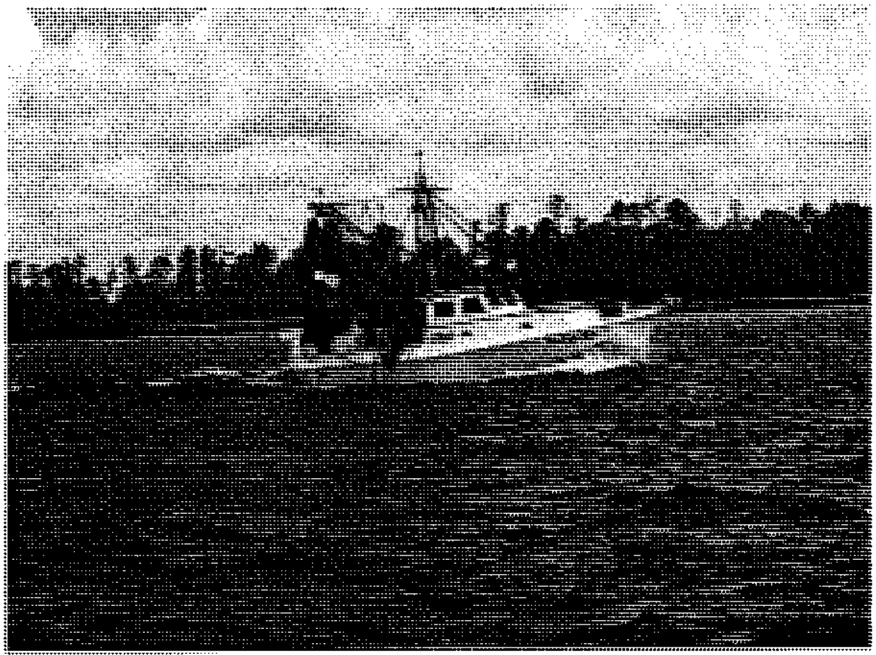
New

Potential Impacts of Bottom Trawling on Water Column Productivity and Sediment Transport Processes



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DISCLAIMER

The contents of this report reflect only the authors' views, who are responsible for the accuracy of the data, the data interpretations, and the recommendations presented herein. The contents do not reflect the official views or policies of the N.C. Sea Grant or East Carolina University.

ABSTRACT

We attempted to evaluate the relative importance of bottom trawling and wind on water column mixing, nutrient loading, and sediment resuspension in South Creek, a major tributary of the Pamlico River estuary, North Carolina. Trawling experiments were carried out in July and October 2001, and in May, June and October 2002, at a "downstream" (closer to the Pamlico River) and an "upstream" (farther from the Pamlico River) area. Each area consisted of a 300 m x 300 m GPS-demarcated "trawl" site and a similarly sized "no trawl" site. The experiments lasted 8 days each in 2001, and 4-5 days each in 2002. Trawling was carried out by a commercial fisherman towing paired crab trawls, and was confined to a single day at each "trawl" site during the midpoint of each experiment. Trawling impacts on the concentration of nitrate-nitrite, ammonium, orthophosphate, chlorophyll a, and total suspended solids (TSS) were assessed. Wind impacts were determined by evaluating the directional daily wind stress in comparison to the same attributes of the same water column parameters.

Our results indicate that wind stress more effectively mixed the water column than did trawling, although trawling was observed to reduce hypoxia on one occasion. However, daily wind stress could only explain about 40% of the variation in water quality data, implying that wind-forced water circulation within South Creek, and between South Creek and the Pamlico River, play a critical role in defining the nutrient and sediment character of the South Creek water column. The most consistent impact of trawling was a 1.5-3-fold increase in the concentration of TSS. However, trawling had only minor impacts on nutrient and chlorophyll a concentrations, and its influence on TSS was ephemeral ($\leq$ one day).

(Key words: trawling, sediment, resuspension, nutrients, diagenisis, eutrophication, porewater, water quality)

INTRODUCTION

Wind-driven mechanisms resulting from wind stress and trawling can directly and indirectly disturb bottom sediments, especially in shallow soft-bottom environments. The objective of this study was to evaluate and quantify the amount of sediment resuspension in a shallow estuarine system, with specific comparisons between natural and trawling-induced disturbances. These disturbances can directly alter the physical structure of the water column and sediments but perhaps more importantly, indirectly alter the chemistry of both. This can occur through the remobilization of sediments and addition of oxygen changing redox potentials in both the surficial sediments and the overlying water column. This change in redox potentials can subsequently degrade water quality as associated organic matter is more efficiently remineralized and thus, increase nutrient concentrations. Therefore, categorizing these disturbances into distinct units (e.g. natural vs. anthropogenic) will provide a means of directly evaluating the potential consequences of human impacts. Heavy trawling activity, in particular, along North Carolina's coast is one of the major obstacles in management plans to protect natural resources (Mallin *et al.*, 2000). Therefore, it is imperative to quantify the effects of trawling, with specific reference to the benthic-pelagic coupling, to gain a more specific understanding of the human impact on estuaries. As such, the specific objectives of this research were to evaluate the extent of resuspension via short-lived radionuclides and water column suspended sediment measurements, assess the change in water column and porewater nutrient concentrations, and evaluate any change in water column productivity associated with a trawling disturbance.

Sediment Resuspension and Possible Effects

Resuspension occurs when an ample force moves sediment particles. Sediment is resuspended by various forces such as currents, wind-wave interaction, tides (Seim *et al.*, 2002), storms (Puig *et al.*, 2001), trawling and large vessels (Schoellhamer, 1996). Wind, for example, can generate currents and increase wave energies. Tengberg *et al.* (2002) observed strong bottom currents associated with large wind events causing a pressure head to develop near that sediment, forcing the onset of resuspension. Wave energies can create orbital velocities that increase sheer stress along the sediment water interface. This increase in sheer stress can resuspend the surficial sediments. Sediment resuspension may also be caused by several biological disturbances, including bioturbation (Drake and Cacchione, 1985, 1986; Moeller *et al.*, 1993). This bioturbation can be caused by both infauna, when the organism buries itself, and epifauna, when the organism moves or attempts to locate food. Although the behavior of estuarine resuspension processes is not well known (Maa *et al.*, 1998; Redondo *et al.*, 2001), the potential impacts to the water column associated with the biological component have been well studied.

Organic productivity forms the base of the biological component. Productivity is dependent on the cycling of nutrients (primarily nitrogen & phosphorus) and organic material between the sediments and the overlying water (Wainright, 1987; Day *et al.*,1989; Ritzrau and Graf, 1992). The majority of water quality research suggests diffusion as the most important mechanism for transferring nutrients from the sediment to the water column. However, productivity can increase in response to resuspension as the organic matter is remineralized more readily under the oxic conditions of the water column (Balls *et al.*, 1994; Pedersen *et al.*, 1995;

Wainright and Hopkinson, 1997; Garstecki *et al.*, 2002). Productivity has also been shown to increase as resuspended bottom sediments release regenerated nutrients, concentrated in porewaters, from the remineralization of freshly deposited organic matter (Loffler, 1974; Rosa *et al.*, 1983; Hopkinson, 1985; Allan, 1986; Wainright, 1990; Nishri, 1993; Wisniewski, 1993). Futhermore, the remobilization of sediments often stimulates more efficient organic matter remineralization by re-oxidizing the surficial sediments. In other words, porewater and diagenetic by-products (carbon/nitrogen/phosphorus) are transported (advected) into the water column during resuspension and can increase nutrient concentrations which directly affect productivity. This continued cycle of resuspension and remineralization in both the water column and sediments may exacerbate nutrient levels in estuaries and subsequently degrade water quality. Therefore, it is important to consider the amount of organic matter stored within the sediment, the frequency of resuspension and transportation of those sediments along with the rate of remineralization when evaluating the potential sources controlling water quality. Continuing research on sediment resuspension suggests that disturbances directly related to bottom trawling can release significant amounts of nutrients into the water column (Fanning *et al.*, 1982; Pilskaln, *et al.*, 1998; Percival *et al.*, 2002, Giffin and Corbett, 2003).

Trawling and Associated Impacts

Both trawling and dredging gear types are directly destructive to critical fish habitat because the gear alters the physical and biological characteristic of the seabed (Watling and Norse, 1998; Hall, 1999). Most of the trawling research has been limited to the physical changes with regard to the benthos, the structure of habitats (Churchill, 1989; Dayton *et al.*, 1995; De Alteris *et al.*, 1999; Collie *et al.*, 2000; Pranovi *et al.*, 2000; Palanques *et al*, 2001; Rosenberg *et al.*, 2002) and with direct epi/infaunal response to trawling events in coarse sediment substrates (Ramsay *et al.*, 1998; Engas *et al.*, 2000; Lindegarth *et al.*, 2000). Population changes within these specific benthic communities have provided insight into the destructive nature of trawling. For example, a degradation of macrofaunal (mollusks, soft corals, sponges etc.) abundance has been observed in trawled compared to non-trawled areas (Morton, 1996; McConnaughey *et al.*, 2000). Smith *et al.* (2000) also observed a significant decrease in abundance and diversity of fauna after trawling. However, discrepancies also exist in the limited amount of research. Inconsistent results with respect to trawling and species abundance were observed (Drabsch *et al*, 2001). Sanchez *et al.* (2000) observed no apparent difference in their trawled and non-trawled areas. Although these studies represent a small fraction of the current research, they acknowledge instances where trawling impacts were not readily observed.

The aforementioned studies, taken as a whole, represent the numerous studies on the direct effects of trawling. Although the studies have provided extensive research into the anthropogenic impact on the marine environment, they are limited to three categories: (1) mortality loss of target species; (2) incidental effects on non-target species; and (3) alteration of benthic habitat. These studies do show that commercial inshore trawling physically disturbs/alters benthic environments, however, the potential impacts on the water column are not as obvious (Churchill *et al.*, 1988; Jones 1992; Collie et al., 1997).
More importantly, the impact of trawling on muddy substrates has not been well studied (Sanchez *et al.*, 2000). The alteration of the benthos from trawling can alter some soft-bottom sediment characteristics such as erosional susceptibility, grain size distribution (Collie *et al.*, 1997; Gilkinson *et al.*, 1998; Pranovi *et al.*, 2000) and porosity (Main and Sangster, 1981).

Therefore, the effects of trawling can lead to direct changes in the natural sediment flux and biologically-active by-products leading to indirect effects on the planktonic food web. These indirect effects may be as important as the direct effects but they have not received significant attention (National Research Council, 2002).

As noted earlier, several variables (wind, trawling etc.) can initiate the onset of resuspension. For example, Booth *et al.* (2000) found wind to be a significant factor in resuspension using a sediment resuspension probability model, within the shallow microtidal Barataria Bay, Louisiana. When both wind and trawling are significant factors, the dominant forcing function may vary between sites, depending on climatic and geomorphic characteristics. Trawling has been characterized as a more important resuspension mechanism than wind on the continental shelf of the Middle Atlantic Bight (Churchill, 1989) and the Kattegat Sea (Floderus and Pihl, 1990). However, little attention has been given to shallow, soft-bottom ecosystems. Furthermore, the combination of strong winds and large shallow estuaries, with bottoms consisting of primarily fine-grained sediments, results in continuously high levels of sediment disturbance (Wells and Kim, 1989). In these cases it is difficult to distinguish the dominant forcing mechanisms, therefore it is necessary to compare the resulting effect of those disturbances (wind vs trawling) in order to evaluate the importance.

This study focuses on a shallow, soft-bottom estuary in North Carolina, typical of the Albemarle-Pamlico Estuarine System (APES) in which it resides. The APES extends from Virginia Beach in the north to Cape Lookout National Seashore in the south. The extensive network of bays and drown-river valleys in the system, formed following the last glacial maximum, delineates the second largest estuarine system in the United States. North Carolina's APES is characterized by relatively shallow depths, typically <6 m. The Outer Banks, to the east, buffer lunar-tides keeping the mean height to <10 cm, wind tides however can exhibit ranges of 0.5- 1.0 m (Hartness, 1977; Giese *et al.*, 1979; Copeland and Riggs, 1984; Wells and Kim, 1989). The drainage area for a significant portion of the system is comprised of marshlands. The limited slope of the region coupled with the surrounding marshlands contributes to low flow velocities entering the system (Hartness, 1977; Wells and Kim, 1989). Sediment texture is related to bathymetry, whereby the shoulders of the estuaries have medium to fine-grained sands and deeper regions are characterized by organic-rich muds with limited variability (Wells and Kim, 1989). The clay portion of the muds are mainly composed of illite (75%) and kaolinite (20%) (Park, 1971; Wright, 1974). A combination of fine-grained sediments, shallow depths and high wind stress cause sediments to settle and resuspended many times before permanent deposition (Wells and Kim, 1989). Therefore, it is necessary to compare the effects of wind with that of bottom trawling since wind-driven disturbances are a primary facilitator of mixing in North Carolina's microtidal estuaries.

Trawling and Site History

North Carolina's trawling season extends from late May/early June through October, targeting the brown shrimp population (North Carolina Division of Marine Fisheries, 1993). Shrimp are harvested using the Otter Trawl (Fig. 1 A&B) as a method of capture. Current trawling regulation consists of proclamations opening areas to trawling. Shrimp must be of a harvestable size in order for the area to be opened. Several factors keeping an area closed include storms that diminish populations, previous over-fishing and the presence of juvenile shrimp.

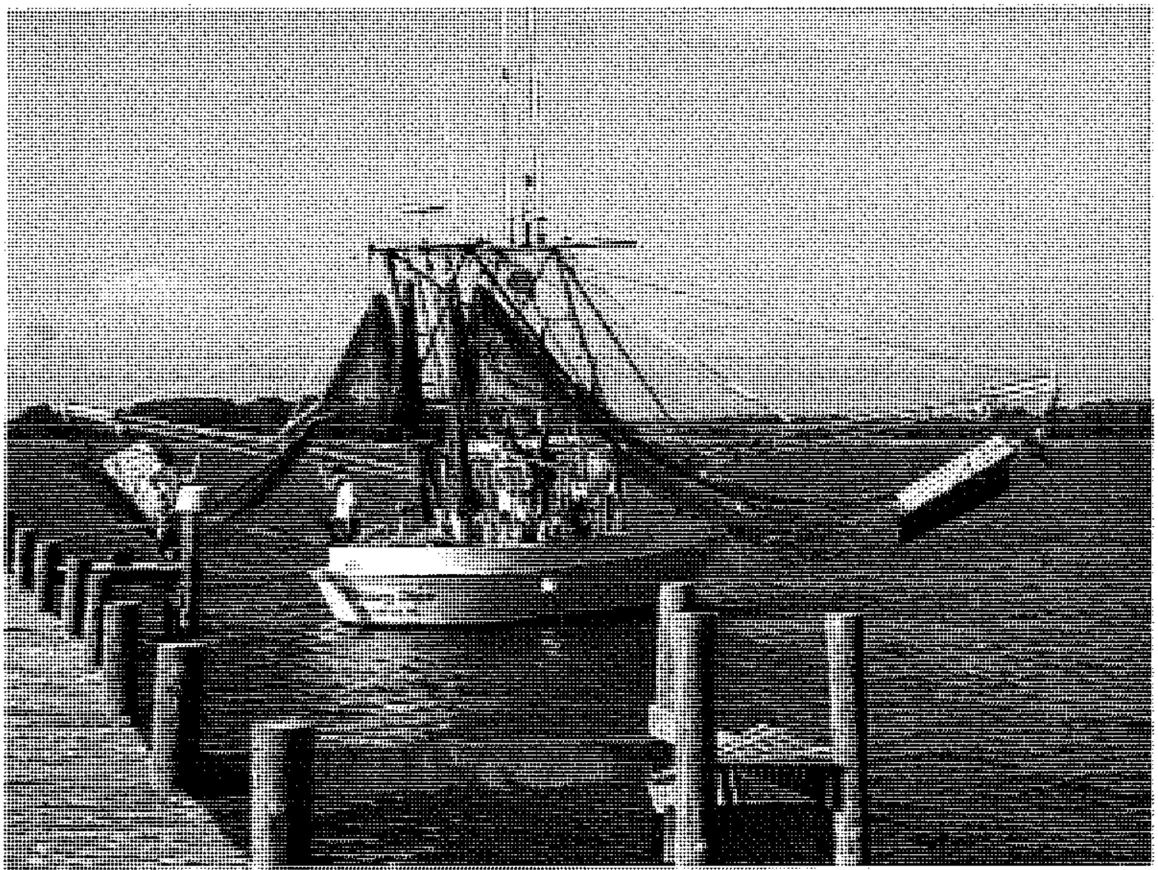
The experimental area for this study is in South Creek (Fig. 2A&B), a tributary of the Pamlico River, northeastern NC. The study was conducted with permission granted by North Carolina Department of Marine Fisheries. The area had been closed to trawling for approximately fifteen years when it became a secondary nursery ground. This specific area was necessary as current restrictions prevented undocumented disturbances (e.g. other trawlers) during experiments. Therefore, the closed area allowed for disturbances to be categorized into either natural or trawling dominated events.

Use of Radionuclides as Particle Tracers

The primordial uranium- and thorium-series radionuclides have been used to evaluate sediment and water column processes in estuarine and marine environments for over 40 years. Th-234, for example, exists as $Th(OH)_n^{(4-n)+}$ in the water column and is extremely reactive allowing it to trace sediment movement. Th-234 ($t_{1/2}$ = 24.1 days) is continuously produced and supported by the alpha decay of its parent nuclide ^{238}U ($t_{1/2} = 4.5 \times 10^9$yr). The short half-life of ^{234}Th also contributes to its particular usefulness as a tracer of particle movement (Kershaw and Young, 1988; Wei and Murray, 1992). The majority of research utilizing ^{234}Th has been in particle flux dynamics, specifically water column export and burial associated with the carbon cycle (Coale and Bruland, 1985; Cochran *et al.*, 1995; Santschi *et al.*, 1999; Coppola *et al.*, 2002). Th-234 is useful when observing sediment/water column interactions due to the physical/chemical differences between it and its direct parent uranium. For instance, resuspension of sediments often leads to a depletion of ^{234}Th in the water column and excess ^{234}Th in the sediments (Kersten *et al.*, 1998; Rutgers van der Loeff *et al.*, 2002). It can also be used to directly measure sediment mixing resulting from bioturbation (Gerino *et al.*, 1998) and turbidity maximum processes in estuaries (Feng *et al.*, 1999a; 1999b). In general, ^{234}Th is an excellent tracer to mark the movement and transport of particles over relatively small time scales (van Geen and Luoma, 1999; Sarin *et al.*, 2000; Quigley *et al.*, 2001; Schmidt *et al.*, 2002).

Cosmogenic isotopes, specifically ^7Be, have also been used as particle tracers (Olsen *et al.*, 1985, 1986; Martin *et al.*, 1986; Wan *et al.*, 1987). Be-7 is produced by cosmic ray spallation reactions with nitrogen and oxygen in the atmosphere. The isotope remains soluble in lower pH rainfall as $^7Be^{2+}$ and is thus transported into the marine environment through precipitation. Upon entrance into the marine environment it adsorbs onto particle surfaces by cationic processes (Bloom and Crecelius, 1983). Within estuaries, ^7Be ($t_{1/2}$ = 53.3 d) activities have been used to study mixing in the upper layers of the benthos and short-term sediment mobility because of shallow depths and high particulate concentrations of these areas compared with the open ocean (Krishnaswami *et al.*, 1980; Robbins and Eadie, 1982; Casey *et al.*, 1986). For example, Dibb and Rice (1989) used changes in ^7Be activities to show sediment movement within the Chesapeake Bay estuary. Quantification of short-term sediment deposition in estuarine and lacustrine environments is also possible using ^7Be. Canuel *et al.* (1990) estimated a depositional rate for sediments within the Cape Lookout Bight, using ^7Be activities, over two years. Metal scavenging rates have also been estimated by using ^7Be activities (Vogler *et al.*, 1996, Steinmann *et al.*, 1999). The overall use of ^7Be as a particle tracer has been well identified and proven to be quite an effective tool (Neubauer *et al.*, 2002).

A



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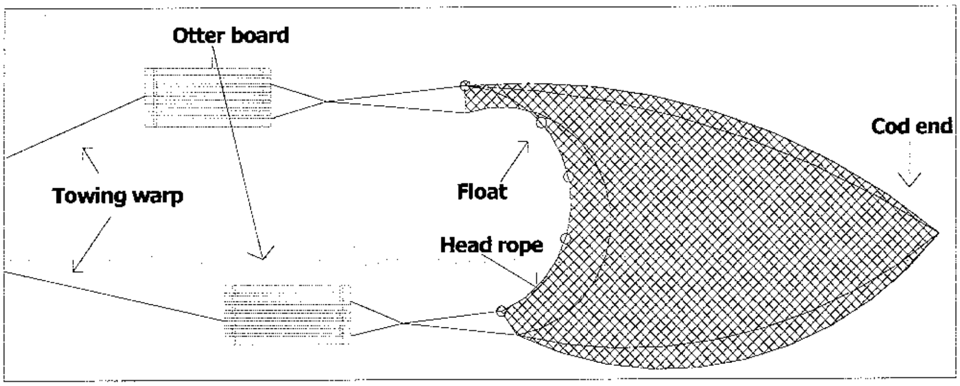
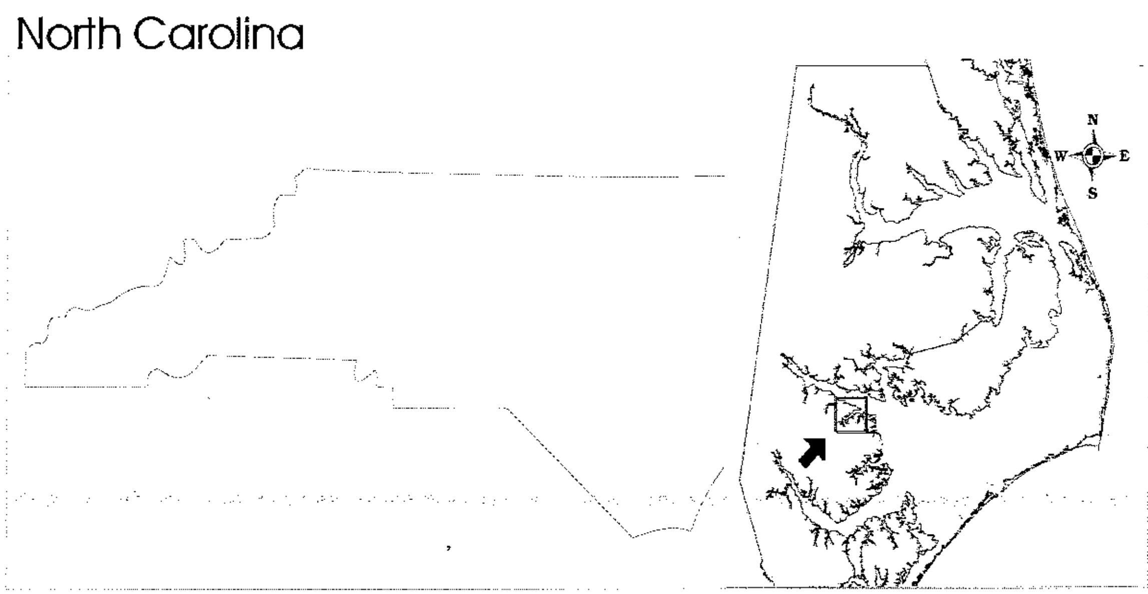


FIGURE 1A&B. Figure 1A is a picture of the Brittany Faye, the trawler used in the experiment and is typical of the vessels used by shrimp trawlers. Figure 1B is a sketch of the trawl gear involved.

A



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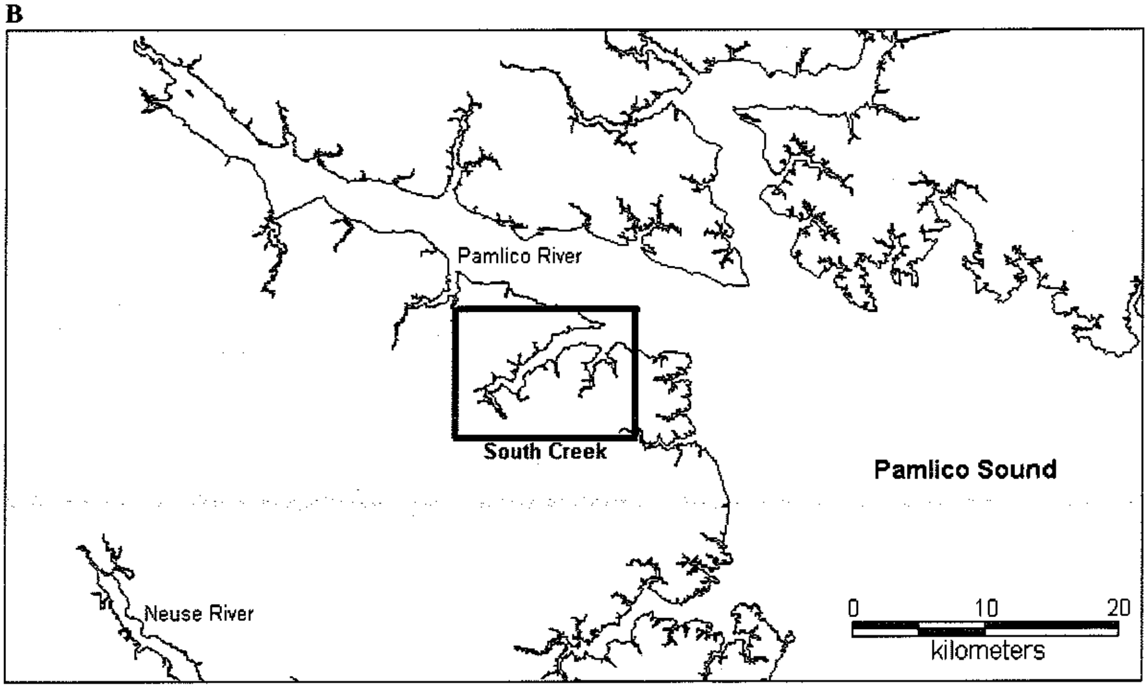


FIGURES 2 A&B. Overview of the field area within the confines of North Carolina.

Used in conjunction, ^{234}Th and ^{7}Be can provide insight into essential sedimentary characteristics such as mixing, sedimentation and erosion. This insight is possible because of their uniquely different sources and particle reactive behavior in combination with relatively short half-lives. The dynamics of these tracers (mean life, reactivity, etc.) coincide with the specific events (high resuspension rates) in estuaries. Therefore, resuspension events generated by wind-driven mechanisms or trawlers, on relatively short time scales (hours to days), can be addressed using these naturally occurring short-lived radionuclides.

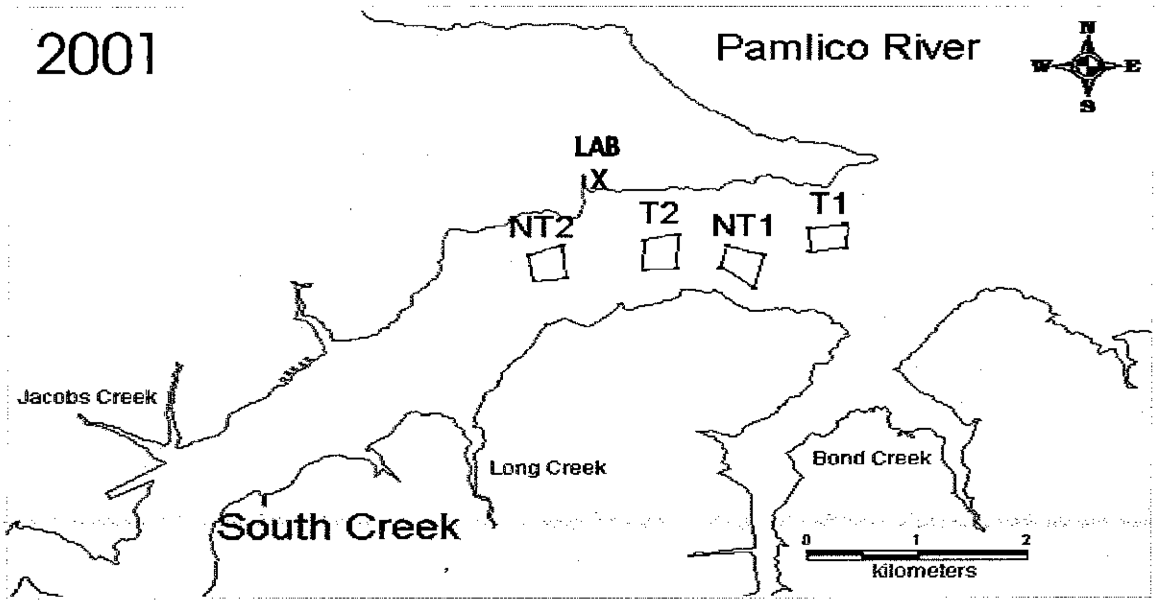
METHODOLOGY

Each experiment was conducted in duplicate using two different areas, downstream (Area 1) and upstream (Area 2). Two sites were occupied within each area, a non-trawl (control) and trawl (experimental) site. A Garmin III GPS was used to outline each site encompassing an estimated 100,000 m^2. During the 2001 experiments, both areas were located in the northern half of South Creek (Fig. 3A). In 2002, the areas were separated further to prevent any possible interference (Fig. 3B). Six separate sampling events were conducted over the two-year period. Two sampling events occurred in 2001, July 16-23 and October 11-18. Four events occurred in 2002, May 20-24, May 27-30, June 11-15 and October 13-16. During each field event, both the control and experiment sites were monitored for at least two days prior to trawling the experimental site. After trawling, sites were monitored for at least another two days. Mr. Henry Daniels conducted the trawling using a 34ft shrimp trawler, Brittany Faye. The experimental sites were trawled continuously for approximately 45 minutes in a back and forth, overlapping pattern. The nets, attached to the head rope, remained open during each trawl. The open nets prevented any catch but provided the same disturbance as a typical trawl.

Atmospheric Analyses

Wind speed and direction were collected hourly from a weather and climate station at the North Carolina State University Aquaculture Field Laboratory (NCSUAFL) near Aurora, NC (Fig. 3). This field station was located a maximum of 2 km from the field sites. The data was retrieved from the North Carolina Agricultural Research Service (NCARS) web site (www.nc-climate.ncsu.edu) for the time period surrounding the experiments and for the entire trawling season of 2001 and 2002. Hourly and daily wind vectors were calculated for each sampling period using a Statistical Analysis Software (SAS) program. This was used to generalize wind patterns that dominated during each experiment and throughout the entire trawling season for the two years of the project.

A.



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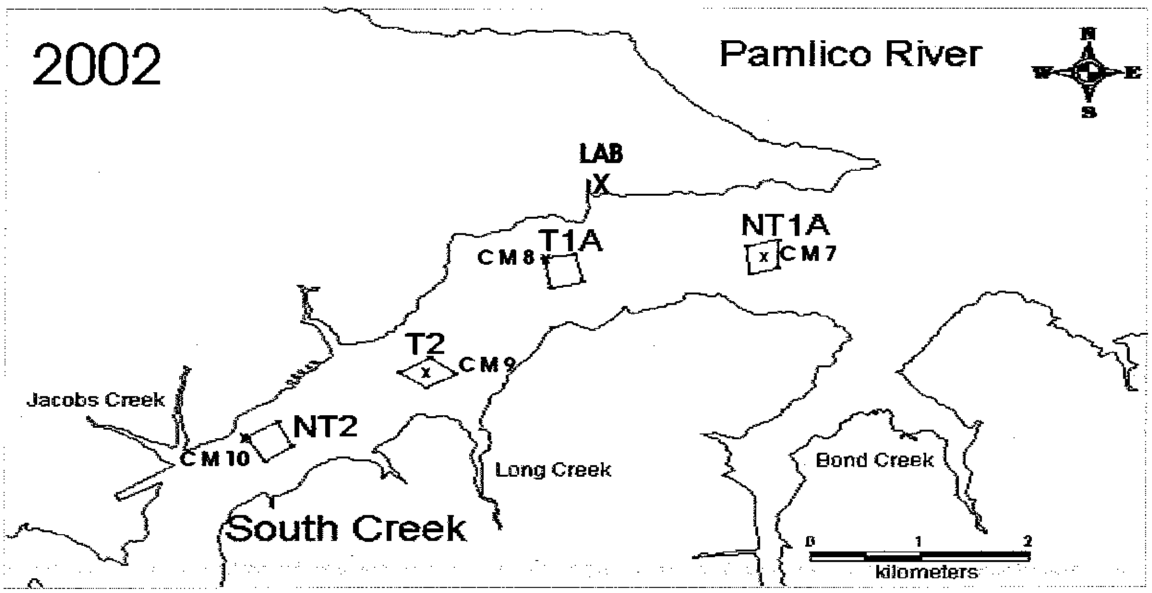


FIGURE 3 A&B. Overview of the 2001 and 2002 field sites. NT and T represent the non-trawl and trawl sites for 2001. Changes in site location are reflected in the 2002 map. The CM (#) refers to the channel marker on which turbidity sensors were placed. The lab refers to the North Carolina State University Aquaculture Field Laboratory.

The wind directions were divided into eight different sectors, each measuring 45°, N(338°-22°), NE(22°-67°), E(67°-112°), SE(112°-157°), S(157°-202°), SW(202°-247°), W(247°-292°) and NW(292°-337°). These data were used to calculate wind stress for each site, both hourly and daily, for the period immediately before sampling. Wind stress was calculated as:

$$\tau_s = CD * \rho_a * W^2 \qquad (1)$$

$$\rho_a = P/RT \qquad (2)$$

where τ_s is the tangential wind stress at the air-water interface (newtons m^{-2}), CD is the drag coefficient (unitless), ρ_a is the air density (kg m^{-3}) where P is the air pressure (pascals), R is the gas constant (287 J kg^{-1} K^{-1}), T is temperature (Kelvin) and W is the wind speed (m s^{-1}) 10 m above the land surface (Bowden, 1983).

Although the CD has historically been given a constant value of $1.3*10^{-3}$, a non-linear CD is used, modified for low wind speeds, as presented by Tenberth *et al.* (1990). The values are 0.00218 for $W \leq 1$ m s^{-1}, $0.001(0.62 + 1.56W)$ for 1 m $s^{-1} < W < 3$ m s^{-1} and 0.00114 for $W \geq 3$ m s^{-1} and are unitless. When statistically analyzing τ_s and TSS, the hourly τ_s uses the values from NCARS for the hour immediately prior to sampling; the daily τ_s uses the 24-hr W resultant and the average P and T values for the closest full 24-hr period prior to sampling. For example, if samples are collected at 1430, the hourly τ_s uses the values from 1300-1400 while the daily τ_s employs the average values from 1400 (day before)-1400 (day of). These are then correlated with the total suspended solids (TSS) concentration for each site/area (surface and bottom), within each experiment. This correlation is helpful in observing the relationship of wind stress and TSS but is not intended to isolate the specific resuspension mechanism generated by the wind stress.

Water Column Analyses

Hydrography

The water column variables temperature, salinity and dissolved oxygen (DO) were measured at the same sites where the aforementioned water samples were collected. Temperature and salinity were measured using an Orion® 140 temperature-conductivity-salinity meter. Coincident dissolved oxygen measurements were taken using a Yellow Springs Instrument (YSI®) Model 60 water quality meter.

Total Suspended Solids/Loss on Ignition

Water column samples were collected at five randomly chosen locations within each site. Duplicate 250 mL samples were collected at the surface and bottom within each location using a 2.0 l Van Dorn sampler. During 2001, samples were collected over eight days. They were collected once a day for the first and last three days (around 1200) and twice (morning and afternoon) for the day before and day of trawling (11122111). During 2002, the sampling was kept to once a day, for four or five days, throughout each experiment. The control sites were sampled prior to trawling of the experimental sites in the same area to limit the potential influence of trawling (eg. transport of sediment). The trawled sites were then sampled within minutes after the cessation of trawling.

Immediately following collection, samples were brought back to the field laboratory setup on the property of the NCSUAFL (Fig. 3A). At the lab, a measured volume of water sample (250-300mL) was filtered through a pre-weighed combusted (450°C for 4 hours) 0.7 µm Whatman GF/F 47 mm filter. The filters were rinsed with deionized (DI) water to remove salts and then frozen to prevent bacterial growth. Upon return to East Carolina University (ECU), filters were dried (105°C for 48 hours) and reweighed to determine the total suspended solids (TSS mg/L):

$$TSS = (105^{o}CW\text{-}IW)/\,SV \qquad (3)$$

where IW(g) is the initial filter weight and 105°CW is the post drying weight (g) and SV is the sample volume (liters). The filters were then combusted in a muffle furnace (500°C for 20 minutes) and reweighed to determine loss on ignition (LOI %):

$$LOI = ((TSS\text{-}500^{o}CW)/(TSS * SV))*100 \qquad (4)$$

where 500°CW is the post combustion weight. Averages and standard errors were then calculated for the five replicate samples collected at each site, each day.

Nutrient and Pigment Analyses

The TSS filtrate was placed in acid-washed 250 ml polypropylene bottles, frozen, and analyzed for dissolved nutrients within 60 days of collection. Ammonium nitrogen was measured using the phenol-hypochlorite method (Solorzano1969); nitrate plus nitrite nitrogen, and ortho-phosphate determinations were carried out according to the automated and manual standard EPA methods (1995), respectively.

Water column pigment concentrations were determined by fluorometry with a Turner Designs ® TD-700 fluorometer. A known volume of water (50 or 100 ml) was filtered through a 0.7 µm Whatman ® GF/F filter. Filters were immediately wrapped in aluminum foil, and kept frozen at –40 °C until analysis (typically completed within one month). Prior to analysis each sample was extracted for 12 hours in a known amount of acetone, methanol, water mixture (45:45:10 by volume). Samples were then centrifuged, and the fluorescence of the supernatant before and after acidification was used to calculate chlorophyll a and phaeopigment concentration (modified from Holm-Hansen et al. 1965).

In Situ Monitors

Conductivity, temperature, depth (CTD) and turbidity meters within each site continuously collected measurements (every 10-60 minutes) during the 2002 experiments. They were attached to channel markers located at each site (Fig. 3B). A total of four were deployed during May and June exercises. The turbidity sensors measured the intensity of infrared light scattered at 90 degrees from the incident beam and converts the data into Nephelometric Turbidity Units (NTU). Two different models were used during each trawling event, the Hydrolab series 4a Minisonde and Datasonde. The meters were left at each station after the conclusion of trawling to assist in further estimation of natural variation.

A Falmouth Scientific Instrument (FSI) 2-D current meter was also used during the 2002 experiments. It was deployed with the turbidity sensor in T1A (CM8) to measure bottom current velocities (approximately 0.5m above the bottom). This instrument took readings every 30 seconds for 2 minutes on 10-minute intervals, which allowed for a total of 24 readings per hour. The data was condensed into hourly and daily vectors, to correlate with the wind vectors, using a SAS wind program.

Sediment Analyses

Sediment samples were collected using an Oceans Instrument multi-corer to provide cores with little to no disturbance at the sediment-water interface. The multi-corer collects four, 6.35 X 33 cm, cores during a single deployment. In 2001, sixteen cores (four deployments) were collected for each site (eg. NT1, T1, etc.). Each site was further subdivided into two random locations within each site (eg. NT1/1;NT1/2). Eight cores were collected from each of these subdivided sites (4 cores per deployment * 2 deployments per location * 2 locations per site * 4 sites per exercise). These duplicates were collected to provide some assessment of spatial variability within each site/location. The cores were collected two days before and the day after trawling during both the July and October exercises. During 2002, cores were collected from only one location within each site one day before, on and after trawling. After collection, cores were brought back to the field laboratory, sectioned at 1 cm intervals and combined from each of the four cores taken during a specific deployment. Subsections were packed into several sample containers for transport back to ECU for subsequent analysis. Samples were analyzed for porosity and radionuclide activities (^{234}Th and ^{7}Be). Samples for porosity were collected at 1 cm intervals and placed into pre-weighed 25 mL glass scintillation containers (2001) or 6 mL plastic containers (2002). Samples for nutrient and radionuclide analyses were collected at 1 cm intervals in 50 mL centrifuge tubes. Samples were centrifuged and filtered for porewater extraction. Samples for radionuclide analyses were then combined at 2 cm intervals. A sub-sample from the porosity and radionuclide samples were used for LOI and grain size, respectively.

Porosity/Loss on Ignition

The volume of individual porosity vials was determined by weight difference following the addition of deionized (DI) water. Samples were weighed (wet) upon the return to ECU, dried for 48 hours at 60°C and reweighed. Porosity was then calculated by the difference in weights wet/dry and applied a correction factor for salinity in the overlying water column as

$$porosity = [((WS-DS)/1.02)/(V)] \quad (5)$$

where WS is the wet sediment weight (g), DS is the dry sediment weight (g), 1.02 is the salinity correction factor and V is the initial volume of the vial (mL).

A sub-sample of dry sediment from each porosity vial was subsequently ground, using a mortar and pestel, and placed into pre-weighed crucibles. These were transferred into a dessicator and left overnight to remove any accumulated water. The samples were weighed and then combusted in a Lindberg Hevi-Duty SB muffle furnace (450°C for 4 hours). LOI was calculated as:

$$LOI = ((SW- CW)/SW)*100 \quad (6)$$

where SW is the dry sediment weight (total weight –crucible weight (g)) and CW is the combusted weight (g). LOI is a relatively good proxy for organic material (Soil and Plant Analysis Council, 2000).

Radionuclide inventories

Samples from all sediment cores were analyzed for ^{234}Th and ^{7}Be by direct gamma counting. The samples were dried in a Fisher Scientific Isotemp oven for 48-72 hours at 60°C. Samples were then removed from the oven, crushed into a uniformly fine powder using a mortar and pestel and subsequently packed into 1oz aluminum tins (coax geometry) or plastic vials (well geometry) and sealed with tape or epoxy for analysis. Sample size ranged between approximately 5 and 40 g depending on counting geometry (vial or tin, respectively). Gamma counting was conducted on one of two, low-background, high efficiency, high purity Germanium detectors (Coaxial and Well-type, Canberra germanium detectors, model GR-1520, GCW-2523) coupled with a multi-channel analyzer. Calibration of detectors was calculated using several natural matrix standards (IAEA-300, 312 and 314), at each energy of interest (except ^{7}Be) in the standard counting geometry for the associated detector. The counting efficiency of ^{7}Be (477 keV) was determined by linear regression of calculated efficiencies for energies between 200-800 keV.

Excess ^{234}Th was calculated by taking the difference between the total ^{234}Th activity from that supported by ^{238}U. Total ^{234}Th (63 keV) was determined by direct gamma counting, while supported ^{234}Th was determined by recounting eight random samples after six months and alpha spectroscopy of ^{238}U from another eight (^{238}U = 3.39 ± 0.38, 3.36 ± 0.10, respectively). Reported data for short-lived nuclides (^{234}Th and ^{7}Be) are corrected for the radioactive decay that had occurred between sampling and analysis. Sediment inventories were calculated according to the following equation (after Canuel *et al.*, 1990):

$$I= \Sigma X_i (1-\phi_i) \rho(xsA_i) \quad (7)$$

where I is the total inventory of the sediment core (dpm cm^{-2}); X_i is the subsection thickness (constant 2 cm); ϕ_i is the porosity of the subsection (unitless); ρ is the sediment density (g cm^3); and xsA_i is the activity, for ^{234}Th it is the activity above the level supported by ^{238}U (dpm g^{-1}). The total inventories before and after trawling can be compared to establish a sediment disturbance associated with trawling. In other words, when trawling resuspends sediment its overall fate is important and would be addressed in terms of an inventory relationship (Fig. 4).

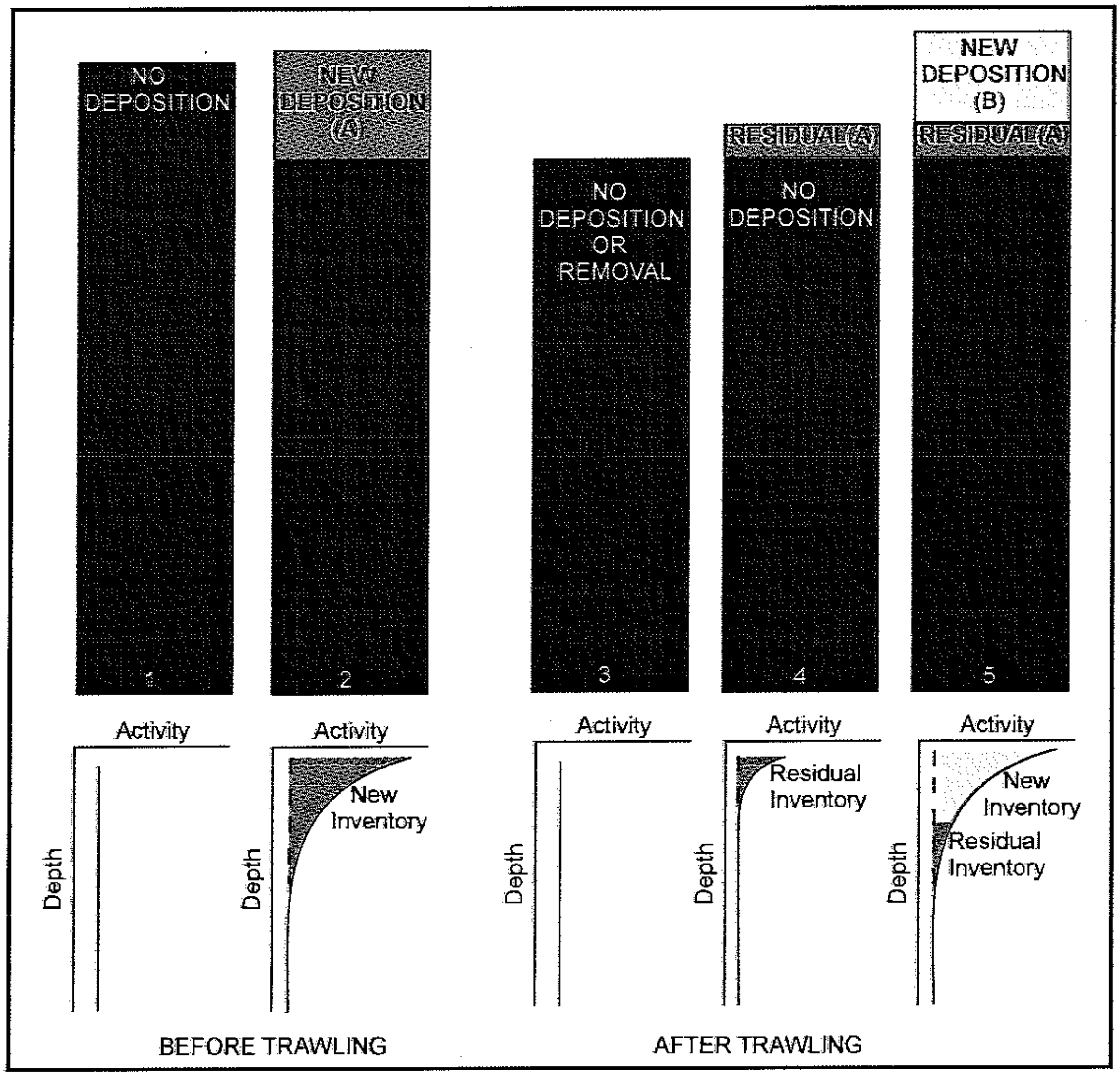


Figure 4. Possible inventory relationships of cores, over time, taken in the same area: 1. No deposition occurred i.e. no measurable ^{7}Be or ^{234}Th (core 1); or 2. New deposition and thus measurable activities of ^{7}Be, mean life <77 days and ^{234}Th, mean life<35day (core2). Subsequent cores taken immediately after trawling for comparison have three distinct possibilities of sediment variability: 1. No change that can be detected (no activities to compare or activities are equal, core 2→4); 2. Removal of sediment equal to a quantifiable difference in activities directly caused by trawling (core 2→3/4); or 3. new deposition of sediment from another area that has been removed by trawling (core 2→3) and deposited in core 5. This is the only likely possibility since measurable sedimentation rates do not typically occur on daily times scales.

Grain size

Two methods were used to remove organic matter from sediments before grain size analysis. Samples analyzed in October 2001, were prepared using a 6% Sodium Hypochlorite solution. Each sample (approximately 5 g) was placed into a separate 400 mL tri-cornered beaker with ~0.5 L of solution. The mixture was agitated for at least five days or until all signs of bubbles at the surface disappeared. Samples collected in 2002 were prepared with 30% hydrogen peroxide as it proved to be a more efficient method. Hydrogen peroxide (~15 ml) was added to each beaker and covered. The samples were then left in a hot bath (75°C) for two days with a daily addition of hydrogen peroxide (~5 mL) until all organics had been removed.

After the organics were removed, regardless of method, the samples were centrifuged for 25 minutes at 4000 rpm, discarding the supernatant. A solution of sodium hexametaphosphate (0.6 g/L) was added following two rinses with deionized water. This solution acts as a dispersant, effectively separating individual sediment grains for analysis. A sub-sample from the centrifuge tube was then analyzed on a Beckman Coulter LS230 Particle-size Analyzer. The grain sizes were given as percent per individual size and then converted to cumulative percent for clay (0-8μm), silt (8-63μm) and sand (>63 μm).

Porewater Nutrient Analyses

Filtered porewater samples were analyzed for ammonium (NH_4^+) using the Solorzano Method (Solorzano 1969) and for dissolved nitrate plus nitrite (NO_3^-+NO_2^-) and phosphate (PO_4^{3-}) using U.S. EPA (1979) and American Public Health Association (1995) Methods. Previous studies have shown that nitrite is barely detectable in comparison to nitrate, therefore NO_3^-+NO_2^- results will be presented only as nitrate (NO_3^-).

RESULTS AND DISCUSSION

Assessment of Disturbance: Sediment Resuspension and Transport

The water column and sediment can be mixed naturally through wind-driven disturbances. Specific disturbances can be a result of wind stress, specifically wind tides, currents and wave orbitals. As the water column is mixed the temperature, salinity and dissolved oxygen values may become more homogeneous if typical estuarine stratification is lost. The mixing process can also increase the TSS concentrations as sediment is resuspended into the overlying water column. Trawling can also physically alter the water column and sediments in a similar way as trawl gear mixes the water column and stirs the soft-bottom sediment.

Impact of Wind

This study intended to provide some insight into the direct natural mechanisms (wind, waves, currents, etc.) that resuspend sediments. However, the limited current meter data and lack of meters at other sites prevented correlations between bottom currents and TSS. Therefore, the wind stress and TSS analysis provided general insight into the indirect influence of wind on the water column.

A strong relationship (p-values < 0.01) was observed for the 24-hr resultant northeast, east and southwest τ_s and near-bottom TSS concentrations in Area 1 (Table 1). This relationship is also observed for a northeast τ_s in Area 2. Other significant correlations were observed during an hourly southwest τ_s in A1 and during a northeast and southwest τ_s in A2. In all these cases, the wind directions were from areas of largest fetch (Fig. 2B).

Therefore, it can be stated that the larger the fetch for an area; the better the correlation of τ_s and the observed TSS values. More importantly, the significant hourly wind vectors coincided with the daily τ_s for all but one observation (A2 SW). Therefore, the strong hourly correlations could be a function of the overriding 24-hr resultant τ_s. The comparison between the 24-hr and hourly resultant wind vectors show that changes in TSS concentrations happen on longer time scales. It seems that hourly winds do not have sufficient time to set up resultant wind driven mechanisms that resuspend sediment. This was also observed in Booth *et al.* (2000), whereby 24-hr wind resultants were better correlated with TSS values.

Significant surficial values that did not coincide with near-bottom values may not be related to resuspension. It is assumed that if the values were related, they would also be reflected in the near-bottom. This occurs as TSS concentrations move from source to sink, or areas closest to sediment then up through the water column. However, it is possible that there are other sources for the surficial TSS concentrations. Other possible sources of TSS are, but not limited to, sediment input from local creeks, streams, Pamlico River and Sound. Surficial TSS could also be transported by wave erosion, precipitation runoff and blown detritus from adjacent land surrounding the field area.

Delineation of Natural versus Trawling

Each experiment can be categorized into the dominant forcing mechanism, natural or trawling induced, by comparing the 24-hr resultant wind vector for each site/area, water column hydrography (stratified or mixed) and TSS concentrations. For example, an experiment was categorized as wind (natural) dominated if most or all of the following occurred: the 24-hr resultant wind direction was from a sector with the largest fetch (e.g. NE or E), the hydrography (T/S/DO) at the surface and near-bottom was relatively homogeneous (well-mixed) in both sites and the TSS concentrations in the trawled site were within the confines of the non-trawled area (natural variation) for the entire exercise and trawl day in specific. Conversely, an experiment was categorized as trawling (anthropogenic) dominated if the following occurred: the 24-hr resultant wind direction prior to trawling was from a sector other than the largest fetch, the hydrography (T/S/DO) exhibited a stratified water column and TSS concentrations within the trawl site exceeded those observed in the non-trawl site immediately after trawling. The delineation of natural or trawling dominated disturbances can be more easily seen by superimposing wind direction on the TSS data within each area (surface and bottom) for each exercise (Fig. 5 - 6). The wind direction encompasses both the changes during each exercise and the specific wind direction for the 24-hr period prior to each trawling event, since it was shown to correlate better with TSS concentrations (Table 1).

TABLE 1. Statistical analysis (r^2,n,p) of total suspended solids (TSS) and daily/hourly wind stress (τ_s) for each wind sector. P-values 0.05 or less are *italicized* and 0.01 or less are **bold**.

τ_s vs TSS	Area 1 Surface			Area 1 Bottom			Area 2 Surface			Area 2 Bottom		
Daily wind	r^2	n	p	r^2	n	p	r^2	n	p	r^2	n	p
N	0.08	8	0.50	0.12	8	0.41	0.03	9	0.68	0.02	9	0.75
NE	0.01	10	0.76	**0.88**	**10**	**0.00**	0.01	10	0.76	**0.74**	**10**	**0.00**
E	0.05	8	0.58	**0.81**	**8**	**0.00**	*0.56*	*8*	*0.03*	0.22	8	0.24
SE	0.32	8	0.14	0.30	8	0.16	0.09	8	0.47	0.01	8	0.81
S	0.00	14	0.97	0.19	14	0.11	0.01	14	0.70	*0.32*	*14*	*0.03*
SW	0.08	12	0.36	**0.56**	**12**	**0.01**	0.14	13	0.20	0.01	13	0.69
W	-	-	-	-	-	-	-	-	-	-	-	-
NW	**0.98**	**4**	**0.01**	0.27	4	0.48	*0.96*	*4*	*0.02*	0.05	4	0.78
Hourly wind												
N	0.23	10	0.16	0.01	10	0.80	*0.30*	*13*	*0.05*	*0.41*	*13*	*0.02*
NE	*0.38*	*11*	*0.04*	0.01	11	0.82	0.55	7	0.06	**0.86**	**7**	**0.00**
E	0.58	6	0.08	0.29	6	0.27	0.23	12	0.11	0.01	12	0.79
SE	0.01	7	0.85	0.00	7	1.00	**0.41**	**14**	**0.01**	0.03	14	0.56
S	**0.74**	**10**	**0.00**	0.14	10	0.28	*0.64*	*8*	*0.02*	0.40	8	0.09
SW	0.28	9	0.14	**0.72**	**9**	**0.00**	*0.69*	*6*	*0.04*	**0.94**	**6**	**0.00**
W	0.49	3	0.50	0.01	3	0.93	0.56	3	0.46	0.02	3	0.90
NW	*0.67*	*6*	*0.04*	0.24	6	0.33	0.96	3	0.14	0.19	3	0.71

Natural Disturbances

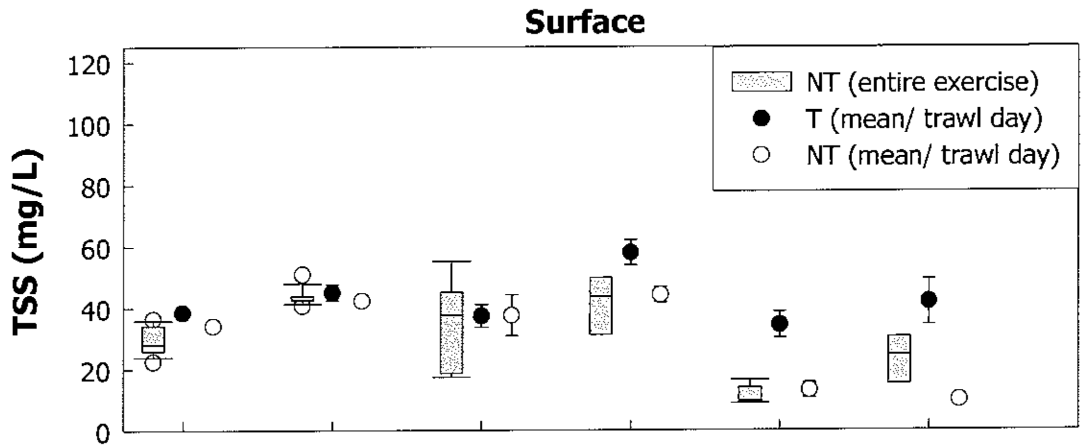
The October 2001 and May 2002 (140-144) observations were a result of dominant natural forcing parameters. The hydrographical parameters and mean trawl site TSS concentrations during each experiment were indicators of more dominant wind-driven disturbances relative to trawling. These disturbances occurred either at one instance or was thought to have been a dominant factor throughout the experiment. October 2001 TSS concentrations in the trawled site of Area 1 were within the confines of the natural variation (NT concentrations) observed. A NW wind dominated the 24-hr period prior to trawling and increased TSS concentrations in both the NT and T sites. However, the link between TSS and NW winds was inferred because the small number of observations (n=4) prevented a better correlation of these variables. Area 2 concentrations for the trawled site were not as consistent. Surficial values after trawling were higher than any natural variation observed and thought to be either directly related to trawling, or a combination of trawling and local creek derived detritus. Near-bottom TSS concentrations were within the natural variation observed, however, the mean value for the T site was higher than the NT mean value on trawl day. Therefore, NW winds may impact the water column in A2 but not to the extent observed in A1. Radionuclide inventories for ^{234}Th and ^{7}Be show spatial and temporal changes in both the NT and T sites for A1 and A2. All of the temporal changes for ^{234}Th and ^{7}Be, except A2 NT ^{234}Th, reflect a decrease in inventories or removal of sediment throughout the entire field area. This area-wide decrease of radionuclide inventories could reflect a disbursement of sediment generated by a wind disturbance and transport, through wind-driven mechanisms out of the field area (Rutgers van der Loeff *et al.*, 2004).

The first May 2002 experiment (140-144) defined a punctuated wind disturbance. Area 1&2 TSS values, in both the NT and T sites immediately after trawling, were within similar ranges. Furthermore, mean NT values after trawling were higher in all instances, except A1 surface, compared to the T site. The increased TSS values were related to the NE winds occurring prior to the trawling event. It has been previously shown that winds from the NE increase near-bottom TSS concentrations. This wind-driven disturbance also increased turbidity levels (~30%) in the NT sites of both areas. Although the increase is not visible in the T sites, any elevation in turbidity levels in the NT sites that coincided temporally with a wind disturbance was thought to directly relate to that event.

Trawling Disturbances

The July 2001, second May (147-150), June and October 2002 experiments were dominated by the trawling disturbance. Specifically, changes in the water column and sediment were more controlled and affected by the invoked trawl event rather than atmospheric forcing. Dominant wind patterns (e.g. S, SE etc.) generated little if any effect on the water column and therefore, allowed the trawling disturbance to be easily observed.

Area 1



Event	July 197-204	October 284-291	May 140-144	May 147-150	June 161-165	October 283-286
Wind Directions	SW-NE	SE-N-NE	N-NE-S	S-SE-E	S-SW-S	NW-N-NE
24-hr Vector	N	NW	NE	SE	S	N
Dominant force	T	W	W	T	T	T

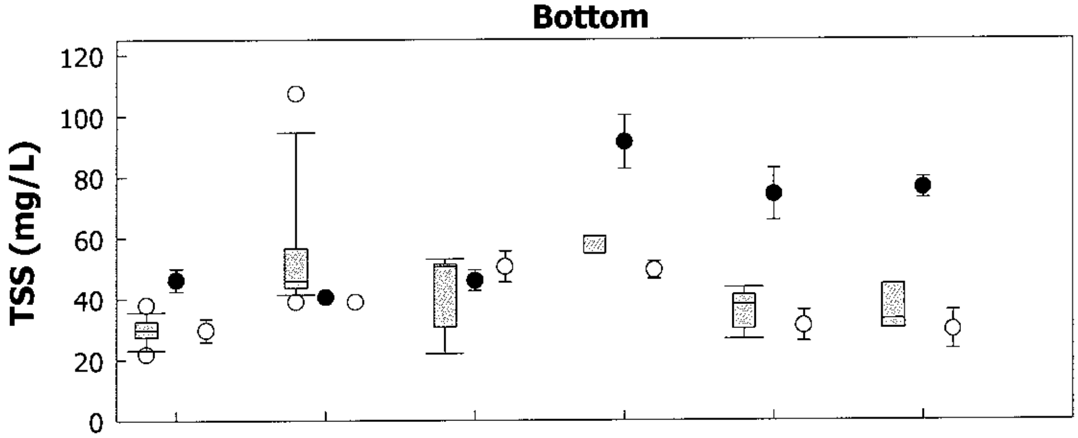
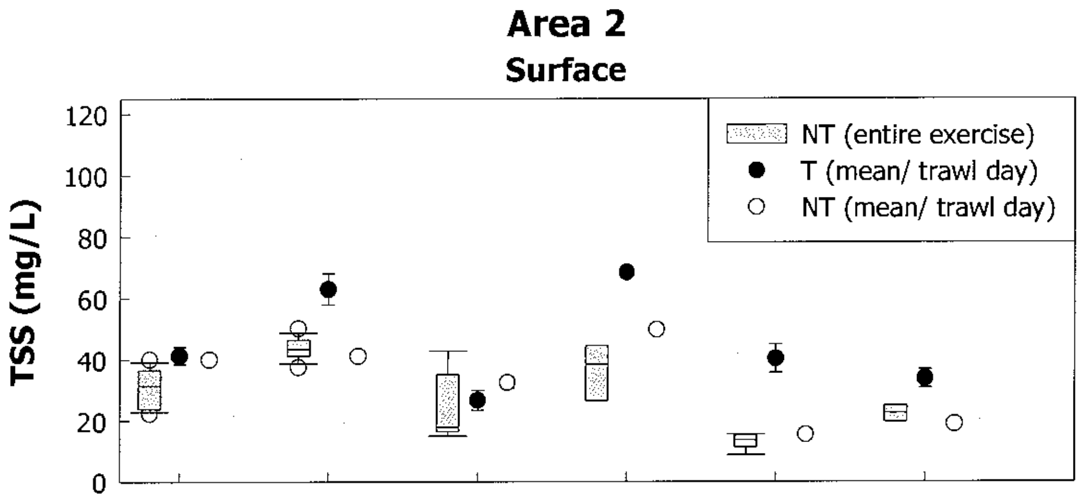


FIGURE 5. Area 1 (downstream) surface and near-bottom TSS data for each exercise vs. total wind and the 24-hr resultant wind vector for the period prior to the trawl event. TSS data is broken up into 1. A box and whisker plot for the NT site data during the entire exercise to show total natural variation, 2. The mean and standard error for the T site data on the day of the trawl event and 3. The mean and standard error for the NT site data on the day of the trawl event. The dominant force believed to control observations is denoted T for trawl or W for wind.

Area 2



Event	July 197-204	October 284-291	May 140-144	May 147-150	June 161-165	October 283-286
Wind Directions	SW-NE	SE-N-NE	N-NE-S	S-SE-E	S-SW-S	NW-N-NE
24-hr Vector	N	NW	NE	SE	S	N
Dominant force	T	W	W	T	T	T

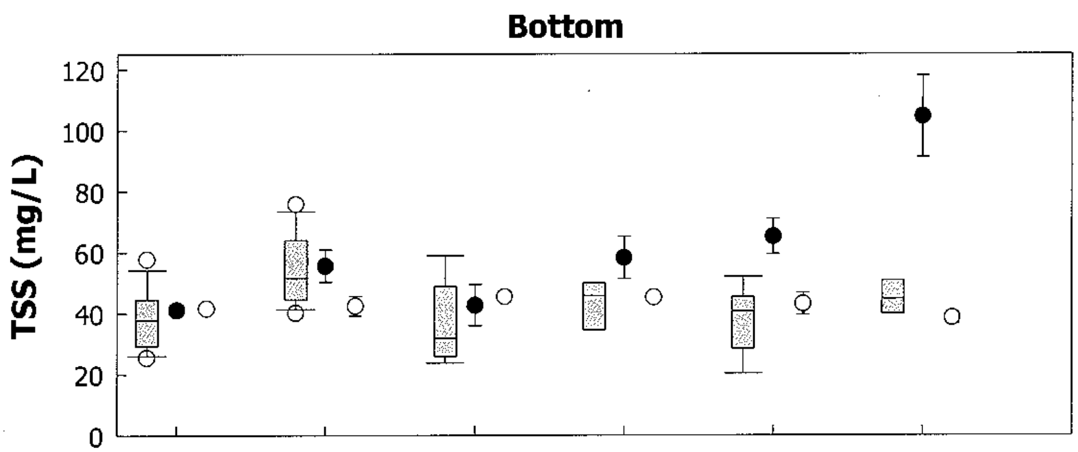


FIGURE 6. Area 2 (upstream) surface and near-bottom TSS data for each exercise vs. total wind and the 24-hr resultant wind vector for the period prior to the trawl event. TSS data is broken up into 1. A box and whisker plot for the NT site data during the entire exercise to show total natural variation, 2. The mean and standard error for the T site data on the day of the trawl event and 3. The mean and standard error for the NT site data on the day of the trawl event. The dominant force believed to control observations is denoted T for trawl or W for wind.

A north wind dominated the 24-hr period prior to trawling during the July 2001 experiment and thus inflicted a limited natural disturbance. A1 trawl day mean TSS concentrations were higher in the T site than the NT site immediately after the trawling event. These T site concentrations were also higher than the natural variation (NT site) throughout the entire experiment. Similar results were detected in A2, except for the near-bottom. This was explained by the insignificant correlation of TSS values and wind stress from north sector. However, it does seem possible that July 2001 represented a combination of trawling and wind induced disturbances. This was evident as the mean trawl day TSS values were within close proximity to the non-trawl area values. The October 2002 exercise was very similar to the July 2001 event. Resultant wind vectors (24-hr) prior to trawling were also from the north and the natural variation of TSS concentrations was within the same range as observed during July. However, the trawl day mean TSS concentrations in both A1&A2 were much higher.

The second May and June 2002 experiments were similar in their response to the trawling event. Winds from the S and SE dominated the entire experiment. A1&A2 trawl day mean TSS concentrations were twice that of the NT site immediately after trawling and also significantly higher than the total range of natural variation observed throughout the experiments. An increase in A1 turbidity levels of ~50% was observed in the T site during both trawl events. An increase in the same range was also observed in the T site during the June experiment. The substantial increase (10-100%) in TSS values and 50% in turbidity measurements compared to all other experiments can be explained by mixing. The water column is well-mixed by wind-induced mechanisms as winds were from the sectors of largest fetch. Therefore, any pulse of sediment directly related to trawling during these wind events was immediately dispersed/transported throughout the water column. This disbursement of sediment produced relatively homogenous TSS concentrations. However, high TSS concentrations directly attributed to trawling were observed when winds were from areas of small fetch (e.g. S, SE, etc.). In that case, the sediment was disbursed into the over-lying water column and not transported out of the area. The significant increase remained for a period of less than 24-hours before it settled out of suspension. This temporal range was solely a function of the sampling protocol whereby the high TSS values were not observed during the next sample collection (day after). The mixing effect was also observed in the DO concentrations.

Thorium-234 data supports these observations as larger temporal variations of inventories existed in the T site compared to the NT site. In all cases, except for the May 2002 (147-150) A1 data, inventories increased relative to the NT site. This increase can be explained by the scavenging of dissolved ^{234}Th, within the water column, by the resuspended sediments (Santschi *et al.*, 1999). The sediment was then re-deposited rather quickly because of the following three factors: the calm atmospheric conditions that limited wind-driven mechanisms (e.g. tides and currents) that promote transport, the salinity concentration (> 2-4 ppt) promoted flocculation of clays and the localized turbid water generated by the trawl gear which aided in particle-particle contact and thus flocculation (McAnally and Mehta, 2002). The re-deposition of these sediments with higher ^{234}Th activities increased the inventories within the T sites relative to the NT sites. This pattern would not have the same effect with respect to ^{7}Be due to the small atmospheric source relative to the *in situ* ^{234}Th source.

Sediment Sources and Nutrient Fluxes

It has been previously mentioned that productivity can increase in response to sediment resuspension as the associated organic matter is remineralized (Wainright and Hopkinson, 1997; Garstecki *et al.*, 2002). Therefore, it was important to discuss the correlation (p-values) of TSS values with the associated LOI (% organics) and how they related to natural or trawling induced disturbances. P-values were typically much greater than 0.01 (0.628/October 2001 and 0.122/May 2002 140-144) in samples collected from surface waters when wind was determined to be the dominant forcing mechanism. During these same exercises, bottom water values were significantly correlated ($p<0.01$). However, p-values were less than 0.01 for both bottom and surface waters in every case when trawling dominated, except surface water in July 2001 ($p = 0.024$) and bottom water in June 2002 ($p = 0.035$). This statistical analysis provides possible insight into the possible origin of the organic matter during these resuspension events. Most of the organic matter (OM) suspended in the bottom waters, regardless of the type of disturbance, more than likely originated from the bottom sediments. This was explained by the stronger correlation of near-bottom TSS and LOI during all exercises. Conversely, surface water OM may have originated from a combination of other sources (e.g. bank erosion, stream transport) during natural or wind-driven resuspension experiments, not simply from the bottom. The strong correlations between the TSS and LOI during the trawling events suggest a common source of sediment (e.g. bottom sediments). Thus, the trawling disturbance resuspends bottom sediments and quickly mixes the water, transporting these sediments into the surface waters.

More importantly, winds from areas of largest fetch occurred only ~50% of the time, during the combined 2001-2002 typical trawling season, May-October (Table 2). This suggests that within South Creek an increase in TSS concentrations directly related to trawling would have been observed approximately half of the time. However, most areas of the Pamlico Sound and other heavily trawled regions are not fetch limited. In that case, wind-driven disturbances may be a more important sediment resuspension mechanism than trawling.

TABLE 2. 24-hour wind vector percentages for the 2001 and 2002 trawling season. Data in bold indicates wind sectors and percentages for areas of largest fetch.

Direction	**2001**	**2002**	**Combined**
N	14.13	8.33	11.26
NE	**10.33**	**19.44**	**14.84**
E	**13.59**	**15.00**	**14.29**
SE	8.15	7.78	7.97
S	21.20	15.56	18.41
SW	**19.02**	**20.56**	**19.78**
W	5.43	5.00	5.22
NW	8.15	8.33	8.24

Assessment of Distrubance : Nutrient Resuspension

In most estuaries, the amount of nutrients supplied by external sources (e.g. atmospheric deposition, river runoff, nitrogen fixation) has consistently been shown to supply less than that required by primary producers (Dugdale and Goering, 1967; Haines, 1976; Windom et al., 1975; Stanley and Hobbie, 1977; Kuenzler et al., 1979; Nixon, 1981; Stanley and Hobbie, 1981; Fisher et al., 1982; Boyer et al., 1988; Kemp and Boynton, 1992). The remainder of the nutrient supplies must, therefore, come from *in situ* regeneration and recycling. A major component of this internal recycling is exchange at the benthic boundary. The benthic environment is particularly important due to the large portion of organic matter that reaches the sediment surface after settling out of the water column. This organic matter is then remineralized, a process during the decomposition of organic matter where inorganic nutrients, such as nitrogen and phosphorus, are released, thus increasing concentrations of these in the interstitial waters. The newly regenerated nutrients are then transported back to the water column through exchange with overlying waters. In most shallow-water systems, surficial sediments and the overlying water are continually interacting, exchanging and redistributing particles and solutes, making this recycling process extremely important for understanding nutrient dynamics in the estuarine environment (Wells and Kim, 1989; Rizzo, 1993; Rizzo and Christian, 1996; Alperin et al., 2000). The amount of nutrients that the sediments deliver to the overlying water column would be considerably greater than diffusion alone in those areas that are frequently disturbed through natural or anthropogenic processes (Fanning et al., 1982; Kristensen et al., 1992; Sondergaard et al, 1992; de Jonge et al., 1995).

Porewater nutrients were measured at1 cm intervals down to 10 cm in cores collected prior, the day of, and following trawling disturbances. Cores were collected in both the non-trawl and trawl study areas. Porewaters were analyzed for ammonium (NH_4^+), nitrate and nitrite ($NO_3^- +$ NO_2^-), and reactive phosphate (PO_4^{-3}).

Vertical profiles of porewater NH_4^+ concentrations for the top 10 cm typically exhibited increasing concentrations with depth for all sampling locations. The NH_4^+ concentrations ranged from approximately 10 μM at the sediment water interface to as high as 1000 μM at near the bottom of the core. Typical NH_4^+ concentrations at 8-10 cm ranged between 500-800 μM. Nitrate and nitrite ranged from 0.1 to 1.5 μM, typically decreasing with depth into the sediments. It can readily be seen that nitrate-nitrite concentrations, as intermediates in sediment N redox reactions, compose a very small amount of the total porewater nitrogen in comparison to ammonium, generally representing <1% of the total N. The distribution of PO_4^{3-} concentrations, ranging from 1 to 80 μM, displayed the same general trends as porewater NH_4^+ concentrations. A representative porewater data set is presented for the June 2002 trawl experiment (Fig. 7 and 8, see appendix for all downcore plots).

In order to facilitate porewater interpretations, depth profiles were integrated to provide a nutrient porewater inventory for the top 10 cm. Inventories were then normalized to the initial core collected at individual sites for each exercise. Therefore, subsequent changes in inventory would either be >1, increase in inventory, or <1, decrease in inventory (Fig. 9-14). However, changes in porewater inventories occurred in both the trawl an no trawl sites at approximately the same magnitude of variation. These cores collected in the trawl area had most certainly been disturbed by the trawls doors, chains, and net. Therefore, any change in porewater concentrations/inventory associated with trawling is either to subtle to measure due to natural variation or recovered quicker than our post-trawl sampling.

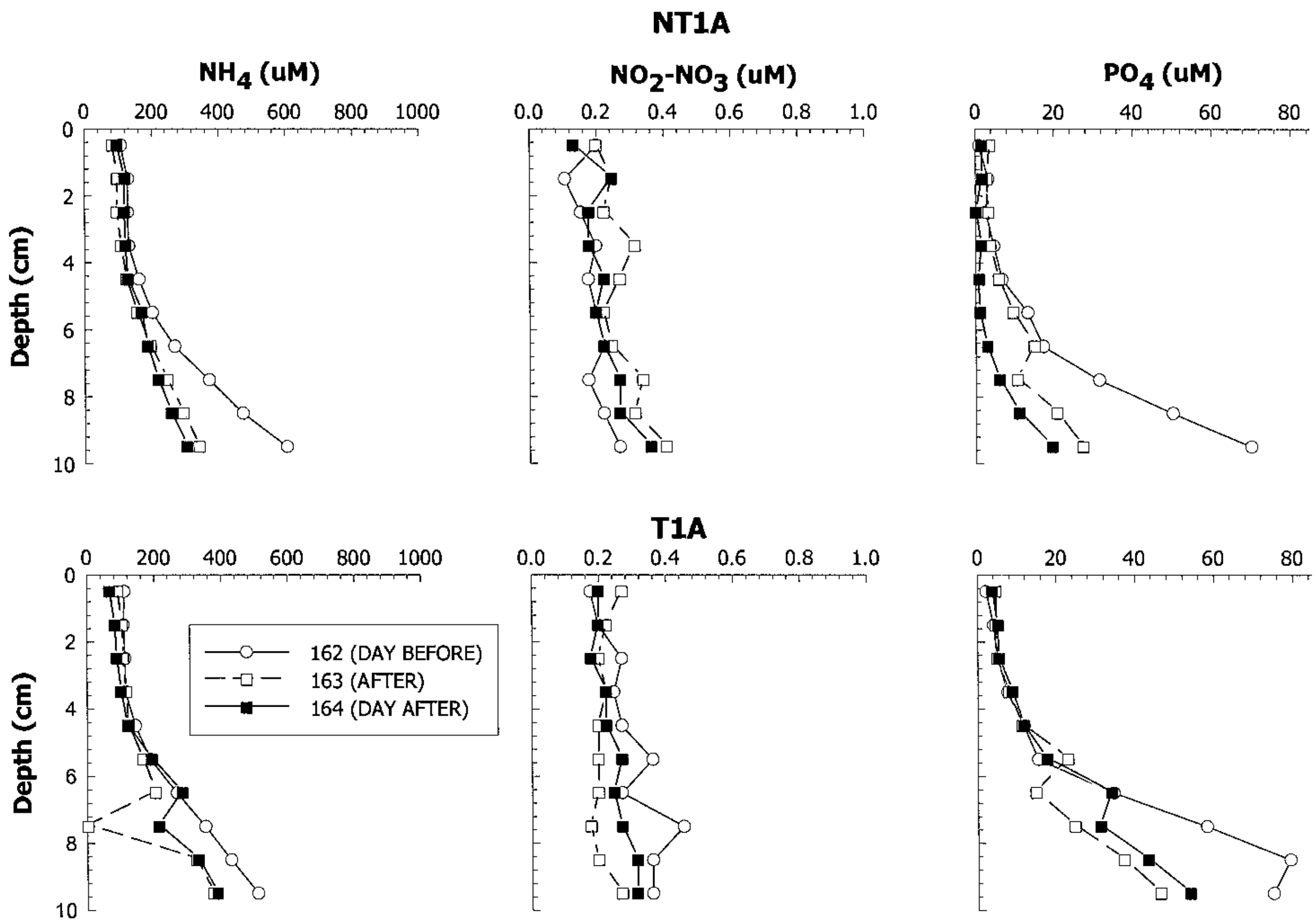


FIGURE 7. Downcore porewater profiles for areas NT1 and T1 during June 2002.

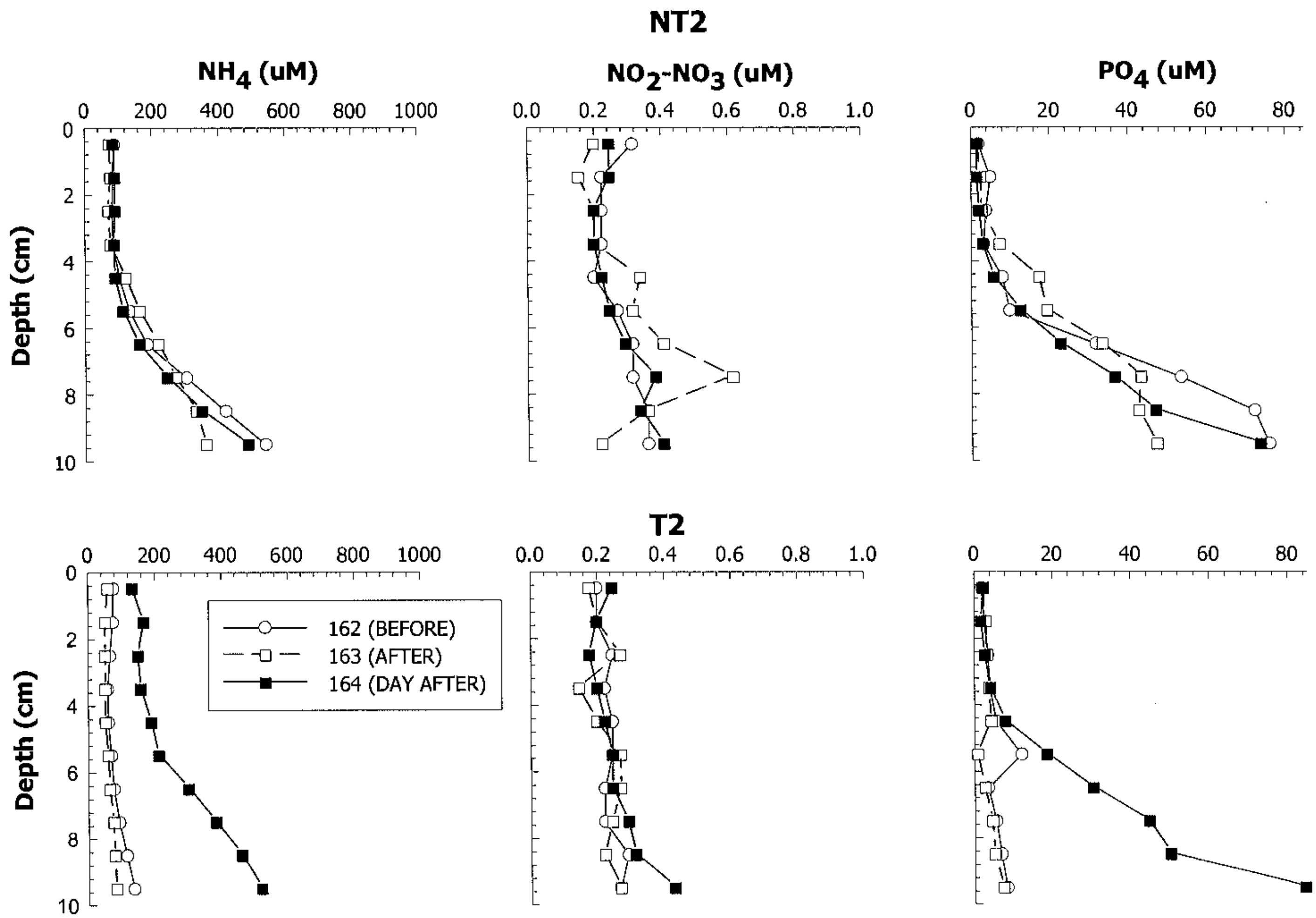


FIGURE 8. Downcore porewater profiles for areas NT2 and T2 during June 2002.

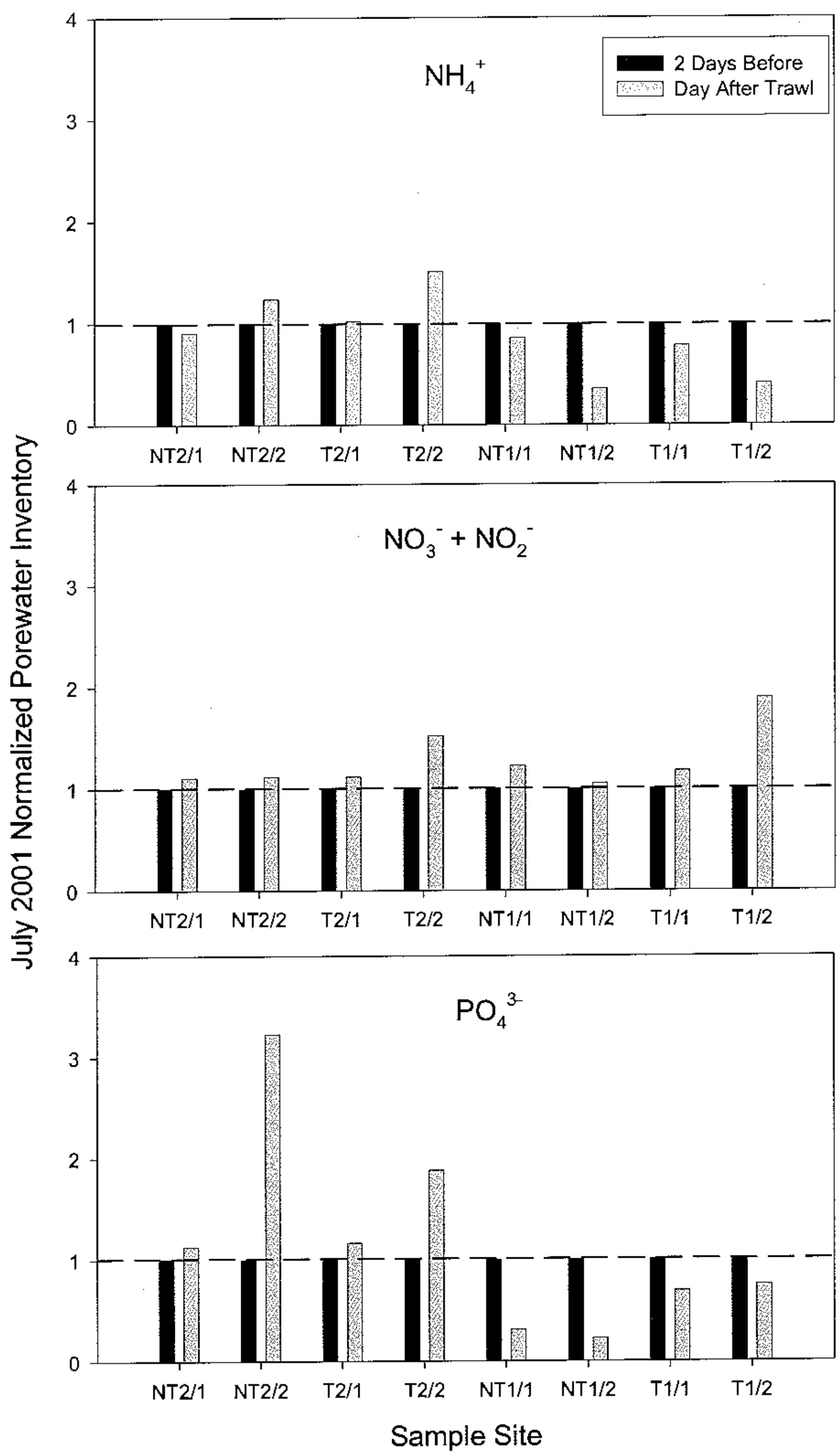


FIGURE 9: Normalized porewater inventories for cores collected during the July 2001 trawling experiment. Two cores were collected from each area in order to evaluate spatial heterogeneity.

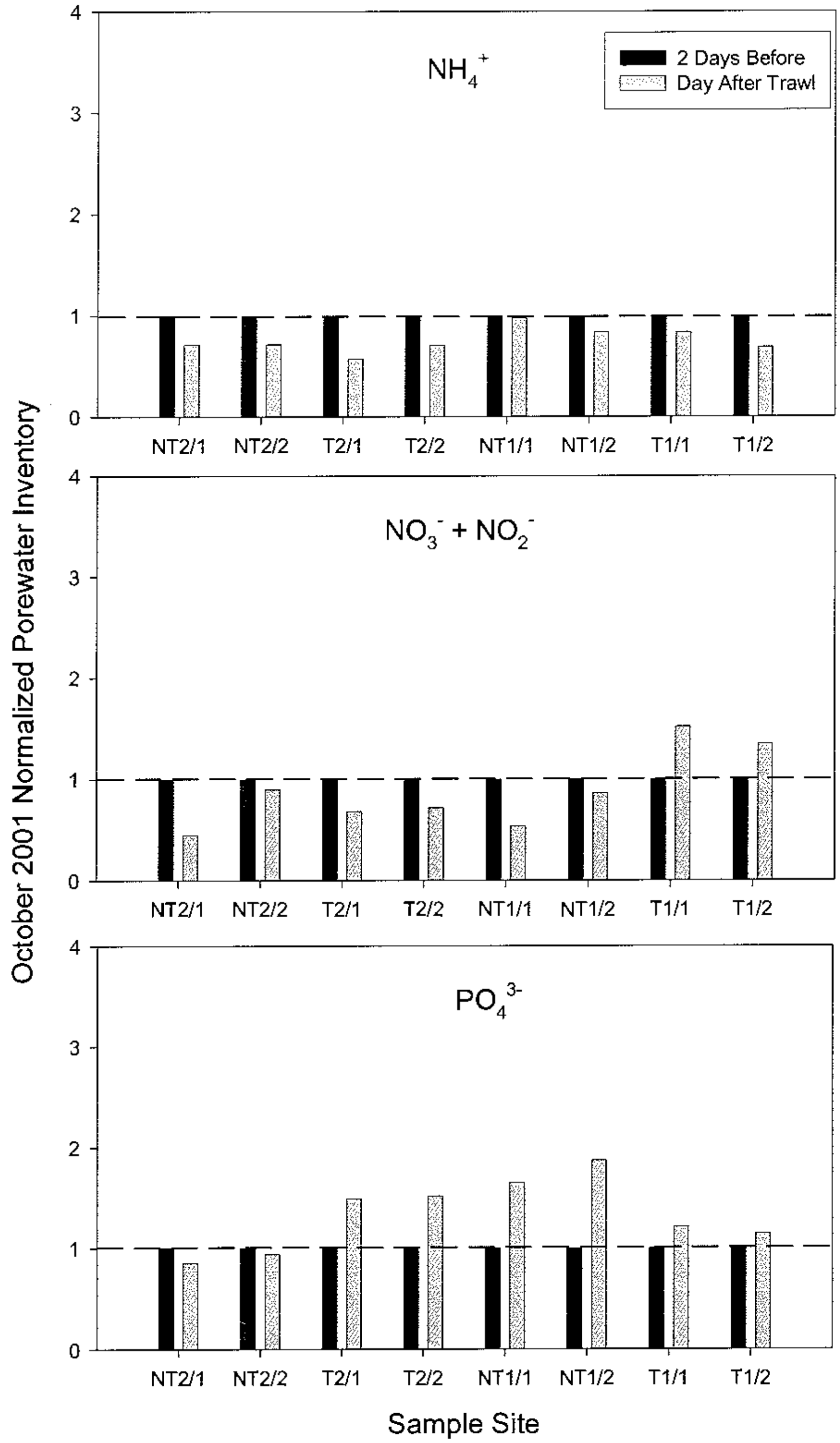


FIGURE 10: Normalized porewater inventories for cores collected during the October 2001 trawling experiment. Two cores were collected from each area in order to evaluate spatial heterogeneity.

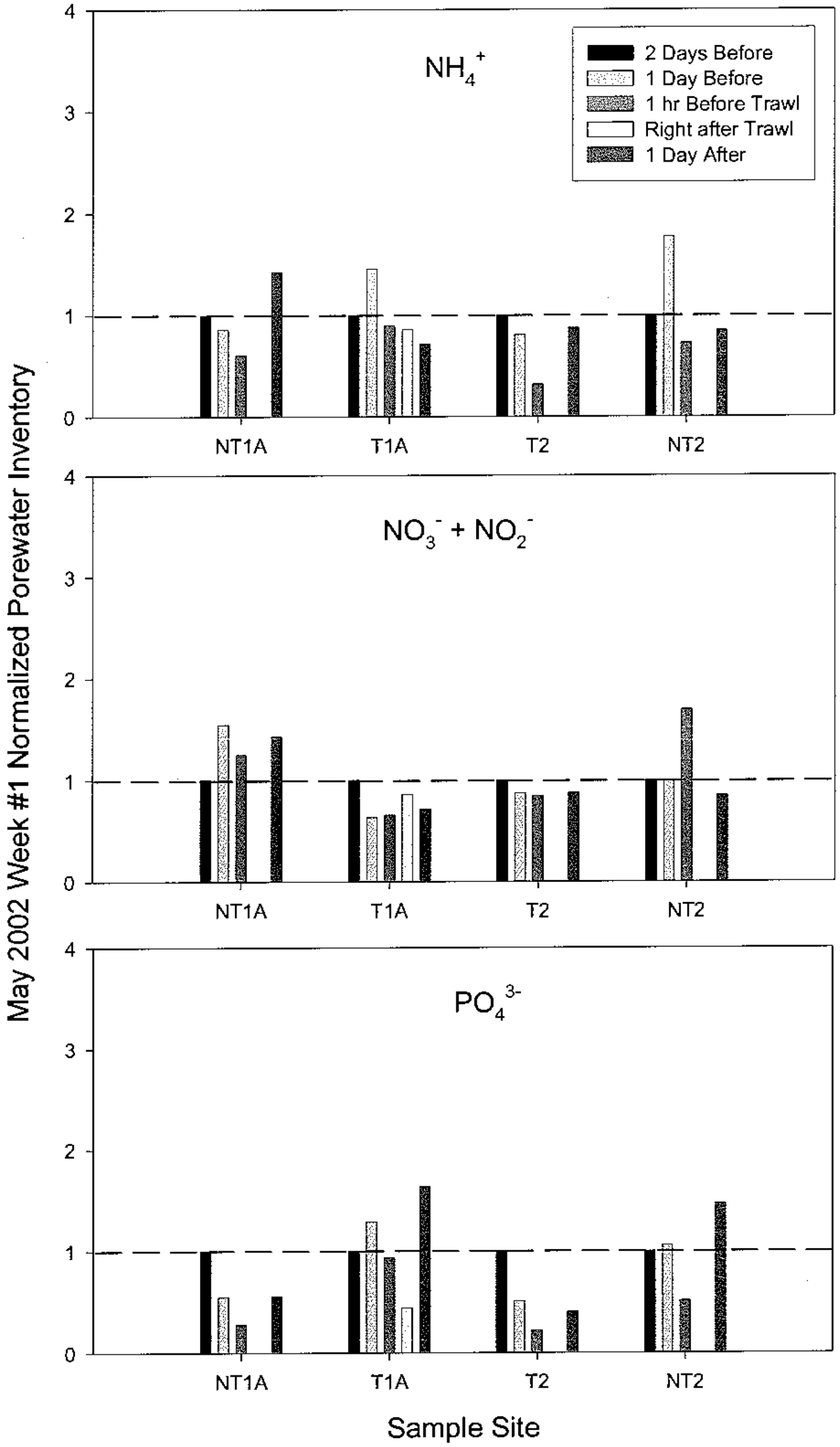


FIGURE 11: Normalized porewater inventories for cores collected during the first week of the May 2002 trawling experiment. Cores were also collected just prior and after trawling.

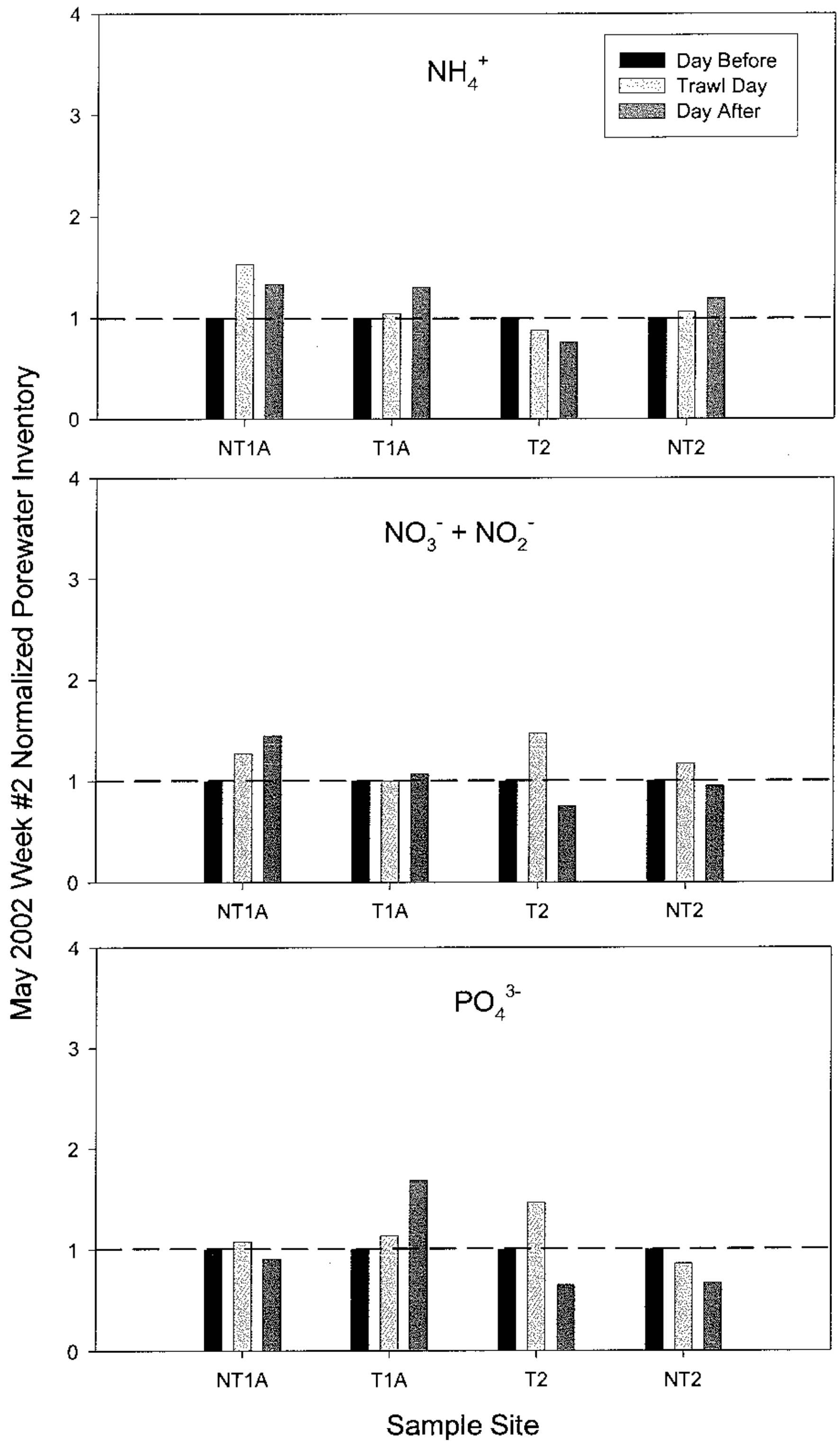


FIGURE 12: Normalized porewater inventories for cores collected during the final week of the May 2002 trawling experiment. Data from Trawl Day refer to cores collected immediately following the cessation of trawling.

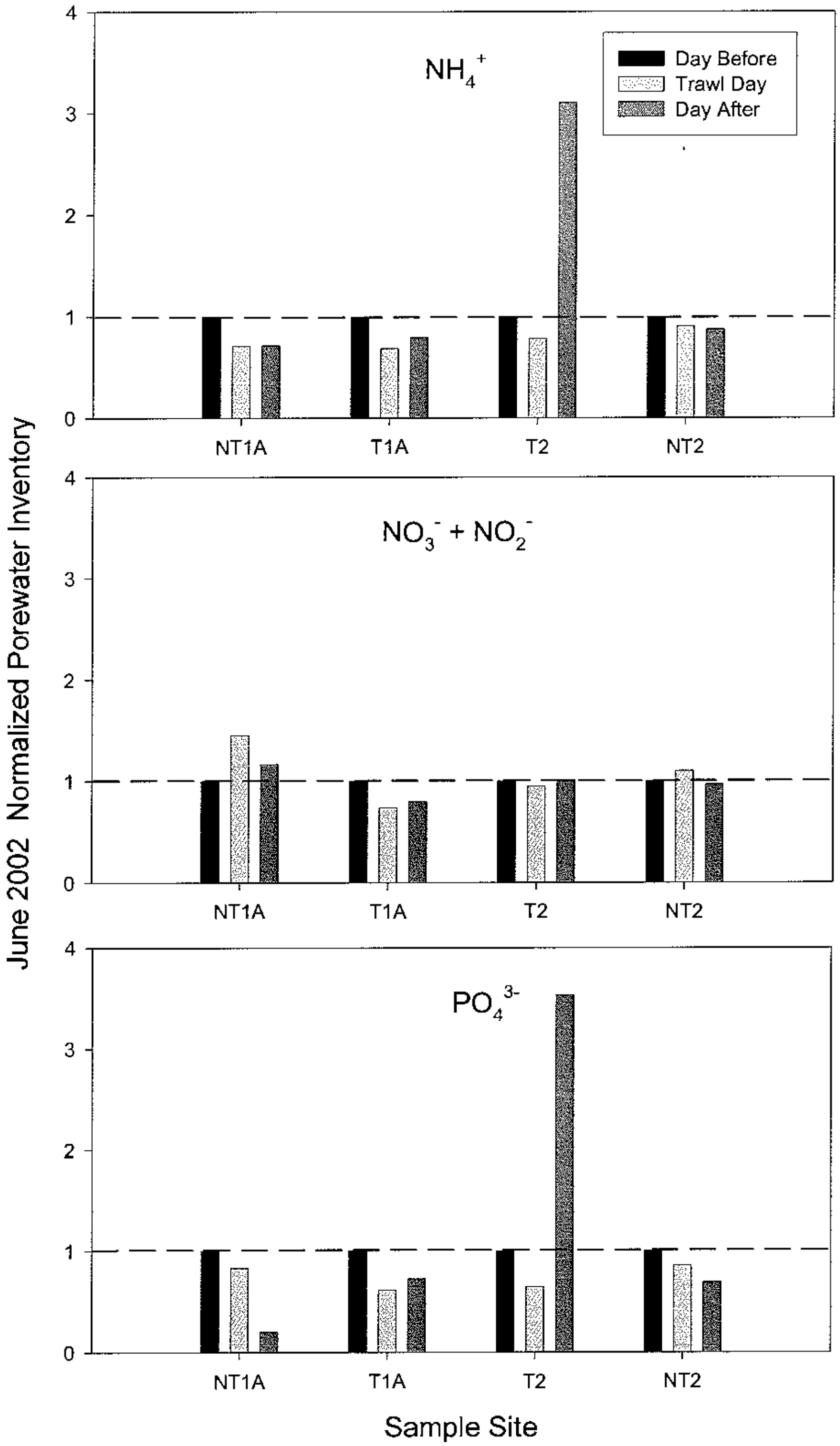


FIGURE 13: Normalized porewater inventories for cores collected during the June 2002 trawling experiment. Data from Trawl Day refer to cores collected immediately following the cessation of trawling.

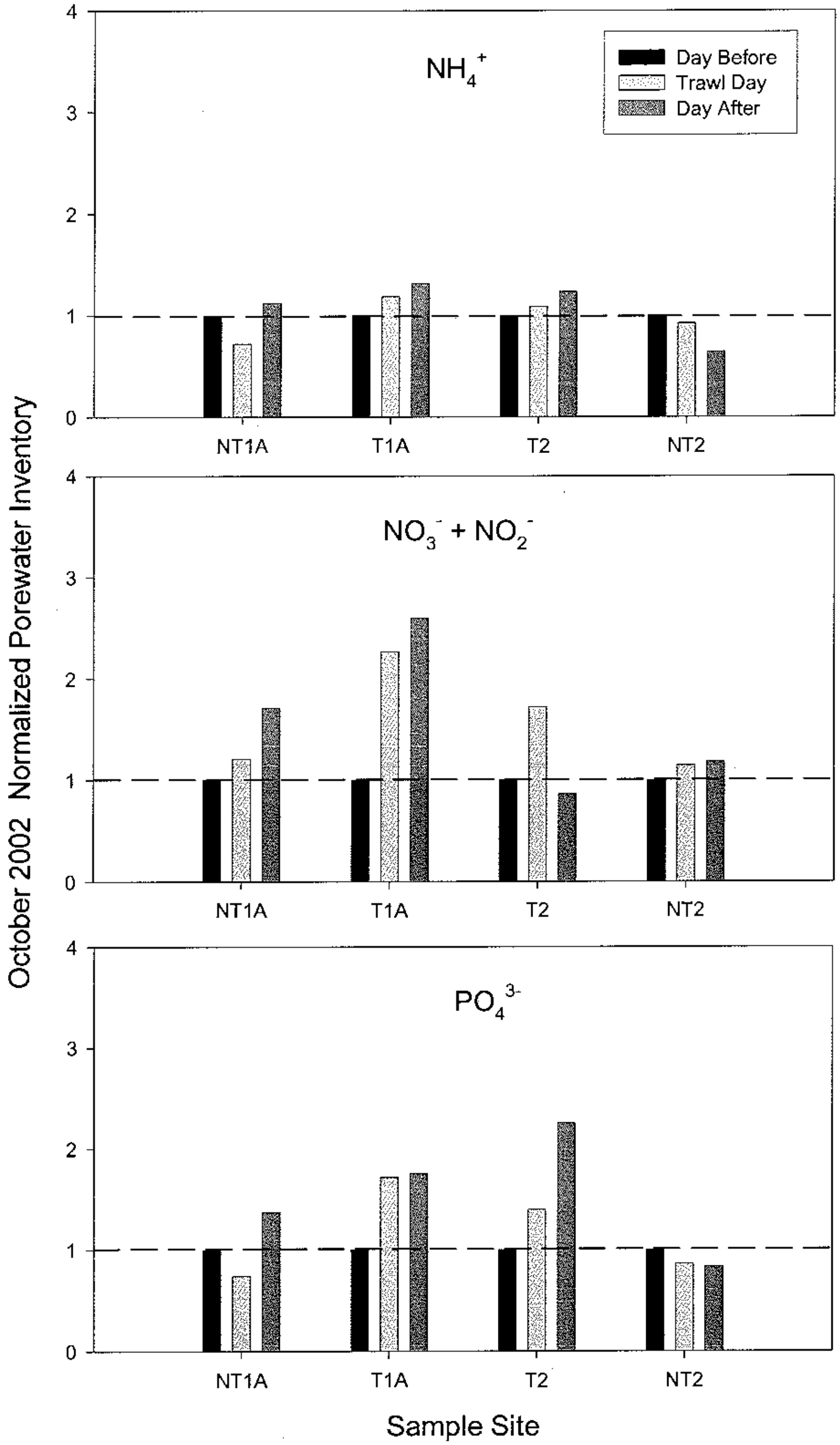


FIGURE 14: Normalized porewater inventories for cores collected during the June 2002 trawling experiment. Data from Trawl Day refer to cores collected immediately following the cessation of trawling.

Water Column Nutrients

Variation in water column parameters in the no-trawl sites.

Temperature, salinity, and dissolved oxygen evinced little temporal or spatial variation during each of the experiments in the no-trawl sites. Temperatures varied 1-3 degrees during an experiment, and annually from 30 °C in July 2001 to 18 °C in May 2002. Salinity averaged about 9 parts per thousand (ppt) in 2001 and 13 ppt in 2002. Salinity stratification was ephemeral and limited to a 3 ppt difference between surface and bottom waters.

The water column commonly stratifies with regard to dissolved oxygen in South Creek, particularly during the warmer months when the bottom water may become hypoxic (Stanley 1988,1997). However, marked differences in surface and bottom dissolved oxygen concentration occurred only sporadically during the course of the experiments, and hypoxia was observed on only 3 days (11 July 2001, 1.4 mg l^{-1}; 28 May 2002, 1.98 mg l^{-1}; 14 June 2002, 1.7 mg l^{-1}). Dissolved oxygen values normally ranged from 4-9 mg l^{-1}.

Nitrate plus nitrite concentrations varied modestly, remained at low concentrations (< 1 μM) during each experiment, and failed to show marked spatial or temporal variability (Figure 15A). Ammonium concentrations typically ranged from 0.5 to 1.5 μM, with outliers as high as 4.5 μM (Figure 15B). Highest daily mean values occurred during July 2001. Bottom concentrations were usually equal to or greater than surface values.

Orthophosphate concentrations were consistent during an experiment, but varied by a factor of 2 or 3 between experiments (e.g. May 24 versus June 10 experiments; Figure 15C). Orthophosphate also showed a strong seasonal pattern in which values increased between July and October 2001, were lowest in May 2002, and rose again in June 2002. Mean orthophosphate concentrations ranged from 0.1 to 1.4 μM.

Mean chlorophyll concentration varied from 8-25 μg l^{-1} throughout the study (Figure 15D). However, variability was high, particularly in the May experiments when individual values ranged from 10-45 μg l^{-1}. Surface and bottom values were usually similar with the exception of the May 27 experiment, when bottom values were consistently higher.

Total suspended solids (TSS) concentrations were the lowest during July 2001 (Figure 15 E). Average TSS values ranged from 20 to 37 mg $^{-1}$ in July, and from 40 to 60 mg $^{-1}$ during the remainder of the study with outliers as high as 80 mg l^{-1}. Daily averages varied by a factor of 2 to 3 during the May 2002 experiments, but by less than half this range during the other experiments. Bottom TSS values usually exceeded surface values.

Photosynthetic active radiation (PAR) decreased sharply with depth. Incident light energy was reduced by 40-80% within the initial 0.25 meters of the water column. Virtually all bottom PAR readings ranged from 0-2% of the light energy level at the air-water interface (data not shown).

None of the above water column parameters showed large or consistent spatial differences between the upstream (Area 2) and downstream (Area 1) sites used for the trawling experiments. Depth was the only consistent variable in this regard; depth at the upstream (Area 2) sites ranged from 1.75-2.4 m, and ranged from 2.25-3.5 m at the downstream sites (data not shown).

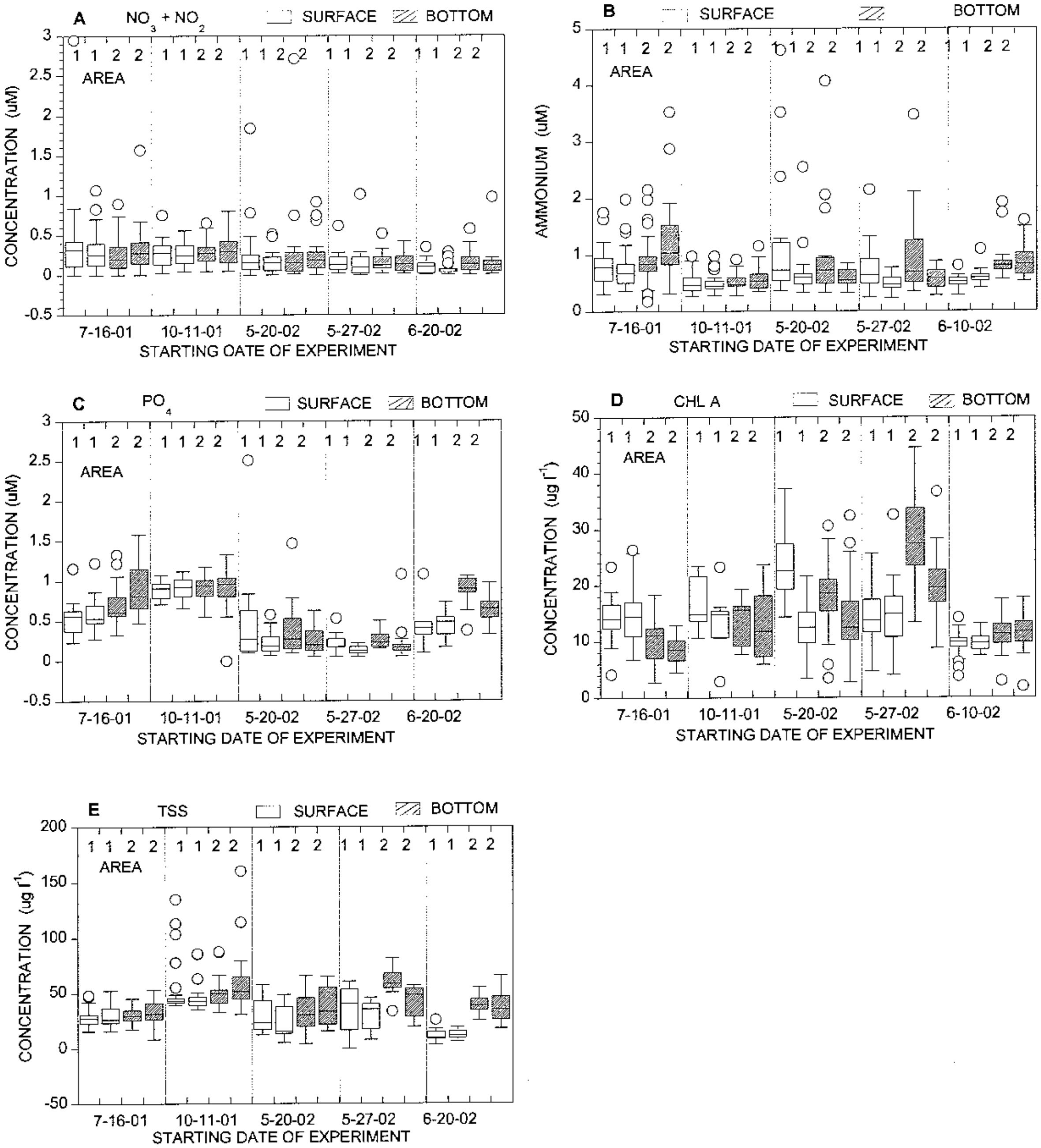


FIGURE 15. Temporal and spatial variation in the concentration of water quality parameters in the no trawl sites during each of the 5 trawling experiments. The graphic for each parameter consists of 5 panels, each panel representing an experiment. Each panel in turn includes a pair of open and a pair of hatched box plots representing water samples taken at the near surface (0.25 m) and near bottom (2.5 – 3 m) depths, respectively. The numbers at the top of each panel indicate the area (1 or 2) the particular site was located in. A) nitrate + nitrite; B) ammonium; C) orthophosphate; D) chlorophyll a; D) total suspended solids

Impacts of trawling

Turbulence produced as trawl gear is pulled through the water column could generate a mixing action similar to that of the wind. However, we found no consistent correlation between trawling and the CV of any of the water column parameters, although there is some indication that trawling can reduce hypoxia. For example, during the June 2002 experiment, bottom dissolved oxygen concentration remained low (~ 4.0 mg l^{-1}) at the upstream no-trawl site but rose to equal surface DO concentrations (~ 6.2 mg l^{-1}) at the trawl site on the day of trawling (Figure 16).

We expected that the diagnostic feature of a trawl impact would be an abrupt elevation in the concentration of nutrients, chlorophyll a, and total suspended solids relative to the untrawled sites. However, significant increases in nutrients and chlorophyll a coincident with trawling were only occasionally observed during the 5 experiments (Table 3). Furthermore, these responses were typically limited to a single area and / or depth. In contrast, surface and bottom concentrations of total suspended solids were usually significantly higher in the trawl sites following trawling than in the corresponding no-trawl sites (Table 3). Concentrations of TSS in the trawl sites on these occasions were 10-40 μg l^{-1} higher than in the untrawled sites (Figure 17 A-B).

All increases in water column nutrients, chlorophyll a and TSS coincident with trawling showed a single peak lasting no more than 24 hours (Figure 17 A-B; Figure 18 A-C). No significant correlation was found between wind stress and either the mean or the coefficient of variation of each nutrient. Furthermore, we detected only a small positive impact of wind stress on mean chlorophyll a concentration.

Ammonium, orthophosphate, and chlorophyll a concentrations observed during this study were similar to those reported for comparable times of the year in South Creek and adjacent regions of the Pamlico River (Stanley 1988, 1997), and in the mid-region of the Neuse River, North Carolina (Christian et al. 1991). However, the nitrate plus nitrite concentrations obtained were less than half of those reported by these workers. Given the importance of riverine input on local nitrate-nitrite concentration (Kuentzler et al. 1984, Stanley 1988, 1997; Mallin 1994; Pinckney et al. 1998), the low values reported here may have resulted from the reduced river flow during the preceding winter. Low river flow would also account for the higher than normal salinity of South Creek during 2001 and 2002 (Stanley 1988, 1997).

The most surprising finding of the study was the minor effect of trawling on nutrient loading of the water column. We observed only a single trawl-related occurrence of elevated ammonium concentration, two occurrences of increased orthophosphate concentration, and no identifiable effect of trawling on nitrate-nitrogen concentration. Trawling also had a similar minor impact on chlorophyll a concentration. Warnken et al. (2003) detected a 3-fold increase in ammonium efflux from trawled sediments held in 8 l incubation chambers. Nevertheless, the range of ammonium efflux rates between untrawled and trawled sediments in their Galveston Bay study was within the normal range of efflux rates of untrawled sediments measured in previous years (Warnken et al. 2000).

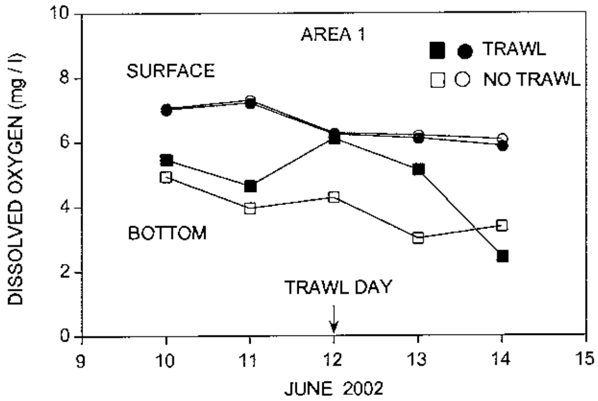


FIGURE 16. The effect of trawling on dissolved water column oxygen concentration at the downstream (Area 1) trawl and no trawl sites during the 10-14 June 2002 experiment. Symbols and error bars denote mean DO concentration ± 1S.E. Trawling occurred only on the designated day (arrow) in the trawl site.

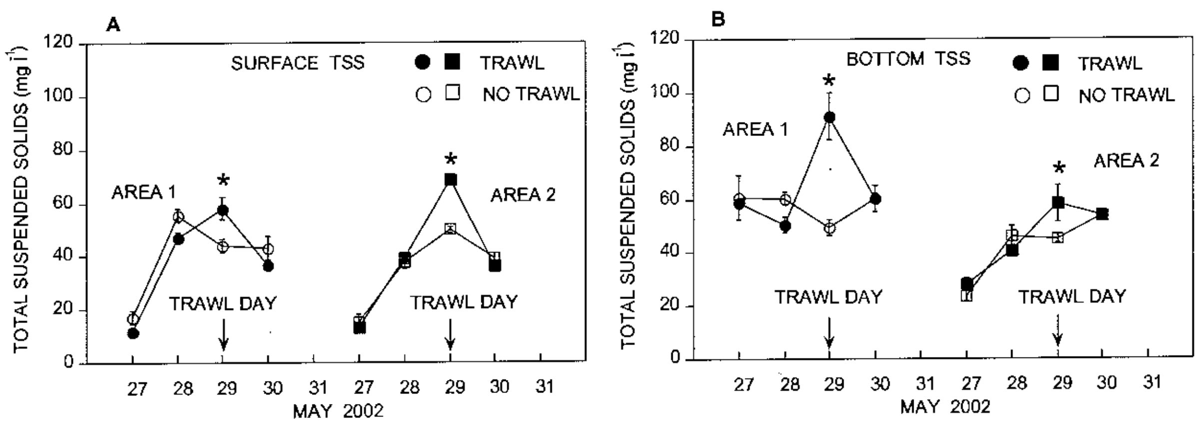


FIGURE 17. The effect of trawling on the concentration of total suspended solids at the upstream (area 2) and downstream (area 1) sites during the two experiments carried out in May 2002. Symbols and error bars denote mean DO concentration ± 1S.E. Trawling occurred only on the designated day (arrow) in the trawl site. A) Near surface samples; B) near bottom samples. The asterisk above a symbol signifies a significantly higher mean TSS value in the trawled versus the untrawled site.

TABLE 3. Results of two way (trawl x day) analyses of variance (ANOVA) evaluating the impact of trawling on the concentration of chlorophyll (CHL), ammonia (NH_4), nitrate plus nitrite (NO_x), orthophosphate (PO_4), and total suspended solids (TSS) in South Creek, North Carolina. Bonferroni multiple comparisons tests were done to determine probability (p) values in the event of significant trawl effect in the ANOVA. Asterisks indicate p values as following: * = $p \leq 0.05$; ** = $p \leq 0.01$; *** = $p \leq 0.001$; **** = $p \leq 0.0001$. "ns" = not significant.

Experiment	Area	Depth	CHL	NH_4	NO_x	PO_4	TSS
July 16-23	1	Surface	ns	ns	ns	ns	****
	1	Bottom	ns	ns	ns	ns	***
	2	Surface	ns	ns	ns	ns	ns
	2	Bottom	ns	ns	ns	ns	***
October 11-18	1	Surface	****	ns	ns	ns	ns
	1	Bottom	ns	ns	ns	ns	ns
	2	Surface	***	ns	ns	ns	ns
	2	Bottom	ns	ns	ns	ns	**
May 20-24	1	Surface	*	ns	ns	ns	ns
	1	Bottom	ns	ns	ns	ns	ns
	2	Surface	ns	ns	ns	ns	ns
	2	Bottom	ns	ns	ns	ns	ns
May 27-30	1	Surface	ns	ns	ns	ns	ns
	1	Bottom	ns	ns	ns	ns	****
	2	Surface	ns	**	ns	****	****
	2	Bottom	ns	ns	ns	ns	*
June 10-14	1	Surface	ns	ns	ns	ns	****
	1	Bottom	ns	ns	ns	ns	****
	2	Surface	ns	ns	ns	****	****
	2	Bottom	ns	ns	ns	****	****

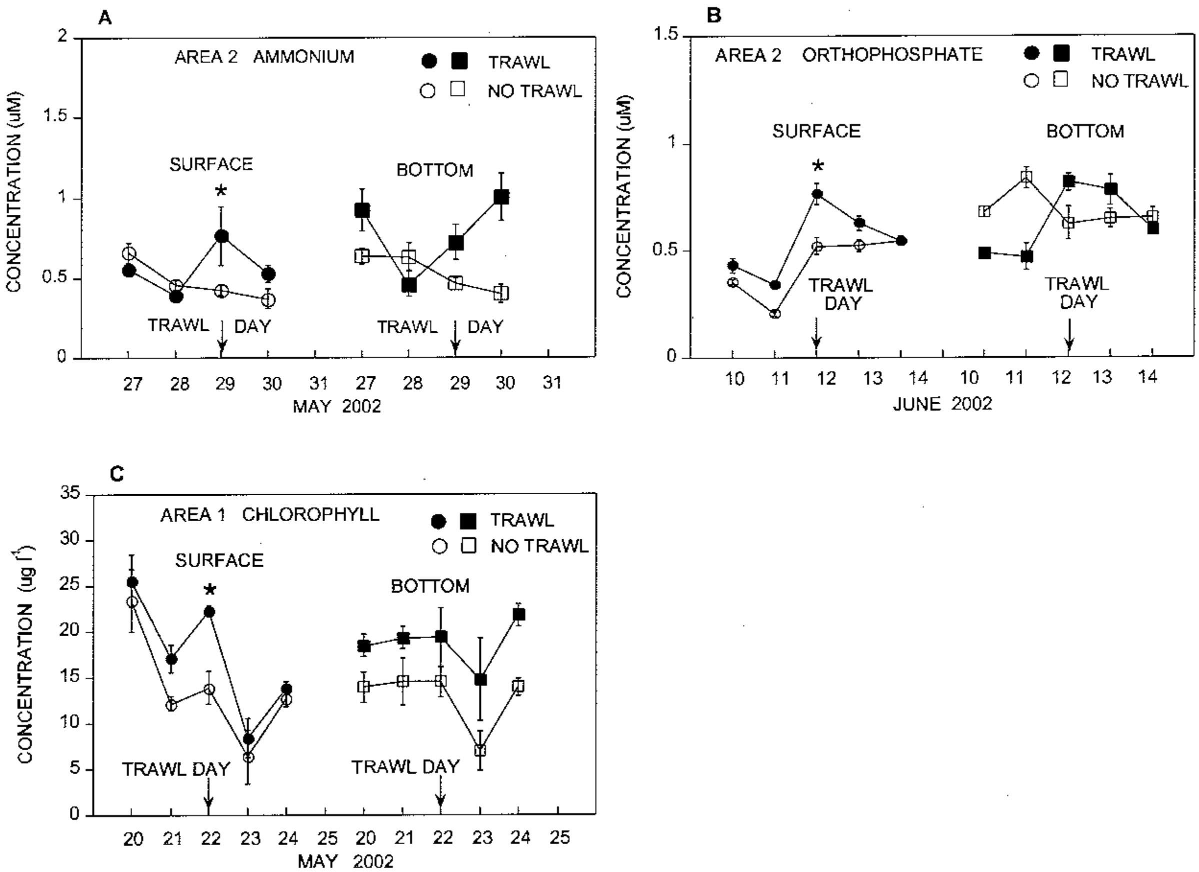


FIGURE 18. The effect of trawling on the concentration of ammonium (A), orthophosphate (B), and chlorophyll a (C) at the designated area during the May or June 2002 experiments. Symbols and error bars denote mean parameter concentration ± 1S.E. Trawling occurred only on the designated day (arrow) in the trawl site. The asterisk above a symbol signifies a significantly higher mean value in the trawled versus the untrawled site.

The impact of trawling on nutrient loading would depend upon the depth of sediment penetration by the trawl gear, nutrient concentrations within the sediment pore water prior to trawling, advective and dilution processes, and the timing of sampling relative to the occurrence of trawling. We were not successful in directly measuring the depth of gear penetration in this study. However, measurements of ammonium pore water concentrations at 1 cm depth intervals in sediment cores taken before and after trawling suggest that at least the upper 1 cm of sediment had been removed. This penetration depth is similar to that reported for commercial shrimp trawlers in Galveston Bay, Texas (Warnken, et al. 2003). Our estimate of ammonium pore water concentration at 1 cm depth varied from 50-150 μM, or about 30 to 100 times higher than the ammonium concentration of the overlying water. If trawling removed the upper 1 cm of sediment of a 300 m x 300 m area, this would represent an input of about 8.1×10^5 l into the water column assuming a sediment porosity of 0.9. Addition of this volume of pore water ammonium into a 3 m deep water column with an ammonium concentration of 1.5 μM, would increase the concentration of ammonium in a completely mixed water column by 0.15 – 0.4 μM. These rough calculations suggest that trawling would have to homogenize 2 or more cm of surface sediments in South Creek to enable detection of a significant increase in water column ammonium concentration under conditions of no advection.

Timing of sampling could also have influenced our estimation of the impact of trawling on nutrient loading. Time-intensive sampling of sediment plumes produced during disposal of dredged sediments in freshwater, estuarine, and marine systems indicate than order of magnitude increases in ammonium and phosphate return to pre-disposal values within 10-30 minutes (Jones and Lee 1981). We began sampling the trawl plume within 5-10 minutes of the cessation of trawling, and continued sampling for approximately 30 minutes. If attenuation rates of suspended ammonium and orthophosphate were similar to those observed by Jones and Lee (1981), then up to half of the samples would have been collected after concentrations had returned to near ambient levels. Sampling during the process of trawling may provide a clearer estimate of the magnitude of nutrient loading.

Assessment of Water Column Productivity

Oxygen production values (mg O_2 liter^{-1} hour^{-1}) obtained from the light / dark bottle experiments were converted to mg Carbon m^{-3} hr-^{1} using the expression

$$\text{Net Photosynthesis (mg C m}^{-3}\text{ hr}^{-1}) = \frac{[(O_2\ LB)-(O_2\ IB)]\ (1000)(0.375)}{(PQ)(t)} \qquad (8)$$

where (O_2 LB) is the dissolved oxygen concentration in the light bottle after t hours, (O_2 IB) is the initial dissolved oxygen concentration, and PQ is the photosynthetic quotient (Wetzel and Likens1991). PQ is a measure of the relative amounts of carbon and oxygen involved in photosynthesis. The value of PQ varies with species of algae and environmental conditions; a value of 1.2 was used in these calculations. The value of 0.375 represents the molar ratio of carbon to oxygen. The conversion of oxygen production to carbon was carried out in order to facilitate comparison with other studies of estuarine primary production.

The hypothesis tested in the primary production experiments was that trawling would stimulate net photosynthesis. This trawl effect was expected to be manifested as an abrupt increase in productivity in the trawled sites relative to the untrawled sites. In the June and

October 2002 experiments, the effect of trawling was assessed by comparing productivity values in the trawl and no trawl sites prior to the day of trawling, with those obtained on the day of trawling. In the August 2003 experiment we added a pre-trawling sampling episode in the trawl sites so that production could be compared before and after trawling, on the day of trawling.

In the June 2002 experiment, productivity of surface water samples in the upstream (Area 1) and downstream (Area 2) trawl sites were similar the day before trawling (11 June) and the day of trawling (12 June) (Fig 19 A-D). In addition, surface productivity of the trawl site on trawl day was either equivalent to that of the no trawl site (Area 1), or significantly less than the no trawl site (Area 2) (Table 4). Bottom water samples showed a qualitatively similar pattern to that of surface water samples on trawl day in the trawl and corresponding no trawl sites. Mean production values ranged from 20-92 mg C m-3 hr-1 for surface samples and from 17 to 74 mg C m-3 hr-1 for bottom samples during the initial half of this experiment. Productivity was higher and showed lower variability at all sites and depths during the latter half of the June experiment with values generally falling within a range of 75-120 mg C m-3 hr-1 (Fig 19 A-D).

Surface and bottom water productivity in the trawl sites during the October 2002 experiment increased markedly between the day prior to trawling (11 October) and the day of trawling (Fig 19 E-H). Productivity on the day of trawling was also significantly higher in trawl sites than in the no trawl sites for water collected from both depths, with the exception of surface water samples in the downstream area (1) (Table 4; Fig 19 G). In this latter case, the rate of net photosynthesis of no trawl samples was approximately 25% higher than the trawl site samples. Mean rates of photosynthesis of surface water samples varied from 100 to 350 mg C m^{-3} hr^{-1}, whereas those for bottom water samples ranged from 25 – 150 mg C m^{-3} hr^{-1}. The primary productivity in October 2002 was approximately twice that observed during the preceding June.

The August 2003 primary production experiment differed from the previous two experiments in two important respects. First, the experiment was confined to the downstream sites (area 1). Second, an additional set of surface and bottom water samples was taken from the designated trawl site immediately before trawling. Surface and bottom rates of photosynthesis were substantially higher in samples collected from the trawl site on the day of trawling compared to those on the day prior to trawling (Fig 19 I-K). Rates of photosynthesis for samples collected from the no trawl site showed little change during this same time period. On the day of trawling, the rates of photosynthesis in both surface and bottom samples collected immediately after trawling were significantly higher than those collected immediately before trawling ("trawl" versus "pre-trawl"; Fig 19 J), and markedly greater than those collected from the no trawl site (Fig 19 J; Table 5). Rates of photosynthesis of surface water samples during this experiment were comparable to the high values obtained during the October 2002 experiment. However, primary productivity of the bottom samples were equal to or greater than that of the surface samples (i.e. 275 –380 mg C m^{-3} hr^{-1}), and thus approximately 2-10 times greater than that obtained during the June and October 2002 work.

The primary production values obtained during the June experiments in South Creek are similar to those reported by others who worked in the Pamlico River (Davis et al. 1978) and the Neuse River (Boyer et al. 1993). However, many of the October and August values lie outside of the ranges reported by these investigators. These high production values apparently reflect an ongoing phytoplankton bloom during October and August, as indicated by the high concentrations of ammonium and orthophosphate (Fig 20 A-F), and the high phytoplankton biomass (Fig 20 G-L) during these experiments.

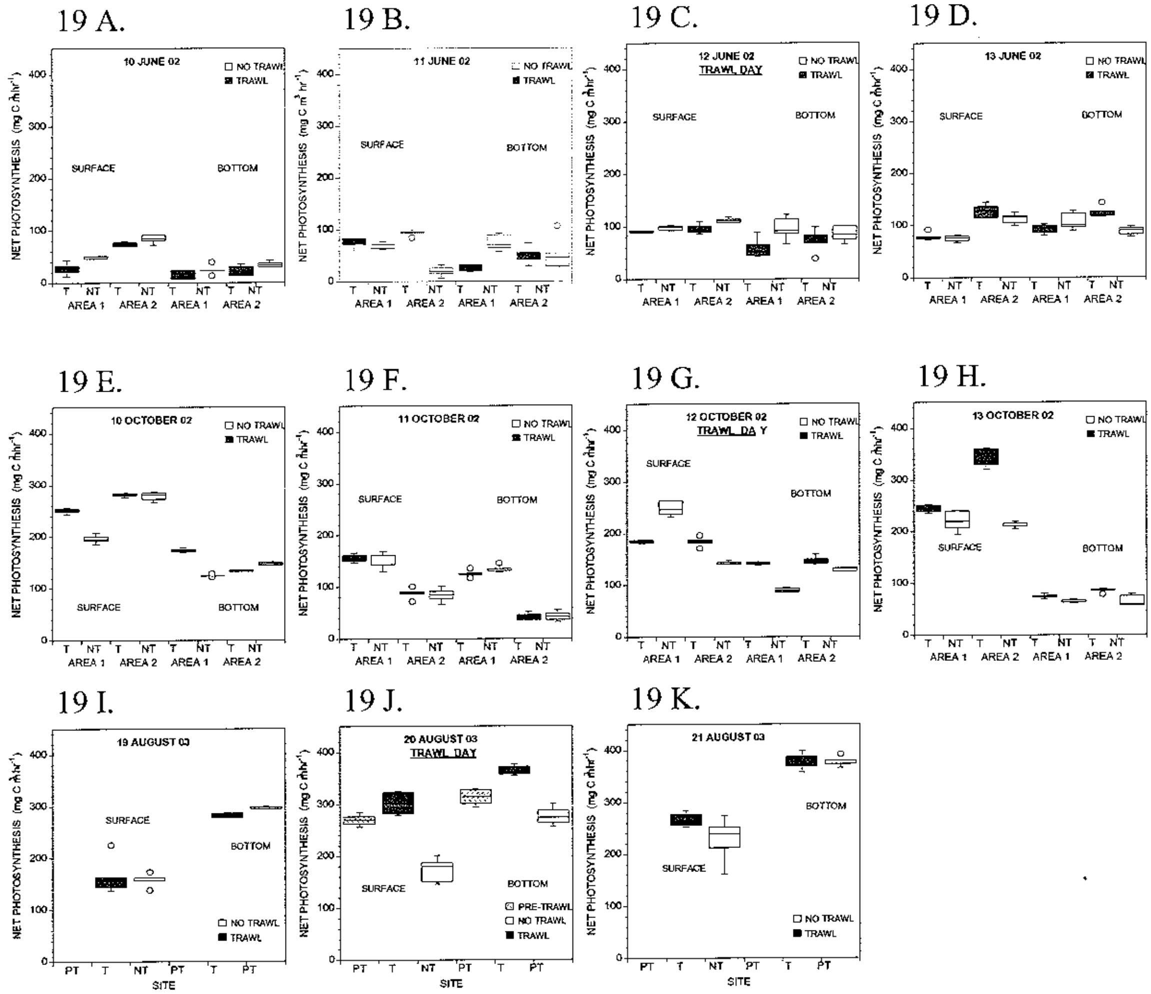


FIGURE 19. Primary production during the June 2002 (A-D), October 2002 (E-H), and August 2003 (I-K) trawl experiments in South Creek, NC.

TABLE 4. Pair-wise comparisons of surface net primary productivity values (mg C m^{-3} hr^{-1}) of the trawl and no-trawl sites during the October 2002 field experiments. Site area is denoted by the number 1 or 2 in the "Site" column. Differences between the means of the paired sites are listed in the "Difference" column, and the corresponding probability of obtaining each difference by chance is given in the "P" column.

Date	Depth	Site	Difference	P
10-10	Surface	trawl,1 - no trawl,1	55.3961	0.000000
		trawl,2 - no trawl,2	2.52038	0.995036
10-10	Bottom	trawl,1 - no trawl,1	49.1868	0.721394
		trawl,2 - no trawl,2	-12.8912	0.000001
10-11	Surface	trawl,1 - no trawl,1	1.40922	0.999973
		trawl,2 - no trawl,2	3.93023	0.991081
10-11	Bottom	trawl,1 - no trawl,1	-9.45670	0.176326
		trawl,2 - no trawl,2	-0.977833	0.999944
10-12 Trawl Day	Surface	trawl,1 - no trawl,1	-63.2212	0.000000
		trawl,2 - no trawl,2	41.3462	0.000000
10-12 Trawl Day	Bottom	trawl,1 - no trawl,1	52.1635	0.000000
		trawl,2 - no trawl,2	16.3462	0.000018
10-13	Surface	trawl,1 - no trawl,1	10.2569	0.035661
		trawl,2 - no trawl,2	21.4976	0.000000
10-13	Bottom	trawl,1 - no trawl,1	10.2569	0.039093
		trawl,2 - no trawl,2	21.4976	0.000020

TABLE 5. Pair-wise comparisons of surface net primary productivity values (mg C m^{-3} hr^{-1}) of the trawl and no-trawl sites during the August 2003 field experiments. All work was confined to Area 1 (downstream). Pre-trawl and post-trawl refer to water samples taken at the trawl site immediately before and after trawling, respectively. Differences between the means of the paired sites are listed in the "Difference" column, and the corresponding probability of obtaining each difference by chance is given in the "P" column.

Date	Depth	Site	Difference	P
8-19	Surface	trawl - no trawl	5.94450	0.676560
8-19	Bottom	trawl - no trawl	-14.0391	0.000035
8-20 Trawl Day	Surface	pre trawl - post trawl post trawl - no trawl	-31.9590 127.157	0.022220 0.000000
8-20 Trawl Day	Bottom	pre trawl - post trawl post trawl - no trawl	-50.2656 87.6160	0.000028 0.000000
8-21	Surface	trawl - no trawl	38.9897	0.043684
8-21	Bottom	trawl - no trawl	1.67014	0.813665

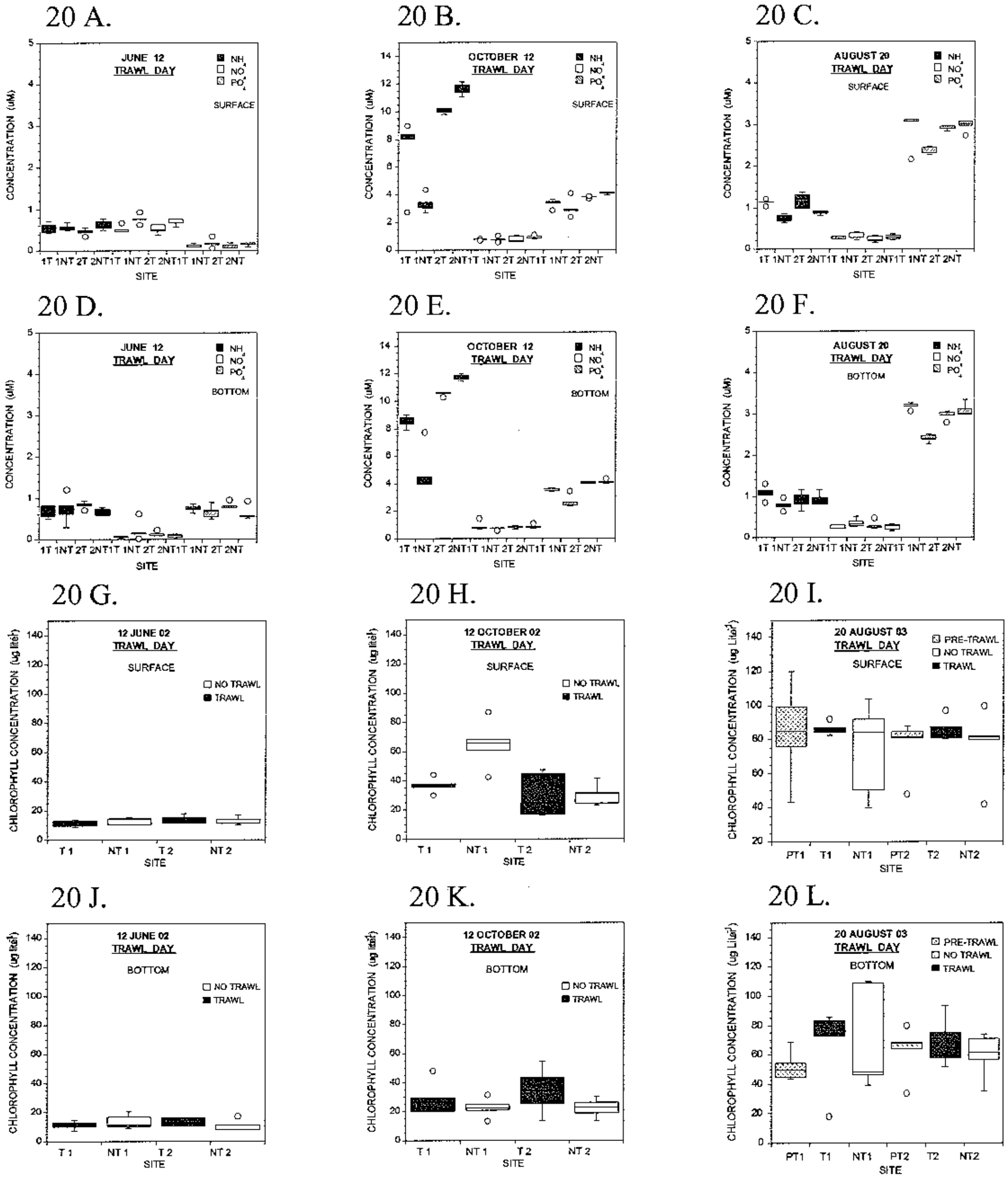


FIGURE 20. Near surface and near bottom water column nutrient (A-F) and chlorophyll (G-L) concentrations at the trawl and no trawl sites in South Creek on trawl day during the June 2002, October 2002, and August 2003 experiments.

Spatial and temporal differences in primary production may reflect differences in phytoplankton biomass, or differences in rates of photosynthesis. In the former instance, more carbon is fixed because more phytoplankton cells are present; in the latter case, more carbon is fixed because each phytoplankter is fixing carbon at a faster rate. Normalizing net photosynthesis to phytoplankton biomass by computing the carbon to chlorophyll ratio can show which of these components of primary production were most important in generating observed differences in production between trawled and non-trawled sites during the field experiments.

In the June experiments, when trawling was not associated with increased primary production, no consistent pattern is apparent in the normalized productivity values (Fig 21 A-D). On of the day of trawling, carbon to chlorophyll ratios for the trawl sites were equal to or less than those of the no trawl sites (Fig 21 C). Thus trawling In June 2002 did not produce a local increase in phytoplankton biomass, nor did it lead to a stimulation of the rate of photosynthesis.

However, in the October 2002 and August 2003 experiments, a temporal shift in the normalized production values for the surface water samples of the trawl sites is clearly evident Fig 21 E-H and I-K). Prior to trawling, productivity per unit biomass of phytoplankton was higher in the no trawl sites, but following trawling, was substantially higher in the trawl sites. Thus the greater primary production described earlier for the downstream (area 1) no trawl site on trawling day during the October experiment resulted from a nearly 2 fold greater abundance of phytoplankton (Fig 20 H). This difference in phytoplankton biomass therefore "masked" an actual relative increase in carbon fixation per unit biomass that occurred in the trawl site samples.

The above findings may be summarized as follows. Trawling was not associated with enhanced net photosynthesis during the June 2002 experiments when nutrient concentrations, phytoplankton biomass, and primary production values were low. However, trawling was coincident with enhanced net photosynthesis in the October2002 and August 2003 experiments when nutrient concentrations, phytoplankton abundances and primary production values were high. The enhanced production was driven by a greater rate of carbon fixation per unit phytoplankton biomass in the surface water samples, and by a greater phytoplankton biomass in the bottom water samples.

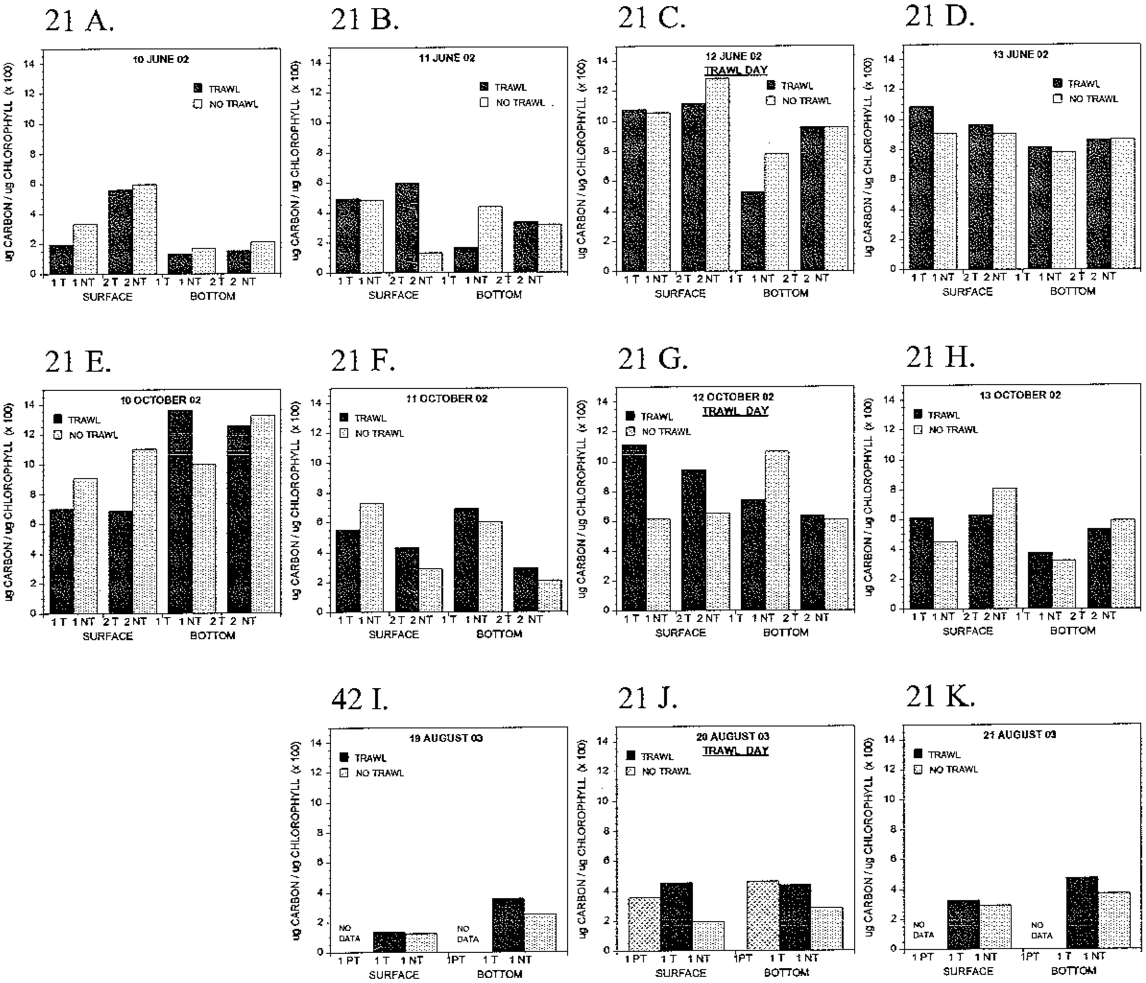


FIGURE 21. Primary production normalized to phytoplankton biomass for water samples collected from near surface and near bottom depths at the trawl and no trawl sites in South Creek, NC, during the June 2002 (A-C), October 2002 (E-H), and August 2003 (I-K) experiments.

SUMMARY AND CONCLUSIONS

- Natural occurrences of sediment resuspension and associated dynamics seem to incur a similar impact on the water column compared to trawling. Wind (24-hr resultant vector) influenced certain resuspension mechanisms that mixed the water column and disturbed the sediments in 2 of the 6 experiments performed. It was also determined that winds from areas of largest fetch had the largest impact on the water column. Specifically, winds from the NE, E and SW sectors have been shown to impact the water column with respect to hydrography, TSS concentrations and turbidity and mask the impacts related to trawling

- The trawling event was the dominant force in the other 4 experiments as the 24-hr resultant wind vectors were from sectors with a relatively small fetch (S & SE). Increases in trawl day near-bottom TSS concentrations were considerably higher in the trawled sites compared to the non-trawled sites. Those trawl site TSS concentrations were also higher (10-100%) than the total range of natural variation observed during each experiment. The associated sediment characteristics (e.g. porosity, grain size, etc.) were relatively homogeneous throughout each experiment and displayed no observable trend with respect to the punctuated trawling event.

- The temporal variations in radionuclide inventories could only be used to describe the fate of resuspended sediments because of the amount of samples collected and the limited statistical analysis that could be performed.

- Porewater nutrient concentrations showed no observable impact associated with trawling. Natural variations during majority of the exercises, as determined in non-trawled areas, were as great as those observed in areas that were actively trawled.

- Trawling was not associated with enhanced net photosynthesis during June 2002 experiments when nutrient concentrations, phytoplankton biomass, and primary production values were low.

- Trawling was coincident with enhanced net photosynthesis in the October 2002 and August 2003 experiments when nutrient concentrations phytoplankton biomass, and primary production values were high.

- The enhanced production was driven by a greater rate of carbon fixation per unit phytoplankton biomass in the surface water samples, and by a greater phytoplankton biomass in the bottom water samples.

- Our findings imply that trawling is not a significant local source of nutrient loading, and that it has a limited impact on sediment dynamics. Nevertheless, it is important to emphasize that we presently understand little of the chronic impacts of trawling on water column parameters, and how trawling disturbance affects the composition and bio-geochemical functioning of displaced particle layers.

- Impacts of bottom trawling on sediment and water column biogeochemistry and functional attributes of the water column (eg. primary production, are subtle with respect to other direct impacts, eg. by-catch and habitat alteration.

IMPACTS AND RECOMMENDATIONS

- Our work did not specifically focus on the sediment water interface, e.g. the benthic nephloid layer. This nepheloid layer is a labile mix of sedimentary particles, detrital matter, and microbiota of water column and benthic origins. It may act as a site of diagenesis and organic carbon cycling and as a food resource for dermersal zooplankton and benthic macrofauna. This layer has not been well-studied in the Pamlico Estuarine System, but given its potential importance in the exchange of energy and materials between the water column and the benthos, more needs to be learned about its functioning and its sensitivity to disturbance in order to place trawling impacts in an appropriate context.

- Our findings suggest that trawling disturbance does not constitute an important source of nutrient loading to estuaries like South Creek. This conclusion carries the caveat that our research, and that of similarly interested other workers, have focused on the short term, acute effects of trawling. Chronic impacts of trawling on nutrient loading remain unstudied.

- Our work certainly had some advantages and limitations; it was conducted South Creek, which has been closed to trawling. This allowed us to isolate the disturbance throughout our field exercises. However, this also limited the study to a very small portion of the Albemarle Pamlico Estuarine System. We recommend that work be extended into Pamlico Sound and include areas of different sediment character and subjected to intensive bottom trawling.

- Our sampling design required a controlled area. We would recommend a change in sampling design when moving into larger bodies of water with little to no control on the areas disturbed. Therefore, a lagrangian approach may be better served in Pamlico Sound or other larger bodies of water.

- During the course of this work, we focused on acute impacts of bottom trawling. Our findings do not support a significant impact with regard to porewater or water column nutrient concentrations. However, further research must be conducted in areas that are consistently trawled on a daily/seasonal basis. Therefore, there needs to be some long-term studies with greater spatial coverage.

EXTENSION OF RESULTS

We have made many attempts to inform others of our work through professional publications, local and national meetings, web sites, and web-based publications. These include:

Presentations

West, T.L., D.R. Corbett, L.M. Clough, M.W. Calfee, J.E. Frank. Effect of wind and trawling on sediment resuspension and primary production in South Creek.. 17th Annual Symposium of the Duke/UNC Oceanographic Consortium. Nov 21-22, 2003

Corbett, D.R., D. Giffin, J. Frank, T. West, L. Clough, W. Calfee. The role of sediment resuspension in nutrient cycling. Estuarine Research Federation, Seattle, Wa. September, 2003.

West, T.L., D.R. Corbett, L.M. Clough, M.W. Calfee, J.E. Frank. Effects of Wind Versus Commercial Fish Trawling on Nutrient Loading and Water Column Productivity in the Pamlico River Estuary, North Carolina. Estuarine Research Federation, Seattle, Wa. September, 2003.

Corbett, D.R., T. West, L. Clough, J. Frank, W. Calfee. Potential Impacts of Bottom Trawling on Water Column Productivity and Sediment Transport Processes. North Carolina Commercial Fishing Show. February 22, 2003.

West, T.L., D.R. Corbett, L.M. Clough, M.W. Calfee, J.E. Frank.. Impacts of trawling on estuarine water column structure and nutrient concentration. 16th annual Symposium of the Duke/UNC Oceanographic Consortium. Nov 22, 2002.

Frank, J., D.R. Corbett, T.L. West, L.M. Clough, M.W. Calfee. Comparative evaluation of natural and trawling sediment disturbance *via* short-lived radionuclides, *in situ* monitors and remote sensing techniques in the Pamlico River Estuary, North Carolina. Symposium on Effects of Fishing Activities on Benthic Habitats: Linking Geology, Biology, Socioeconomics, and Management. Tampa, Fl. November 12-14, 2002.

West, T.L., D.R. Corbett, L.M. Clough, M.W. Calfee, and J. Frank. Impacts of trawling and wind disturbance on water column processes in the Pamlico River Estuary, North Carolina. Symposium on Effects of Fishing Activities on Benthic Habitats: Linking Geology, Biology, Socioeconomics, and Management. Tampa, Fl. November 12-14, 2002

West, T., R. Corbett, L. Clough, W. Calfee, J. Frank. Impacts of natural and anthropogenic disturbance on water column attributes of the Pamilco River Estuary, NC. BENTHIC Conference, Orlando, NC March 21-23, 2002.

Publications

West, T., R. Corbett, L. Clough, W. Calfee, J. Frank. Impacts of trawling and wind disturbance on water column structure, sediment resuspension, and nutrient loading in the Pamlico River Estuary, North Carolina. Estuarine, Coastal and Shelf Science, In Prep.

West, T., R. Corbett, L. Clough, W. Calfee, J. Frank. Primary Production in trawled and non-trawlied locations in South Creek, NC. In Prep.

Frank, J., D.R. Corbett, T.L. West, L.M. Clough, M.W. Calfee. . Natural and Trawling Induced Sediment Disturbances in a Tributary of the Pamlico River Estuary, NC. . Estuarine, Coastal and Shelf Science, In Prep.

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Many students were involved in this project directly (see list of Theses/Dissertations below) and through volunteer help. These students include:

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Theses/Dissertations

Frank, James, 2004. . Natural and Trawling Induced Sediment Disturbances in a Tributary of the Pamlico River Estuary, NC. MS in Geology, East Carolina University.

Calfee, W. Micorbial Response to Disturbance in the Pamlico River Estuary. PhD Dissertation in progress. Expected graduation: Spring 2006

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REFERENCES

Allan, R.J., 1986. The role of particulate matter in the fate of contaminants in aquatic ecosystems. NWRI Report, NO. 142, Canada Centre for Inland Waters,Burlington Ontario, Canada.

Alperin, M.A., E.J. Clesceri, J.T. Wells, D.B. Albert, J.E. McNinch and C.S. Martens, 2000. Sedimentary Processes and Benthic-Pelagic Coupling. In: Neuse River Estuary MODeling and MONitoring Project: Final Report, Draft #4. Water Resources Research Institute. Raleigh, NC.

Balls, P.W., Laslett, R.E., and Price, N.B., 1994. Nutrient and trace metal distributions over a complete semi-diurnal tidal cycle in the Forth Estuary, Scotland. Netherlands Journal of Sea Research. 33: 1-17.

Bloom, N. and Crecelius, E.A., 1983. Solubility behavior of atmospheric ^{7}Be in the marine environment. Marine Chemistry. 12: 323-331.

Booth, J.G., Miller, R.L., McKee, B.A., and Leathers, R.A., 2000. Wind-induced bottomsediment resuspension in a microtidal coastal enviroment. Continental Shelf Research. 20: 785-806

Bowden, K. F. 1983. Physical Oceanography of Coastal Waters. Ellis Harwood Series in Marine Science. T. D. Allan (Ed.). Halstead Press, N.Y. pp. 302

Boyer, J.N., D.W. Stanley, R.R. Christian, W.M. Rizzo, 1988. Modulation of nitrogen loading impacts within an estuary. In W.L. Lyke and T.J. Hoban (eds) Proceedings N.C. Amer. Water Resoures Assoc., Syposium on Coastal Water Resources. AWRA Technical Publ. Series TPS-88-1. AWRA, Bethesda, MD, p. 165-176.

Boyer, J. N, R. R. Christian, and D. W. Stanley. 1993. Patterns of phytoplankton primary productivity in the Neuse River estuary, North Carolina. Marine Ecology Progress Series 97: 287-297.

Canuel, E.A., Martens, C.S., and Benninger, L.K., 1990. Seasonal variations in ^{7}Be activity in the sediments of Cape Lookout Bight, North Carolina. Geochimica et Cosmochimica Acta. 54: 237-245.

Casey, W.H., Larsen, I.L., and Olsen, C.R., 1986. The distribution of cosmogenic ^{7}Be in salt marsh sediments. Geophysical Research Letters. 13: 322-325.

Christian, R. R., J. N. Boyer, and D. W. Stanley. 1991. Multi-year distribution patterns of nutrients within the Neuse River Estuary, North Carolina. Marine Ecology Progress Series 71: 259-274.

Churchill, J.H., 1989. The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight. Continental Shelf Research. 9: 841-864.

Churchill, J.H., Biscayne, P.E., and Aikman III, F., 1988. The character and motion of suspended particulate matter over the shelf-edge and upper slope off Cape Cod. Continental Shelf Research. 8: 789-809.

Coale, K.H. and Bruland, K.W., 1985. 234Th:238U disequilibria within the California current. Limonology and Oceanography. 30(1): 22-33.

Cochran, K., Barnes, C., Achman, D., and hirschberg, D.J., 1995. Thorium-234/Uranium-238 disequilibrium as an indicator of scavenging rates and particulate organicmatter fluxes in the Northeast Water Polynya, Greenland. Journal of Geophysical Research. 100(C3): 4399-4410.

Collie, J.S., Escanero, G.A., and Valentine, P.C., 1997. Effects of bottom fishing on the benthic mega-fauna of Georges Bank. Marine Ecology Program Series. 155:159-172.

Collie, J.S., Hall, S.J., Kaiser, M.J., and Poiner, I.R., 2000. A quantitative analysis of fishing impacts on shelf-sea benthos. Journal of Animal Ecology. 69(5): 785-798.

Copeland, B. and Riggs, S., 1984. The ecology of the Pamilco River, North Carolina: An estuarine profile. U.S. Department of the Interior, Fish and Wildlife Service FWS/OBS 82/06. 83pp.

Coppola, L., Roy-Barman, M., Wassman, P., Mulsow, S., and Jeandal, C., 2002. Calibration of sediment traps and particulate organic carbon export using ^{234}Th in the Barents Sea. Marine Chemistry. 80: 11-26.

Davis, G. J., M. M. Brinson, and W. A. Burke. 1978. Organic carbon and deoxygenation in the Pamlico River estuary. University of North Carolina WRRI 78-131. 214 pp.

Day, JW, Jr., Hall, C.A., Kemp, W.M., and Yanez-Arancibia, A., 1989. Estuarine Ecology. John Wiley and Sons, New York. 558pp.

Dayton, P.K., Thrush, S.F., Agardy, M.T., and Hofman, R.J., 1995. Environmental effects of marine fishing. Aquatic Consevration: Marine and Freshwater Ecosystems. 5: 205-232.

De Alteris, J., Skrobe, L., and Lipsky, C., 1999. The Significance of Seabed Disturbance by Mobile Fishing Gear Relative to Natural Processes: A Case Study inNarragansett Bay, Rhode Island in Benaka, L., editor Fish Habitat: essential fish habitat and rehabilitation. American Fisheries Science Syposium 22, Bethesda, MD. 224-237.

de Jonge, V. N., and J.E.E. van Beusekom 1995. Wind- and tide-induced resuspension of sediment and microphytobenthos from tidal flats in the Ems estuary. Limnol. Oceanog. 40: 766-778.

Dibb, J.E. and D.L. Rice, 1989. Temporal and Spatial Distribution of Beryllium-7 In the Sediments of Chesapeake Bay. Estuarine, Coastal and Shelf Science. 28: 395-406.

Drabsch, S.L., Tanner, J.E., and Connell, S.D., 2001. Limited infaunal response to experimental trawling in previously untrawled areas. ICES Journal of Marine Sciences. 58: 1261-1271.

Drake, D.E. and Cacchione, D.A., 1985. Seasonal variations in transport on the Russian River shelf, California. Continental Shelf Research. 4: 495-514.

Drake, D.E. and Cacchione, D.A., 1986. Field observations of bed sheer stress and sediment resuspension on continental shelves, Alaska and California. Continental Shelf Research. 6: 415-429.

Dugdale, R.C. and J.J. Goering, 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. Limnol. Oceanog. 12: 196-206.

Engas, A., Godo, O.R., and Jorgensen, T., 2000. A comparison between vessel and trawl tracks as observed by the ITI trawl instrumentation. Fisheries Research. 45: 297-301.

Fanning, K.A., Carder, K.L., Betzer, P.R., 1982. Sediment resuspension by coastal waters: a potential mechanism for nutrient re-cyling on the ocean's margins. Deep Sea Research. 29(8A): 953-962.

Feng, H., Cochran, J.K., and Hirschberg, D.J., 1999a. ^{234}Th and ^{7}Be as tracers for the transport and dynamics of suspended particles in a partially mixed estuary. Geochimica et Cosmochimica Acta. 63: 2487-2505.

Feng, H., Cochran, J.K., and Hirschberg, D.J., 1999b. ^{234}Th and ^{7}Be as tracers for the Sources of Particles to the Turbidity Maximum of the Hudson River Estuary. Estuarine, Costal and Shelf Science. 49: 629-645.

Fisher, T.R., P.R. Carlson, R.T. Barber, 1982. Sediment nutrient regeneration in three North Carolina Estuaries. Estuar. Coast. Shelf Sci. 14:101-116.

Floderus, S. and Pihl, L., 1990. Resuspension in the Kattegat: impact of variation in wind climate and fishery. Estuarine, Costal and Shelf Science. 31: 487-498.

Garstecki, T., Wickham, S.A., and Arndt, H., 2002. Effects of Experimental Sediment Resuspension on a Coastal Planktonic Microbial Food Web. Estuarine, Coastal and Shelf Science. 55: 751-762.

Gerino, M., Aller, R.C., Lee, C., Cochran, J.K., Aleer, J.Y., green, M.A., and Hirschberg, D., 1998. Comparison of Different Tracers and Methods Used to Quantify Bioturbation During a Spring Bloom: 234- Thorium, Luminophores and Chlorophyll *a*. Estuarine, Coastal and Shelf Science. 46: 531-547.

Giese, G., Wilder, H., and Parker, G., Jr., 1979. Hydrology of major estuaries and sounds of North Carolina. U.S. Geological Survey Water Resources Investigations 79-46. 175pp.

Giffin, D. and Corbett, D.R., 2003. Evaulation of sediment dynamics in coastal systems via shortlived radioisotopes. Journal of Marine Systems. 42: 83-96.

Gilkinson, K., Paulin, M., Hurley, S., and Schwinghamer, P., 1998. Impact of trawl door scouring infaunal bivalves: results of physical trawl door/dense sand interaction. Journal of Experimental Marine Biology and Ecology. 224: 291-312.

Haines, E.B., 1976. Nitrogen content and acidity of rain on the Georgia coast. Water Resour. Bull. 12: 1223-1231.

Hall, SJ., 1999. The Effects of Fishing on Marine Ecosystems and Communities. Blackwell Science, Oxford. 274 pp.

Hartness, T.S., 1977. Distribution and clay mineralogy of organic-rich mud sediments in the Pamilco River Estuary, North Carolina. East Carolina University, Department of Geology Thesis.

Hopkinson, C.S., Jr., 1985. Shallow-water benthic and pelagic metabolism: evidence of heterotrophy in nearshore Georgia Bight. Marine Biology. 87: 19-32.

Jones, J.B., 1992. Environmental impacts of trawling on the seabed; a review. New Zealand J. Marine Freshwater Research. 26: 59-67.

Jones, R. A. and G. F. Lee. 1981. The significance of dredging and dredged material disposal as a source of nitrogen and phosphorus for estuarine waters. In: Nutrients and Estuaries, B. J. Neilson and L. W. Cronin (Eds.), Humana Press

Kemp, W.M. and W.R. Boynton, 1992. Benthic-pelagic interactions: nutrient and oxygen dynamics. In: Oxygen dynamics in the Chesapeake Bay: A Synthesis of Recent Research, D.E. Smith, M. Leffler, and G. Mackiernan (eds), Maryland Sea Grant, p. 149-221.

Kershaw, P. and Young, A., 1988. Scavenging of 234Th in the Eastern Irish Sea. Journal of Environmental Radioactivity 6: 1-23.

Kersten, M., Thomsen, S., Priebsch, W, and Garbe-Schonberg, C-D., 1998. Scavenging and particle residence times determined from $^{234}Th/^{238}U$ disequilibria in the coastal waters of Mecklenburg Bay. Applied Geochemistry 13: 339-347.

Krishnaswami, S., Benninger, L.K., Aller, R.C., and von Damm, K.L., 1980. Atmospherically-derived radionuclides as tracers of sediment mixing andaccumulation in near-shore marine and lake sediments: evidence from ^{7}Be, ^{210}Pb and $^{239,240}Pu$. Earth and Planetary Science Letters. 47: 307-318.

Kristensen, P., Sondergaard, M., and E. Jeppesen 1992. Resuspension in a shallow eutrophic lake. Hydrobiologia 228: 101-109.

Kuenzler, E.J., D.W. Stanley, J.P. Koenings, 1979. Nutrient kinetics of phytoplankton in the Pamlico River, NC, NC WRRI Report No. 139.

Kuenzler, E. J., D. A. Albert, G. S. Allgood, S. E. Cabaniss, and C. G. Wanat. 1984. Benthic nutrient cycling in the Pamlico River. University of North Carolina Water Resources Research Institute, Report No. 215. Raleigh, N. C. 148 pp.

Lindegarth, M., Valentinsson, D., Hansson, M., and Ulmestrand, M., 2000. Interpreting large-scale experiments on effects of trawling on benthic fauna: an empirical test of the potential effects of spatial confounding in experiments without replicated control and trawled areas. Journal of Experimental Marine Biology and Ecology. 245: 155-169.

Loffler, H., 1974. Der Neusiedlersee. Naturgeschichte eines Steppensees. Molden, Wien, 175pp.

Maa, J., Sanford, L., and Halka, J.P., 1998. Sediment resuspension characteristics in Baltimore Harbor, Maryland. Marine Geology. 146: 137-145.

Main, J. and Sangster, G., 1981. A study of sand clouds produced by trawl boards and their possible effect on fish capture. Department of Agriculture and Fisheries for Scotland, Scottish Fisheries Research Report No. 20. (ISSN 0308-8022): 21pp.

Mallin, M. A. 1994. Phytoplankton ecology of North Carolina Estuaries. Estuaries 17: 561-574.

Mallin, M.A., Burkholder, J.M., Cahoon, L.B., and Posey, M.H., 2000. North and South Carolina Coasts. Marine Pollution Bulletin. 41: 56-75.

Martin, J.M., Mouchel, J.M., and Thomas, A.J., 1986. Time concepts in hydrodynamic systems with an application to ^{7}Be in the Gironde estuary. Marine Chemistry. 18: 369-392.

McAnally, W.H. and A.J. Mehta, 2002. Significance of Aggregation of Fine Sediment Particles in Their Deposition. Estuarine, Coastal and Shelf Science. 54: 643-653.

McConnaughey, R.A., Mier, K.L., and Dew, C.B., 2000. An examination of chronic trawling effects on soft-bottom benthos of the eastern Bering Sea. ICES Journalof Marine Science. 57: 1377-1388.

Moeller, C., Huh, O., Roberts, H., Gumley, L., and Menzel, P., 1993. Response of the Louisiana coastal environments to a cold front passage. Journal Coastal Research. 9: 434-447.

Morton, B., 1996. The Subsidiary Impacts of Dredging (and Trawling) on a Subtidal Benthic Molluscan Community in the Southern Waters of Hong Kong. Marine Pollution Bulletin. 10: 701-710.

National Research Council. 2002. Effects of Trawling and Dredging on Seafloor Habitat. National Academy Press, Washington D.C. 125 pp.

Neubauer, S.C., Anderson, I.C., Constantine, J.A., and Kuehl, S.A., 2002. Sediment Depostion and Accretion in a Mid-Atlantic (U.S.A.) Tidal Freshwater Marsh. Estuarine, Coastal and Shelf Science. 54: 713-727.

Nishri, A., 1993. Suspended sediments as a source of P to summer biota of Lake Kinnert. Hydrobiologia 253/Dev. Hydrobiologia. 84: 217.

Nixon, S. W. 1981. Remineralization and nutrient cycling in coastal marine ecosystems. In: Nutrients and Estuaries, B. J. Neilson and L. W. Cronin (Eds.), Humana Press pp. 111-138.

North Carolina Division of Marine Fisheries. 1993. Description of North Carolina's coastal fishery resources 1972-1991. North Carolina Department of Enviroment, Health, and Natural Resources. 231 pp.

Olsen, C.R., Larsen, I.L., Lowry, P.D., Cutshall, N.H., Todd, J.F., Wong, G.T.F., and Casey, W.H., 1985. Atmospheric fluxes and marsh-soil inventories for ^{7}Be and ^{210}Pb. Journal of Geophysical Research. 90: 10,487-10,495.

Olsen, C.R., Larsen, I.L., Lowry, P.D., Cutshall, N.H., and Nichols, M.M., 1986. Geochemistry and deposition of ^{7}Be in river-estuarine and coastal waters. Journal Geophysical Research. 91: 896-908.

Palanques, A., guillen, J., and Puig, P., 2001. Impact of bottom trawling on water turbidity and muddy sediment of an unfished continental shelf. Limnology and Oceanography. 46: 1100-1110.

Park, B., 1971. Mineralogy of recent sediments of North Carolina sounds and estuaries. East Carolina University, Department of Geology Thesis.

Pedersen, O.B., Christiansen, C., and Laursen, M.B., 1995. Wind induced long term increase and short term fluctuations of shallow water suspended matter and nutrient concentrations, Ringkobing Fjord, Denmark. Ophelia. 41: 473-487.

Percival, P., Frid, C.L.J., Upstill-Goddard, R.C., Polunin, N.V.C., 2002. The role of bioturbation in bethic Nutrient dynamics and Sediment-Water Exchange. (2002 Ocean Sciences Meeting, published as supplement to) EOS, Transactions, American Geophysical Union 83(4): 65.

Pilskaln, C.H., Churchill, J.H. and Mayer, L.M., 1998. Resuspension of sediment by bottom Trawling in the Gulf of Maine and potential geochemical consequences. Conservation Biology. 12: 1223-1229.

Pinckney, J. L., H. W. Paerl, M. B. Harrington, and K. E. Howe. 1998. Annual cycles of phytoplankton community-structure and bloom dynamics in the Neuse River Estuary, North Carolina. Marine Biology 131: 371-381.

Pranovi, F., Raicevich, S., Franceschini, G., Farrace, M.G., and Giovanardi, O., 2000. Rapido trawling in the northern Adriatic Sea: effects on benthic communities in an experimental area. ICES Journal of Marine Science. 57: 517-524.

Puig, P., Palanques, A., and Guillen, J., 2001. Near-bottom suspended sediment variability caused by storms and near-inertial internal waves on the Ebro mid continental shelf (NW Mediterranean). Marine Geology. 178: 81-93.

Quigley, M.S., Santschi, P.H., Guo, L., and Honeyman, B.D., 2001. Sorption irreversibility and coagulation behavior of ^{234}Th with marine organic matter. Marine Chemistry. 76: 27-45.

Ramsey, K., Kaiser, M.J., and Hughes, R.N., 1998. Responses of benthic scavengers to fishing disturbance by towed gears in different habitats. Journal of Experimental Marine Biology and Ecology. 224: 73-89.

Redondo, J.M., Durrieu de Madron, X., Medina, P., Sanchez, M. A., and Schaaff, E., 2001. Comparison of sediment resuspension measurements in sheared and zero-mean turbulent flows. Continental Shelf Research. 21: 2095-2103.

Ritzrau, W. and Graf, G., 1992. Increase of microbial biomass in the benthic turbidity zone of Kiel Bight, Baltic Sea, after resuspension by a storm event. Limonology Oceanography. 37: 1081-1086.

Rizzo, W.M. 1993. Sediment-water phosphate exchange in the Neuse River, North Carolina. NC WRRI Repot No. 275. 64 p.

Rizzo, W.M. and R.B. Christian, 1996. Significance of Subtidal Sediments to Heterotrophically-Mediated Oxygen and Nutrient Dynamics in a Temperate Estuary. Estuaries, v.19, no. 2B, p.475-487.

Robbins, J.A. and Eadie, B.J., 1982. Beryllium 7: A tracer of seasonal particle transport processes in Lake Michigan (Abstract). EOS Transactions of the American Geophysical Union. 63: 957.

Rosa, F., Nriagu, J.O., Wong, H.K.T. and Burns, N.M., 1983. Particulate flux at the bottom of Lake Ontario. Chemosphere. 12: 1345-1354.

Rosenberg, R., Nilsson, H.C., Gremare, A., and Amouroux, J-M., 2002. Effects of demersal trawling on marine sedimentary habitats analysed by sediment profile imagery. Journal of Experimental Marine Biology and Ecology. 4087: 1-13.

Rutgers van der Loeff, M.M., Meyer, R., Rudels, B., and Rachor, E., 2002. Resuspension and particle transport in the benthic nepheloid layer in and near Fram Strait in relation to faunal abundances and ^{234}Th depletion. Deep-Sea Research. 49: 1941-1958.

Rutgers van der Loeff, M.M., 2004. Radionuclides as tracers for particle flux and transport of water masses in the Atlantic sector of the Southern Ocean. In: Wefer, Gerold; Mulitza, Stefan; Ratmeyer, Volker (Eds.) The South Atlantic in the Late Quaternary: Reconstruction of Material Budgets and Current Systems. SFB 261 Synthesis Volume. Springer, 2004: 315.

Sanchez, P., Demestre, M., Ramon, M., and Kaiser, M.J., 2000. The impact of otter trawling on mud communities in the northwestern Mediterranean. ICES Journal of Marine Science. 57: 1352-1358.

Santschi, P.H., Guo, L., Walsh, I.D., Quigley, M.S., and Baskaran, M., 1999. Boundary exchange and scavenging of radionuclides in continental margin waters of the Middle Atlantic Bight: implications for organic carbon fluxes. Continental Shelf Research. 19: 609-636.

Sarin, M.M., Krishnaswami, S., Dalai, T.K., Ramaswamy, V., and Ittekkot, V., 2000. Settling fluxes of U- and Th- series nuclides in the Bay of Bengal: results from time-series sediment trap studies. Deep-Sea Research. 47: 1961-1985.

Schmidt, S., van Weering, Tj. C.E., Reyss, J.-L., and vanBeek, P., 2002. Seasonal deposition and reworking at the sediment-water interface on the northwestern Iberian margin. Progress in Oceanography. 178: 81-93.

Schoellhamer, D.H., 1996. Anthropogenic Sediment Resuspension Mechanisms in a Shallow Microtidal Estuary. Estuarine, Costal and Shelf Science. 43: 533-548.

Seim, H.E., Blanton, J.O., and Gross, T., 2002. Direct stress measurements in a shallow, sinuous estuary. Continental Shelf Research. 22: 1565-1578.

Smith, C.J., Papadopoulou, K.N., and Diliberto, S., 2000. Impact of otter trawling on an eastern Mediterranean commercial trawl fishing ground. ICES Journal of Marine Science. 57: 1340-1351.

Soil and Plant Analysis Council, 2000. Soil Analysis Handbook of Reference Methods. CRC Press. Boca Raton.

Sondergaard, M., Kristensen, P., and E. Jeppesen 1992. Phosphorus release from resuspended sediment in the shallow and wind-exposed Lake Arreso, Denmark. Hydrobiologia 228: 91-99.

Stanley, D.W. and J.E.Hobbie, 1977. Nitrogen cycling in the Chowan River. NC WRRI Report No. 121.

Stanley, D.W. and J.E. Hobbie, 1981. Nitrogen cycling in a North Carolina coastal river. Limnol. Oceanog. 26: 30-42.

Stanley, D. W. 1988. Water quality in the Pamlico River Estuary: 1967-1986. A Report to Texasgulf Chemicals Co. Institute for Coastal and Marine Resources Technical Report 88-01. 199 pp.

Stanley, D. W. 1997. Water Quality in the Pamlico River Estuary: 1989-1996. A Report to PCS Phosphate. Institute for Coastal and Marine Resources Report 97-02. 77 pp.

Steinmann, P., Billen, T., Loizeau, J.-L., and Dominik, J., 1999. Beryllium-7 as a tracer to study mechanisms and rate of metal scavenging from lake surface waters. Geochimica et Cosmochimica Acta. 63: 1621-1633.

Tenberth, K.E., Large, W.E., and Olson, J.G., 1990. The mean annual cycle in global ocean wind stress. Journal Physical Oceanography. 20: 1742-1760.

Tengberg, A., Almroth, E., and Hall, P., 2002. Resuspension and its effects on organiccarbon recycling and nutrient exchange in coastal sediments: in situ measurements using new experimental technology. Journal of Experimental Marine Biology and Ecology. 4051: 1-24.

van Geen, A. and S.N. Luoma, 1999. The impact of human activities on sediments of San Francisco Bay, California: an overview. Marine Chemistry. 64: 1-6.

Vogler S., Mangini A. and Jung M., 1996. Th-230 and Be-7 in Lake Constance. Limnology and Oceanography 41(7): 1384-1393.

Wainwright, S.C., 1987. Stimulation of heterotrophic microplankton production by resuspended marine sediments. Science. 238: 1710-1712.

Wainwright, S.C., 1990. Sediment to water fluxes of particulate material and microbes by resuspension and their contribution to the planktonic food web. Marine Ecology Program Series. 62: 271-281.

Wainright, S.C. and C.S. Hopkinson Jr., 1997. Effects of sediment resuspension on organic matter processing in coastal environments: a simulation model. Journal of Marine Systems. 11: 353-368.

Wan, G.J., Santschi, P.H., Sturm, M., Farrenkothen, K., Lucek, A., Werth, E., and Schuler, C., 1987. Natural (^{210}Pb, ^{7}Be) and fallout (^{137}Cs, ^{239,240}Pu, ^{90}Sr) Radionuclides as geochemical tracers of sedimentation in Greifensee, Switzerland. Chem. Geol. 63: 181-196.

Warnken, K. W., G. A. Gill, P. H. Santschi, and L. L. Griffin. 2000. Benthic exchange of nutrients in Galveston Bay, Texas. Estuaries 23: 647-661.

Watling, L. and Norse, E.A., 1998. Disturbance of the seabed by mobile fishing gear:a comparison to forest clearcutting. Conservation Biology. 12: 1180-1197.

Wei, C. L. and Murray, J. W., 1992. Temporal variations of 234Th activity in the water column of Dabob Bay: particle scavenging. Limnology Oceanography 37(2): 296-314.

Wells, J.T. and S. Kim, 1989. Sedimentation in the Albemarle-Pamilco Lagoonal System: Synthesis and Hypothesis. Marine Geology. 88: 263-284.

West, T., Corbett, D.R., Clough, L., Calfee, M.W. and Frank, J.E., In Review. Impacts of trawling and wind induced disturbance on water quality in South Creek, North Carolina. American Fisheries Research Society Annual Publication.

Windom, H.L., W.M. Dunstan, W.S. Gardner, 1975. River input of inorganic phosphorus and nitrogen to the southeastern salt marsh estuarine environment. Recent Advances in Estuarine Research 1, 309-313.

Wisniewski, R., 1993. The release of phophorus during sediment resuspension. Hydrobiologia. 84: 321-322.

Wright, T.O., 1974. Sedimentary Geochemistry of Central Pamlico Sound, North Carolina. East Carolina University, Department of Geology Thesis.