years, it will be more plausible to attain this interim goal than the historical maximum extent recommended in the 2021 amendment of the CHPP.[47] If APNEP's monitoring network provides data indicating that the trend in seagrass decline has been reversed, such an interim goal could be adjusted upward within the boundaries of the historical maximum extent.

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APPENDIX

Data Description

All imagery for Surveys 1 and 2 were collected with Intergraph's Z/I Digital Mapping Camera (DMC) (bands = red, green, blue, near infrared). For Survey 1, images along the mainland and Outer Banks of Bogue Sound and Back Sound, and the mainland side of Core Sound north to Atlantic, North Carolina were collected on May 31 and June 1, 2006. Aircraft height was 10,000 ft (3,048 m) for a final imagery product with 1 ft (0.3 m) pixel size. All other areas for Survey 1 were collected on October 12, 14, and 15, 2007 with an aircraft height of 20,000 ft (6,096 m) for a final imagery product with 3.28 ft (1.0 m) pixel size.

For Survey 2, all data were collected at an aircraft height of 10,000 ft (3,048 m) for a 1 ft (0.3 m) pixel size. Images along the mainland and Outer Banks of Bogue Sound and Back Sound were collected on May 27, 2013. Images along the Outer Banks of Pamlico Sound from Ocracoke Inlet to Manteo (north to Highway 64) were collected on May 30, 2013.

Imagery for Survey 3 was collected with Vexcel Imaging's UC Eagle Mark 3 Camera (bands = red, green, blue, near infrared). Aircraft height was 11,300 ft (3,444 m) for a final imagery product with 0.5 ft (0.15 m) pixel size. Imagery for the South and Central Zones was collected May 16, 2020, and for the North Zone on June 1, 2020.

Data Manipulation

The imagery was loaded into ArcGIS (Environmental Systems Research Institute) for manual on-screen digitizing using procedures described in Rohmann and Monaco (2005). The digitizing scale was typically set to 1:1,500 except when larger homogenous areas required zooming out to a greater extent that was usually accomplished at approximately 1:6,000. Habitat boundaries were delineated around benthic habitat features (e.g., areas with visually discernable differences in color and texture patterns). The scanned images were occasionally manipulated in terms of brightness, contrast and color balance to enhance interpretability of subtle features and boundaries. This was extremely helpful, especially in deeper water where subtle boundaries or problems caused by turbidity made features difficult to detect. The classification scheme consisted of three spatial cover classes: continuous, patchy, and no seagrass. Continuous seagrass was defined as areas covering 70% or greater of the substrate that may contain unvegetated or sparsely vegetated areas that are smaller than the minimum mapping unit (MMU = approximately 0.2 ha in this study). Patchy seagrass was defined as discontinuous communities covering more than 10% but less than 70% of the substrate. These areas were diffuse and irregular consisting of isolated patches that are below the MMU. Areas with less than 10% seagrass are considered beyond the level of detection of the imagery used and thus were not mapped. For purposes of a change-detection analysis, these unmapped areas with less than 10% seagrass were classified as "no seagrass".

The categorical transition classes shown in Tables 3, 5, 8 and 10 could not be generated using polygonal data. Therefore, the polygonal data was rasterized to a 2 m pixel size in ArcGIS Pro using the "Polygon to Raster" tool. In the rasterization process, all areas in each survey period with no seagrass cover were labeled “No Seagrass”. To perform the change analysis between two surveys, the pixels were first reclassified to numerical values (Table A1) using the ArcGIS Pro “Reclassify” tool.

Table A1. After rasterizing the seagrass maps, the habitat classes were reclassified to the numerical values indicated below.

Vegetation Class	**Reclassified Value**	
	Survey A	**Survey B**
Continuous	1	100
Patchy	2	200
No Seagrass	3	300

The change analyses were then generated by subtracting the later survey period from the initial survey period in the ArcGIS Pro “Raster Calculator” tool. The resultant values were then linked back to the vegetation classes so that the descriptions could be attributed to the changes (Table A2).

Table A2. The values are the result of the subtraction of the rasterized, reclassified later time period survey from the initial survey. The descriptions are the vegetation transition classes.

Value	**Description**
-99	Continuous Seagrass Both Years of Analysis
-98	Patchy Seagrass to Continuous Seagrass
-97	No Seagrass to Continuous Seagrass
-199	Continuous Seagrass to Patchy Seagrass
-198	Patchy Seagrass Both Years of Analysis
-197	No Seagrass to Patchy Seagrass
-299	Continuous Seagrass to No Seagrass
-298	Patchy Seagrass to No Seagrass

Data Quality/Caveats

While the relative clarity and shallowness of high-salinity estuarine waters where seagrass habitat exists in APES allow a theoretical census of seagrass habitat via high-altitude aerial surveys, there are places and conditions where the seagrass is invisible on the digital images regardless of the interpreters’ skills. For example, areas of high boat traffic or localized thunderstorms can cause turbidity that can temporarily obscure seagrass beds.

There were also seasonal imagery acquisition differences that complicated the analyses. The 2007 imagery (1.0 m pixel resolution) for the North and Central Zones was acquired in September/October, while all three zones in 2013 were acquired in May/June (0.3 m pixel resolution) and all three zones in 2020 were acquired in May/June (0.15 m pixel resolution). The South Zone was the only zone where imagery was acquired in the same season; first in May 2006

(0.3 m pixel resolution), next in May 2013 (0.3 m pixel resolution) and finally in May 2020 (0.15 m pixel resolution). The analyses are confounded by the presence of two dominant seagrass species that have different seasonal cycles of abundance. The temperate species, *Zostera marina*, reaches peak abundance in spring and early summer, while the tropical species, *Halodule wrightii*, peaks in summer and early fall. The ideal time to capture both species in the imagery is in early summer, but due to haze, cloud cover, and turbidity caused by rain, it is very difficult to acquire imagery during the ideal signature period. Therefore, some of the changes observed in the North and Central Zones, especially the transitions between continuous and patchy classes, could reflect the seasonal transition in the relative abundance of the two species.

Approximately 1,000 field points were visited in Survey 1 and 800 in Survey 2. The points were randomly generated in GIS, based on areas where seagrass was previously mapped or in water down to two meters in depth. Points were located in small craft with the aid of Differential Global Positioning Systems (DGPS) or Wide Area Augmentation System (WASS). Areas were identified visually from the boat (or wading in shallow waters) or with the aid of rakes where the bottom could not be visualized. Field points from Survey 1 were used as training data in some parts of the study area. Field points from Survey 2 did not become available in time to inform the interpretation of that image data set. The field points, from both surveys, while randomly selected, were not used to perform accuracy assessments. It was determined that the use of rakes, especially near the 2-m maximum depth of seagrass occurrence often missed seagrass in obviously patchy areas, simply by raking between patches. It was also probable that rakes sometimes picked up loose seagrass with root material, drifting along the bottom, giving false positives for seagrass where none existed. Due to Covid restrictions, no field points were collected in 2020.

Data Availability

The data, in GIS format, can be downloaded from the NCDEQ GIS data portal found here.

Data Gaps

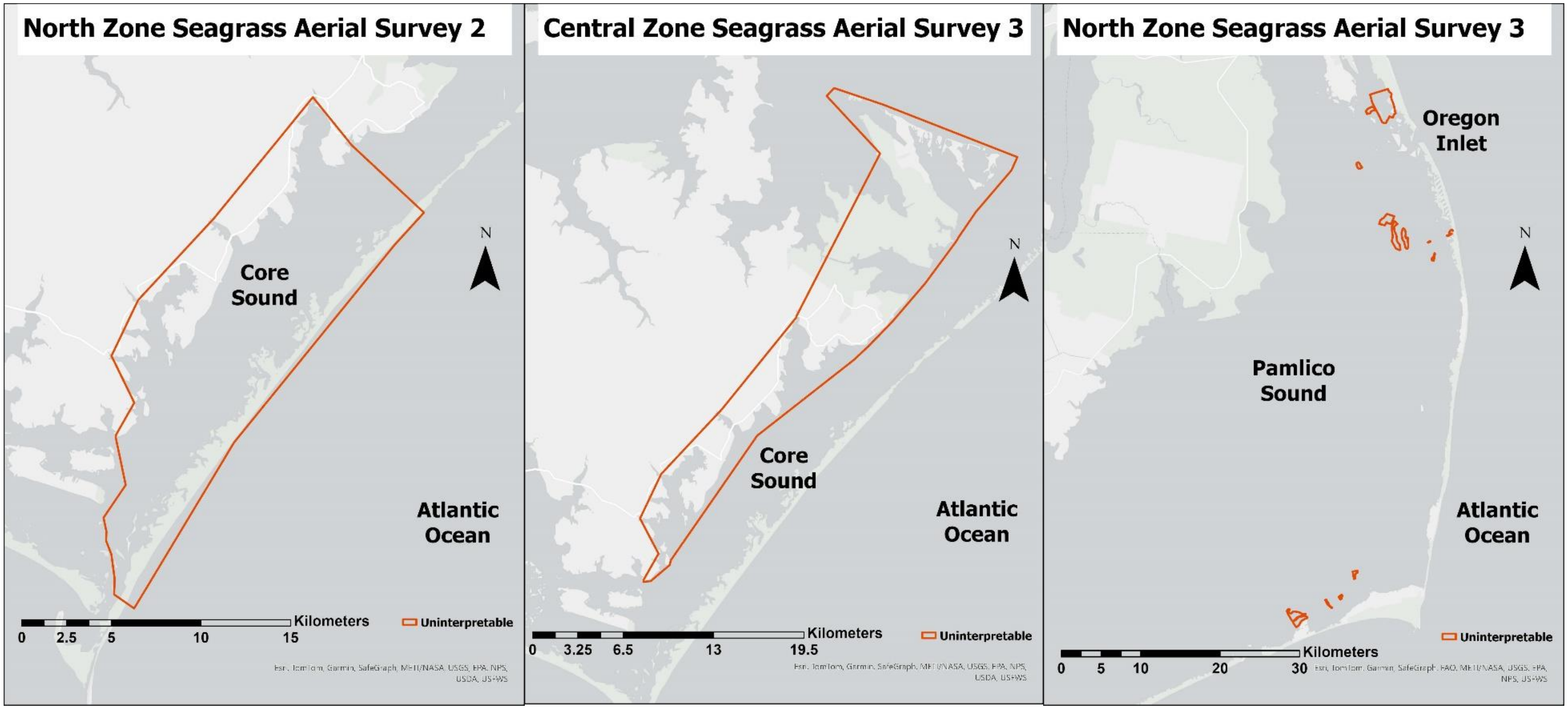

Figure A1. *Areas delineated by the red polygons were uninterpretable in the Central Zone in Survey 2 due to clouds, the Central Zone in Survey 3 due to turbidity and the North Zone in Survey 3 due to turbidity.*

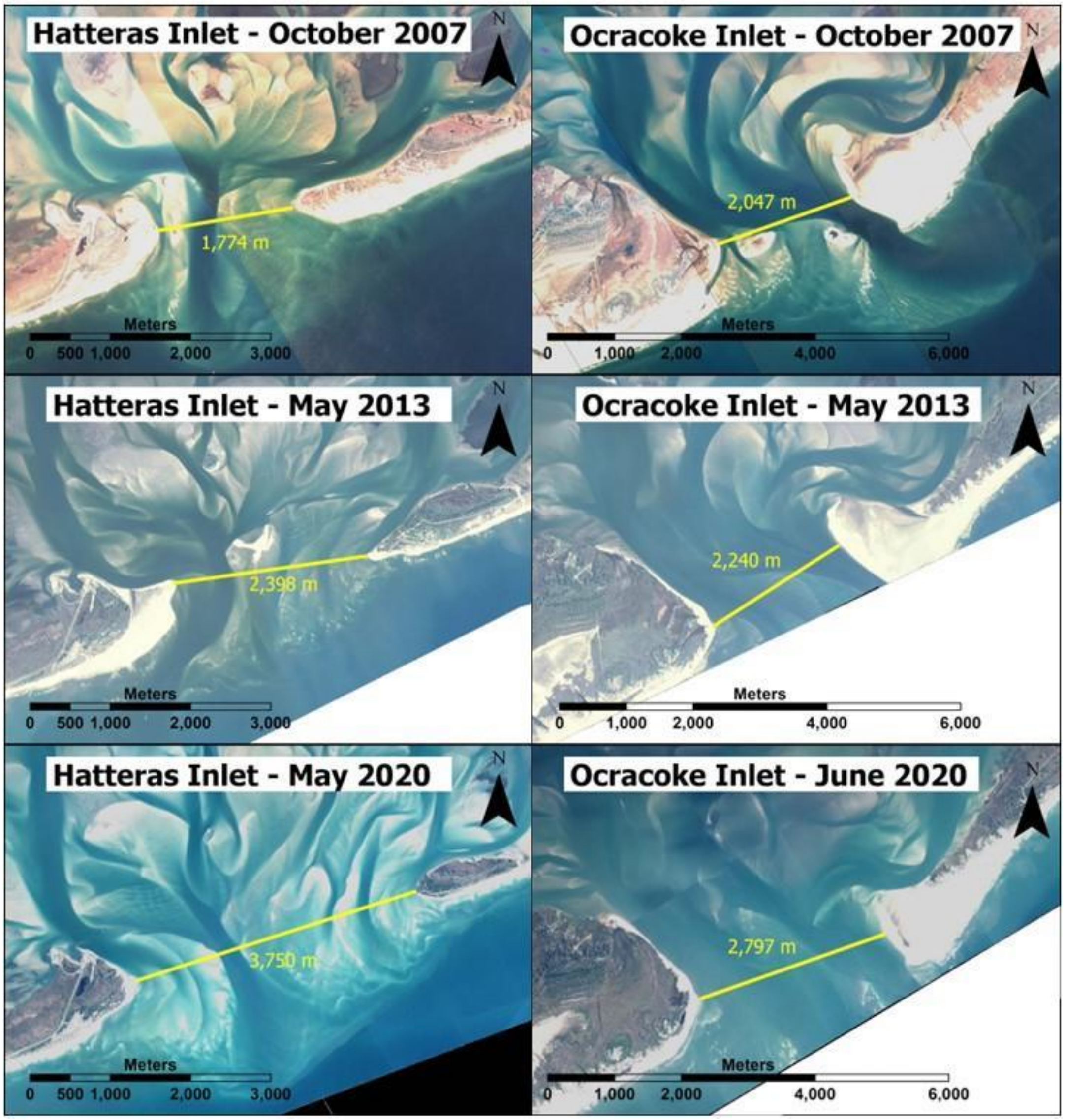

Figure A2. *Aerial imagery and inlet widths for Hatteras and Ocracoke Inlets from all three survey periods. Inlet width was a simple measurement between the land points on both banks that extended farthest into the inlet.*

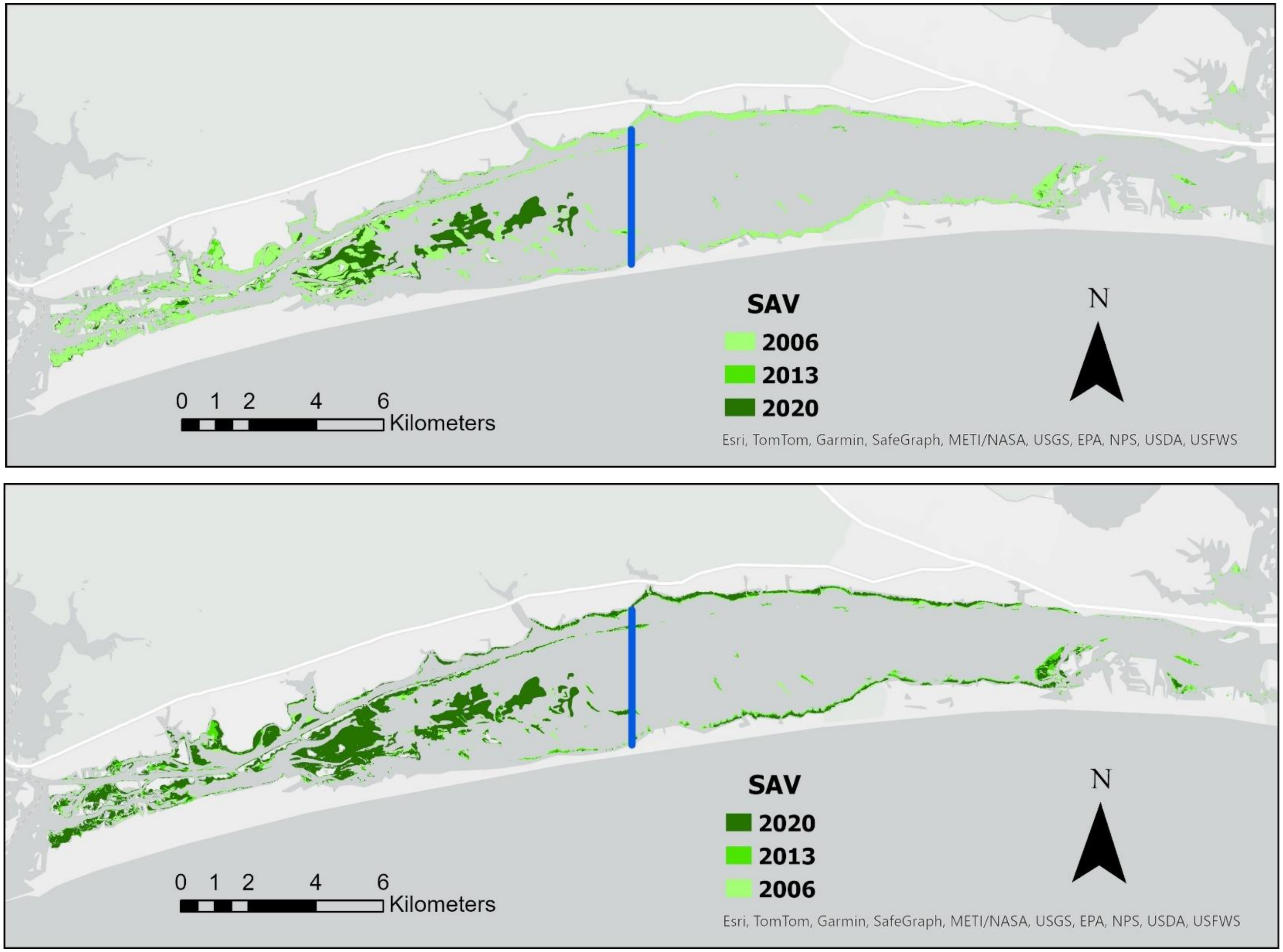

Figure A3. *Seagrass extent (continuous and patchy combined) in Bogue Sound during Surveys 1(2006), 2 (2013) and 3 (2020). Blue line delineates the boundary where seagrass habitat increased in western Bogue Sound and decreased in eastern Bogue Sound. Top panel shows the 2006 extent (apple green) on the bottom. The bottom panel shows the 2020 extent (dark green) on the bottom.*

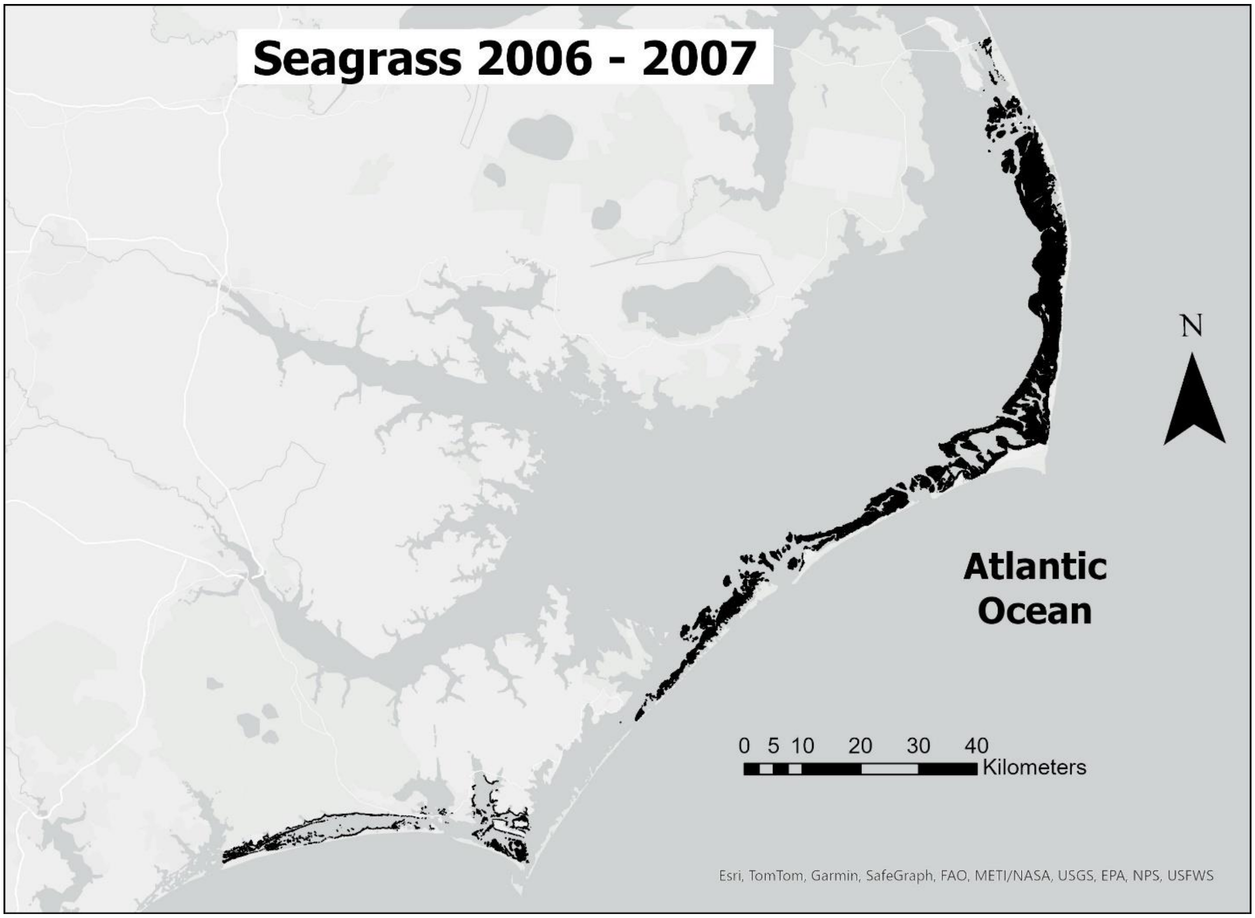

Figure A4. *Map showing the adjusted 2006-07 seagrass extent. Both continuous and patchy cover categories are displayed in black to highlight the areas where imagery was interpreted across all three mapping periods.*