A Brown Tide Bloom Index based on the potential harmful effects of the brown tide alga, *Aureococcus anophagefferens*

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Harmful algal blooms are an increasing phenomenon in coastal areas of the world. Recurring harmful brown tides caused by the minute alga, *Aureococcus anophagefferens*, are a chronic problem in the northeast Atlantic states of the United States. Brown tide blooms may cause significant ecological impacts on natural resources. A Brown Tide Bloom Index was developed based on published scientific studies and agency reports that relates concentrations of the brown tide organism to potential negative impacts on natural resources including shellfish, seagrasses and protozoa. For the first time, the index provides terminology that can be used to convey accurate information about impacts to natural resources resulting from concentrations of brown tide to scientists, environmental managers and the public. The purpose of the Brown Tide Bloom Index is to provide a metric, based on available scientific studies, which can be used by environmental managers to communicate the magnitude of brown tide blooms and impacts to natural resources. The Brown Tide Bloom Index includes three categories of brown tide blooms: Category 1 blooms (algal concentrations at \(<35,000 \text{ cells ml}^{-1}\)) have no reported impacts; Category 2 blooms (\(\geq 35,000 \text{ to } <200,000 \text{ cells ml}^{-1}\)) have potential negative impacts on feeding and growth in shellfish; Category 3 blooms (\(\geq 200,000 \text{ cells ml}^{-1}\)), discolor the water a yellow-brown and may cause severe impacts and mortality on shellfish, reduction in seagrasses and planktonic organisms.

**Keywords:** harmful algal blooms, metric

**Introduction**

Harmful algal blooms are an increasing phenomenon in coastal areas of the world. Harmful brown tides caused by the minute (ca. 2–3 μm in diameter) pelagophycean algae, *Aureococcus anophagefferens*, are a chronic problem in the coastal bays in the northeast Atlantic region of the United States. Brown tide blooms, first observed in Narragansett Bay, RI and the non-contiguous coastal bays of Long Island, NY in 1985, caused massive damage to shellfish (Casper et al., 1987; Sieburth et al., 1988; Nuzzi and Waters, 1989). While these blooms did not recur in Narragansett Bay (Smayda and Borkman, 2000), they have chronically appeared in coastal bays of Long Island, NY. Since then brown tide has also been identified in Barnegat Bay, NJ (NJDEP, 1989, 1995, 1999; Casper et al., 1990; Nuzzi et al., 1996; Gastrich, 2000a, b, 2001; Gastrich et al., 2000, 2001), the coastal bays of Delaware (Humphries, 2001) and Maryland (Wazniak, 2001). The current southern extent of brown tide *Aureococcus anophagefferens* blooms in the U.S. is Chincoteague Bay, MD (Wazniak, 2001). Additionally, brown tides have been documented outside the
U.S. in South Africa during the 1990s (Probyn et al., 2001).

Brown tide blooms continue to be a recurring problem in the Northeast region and have been extensively monitored and studied in coastal Long Island bays, including Peconic Bay, Great South Bay, Moriches Bay and Shinnecock Bay, since the mid-1980s (Nuzzi, 2001). The states of New Jersey, Maryland and Delaware have only recently instituted monitoring programs and/or special studies to characterize the spatial and temporal extent of the brown tide blooms in their coastal embayments (Gastrich, 2001; Humphries, 2001; Waźniak, 2001). While these blooms are not reported to be harmful to bathers or consumers of shellfish, they can cause significant ecological impacts to shellfish and eelgrasses (Bricelj and Lonsdale, 1997).

Because of the regional nature of brown tide blooms, government agencies and scientists need to communicate with each other and the public regarding the status of blooms in the region as well as potential impacts. Previously, information about brown tide blooms has been qualitatively reported as “significant,” “major,” “moderate,” “small” and “low” blooms by various groups and individuals based upon different concentrations and/or different understandings of the impacts to natural resources. Hence, there is a need to have a consistent terminology used by agencies and scientists in reporting these blooms that is based on specific concentrations and impacts to natural resources.

Since the term Harmful Algal Blooms refers to algal blooms that either contain a toxin or have negative ecological impacts, a bloom index may be related to one or both of these impacts. When the toxin is known and well understood, a toxicological index can be defined based on the concentration of the toxin in the water or in fish tissue (Suter, 1993). For example, Cosper and Cerami (1996) developed a system for harmful algal blooms that used 15 categories and criteria that were mainly directed at human health concerns and not readily adaptable to brown tide blooms. Although the toxins associated with brown tide have not yet been defined, brown tide blooms can kill marine organisms. Therefore, an index based upon the ecological impacts is needed. Many times a bloom may be defined by the concentration at which the water turns a specific color versus the actual ecological impacts. Our objective is to describe a Brown Tide Bloom Index (BTBI) which will communicate information about the magnitude of brown tide blooms and their potential impacts on natural resources in a way that can be readily understood by scientists and environmental managers (Gastrich et al., 2001).

Methodology

Existing laboratory and field research studies that specifically related concentrations of the brown tide organism, *Aureococcus anophagefferens*, to negative ecological impacts were identified. The available data from studies fit into a three category continuum system which could be used to generally describe the magnitude of brown tide blooms based on concentrations and related ecological impacts.

In developing the BTBI, several assumptions were made: 1) the index addresses only the blooms caused by *Aureococcus anophagefferens* in the northeast states and does not apply to the Texas brown tides caused by *Aureoumbra lagunensis* or other brown alga (e.g., Suldanha Bay, S.A.); 2) appropriate methods were used to collect water samples and enumerate *Aureococcus anophagefferens* (e.g., Anderson et al., 1989, 1993; Caron, 2001; D.A. Caron et al., Univ. S. Calif, unpubl. data); 3) the index is not meant to be a toxicity index (e.g., it is not based upon an identified toxin and a concentration-response) although it assumes some level of toxicity to the organism; 4) the index does not predict impacts of specific concentrations of *Aureococcus anophagefferens* concentrations in natural populations but it does provide information on potential impacts and it is assumed that the increased concentrations and/or increased duration of blooms may potentially cause more severe impacts (e.g., dense shading of seagrasses); and 5) because the index categories are arbitrarily based on available scientific data and field observations, the use of the index is independent of differing monitoring designs; therefore, the highest observed *Aureococcus* concentrations should be used when applying the index.

Results

Table 1 summarizes potential ecological impacts to natural resources at different concentrations of *Aureococcus anophagefferens* into three general categories based upon scientific studies. Category 1 represents the lowest level of *Aureococcus* concentrations, <35,000 cells ml⁻¹, a concentration that scientific studies have shown produces no toxic effects on shellfish. As well, no other ecological impacts have been shown at this level. Juvenile *Mercenaria mercenaria* (hard clams) have been reported to maintain normal feeding
Table 1. Brown Tide Bloom Index: *Aureococcus anophagefferens*, cells ml⁻¹. Table is based on available scientific data; some of the available data may need to be reassessed through additional research; and there may be complex ecological interactions (e.g., trophic level interactions, presence of additional algal species, etc.) which may affect impacts which are not fully addressed in the table; Categories are relative and related to different threshold concentrations of brown tide.

<table>
<thead>
<tr>
<th>Cells ml⁻¹ (Category)</th>
<th>Potential Impact</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;35,000</td>
<td>• <strong>Shellfish</strong>: no known impact on <em>Mercenaria mercenaria</em> juveniles</td>
<td>Bricelj et al., 2001; Schaffner, 1999</td>
</tr>
<tr>
<td>35,000 to &lt;200,000</td>
<td>• <strong>Shellfish Impacts</strong></td>
<td></td>
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| <200,000              | • **Hard Clams** (*Mercenaria mercenaria*)  
  The threshold concentration of toxic clones that inhibit clearance (feeding rates) on co-occurring phytoplankton species was determined to be at 35,000 to 50,000 *Aureococcus* cells ml⁻¹ for juvenile (10 mm) hard clams.  
  Short term feeding study (1–2 hrs) showed that an isolate of *Aureococcus* (from West Neck Bay, NY, 1995) at ≥35,000 cells ml⁻¹ significantly reduced feeding (clearance rate) of juvenile hard clams (ca. 10 mm); longer term growth studies (2–3 wks) showed similar results.  
  • **Mussels** (*Mytilus edulis*)  
  At 1–3 × 10⁶ *Aureococcus* cells ml⁻¹, mussels in bloom areas show stronger growth reduction than quahogs relative to non-bloom sites and growth of juvenile mussels in Peconic Bay significantly reduced  
  • **Bay Scallops** (*Argopecten irradians*)  
  Significant growth reduction and high mortalities of bay scallop larvae at 190,000–750,000 *Aureococcus anophagefferens* ml⁻¹ |
| 200,000 to >1,000,000 | 3 • **Physical Characteristics**  
  Water becomes discolored at 200,000 *Aureococcus* ml⁻¹ | Gallager et al., 1989 |
| >1,000,000            | • **Shellfish Impacts**  
  Bivalves may experience sub-lethal, adverse effects at *Aureococcus* densities of 10⁵ cells ml⁻¹ | Bricelj and Lonsdale 1997; Bricelj and Kuenster, 1989 |
|                       | • **Mussels and Hard Clams**  
  Grazing (clearance) rates of adult *Mytilus edulis* and *Mercenaria mercenaria* markedly inhibited during Narragansett Bay brown tide in 1985 (*Aureococcus* concentrations > 10⁶ cells ml⁻¹); dilution experiments in Narragansett Bay water showed *Aureococcus anophagefferens* at > 2.5 × 10⁶ cells ml⁻¹ were required to inhibit clearance rates of adult *Mytilus edulis* on *Isochrysis galbana*  
  Effects of toxic strains of > 10⁶ ml⁻¹ *Aureococcus* on clearance (feeding) rates of juvenile mussels  
  Growth of juvenile mussels significantly reduced in Peconic Bay sites at *Aureococcus* concentrations ~100,000 to 300,000 cells ml⁻¹  
  Growth of juvenile *Mercenaria mercenaria* undetectable at toxic *Aureococcus* clone concentrations ≥400,000 cells ml⁻¹ | Tracey, 1988; Bricelj, 1999; Bricelj et al., 2001 |

(Continued on next page)
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<tr>
<td>Bay Scallops (<em>Argopecten irradians</em>)</td>
<td>Massive recruitment failures of the 1985 year class of the bay scallop, <em>Argopecten irradians</em>, as a result of brown tide blooms in Long Island embayments.</td>
<td>Cosper et al., 1997; C. Smith, pers. comm. in Bricelj and Lonsdale, 1997</td>
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<td><em>Aureococcus anophageferens</em> causes significant growth reduction and high mortalities of <em>Argopecten irradians</em> larvae at concentrations of 190,000–750,000 cells ml⁻¹. Field data suggest inhibitory effects on growth of bay scallops at ca. 2 × 10⁵ <em>Aureococcus</em> cells ml⁻¹ in Long Island Bays.</td>
<td>Gallagher et al., 1989; Bricelj et al., 1987</td>
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<tr>
<td>Hard Clams and Mussels</td>
<td>No significant growth (measured by change in the ash-free dry weight or organic weight of juvenile hard clams 6 mm in initial shell length) of juvenile hard clams at concentrations of the same isolate of <em>Aureococcus</em> ≥400,000 cells ml⁻¹; similar results with juvenile mussels.</td>
<td>Bricelj, 1999</td>
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<td>Observations of a reduction in feeding and development of hard clam larvae, reported by a commercial aquaculture facility, during a 1995 brown tide bloom in Tuckerton Bay, N.J., with <em>Aureococcus</em> cell counts ranging from 1.1 to 1.8 × 10⁶ cells ml⁻¹.</td>
<td>Nuzzi et al., 1996</td>
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<tr>
<td>Reports of reductions in juvenile hard clams during 1999 and 2000 brown tide blooms in Little Egg Harbor (as reported by Biosphere, Inc., an aquaculture facility in Tuckerton, NJ), with <em>Aureococcus</em> counts reported &gt;10⁶ cells ml⁻¹ in 1999, &gt;2.0 × 10⁶ cells ml⁻¹ in June 2000, and &gt;240,000 cells ml⁻¹ in June 2001.</td>
<td>Gastrich, 2000a, b; Gastrich, 2001; Gastrich et al., 2000; NJDEP, 1999</td>
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<td>Macrobenthos Impacts</td>
<td>Negative impacts to macrobenthos such as eelgrass, <em>Zostera marina</em> (e.g., die-off) at <em>Aureococcus</em> densities of 0.05 to 2.6 × 10⁶ cells ml⁻¹ with a mean of 0.66 × 10⁶ cells ml⁻¹ leading to an increase in light scattering and a severe reduction in light penetration) and bay scallops, <em>Argopecten irradians</em> in Long Island Bays (<em>Aureococcus</em> concentrations &gt;10⁶ cells ml⁻¹)</td>
<td>Dennison et al., 1989; Cosper et al., 1987; Bricelj et al., 1987</td>
</tr>
<tr>
<td>Planktonic Impacts</td>
<td>From the onset of brown tide in West Neck Bay, N.Y. in 1995 to the peak (<em>Aureococcus</em> concentrations of 1.1 × 10⁶ cells ml⁻¹ microzooplankton population declined from &gt;10,000 to &lt;900 ind. l⁻¹. Copepod production in Narragansett Bay in 1985 was reduced at <em>Aureococcus</em> concentrations of 7.6 × 10⁵ cells ml⁻¹. Copepod production was also reduced in West Neck Bay, NY at <em>Aureococcus</em> concentrations of 1.5 × 10⁶ cells ml⁻¹.</td>
<td>Mehran 1996; Durbin and Durbin, 1989; Lonsdale et al., 1996</td>
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activity with normal clearance below this threshold *Aureococcus* concentration (Bricełj, 1999; Schaffner, 1999; Bricełj et al., 2001).

Category 2 blooms are marked by the lower threshold concentration of 35,000 cells ml\(^{-1}\) at which concentration scientific studies report a sharp reduction in clearance rates of juvenile *Mercenaria mercenaria* (Schaffner, 1999; Bricełj et al., 2001). At *Aureococcus* concentrations of 50,000 cells ml\(^{-1}\), there was a 94% decline in juvenile *Mercenaria mercenaria* (Bricełj et al., 2001). As Category 2 concentrations increase to less than 200,000 cells ml\(^{-1}\), there are increased ecological effects such as the reduction in the growth of juvenile *Mytilus edulis* (mussels) in Peconic Bay (Bricełj and Lonsdale, 1997) and *Argopecten irradians* (bay scallops) (Gallagher et al., 1989; Tracey, 1988). Category 3 blooms are demarcated at 200,000 cells ml\(^{-1}\) because a yellow-brown discoloration of the water is usually observed (W. Dawydiak and R. Nuzzi, Suffolk County Department of Health Services, pers. comm.) and are open ended at the highest end (highest values currently observed in the field are over 2 \(\times 10^6\) cells ml\(^{-1}\)). Several scientific studies document the most severe potential effects occurring in this range to include such significant adverse effects as changes in feeding rates, significant reduction in growth and/or mortalities in adult shellfish, negative impacts to other species (e.g., seagrasses, plankton) and massive recruitment failures at the population level (summarized in Bricełj and Lonsdale, 1997; Tracey, 1988).

Some of the negative impacts related to brown tide concentrations reported from field and laboratory studies using toxic clones of *Aureococcus* show that this range includes inhibited grazing (clearance rates) of juvenile and adult *Mytilus edulis* and *Mercenaria mercenaria* (Bricełj et al., 2001). One study found that the growth of juvenile *Mercenaria mercenaria* was undetectable at clone concentrations \(\geq 400,000\) cells ml\(^{-1}\) (Bricełj et al., 2001). At some of highest reported brown tide bloom concentrations (0.8–2.2 \(\times 10^6\) cells ml\(^{-1}\)) in the field, there were high mortalities (1995 in Peconic Bay) and massive recruitment failures of the *Argopecten irradians* (1985 Long Island embayments) in New York (Cospé et al., 1987; Bricełj and Lonsdale, 1997), while in Barnegat Bay, NJ, there were observations of reduction in feeding and development of *Mercenaria mercenaria* larvae, reported by a commercial aquaculture facility, during a 1995 brown tide bloom in Tuckerton Bay, N.J., with *Aureococcus* cell counts ranging from 1.1 to 1.8 \(\times 10^6\) cells ml\(^{-1}\) (Nuzzi et al., 1996). Category 3 concentrations were also associated with negative impacts to macrobenthos such as eelgrass, *Zostera marina* (e.g., die-off; Dennison et al., 1989) at *Aureococcus* densities of 0.05 to 2.6 \(\times 10^6\) cells ml\(^{-1}\) with a mean of 0.66 \(\times 10^6\) cells ml\(^{-1}\) (leading to an increase in light scattering and a severe reduction in light penetration) and *Argopecten irradians* (Cospé et al., 1987; Bricełj and Kuenster, 1989; Bricełj et al., 1987) in Long Island Bays. Lastly, Category 3 concentrations of *Aureococcus* at 1.1 \(\times 10^6\) cells ml\(^{-1}\) were associated with microzooplankton population declines in West Neck Bay, NY in 1995 (Mehran, 1996; Lonsdale et al., 1996) while *Aureococcus* concentrations at 7.6 \(\times 10^5\) cells ml\(^{-1}\) were associated with reduced copepod production in Narragansett Bay in 1985 (Durbin and Durbin, 1989).

**Discussion**

The BTBI is intended to be used by scientists and environmental managers to communicate bloom conditions and to inform the public. Some caution is advised when using the index because it is based on available scientific data which may be reassessed through additional research. For example, while no negative impacts have been observed for Category 1 blooms, it should not be assumed that there are no negative impacts because future studies may show adverse effects to specific populations at these levels. Additionally, the index does not incorporate complex ecological interactions that have additional impacts on natural resources.

In using the index, any concentration of *Aureococcus anophagefferens* less than 35,000 cells ml\(^{-1}\) should be considered Category 1. Category 1 is based upon only a few scientific studies that document a dose-response relative to the toxicity of the alga to living organisms (Schaffner, 1999; Bricełj et al., 2001). In comparing the categories of the BTBI to conventional toxicity indices, Category 1 blooms are roughly analogous to “no observed adverse effect concentration.” Category 2 blooms can be roughly compared to standard toxicity measures representing the “lowest observed effect concentration” used in standard toxicity studies. However, as brown tide concentrations increase to Category 3, with *Aureococcus* concentrations of 200,000 cells ml\(^{-1}\) or greater, the gaps in a comprehensive gradient of concentrations become apparent and it is more difficult to relate to other toxicity categories.

The BTBI is a communication tool that can be used to reduce complex information about the potential severity of brown tide blooms for the public and provide a common lexicon for managers who need to communicate information about brown tide blooms in...
the northeast region. A relatively simple categorical system can relate information that can serve as a screening tool or an alert for harmful brown tide blooms. It is not assumed that the impacts listed in the index can be applied to all clones of *Aureococcus anophagefferens* or related species of *Aureococcus* or even to all natural populations of the genus. Rather they alert managers, policy makers and the public of the potential negative impacts to natural resources. Recent studies have demonstrated that different clones of *Aureococcus anophagefferens* have differing toxicities to living organisms (Bricelj et al., 2001). Because a specific toxin has not been isolated or quantified, the index is only a measure of potential effects and does not relate or predict the effect of specific brown tide concentrations. This index does not directly translate concentrations of *Aureococcus anophagefferens* into effects ranges used in toxicity studies; however, comparable units are suggested. It is important to realize that dose-response studies on the effects of *Aureococcus anophagefferens* are limited and that data collection, which supports these studies, is limited in some states. In addition, brown tide blooms are ecologically harmful to organisms regardless of toxicity (for example, shading on seagrasses (Dennison et al., 1989)).

Finally, it is assumed there may be complex ecological interactions (e.g., trophic level interactions, presence of additional algal species, etc.) that have additional impacts on natural resources under each category, which are not fully addressed in the table. While distinctions between potential impacts and duration of blooms and/or severity of blooms are not specifically addressed in this index, it is assumed that extended or prolonged blooms have a greater potential for negative impacts than blooms of shorter duration because of cumulative or shading effects.

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## References


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