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# Nutrient limitation and algal blooms in urbanizing tidal creeks

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**Abstract**

Tidal creeks are commonly found in low energy systems on the East and Gulf Coasts of the United States, and are often subject to intense watershed human development. Many of these creeks are receiving urban and suburban runoff containing nutrients, among other pollutants. During the period 1993–2001, we studied three tidal creeks located in southeastern North Carolina, a rapidly urbanizing area. All three creeks received anthropogenic nutrient loading. Oligohaline to mesohaline stations in upper tidal creek regions had much higher nutrient (especially nitrate–N) concentrations than lower creek areas, and hosted spring and summer phytoplankton blooms that at times exceeded 200 μg chlorophyll *a* $l^{-1}$. Phytoplankton biomass during winter was low at all stations in all three creeks. Spring and summer nutrient addition bioassay experiments were conducted to characterize the nutrients limiting phytoplankton growth. Water from high salinity stations in all three creeks always showed significant positive responses to nitrate–N inputs, even at concentrations as low as 50 μg N $l^{-1}$. Low salinity stations in upper creek areas often showed significant responses to nitrate–N inputs, but on occasion showed sensitivity to phosphorus inputs as well, indicating the influence of anthropogenic nitrate loading. During several experiments, one of the upper stations showed no positive response to nutrient inputs, indicating that these stretches were nutrient replete, and further phytoplankton growth appeared to be light-limited either by phytoplankton self-shading or turbidity. Water from upper creek areas yielded much higher chlorophyll *a* concentrations in bioassay experiments than did lower creek water. In general, these urbanizing tidal creeks were shown to be very sensitive to nitrogen loading, and provide a physical environment conducive to phytoplankton bloom formation in nutrient-enriched areas. Tidal creeks are important ecological resources in that they are considered to be nursery areas for many species of fish and shellfish. To

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protect the ecological function of these small, but very abundant estuarine systems, management efforts should recognize their susceptibility to algal blooms and focus on control of nonpoint source nutrient inputs, especially nitrogen.


*Keywords:* Tidal creeks; Phytoplankton; Nitrogen; Nutrient limitation

## 1. Introduction

Tidal creeks are extremely abundant estuarine systems that are most commonly found in low energy systems such as the backside of major sounds, or as tributaries to larger riverine estuaries or other protected estuarine systems such as the Atlantic Intracoastal Waterway. They are most common along the Atlantic Coast from Delaware through Florida, and in the Gulf Coast region. Tidal creeks are important ecologically for materials transfer from the terrestrial to the marine biome, as habitat to numerous mammals and birds, and as fisheries primary nursery areas. They also serve as rich sport and commercial finfish and shellfisheries. Their aesthetic beauty, however, makes them prime locations for human development.

Human development of these creeks can range from very low, such as the relatively pristine tidal creeks of North Inlet, SC (Wolaver et al., 1984; Lewitus et al., 1998) to heavily industrialized, as some estuarine creeks are near Charleston, SC (Lerberg et al., 2000). Many tidal creeks in the southeastern United States are either heavily urbanized by housing, marinas, and golf courses, or are presently undergoing a change from near pristine to urbanization. This trend is exemplified in southeastern North Carolina, which has undergone rapid population increase in recent years (Mallin et al., 2000a).

Development brings with it strong potential for pollution inputs of many kinds, including nutrients (nitrogen and phosphorus). Nutrient inputs into estuarine systems can lead to algal blooms with the consequent potential for hypoxia (Rabalais, 2002), and increases in blooms of potentially toxic algal species (Burkholder, 1998). The tidal creeks in southeastern North Carolina are showing susceptibility to algal bloom formation (Mallin et al., 1999a, 2000a). In order to protect the ecological function of tidal creeks, it is important to determine their susceptibility to nutrient loading, and obtain evidence of what nutrient(s) limit the growth of phytoplankton. While there have been many nutrient limitation studies conducted on water from large estuarine systems (Howarth, 1988; Rudek et al., 1991; Doering et al., 1995; Mallin et al., 1999b) studies of limiting nutrients on these small, but abundant tidal creek systems have been rare (Lewitus et al., 1998). Once evidence of nutrient sensitivity of a tidal creek can be demonstrated, then corrective or at least protective management actions can be taken.

The objectives of this research were to assess the temporal and spatial variability in nutrient and phytoplankton biomass for a system of tidal creeks in various stages of human development, and to experimentally determine what nutrients limit phytoplankton production in areas of different salinity in selected creeks.

## 2. Methods

### 2.1. Site description

We studied three creeks located in New Hanover County, southeastern North Carolina. Salinities in the three creeks range from freshwater in first-order tributaries (about 4 km upstream) to full-strength salinities at the outflow into the U.S. Atlantic Intracoastal Waterway (ICW—Fig. 1). Futch Creek is a second-order stream with comparatively low human development (about 11% impervious surface watershed coverage), located at 34°18′ N latitude and 77°55′ W longitude. Howe Creek is a second-order stream with 14% watershed imperious surface coverage located at 34°15′ N latitude and 77°47′ W longitude. Hewletts Creek is a third-order stream with about 21% watershed impervious surface coverage located at 34°11′ N latitude and 77°50′ W longitude. The lower creek areas are characterized by sandy sediments interspersed with oyster (*Crassostrea virginica*) reefs and salt marsh (mainly *Spartina alterniflora*) vegetation. The upper reaches are characterized by muddy channels and oligohaline (mainly *Juncus roemerianus*) vegetation. Between five and eight stations per creek were sampled during the period 1993–2001; discussion will be limited in this paper to four stations per creek representing a

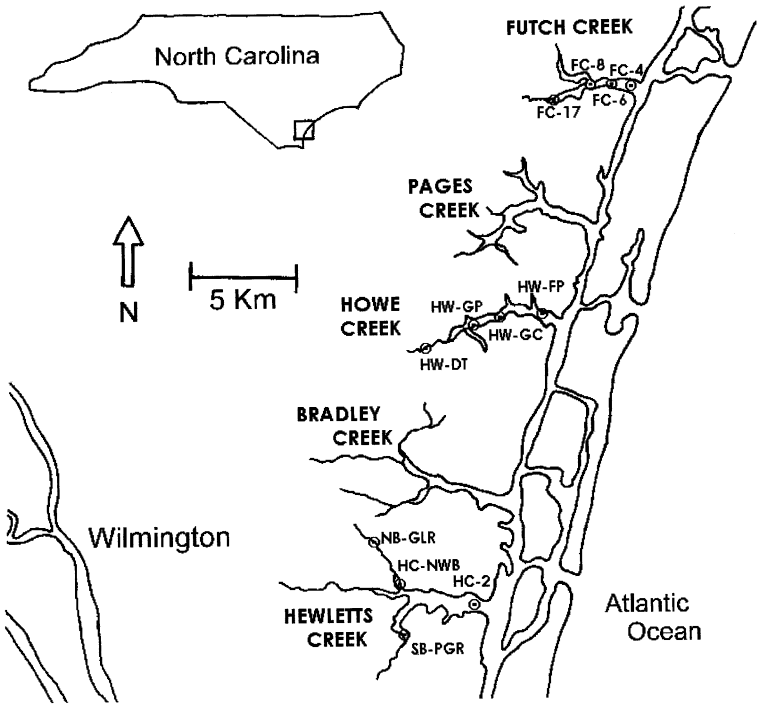


Fig. 1. Map of the tidal creek complex in New Hanover County, North Carolina, USA.

Table 1
Nutrient (mg $l^{-1}$) and chlorophyll *a* (μg $l^{-1}$) concentrations as mean and range for different salinity zones collected at high tide for Futch Creek, North Carolina, 1993–2001

| Station | Salinity | $NO_x$ | $NH_4$ | $PO_4$ | N/P | Chl *a* |
|---|---|---|---|---|---|---|
| FC-4 | 32.9 | 0.006 | 0.020 | 0.004 | 11.2 | 1.8 |
| | 24.6–36.5 | 0.001–0.035 | 0.001–0.139 | 0.001–0.011 | 1–37 | 0.2–6.7 |
| FC-8 | 30.2 | 0.018 | NA | 0.005 | NA | 2.3 |
| | 15.4–36.1 | 0.001–0.200 | | 0.001–0.021 | | 0.2–11.0 |
| FC-13 | 25.5 | 0.061 | NA | 0.008 | NA | 5.1 |
| | 13.9–34.7 | 0.001–0.268 | | 0.001–0.165 | | 0.2–27.0 |
| FC-17 | 20.9 | 0.139 | 0.024 | 0.013 | 36.1 | 8.1 |
| | 1.2–33.8 | 0.004–0.846 | 0.001–0.067 | 0.001–0.233 | 6–304 | 1.0–106.0 |

salinity range from oligohaline to euhaline (Table 1). Most of the 12 stations were sampled monthly for 6 or 7 years, except for HC-NWB (2 years) and HW-DT (3 years). At high tide, depths at the stations nearest the ICW were up to 2.5 m; high tide depths at upper stations were as low as 1.0 m. Tidal range in this region is about 1.1 m (Dame et al., 2000). These three creeks do not receive point source nutrient inputs, but are subject to considerable nonpoint source anthropogenic runoff, particularly in upper Howe and Hewletts Creeks. Futch Creek receives little nutrient runoff, but receives groundwater inputs of nitrate by small springs in several locations. A 2001 monthly survey indicated that the nitrate concentration in this spring water is usually between 0.5 and 1.0 mg N $l^{-1}$, but at times can exceed 10 mg N $l^{-1}$, which may originate from fertilization of a golf course located upstream of the prevailing groundwater movement (Roberts 2002).

## 3. Field sampling and laboratory methods

Sampling was conducted monthly from August 1993 through July 2001, at or near high tide. Field parameters (water temperature, pH, dissolved oxygen, turbidity, salinity, and conductivity) were measured at each site using a YSI 6920 Multiparameter Water Quality Probe (sonde) linked to a YSI 610D display unit. YSI Model 85 and 55 dissolved oxygen

Table 2
Nutrient (mg $l^{-1}$) and chlorophyll *a* (μg $l^{-1}$) concentrations as mean and range for different salinity zones collected at high tide for Howe Creek, North Carolina, 1993–2001

| Station | Salinity | $NO_x$ | $NH_4$ | $PO_4$ | N/P | Chl *a* |
|---|---|---|---|---|---|---|
| HW-FP | 32.7 | 0.004 | 0.017 | 0.005 | 10.8 | 2.4 |
| | 7.2–37.0 | 0.001–0.023 | 0.001–0.072 | 0.001–0.019 | 1–31 | 0.2–13.0 |
| HW-GC | 28.3 | 0.012 | NA | 0.006 | NA | 4.0 |
| | 8.7–35.7 | 0.001–0.143 | | 0.001–0.035 | | 0.4–62.0 |
| HW-GP | 15.4 | 0.012 | 0.034 | 0.008 | 18.2 | 12.6 |
| | 0.2–33.7 | 0.001–0.143 | 0.001–0.135 | 0.001–0.088 | 1–47 | 0.5–88.0 |
| HW-DT | 3.5 | 0.057 | 0.036 | 0.010 | 23.7 | 31.3 |
| | 0.1–12.4 | 0.001–0.190 | 0.010–0.089 | 0.001–0.042 | 2–40 | 1.0–208.0 |

Table 3
Nutrient (mg $l^{-1}$) and chlorophyll *a* (μg $l^{-1}$) concentrations as mean and range for different salinity zones collected at high tide for Hewletts Creek, North Carolina, 1993–2001

| Station | Salinity | $NO_x$ | $NH_4$ | $PO_4$ | N/P | Chl *a* |
|---|---|---|---|---|---|---|
| HC-2 | 31.6 | 0.008 | 0.016 | 0.005 | 11.2 | 2.2 |
| | 6.7–37.0 | 0.001–0.049 | 0.001–0.077 | 0.001–0.014 | 1–42 | 0.1–10.0 |
| HC-NWB | 21.9 | 0.062 | NA | 0.008 | NA | 4.5 |
| | 0.5–35.1 | 0.006–0.247 | | 0.001–0.025 | | 0.3–22.0 |
| SB-PGR | 15.7 | 0.107 | 0.038 | 0.009 | 22.9 | 16.1 |
| | 0.3–35.2 | 0.001–0.698 | 0.001–0.117 | 0.001–0.038 | 6–86 | 2.0–204.0 |
| NB-GLR | 9.9 | 0.105 | 0.047 | 0.014 | 57.9 | 14.3 |
| | 0.1–33.4 | 0.001–0.582 | 0.001–0.138 | 0.001–0.058 | 2–1189 | 1.0–159.0 |

meters were also used on occasion. The instruments were calibrated prior to each sampling trip to ensure accurate measurements. The light attenuation coefficient *k* was determined from data collected on site using vertical profiles obtained by a Li-Cor LI-1000 integrator interfaced with a Li-Cor LI-193S spherical quantum sensor.

For nitrate + nitrite (hereafter referred to as nitrate) and orthophosphate assessment, three replicate acid-washed 125-ml bottles were placed ca. 10 cm below the surface, rinsed, filled, capped, and stored on ice until processing. In the laboratory, the triplicate samples were filtered simultaneously through 25-mm Gelman A/E glass fiber filters (nominal pore size 1.0 μm) using a manifold with three funnels. The pooled filtrate was stored frozen until analysis. Nitrate + nitrite and orthophosphate were analyzed using a Technicon AutoAn-

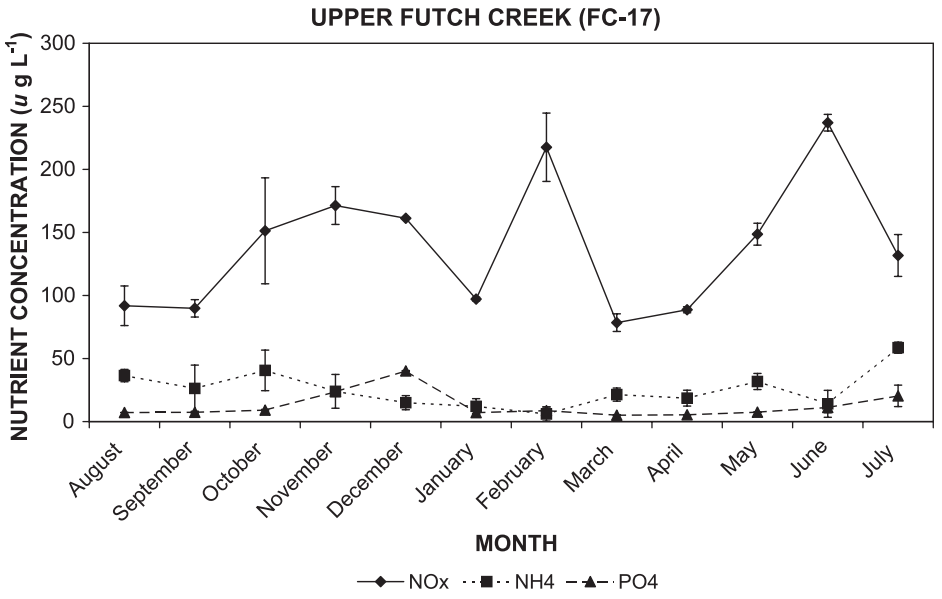


Fig. 2. Average nutrient concentrations at upper Futch Creek station FC-17, 1993–2001.

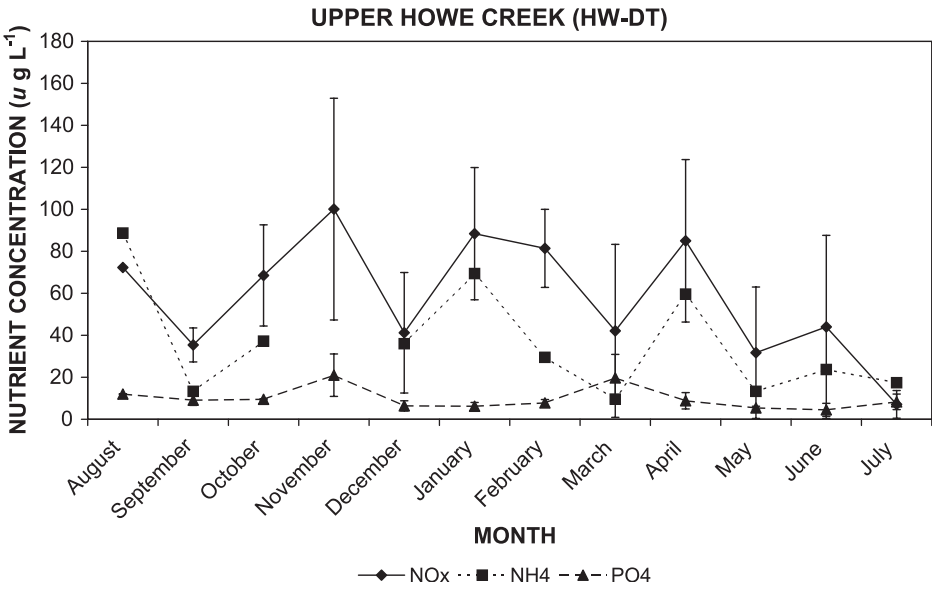


Fig. 3. Average nutrient concentrations at upper Howe Creek station HW-DT, 1993–2001.

alyzer following EPA protocols. Samples for ammonium were collected in duplicate, field-preserved with phenol, stored on ice, and analyzed in the laboratory according to the methods of Parsons et al. (1984). Ammonium sampling began in late 1998.

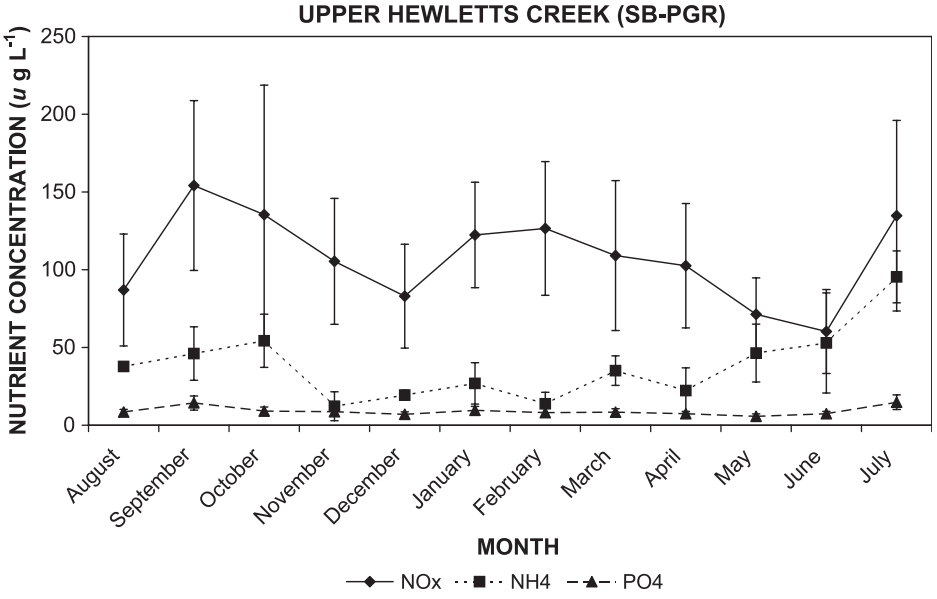


Fig. 4. Average nutrient concentrations at upper Hewletts Creek station SB-PGR, 1993–2001.

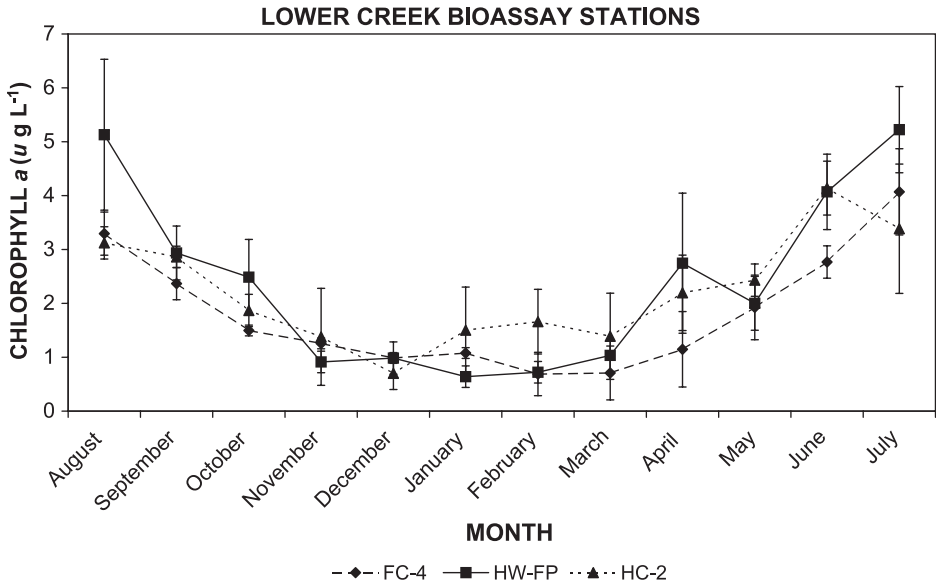


Fig. 5. Average chlorophyll *a* concentrations at lower bioassay stations in Futch, Howe, and Hewletts Creeks, 1993–2001.

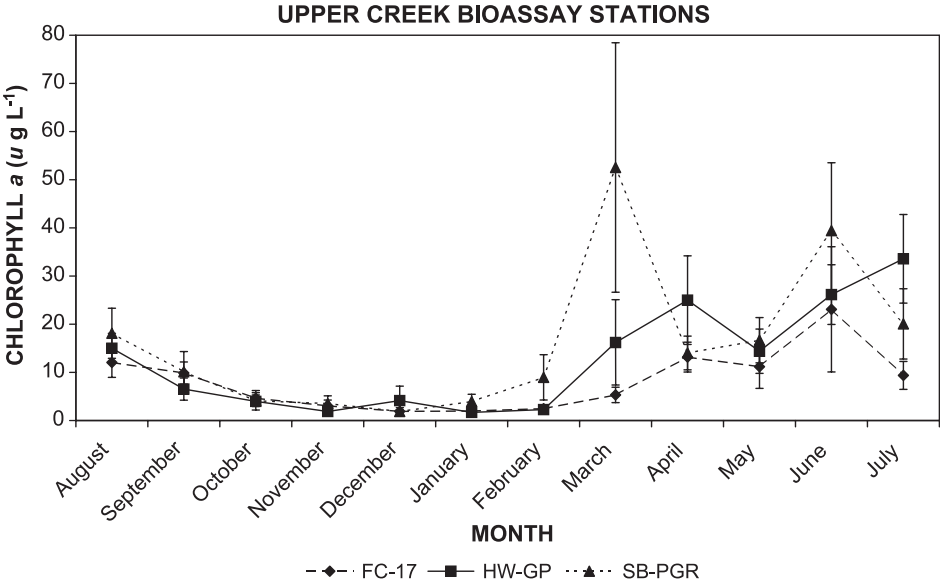


Fig. 6. Average chlorophyll *a* concentrations at upper bioassay stations in Futch, Howe, and Hewletts Creeks, 1993–2001.

Table 4
Results of correlation analyses among physical, chemical, and biological parameters for Futch Creek, all stations combined

| | Nitrate | Ammonium | Orthophosphate | Chlorophyll *a* | DO |
|---|---|---|---|---|---|
| Salinity | − 0.537 | − 0.218 | − 0.145 | − 0.291 | ns |
| | 0.0001 | 0.0308 | 0.0001 | 0.0001 | |
| | 510 | 98 | 598 | 615 | |
| Temperature | ns | 0.415 | − 0.084 | 0.349 | − 0.709 |
| | | 0.0001 | 0.0387 | 0.0001 | 0.0001 |
| | | 98 | 597 | 614 | 606 |

Presented as correlation coefficient (*r*)/probability (*p*)/*n*.
ns = nonsignificant at $a = 0.05$.

Chlorophyll *a* concentrations were determined from the filters used for filtering samples for nitrate + nitrite and orthophosphate analyses. All filters were wrapped individually in aluminum foil, placed in an airtight container with dessicant and stored in a freezer. During the analytical process, the glass fiber filters were separately immersed in 10 ml of a 90% acetone solution. The acetone was allowed to extract the chlorophyll from the material for 18–24 h. The extracted material was then analyzed for chlorophyll *a* concentration using a Turner AU-10 fluorometer. This method uses an optimal combination of excitation and emission bandwidths that reduces the errors inherent in the acidification technique (Welschmeyer, 1994). Correlation analyses were run among physical and chemical parameters using SAS (Schlotzhauer and Littell, 1987).

## 4. Nutrient addition bioassays

We used nutrient addition bioassays to test the hypothesis that nitrogen was the principal nutrient limiting phytoplankton growth in these tidal creeks. The basis of these experiments was to add the experimental nutrient(s) to replicated creek water samples and determine if the planktonic communities in the samples showed a positive response (i.e. a chlorophyll increase). A replicated set of control samples (no nutrient additions) was incubated to serve as a baseline. The experimental design was as follows. Water was collected on site in 25-l carboys, returned to the laboratory, and dispensed into 4-l cubitainers (3 l per cubitainer).

Table 5
Results of correlation analyses among physical, chemical, and biological parameters for Howe Creek, all stations combined

| | Nitrate | Ammonium | Orthophosphate | Chlorophyll *a* | DO |
|---|---|---|---|---|---|
| Salinity | − 0.446 | − 0.431 | − 0.272 | − 0.422 | ns |
| | 0.0001 | 0.0001 | 0.0001 | 0.0001 | |
| | 355 | 77 | 353 | 359 | |
| Temperature | − 0.237 | ns | ns | 0.233 | − 0.630 |
| | 0.0001 | | | 0.0001 | 0.0001 |
| | 354 | | | 357 | 357 |

Presented as correlation coefficient (*r*)/probability (*p*)/*n*.
ns = nonsignificant at $a = 0.05$.

Table 6
Results of correlation analyses among physical, chemical, and biological parameters for Hewletts Creek, all stations combined

| | Nitrate | Ammonium | Orthophosphate | Chlorophyll *a* | DO |
|---|---|---|---|---|---|
| Salinity | – 0.603 | – 0.433 | – 0.588 | – 0.347 | – 0.108 |
| | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0496 |
| | 352 | 122 | 358 | 377 | 329 |
| Temperature | ns | ns | 0.139 | 0.205 | – 0.569 |
| | | | 0.0091 | 0.0001 | 0.0001 |
| | | | 354 | 373 | 329 |

Presented as correlation coefficient (*r*)/probability (*p*)/*n*.
ns = nonsignificant at $a = 0.05$.

Nutrient treatments (expressed as final concentration) were added as follows: inorganic phosphate as 25 or 50 μg $l^{-1}$ (1.6 or 3.2 μM as P), nitrate as 50 and 100 μg $l^{-1}$ (3.5 or 7.1 μM as N), and a control of no additions. All treatments were conducted in triplicate. Nutrient addition bioassays were run using Futch Creek water from stations FC-4 and FC-17 in May, June, and July 1999; using Hewletts Creek water from stations HC-2 and SB-PGR in February, March, April, June, July, and August 1998, and using Howe Creek water from stations HW-FP and HW-GP in May, June, and July 1999. An additional Howe Creek bioassay was run in February 1999 using the following treatments; nitrate at 100 μg N $l^{-1}$, orthophosphate at 50 μg-P $l^{-1}$, and an N + P combination using the same concentrations.

Cubitainers were floated on flow-through pools, with the cubitainers covered by two layers of neutral density screening to pass about 30% of incident solar radiation to prevent photostress to the phytoplankton. The cubitainers were kept in motion by constant circular agitation of the pool water using a submerged bilge pump, which kept the phytoplankton

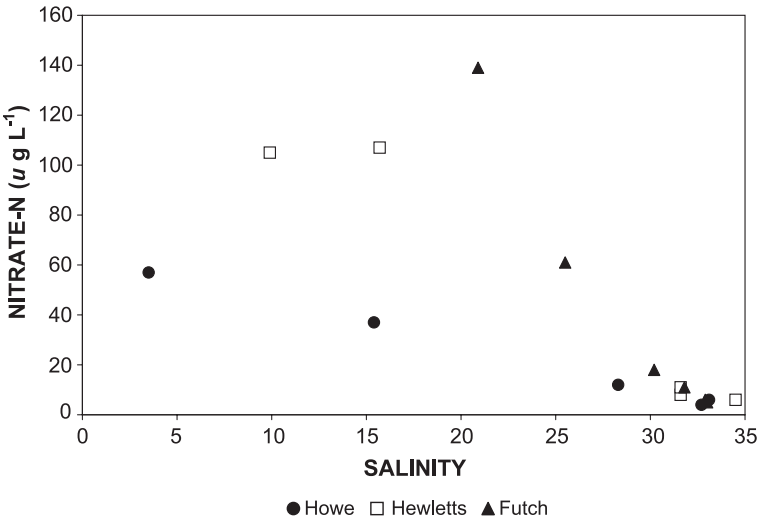


Fig. 7. Average nitrate–N concentrations versus salinity for the sampling stations in Futch, Howe, and Hewletts Creeks, 1993–2001.

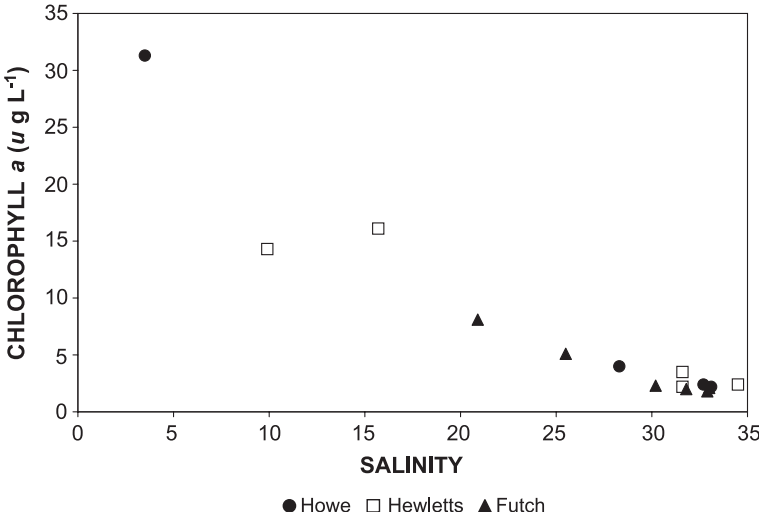


Fig. 8. Average chlorophyll *a* concentrations versus salinity for the sampling stations in Futch, Howe, and Hewletts Creeks, 1993–2001.

and turbidity particles suspended. The cubitainers were incubated for 3 days and sampled daily for chlorophyll *a* content. Filtrations for subsamples were conducted using Gelman A/E filters, as previously described.

Statistical analyses of nutrient limitation test results were performed using the SAS procedure of analysis of variance (ANOVA). The means of days 1–3 were computed for chlorophyll yields, and compared for each experiment using ANOVA. If there was a

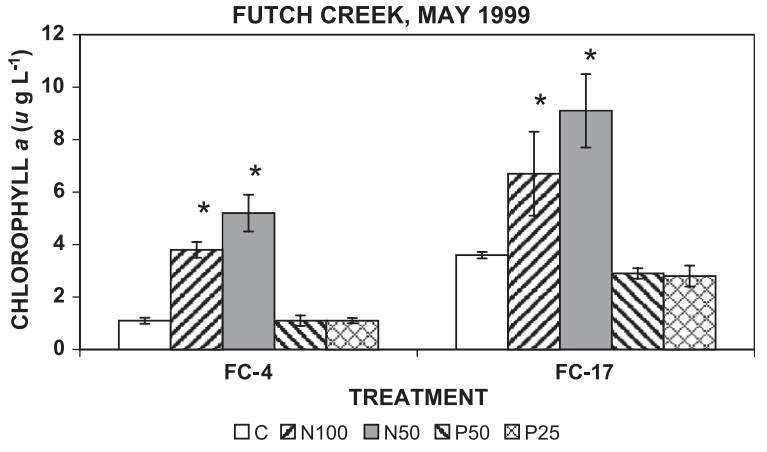


Fig. 9. Results of nutrient addition bioassay experiments for Futch Creek lower (FC-4) and upper (FC-17) stations, May 1999. Response is 3-day chlorophyll *a* average ± one standard error. * indicates significantly greater than control, $p < 0.05$.

significant difference ($p < 0.05$) among the response means of the various nutrient treatments and controls, the ANOVA test was followed by treatment ranking by Fisher's least significant difference procedure (Day and Quinn, 1989; Rudek et al., 1991).

## 5. Results

### 5.1. Distribution of nutrients and chlorophyll

At all three creeks, average nitrate concentrations decreased over 90% from the upper sites to the sites nearest the ICW (Tables 1–3). Ammonium decreases from upper to lower sites were much less, ranging from 17% at Futch Creek to 66% at Hewletts Creek. Orthophosphate decreases from upper to lower sites ranged from 50% to 69% in the three

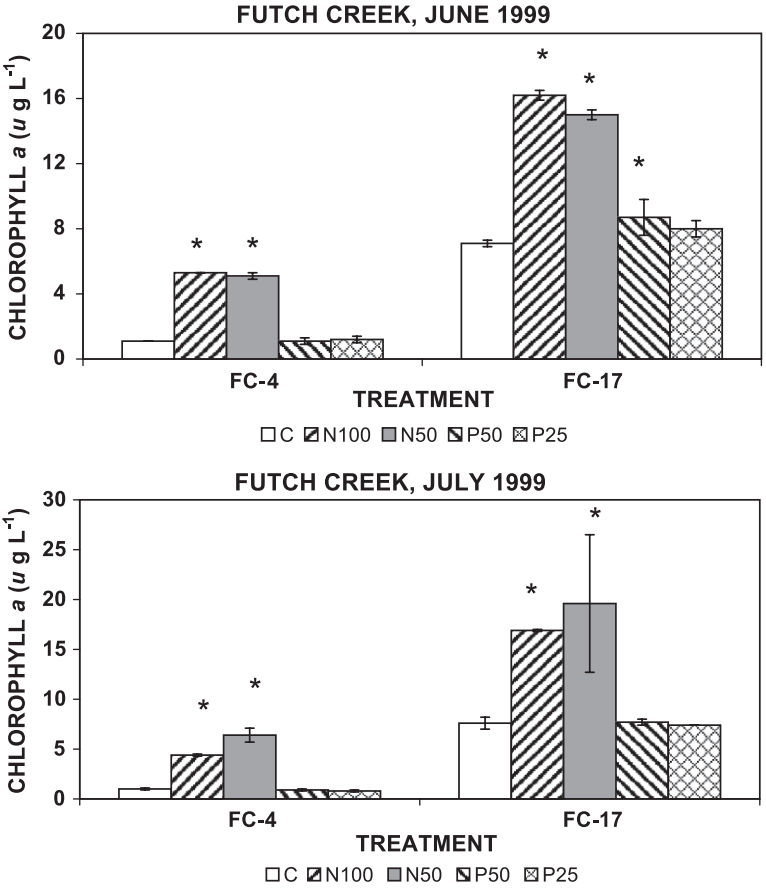


Fig. 10. Results of nutrient addition bioassay experiments for Futch Creek lower (FC-4) and upper (FC-17) stations, June and July 1999. Response is 3-day chlorophyll *a* average ± one standard error. * indicates significantly greater than control, $p < 0.05$.

creeks. Nitrate concentrations were generally highest in Futch Creek, followed by Hewletts and Howe Creeks, respectively. Average orthophosphate concentrations did not exceed 0.014 mg $l^{-1}$, and varied little among the three creeks. As a result, inorganic molar N:P ratios in upper creek areas were higher in Hewletts and Futch Creeks than in Howe Creek. N:P ratios were similar among the euhaline sites of all three creeks (Tables 1–3). There appeared to be little seasonal influence over nutrient loading to these tidal creeks. The dominant inorganic nitrogen form was nitrate, which showed no temporal pattern in the uppermost creek stations (Figs. 2–4). Ammonium showed no seasonal pattern in Howe Creek (Fig. 3) but did show greater summer concentrations in Futch and Hewletts Creeks (Figs. 2 and 4). Phosphate showed no apparent seasonal patterns in the upper creek stations (Figs. 2–4).

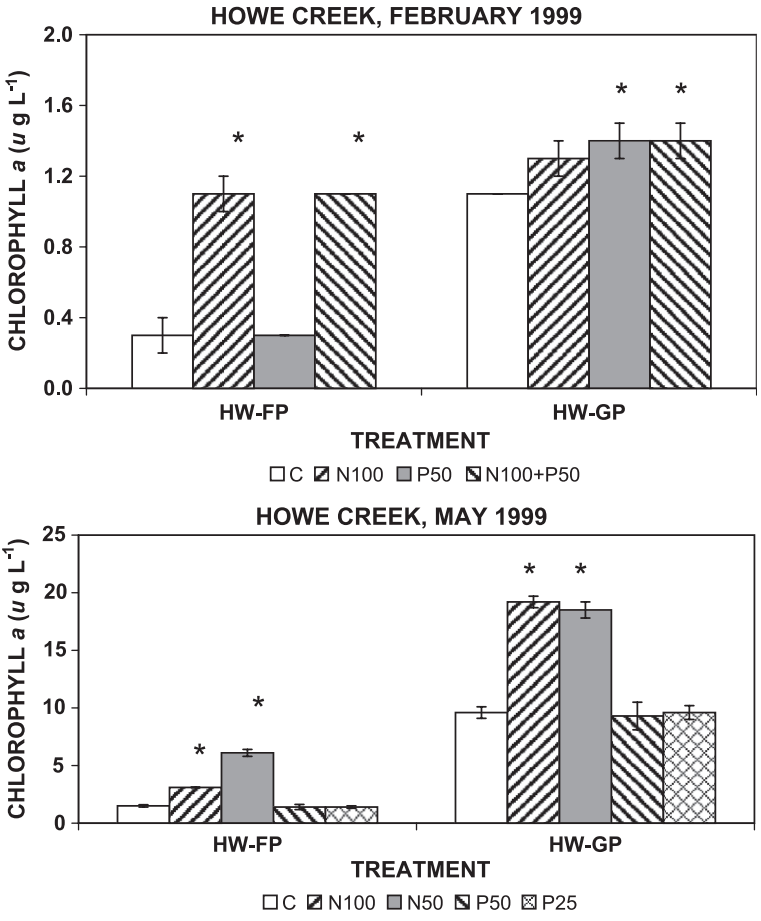


Fig. 11. Results of nutrient addition bioassay experiments for Howe Creek lower (HW-FP) and upper (HW-GP) stations, February and May 1999. Response is 3-day chlorophyll *a* average ± one standard error. * indicates significantly greater than control, $p < 0.05$.

The state of North Carolina has a legal water quality (algal bloom) standard of 40 μg chlorophyll *a* $l^{-1}$ to indicate impaired waters (NCDEHNR, 1996). All three creeks expressed phytoplankton blooms in excess of 40 μg $l^{-1}$ of chlorophyll *a* at times, although this occurred only once in Futch Creek (Tables 1–3). These blooms normally occurred in oligohaline or mesohaline sites, and rarely occurred at locations with average salinities exceeding 20. On occasion, both Hewletts and Howe Creeks hosted blooms exceeding 200 μg $l^{-1}$ of chlorophyll *a* (Tables 2 and 3). Blooms mainly occurred in spring or summer, and winter chlorophyll *a* concentrations were usually below 5 μg $l^{-1}$ chlorophyll *a* at all sites in all three creeks. On average, phytoplankton biomass was greatest in upper Howe and Hewletts Creeks, and blooms were most frequent at stations HW-DT in Howe Creek (9 out of 24 samples), and SB-PGR in Hewletts Creek (7 out of 84 samples). The lower bioassay stations in all three creeks displayed a clear temporal pattern of highest

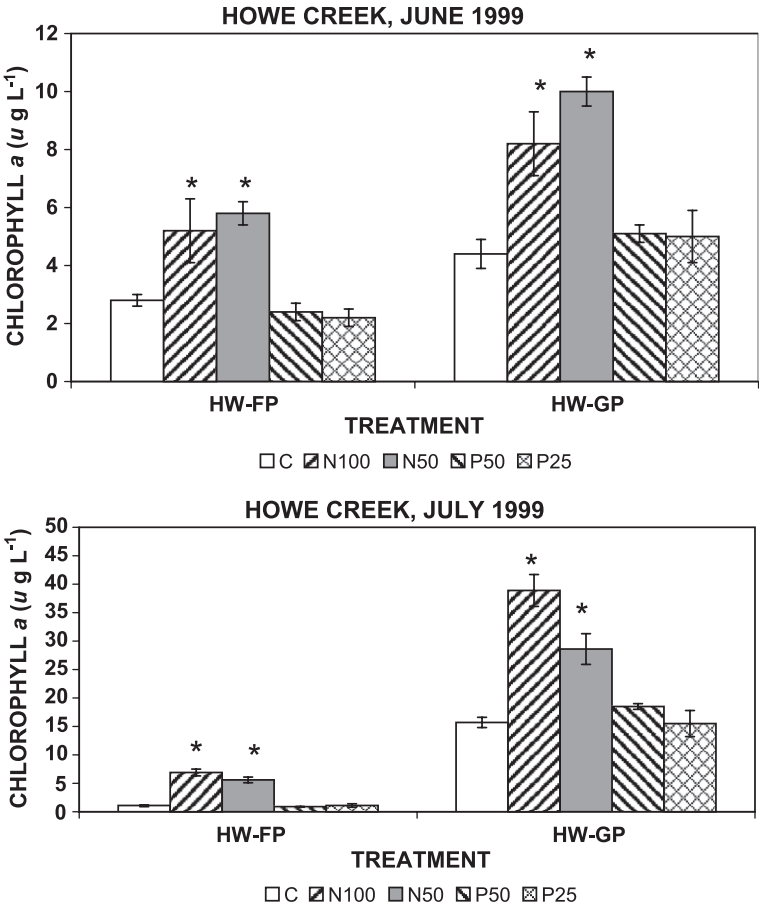


Fig. 12. Results of nutrient addition bioassay experiments for Howe Creek lower (HW-FP) and upper (HW-GP) stations, June and July 1999. Response is 3-day chlorophyll *a* average ± one standard error. * indicates significantly greater than control, $p < 0.05$.

chlorophyll *a* concentrations June–September and lowest concentrations November–March (Fig. 5). The upper bioassay stations (Fig. 6) maintained lowest concentrations October–February, but displayed substantial blooms in spring as well as during summer.

In all three creeks there were significant, moderate to strong inverse relationships between salinity and nutrient concentrations, particularly with nitrate (Tables 4–6). Whereas nitrate–N concentrations differed considerably among the three creeks in the upper stations, concentrations were very similar among creeks at the lower estuary stations (Fig. 7). There wee weak to moderate inverse relationships between ammonium and salinity (Tables 4–6). With the exception of Hewletts Creek (Table 6), orthophosphate showed only a weak inverse correlation with salinity. Chlorophyll *a* concentrations were also inversely related to salinity, with the strength of the correlation varying according to creek. Chlorophyll *a* concentrations at the mouths of all three creeks were similar (Fig. 8). Water temperature showed a weak to moderate positive correlation with chlorophyll *a*, and was positively correlated with ammonium in Futch Creek.

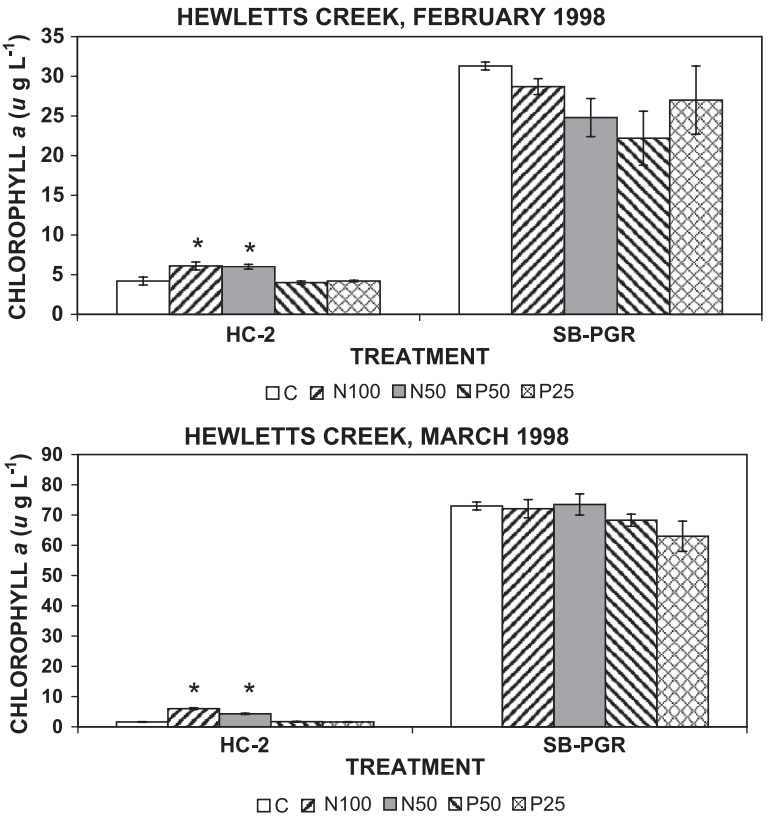


Fig. 13. Results of nutrient addition bioassay experiments for Hewletts Creek lower (HC-2) and upper (SB-PGR) stations, February and March 1998. Response is 3-day chlorophyll *a* average ± one standard error. * indicates significantly greater than control, $p < 0.05$.

Hypoxic dissolved oxygen conditions ($<4.0$ mg $l^{-1}$) were periodically seen in all three creeks, mainly during summer and in mid to upper creek areas. Dissolved oxygen concentrations were negatively correlated with water temperature in all three creeks (Tables 4–6). Average light attenuation values $k$ $m^{-1}$ were 0.9 at FC-4, 1.7 at FC-17, 0.6 at HC-2, 2.8 at SB-PGR, 0.7 at HW-FP, and 2.0 at HW-GP.

### 5.2. Nutrient addition bioassays

The lower creek areas nearest the ICW showed positive responses to nitrogen additions during all experiments for Futch Creek (Figs. 9 and 10), Howe Creek (Figs. 11 and 12), and Hewletts Creek (Figs. 13–15). Both the 50 and 100 μg N $l^{-1}$ treatments were significantly greater than control. The lower creek 3-day average chlorophyll *a* responses ranged from two to four times the control concentrations, although average responses were all less than 15 μg $l^{-1}$ and usually less than 10 μg $l^{-1}$ as chlorophyll *a* (Figs. 9–15).

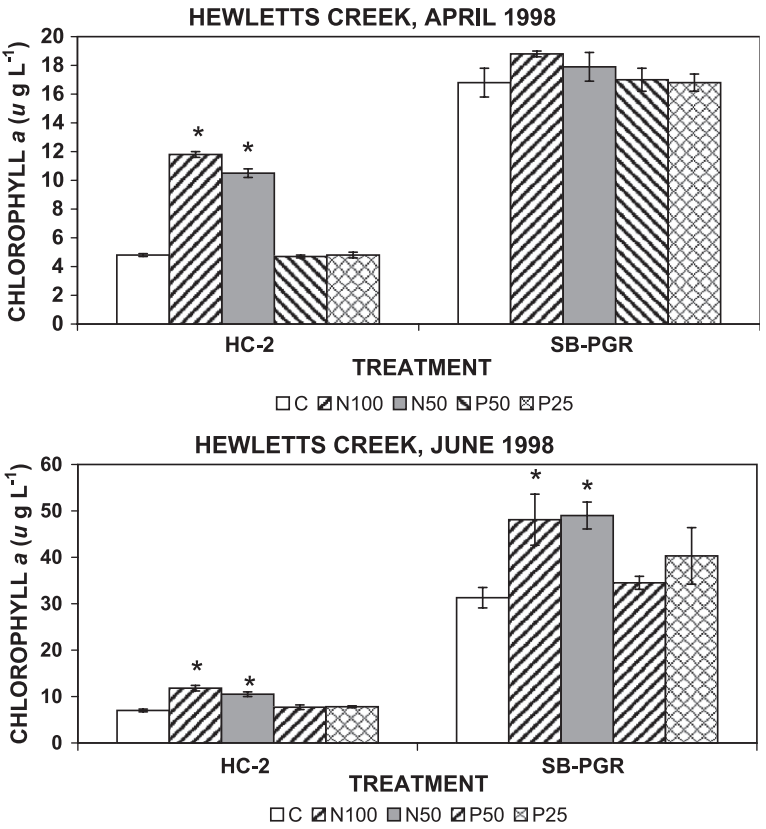


Fig. 14. Results of nutrient addition bioassay experiments for Hewletts Creek lower (HC-2) and upper (SB-PGR) stations, April and June 1998. Response is 3-day chlorophyll *a* average ± one standard error. * indicates significantly greater than control, $p<0.05$.

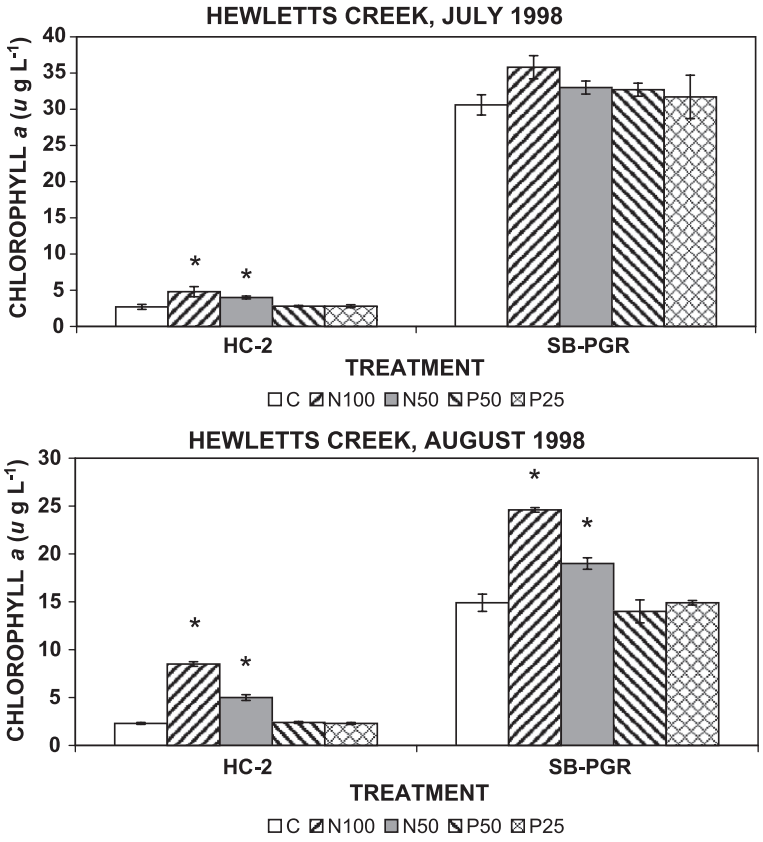


Fig. 15. Results of nutrient addition bioassay experiments for Hewletts Creek lower (HC-2) and upper (SB-PGR) stations, July and August 1998. Response is 3-day chlorophyll *a* average ± one standard error. * indicates significantly greater than control, $p < 0.05$.

Water from the upper stations often showed significant positive responses to both nitrogen addition treatments, except for the February, March, April, and July Hewletts Creek experiments, in which none of the treatments showed significant yield over control (Figs. 13–15). Also, the June Futch Creek and February Howe Creek experiments showed significant positive response to the 50 μg $l^{-1}$ phosphorus treatment in addition to the nitrogen responses (Figs. 10 and 11). Average chlorophyll *a* yield for the upper stations ranged up to 2.5 × that of control.

The highest 3-day average chlorophyll *a* responses in the bioassays occurred in water from the upper stations in Howe Creek in July (40 μg $l^{-1}$), Futch Creek in July (20 μg $l^{-1}$), and Hewletts Creek in March (75 μg $l^{-1}$) and June (50 μg $l^{-1}$). In contrast, the lowest chlorophyll *a* yields occurred in Howe Creek in February at both the upper (1.4 μg $l^{-1}$) and lower (0.9 μg $l^{-1}$) stations. Thus, nitrogen limited phytoplankton growth at all times in the lower creek stations, and during most experiments at upper creek stations. Chlorophyll *a* yield in the bioassays was usually much higher in water from the upper creek stations than

the lower creek stations, but on several occasions, summer chlorophyll *a* yield was no greater than spring yield.

## 6. Discussion

Nutrient sources to these tidal creeks are nonpoint in origin. The lower and middle creek areas have single family homes that front on the creek banks, and are thus subject to direct nutrient loading from runoff of fertilizers and pet manure. Upper Futch Creek has low-density development, but both upper Howe and Hewletts Creeks feature watersheds that drain heavily developed subdivisions and commercial areas. Lawn and garden fertilizers and pet manure are likely nutrient sources in these areas, and are transported to the tidal creeks through runoff ditches and storm drain systems. This area is largely sewered, and the existing septic systems are not known to be problematic in these areas. Two golf courses drain nutrients into Hewletts Creek with average nitrate–N concentration in these drainages of about 0.32 mg $l^{-1}$; one golf course drains into Howe Creek with average nitrate–N concentration in the drainage of about 0.10 mg $l^{-1}$ (Mallin and Wheeler, 2000). As mentioned, Futch Creek receives nitrate loading from groundwater springs, with the nitrate apparently originating from a golf course upslope of the creek (Roberts, 2002). These anthropogenic nutrient sources stand in contrast to tidal creeks in undeveloped North Inlet, where ammonium is the principal inorganic nitrogen compound, and it and phosphate are delivered to tidal creek water through sediment recycling, oyster reef regeneration, and woodland runoff (Wolaver et al., 1984; Lewitus et al., 1998). The average dissolved inorganic nitrogen (DIN) concentrations in the upper creek stations were below those of a sewage polluted tidal creek in North Carolina (Sanders and Kuenzler, 1979), and somewhat greater than a runoff polluted tidal canal in Hawaii (Laws et al., 1994). The DIN concentrations in the upper creeks (Fig. 7) were well above those of pristine North Inlet (Lewitus et al., 1998) and human-impacted canals in the Florida Keys (Lapointe and Clark, 1992), whereas the DIN concentrations in the lower tidal creek stations were similar to DIN levels in North Inlet and Florida Keys canals.

Upper, low salinity reaches of these tidal creeks provide good habitat for formation of algal blooms. Besides receiving anthropogenic nutrients, upper tidal creeks are often also areas where feeder streams and ditches emerge from woods or piped drainages into an open oligohaline marsh, thus exposing the nutrient-enriched water to abundant sunlight. Nitrate concentrations in the upper stations varied according to creek, but all reached similar low levels in waters with salinities >30 (Fig. 7), demonstrating the strong influence of conservative mixing with the low nutrient waters of the ICW. Recent research in Futch and Howe Creeks showed that both creeks exchange about 46% of their water over a tidal cycle, comparatively high rates of exchange for area tidal creeks (Hales 2001). Uptake by phytoplankton and marsh plants, and possibly denitrification in marsh sediments are also loss factors.

Chlorophyll *a* concentration plotted against salinity indicates that this relationship has fairly similar slopes among all three creeks (Fig. 8). This suggests that in areas with anthropogenic nutrient loading and similar low salinities, one can expect algal blooms to occur. Futch Creek had the highest salinities for upstream stations on average (Table 1;

Fig. 8). It is notable that the mouth of this creek was dredged several years ago, leading to considerably higher salinities in upstream areas (Mallin et al., 2000b).

Nonimpacted North Inlet's tidal creek system showed a strong seasonal chlorophyll *a* pattern of summer peaks, and low concentrations from October through May (Lewitus et al., 1998). The lower creeks stations in our urbanized system showed a similar seasonal pattern (Fig. 5), but the upper creek areas exhibited blooms during most periods except October–February, as well as much higher chlorophyll *a* levels than in the lower creeks (Table 1; Fig. 6).

Median inorganic N:P ratios in the uppermost stations were 21, 30, and 25 for Futch, Howe, and Hewletts Creeks, respectively. These ratios are greater than the Redfield ratio of 16, and show the potential for P limitation of phytoplankton growth in upper creek areas. However, N limitation was clearly predominant. N/P ratios in lower Futch Creek (FC-4) during the May, June, and July 1999 experiments were 19, 12, and 19, respectively, near the Redfield ratio. Nitrogen limited phytoplankton growth during all three of those experiments. During the four experiments in lower Howe Creek (HW-FP), N/P ratios remained below 7, and algal growth was experimentally N-limited. Since ammonium data were only collected beginning in late 1998, N/P ratios are not available for the Hewletts Creek experiments. In upper Futch Creek (FC-17), N/P ratios in May, June, and July were 148, 35, and 20, respectively. Despite these high N/P ratios, N stimulation was significant in all three experiments, although P stimulation was significant in June as well. In upper Howe Creek (HW-GP), P stimulation was significant rather than N in February, when the N/P ratio was 29. However, N stimulation was solely significant in June when the N/P ratio was 12 and in May, when the N/P ratio was 25 (ammonium data are not available for July at this location). Thus, the experimental data demonstrate that N/P ratios alone are not always useful in predicting the limiting nutrient in these creeks, and N/P ratios alone are insufficient data upon which to base management decisions for controlling algal blooms.

Nitrogen has been documented as the nutrient limiting phytoplankton growth in coastal marine and mesohaline waters in this region (Paerl et al., 1990; Rudek et al., 1991) and elsewhere (Howarth, 1988). In some estuaries, sensitivity to phosphorus inputs is believed to increase as one moves landward along the salinity gradient to oligohaline waters (Doering et al., 1995), as does the potential for phytoplankton limitation by light due to turbidity (Mallin et al., 1999b). These tidal creeks, while generally $<5$ km in length, appear to reflect in part some of these trends on a more limited spatial scale.

During four of the six upper Hewletts Creek experiments using water from SB-PGR, none of the nutrient additions yielded significantly greater chlorophyll *a* concentrations than the control (Figs. 13–15). Evidently, sufficient nutrients were available for growth, as relatively high chlorophyll *a* levels were attained in most of these experiments, and this station has hosted some of the largest and most frequent algal blooms. In pristine North Inlet microzooplankton grazing, rather than nutrients, limited phytoplankton (primarily picoplankton *Synechococcus* spp.) growth during summer, and nitrogen limited phytoplankton (mainly nanoplankton) during cooler months (Lewitus et al., 1998). While species identifications were not conducted during our bioassays, previous research in these creeks (Mallin et al., 1999a) showed a flora dominated by nanoplankton and net plankton (cryptomonads, diatoms, dinoflagellates, and chrysophytes), a community that during spring was limited by nutrients in North Inlet (Lewitus et al., 1998). It is likely that further

phytoplankton growth at SB-PGR was light-limited, either through self-shading by the phytoplankton itself, or possibly elevated turbidity from other sources. Station SB-PGR had by far the highest average light attenuation coefficient (2.8 $m^{-1}$) of any of the six test locations in our system, arguing for potential light limitation.

The year-round average chlorophyll *a* concentrations in upper Howe Creek (Table 2) exceed summer average chlorophyll *a* levels in polluted dead end estuarine canals in Delaware and Maryland (Maxted et al., 1997). Our chlorophyll *a* data were collected at or near high tide, and our previous research demonstrated that chlorophyll *a* biomass is usually much higher at the same location during low tide (Mallin et al., 1999a). Thus, the data in this paper are conservative, and blooms are likely much more frequent than what we report here. These blooms can also support undesirable grazers, as we have documented a cryptomonad bloom (13,600 cells $ml^{-1}$) in Hewletts Creek being grazed by large numbers (2600 $ml^{-1}$) of nontoxic *Pfiesteria* spp. zoospores (Mallin et al., 1999a).

## 7. Conclusions

Salt marsh tidal creeks and the marsh areas they drain are considered to be primary nursery habitat for many finfish and shellfish species (Hoss and Thayer, 1993; Beck et al., 2001). As such, a moderate amount of phytoplankton production is essential to support the food web leading to these tertiary producers. Tidal creeks can provide good habitat for algal bloom formation, provided that there is a supply of anthropogenically derived nutrients. However, algal blooms can lead to excess biochemical oxygen demand and contribute to hypoxia and anoxia (Rabalais, 2002), can support nondesirable algal species such as *Pfiesteria* (Glasgow et al., 2001), and can be legally indicative of impaired waters (NCDEHNR 1996). In these urbanizing tidal creeks, it appears that large creek areas are sensitive to nitrogen inputs, even at low levels. To avoid algal bloom formation, these nutrient-sensitive waters should be protected from anthropogenic nutrient, especially nitrogen, inputs. An assessment of regional golf courses showed that on-course management practices including use of detention ponds, wetland filters, small catchments, and vegetated streamside buffers help reduce anthropogenic nutrient loading to receiving waters (Mallin and Wheeler, 2000). These measures, along with building practices that emphasize use of green space as biofilters, should be made standard coastal development practices to protect sensitive estuarine creeks from eutrophication and other pollution problems.

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