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Contrasting food-web support bases for adjoining river-influenced and non-river influenced continental shelf ecosystems

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Abstract

Nutrient and chlorophyll *a* concentrations and distributions in two adjoining regions of the South Atlantic Bight (SAB), Onslow Bay and nearshore Long Bay, were investigated over a 3-year period. Onslow Bay represents the northernmost region of the SAB, and receives very limited riverine influx. In contrast, Long Bay, just to the south, receives discharge from the Cape Fear River, draining the largest watershed within the State of North Carolina, USA. Northern Long Bay is a continental shelf ecosystem that has a nearshore area dominated by nutrient, turbidity and water-color loading from inputs from the river's plume. Average planktonic chlorophyll *a* concentrations ranged from 4.2 $\mu g\ l^{-1}$ near the estuary mouth, to 3.1 $\mu g\ l^{-1}$ 7 km offshore in the plume's influence, to 1.9 $\mu g\ l^{-1}$ at a non-plume station 7 km offshore to the northeast. Average areal planktonic chlorophyll *a* was approximately 3X that of benthic chlorophyll *a* at plume-influenced stations in Long Bay. In contrast, planktonic chlorophyll *a* concentrations in Onslow Bay were normally $<0.50\ \mu g\ l^{-1}$ at a nearshore (8 km) site, and $<0.15\ \mu g\ l^{-1}$ at sites located 45 and 100 km offshore. However, high water clarity (K_{PAR} 0.10–0.25 m^{-1}) provides a favorable environment for benthic microalgae, which were abundant both nearshore (average 58.3 mg m^{-2}) and to at least 45 km offshore in Onslow Bay (average 70.0 mg m^{-2}) versus average concentrations of 10–12 mg m^{-2} for river-influenced areas of Long Bay. This provides evidence that much of the inner shelf food web in Onslow Bay is based on benthic microalgal production, in contrast to a plankton-based food web in northern Long Bay and more southerly areas of the SAB.

Keywords: chlorophyll *a*; nutrients; river plume; light attenuation; South Atlantic Bight

1. Introduction

The South Atlantic Bight (SAB) comprises a broad area bounded to the north by the Middle Atlantic Bight near Cape Hatteras, to the east by the continental shelf break, and to the south by Cape Canaveral in Florida. Nearshore areas of this region support an active commercial fishery for both finfish and shellfish (Mallin et al., 2000). Commercial fisheries catches in North Carolina exceed those of South Carolina, Georgia, and eastern Florida combined, with finfish dominating the catches in North Carolina and Florida and shellfish the catches in South Carolina and Georgia (Dame et al., 2000). While the type and productivity of estuarine nursery grounds play a major role in this catch distribution (Dame et al., 2000), support (i.e. phytoplankton and benthic microalgal production) for the SAB inshore and offshore food webs is critical to maintain catches (Mallin et al., 1992).

The northern portion of the SAB consists of Long Bay in northern South Carolina and southern North Carolina, Onslow Bay, and Raleigh Bay, the northernmost boundary where the SAB and Middle Atlantic Bight meet near Cape Hatteras. The southern end of Long Bay receives freshwater inputs from the

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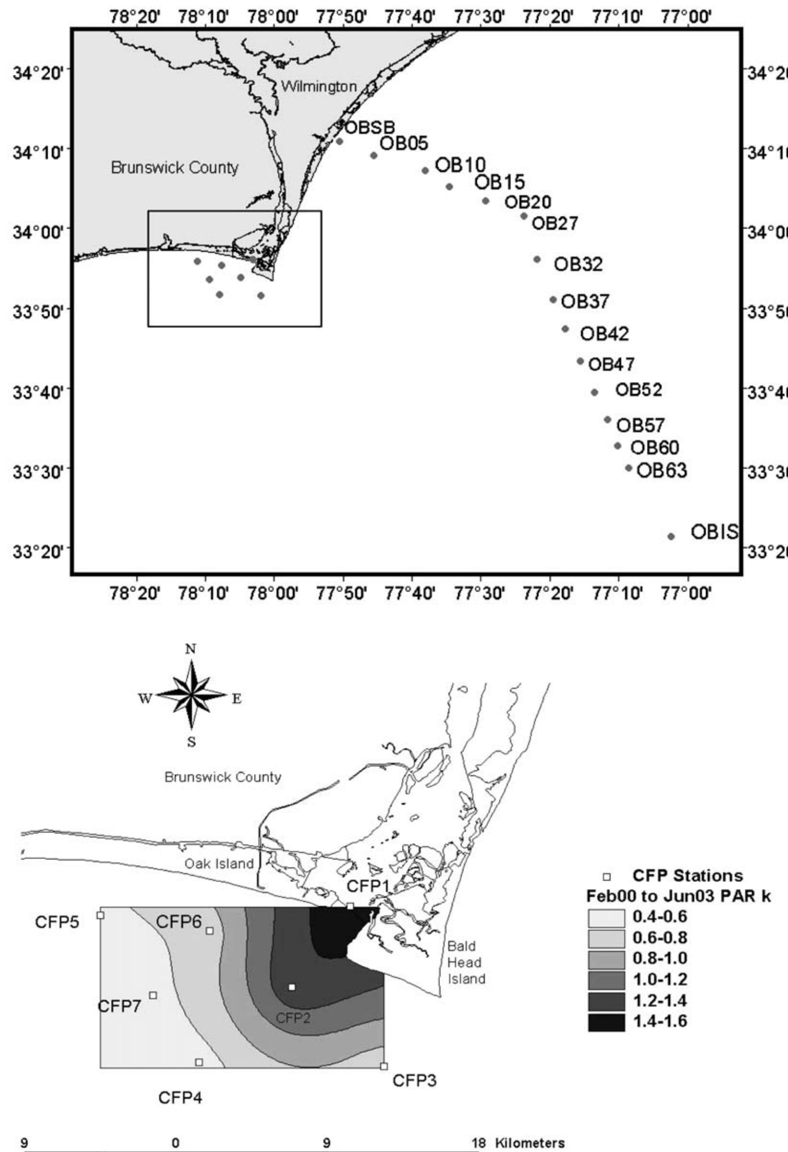

Fig. 1. Map of sampling area near the North Carolina, USA, coast, showing stations along the offshore Onslow Bay transect (above), and a close-up of the stations in the Cape Fear River plume in Long Bay (below), along with the average K_{PAR} spatial distribution.

Waccamaw, Black, and Pee Dee rivers through Winyah Bay, while the middle portion of Long Bay has only minor riverine inputs. Freshwater supply to northern Long Bay is dominated by Cape Fear River discharge (Fig. 1), which on average is about 220 $m^3\ s^{-1}$ (Dame et al., 2000), with a median estuarine flushing time of 6.7 days (Ensign et al., 2004). The Cape Fear River is a sixth order stream draining a watershed of 23,310 km^2, with significant inputs of relatively turbid "brownwater" from the Piedmont, and low-turbidity blackwater from two fifth-order Coastal Plain tributaries, the Black and Northeast Cape Fear Rivers (Mallin et al., 1999). Coastal ocean regions that receive large river discharges (most notably the Mississippi discharge into the Gulf of Mexico) can exhibit elevated phytoplankton production (Lohrenz et al., 1990) that leads to enhanced zooplankton abundance (Dagg and Whitledge, 1991) and fishery production (Grimes, 2001).

The nearshore region of the southern SAB, largely influenced by Savannah River discharge, has high phytoplankton productivity and biomass, and efficient recycling of nutrients between the phytoplankton and microflagellate grazer community (Verity et al., 1993). A frontal zone 10–20 km offshore extends along a 400 km length of the southeast coast northward from Florida (Blanton, 1981), preventing cross-shelf transport and retaining nutrients and chlorophyll within the nearshore region (Verity et al., 1993). In southern South Carolina the North Edisto Estuary and delta has elevated chlorophyll *a* concentrations as well, caused primarily by wind-driven downwelling and upwelling and tidal stirring of benthic microalgae (Verity et al., 1998).

Onslow Bay, the section of the SAB lying north of Cape Fear and south of Cape Lookout, differs greatly from the southern and middle portions of the SAB in that there is very limited river discharge entering this area. Cahoon et al. (1990, 1992) have characterized the primary production in Onslow Bay as dominated by benthic microalgae, rather than phytoplankton, indicating a strong food web interaction with demersal zooplankton grazers (Cahoon and Tronzo, 1992). Multiple stable isotope analyses (Thomas and Cahoon, 1993) as well as gut content analyses (Lindquist et al., 1994) have confirmed that benthic microalgae support Onslow Bay shelf food chains. Thus, Onslow Bay and its food web structure may be unique compared with the middle and southern areas of the SAB.

The proximity of Long Bay to Onslow Bay presents an opportunity to examine nutrient, solar irradiance, and phytoplankton biomass differences between two adjoining coastal ocean areas, one strongly influenced by freshwater riverine inputs and one with minimal freshwater inputs. The Coastal Ocean Research and Monitoring Program (CORMP), based at the University of North Carolina at Wilmington, initiated field investigations in both of these areas in February 2000.

2. Study sites

Seven sites were sampled in the Cape Fear River (CFR) plume region in Long Bay at monthly to bimonthly intervals from February 2000 through June 2003 (Fig. 1). Cruises in the plume region were conducted during the outgoing tide. Station CFP1 was located within the estuary proper, CFP2 was located approximately 5 km outside of the estuary mouth in the direct influence of estuarine discharge, CFP3 was located 7 km southeast of the estuary mouth and was considered to be a control area out of the influence of the river plume, CFP4 was located 12 km south-southwest of the estuary, CFP5 was located 12 km west of the estuary mouth, CFP6 was located 7 km west of the estuary, and Station CFP7 was located 10 km west-southwest of the estuary. All seven stations were approximately 10 m deep. Coordinates of the estuary mouth station CFP1 were N 33° 53.281, W 78° 00.473. During most of the sampling period North Carolina was suffering from severe drought conditions. Thus, river discharge was generally well below average (USGS data, Raleigh, NC).

The CORMP maintains a sampling transect in Onslow Bay beginning about 5 km near shore in 10 m water depth and extending offshore 100 km to a depth of 118 m (Fig. 1). For the purposes of the present research three of these locations were sampled periodically from February 2000 through June 2003. OB5 (=OB05 in Fig. 1) was 15 m deep and located 8 km offshore, OB27 was 27 m deep and located 45 km offshore, and OB63 was 118 m deep and located 100 km offshore (Fig. 1). Coordinates of these stations were OB5: N 34° 08.400, W 77° 42.900; OB27: N 33° 59.600, W 77° 21.200; OB63: N 33° 23.000, W 77° 06.000.

3. Methods

On each CFR plume trip, physical parameters (temperature, salinity, turbidity, pH, dissolved oxygen) were obtained at surface, middle, and near-bottom depths using a YSI 6920 multiparameter water quality probe (sonde) linked to a YSI 610D display unit. Surface samples were collected in triplicate for chlorophyll *a*, nitrate, and orthophosphate, and duplicate samples were collected for ammonium and silicate. At the Onslow Bay locations surface, middle, and bottom samples for water temperature, salinity, dissolved oxygen, pH, chlorophyll *a* (in triplicate), nitrate, ammonium, orthophosphate, and silicate were collected using a SBE25 CTD Sea Logger and SBE32 Carousel water sampler linked to a SBE33 Carousel Deck Unit. During 2003 selected plume and Onslow Bay stations were sampled for benthic microalgal biomass (as chlorophyll *a*). Sediment samples were collected using a petite Ponar grab sampler, with intact sediment samples cored to 5 cm depth using a 2.5 cm diameter plastic tube.

In the laboratory the triplicate water samples were filtered simultaneously through 25 mm Gelman A/E glass fiber filters (nominal pore size 1.0 μm) using a manifold with three funnels. The pooled filtrate was stored frozen until used for inorganic nutrient analysis. Nitrate and orthophosphate were analyzed at the UNCW Center for Marine Science Nutrient Laboratory using a Bran and Luebbe AutoAnalyzer 3. Samples for ammonium were field-preserved with phenol, stored on ice, and analyzed in the laboratory according to the methods of Parsons et al. (1984). Dissolved silica was measured using the method described in Parsons et al. (1984).

Chlorophyll *a* concentrations were determined from the filters used for filtering samples for nitrate+nitrite and orthophosphate analyses. All filters were wrapped individually in aluminum foil, placed in an airtight container with desiccant and stored in a freezer. During the analytical process, the glass fiber filters were separately immersed in 10 ml of a 90% acetone solution. The acetone was allowed to extract the chlorophyll from the material for 18–24 h. The extracted material was then analyzed for chlorophyll *a* concentration using a Turner 10-AU fluorometer (Welschmeyer, 1994). Chlorophyll *a* in sediment samples was analyzed according to Whitney and Darley (1979). This method, which employs spectrophotometric measurement of pigment extracted in acetone and partitioned with hexane and dilute

NaCl solution eliminates interference from degradation products.

Diffuse attenuation (K_d) of photosynthetically active radiation (PAR) of the water column at each station was measured using two Li-Cor scalar quantum sensors connected to a LI-1000 data logger. One sensor was attached to a lowering frame and measurements were obtained at 1- (CFRP) or 2-meter (OB) depth intervals. Depth profile PAR measurements were normalized to the surface incident irradiance using a second sensor mounted on a mast and subtended by a 0.6 m diameter black disk to reduce surface reflection (McPherson and Miller, 1987). Bottom irradiance I_z as percent of surface irradiance was calculated by using the following formula:

$$I_z = I_0(e^{-kz})$$

where I_0 is surface irradiance (100%), k is the light attenuation coefficient (K_d), and z is bottom depth in meters.

Data were tested for normality by use of the Shapiro–Wilk test, which indicated that log transformations were required for normalization except for salinity. Spatial differences among means of selected parameters in the Long Bay Cape Fear River plume area stations and the nearshore Onslow Bay station OB5 were tested for significance ($P < 0.05$) using PROC ANOVA in SAS and ranked using Fisher's LSD Test (Schlotzhauer and Littell, 1987).

4. Results

The Cape Fear River plume usually flowed to the west of the estuary mouth once it entered the Atlantic Ocean (Fig. 1). All plume area stations had average salinity values lower than 35, ranging from a minimum average value of 29.1 at CFP1 up to a maximum average value of 34.7 (Fig. 2). During the course of the study minimum salinities at the outlying stations CFP4, CFP5, and CFP7 reached 24.6, 28.1, and 26.5, respectively, showing that the plume at times discharged river water well beyond the 12 km distance from the estuary mouth. This was especially evident in late spring and early summer 2003, when the drought had ended and river discharge was much higher than during the previous three springs.

Constituent (nutrients and chlorophyll *a*) concentrations within the sampling grid were significantly higher at CFP1 (in the estuary) than at CFP2 (5 km outside the estuary) except for silicate and nitrate, which were similar at those two stations (Figs. 2 and 3). Both CFP1 and CFP2 maintained significantly higher constituent concentrations than the remaining stations; however, chlorophyll *a*, ammonium, and silicate

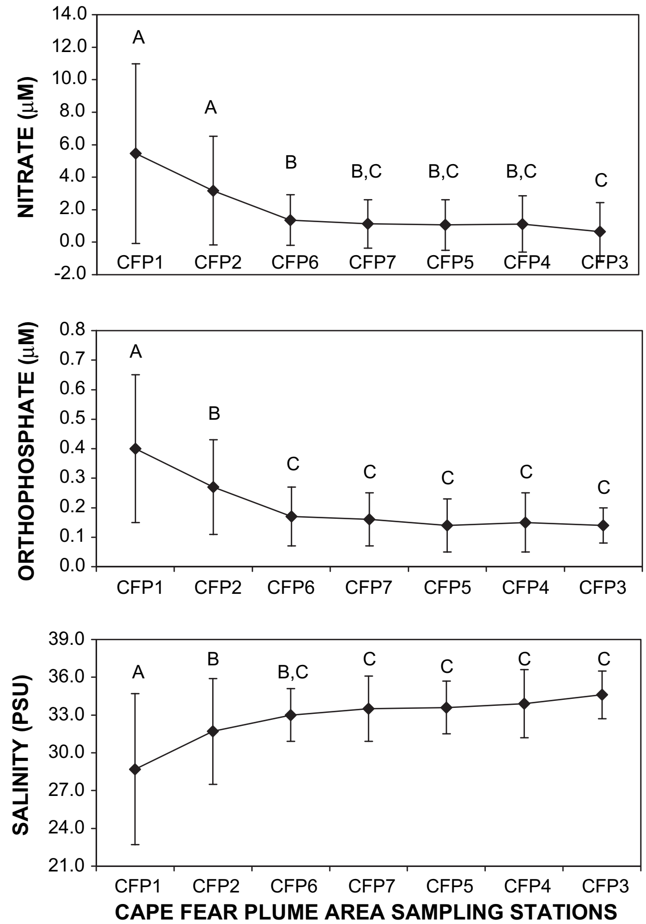

Fig. 2. Mean concentrations of nitrate, orthophosphate, and salinity at Cape Fear River plume associated stations in Long Bay. Error bars are standard deviation, $n = 29$. Similar letters indicate no significant ($P < 0.05$) station difference in parameter concentrations.

concentrations at CFP6 were statistically indistinguishable from those at CFP2 (Fig. 3). Following CFP6, the influence of river borne constituents was statistically indistinguishable among CFP7, CFP5, CFP4, and CFP3 (Figs. 2 and 3). Station CFP6 maintained chlorophyll *a* concentrations intermediate between those at CFP1 and CFP2 and the remaining ocean stations (Fig. 3). CFP6 was also an area of depressed nutrient concentration (Figs. 2 and 3), and is thus considered a plume-impacted area of elevated biological activity.

Average nitrate concentrations ranged from 5.5 µM in the lower estuary station CFP1 to 0.7 µM at the control station CFP3 (Fig. 2). The maximum nitrate concentration measured during the study was 19.0 µM at CFP1. Average ammonium concentration at CFP1 was 2.3 µM, but all other stations ranged between 0.9 and 1.6 µM (Fig. 3). Phosphate concentrations ranged from 0.40 µM at CFP1 to 0.14 µM at CFP3 (Fig. 2), with a maximum concentration of 0.9 µM at CFP1. Silicate showed a strong riverine signal, with average concentrations ranging from 18.7 µM at CFP1 down to 3.3 µM at CFP3 (Fig. 3). The maximum silicate

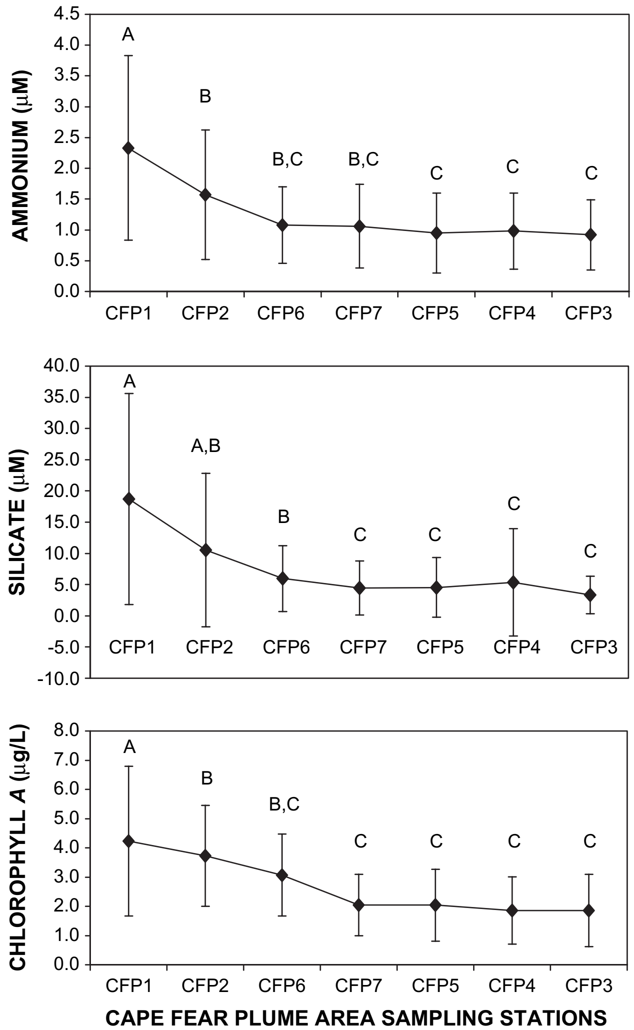

Fig. 3. Mean concentrations of ammonium, silicate, and chlorophyll *a* at Cape Fear River plume associated stations in Long Bay. Error bars are standard deviation, $n = 28$ for ammonium, $n = 24$ for silicate, and $n = 28$ for chlorophyll *a*. Similar letters indicate no significant ($P < 0.05$) station difference in parameter concentrations.

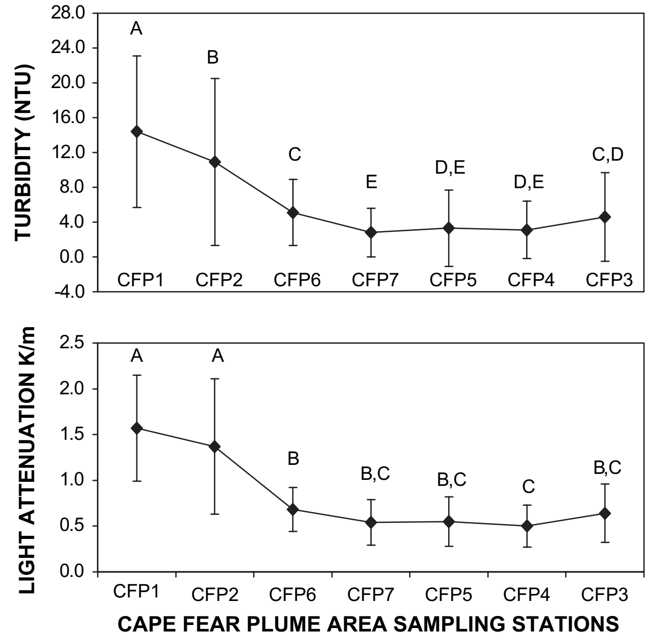

Fig. 4. Mean concentrations of turbidity and mean light attenuation coefficient values at Cape Fear River plume associated stations in Long Bay. Error bars are standard deviation, $n = 29$. Similar letters indicate no significant ($P < 0.05$) station difference in parameter concentrations.

concentration was 56.8 μM at CFP1, and on rare occasions silicate fell below 1.0 μM at selected stations.

Light was significantly more strongly attenuated at CFP1 and CFP2 than the remaining stations (Figs. 1 and 4). The irradiance field became much more favorable to phytoplankton production between CFP2 and CFP6 (Fig. 1), as turbidity and light attenuation both showed considerable decreases (Fig. 4). It is notable that CFP3 did not maintain the lowest turbidity, rather it was equivalent to CFP6 while CFP4, CFP5 and CFP7 had lower turbidity concentrations than CFP6. The location of CFP3 amongst shoals likely led to some water column turbidity through sediment stirring by wind and current action.

The Onslow Bay sites produced very different data (Tables 1 and 2). Nitrate was low in surface waters at all three sites (Table 1), but was occasionally elevated by more than an order of magnitude at the bottom at Station OB63 and on rare occasions at the bottom at OB27 (Table 2). In Onslow Bay surface samples ammonium was the dominant form of inorganic nitrogen, with mean values 2–3 times that of nitrate at all three locations (Table 2). However, at OB63 nitrate concentrations well exceeded ammonium at both the middle and bottom depths (Table 2). Nitrate and ammonium concentrations at OB5 in Onslow Bay were significantly lower than concentrations at CFP1 and CFP2 in Long Bay, but due to high variability were not significantly different from the other Long Bay stations (Tables 1 and 2). Phosphate concentrations at all Long Bay plume area stations were significantly higher than at OB5 in Onslow Bay, but most plume stations were in the same range as concentrations at OB27 and OB63 (Table 2 and Fig. 2). Average silicate in the Cape Fear plume area was generally an order of magnitude higher than at all three Onslow Bay stations (Table 2 and Fig. 2). Water column chlorophyll *a* concentrations at all stations in Long Bay were significantly ($P < 0.05$) greater than those at OB5 in Onslow Bay (Table 1), which in turn were 3–4 times higher than at OB27 and OB63 (Table 2).

5. Discussion

Nitrogen and phosphorus loads in the Cape Fear Estuary are among the highest in estuaries feeding the

Table 1
Average nutrient, chlorophyll *a*, and solar irradiance characteristics of selected CORMP surface water sampling stations in a river-influenced area of Long Bay compared with non-river influenced Onslow Bay (2000–2003)

Station	CFP2	CFP6	OB5	OB27	OB63
Chlor *a* ($\mu g\ l^{-1}$)	3.73 ± 1.73	3.07 ± 1.40	0.42 ± 0.20	0.10 ± 0.08	0.12 ± 0.17
NO_3 (μM)	3.17 ± 3.34	1.36 ± 1.56	0.11 ± 0.18	0.24 ± 0.17	0.41 ± 0.43
NH_4 (μM)	1.57 ± 1.05	1.08 ± 0.62	0.30 ± 0.30	0.70 ± 0.50	0.84 ± 0.82
Depth z (m)	10	10	15	27	118
K_{PAR}/m	1.37 ± 0.74	0.68 ± 0.24	0.23 ± 0.06	0.14 ± 0.06	0.16 ± 0.03
I_Z as % I_0	0.01	0.11	3.17	2.28	<0.01
Distance from shore (km)	5	7	8	45	100

Chlorophyll, nutrient and K_{PAR} data are given as mean ± standard deviation.

SAB, comparable to or exceeding the loads in the Savannah and the Pee Dee Estuaries and well exceeding loads in other South Carolina and Georgia estuaries (Dame et al., 2000). Because this estuary is open to the sea, rather than constrained by barrier islands, and rapidly flushed, only 5–9% of its nitrogen load is retained within the estuary (Ensign et al., 2004). As such, average nitrate concentrations in the plume area of Long Bay were 4–10 times greater than at Stations OB5 and OB27 in Onslow Bay. Mean nitrate concentrations at all sampling sites in the Cape Fear River plume area exceeded the average nitrate concentrations in nearshore waters off Savannah (Verity et al., 1993). Onslow Bay nitrate concentrations, while low, were approximately double those at an offshore station in the Savannah area (Verity et al., 1993). Nitrate was the predominant form of inorganic nitrogen in the plume area, in contrast to Onslow Bay, where ammonium was the dominant form (Tables 1 and 2). Ammonium was also the dominant inorganic nitrogen form both inshore and offshore in the northern Georgia area of the SAB (Verity et al., 1993). Phosphate concentrations in Long Bay, even at the lower Cape Fear Estuary station CFP1, were considerably lower than in the nearshore area near Savannah (Verity et al., 1993). Silicate concentrations in the Cape Fear plume area, except for CFP1, were much lower than concentrations at the nearshore Savannah area site, and Onslow Bay silicate concentrations were lower than concentrations at the offshore Savannah area site (Verity et al., 1993).

Table 2
Nutrient and chlorophyll *a* distribution at surface (S), middle (M), and bottom (B) stations at the Onslow Bay (OB) sampling sites, presented as mean and standard deviation. Mid-depths were approximately 7, 13, and 58 m, for OB5, OB27, and OB63, respectively (2000–2003)

Station		OB5 (n = 7)	OB27 (n = 23)	OB63 (n = 15)
NO_3 (μM)	S	0.11 ± 0.18	0.24 ± 0.17	0.41 ± 0.43
	M	0.08 ± 0.15	0.23 ± 0.17	1.38 ± 1.11
	B	0.13 ± 0.07	0.24 ± 0.18	4.66 ± 3.06
NH_4 (μM)	S	0.33 ± 0.30	0.70 ± 0.50	0.84 ± 0.82
	M	0.31 ± 0.27	0.81 ± 0.88	0.73 ± 0.36
	B	0.33 ± 0.24	0.83 ± 1.08	1.07 ± 0.98
PO_4 (μM)	S	0.11 ± 0.03	0.26 ± 0.55	0.20 ± 0.30
	M	0.13 ± 0.05	0.27 ± 0.56	0.31 ± 0.21
	B	0.15 ± 0.09	0.17 ± 0.12	0.59 ± 0.38
$Si(OH)_4$ (μM)	S	NA	1.18 ± 1.54	0.82 ± 0.60
	M	NA	1.13 ± 1.12	1.00 ± 0.52
	B	NA	0.40 ± 0.46	1.19 ± 0.72
Chlor *a* ($\mu g\ l^{-1}$)	S	0.42 ± 0.20	0.10 ± 0.08	0.12 ± 0.17
	M	0.41 ± 0.19	0.12 ± 0.09	0.14 ± 0.10
	B	0.47 ± 0.18	0.24 ± 0.19	0.11 ± 0.17

NA, no data available.

Average chlorophyll *a* concentrations at CFP1, CFP2 and CFP6 were 4.2, 3.7 and 3.1 $\mu g\ l^{-1}$, respectively. These values show a continuing spatial decrease from the chlorophyll *a* concentration of 7.1 $\mu g\ l^{-1}$ averaged from the lower third of the Cape Fear River Estuary during 1995–1998 (Mallin et al., 1999). Lowest chlorophyll *a* concentrations (1.9 $\mu g\ l^{-1}$) were found at CFP3, the control site. However, average water column chlorophyll *a* concentration for all seven plume area stations combined was 2.7 $\mu g\ l^{-1}$, or 6 times that of OB5, and 25 times that of OB27. Despite being out of the plume's direct influence, even CFP3 maintained chlorophyll *a* concentrations 4 times that of OB5.

Chlorophyll *a* concentrations in nearshore waters of the southern SAB near Savannah were higher than in the Cape Fear plume, averaging 9.0 $\mu g\ l^{-1}$ in summer and 5.3 $\mu g\ l^{-1}$ in winter (Verity et al., 1993). Chlorophyll *a* was likewise higher in the mouth and delta of the North Edisto Estuary in southern South Carolina (Verity et al., 1998). The elevated chlorophyll *a* in the North Edisto area was attributed largely to benthic diatoms (observed using microscopy) entrained into the water column by strong tidal stirring (Verity et al., 1998). Tidal stirring does not appear to be as important in the Cape Fear plume area; in Georgia and southern South Carolina the tidal range is 2–3 m (Verity et al., 1993), but in the Cape Fear area it is only 1 m (Dame et al., 2000). A taxonomic survey of the phytoplankton community in the Cape Fear Estuary and in its plume offshore found the community in both areas dominated by diatoms, dinoflagellates and cryptomonads such as *Skeletonema costatum, Asterionella japonica, Thalassiosira nana, Katodinium* *rotundatum* and *Chroomonas amphioxiae* (Carpenter, 1971) that are commonly found in surveys of the regional estuarine and nearshore plankton community (Marshall, 1976; Marshall, 1982; Mallin, 1994). Thus, the estuarine discharge influences phytoplankton community composition and biomass in the Cape Fear plume area of Long Bay.

The irradiance field differed considerably between nearshore Long Bay and nearshore and offshore Onslow Bay (Table 1 and Fig. 4). Bottom irradiances at OB5 and OB27 (Table 1) were well within light intensities that can support productive benthic microalgal mats (Cahoon, 1999; Jahnke et al., 2000). Sampled benthic microalgal data for both OB5 and OB27 (Table 3) show relatively high benthic chlorophyll *a* concentrations (58.3 ± 21.0 and 70.0 ± 21.0 mg m^{-2}, respectively), as did previous research (Cahoon et al., 1990; Cahoon and Cooke, 1992). On an areal basis, benthic microalgal concentrations in Onslow Bay are much greater than integrated water column concentrations (Table 3). If one considers the 1% irradiance level as the minimum for net production and the 0.1% irradiance level as a theoretical minimum for benthic microalgal survival (Cahoon et al., 1992; Cahoon, 1999), then OB63 should have little or no productive benthic microalgae present. Benthic chlorophyll *a* concentrations from areas near OB63 have been measured as <10 mg m^{-2} (Cahoon et al., 1992). The average areal planktonic chlorophyll *a* from this site is close to this number (Table 3), although it is likely very diffuse due to the depth (118 m) at this site. The phytoplankton community in Onslow Bay is dominated by small centric diatoms, e.g. *Skeletonema costatum*, *Chaetoceros* spp., *Thalassiosira* spp., *Melosira* spp., *Coscinodiscus* spp., *Rhizosolenia* spp., taxonomically quite distinct from the benthic microflora, which is dominated by many pennate diatom species and by some facultatively benthic centric forms (Marshall, 1982; Cahoon and Laws, 1993).

Based on availability of light at the sediments (Table 1), the plume area stations should have low benthic microalgal concentrations as well in nearshore Long Bay. Measured benthic chlorophyll *a* data from autumn 2003 showed concentrations of 12.3 ± 14.4 and 10.7 ± 8.8 mg m^{-2} from CFP2 and CFP6, respectively, close to what would have been predicted from oceanic areas of similar bottom irradiances (Cahoon et al., 1992; Cahoon, 1999). The high variability at CFP2 and CFP6 is likely due to variable river discharge and periodic burial by inorganic suspended sediments (Piedmont clays) sedimenting from the Cape Fear River plume. On an areal basis phytoplankton chlorophyll *a* was approximately triple that of benthic chlorophyll *a* in the plume area of Long Bay (Table 3). As a comparison, data from Jahnke et al. (2000) from a transect offshore of Wassaw Sound, Georgia, showed that benthic chlorophyll *a* concentrations were greater there than below the Cape Fear River plume in Long Bay, but less than the concentrations at OB5 and OB27 in Onslow Bay (Table 3). Integrated water column chlorophyll *a* concentrations in the Cape Fear River plume (Table 3) were 2–4 times greater than those measured off of Wassaw Sound (Jahnke et al., 2000), which were approximately 1–2 times those in Onslow Bay (Table 3).

Whereas nitrate concentrations were low at all surface sites in Onslow Bay, the bottom station at OB63 periodically had much higher concentrations (Table 2). These bottom nitrate pulses were probably caused by Gulf Stream intrusions of denser, nutrient rich water (Atkinson, 1977). However, at OB63 the bottom and middle depth stations do not receive sufficient solar irradiance to support elevated chlorophyll *a*, regardless of the nutrient concentration (Tables 1 and 3).

Despite the relatively shallow depths at the Long Bay plume area stations (ca. 10 m), integrated water column areal chlorophyll *a* is considerably greater than areal benthic chlorophyll *a* (Table 3). In contrast, Onslow Bay shelf stations <50 m in depth maintain much greater benthic chlorophyll *a* on an areal basis. In deeper shelf waters such as OB63, integrated water column chlorophyll *a* will exceed benthic chlorophyll *a* on an areal basis (Table 3). Thus, northern Long Bay presents a continental shelf ecosystem that has a nearshore area dominated by nutrient, turbidity and water-color loading from a large riverine estuary (the Cape Fear). Planktonic chlorophyll *a* concentrations were much greater than those of both inshore and offshore Onslow Bay, even in areas out of direct plume influence. However, phytoplankton biomass in nearshore Long Bay was lower than nearshore SAB waters off northern Georgia, and a tidally stirred estuary and delta with limited river discharge (the North Edisto) in South Carolina. Onslow Bay presents a contrast to all of these systems. Planktonic chlorophyll *a* concentrations are much lower, even near shore (8 km from land). However, penetration of solar irradiance to the bottom provides a favorable environment for benthic microalgal growth, which is abundant at least 45 km offshore in Onslow Bay. Along with previous research (Thomas and Cahoon, 1993; Lindquist et al., 1994) this provides

Table 3
Average areal chlorophyll *a* concentrations of selected CORMP water column (WC) and sediment (SED) sampling stations in a river-influenced Long Bay area and non-river influenced Onslow Bay (2000–2003)

Station	CFP2	CFP6	OB5	OB27	OB63
WC Chlor *a* (mg m^{-2})	37.3	30.7	6.5	3.4	14.6
SED Chlor *a* (mg m^{-2})	12.3	10.7	58.3	70.0	<10.0

SED Chlor *a* for CFP2 and CFP6 was computed from samples collected during 2003 ($n = 7$ and $n = 8$, respectively); SED Chlor *a* for OB5 and OB27 was also collected in 2003 ($n = 12$ and $n = 11$, respectively), and OB63 was obtained from Cahoon et al. (1990, 1992).

evidence for the contention that much of the shelf food web in Onslow Bay is based on benthic microalgal production, in contrast to a plankton-based food web in nearshore Long Bay and more southerly areas of the SAB. Preliminary benthic data show that in Long Bay areas influenced by the plume there are higher abundances of certain epifauna, and higher biomass per individual of infauna (M.H. Posey and T.D. Alphin, University of North Carolina at Wilmington, personal communication). An important line of further investigation is the offshore extent of the plume's influence into Long Bay in terms of nutrients, chlorophyll, and pelagic consumers, and how variation in river discharge influences this extent.

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