

# An Integrated Assessment of Habitat Quality of National Estuarine Research Reserves in the Southeastern United States

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## ABSTRACT

Multiple indicators of water quality, sediment quality, and biological condition were used to assess the status of ecological condition of National Estuarine Research Reserve System (NERRS) sites in North Carolina, South Carolina, and Georgia relative to a suite of corresponding scoring criteria. All measurements were made in subtidal aquatic habitats. Calculated scores were integrated into an overall index of habitat quality and used to make comparisons among the various NERR and non-NERR estuaries throughout the region. Sediment quality scores varied considerably among NERR sites, but in most cases were similar between individual NERR and non-NERR sites in corresponding states. Water quality and biological condition indicators scored consistently higher for NERRs versus non-NERR sites. Overall habitat quality scores also were consistently higher for NERRS sites, suggesting that these areas are on par with if not in slightly better condition ecologically than neighboring non-NERR estuaries. Portions of individual NERR sites rated as poor with respect to overall habitat quality were limited to relatively small areas (<13% of a reserve's total sampling area). *Integr Environ Assess Manag* 2014;X:000–000. Published 2014 SETAC. This article is a US government work and, as such, is in the public domain in the United States of America.

**Keywords:** Coastal ecosystem health Habitat quality National Estuarine Research Reserve System NERRS Southeastern US estuaries

## INTRODUCTION

The National Estuarine Research Reserve System (NERRS) consists of a network of 28 protected areas throughout different biogeographic regions of the United States and Puerto Rico, established for long-term research, water- and atmospheric-quality monitoring, education, and coastal stewardship. The NERRS was created by the Coastal Zone Management Act of 1972, as amended, and is a partnership program between the National Oceanic and Atmospheric Administration (NOAA) and coastal states and territories. The NERR System-Wide Monitoring Program (SWMP) was developed to improve fundamental understanding of the temporal and spatial dynamics of estuarine processes and to provide baseline information for evaluating change in ecosystem function in response to natural and human disturbances (NERRS 2011a). Although water quality monitoring has been a major focus of SWMP, additional research efforts of various partnering institutions provide a variety of other complementary data to help address NERRS science and management needs.

NOAA's National Centers for Coastal Ocean Science (NCCOS) routinely conduct integrated assessments of ecological condition and stressor impacts in coastal regions of the United States from estuaries to offshore areas of the continental shelf. As part of this effort, NCCOS conducted studies in partnership with NERRS throughout subtidal estuarine habitats of the 4 North Carolina (NC) NERRS components in 2006 (Cooksey et al. 2008) and the Sapelo Island, Georgia (GA) NERR in 2009 (Balthis et al. 2012). The GA NERR study also represents part of the subtidal-benthic component of an ongoing, multidisciplinary, collaborative Ecological Assessment Project at the reserve (NERRS 2013).

The NC NERR includes 4 geographically separate components. The northernmost component, Currituck Banks, encompasses 3.9 km<sup>2</sup> of estuarine open water and irregularly exposed mud flats, marsh, upland, and ocean shoreline habitat along the northern NC Outer Banks. Tidal influence on the Currituck Sound side is virtually absent because the nearest ocean inlet is located approximately 70 km away. This latter area is characterized by low salinities (0 to 20 psu), shallow water depths, and areas of submerged aquatic vegetation (SAV). The Rachel Carson component (9.4 km<sup>2</sup>) of the NC NERR is located in the central coastal portion of the state near Beaufort, NC. Except for Taylor's Creek that is dredged periodically to a depth of 4 m, water depths are typically less than 2 m. Adjacent to Beaufort Inlet, Rachel Carson experiences salinities close to ocean concentrations of approximately 35 psu. Masonboro Island is the largest NC NERR component

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(22.9 km<sup>2</sup>) and is the largest undisturbed barrier island along the southern part of NC (NERRS 2008a). The fourth NC NERR component, Zeke's Island (6.6 km<sup>2</sup>), is located in southeastern NC just to the south of Kure Beach. The last oceanic inlet in the area closed in 1999; hence, Zeke's Island has no direct water exchange with the Atlantic Ocean and is dependent on the water quality of the lower Cape Fear River estuary (NERRS 2008a).

The Sapelo Island, GA NERR includes 24.7 km<sup>2</sup> of tidal salt marsh and associated hammocks and upland maritime forest in the Duplin River estuary, in coastal GA. The Duplin River drains a tidal bay and an extensive network of salt marshes approximately 6 miles long, and is more accurately described as a large tidal creek than a river (NERRS 2008b). Mean tidal range at Sapelo Island is approximately 2 m and tidal flushing is incomplete, as there is little freshwater entering the system. Much of the water in the estuary oscillates back and forth, rather than draining away and being replaced (NERRS 2008b).

Another related collaborative effort, the South Carolina Estuarine and Coastal Assessment Program (SCECAP), involves the South Carolina Department of Natural Resources (SCDNR) and South Carolina Department of Health and Environmental Control (SCDHEC), as the 2 lead state agencies, and NCCOS laboratories in Charleston, South Carolina (SC). SCECAP was initiated in 1999 to conduct periodic assessments aimed at evaluating the overall health of SC estuaries based on a combination of water quality, sediment quality, and biological condition indicators (Bergquist et al. 2009, 2011; Van Dolah et al. 2013). Some of the stations sampled in SCECAP fall within the boundaries of 2 SC NERRs: Ashepoo-Combahee-Edisto (ACE) Basin NERR and North Inlet-Winyah Bay (NIWB) NERR.

The NIWB Reserve (76.5 km<sup>2</sup>) consists of 2 separate, although connected, estuaries. North Inlet is a small, ocean-dominated estuary that is minimally impacted by human activities. Most of the North Inlet watershed is currently in an undeveloped state. Winyah Bay, a classic estuary fed with freshwater from 4 major rivers, is adjacent to the city of Georgetown, which includes residential, commercial, and industrial developed areas (NERRS 2011b). The ACE Basin NERR is located in portions of Colleton, Charleston, Beaufort, and Hampton counties and encompasses approximately 400 km<sup>2</sup> that includes salt and brackish-water marsh, maritime forest, upland pine, and bottomland hardwood habitats in a largely undeveloped landscape (SCDNR 2011).

Both the NCCOS and SCECAP studies incorporate many of the same standard methods and indicators applied in the United States Environmental Protection Agency's (USEPA) National Coastal Assessment (NCA), a nationwide program conducted in partnership with other federal, state, and academic institutions to assess status of ecosystem condition throughout the nation's coastal waters (USEPA 2012). In all of these programs, multiple measurements of water quality, sediment chemistry and toxicity, benthic infaunal assemblages, and tissue contaminants are obtained using standard sampling procedures and rigorous quality assurance (QA) protocols. A probabilistic sampling design, which selects stations randomly throughout the various survey areas, is also used to provide a basis for estimating the spatial extent of condition relative to the various measured indicators and corresponding evaluation threshold values (Diaz-Ramos et al. 1996; Stevens and Olsen 2004).

The consistent approach used in these various studies enables comparisons among the various southeastern (SE) NERR reserves, and between NERR and non-NERR (NCA) estuarine areas. In this article, we provide an assessment of the status of habitat quality throughout NERR reserves in NC, SC, and GA using a common suite of water quality, sediment quality, and biological condition indicators. An additional goal is for this approach to serve as a model for similar applications in other regions to support comparisons of the health of NERRS resources as a national network of sentinel monitoring sites.

## METHODS

Data used in this study were compiled from field surveys conducted between 2005 and 2009 by NOAA, SCECAP, and EPA (Table 1). Data from NC NERR sites were collected by NOAA in 2006 (Cooksey et al. 2008). Data from SC NERR sites (ACE Basin and NIWB) were collected through the SCECAP program between 2005 and 2009 (Bergquist et al. 2009, 2011; Van Dolah et al. 2013). GA NERR data were collected by NOAA in 2009 (Balthis et al. 2012). Comparisons of NERRS sites to other, non-NERRS sites throughout the southeast (NC, SC, GA) were made using NCA data from 2005 to 2006 (USEPA 2006). Although SCECAP also collected data from non-NERR sites in SC from 2007 to 2009, those data were not used in the present analysis because NCA data from non-NERR sites in other states were only available for 2005 to 2006.

**Table 1.** Sources of data for NERR and non-NERR estuaries

Region	Source of data	Subregions	Sampled area (km <sup>2</sup> )	Nr sampling sites
NERRS	NOAA (2006, 2009)	North Carolina	22	30
		Sapelo Island, Georgia	3	30
	SCMRR/SCECAP (2005–2009)	ACE Basin, South Carolina	163	28
		North Inlet-Winyah Bay, South Carolina	24	3
Non-NERRS	USEPA (NCA 2005–2006)	North Carolina	15,476	50
		South Carolina	1508	85
		Georgia	1332	50

Sampling sites were distributed throughout each respective sampling area using a stratified, equal-probability survey design (Diaz-Ramos et al. 1996; Stevens and Olsen 2004; also see above individual project references). Estuarine subtidal boundaries were delineated using a combination of US Fish and Wildlife Service National Wetlands Inventory (NWI) (Cowardin et al. 1979), NOAA Coastal Change Analysis Program (2013), and NERRS Habitat Classification Scheme (Kutcher et al. 2005) data sources. Although a stratified design was used for sampling, the analyses were conducted as if the design were unstratified, using strata to define subpopulations for analysis (Kincaid 2012).

Instantaneous measurements of near-bottom water temperature (T), salinity (S), dissolved oxygen (DO), and pH were acquired using multiple-sensor data sondes. For SC NERR sites, bottom pH was only available as readings logged in 15 min intervals over a 25 h period; hence, the 25 h average pH reading was used for SC NERR sites. Near-surface water samples were analyzed for total nitrogen (TN), total phosphorus (TP), chlorophyll *a* (CHL-*a*), total suspended solids (TSS), turbidity (TU), and fecal coliform bacteria (FC) using standard procedures. No FC counts were available for NC NERR sites. Samples of bottom sediments were collected using a 0.04 m<sup>2</sup> Young-modified Van Veen grab sampler. Surficial sediments (upper 2 cm) from multiple grabs were composited on-site for subsequent laboratory analysis of chemical contaminants, sediment toxicity, grain size, and total organic carbon (TOC). Separate grab replicates were retained for identification and enumeration of benthic macro-infauna (sieved at 0.5 mm). Although measurements of sediment toxicity were available for all study areas, results presented here for NERR sites were based on the Microtox<sup>®</sup> solid-phase assay (Microbics 1992); those for non-NERR/NCA sites in NC and GA were obtained using the *Ampelisca abdita* amphipod assay (1993); results for SC (non-NERR/NCA) were based on a 7 d juvenile clam growth assay using *Mercenaria mercenaria* (Ringwood and Keppler 1998). For further details on methods of sample collection and analysis, the reader is referred to individual project reports for corresponding study areas: NC NERRS (Cooksey et al. 2008), SC NERRS (Bergquist et al. 2009, 2011; Van Dolah et al. 2013), GA NERRS (Balthis et al. 2012), and non-NERR southeastern estuaries (USEPA 2012).

Individual measures of water quality, sediment quality, and biological condition were combined into an overall habitat quality index (HQI) using a scoring approach similar to those used by federal agencies in national coastal condition reports (USEPA 2012) and some states in their state-level assessments (Carlton et al. 1998; Partridge 2007). The indices applied here follow closely those developed for SCECAP (Van Dolah et al. 2013). Briefly, individual measures of water quality, sediment quality, and biological condition were classified according to the criteria shown in Figure 1 into categories of “poor” (=0), “fair” (=3), and “good” (=5). Each index was obtained by averaging the component scores, then reclassifying the resulting mean score as “poor” (<3), “fair” (≥3 and <4), or “good” (≥4). Note that although the SCECAP protocol includes fecal coliforms in the calculation of the Water Quality Index (WQI), coliform data were excluded from the present calculations because these data were not available for all site categories (i.e., NC NERR and non-NERR/NCA sites). The sediment quality index (SQI) incorporated measures of TOC, toxicity, and mean effects–range median quotient (mean ERM-Q) (Long et al. 1995). A benthic biological condition

index (BCI) was obtained by classifying calculated values of the benthic index of biological integrity (B-IBI), a multimetric index that incorporates measures of infaunal abundance, richness, percent dominance, and percent sensitive taxa (Van Dolah et al. 1999). Although the reader is referred to Van Dolah et al. (1999) for details of B-IBI calculations, the basic approach classifies sites according to scores calculated from values of the benthic metrics listed above, specified for each of 4 habitat types defined by latitude and salinity. The BCI used here is obtained from values of the B-IBI as shown in Figure 1 (i.e., “poor” = B-IBI < 2, “good” = B-IBI ≥ 3).

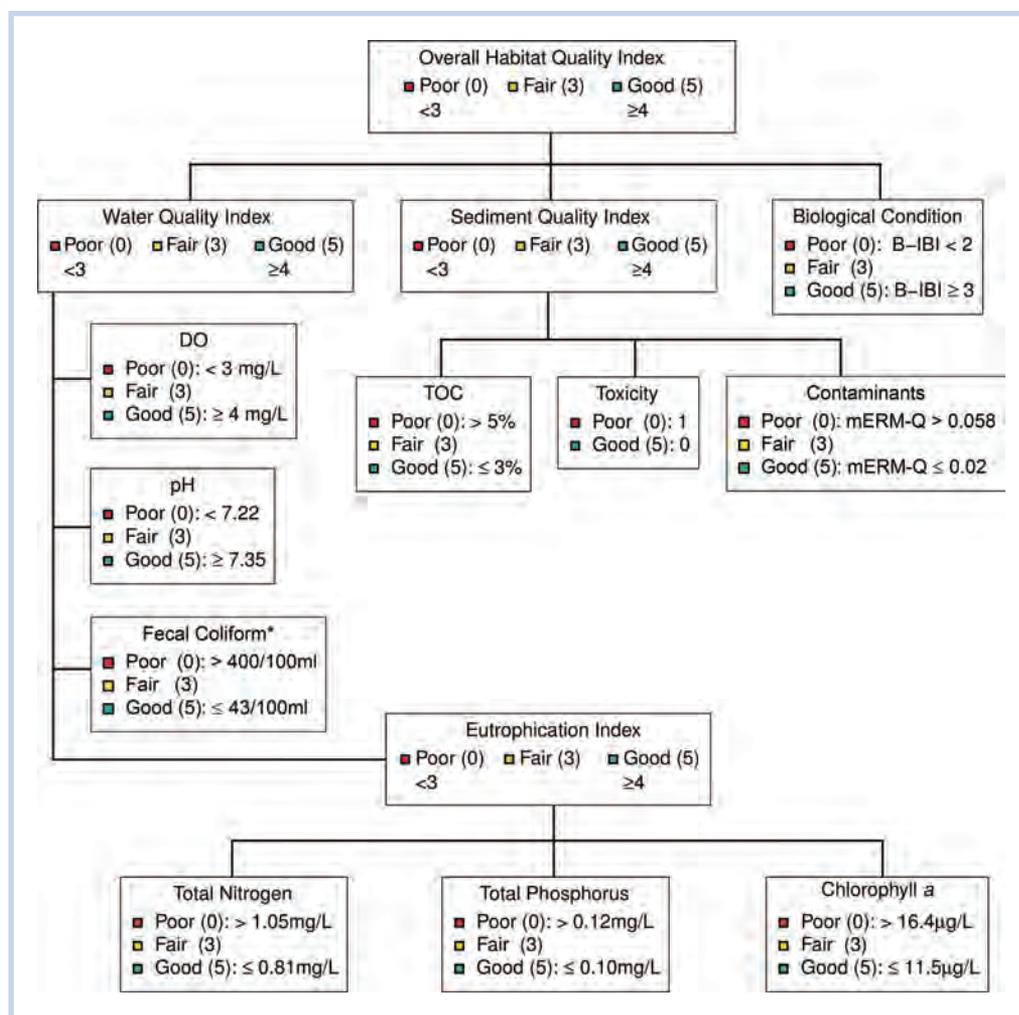
The use of a probabilistic sampling design allowed estimation, with known confidence, of the percent area of the surveyed region classified as “poor,” “fair,” or “good,” as described above. Estimates were based on procedures described in Diaz-Ramos et al. (1996) for obtaining an approximate cumulative distribution function (CDF) and implemented in the *spsurvey* package (Kincaid and Olsen 2013) for R statistical software (R Core Team 2013).

## RESULTS

Summary statistics (mean ± standard error [SE]) for individual measures and combined indices of water and sediment quality, biological condition, and overall habitat quality are presented in Table 2, separately for each NERR (NC, SC, GA) and for non-NERR estuaries by state (NCA data for NC, SC, and GA, 2005–2006). Table 3 lists point estimates of the percent area rated as good, fair, or poor based on individual scoring criteria for each of the combined indices and corresponding component metrics. Figure 2 provides a visual comparison of these estimates (% area with 95% confidence intervals [95% CI]) among NERRs and non-NERR estuaries for the overall HQI and its 3 main component indices (WQI, SQI, and BCI). Combined estimates for NERRs (SENERR) and non-NERR estuaries (southeast NCA) are also shown for comparison (but see cautionary note in Discussion section).

Although there was considerable overlap of confidence intervals among site categories for most indices, some notable patterns are apparent from Figure 2. With respect to the WQI, proportions of area rated as good were consistently higher at individual NERRs compared to non-NERR estuaries in corresponding states—88% versus 61%, 83% versus 76%, and 87% versus 72% for NC, SC, and GA, respectively (Figure 2, Table 3). The difference was the largest (with nonoverlapping 95% CIs) in the case of NC. In contrast, the proportion of area with WQI scores in the fair range was higher at non-NERR sites in NC compared to NERRs in NC as well as other subregions. Very few sites (<13% area of each respective subregion, Table 3) were rated poor for water quality, with none of the NC NERR sites having WQI scores in this low category. Although the GA NERR had a low proportion (27% area) rated good for DO, high scores in all of the other water quality components resulted in a relatively high proportion of the reserve (87% area) rated as good with respect to the WQI (Table 3).

Proportions of area rated as good, fair, or poor with respect to sediment quality in most cases were comparable between NERR and non-NERR estuaries in corresponding states (Figure 2). Most NERR and non-NERR site categories had large proportions of area, 76% or more (Table 3), with SQI scores rated in the good range. However, as an exception to this general pattern, the GA NERR had a lower percentage of area (63%) with SQI scores rated as good compared to non-NERR GA estuaries



**Figure 1.** Scoring criteria used to derive indices of eutrophication and water quality, sediment quality, biological condition, and overall habitat quality. \*Note: Fecal coliform data were not available for NC NERR or non-NERR NCA sites and thus were excluded from calculation of WQI.

(94%). Moreover, the GA NERR had higher proportions of area with SQI scores in the fair and poor ranges compared to non-NERR estuaries in GA. Differences in SQI scores between NERR and non-NERR sites in GA resulted mainly from the proportion rated as good with respect to sediment toxicity: the majority of non-NERR sites in GA (98% area) were rated as good for sediment toxicity (based on the *A. abdita* assay) compared to only 70% area of GA NERR (based on the Microtox assay). The potential implications of comparisons using different toxicity tests is discussed further below.

All 3 NERRs had large portions, 76% or more (Figure 2, Table 3), with healthy benthic communities as evidenced by BCI scores in the good range. Percentages of area with BCI scores rated as good were consistently higher at individual NERR reserves compared to non-NERR estuaries in corresponding states—76% versus 64%, 87% versus 81%, and 80% versus 50% for NC, SC, and GA, respectively. The difference was the largest (with nonoverlapping 95% CIs) in the case of GA. The proportion of area with BCI scores in the fair range was also highest for non-NERR sites in GA although the 95% CI overlapped those from the corresponding GA NERR.

As described above, the water quality, sediment quality, and biological condition scores were used to derive an overall index of habitat quality (HQI) similar to the approach used in SCECAP (Van Dolah et al. 2013). The proportions of area

with HQI scores rated as good, fair, or poor were similar among the various NERRs and between individual NERRs and non-NERR estuaries in corresponding states (Figure 2). In all cases, overall habitat quality was rated as good over the majority (at least 62%) of the corresponding assessment areas (Table 3, Figure 2). However, as a general pattern, the % area rated as good was consistently higher at individual NERR reserves compared to non-NERR estuaries in corresponding states—76% versus 62%, 77% versus 73%, and 73% versus 68% for NC, SC, and GA, respectively. Proportions of NERRs rated as poor with respect to overall habitat quality were limited to relatively small areas—7%, 13%, and 10% for the NC, SC, and GA NERRs, respectively.

## DISCUSSION

Some of the patterns that emerged from these data may be explained by considering the interaction of both natural and anthropogenic controlling factors. For example, NC NERR sites had higher mean DO concentrations compared to other, non-NERR sites in NC thus contributing to higher WQI scores. This could be due to the close proximity to ocean inlets of many of the NERR sites in NC, whereas many non-NERR NC sampling sites are located in the Albemarle-Pamlico Estuarine System (APES) where flushing rates are low (Christian et al. 1991).

**Table 2.** Summary statistics (mean  $\pm$  SE) for water and sediment quality, biological condition, and overall habitat quality measures

Measure	NERRS			NCA		
	NC	SC	GA	NC	SC	GA
<b>Water quality</b>						
DO (mg/L)	5.9 $\pm$ 0.1	4.4 $\pm$ 0.2	3.7 $\pm$ 0.1	4.6 $\pm$ 0.3	4.2 $\pm$ 0.1	4.4 $\pm$ 0.1
pH	7.8 $\pm$ 0.05	7.6 $\pm$ 0.04	7.3 $\pm$ 0.03	7.6 $\pm$ 0.1	7.6 $\pm$ 0.03	7.7 $\pm$ 0.05
Fecal coliform (CFU/100 mL)		3 $\pm$ 0.8	13 $\pm$ 1.6		26 $\pm$ 7.4	
Total N (mg/L)	0.58 $\pm$ 0.07	0.3 $\pm$ 0.04	0.6 $\pm$ 0.01	0.63 $\pm$ 0.04	0.43 $\pm$ 0.03	0.61 $\pm$ 0.03
Total P (mg/L)	0.05 $\pm$ 0.004	0.07 $\pm$ 0.006	0.08 $\pm$ 0.002	0.05 $\pm$ 0.004	0.08 $\pm$ 0.006	0.1 $\pm$ 0.01
Chl-a ( $\mu$ g/L)	6.9 $\pm$ 1.5	7.6 $\pm$ 0.7	7.1 $\pm$ 0.5	8.8 $\pm$ 0.9	8.1 $\pm$ 0.7	11.8 $\pm$ 1.0
Eutrophication score	4.4 $\pm$ 0.2	4.7 $\pm$ 0.1	4.9 $\pm$ 0.04	4.5 $\pm$ 0.1	4.6 $\pm$ 0.1	3.9 $\pm$ 0.2
Temperature ( $^{\circ}$ C)	24.3 $\pm$ 0.2	30.0 $\pm$ 0.1	27.2 $\pm$ 0.1	28.4 $\pm$ 0.1	29.8 $\pm$ 0.1	29.9 $\pm$ 0.1
Salinity (ppt)	25.9 $\pm$ 2.3	29.4 $\pm$ 0.7	21.4 $\pm$ 0.4	14.7 $\pm$ 1.3	26.8 $\pm$ 0.9	24.6 $\pm$ 0.9
TSS (mg/L)	11.8 $\pm$ 0.8	45.9 $\pm$ 5.1	65.4 $\pm$ 3.3		30.8 $\pm$ 2.5	
Turbidity (NTU)		17.3 $\pm$ 1.9	8.5 $\pm$ 0.5		12.5 $\pm$ 1.0	
WQ score	4.7 $\pm$ 0.1	4.5 $\pm$ 0.1	4.3 $\pm$ 0.1	4.2 $\pm$ 0.1	4.3 $\pm$ 0.1	4.3 $\pm$ 0.1
<b>Sediment quality</b>						
Silt + clay (%)	17.4 $\pm$ 3.8	16.6 $\pm$ 4.2	41.0 $\pm$ 6.0	39.7 $\pm$ 5.3	21.7 $\pm$ 2.8	26.3 $\pm$ 4.0
TOC (%)	0.7 $\pm$ 0.2	0.6 $\pm$ 0.2	1.3 $\pm$ 0.2	1.5 $\pm$ 0.3	0.9 $\pm$ 0.1	0.7 $\pm$ 0.1
<b>Toxicity<sup>a</sup> (nr sites)</b>						
Toxic	7	5	9	3	15	1
Nontoxic	23	26	21	37	70	49
Mean ERM-Q	0.009 $\pm$ 0.002	0.008 $\pm$ 0.002	0.015 $\pm$ 0.002	0.023 $\pm$ 0.003	0.017 $\pm$ 0.002	0.014 $\pm$ 0.002
Sediment quality score	4.5 $\pm$ 0.2	4.6 $\pm$ 0.2	4.2 $\pm$ 0.2	4.4 $\pm$ 0.1	4.5 $\pm$ 0.1	4.8 $\pm$ 0.1
<b>Biological condition</b>						
Benthic abundance (per 0.04 m <sup>2</sup> )	109 $\pm$ 14	227 $\pm$ 48	132 $\pm$ 19	98 $\pm$ 15	242 $\pm$ 36	116 $\pm$ 20
Nr benthic taxa (per 0.04 m <sup>2</sup> )	17 $\pm$ 2	20 $\pm$ 3	14 $\pm$ 1	10 $\pm$ 1	19 $\pm$ 1	12 $\pm$ 1
Benthic diversity (H', log <sub>2</sub> )	2.8 $\pm$ 0.2	2.9 $\pm$ 0.1	2.7 $\pm$ 0.1	2.3 $\pm$ 0.1	2.8 $\pm$ 0.1	2.2 $\pm$ 0.1
B-IBI	3.6 $\pm$ 0.2	3.6 $\pm$ 0.2	3.3 $\pm$ 0.1	3.2 $\pm$ 0.2	3.6 $\pm$ 0.1	2.8 $\pm$ 0.1
Overall habitat quality score	4.4 $\pm$ 0.2	4.4 $\pm$ 0.2	4.3 $\pm$ 0.2	4.1 $\pm$ 0.2	4.3 $\pm$ 0.1	4.1 $\pm$ 0.1

B-IBI = benthic index of biological integrity; DO = dissolved oxygen; GA = Georgia; NC = North Carolina; NCA = data for non-NERR sites in NC, SC, and GA from the National Coastal Assessment database (USEPA 2006); SC = South Carolina; TOC = total organic carbon; TSS = total suspended solids; WQ = water quality. <sup>a</sup>For NERR sites, toxicity is based on Microtox assay. For NCA sites, toxicity is based on *A. abdita* (NC, GA) or *M. mercenaria* (SC) assay.

The GA NERR had the lowest mean DO levels in comparison to other southeastern NERRs and other non-NERR estuaries in GA (Table 2). Consequently, a smaller proportion (27% area) of the GA NERR was rated as good with respect to DO and a larger proportion (63% area) was rated as fair compared to the other NERR and non-NERR areas (Table 3). This likely results from a large number of GA NERR stations falling within the Duplin River, which experiences a longitudinal DO gradient with higher biological O<sub>2</sub> demands in the upper river (Pomeroy and Cai 2006) due to high concentrations of particulate and dissolved

organic carbon (Chalmers 1997). Verity et al. (2006) have shown that percent O<sub>2</sub> saturation is steadily declining in the lower reaches of rivers and well-mixed estuaries of Georgia and that hypoxia can occur directly from stimulation of microbial respiration in surface water, even in the face of strong vertical and horizontal mixing. Despite the lower DO scores for the GA NERR, the overall WQI scored higher at this reserve compared to non-NERR sites in GA due to high scores for other component metrics (i.e., nutrients and chlorophyll), which was a consistent pattern observed in NC and SC as well.

**Table 3.** Estimated percent area rated as “Good”, “Fair”, or “Poor” based on scoring criteria for water and sediment quality, biological condition, and overall habitat quality

	NERR									NCA								
	NC			SC			GA			NC			SC			GA		
	G	F	P	G	F	P	G	F	P	G	F	P	G	F	P	G	F	P
<b>Water quality</b>																		
Water Quality Index	88	12	0	83	7	10	87	7	6	61	31	8	76	11	13	72	18	10
DO (mg/L)	100	0	0	71	19	10	27	63	10	67	5	28	55	32	13	68	26	6
pH (salinity-corrected)	100	0	0	91	2	7	90	10	0	95	1	4	90	7	3	100	0	0
Fecal coliform (CFU/100 mL)	—	—	—	99	0	0 <sup>a</sup>	100	0	0	—	—	—	83	16	1	—	—	—
Eutrophication Index	78	11	11	92	6	2	100	0	0	82	10	8	87	4	9	56	26	18
Total N (mg/L)	71	18	11	95	2	0 <sup>a</sup>	100	0	0	87	5	8	75	6	1 <sup>a</sup>	86	12	2
Total P (mg/L)	89	11	0	86	6	7 <sup>a</sup>	93	7	0	95	4	1	72	8	10 <sup>a</sup>	66	12	22
Chl-a (µg/L)	88	0	12	80	19	1	93	7	0	79	7	14	86	9	5	56	20	24
<b>Sediment quality</b>																		
Sediment Quality Index	76	17	7	86	6	8	63	20	17	82	8	10	79	14	7	94	4	2
Mean ERM quotient	89	11	0	91	9	0	70	30	0	57	36	6 <sup>a</sup>	78	18	4	76	24	0
Toxicity <sup>b</sup>	76	—	24	87	—	13	70	—	30	74	—	6 <sup>a</sup>	88	—	12	98	—	2
TOC (%)	93	7	0	92	2	6	90	10	0	84	13	3	90	5	5	94	4	0 <sup>a</sup>
<b>Biological condition</b>																		
BCI	76	13	11	87	2	11	80	20	0	64	21	15	81	14	5	50	32	18
<b>Habitat quality</b>																		
Habitat Quality Index	76	17	7	77	10	13	73	17	10	62	21	17	73	15	12	68	14	18

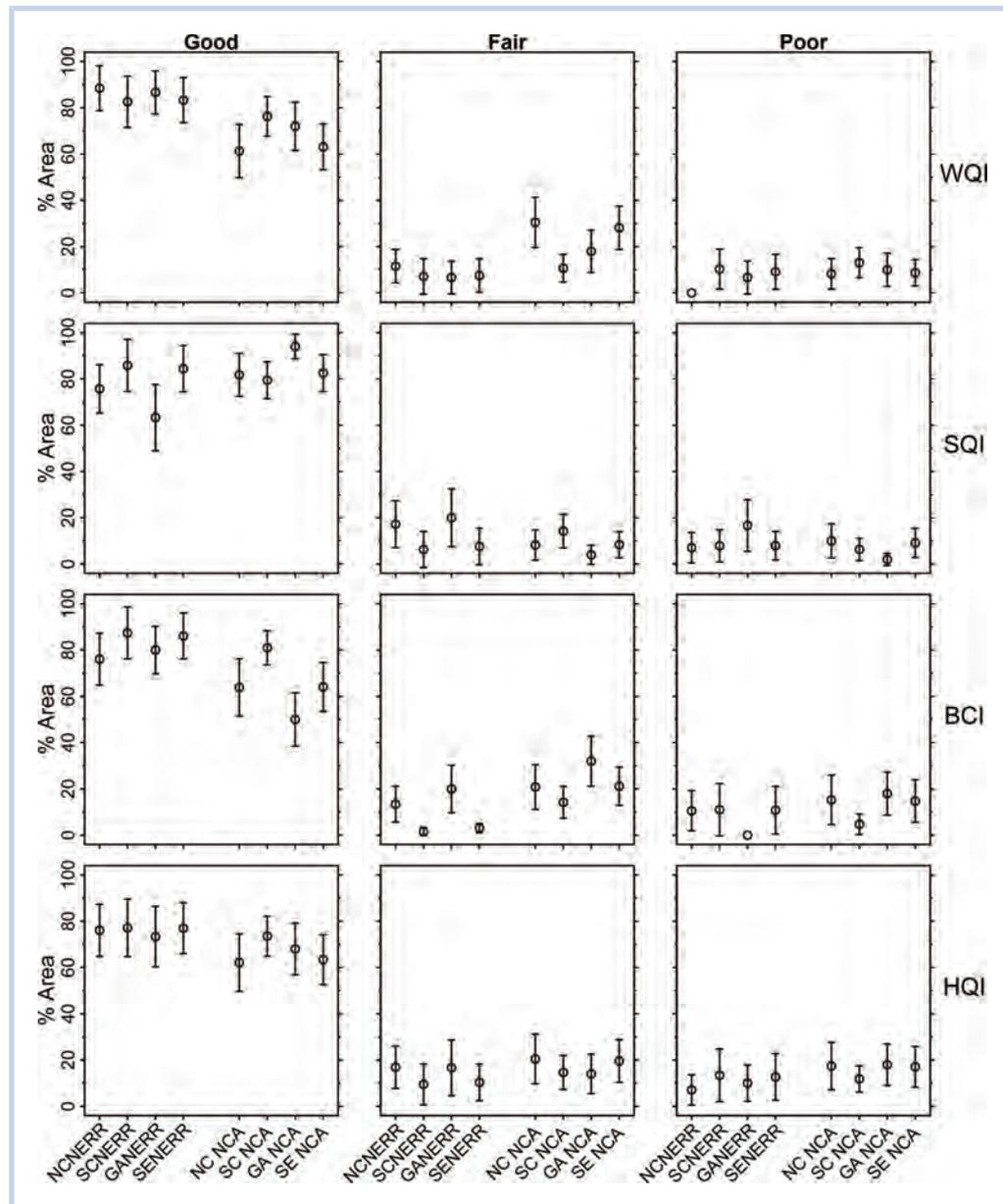
BCI = biological condition index; ERM = effects–range median; F = fair; G = good; GA = Georgia; NC = North Carolina; NCA = National Coastal Assessment; NERR = National Estuarine Research Reserves; P = poor; SC = South Carolina.

<sup>a</sup>Total area percentages do not sum to 100% due to missing data.

<sup>b</sup>For NERR sites, toxicity is based on Microtox assay. For NCA sites, toxicity is based on *A. abdita* (NC, GA) or *M. mercenaria* (SC) assay.

Although WQI values tended to be higher for NERR sites compared to non-NERR estuaries, SQI scores did not follow this pattern. In most cases, proportions of areas rated as good, fair, or poor with respect to sediment quality were comparable between NERR and corresponding non-NERR estuaries. However, the % of area rated as good for sediment quality at the GA NERR was lower (with nonoverlapping 95% CI) than non-NERR GA estuaries. At the GA NERR, significant sediment toxicity accompanied by elevated mean ERM-Q values (>0.02–0.058) was observed at 5 of 30 sites (17% area). The authors of a previous study at the GA NERR (Balthis et al. 2012), which produced the data used in the present analysis, found that mean ERM-Qs at a number of sites fell within the range (>0.02–0.058) associated with a moderate risk of impacts to benthic infauna, though none were in a high probable bioeffect range (> 0.058) (Hyland et al. 1999). The authors noted a lack of evidence of major biological impacts linked to poor sediment quality and proposed that current stressor levels may not be of sufficient magnitude to be expressed clearly as bioeffects. As noted earlier, SQI scores were lower for GA NERR sites compared to non-NERR GA estuaries (63% vs 94% area rated as good, respectively), with differences in toxicity

scores mainly being responsible for this difference. However, as pointed out previously, different tests were used to assess toxicity of NERR sites (Microtox) and non-NERR estuaries (*A. abdita* assay in NC and GA, *M. mercenaria* in SC), thereby introducing a potential confounding factor in comparison of SQI values among NERR and non-NERR sites. The Microtox assay has been effective in discriminating polluted from nonpolluted sites (Cleveland et al. 1997; Doherty 2001; Cotou et al. 2002; Beg and Ali 2008; Onorati et al. 2013) and has been shown to be more sensitive than the *A. abdita* assay (Hyland et al. 1998; Ringwood and Keppler 1998). It has also been noted (Van Dolah et al. 2006) that the Microtox assay may have a tendency to produce false positives (indicating significant toxicity when contamination is low). Some of the authors listed above (Hyland et al. 1998; Ringwood and Keppler 1998; Van Dolah et al. 2006) have found the *A. abdita* assay to be less sensitive than either the Microtox or seed clam (*M. mercenaria*) assay. Such discrepancies among toxicity tests complicate interpretation of sediment quality status between NERR and non-NERR sites (and also potentially between non-NERR sites in SC versus NC and GA). However, calculated indices of sediment quality and overall habitat quality for NERR sites may represent worst-case



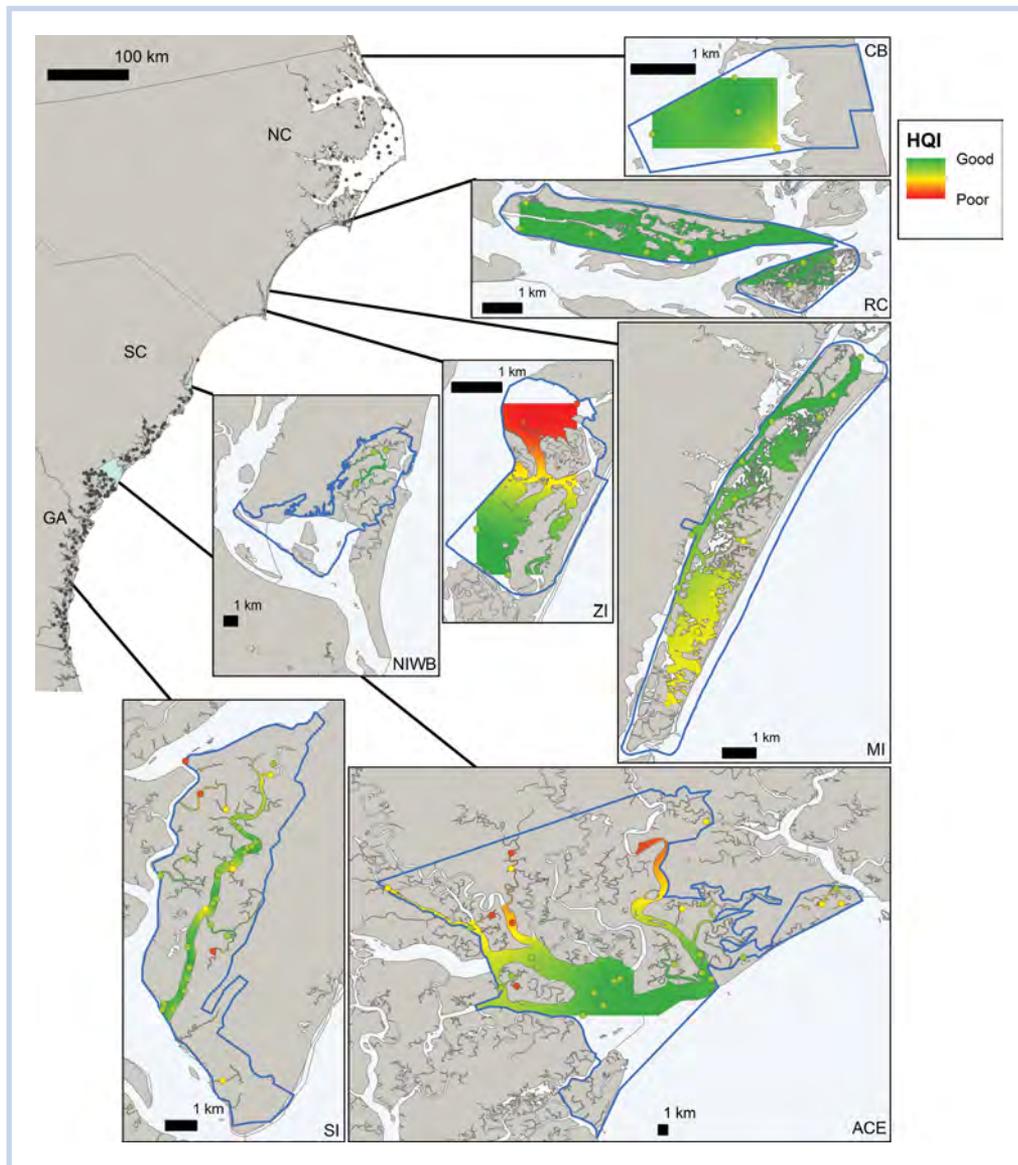
**Figure 2.** Estimated percent area (and 95% confidence intervals) rated as “Good,” “Fair,” or “Poor” based on calculated indices of water quality (WQI), sediment quality (SQI), biological condition (BCI), and overall habitat quality (HQI) for NERR and non-NERR (NCA) estuaries in North Carolina, South Carolina, and Georgia. Overall combined estimates for NERR (SENERR) and non-NERR (southeast NCA) estuaries also are shown for comparison.

estimates with respect to sediment toxicity, because the *Microtox* assay has been demonstrated to be more sensitive than the *A. abdita* assay (although perhaps comparable to the *M. mercenaria* assay). Ideally, future applications of the methods described here should combine the results of multiple toxicity tests in deriving the toxicity score. Such an approach would be consistent with recommendations to employ a battery of tests in assessing sediment toxicity (Chapman and Anderson 2005; Greenstein et al. 2008), although the appropriateness of any single assay or group of assays for sediment assessments can be highly site-specific (Doherty 2001).

With respect to biological condition, proportions of NERR sites rated as good were consistently greater than corresponding non-NERR estuaries in the respective states. However, there were some indications of a degraded benthos in both the NC and SC (ACE Basin) NERRs. Out of a total of 5 sites in NC and SC NERRs rated as poor, 4 of the 5 were accompanied by

either moderate levels of chemical contaminants (mean ERM-Qs between 0.02–0.058) (Hyland et al. 1999) or significant sediment toxicity. At 3 sites, degraded benthic conditions were associated with both contamination and toxicity. Hence, in these cases, levels of environmental stressors appear to have been of sufficient magnitude to elicit a biological response.

The spatial distribution of overall habitat quality ratings for each of the NERR components is illustrated in Figure 3. As noted above, proportions of NERRs rated as poor were limited to relatively small areas—7%, 13%, and 10% for the NC, SC, and GA NERRs, respectively. For NC, these impacted areas were represented by 2 stations in the northern (“Basin”) portion of Zeke’s Island Reserve rated as having poor sediment quality and impaired benthic condition. The incidence of impacts in this area is consistent with the reserve’s location, removed from direct water exchange with the Atlantic Ocean and dependent on the water quality of the lower Cape Fear



**Figure 3.** Overall habitat quality index (HQI) values among NERR sites. North Carolina: CB = Currituck Banks, MI = Masonboro Island, RC = Rachel Carson, ZI = Zeke's Island. South Carolina: ACE = Ashepoo-Combahee-Edisto, NIWB = North Inlet-Winyah Bay. Georgia: SI = Sapelo Island.

River, the largest river basin in NC draining some highly developed and industrialized areas. The remaining impacted areas were represented by 5 stations in upper estuarine reaches of the ACE Basin Reserve in SC (3 due to poor water quality and 2 due to a combination of poor sediment quality and impaired benthic condition) and 3 stations in shallow tidal creeks within the Sapelo Island, GA Reserve (2 due to poor sediment quality and one due to a combination of poor sediment and water quality). The incidence of impacts in these latter cases is inconsistent with their remote locations in relatively undeveloped coastal areas and remains unexplained.

The results presented in this study should be considered in light of a few cautionary notes. First, the areas represented by the sites sampled in each of the respective NERRs and non-NERR estuaries differ substantially. The ACE Basin NERR in SC comprises more than 75% of the combined area of the 3 NERRs in NC, SC, and GA. Similarly, the area represented by non-NERR sites is dominated by NC estuaries, which make up more than 80% of the total non-NERR area. This is evidenced by the fact that the bar corresponding to overall combined

percent area of SENERR tracks the SCNERR bar in Figure 2, whereas the bar for combined southeast NCA estuaries tracks with NC NCA. Hence, estimates of condition combined for NERRs or non-NERR estuaries are indicative primarily of conditions observed in the subregion representing the largest area (SC NERR or NC non-NERR, respectively). Second, the combined area of non-NERR estuaries in NC, SC, and GA is much larger than the overall area of NERRs in the region, thus any comparison of condition between these 2 mega categories must take into consideration the disproportionate areas that they represent. Accordingly, present efforts to evaluate how well southeastern NERRs are faring ecologically have focused on comparisons of condition within an individual NERR to that of non-NERR estuaries in the corresponding state. Similarly, although the SENERR and SE NCA bars in Figure 2, representing conditions for combined NERR and non-NERR estuaries respectively, are included for rough qualitative comparison purposes, they should be used with caution.

Results of this study suggest that each of these southeastern NERR sites is faring slightly better than neighboring non-

NERR estuaries with respect to overall habitat quality (73%–76% in good condition based on the HQI, vs 62%–73% for non-NERR estuaries) and that poor habitat quality is limited to relatively small areas (<13% of a reserve's total sampling area). This is a good take-home message for coastal management, indicating that the concept of setting aside such areas to help protect the integrity of natural-resource components is apparently working (in this case) and that such areas can serve as valuable reference sites, for spatial comparisons with other estuarine areas, as well as sentinels of future change. However, indications of environmental stress, accompanied in some cases by biological impacts, suggest that these areas are not free from pressures that may originate from within or outside NERR boundaries. This only serves to highlight the value of preserving and protecting these areas from any additional impacts to the extent possible. It is also anticipated that the methods and indicators used here, which incorporate measures of biological condition and sediment quality in addition to water quality, may serve as a useful model for similar applications in other NERRS regions to support comparisons at multiple spatial scales (i.e., from a single reserve to the national network of reserves) and to complement system-wide water-quality monitoring (SWMP) and other site-specific research activities currently underway in the NERRS program.

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