AIRBORNE DETECTION OF ECOSYSTEM RESPONSES TO AN EXTREME EVENT: PHYTOPLANKTON DISPLACEMENT AND ABUNDANCE AFTER HURRICANE INDUCED FLOODING IN THE PAMLICO-ALBEMARLE SOUND SYSTEM, NORTH CAROLINA

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Left running head: P.A. Tester et al.
Right running head: Ecosystem Responses to an Extreme Event

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ABSTRACT: Airborne laser induced fluorescence measurements were used to detect and monitor ecosystem wide changes in the distribution and concentration of chlorophyll biomass and colored dissolved organic matter in the largest lagoonal estuary in the United States, following massive flooding caused by a series of three hurricanes in the late summer of 1999. These high-resolution data provided a significantly more detailed representation of the overall changes occurring in the system than could have been achieved by synoptic sampling from any other platform. The response time for the distribution of chlorophyll biomass to resume pre-flood conditions was used as a measure of ecosystem stability. Chlorophyll biomass patterns were reestablished within four months of the flooding, whereas higher chlorophyll a biomass concentrations persisted for 6-12 months. The primary trophic level in the Pamlico-Albemarle Sound system returned to equilibrium within a year of a major perturbation.
INTRODUCTION

Phytoplankton are good indicators of ecological change because their responses to environmental variations are rapid. Over an annual cycle, there is a high degree of predictability in the overall pattern of phytoplankton abundance in space and time in estuarine systems (Loftus et al. 1972; Pinckney et al. 1998). How phytoplankton biomass deviates from general patterns in response to forcing functions, anthropogenic or natural events, is a measure of the severity of the perturbation to the system. Consequently, the time for recovery of phytoplankton biomass, to its average abundance and distribution patterns after different levels of disturbance, helps define the stability of an estuarine ecosystem (Loftus et al. 1972). The response time for normalization of the distribution and abundance of phytoplankton biomass in the Pamlico-Albemarle Sound (PAS) system and associated tributaries, after three successive hurricanes, is suggested as a first order measure of this ecosystem’s stability after an extreme event.

Record rainfall and extensive flooding accompanied the Hurricanes Dennis, Floyd, and Irene that made landfall in coastal North Carolina in September-October 1999. The physical and chemical changes following this massive freshwater influx served as a large-scale natural experiment. In a matter of weeks, half of the annual supply of nutrients was delivered to the PAS as freshwater runoff (Paerl et al. 2001). Distribution and abundance of phytoplankton biomass (chlorophyll), as measured by laser-induced fluorescence, was chosen as an indicator of integrated phytoplankton response. The time required to reestablish normal chlorophyll $a$ concentrations and distribution patterns was monitored to estimate the stability of the PAS system after record rainfalls inundated the watershed.
The phytoplankton dynamics of the major tributaries of the PAS system are meteorologically driven (Pinckney et al. 1998; Litaker et al. 2002), with the phytoplankton primary production in the Neuse River (Fisher et al. 1982; Matson et al. 1983; Mallin 1991; Rudek et al. 1991; Boyer et al. 1994), Tar-Pamlico River (summer) and Chowan River (summer) controlled primarily by nitrogen availability (Stanley and Hobbie 1977; Kuenzler et al. 1979). Pinckney et al. (1998) studied the annual cycles of phytoplankton in the Neuse River over a 3-year period and characterized it as a stable ecosystem with good species evenness and diversity. They determined the contribution of each of the five algal groups (dinoflagellates, diatoms, cryptomonads, chlorophytes, cyanobacteria) to the total chlorophyll $a$ was nearly equal (20%). A similar study of phytoplankton in the lower Chesapeake Bay found several common assemblages that changed seasonally in composition but varied in a predictable pattern from year to year (Marshall and Nesius 1996). Characteristically, in these estuarine systems, the highest phytoplankton biomass and major blooms occur in mixing zones or at density fronts (Boyer et al. 1994; Litaker et al. 2002). In the PAS system, these highly productive mixing zones are normally found in the Neuse and Tar-Pamlico Rivers, major tributaries of the sound.

Synoptic sampling of phytoplankton biomass in the PAS system in the aftermath of Hurricanes Dennis, Floyd and Irene was accomplished using a twin engine NOAA research aircraft equipped with NASA’s airborne oceanographic light detection and ranging instrument (AOL3). The AOL3 fluorosensor acquires measurements of laser-induced fluorescence (LIF) of chlorophyll and colored dissolved organic matter (CDOM). A series of four missions was flown between 25 September and 31 October 1999 over the PAS system, its major tributaries, a coast parallel transect that included each of the inlets along the Outer Banks of North
Carolina and a control transect across the continental shelf with measurements in the Gulf Stream. After a season with no hurricane activity, a fifth mission was flown over the same flight path on 11 October 2000 to serve as a comparison (non-flood control).

METHODS

On each of the over flight dates, surface water samples and subsurface profiles were taken along a transect from the intersection of the Atlantic Intracoastal Waterway and the Neuse River east across the central axis of the Pamlico Sound (Fig. 1). Chlorophyll $a$ pigments extracted from surface samples were used to calibrate the 685 nm LIF emission signal excited at 532 nm. CDOM fluorescence measurements served to normalize the 450 nm (emission) LIF signal excited at 355 nm. Subsurface profiles of salinity, temperature, dissolved oxygen and photosynthetically active radiation (PAR) were used to assess the degree of water column stratification and light penetration.

Freshwater inflow to Pamlico Sound was estimated using U.S. Geological Survey (USGS) stream flow data from the two major tributaries: the Neuse River (gauge 02089500 at Kinston, North Carolina) and the Tar-Pamlico River (gauge 02083500 at Tarboro, North Carolina). These data were averaged daily, and while they do not include the freshwater runoff downstream of the gauges (see Bales et al. 2000), they do serve as relative measures of the flow rates after the three storms. The combined average daily flow rates from the Kinston and Tarboro stream gauge stations from 1932 through 2000 was 8 m$^3$s$^{-1}$ and served as a baseline.

Wind speeds and directions were used to help determine the potential transport of phytoplankton biomass within the PAS system and the extent of export of biomass through the inlets and into the coastal ocean. Wind speeds and directions were averaged over 12-hour
periods at Cape Hatteras Fishing Pier for 15 August through 31 October 1999. Data for tidal
predictions and observed water levels were accessed from three National Water Level
Observation Network stations located at Oregon Inlet (8652587), Hatteras Inlet (8654400),
and Beaufort Inlet, North Carolina (8656483). The storm surge that occurred during
Hurricane Floyd was calculated as the difference between predicted and observed tidal
heights and was provided by the NOAA Center for Operational Oceanographic Products and
Services.

**SURFACE WATER SAMPLES**

Sampling stations in the lower Neuse River and Pamlico Sound were selected to
correspond with the basin hydrologic units delineated by shoals, tidal deltas, inlets and
shoreface limits (barrier islands) (Ferguson et al. unpublished data) (Fig. 1). The
geomorphologic features of a lagoonal estuary greatly affect basin circulation, mixing time of
freshwater, retention times and the transport of biomass through inlets in the barrier islands.
Since Bluff Shoal extends from Ocracoke Inlet across the sound to Bluff Point it effectively
separates Pamlico Sound into two basins. Station locations were chosen to include areas east
and west of Bluff Shoal.

Chlorophyll $a$ samples (50-750 ml) were filtered under gentle vacuum ($<5$ mm Hg)
onto a 2.5 cm diameter Whatman GF/F filter and extracted with 7.5 ml acetone and water
(90:10), homogenized in a tissue grinder and placed in the dark at -20°C for 18 h (Parsons et
al. 1984). After centrifugation samples were read, acidified and reread using a Turner
Designs fluorometer (AU-10 analog) calibrated with chlorophyll $a$ standards from Turner
Designs (Sunnyvale, California). Chlorophyll $a$ and phaeophytin were calculated using the
equations of Parsons et al. (1984).
Colored dissolved organic matter was measured at each station. Surface water was filtered through a 0.2 µm Nucleopore filter and stored in brown glass bottles that had been heated to 450°C in a muffle furnace for a minimum of 24 h, sealed with an acid treated Teflon coated lid and stored at 4°C. Samples were analyzed using a Turner Designs analog fluorometer (AU-10) retrofitted with the CDOM Optical Kit (10-303) that included a near UV mercury vapor lamp, 310-390 nm excitation filter, a 410-460 nm emission filter, a 1:75 attenuator plate and a 10-300 reference filter (>300 nm). The relative fluorescence signal was scaled using quinine sulfate (after Hoge et al. 1993).

Total suspended solids were measured from surface water samples filtered onto an oven dried, preweighed Whatman GF/F filter. Sample filters were dried at 60°C for 24 h, cooled in a dissector and reweighed to five decimal places.

WATER COLUMN PROFILES

Salinity and temperature (as conductivity) and dissolved oxygen were measured using a YSI Incorporated Sonde 6600 (Yellow Springs Instruments, Inc., Yellow Springs, Ohio). The diffuse attenuation coefficient for photosynthetically active radiation (PAR) was measured throughout the water column using a 2 π LiCor sensor on a YSI Sonde and reported as µEinsteins m⁻²s⁻¹. The depth limit of the photic zone was determined from PAR profiles and data were normalized to percent of surface PAR.

AIRBORNE OCEANOGRAPHIC LIGHT DETECTION AND RANGING INSTRUMENT

The NASA AOL3 (airborne oceanographic light detection and ranging instrument) is designed to acquire individual laser-induced fluorescence (LIF) spectra from two excitation frequencies (355 and 532 nm) emitted from a single laser transmitter (Wright et al. 2001). As a fluorosensor the AOL measures phytoplankton chlorophyll (Hoge and Swift 1981; Smith et al.
1987; Walsh et al. 1988) and chromophoric dissolved organic carbon (Hoge et al. 1995). The water Raman backscatter is also acquired and used to normalize the laser-induced fluorescence data for surface layer spatial differences in water attenuation properties (Bristow et al. 1981). The AOL is typically flown at an altitude of 150 m at airspeeds of ~150 m sec\(^{-1}\) and the position of the plane is recorded by a GPS receiver.

Extracted chlorophyll samples were used to calibrate the LIF signal received in the 685 nm channel (Fig. 2). Note the difference in the relationship between extracted chlorophyll \(a\) and the LIF signal from the flood period (Sept.- Oct. 1999) and one year later (Oct. 2000, non-flood control). This is likely due to the interference by high CDOM concentrations in the floodwater. As expected, the CDOM signal in October 2000 (non-flood control) was lower than all but one observation made during the flood period between September and October 1999.

The CDOM fluorescence measurements (standardized using a dilution series of quinine sulfate) served to normalize the LIF signal at 450 nm (Fig. 3). Once the LIF data were normalized, they were displayed using ArcView GIS software (ESRI, Redlands, CA).

**RESULTS**

Normally the highest chlorophyll values in the PAS system are found in the rivers at the interface of freshwater and brackish water, well up stream from the mouths of the Neuse and Pamlico Rivers. The most striking feature of the chlorophyll distribution on 25 September 1999, nine days after the passage of Hurricane Floyd, is the low levels of chlorophyll in the Neuse and Tar-Pamlico Rivers (Fig. 4). High river discharge (>560 fold normal) following Hurricane Floyd (21 September 1999) (Fig. 5) resulted in a marked reduction in phytoplankton biomass (chl) in the rivers. By 25 September the highest
chlorophyll concentrations had been displaced down river into the western basin of Pamlico Sound and into the middle reach of Albemarle Sound nearly to the mouth of the Alligator River (Fig. 4). Southerly and southwesterly winds associated with the passage of Hurricane Floyd moved high concentrations of phytoplankton biomass throughout the PAS system and through all the inlets along the outer banks. However, the exported phytoplankton rich floodwater did not mix across the continental shelf. By 2 October 1999, the date of the second overflight, most of the phytoplankton biomass was in the western and central areas of Pamlico Sound on both sides of Bluff Shoal and in the outer portion of Albemarle Sound (Fig. 4). The biomass was lower throughout the system than on 25 September and there was little evidence for chlorophyll rich water on the continental shelf. A majority of the chlorophyll biomass was retained in the PAS as only limited outflow occurs through the inlets in the barrier islands (Pietrafesa et al. 1996)

By the third overflight on 15 October 1999, the phytoplankton dilution rate was much lower because the combined stream flow rates of the Neuse and Tar-Pamlico Rivers were only about 10% of their maximum combined flow rate recorded on 21 September 1999 (~2,820 m$^3$ s$^{-1}$). The highest phytoplankton biomass on 15 October was in the central axis of Pamlico Sound east of Bluff Shoal and was likely augmented by in situ production (Fig. 4). Export of biomass to the coastal ocean through Oregon Inlet was evident prior to the passage of Hurricane Irene on 17 October (see Werner et al. 1999; Xie and Pietrefesa 1999). The Albemarle Sound is oligohaline and its major tributary, the Chowan River, historically has lower chlorophyll than the Neuse or Tar-Pamlico Rivers (Stanley 1996; J. Overton personal communication). By mid-October the Albemarle Sound still had low chlorophyll levels while the chlorophyll in the lower sections of the Tar-Pamlico and Neuse Rivers started to increase.
The highest phytoplankton biomass in the Albemarle Sound was mid-way along its central axis (Fig. 4).

Between the dates of the third and fourth over flights, Hurricane Irene came ashore near Beaufort North Carolina (17-18 October 1999), and the combined daily stream flow of the Tar-Pamlico and Neuse Rivers doubled within two days (~660 m$^3$ s$^{-1}$ on 19 October 1999) and increased 3-fold by 23 October. The relatively low chlorophyll signal from the rivers on 31 October again reflected the effects of high stream flow as the highest phytoplankton biomass washed into the western basin of Pamlico Sound and extended almost to Bluff Shoal (Figs. 4 and 6). At this time, only small amounts of chlorophyll were moving through Oregon, Hatteras and Ocracoke Inlets (Fig 4).

After a year of no hurricane activity, another over flight was conducted to serve as a control. The highest chlorophyll areas were in the mesohaline regions of the Tar-Pamlico and Neuse Rivers with relatively high phytoplankton biomass throughout Pamlico Sound (Figs. 4 and 6). There was some export of chlorophyll through Oregon Inlet, but uniformly low chlorophyll in the near shore region. The normally low chlorophyll in the Chowan River served as a contrast to the Tar-Pamlico and Neuse Rivers but Albemarle Sound. This overall pattern of chlorophyll represents the average phytoplankton biomass and distribution normally found in late summer to early fall.

The normal ranges of measured chlorophyll $a$ values in the Neuse River for the September – November period are ~5-30 µg l$^{-1}$ (Pinckney et al. 1998; MODMON Phase II Report) and ~2-8 µg l$^{-1}$ in Pamlico Sound. Shortly after Hurricanes Dennis and Floyd, the chlorophyll $a$ biomass in the Neuse River was substantially reduced relative to normal (Fig. 4, 25 Sept. and 2 Oct. 1999) at the same time chlorophyll $a$ concentrations in Pamlico Sound
were higher than normal. As the river flow decreased, lower dilution rates allowed increased in situ biomass to accumulate in the Pamlico Sound even more (Fig. 4-6, 15 Oct. 1999).

At the beginning of September 1999, the observed water levels exceeded those predicted for the PAS system because of the precipitation associated with Hurricane Dennis. A peak in water levels was observed at Oregon Inlet and Hatteras Inlet stations on the morning of 16 September due to the passing of Hurricane Floyd. The maximum storm surge on the United States east coast due to Hurricane Floyd occurred at Beaufort Inlet and set a historical record for that station and the Oregon Inlet station (>1.5 m s\(^{-1}\)) (Zervas 2001). Water levels remained high at all stations. The Hatteras Inlet station failed because of Hurricane Floyd on 17 September and did not return to normal operation until sometime after 25 October 1999. The storm surge and subsequent flooding inundated areas infrequently covered by standing water. The 500-year flood level was reached in some parts of the drainage basin (Yang et al. unpublished data) and this inundation covered large peat deposits rich in dissolved organic materials.

Material released after extensive and prolonged flooding of marshes and peat rich areas contributed to the high concentrations of CDOM observed after Hurricane Floyd. The patterns of CDOM abundance paralleled the surface chlorophyll distribution in most cases and may be a proxy nutrient signal. The highest CDOM concentration on 25 September 1999 was located in the western part of Pamlico Sound and the Alligator River (Albemarle Sound) where extensive peat rich marshes and pocosins drain (Fig. 7). The CDOM signal was strongest in the western basin of Pamlico Sound and into the central region of the sound during the second over flight (2 October 1999) reflecting the large amount of freshwater input (Figs. 5 and 7). Note the strong signal near Cape Lookout. The effects of lower river flow
rates (15 October 1999), seen in the chlorophyll distribution, are also apparent in the high CDOM signal in the western basin of Pamlico Sound and the lower Tar-Pamlico and Neuse Rivers (Figs. 4, 5 and 7). The precipitation accompanying Hurricane Irene (17-18 Oct. 1999) resulted in runoff with less CDOM than observed from the previous storm events. This resulted in uniformly lower CDOM throughout the PAS system (Fig. 7). The highest signals at this time were all in the coastal region associated with inlets. The over flight conducted one year later (11 October 2000) depicts a pattern of CDOM that is easily interpretable. The Sounds are uniformly low and the rivers have a higher level of CDOM (11 October 2000, Fig. 7) though not nearly as high as during the flood period (Fig. 7, 11 Oct. 2000).

Total suspended solids (TSS) were measured to determine the contribution of particulates versus CDOM. During the high river flow period following the flooding, total suspended solids were not high ($\geq 20$ mg l$^{-1}$ in western Pamlico Sound). Somewhat surprisingly the TSS values measured a year after the flooding were all higher than the TSS measured during the 1999 flood period except for the eastern most Pamlico Sound station on the first day of sampling (25 September 1999) (Fig. 8). With few particulate solids in the surface floodwaters, we can interpret the LIF signals at 685 and 450 nm as representative of chlorophyll and CDOM respectively with little interference from particulates.

There was an inverse relationship between CDOM and the 1% light level (Fig. 9A). There was also a highly significant inverse relationship between relative CDOM and chlorophyll $a$ indicating light limitation (Fig. 9b). The large CDOM inputs associated with runoff, particularly following Hurricane Floyd, lowered the average light penetration in the water column effectively reducing the productive depth of the water column.
The NOAA observation aircraft was not available for continued biweekly monitoring of the PAS after 31 October 1999. An alternate way to estimate chlorophyll distribution was available from ocean color satellite images (SEAWiFS). These data were reprocessed using a regional algorithm for chlorophyll in order for the SeaWiFS data to be consistent with field measurements made during this study (Stumpf et al. 2000). Interpretation of the ocean color scenes were made carefully because in shallow, near shore waters (Case II) high particulate loads, high DCOM concentrations and bottom reflectance can lead to inaccurate chlorophyll estimates. Consequently, the interpretations were made based on trends rather than specific values from a single scene. All cloud-free scenes from 23 September 1999 to 19 October 2000 were examined for chlorophyll distribution throughout the PAS and 17 scenes (approx 3 week intervals) were selected for close examination (data not shown). The scene from 28 October 1999 was typical for that time period and shows relatively low chlorophyll abundance in the rivers and higher phytoplankton biomass in the central and eastern areas of the PAS (Fig 10). Within two weeks after Hurricane Irene on 17 October 1999, river flows had declined by half, and within a month, flow rates were approaching seasonal averages. By 6 January 2000, ocean color imagery indicated higher chlorophyll values in the rivers (Fig. 10), returning to a normal pattern.

While these data indicate that phytoplankton biomass distribution over the entire PAS system returned to a normal pattern within four months after the passage of Hurricane Floyd, the abundance of chlorophyll \textit{a} remained higher than before the hurricane season (Fig. 11). From chlorophyll \textit{a} measurements made in Pamlico Sound pre-September 1999, it is possible to say that chlorophyll \textit{a} concentrations returned to pre-flood levels within 6-12 months.

**DISCUSSION**
The Pamlico-Albermarle Sound system represents one of the largest lagoonal and most productive estuaries in the world (Boynton et al. 1982). Under normal flow conditions, the highest chlorophyll $a$ biomass is found in the brackish portions of the rivers and tributaries entering the sound. High river discharge caused by extensive flooding following a series of hurricanes in 1999 displaced phytoplankton biomass down stream from the rivers and tributaries 20-50 km into the PAS system. This displacement event was reflected by the pattern of CDOM concentrations, with the greatest CDOM levels representing regions of highest phytoplankton dilution (Figs. 4 and 7). Some of this displaced biomass was exported through the three relatively small inlets that connect the PAS with the continental shelf. Most of the biomass, however, was retained in the sound.

In systems like Chesapeake Bay the response of phytoplankton to large nutrient inputs is generally rapid growth. Loftus et al. (1972), for example, reported chlorophyll $a$ concentrations up to 40 times pre-bloom values (300 $\mu$g l$^{-1}$) in Chesapeake Bay within four days after a storm. Within the first two weeks the overall chlorophyll $a$ declined, but after an additional 70 mm of rain, continued runoff extended the bloom. The presence of high phytoplankton concentrations was due to continued runoff and replenishment of the surface layer. By day 21 the chlorophyll $a$ standing crop was uniform. The maximum doubling time for chlorophyll $a$ biomass was $\sim$1.5 days, and the time for dissipation of the increased chlorophyll $a$ was estimated by Loftus et al. (1972) to be 8-10 days. The concentrations of dissolved inorganic nitrogen (DIN) and the assimilation values they reported during the Chesapeake Bay bloom were not significantly different from the pre-bloom values. It follows that the turnover time for available nitrogen can be extremely rapid. A similar rapid increase in chlorophyll $a$ biomass was observed following the massive flooding associated with
Hurricane Floyd, first in the western basin of Pamlico Sound and then throughout the PAS system, with the exception of the Chowan River that is largely freshwater. Within four weeks after the peak river flow, significant in situ growth was observed in the central to eastern Pamlico Sound.

Ramus et al. (2003) measured the DIN after the flooding caused by Hurricane Floyd. The DIN increased in surface waters and surface chlorophyll $a$ eventually increased up to four times the pre-hurricane Floyd levels. The chlorophyll $a$ biomass increase was not as rapid, nor did the chlorophyll $a$ biomass reach the levels expected based on the nutrient inputs into the system. The delayed increase in chlorophyll $a$ biomass observed in the PAS can be largely accounted for by the reduction in light attenuation in the system caused by the large inputs of CDOM (Figs. 7 and 9). Only after the CDOM levels began to decrease did phytoplankton levels begin to increase substantially (Figs. 4 and 7, 15 Oct. 1999).

The high concentrations of CDOM and the timing of the series of storms in late summer 1999 lessened the impact this event would have had earlier in the year. The high CDOM concentrations effectively light-limited the phytoplankton and reduced the potential for massive blooms that could have used all the available DIN and caused widespread anoxia. Hurricane Dennis cooled the water off the Georgia and Carolina coasts by 3°C and nearly doubled the depth of the mixed water layer beneath it (D’Asaro in press). This reduced Hurricane Floyd’s energy so it was only a category 3 (Safford-Simpson scale) (Simpson 1974) when it made landfall. Cooler water temperatures, shorter day length and lower sun angle all helped modify the productivity of the PAS system from what it would have been earlier in the summer. The influence of CDOM on productivity may represent a major
difference between lagoonal estuarine systems such as the PAS and open systems such as Chesapeake Bay where CDOM can be more rapidly diluted from the system.

As the river flow rates subsided still further, the highest phytoplankton biomass moved toward the river mouths and eventually the pattern of higher riverine productivity and biomass was reestablished. Only about 4 months was required for the PAS system to reestablish this pre-flood pattern of phytoplankton distribution. Though the pattern reestablished quickly, it should be noted that overall phytoplankton biomass throughout the system exceeded pre-flood values for 6-12 months. Presumably, the increased biomass values reflect the utilization of higher inorganic nutrient loading as well as some remineralization (Stanley and Hobbie 1981; Paerl et al. 2001).

Rapid reestablishment of pre-storm patterns of chlorophyll biomass distributions seems to be common in estuarine systems. This recovery time generally takes from a few weeks to a few months depending on the magnitude of the storm. Within two months of Hurricane Agnes (June 1972), for example, the distribution of chlorophyll \( a \) in Chesapeake Bay had returned to the normal pattern with lower levels in the sound and higher levels in the mesohaline rivers leading into the sounds (Seliger and Loftus 1974). After Hurricane Fran (September 1996), there was a marked reduction in phytoplankton biomass in the Neuse River (<10 \( \mu g \) l\(^{-1} \)) for a four month period because high river discharge and flushing of the estuary in October and November precluded significant increases in biomass in the river (Pinckney et al. 1998).

Though this paper addresses the rapid response and recovery of the primary trophic level to a massive flooding event, no inferences should be made as to the recovery times for higher trophic levels. It should be emphasized that the timing of hurricanes may also greatly
affect the amount of damage to secondary trophic levels. Most hurricanes strike the east coast of the United States strike in September and October. At this time of the year water temperatures are beginning to drop and day length and sun angle are declining significantly. The reduced temperatures mean that the biological decomposition of organic matter is slowed relative to that in late July or August. Even though biological oxygen demand can cause anoxia in September and October, those demands would be even higher during the summer months (Paerl et al. 1998).

While not a single intense hurricane made landfall along the United States East Coast from 1966 through 1984 and low hurricane activity characterized the next decade, the period from the mid 1990s is described as “extremely active” (Landsea and Gray 1992; Landsea et al. 1996; Landsea et al. 1999). If predictions of more intense hurricane activity in the Atlantic are correct (Goldenberg et al. 2001), the characteristics of the response to extreme events (Scavia et al. 2002) and reestablishment of equilibrium conditions of large ecosystems like the Pamlico-Albemarle Sound will be critical to the trophic links that support fisheries in much of the Southeast United States.
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**SOURCE OF UNPUBLISHED MATERIALS**


Jimmie Overton, North Carolina Department of Environmental and Natural Resources, Division of Water Quality, Raleigh, North Carolina (personal communication).

Figure 1. Sampling stations plotted to show locations of shoals, inlets and barrier islands that affect the circulation patterns within Pamlico Sound. ▲ = routinely monitored stations; ○ = ancillary stations.

Figure 2. Relationship between extracted chlorophyll $a$ and laser induced fluorescence at 685 nm. ◆ = Sept-Oct 1999; ○ = Oct 2000.

Figure 3. Relationship between measured values of colored dissolved organic matter (CDOM) normalized to quinine sulfate (Hoge et al. 1993) and the laser induced fluorescence at 450 nm. ◆ = Sept-Oct 1999; ○ = Oct 2000.

Figure 4. Chlorophyll abundance and distribution in the Pamlico-Albemarle Sound system measured as laser induced fluorescence (LIF) at 685 nm. The LIF signal was normalized to chlorophyll using the regression equation $y=0.02x+0.26$, $r^2=0.63$ for data collected from 25 September to 31 October 1999. The LIF signal from the non-flood control over flight one year later (11 October 2000) was normalized to chlorophyll using $y=0.01x+0.12$, $r^2=0.76$. See Fig. 1 for locations of inlets.

Figure 5. Daily mean stream flow from September to December 1999 for the Neuse River at Kinston, North Carolina, Tar-Pamlico River at Tarboro, North Carolina, and combined mean daily stream flow from both the Neuse River and Tar-Pamlico Rivers. The passage of Hurricanes Dennis (24 August-5 September 1999), Floyd (16 September 1999) and Irene (17 October 1999) are marked. The timing of each of four the airborne sensor flights is indicted by OF1-OF14. Stream flow data are from the United States Geological Survey.

Figure 6. Chlorophyll biomass measured by NASA’s AOL3 fluorosensor laser induced fluorescence (LIF) at 685 nm as described in Fig. 4. The representative flight path was
plotted as an east-west transect across Pamlico Sound (77W to 75.60W). Chlorophyll *a* water samples used to calibrate the LIF signal were collected simultaneously with each over flight (25 September, 2 October, 15 October and 31 October 1999). On 11 October 2000, about year later, equivalent over flight and field data were collected to use for a non-flood comparison.

Figure 7. Colored dissolved organic matter (CDOM) abundance and distribution in the Pamlico-Albemarle Sound system measured as laser induced fluorescence (LIF) at 450 nm. The LIF signal was normalized to colored dissolved organic material (CDOM) using the regression equation $y=2128x+2483$, $r^2=0.31$ for data collected from 25 September to 31 October 1999 and 11 October 2000 as in Fig. 3. Pale blue is equivalent to the lowest relative CDOM and dark purple represents the highest CDOM. See Fig. 1 for locations of inlets.

Figure 8. Total suspended solids (TSS) from Pamlico Sound during the flood period (1999) and one year later (October 2000).

Figure 9. A. Field measurements of 1% surface light levels (photosynthetic active radiation PAR) at different concentration of colored dissolved organic matter (CDOM). Data are from both flood (1999) and non-flood (2000) years. B. Field measurements of chlorophyll *a* biomass measured at different concentrations of CDOM. Data are from flood (1999) and non-flood (2000) years.

Figure 10. Ocean color satellite scenes acquired by the Sea-Viewing Wide Field-of-View Sensor (SEAWiFS) carried by the OrbView-2 spacecraft representing the chlorophyll distribution and abundance in the Pamlico-Albemarle Sound. Imagery provided by NESDIS, NOAA, the Goddard Earth Sciences DAAC, NASA and Orbimage, Inc.
Figure 11. A comparison of pre- and post-flood chlorophyll $a$ values in the lower Neuse River and Pamlico Sound. (See Fig. 1 for station locations).
Tester et al. Fig. 2

\[ y = 0.02x + 0.26 \]
\[ R^2 = 0.63 \]

\[ y = 0.01x + 0.12 \]
\[ R^2 = 0.76 \]
Tester et al. Fig. 3

LIF at 450 nm

Relative CDOM

\[ y = 2128x + 2483 \]

\[ R^2 = 0.31 \]
Tester et al. Fig. 5

Streamflow (m³/s⁻¹)

- Neuse River at Kinston
- Tar River at Tarboro
- Kinston and Tarboro Combined


Floyd
Dennis
OF1
OF2
Irene
OF3
OF4
Tester et al. Fig 6
Fig. 7

Dates:
- 25 Sept 1999
- 2 Oct 1999
- 15 Oct 1999
- 31 Oct 1999
- 11 Oct 2000

Scale: 0 - 50 - 100 Kilometers
Tester et al. Fig. 8
Tester et al. Fig. 9

A

Depth of 1% Light Level (m)

y = -1.92x + 5.32
R² = 0.36

B

Chlorophyll a (µg l⁻¹)

y = -18.91x + 38.31
R² = 0.87
Tester et al. Fig. 10

[Image of a map comparing chlorophyll levels between 28 Oct 1999 and 6 Jan 2000, with a color scale indicating chlorophyll concentration (µg L⁻¹)].
Chlorophyll a (µg/l⁻¹)

- △ station 1
- ▲ station 2
- ■ station 3
- ◇ station 4
- ▼ station 5
- ○ all other Pamlico Sound stations
- □ all other Neuse River stations

Start of 1999 Hurricane Season

- Mar-97
- Sep-97
- Apr-98
- Nov-98
- Mar-99
- Jun-99
- Jul-99
- Aug-99
- Sep-99
- Oct-99
- Nov-99
- Dec-99
- Jan-00
- Jun-00
- Jul-00
- Aug-00
- Sep-00
- Oct-00
- Nov-00
- Dec-00
- Jan-01
- Feb-01
- Mar-01
- Apr-01
- May-01
- Jun-01