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Toward scrubbing the bay: Nutrient removal using small algal turf scrubbers on Chesapeake Bay tributaries

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ABSTRACT

Restoration of the Chesapeake Bay poses significant challenges because of increasing population pressure, conversion of farmland to urban/suburban development, and the expense of infrastructure needed to achieve significant and sustained nutrient reductions from agricultural and urban sources. One radical approach for removing non-point source nutrients before they reach the bay is to deploy large-scale algal turf scrubbers along its tributaries. The objective of this study was to determine rates of nutrient removal and algal fatty acid production using small ATS units located along three Chesapeake Bay rivers. Small-scale ATS units (each containing 1 m^2 growing area) were operated for 5–10 months from April 2007 to April 2008 on three western shore tributaries of the Chesapeake Bay in Maryland: the Bush River, the Patapsco River and the Patuxent River. Total nitrogen (TN) and total phosphorus (TP) removal rates at the Patuxent site fluctuated considerably but averaged 250 mg TN, 45 mg TP m^{-2} day^{-1} from May to October 2007, then decreased to 16 mg TN, 3 mg TP m^{-2} day^{-1} from December 2007 to February 2008. Nutrient removal rates at the Bush river site also fluctuated but averaged only 85 mg TN, 10 mg TP m^{-2} day^{-1} from May to June 2007, before decreasing to <10 mg TN, <1 mg TP m^{-2} day^{-1} from July to September 2007. The Patapsco River unit began operation in August 2007, reached its maximum removal values of 150 mg TN, 18 mg TP m^{-2} day^{-1} from mid-October to late-November 2007, then decreased to values of 45 mg TN, 4 mg TP m^{-2} day^{-1} from November 15, 2007 to mid-April 2008. In the best case (Patuxent site from May to October 2007), daily removal rates of 250 mg N and 45 mg P m^{-2} are equivalent to removal rates of 380 kg N and 70 kg P ha^{-1} over a 150-day season in Maryland. Fatty acid (FA) content of the harvested material was consistently low (0.3–0.6% of dry weight) and varied little between sites. Mean algal FA production rates (23–54 mg FA m^{-2} day^{-1}) are equivalent to rates of 34–81 kg FA ha^{-1} $year^{-1}$ based on a 150-day operational season in Maryland.

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1. Introduction

Restoration of the Chesapeake Bay poses significant challenges because of increasing population pressure, conversion of farmland to urban/suburban development, and the expense of infrastructure needed to achieve significant and sustained nutrient reductions from agricultural and urban sources (Chesapeake Bay Commission, 2004; Chesapeake Bay Foundation, 2004). One radical approach for removing non-point source nutrients is to deploy large-scale water treatment systems along rivers that feed the Chesapeake Bay. Algal turf scrubber (ATS) technology has been shown to provide potential nutrient treatment for a variety of pollution sources, including agricultural runoff and manure effluents (Adey et al., 1993, 1996; Craggs et al., 1996; Kebede-Westhead et al., 2006; Mulbry et al., 2008b). As a light-driven process, ATS systems are agricultural in scale and are limited to areas where land prices are relatively low. However, unlike most nutrient management practices, ATS systems offer a sustainable and verifiable means to remove nutrients using farm-scale equipment and yield a biomass suitable for use as a slow-release organic fertilizer (Pizarro et al., 2006; Mulbry et al., 2006). Harvested biomass may also have value as an extractable or fermentable biofuel feedstock (Mulbry et al., 2008a).

A 6-month pilot scale project in southern Florida demonstrated nutrient removal values of approximately 300 mg N, 75 mg P m^{-2} day^{-1} (Hydromentia Inc, 2005). Results from a pilot scale ATS project in Maryland treating diluted dairy manure effluent yielded nutrient removal values of approximately 1000 mg N,

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150 mg P m^{-2} day^{-1} (Mulbry et al., 2008b). The primary objective of this study was to determine comparable productivity and nutrient content values using small ATS units located along three Chesapeake Bay rivers. A second objective was to determine the fatty acid content and composition of a subset of ATS biomass samples from the three sites for comparison with values from manure-grown ATS biomass.

2. Methods

2.1. Operation of algal turf scrubbers

Small-scale fiberglass ATS units (each containing 1 m^2 growing area) were operated for 5- to 10-month periods from April 2007 to April 2008 (Figs. 1 and 2). ATS units were located on docks (away from tree shadows) on three western shore tributaries of the Chesapeake Bay in Maryland: the Bush River, the Patapsco River and the Patuxent River (Fig. 3). Two units were operated at the Jackson Landing site in the Patuxent River Park for 10 months (April 1, 2007 to February 10, 2008). Two units were operated at the Otter Point Creek National Estuarine Research Reserve on the Bush River for 5 months (April 8–September 7, 2007) but were stopped prematurely after being vandalized. One unit was operated on Back Creek on the Patapsco River for 8 months (August 2, 2007 to April 2, 2008). Water for each unit was provided by a submerged magnetic drive water pump (Danner Inc., Islandia, NY, USA) at a flow rate of approximately 55 l min^{-1}. Units were operated with a slope of approximately 1% and were not inoculated prior to installation. Wet algal biomass (along with trapped sediment) was harvested every 6–8 days using a wet/dry vacuum, dewatered by sieving harvested material through 2 mm mesh nylon netting (Aquatic Ecosystems, Apopka, FL) to approximately 10% solids content, then air-dried at 25 °C using an electric fan for approximately 48 h to approximately 90% solids content.

Fig. 1. Photograph of algal turf scrubber unit on a dock at the Patuxent River Park on the Patuxent River.

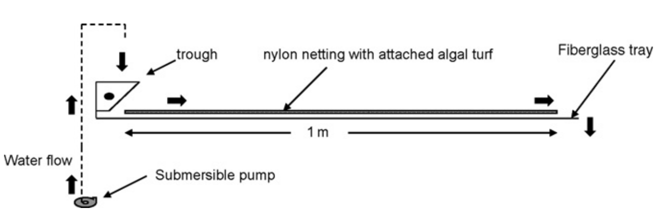

Fig. 2. Schematic drawing of small-scale ATS units used in this study. A submerged pump delivers river water at a flow rate of 55 l min^{-1} up to a trough at one end of the ATS. The trough fills and tips over, releasing pulses of water that wash over the attached algal turf every 8–15 s before draining from the unit.

2.2. Sample preparation and nutrient analyses

Dried harvested solids were ground in a Wiley Mill to pass a 3 mm sieve and stored in sealed plastic bags at 20–25 °C prior to analysis for moisture, ash, total Kjeldahl nitrogen (TKN), and total phosphorus (TP) (Kebede-Westhead et al., 2003). River water samples were collected on harvest days, acidified to pH 3–5 by the addition of 6 N sulfuric acid, and stored at 4 °C prior to analysis for TKN and TP. For fatty acid (FA) analyses, sub-samples of air-dried harvested solids were ground to pass a 0.5 mm sieve and stored in sealed plastic bags prior to extraction.

In order to characterize sediment and filamentous algae in the harvested material, sub-samples of freshly harvested material from the Patuxent site were subjected to multiple rounds of washing and sieving. In these instances (five dates from May to September, 2007), fresh dewatered solids (approximately 10% solids as described above) were vigorously resuspended for five minutes in approximately 5 l of distilled water and the washed filamentous algae were collected using 1.5 mm sieve. After 3 to 5 such washing cycles, the washed algae was air-dried as described above. The suspended solids (material that passed through the 1.5 mm sieves) were precipitated by the addition of aluminum sulfate (to a final concentration of 0.2 g l^{-1}), collected after decanting the supernatant, and air-dried. The resulting washed algae and precipitated solids were ground prior to analysis for moisture, ash, TKN and TP as described above.

In order to qualitatively assess the composition of the algal turfs, two to four samples of algae from representative patches were removed from the turfs at each harvest and examined with light microscopy. The most common algal taxa in these samples were subjectively assessed and recorded.

2.3. Extraction and analysis of fatty acids from ATS biomass

Extraction and analysis of algal fatty acids was performed as described previously (Mulbry et al., 2008a). A subset of dried samples (five to eleven samples of harvested solids from each site) were extracted using a Dionex 200 accelerated solvent extraction (ASE) system (Dionex Corporation, Salt Lake City, UT, USA) and a chloroform/methanol mixture (2:1) as the extraction solvent. Fatty acid methyl esters (FAME) were prepared from aliquots of the ASE extracts and analyzed using gas chromatography (MIDI system, Microbial ID, Inc., Newark, DE, USA).

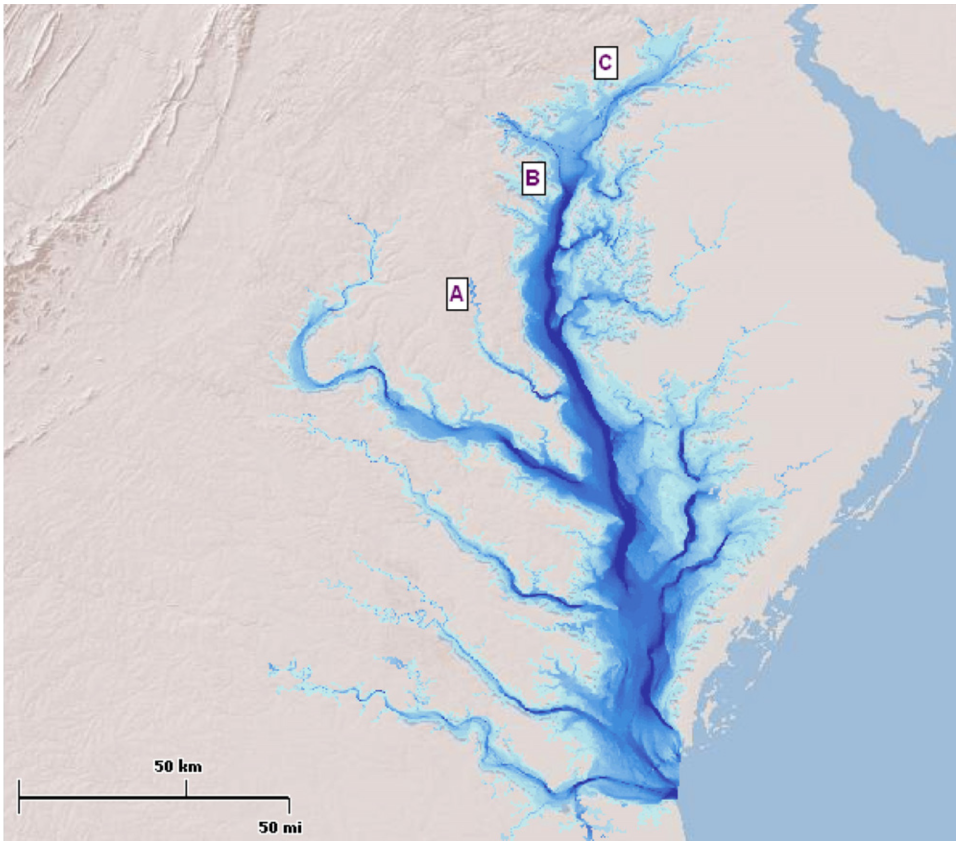

Fig. 3. Map showing approximate locations of ATS sites on the Patuxent, Patapsco, and Bush rivers and hypoxic zones within the Chesapeake Bay. The Patuxent river site (A) was located at Patuxent River Park near Upper Marlboro, MD. The Patapsco River site (B) was a private dock in Back Bay near Pasadena, MD. The Bush River site (C) was at the Otter Point National Research Reserve near Abingdon, MD.

Table 1
Water quality at the three ATS sites.

	Patuxent River (n = 35)[a]	Bush River (n = 19)	Patapsco River (n = 19)
TN (mg l^{-1})	1.29 ± 0.25	1.03 ± 0.20	1.05 ± 0.42
TP (mg l^{-1})	0.23 ± 0.09	0.14 ± 0.7	0.11 ± 0.09
Salinity (g l^{-1})	0.53 ± 0.29	1.0 ± 1.0	10.2 ± 1.9

[a] Values are the means ± SD of 19–35 weekly samples. n, number of samples.

3. Results

3.1. Site characterization and algal composition

Nutrient levels in the tributary waters were comparable at the three sites and generally ranged from 1 to 2 mg l^{-1} total nitrogen (TN) and <0.1 to 0.2 mg l^{-1} total phosphorus (TP) (Table 1). Salinity values (in g l^{-1}) ranged 0.2–1.5 (Patuxent River), 0.2–3.2 (Bush River), and 7–12 (Patapsco River). Water temperatures ranged seasonally from 5 to 30 °C at the three sites. Data from automated NOAA weather stations at the Patuxent and Bush River sites showed that light levels (daily total integrated PAR) ranged seasonally from 5000 to 30,000 mole m^{-2} day^{-1}. All three sites were tidal with a tidal flux of about 60 cm.

A qualitative assessment of the algal turfs was performed in order to characterize the relative abundances and seasonal succession of species. Dominant algal species were similar at the two sites with predominantly freshwater conditions (Patuxent and Bush River sites). Detailed observations were made at the Patuxent site with algal samples examined by microscopy after every harvest. A seasonal succession of dominant taxa was observed at this site. The filamentous diatom, *Melosira* sp., dominated in the winter/spring and it was found at lower densities throughout the remainder of the year. The blue-green alga, *Lygnbya* sp., and the green alga, *Spirogyra* sp., dominated in the summer/fall. Species of *Ulothrix*, *Microspora* and *Claophora* were also observed along with numerous pennate diatoms that occurred primarily as epiphytes on the filamentous algae. The composition of algal community at the Patapsco River site differed completely from the freshwater sites due to the higher salinity. Filamentous diatoms and the green alga, *Enteromorpha* sp., dominated year-round at this site.

3.2. Nutrient removal rates

Nutrient removal rates were calculated by multiplying the values for total harvested solids by the nutrient content. Of these two factors, values for harvested solids had a greater determinative role since they varied seasonally while nutrient values were much more consistent through time (Table 2). There were significant seasonal differences in nutrient removal values and differences in the nutrient removal values between the three sites. Average N and P removal values at the Patuxent river site fluctuated considerably but averaged 250 mg TN, 45 mg TP m^{-2} day^{-1} from May to October 2007, then decreased to 16 mg TN, 3 mg TP m^{-2} day^{-1} from December 2007 to February 2008 (Table 2, Fig. 4B and C). Average nutrient removal values at the Bush river site also fluctuated but averaged only 40 mg TN, 7 mg TP m^{-2} day^{-1} from May to June 2007, before decreasing to <10 mg TN, 3 mg TP m^{-2} day^{-1} from July to September 2007 (Table 2, Fig. 4E and F). The Patapsco River unit began

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Table 2
Harvested solids, nutrient content, and N and P removal rates for ATS units at three Chesapeake tributaries.

Output (m^{-2} day^{-1})	Patuxent					Bush		Patapsco	
	May 16–June 28 (n = 8)[a]	July 3–August 25 (n = 11)	September 2–October 10 (n = 6)	October 18–November 29 (n = 5)	December 11–February 2 (n = 4)	May 24–June 26 (n = 4)	July 3–August 22 (n = 4)	October 11–November 27 (n = 7)	December 11–April 2 (n = 6)
Harvested solids (g DW)	21.4 ± 8.5	18.7 ± 7.0	13.8 ± 6.4	6.6 ± 1.7	1.2 ± 0.7	7.2 ± 3.2	0.61 ± .6	5.9 ± 1.6	2.3 ± 1.8
N content (%)	1.6 ± 0.4	1.2 ± 0.2	1.5 ± 0.3	1.2 ± 0.4	1.3 ± 0.4	1.2 ± 0.3	2.8 ± 0.4	2.5 ± 0.4	2.1 ± 0.5
TN in harvested solids (mg)	320 ± 96	214 ± 66	202 ± 103	78 ± 37	16 ± 12	85 ± 34	9.5 ± 6.5	148 ± 33	46 ± 28
P content (%)	0.27 ± 0.05	0.23 ± 0.02	0.26 ± 0.03	0.26 ± 0.06	0.29 ± 0.05	0.14 ± 0.01	0.28 ± 0.06	0.31 ± 0.05	0.21 ± 0.07
TP in harvested solids (mg)	55 ± 16	41 ± 14	35 ± 16	17 ± 4.4	3.5 ± 2.4	9.6 ± 4.3	0.9 ± 0.6	18.1 ± 5.3	4.3 ± 2.7
N/P	5.8 ± 0.4	5.7 ± 1.2	5.8 ± 0.7	4.2 ± 1.0	4.3 ± 0.7	9.3 ± 1.4	10 ± 0.5	8.3 ± 0.9	10.7 ± 2.2
Ash content	77 ± 5	73 ± 10	77 ± 4	77 ± 2	79 ± 3	77 ± 3	62 ± 2	67 ± 3	69 ± 4
Mean N removal rate	380 kg N-ha^{-1} over 150 days at average of 2.5 kg N per ha^{-1}-day^{-1}			nc[b]	nc	nc	nc	nc	nc
Mean P removal rate	70 kg P-ha^{-1} over 150 days at average of 0.45 kg P per ha^{-1}-day^{-1}			nc	nc	nc	nc	nc	nc

[a] Values are the means ± SD of four to seven samples. from different weekly harvests. n, number of samples.
[b] Not calculated.

Table 3
N and P content of washed algae and remaining fine solids from four harvests from the Patuxent site in 2006.

	July 29[a]	August 3	August 7	August 13
Fine solids				
Mass (g DW m^{-2} day^{-1})	nd[b]	6.7 ± 5.9	10.6 ± 4.8	9.1 ± 0.4
Ash content (%)	nd	81 ± 4	83 ± 3	84 ± 7
N content (%)	nd	0.87 ± 0.05	0.92 ± 0.20	0.94 ± 0.05
TN (mg m^{-2} day^{-1})	nd	56 ± 48	93 ± 26	85 ± 8
P content (%)	nd	0.21 ± 0.04	0.23 ± 0.01	0.23 ± 0.02
TP (mg m^{-2} day^{-1})	nd	13 ± 10	24 ± 9.4	20 ± 2.7
Washed algae				
Mass (g DW m^{-2} day^{-1})	4.9 ± 0.2	4.2 ± 1.0	6.8 ± 3.5	13 ± 13
Ash content (%)	68 ± 9.9	60 ± 16	57 ± 4.9	61 ± 5.7
N content (%)	1.9 ± 0.2	2.2 ± 0.6	2.3 ± 0.4	2.1 ± 0.4
TN (mg m^{-2} day^{-1})	92 ± 15	94 ± 48	147 ± 53	304 ± 316
P content (%)	0.28 ± 0.05	0.29 ± 0.05	0.29 ± 0.04	0.29 ± 0.04
TP (mg m^{-2} day^{-1})	13 ± 3.0	12 ± 4.9	19 ± 7.4	40 ± 40
Recovery in washed algae (%)				
Mass	nc[c]	45 ± 19	38 ± 2.1	51 ± 27
TN	nc	66 ± 10	61 ± 2.0	68 ± 25
TP	nc	53 ± 11	44 ± 0.5	56 ± 27

[a] Values are the means ± SD of values from duplicate ATS units.
[b] Samples not collected.
[c] Not calculated.

operation in August 2007 and reached maximum removal values of 130 mg TN, 15 mg TP m^{-2} day^{-1} from October 15 to November 15, 2007, then decreased to values of 50 mg TN, 8 mg TP m^{-2} day^{-1} from November 15, 2007 to early April 2008(Table 2, Fig. 4E and F). In the best case (Patuxent site from May to October 2007), daily removal rates of 250 mg N and 45 mg P m^{-2} are equivalent to removal rates of 380 kg N and 70 kg P ha^{-1} over a 150-day season in Maryland (Table 2).

Although these ATS units were short and vigorously flushed, sediment was evident in the harvested material from all three sites. Sediment in the system (and associated captured nutrients) will influence the choice and efficiency of biomass harvesting and dewatering equipment in large-scale ATS systems. In order to characterize the relative proportions of solids and nutrients associated with sediment and filamentous algae in ATS harvests, sub-samples of harvested material from the Patuxent site were subjected to multiple rounds of washing and sieving. The proportions of solids, N, and P associated with washed filamentous algae versus the fine solids from four harvests are shown in Table 3. N content in the washed algae (mean values ranging from 1.9% to 2.3% N) was roughly twice as high as the N content of the fine solids (mean values of 0.9% N). P content of the washed algae (0.29% P) was about 25% higher than the P content of the fine solids (0.23% P). Mean ash content values of the washed algae and fine solids were about 60% and 83%, respectively. Calculated recovery values show that the washed algae constituted 40–50% of the total dry harvested mass, 65% of total N and 45–55% of total P.

3.3. Fatty acid content and composition of ATS biomass

Fatty acid (FA) content of the harvested material from each site was relatively consistent over time and varied only slightly between sites (from 0.4% of DW at the Patuxent site to 0.7% of DW at the Patapsco site) (Table 4). In order to characterize the fatty acids associated with sediment versus those associated with filamentous algae in ATS harvests, we determined the FA content of four Patuxent River samples of washed filamentous algae and the corresponding fine sediment samples (described above). As expected, the FA content of the washed algae was considerably

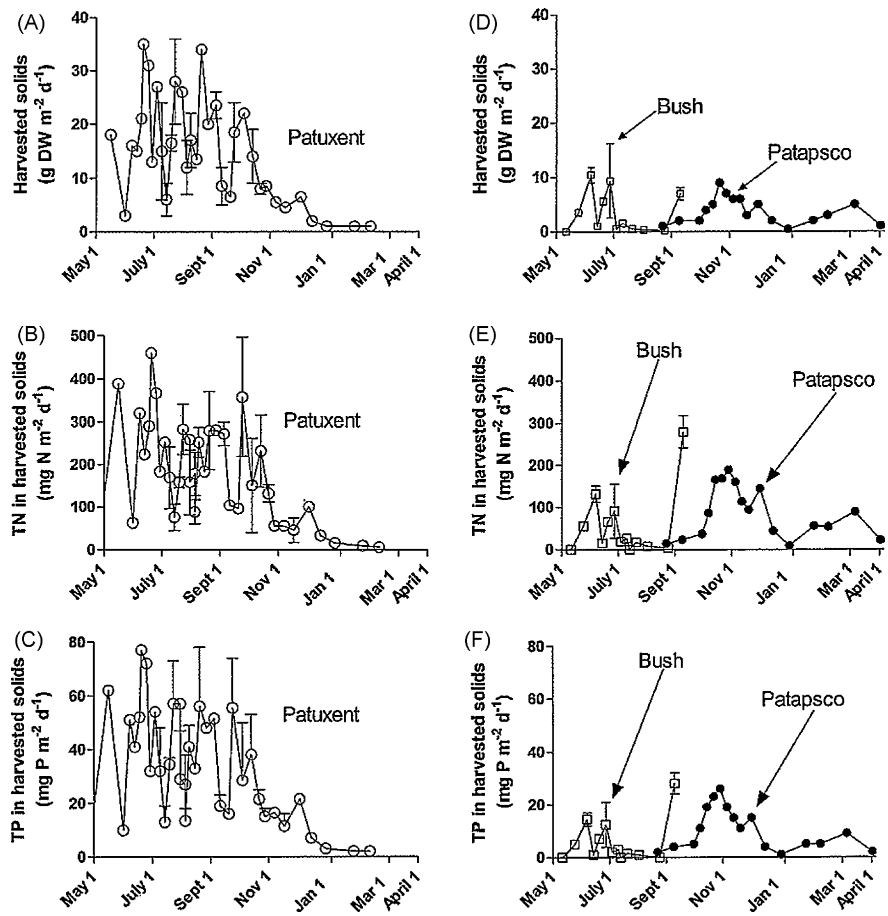

Fig. 4. Harvested solids and nutrient removal rates from ATS units at three river sites during May 2006 to April 2007. Values are from a single ATS unit (Patapsco site) or are average values from two units (Patuxent and Bush River sites). Error bars are standard error.

Table 4
Fatty acid content, production rate, and composition (means ± std. dev.) in algal biomass from ATS units at three Chesapeake Bay tributaries.

	Patuxent (n = 11)[a]	Bush (n = 5)	Patapsco (n = 9)
Harvested solids (g DW m^{-2} day^{-1})	16.3 ± 9.0[b]	3.6 ± 4.7[c]	3.8 ± 2.4[d]
Fatty acid content (% of DW)	0.34 ± 0.14	0.51 ± 0.19	0.65 ± 0.21
Fatty acid productivity (mg FA m^{-2} day^{-1})	54 ± 22	23 ± 13	25 ± 8
Fatty acid productivity (kg FA ha^{-1} $year^{-1}$)[e]	81 ± 33	34 ± 20	37 ± 12
Fatty acid			
14:0	20.0 ± 4.5[f]	16.2 ± 3.7	26.5 ± 8.0
16:0	46.0 ± 8.8	41.5 ± 5.9	41.8 ± 5.9
16:1ω7	23.3 ± 8.9	16.5 ± 5.6	20.8 ± 9.7
18:0	4.3 ± 3.8	8.1 ± 3.1	4.3 ± 4.5
18:1ω9	3.8 ± 6.4	5.6 ± 1.4	0.7 ± 1.4
18:2ω6	1.1 ± 2.9	4.7 ± 7.2	nd[g]

[a] Number of samples.
[b] Mean value for May 16–October 10, 2007.
[c] Mean value for May 21–August 22, 2007.
[d] Mean value for October 11, 2007 to April 2, 2008.
[e] Calculated value based on 150 days of operation per year.
[f] FA composition values are expressed as % of total FA in the sample.
[g] Not detected or <1% of total FA.

higher (0.8–1.1% of DW) than that of the fine sediment (0.2–0.5% of DW) (not shown). However, the FA compositions of washed algae and corresponding fine sediment samples from the Patuxent site were very similar (not shown). The FA composition of the harvested material was relatively consistent among all samples and >75% of the FA content consisted of the three fatty acids 14:0, 16:0, and 16:1ω7 (Table 4).

4. Discussion

4.1. Nutrient removal

The primary focus of this study was to determine seasonal ATS nutrient removal values from Chesapeake estuaries. In the best case (Patuxent River site from May to October 2007), daily removal rates of 250 mg N and 45 mg P m^{-2} are equivalent to removal rates of 375 kg N and 68 kg P ha^{-1} over a 150-day season. However, nutrient removal values at the Bush River site were much lower over the same period (averaging only 40 mg TN, 7 mg TP m^{-2} day^{-1} from May to June 2007, before decreasing to <10 mg TN, 3 mg TP m^{-2} day^{-1} for July to October). At present, we cannot explain the cause of the lower productivity at the Bush River site. Nutrient levels of the influent water (as measured by weekly grab samples) were roughly similar at both sites and submerged aquatic vegetation was abundant at both sites. Chironomid larvae were evident in the biomass at both sites. We were not able to separate grazing effects from net productivity values. Nutrient removal values at the third site (Patapsco River) were available only for the late summer through winter. During this period, when light presumably limited growth, removal values were comparable to values from the Patuxent site.

A pilot-scale ATS facility in southern Florida using agricultural drainage water reported average nutrient removal rates of 360 mg N, 90 mg P m^{-2} day^{-1} (based on productivity and biomass content values of 12 g m^{-2} day^{-1}, 3% N, 0.75% P, respectively) (Hydromentia Inc, 2005). These rates correspond to annual rates of 1300 kg N, 330 kg P ha^{-1}, assuming continuous operation throughout the year. Our much lower estimates for nutrient removal rates in Maryland are due to a much shorter operational period (150 days) and to much lower values for N and P content (1.2% and 0.2%, respectively) in the harvested material.

4.2. Fatty acid production

The FA content values of ATS algae grown on diluted dairy or swine effluent in a closed recirculating ATS system generally ranged from 1% to 2% DW (Mulbry et al., 2008a). Prior to this study, the FA content of ATS algae grown using natural waters had not been reported and we speculated that FA values might be relatively high in a single pass system using natural waters because of the presence of diatoms. However, our results did not support this hypothesis. FA content of the harvested material was consistently low over time and varied little between the sites (from 0.35% to 0.65% DW). As expected, the presence of fine sediment with low FA content in the harvested material contributed to the low overall FA content. Mean algal FA production rates (23–54 mg FA m^{-2} day^{-1}) are equivalent to rates of 34–81 kg FA ha^{-1} $year^{-1}$ based on a 150-day operational season in Maryland. It is unlikely that this biomass would successfully compete with other feedstocks (Chisti, 2007).

The potential of biofuel production with the Chesapeake Bay watershed as been reviewed (Chesapeake Bay Commission, 2007, 2008) and opportunities may exist to utilize biomass from algal turf scrubbers for this purpose. Beyond biodiesel production, a variety of algae-based bioenergy strategies have been proposed, including low temperature gasification, direct incineration and fermentation (Chen and Oswald, 1998; Minowa and Sawayama, 1999; Sawayama et al., 1999; Li et al., 2007; Cantrell et al., 2008). Within these strategies, wastewater-grown biomass is likely to compete very well with biomass cultivated only for its biofuel value. Ultimately, life cycle assessments will be essential in determining the best use for wastewater-grown biomass (Aresta et al., 2005).

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References

Adey, W.H., Luckett, C., Jenson, K., 1993. Phosphorus removal from natural wasters using controlled algal production. Restor. Ecol. 1, 29–39.

Adey, W.H., Luckett, C., Smith, M., 1996. Purification of industrially contaminated groundwaters using controlled ecosystems. Ecol. Eng. 7, 191–212.

Aresta, M., Dibenedetto, A., Barberio, G., 2005. Utilization of macro-algae for enhanced CO_2 fixation and biofuels production: development of computing software for an LCA study. Fuel Process. Technol. 86, 1679–1693.

Cantrell, K., Ducey, T., Ro, K., Hunt, P., 2008. Livestock waste-to-energy generation opportunities. Bioresour. Technol. 99, 7941–7953.

Chen, P.H., Oswald, W.J., 1998. Thermochemical treatment for algal fermentation. Environ. Int. 24, 889–897.

Chesapeake Bay Commission, 2004. Cost Effective Strategies for the Bay, 13 pp. http://www.chesbay.state.va.us/cost%20effective.pdf.

Chesapeake Bay Commission, 2007. Biofuels and the Bay, Getting It Right to Benefit Farms, Forests and the Chesapeake, 34 pp. http://www.chesbay.state.va.us/Publications/BiofuelsAndTheBay1.pdf.

Chesapeake Bay Commission, 2008. Next-Generation Biofuels, Taking the Policy Lead for the Nation, 40 pp. http://www.chesbay.state.va.us/Publications/nexgen%20biofuels1.pdf.

Chesapeake Bay Foundation, 2004. Manure's Impact on Rivers, Streams and the Chesapeake Bay: Keeping Manure Out of the Water, 26 pp. www.cbf.org/site/DocServer/0723manurereport_noembargo_.pdf?docID=2143.

Chisti, Y., 2007. Biodiesel from microalgae. Biotechnol. Advan. 25, 294–306.

Craggs, R.J., Adey, W.H., Jessup, B.K., Oswald, W.J., 1996. A controlled stream mesocosm for tertiary treatment of sewage. Ecol. Eng. 6, 149–169.

Hydromentia Inc., 2005. S-154 Pilot Single Stage Algal Turf Scrubber Final Report. South Florida Water Management District Contract No. C-13933. http://www.hydromentia.com/Products-Services/Algal-Turf-Scrubber/Product-Documentation/Assets/2005_HMI_S1540-Single-Stage-ATS-Final-Report.pdf, 81 pp.

Kebede-Westhead, E., Pizarro, C., Mulbry, W., 2003. Production and nutrient removal by periphyton grown under different loading rates of anaerobically digested flushed dairy manure. J. Phycol. 39, 1275–1282.

Kebede-Westhead, E., Pizarro, C., Mulbry, W., 2006. Treatment of swine manure effluent using freshwater algae: production, nutrient recovery, and elemental composition of algal biomass at four effluent loading rates. J. Appl. Phycol. 18, 41–46.

Li, X., Xu, H., Wu, Q., 2007. Large-scale biodiesel production from microalga Chlorella protothecoides through heterotrophic cultivation in bioreactors. Biotechnol. Bioeng. 98, 764–771.

Minowa, T., Sawayama, S., 1999. A novel microalgal system for energy production with nitrogen cycling. Fuel 78, 1213–1215.

Mulbry, W., Kondrad, S., Buyer, J., 2008a. Treatment of dairy and swine manure effluents using freshwater algae: fatty acid content and composition of algal biomass at different manure loading rates. J. Appl. Phycol. 20, 1079–1085.

Mulbry, W., Kondrad, S., Pizarro, C., Kebede-Westhead, E., 2008b. Treatment of dairy manure effluent using freshwater algae: algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers. Bioresour. Technol. 99, 8137–8142.

Mulbry, W., Kondrad, S., Pizarro, P., 2006. Biofertilizers from algal treatment of dairy and swine manure effluents: characterization of algal biomasss as a slow release fertilizer. J. Veg. Sci. 12, 107–125.

Pizarro, C., Mulbry, W., Blersch, D., Kangas, P., 2006. An economic assessment of algal turf scrubber technology for treatment of dairy wastewater. Ecol. Eng. 26, 321–327.

Sawayama, S., Minowa, T., Yokoyama, S.-Y., 1999. Possibility of renewable energy production and CO_2 mitigation by thermochemical liquefaction of microalgae. Biomass Bioenergy 17, 33–39.