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Authors: Chen, Jennifer, Oseji, Ozuem, Mitra, Madhumi, Waguespack, Yan, and Chen, Nianhong

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Phytoplankton Pigments in Maryland Coastal Bay Sediments as Biomarkers of Sources of Organic Matter to Benthic Community

Jennifer Chen, Ozuem Oseji*, Madhumi Mitra, Yan Waguespack, and Nianhong Chen

Department of Natural Sciences
University of Maryland Eastern Shore
Princess Anne, MD 21853, U.S.A.

ABSTRACT


In this study, the sources of pelagic organic matter and their transport to the surface sediment in the Maryland Coastal Bays (MCB), part of the U.S. mid-Atlantic coastal lagoon system, were examined. Photosynthetic pigments (chlorophylls a and b), accessory pigments (peridinin, fucoxanthin, zeaxanthin, alloxanthin, etc.), and chlorophyll a decomposition products (chlorophyllide a, pheophorbide a, pheophytin a, and pyropheophytin a) from surface sediments collected at 13 sites in the MCB in March 2013 were analyzed using high performance liquid chromatography. The spatial distributions of diagnostic pigments in surface sediments indicated that organic matter was mainly derived from nano- and pico phytoplankton (i.e. cyanobacteria, cryptophytes, and chlorophytes) at sites characterized by high nutrient input, although diatoms dominated the standing phytoplankton biomass throughout the MCB except at one site. We attribute this phenomenon to selective microzooplankton grazing on nano- and pico phytoplankton in the cold season and low grazing pressure on large phytoplankton species of diatoms and dinoflagellates resulting in the diatom bloom in early spring. At sites characterized by strong tidal current and mixing of bay waters and ocean waters, information from pigment data supports the deposition of dead/senescent diatoms. Results from this study indicate that nano- and pico phytoplankton may play a crucial role in supplying organic matter to the benthic community, although their standing stock is low in the cold season.

ADDITIONAL INDEX WORDS: Spring diatom bloom, chlorophyll a decomposition products, selective grazing.

INTRODUCTION

Coastal lagoons are among the most productive environments worldwide, representing important feeding and nursery grounds for invertebrates, fish, and birds (Vizzini and Mazzola, 2008). High primary production is supported by several factors, such as a large number of primary producers, high nutrient concentrations, retention, and recycling of both internal nutrients and those from adjacent habitats (terrestrial, wetland, and open sea). An important feature of the coastal marine ecosystem is the interaction between pelagic and benthic communities. Pelagic primary production may often be the major source of organic material to benthic communities (Bianchi, Findlay, and Dawson 1993; Nowicki and Nixon, 1985; Welschmeyer and Lorenzen, 1985).

The flux of organic matter from the water column to benthic sediment in shallow coastal lagoons is expected to be high due to enhanced primary productivity throughout the water column and high deposition rates of particulate matters in shallow coastal lagoons (Clavier, Chardy, and Chevillon, 1995). The mechanisms for such a flux include direct deposition of dead phytoplankton cells and fecal pellets from zooplankton grazing. Chlorophyll a (Chl-a) is commonly present in phytoplankton (Bidigare et al., 1986; Millie, Parel, and Hurley, 1993), and its degradation products are diagnostic indicators of the physiological condition and grazing processes affecting phytoplankton (Lorenzen, 1967; Welschmeyer et al., 1984). The most important degradation products of Chl-a found in the marine environment are chlorophyllide a (ChlId-a), pheophorbide a (Phe-a), pheophytin a (Phtin-a), and pyropheophytin a (Pphtin-a). These derivatives are formed during the breakdown of Chl-a by herbivorous zooplankton and senescent algae cells (Bianchi and Findlay, 1991; Chen, Bianchi, and Bland, 2003; Louda et al., 1998; Louda et al., 2000; Roy, 1989; Welschmeyer et al., 1984).

Chl-a decomposition products have been used as biomarkers of organic matter derived from phytoplankton in the water column and surface benthic sediments in various environments, from oligotrophic open oceans to eutrophic inland lakes (Bianchi, Dibb, and Findlay, 1993; Bianchi, Findlay, and Dawson, 1993; Chen, Bianchi, and Bland, 2003; Mantoura and Llewellyn, 1983; Villanueva and Hastings, 2000). In shallow coastal lagoons, the application of Chl-a decomposition products as biomarkers of phytoplankton source material is complicated by the fact that there are multiple sources contributing to overall Chl-a and its decomposition products (i.e. terrestrial input, benthic micro- and macroalgae, and seagrasses). In addition, benthic grazing also contributes to the decomposition of Chl-a and further breakdown of its decomposition products deposited from the water column to benthic...
sediments (Cartaxana, Jesus, and Brotas, 2003). Furthermore, the mechanisms controlling transformation of Chl-α in aquatic environments are still a subject of controversy. While numerous studies have addressed this problem, many studies give contradicting results. For example, Phide-α has been considered a biomarker of zooplankton grazing (Bianchi, Findlay, and Dawson, 1993; Carpenter et al., 1988; Welschmeyer and Lorenzen 1985), while other studies show that this pigment is the main transformation product resulting from cell senescence of some diatom species (Head, Hurgruve, and Subba Rao, 1994).

Other factors contributing to variability in decomposition of Chl-α are the various types of phytoplankton and zooplankton grazing. Nano- and picophytoplankton cells sink very slowly when they die and are more likely to be recycled in the water column before reaching the bottom, whereas large phytoplankton cells sink faster. For example, diatoms have siliceous walls and thus sink very fast when they die. This is responsible for the large quantity of diatom deposits on the surface of sediments following a spring diatom bloom. Microzooplankton (20–200 μm) are able to graze on small cells (<20 μm) such as pico- and nanoplankton, and they channel carbon from the smallest primary producers to the pelagic food web (Stelfox et al., 1999). Larger grazers (e.g., copepods) can only graze on large phytoplankton species such as diatoms and dinoflagellates (Sherr, Sherr, and Paffenhfer, 1986; Stelfox et al., 1999). In addition to the size, the sinking velocity of fecal material is also determined by the shape and density of the pellets (Fowler and Small, 1972). All these further complicate the application of Chl-α decomposition products as biomarkers of source organic matter transported from the water column to the benthic sediments.

In this study, we collected surface sediments following a spring diatom bloom at various sites in the Maryland Coastal Bays (MCB). Photosynthetic pigments and Chl-α decomposition products were analyzed using high performance liquid chromatography (HPLC) for each site. The main objective of this study was to examine the source(s) of organic matter deposited on surface sediments and the relative importance of grazing and senescence in the transportation of phytoplankton-derived material from the water column to the benthic sediments in a shallow coastal lagoon.

METHODS

Water and surface sediment samples were collected at 13 sites in the MCB in March 2013. The study area and the procedures of sample collection, processing, and analysis are described below.

Study Sites

The Maryland Coastal Bays, part of the mid-Atlantic coastal lagoon system in the United States, are characterized by shallow waters (<3 m) and relatively long water residence times (Wazniak, Wells, and Hall, 2004) due to limited exchange with the open Atlantic Ocean through small channels (Figure 1). Circulation within the bays is controlled by wind and tides. The river inputs are fairly low due to the area’s flat landscape and sandy soils, and groundwater is a major pathway for the introduction of freshwater and nutrients to the bays (Wazniak, Wells, and Hall, 2004). Water and surface sediment samples were collected at 13 preselected sites with variable characteristics (Table 1). Site 8, which is near the Ocean City inlet, showed higher mixing of bay water and seawater than other sites, as indicated by high bottom stress and low clay/silt content in sediments (type I). Sites 4, 6, 10, 12, and 13 are located near stream/river mouths, where nutrient input is usually stronger, and sediments at these sites are muddier than at other sites (type III). Other sites (type II) are generally considered open bay sites with characteristics between type I and type III sites.

Sample Collection/Processing

Approximately 1 L of water was collected from 1.0 m below the surface at each site using a peristaltic pump and was stored on ice in a cooler. In the laboratory, the water samples were filtered through a Whatman GF/F 47 mm glass fiber membrane (GE Healthcare Bio-Sciences, Pittsburgh, Pennsylvania, U.S.A.) with a Fisherbrand vacuum microfiltration system (Fisher Scientific, Pittsburgh, Pennsylvania, U.S.A.). The filtrates were used for nutrient analysis. The filters were then placed in 5–10 mL of 100% acetone in a 15 mL polypropylene centrifuge tube, sonicated, and extracted in darkness at 4°C overnight. The pigment extracts were then centrifuged and the supernatants collected and dried by exposing to a nitrogen stream. To redissolve the residual, 200 μL methanol/water (9:1 v/v) was added and 20 μL solution was injected to the HPLC.

Surface sediment samples were collected with a bottom grab sampler, stored in glass bottles, and stored on ice in a box. In the laboratory, about 100 g sediment were freeze dried, and approximately 1 g freeze-dried sediment was weighed into a 10
TABLE 1. Salinity, mud content, sediment texture, and nutrients of the sampling sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Salinity</th>
<th>% Clay + Silt</th>
<th>Site Characteristics</th>
<th>Nutrient Condition</th>
<th>TDN (mg N/L)</th>
<th>DRP (mg P/L)</th>
<th>DSi (mg SiO₂/L)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30.9 ± 4.2</td>
<td>5.7</td>
<td>open bay</td>
<td>low</td>
<td>0.25</td>
<td>0.08</td>
<td>0.05</td>
<td>II</td>
</tr>
<tr>
<td>2</td>
<td>30.1 ± 4.1</td>
<td>14.4</td>
<td>open bay</td>
<td>low</td>
<td>0.21</td>
<td>0.06</td>
<td>0.08</td>
<td>II</td>
</tr>
<tr>
<td>3</td>
<td>30.5 ± 4.1</td>
<td>6.3</td>
<td>open bay</td>
<td>low</td>
<td>0.24</td>
<td>0.08</td>
<td>0.05</td>
<td>II</td>
</tr>
<tr>
<td>4</td>
<td>30.2 ± 4.1</td>
<td>37.1</td>
<td>open bay</td>
<td>low</td>
<td>0.19</td>
<td>0.08</td>
<td>0.06</td>
<td>III</td>
</tr>
<tr>
<td>5</td>
<td>30.0 ± 3.7</td>
<td>2.5</td>
<td>open bay</td>
<td>low</td>
<td>0.22</td>
<td>0.07</td>
<td>0.10</td>
<td>III</td>
</tr>
<tr>
<td>6</td>
<td>25.7 ± 3.8</td>
<td>23.7</td>
<td>river mouth</td>
<td>high</td>
<td>0.27</td>
<td>0.14</td>
<td>0.57</td>
<td>III</td>
</tr>
<tr>
<td>7</td>
<td>31.2 ± 4.4</td>
<td>1.9</td>
<td>narrow bay</td>
<td>low</td>
<td>0.15</td>
<td>0.12</td>
<td>0.12</td>
<td>I</td>
</tr>
<tr>
<td>8</td>
<td>32.6 ± 3.2</td>
<td>0.2</td>
<td>narrow bay/near inlet</td>
<td>low</td>
<td>0.18</td>
<td>0.06</td>
<td>0.10</td>
<td>I</td>
</tr>
<tr>
<td>9</td>
<td>32.1 ± 2.8</td>
<td>20.0</td>
<td>open bay</td>
<td>low</td>
<td>0.18</td>
<td>0.05</td>
<td>0.23</td>
<td>II</td>
</tr>
<tr>
<td>10</td>
<td>29.0 ± 3.1</td>
<td>34.2</td>
<td>near shore/river mouth</td>
<td>high</td>
<td>0.70</td>
<td>0.10</td>
<td>1.03</td>
<td>III</td>
</tr>
<tr>
<td>11</td>
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<td>18.2</td>
<td>open bay</td>
<td>low</td>
<td>0.18</td>
<td>0.05</td>
<td>0.20</td>
<td>II</td>
</tr>
<tr>
<td>12</td>
<td>28.1 ± 3.7</td>
<td>48.3</td>
<td>river mouth</td>
<td>high</td>
<td>0.28</td>
<td>0.06</td>
<td>0.13</td>
<td>III</td>
</tr>
<tr>
<td>13</td>
<td>27.5 ± 4.1</td>
<td>23.8</td>
<td>river mouth</td>
<td>high</td>
<td>0.32</td>
<td>0.06</td>
<td>0.08</td>
<td>III</td>
</tr>
</tbody>
</table>

a Average of salinities measured from June 2011 to July 2013.
b Sediment size distribution of dried sediment was measured with a set of six sieves; the mud (silt + clay) content is the fraction which passes the 0.039 mm sieve.
c Nutrient condition refers to nutrient input from stream.
d Type 1 = Low clay/silt content and high bottom stress, Type 2 = Medium clay/silt content, Type 3 = High clay/silt content.

ml test tube. Pigments were extracted with 5 mL acetone, mixed thoroughly with a vortex mixer, sonicated, and allowed to stand in the dark at 4°C overnight. Test tubes were placed in a centrifuge at 2500 rpm for 5 minutes, and 3 mL extract was filtered with a syringe filter (0.2 μm). The extract was then dried with a nitrogen stream. To the residual, 200 μL methanol/water (9:1 v/v) was added and 20 μL solution was injected into HPLC.

**Nutrient Analysis**

Total dissolved nitrogen (TDN) in the filtrate was analyzed by high-temperature combustion method using a TNM-1 total nitrogen analyzer module (Shimadzu Scientific Instruments, Columbia, Maryland, U.S.A.) coupled to a TOC-VCSH total organic carbon analyzer (Shimadzu Scientific Instruments) (Álvarez-Salgado and Miller, 1998). Standard calibration for TDN was achieved using potassium nitrate. A DR4000 spectrophotometer (Hach Company, Loveland, Colorado, U.S.A.) was used to measure dissolved reactive phosphorus (DRP; Hach method 8048) and dissolved silica (DSi, Hach method 8185). TDN was chosen to represent the availability of nitrogen nutrients since concentration of nitrogen in the sample was usually very low year-round and represents only a minor contribution to the total dissolved nitrogen pool (Glibert et al., 2014).

**HPLC Analysis of Pigments**

The separation of pigments was conducted on an 1100 Series model G1322A HPLC with a binary pump (Agilent Technologies, Santa Clara, California, U.S.A.) according to the method described in Zapata, Rodríguez, and Garrido (2000). The two eluents used were methanol/acetonitrile/0.25 M aqueous pyridine (50:25:25 v/v/v) and acetonitrile/acetone (80:20 v/v). All organic solvents were HPLC grade and prepared as described in Zapata, Rodríguez, and Garrido (2000). Analytical separations were performed using a Symmetry C8 column (150 x 4.6 mm, 3.5 μm particle size, 100 Å pore size; Waters Corporation, Milford, Massachusetts, U.S.A.). The gradient was a version modified from Zapata, Rodríguez, and Garrido (2000) that achieves partial separation between zeaxanthin (Zeax) and lutein (Lut).

RESULTS

In this section we exhibit relevant data obtained from pigment analysis, describing the community characteristics, spatial variation of Chl-a, accessory pigments, and Chl-a decomposition products in both the water column and surface sediments of the MCB.

**Phytoplankton Community Characteristics in the MCB**

In March 2013, fucoxanthin (Fuco) was the dominant accessory pigment at all sites except site 10, where peridinin (Peri, 3.90 nMol/L) was higher than Fuco (Figure 2). The highest concentration of Fuco (7.49 nMol/L) was detected at site 6, where relatively high concentrations of TDN, DRP, and DSi were observed. The unusual nutrient condition at site 10, with...
the highest TDN and DSI among all sites (Table 1), may explain the high abundance of dinoflagellates, indicated by high concentration of Peri at this nearshore site. Excluding sites 6 and 10, Chl-a had a moderate negative relationship with both TDN ($R = -0.64, p < 0.05$) and DRP ($R = -0.73, p < 0.05$) and a positive relationship with DSI ($R = 0.50, p < 0.05$), indicating that the primary production was likely limited by DSI throughout the bay except at sites where nutrients were supplied by streams.

The average concentration of Fuco (2.32 ± 0.27 nMol/L) was higher than the other diagnostic pigments by approximately one order of magnitude. In addition, the average Fuco concentration in March 2013 was highest among all sampling periods since 2012, when we started monitoring the photosynthetic pigments in the MCB; this is consistent with a moderate to strong spatial variation of Chl-a (sum of normal and epimer of Chl-a) and accessory pigments was observed in surface sediments (Figure 3). The highest concentration of Chl-a was observed at site 10 (0.12 nMol/g) followed by Sites 2, 7, 8, and 9 (Figure 4). Fuco, Zeax, Lut, Allox, and Chl-b were detected in surface sediment at all sites, and prasinoxanthin (Pras) was detected at most sites. Neoxanthin, violaxanthin, 19′-butanoyloxy-fucoxanthin, and 19′-hexanoyloxy-fucoxanthin were only detected at a few sites, and their concentrations were also much lower than the other pigments. Average concentration of Zeax (0.13 ± 0.15 nMol/g) was the highest among accessory pigments, followed by Fuco (0.080 ± 0.062 nMol/g), Lut (0.045 ± 0.048 nMol/g), Allox (0.044 ± 0.054 nMol/g), Peri (0.027 ± 0.018 nMol/g), β-Car (0.023 ± 0.027 nMol/g), and Pras (0.017 ± 0.022 nMol/g). This suggested that the main sources of phytoplankton-derived organic matter included cyanobacteria, diatoms, cryptophytes, dinoflagellates, and prasinophytes. However, caution must be used when interpreting photosynthetic pigments as biomarkers of sources of phytoplanktonic material, since stability

Spatial Variation of Chl-a and Accessory Pigments in Surface Sediments

Strong spatial variation in Chl-a and accessory pigments was observed in surface sediments (Figure 3). The average concentration of fresh Chl-a (0.065 ± 0.043 nMol/g) in sediments is generally low throughout the coastal bays. The highest concentration of Chl-a was observed at site 10 (0.12 nMol/g) followed by Sites 2, 7, 8, and 9 (Figure 4). Fuco, Zeax, Lut, Allox, Peri, and Chl-b were detected in surface sediment at all sites, and prasinoxanthin (Pras) was detected at most sites. Neoxanthin, violaxanthin, 19′-butanoyloxy-fucoxanthin, and 19′-hexanoyloxy-fucoxanthin were only detected at a few sites, and their concentrations were also much lower than the other pigments. Average concentration of Zeax (0.13 ± 0.15 nMol/g) was the highest among accessory pigments, followed by Fuco (0.080 ± 0.062 nMol/g), Lut (0.045 ± 0.048 nMol/g), Allox (0.044 ± 0.054 nMol/g), Peri (0.027 ± 0.018 nMol/g), β-Car (0.023 ± 0.027 nMol/g), and Pras (0.017 ± 0.022 nMol/g). This suggested that the main sources of phytoplankton-derived organic matter included cyanobacteria, diatoms, cryptophytes, dinoflagellates, and prasinophytes. However, caution must be used when interpreting photosynthetic pigments as biomarkers of sources of phytoplanktonic material, since stability
The highest concentration of Fuco was observed at site 8 (0.25 nMol/g), where other accessory pigments were very low or not detected. Relatively high concentrations of Fuco were also detected at sites 7 and 9, the two sites closest to site 8. This distribution is different from the water column Fuco distribution, which actually peaked at site 6 and remained relatively high throughout the bays (Figure 3). We speculate that the high Fuco concentration in surface sediment at site 8 might be caused by sinking of diatoms at locations with relatively stronger mixing of bay water and seawater. In addition, the bottom stress at site 8 was also the highest, as indicated by very low clay/silt contents (Table 1). High bottom stress may also prevent deposition and burial of organic matter derived from other phytoplankton groups due to lack of silicate shells such as diatoms.

Spatial Variation of Chl-\(a\) Decomposition Products in Surface Sediments

The major Chl-\(a\) decomposition products in surface sediments are Phtin-\(a\) (mean 0.083 ± 0.114 nMol/g) and Phide-\(a\) (mean 0.083 ± 0.097 nMol/g) at all sites (Figure 4). There were strong spatial variations in Chl-\(a\) decomposition products. Phtin-\(a\) showed a very different pattern than Chlide-\(a\), Phide-\(a\), and pPhtin-\(a\). The highest concentration of Phtin-\(a\) was observed at site 8 (0.44 nMol/g), where the highest concentration of Fuco was observed. The highest concentration of Phide-\(a\) (0.17 nMol/g) was observed at site 13. Chl-\(a\) and pPhitn-\(a\) generally followed the pattern of Phide-\(a\), and this is further supported by regression analysis (Table 3). In this table, the concentrations of Chl-\(a\), Phide-\(a\), and Phtin-\(a\) include their respective epimers.

Statistical Analysis

Pearson correlation analysis was conducted for sedimentary photosynthetic pigments and Chl-\(a\) decomposition products with SPSS Statistics 20 (IBM Corporation, Armonk, New York, U.S.A.) to provide information on sources of phytoplankton-derived organic matter in benthic sediments and Chl-\(a\) decomposition pathways in the MCB (Table 3). We observed strong correlations between Fuco and Phtin-\(a\) \((R = 0.81, p < 0.05)\), some pheopigments (Chlide-\(a\), Phide-\(a\) and pPhitn-\(a\)), and also some carotenoids (Allox, Zeax, Lut, and \(\beta\)-Car).

Table 3. Correlations (\(R\)) between pigments (\(n = 13\)) from Pearson correlation analysis. Significant relationships \((p < 0.05)\) are given in bold. Abbreviations of pigments are listed in Table 2.

<table>
<thead>
<tr>
<th>Pigment</th>
<th>Per</th>
<th>Chlide-(a)</th>
<th>Chlide-(a)'</th>
<th>Phide-(a)</th>
<th>Phide-(a)'</th>
<th>Fuco</th>
<th>Allox</th>
<th>Zeax</th>
<th>Lut</th>
<th>Chl-b</th>
<th>O-Chl-(a)</th>
<th>Chl-(a)</th>
<th>Chl-(a)'</th>
<th>Phtin-(a)</th>
<th>Phtin-(a)'</th>
<th>(\beta)-Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chl-(a)</td>
<td>-0.02</td>
<td>0.93</td>
<td>0.79</td>
<td>0.61</td>
<td>0.03</td>
<td>-0.08</td>
<td>0.09</td>
<td>0.09</td>
<td>0.05</td>
<td>-0.30</td>
<td>0.20</td>
<td>-0.14</td>
<td>0.30</td>
<td>0.17</td>
<td>-0.16</td>
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</tr>
<tr>
<td>Chl-(a)'</td>
<td>0.14</td>
<td>0.93</td>
<td>0.71</td>
<td>0.65</td>
<td>-0.13</td>
<td>-0.17</td>
<td>0.01</td>
<td>0.01</td>
<td>0.08</td>
<td>-0.25</td>
<td>-0.26</td>
<td>-0.15</td>
<td>0.08</td>
<td>0.12</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Phide-(a)</td>
<td>-0.02</td>
<td>0.79</td>
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<td>0.89</td>
<td>0.04</td>
<td>0.19</td>
<td>0.34</td>
<td>0.25</td>
<td>-0.06</td>
<td>-0.10</td>
<td>0.05</td>
<td>0.18</td>
<td>0.28</td>
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</tr>
<tr>
<td>Phide-(a)'</td>
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<td>0.25</td>
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<td>0.00</td>
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<td>0.94</td>
<td>0.96</td>
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<td>-0.20</td>
<td>0.87</td>
<td>0.96</td>
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<td>0.19</td>
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<td>-0.18</td>
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Figure 4. Spatial distribution of Chl-\(a\) and its decomposition products in surface sediments of the MCB, indicative of the source of organic matter either through senescence or zooplankton grazing. Chl-\(a\), Chlide-\(a\), Phide-\(a\) and Phtin-\(a\) in this figure represent the sum of normal chloropigments and their epimers, respectively.

Table 3. Correlations (\(R\)) between pigments (\(n = 13\)) from Pearson correlation analysis. Significant relationships \((p < 0.05)\) are given in bold. Abbreviations of pigments are listed in Table 2.

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DISCUSSION

In this section, we describe in detail the source of photosynthetic pigments, selective zooplankton grazing, and the pathway of Chl-α decomposition in surface sediments of the MCB.

Sources of Photosynthetic Pigments in Surface Sediments

Photosynthetic pigments in MCB waters have been monitored monthly since February 2012. No strong spring blooms have been observed. In both 2012 and 2013, average Chl-α concentrations increased moderately from February (<1 nMol/L) to March (1–2 nMol/L) and quickly decreased to very low levels (<0.2 nMol/L; O. Oseji, unpublished data) in April. The highest average Chl-α concentration, which may reach >5 nMol/L at certain sites in some years, usually occurs in June or July and is caused by a “brown tide” (Trice et al., 2004). Diatoms are dominant species year-round, and their dominance is more remarkable in winter and early spring. Chl-α concentration remains relatively high in summer and decreases gradually in fall and winter.

The main pathway for pelagic diatoms to reach surface sediments is through zooplankton grazing and direct deposition of dead/senescent diatom cells (Itoh et al., 2007; Roy, 1989). There is strong evidence that diatoms were deposited directly at site 8 near the Ocean City inlet, where stronger mixing of coastal bay water with seawater occurred. First, Phtin-α and Fuco dominated Chl-a decomposition products and accessory pigments at site 8, indicating that the most likely source of Phtin-α at this site was the deposition of dead/senescent diatoms. This trend is further evidenced by the strong linear relationship between Fuco and Phtin-α (\( r^2 = 0.81, p < 0.01 \); Table 3). The concentrations of other accessory pigments in surface sediment were very low at site 8, probably due to low grazing activity or high bottom stress, which prevents the deposition and burial of organic matter derived from phytoplankton. Furthermore, correlation analyses also suggested that the main source of Chlide-α, Phide-α, and PpHtin-α was similar—most likely grazing, as indicated by strong linear relationships between these biomarkers (Table 3). However, no accessory pigments showed any clear linear relationship with Chlide-α, Phide-α, and PpHtin-α, likely due to spatial variation in the composition of phytoplankton.

Another source of photosynthetic pigments and decomposition products is the phytobenthos. Wazniak (2004) measured Chl-α of viable algal cells in surface sediments and found that its concentration varied remarkably (from 8.5 to 259 mg/m²). Wazniak (2004) suggested that the phytobenthos may represent an important primary producer within the system. The pigments in our samples included both pelagic and benthic sources, and the benthic contribution to photosynthetic pigments may vary significantly. For example, at site 8, a remarkably high concentration of Fuco coincided with the highest concentration of Phtin-α among all sites. Chl-α was not higher at site 8 than the adjacent sites (7 and 9), indicating the pigments at this site were mainly derived from deposition of senescence/death of pelagic diatoms. In contrast, at the four sites located near the river mouths with high concentrations of nutrients and finer sediments (sites 6, 10, 12, and 13), Zeax concentrations were overwhelmingly higher than other carotenoids, while Zeax concentration in the water column was very low, suggesting that benthic cyanobacteria may contribute remarkably to the overall pigment budget (Chl-α and Zeax). However, the relatively low concentration of fresh Chl-α and high concentrations of Chl-α decomposition products at these sites indicated that viable phytobenthos was not likely the major source of photosynthetic pigments.

Selective Grazing on Phytoplankton in the Water Column

Selective grazing of zooplankton on phytoplankton has been observed in many previous studies (Burkill et al., 1987; Granéli and Turner, 2002; Huang et al., 2008; Liu et al., 2010; Stoecker, Guillard, and Kavee, 1981). A recent study on the grazing impact of microzooplankton on phytoplankton in Xiamen Bay, China, revealed that microzooplankton preferentially grazed on nano- and picophytoplankton and avoided harvesting large phytoplankton species such as diatoms in the cold season (Huang et al., 2008). The peak grazing pressures for dinoflagellates and chlorophytes occurred in early spring, and for cryptophytes and cyanobacteria in winter (December). In contrast, peak grazing pressures for diatoms occurred in summer, presumably due to the larger zooplankton species such as copepods. If the seasonal variations of zooplankton grazing in the MCB follow the same pattern, the relatively low standing biomass of nano- and picophytoplankton (prasinophytes, chlorophytes, cyanobacteria, and cryptophytes) in winter can be interpreted as preferential grazing by microzooplankton, and the remarkable dominance of standing biomass of diatoms in the cold season can be attributed to the lack of grazing pressure.

High concentrations of Zeax, Lut, and Allox coupled with high concentrations of Chlide-α, Phide-α, and PpHtin-α in sediments at sites 6, 10, 12, and 13 with high nutrients in the water column are consistent with selective grazing at these sites. The strong linear relationships among Zeax, Allox, and Lut, and the linear relationships among Chlide-α, Phide-α, and PpHtin-α further support this view (Table 3), indicating that the main source of phytoplankton-derived organic matter at these sites were from fecal materials from microzooplankton grazing. Phytobenthos may contribute to the total chlorophyll and carotenoids, and benthic grazers and suspension feeders may contribute to the production of Chl-α decomposition products. However, since the diets of benthic grazers and suspension feeders are not selective or are less selective compared with zooplankton/protozoa, the inference about selective grazing based on the pigment compositions in the water column and sediments holds true. In addition, the low temperature during the sampling period may subdue the feeding activities of benthic grazers and suspension feeders.

Chl-α Decomposition Pathway

The results from this study also shed light on the Chl-α decomposition pathway in the MCB. Two main pathways can be proposed based on the current results. The presence of maximum concentrations of both Fuco and Phtin-α at site 8 and the strong linear relationship between Fuco and Phtin-α support the production of Phtin-α through the senescence of diatoms at that site. The low concentrations of Chlide-α and
of Phide-$a$ through chlorophyllase-catalyzed autolytic decomposition of Chl-$a$ during diatom senescence, a process limited to sites with strong mixing of bay water and seawater. Another pathway is formation of Chlide-$a$, Phide-$a$, and pPhtin-$a$ through selective grazing of microzooplankton on nano- and picophytoplankton and/or benthic grazing and suspension filter feeding.

**ACKNOWLEDGMENTS**

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**LITERATURE CITED**


