Final Report on the Susquehanna River Algal Turf Scrubber Project

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Main Findings of the Report:

Over a growing season of 8 months, net biomass production averaged 14.0 grams dry weight/m2/day for the aluminum ATS and 11.7 grams dry weight/m2/day for the wooden ATS with a peak of 24.5 grams dry weight/m2/day on 7/28/08.

These net biomass production values are higher than any published values from natural aquatic plant communities in the Chesapeake Bay.

Biomass production was composed of the vacuum harvest (52% of the total production for the aluminum ATS and 29% for the wooden ATS), the "greenwater" (42% of the total production for the aluminum ATS and 66% for the wooden ATS) and the slough (6% of the total production for the aluminum ATS and 5% for the wooden ATS).

During 2009 at peak metabolism the wooden ATS decreased nutrient concentrations to a greater degree (nitrate-N 27%, orthophosphate-P 50%, total N 37% and total P 17%) than the aluminum ATS (nitrate-N 18%, orthophosphate-P 17%, total N 28% and total P 9%).

Algal biomass averaged between 2-3% nitrogen content and between 0.25-0.35% phosphorus content, depending on the component (vacuum harvest, greenwater, slough).

Net production based on ecosystem metabolism measurements of the two ATS varied seasonally from 2.8 to 22.1 grams oxygen/m2/day.

Species diversity of the ATS was high: 195 species from six algal phyla on the aluminum ATS and 196 species from five algal phyla on the wooden ATS

NARRATIVE

This is the final report on the Susquehanna River ATS (algal turf scrubber) project. The proposal for the project was submitted in late spring of 2007 and the intention was to have the ATS operational by early spring 2008. The summer of 2007 was spent searching for a suitable site with close proximity to the river, no shading and security. Contact was eventually made with the Exelon Energy Corporation, which operates several power plants on the lower Susquehanna River. The manager of the Conowingo hydroelectric plant became interested in the project and she assisted in establishing and conducting the project since the first contact. Meetings were held with Exelon administrators during the fall and winter in order to secure corporate permission to operate the ATS on Exelon property. After extensive communications between the Exelon Corporation, the Smithsonian Institute's National Museum of Natural History and the University of Maryland, a suitable agreement was established for the research to be carried out at the Muddy Run hydroelectric power plant in Lancaster County, Pennsylvania. The Hydromentia Corporation of Ocala, Florida fabricated the ATS from aluminum and had it shipped to the site in late spring of 2008. The system was constructed at Muddy Run with assistance from Exelon staff and from the company Living Ecosystems of Easton, Maryland. The dimensions of the original system were 1' by 300' and it was positioned at a 2% slope.

Construction of the ATS was completed on 6/6/08 with water input from the Muddy Run Reservoir. Rocks from the Susquehanna River at Muddy Run were added to the ATS to both provide a seed source for benthic algae and to submerge the ATS screen, which was not physically attached to the trough or bed of the ATS. Wire braces were also installed in order to keep the screen submerged. Benthic algae from a local creek, which were placed in bags fashioned from the ATS screen material, was also used to seed the system. Local streams were searched for Cladophora, which was not found at the Muddy Run site. Two nearby streams with Cladophora were located and rocks from these streams were added to the system with the intention of adding this genus to the scrubber community.

An algal community developed relatively rapidly and the system was first harvested on 6/23/08 to initiate the study of biomass production and nutrient dynamics. Measurements of biomass production, or net primary production, began on 6/28/08 and continued throughout the growing season approximately every five-seven days. Once the algal community was well established, the rocks and screen bags were removed from the system on 7/3/08. This action unfortunately caused the screen to float more than anticipated, which in turn significantly reduced algal growth. Thus, the rocks were added back into the system on 7/8/08 and the algal growth rate rebounded after several harvests.

An additional ATS was constructed out of wood with fiberglass coating by Living Ecosystems with the same dimensions as the original aluminum ATS. This system was installed parallel to the aluminum ATS at a 1% slope in order to investigate the effect of system slope on productivity and nutrients. The wooden ATS also differed from the aluminum ATS in mesh size of the screen used to grow algae: the wooden ATS had a mesh size of 0.04 cm2 while the original aluminum ATS had a mesh size of 0.25 cm2. The different mesh sizes were used to investigate the effort of screen surface area (which was assumed to be inversely related to mesh size) on productivity. The wooden ATS was constructed in the early fall 2008 and it was first harvested on 10/16/08. Both ATS were operated through the fall and the last harvests were taken on 12/8/08.

The intention was to operate both ATS through the winter but cold temperatures (see Figure 1) caused the water in the systems to freeze periodically. Freezing started at the bottom of the ATS and this caused water to spill on to the ground creating a sheet of ice around the systems. The ice was a safety hazard so the ATS were shut down several times during the winter and early spring. Thus, no harvests were taken during the winter because of the freezing problem.

Water flow was restored in March 2009 and algal growth occurred immediately. The systems were first harvested on 4/14/09. After an annual cycle of data was gathered from the original aluminum ATS at the end of July 2009, its slope was dropped to 0.5% in order to investigate the effect on productivity through the late summer and fall. The last harvest of the study occurred on 10/29/09 once an annual cycle of data had been gathered on the wooden ATS. After this time, emphasis in the project shifted from field work to analysis of data and to final report preparation.

A four month-long infestation of herbivorous chironomid fly larvae occurred in 2009 that dominated the ecology of the systems. This infestation was somewhat surprising since no chironomids were observed in the systems in 2008. The chironomids first appeared in late May 2009 in the aluminum ATS and they cleared algae from portions of the screens in the lower and middle sections of the ATS by feeding throughout the summer. The larvae were present in the wooden ATS during this time but they did not cause visible eat-outs until late July. The intensity of the herbivory was not uniform throughout the ATS but the chironmids did consume enough algae to cause large areas of bare screen in the systems. Several control techniques were used to manage the infestation including altered harvest frequencies, short term (usually 3 day duration) drainage of the systems and introduction of a bacterial insecticide. These control techniques did reduce chironomid densities but the fly larvae always returned. The chironomids seemed to enter the system through the input water, though it is possible that egg laying by adults within the raceways could have contributed to the population. The infestation disappeared in mid-September, presumably due to seasonal completion of the fly life cycle. After this time algal growth increased and full coverage of the screens developed.

METHODS

Basic Water Quality

Water quality parameters were measured before each harvest in the late morning or afternoon in order to quantify the maximum effect of metabolism of the algal community. Measurements were made at the top of the system, where water enters from the Muddy Run reservoir, and at the bottom of the system, as the water flows into the river. The difference between bottom and top values indicates the effect of algal metabolism as water passes over the turf. Water temperature, dissolved oxygen concentration and percent saturation of dissolved oxygen in the water were measured with a YSI meter and pH was measured with an Accumet meter. On 10 dates, water quality parameters were measured over a diurnal cycle in order to assess ecosystem metabolism of the turf communities.

Biomass Harvest

Algal biomass was harvested in sample sections along the length of the ATS in order to identify possible longitudinal changes in the community. Several different patterns of harvests were tried initially. The final pattern of harvest was established on 7/28/08 and it was used throughout the study. For the aluminum ATS biomass was harvested in two adjacent 10' sections of the scrubber near the top of the system (T1 at 50 to 60 feet downstream from the surge box, T2 at 60 to 70 feet), in the middle (M1 at 170 to 180 feet, M2 at 180 to 190) and at the bottom of the system (B1 at 280 to 290 feet and B2 at 290 to 300 feet). This pattern of harvest included replication of sampling (n=2) at three different locations along the longitudinal gradient of input of water at the top of the system to the output of water at the bottom of the system. Each individual section of the aluminum ATS had an area of approximately 0.9 m2 (the one foot wide trough x a 10' section between supports on the trough) while each section of the wooden ATS had an area of approximately 0.7 m2. For the aluminum ATS the total sample area at each harvest was then 5.4 m2 which is 20 % of the total scrubber area (27.6 m2) for the aluminum ATS. At the time of harvest the water input to the ATS was turned off at the inflow faucet and the scrubber was allowed to drain for between ½ - 1 hour. Harvesting was done with a wet/dry vacuum. Each sample section of the trough was vacuumed, starting at the top of the system and working sequentially downstream. The entire ATS area (except for the first section below the surge box which was maintained as an unharvested refuge) was harvested but only the biomass production samples were retained for measurements. After a sample section was vacuumed, the resulting slurry was dewatered by sieving the harvested material through a 3mm mesh nylon netting (Aquatic Ecosystems, Apopka, FL). The biomass retained in the net was air-dried at 25 degrees C using an electric fan, oven-dried at 70 degrees C for 24 hours and then weighed. Data for biomass production or net primary production were calculated by dividing the oven-dried mass by the number of days between harvest dates. Throughout the study 235 vacuum harvest samples were analyzed for the aluminum ATS and 160 were analyzed for the wooden ATS.

Two other components of the biomass production of the algal turf community were assessed: algal biomass suspended in the water that was sieved through the nylon netting (termed "green water") and algal biomass that broke off from the turf between harvests (termed "slough"). For biomass in green water, the volume of sieved water was measured at the time of harvest and a one liter sample was collected and returned to the laboratory. The biomass was allowed to settle out of suspension in the sample bottle creating a dense layer in the bottom of the bottle. The overlying water was removed by vacuuming or decanting and the remaining slurry that contained the biomass was spread out on a tray lined with a plastic film and the water was allowed to evaporate. The biomass remaining after evaporation was oven-dried at 70 degrees C and weighed. Biomass production of the green water component was calculated by dividing the biomass by the area of turf that was harvested and sieved and by the number of days between harvest dates. Routinely, green water was combined for paired samples at the top, middle and bottom of the ATS resulting in three samples for each harvest date after 7/28/08. Throughout the study 105 greenwater samples were analyzed for the aluminum ATS and 68 were analyzed for the wooden ATS. Biomass that sloughed from the turf between harvest dates was collected in a nylon mesh bag that was attached to the outlet drain pipe at the bottom of the ATS. Material collected in the bag was removed at the time of harvest and it was processed by the same procedure as the biomass harvest collected with the wet/dry vacuum. To calculate the slough production, the biomass collected between harvest dates was divided by the total area of the scrubber and by the number of days between harvests. Throughout the study 23 slough samples were analyzed for the aluminum ATS and 10 were analyzed for the wooden ATS.

Ecosystem Metabolism

Diurnal curve analysis of dissolved oxygen concentration was used to estimate ecosystem metabolism and to help assess the functioning of the ATS systems. Nine diurnal curves were measured during the study period covering all of the seasons of the year. The basic water quality parameters of temperature, dissolved oxygen concentration, percent saturation of oxygen and pH were measured at various time intervals over a 24-hour time period to create the diurnal curves. Ecosystem metabolism was estimated using the dissolved oxygen concentration data. The concentration at the top of the system (input water) was subtracted from the concentration at the bottom of the system (output water) and this difference was divided by the turnover time of water in the system (an average of 10 minutes was used) to calculate rates of oxygen change. These rates of change in oxygen concentration were then plotted over 24 hours and graphically integrated to estimate metabolism. This approach is essentially a modified version of the standard upstream-downstream technique for measuring ecosystem metabolism in flowing water systems (Odum 1956).

No corrections to the rate-of-change curves were made for ambient diffusion based on three reasons. First, percent saturation of dissolved oxygen was usually near 100% when top (input) and bottom (output) samples were averaged. Second, it was assumed that the fast turnover time of water in the system (about 10 minutes) precludes any major changes in oxygen concentration due to diffusion. Third, upstream-downstream sampling of dead turfs, either during the winter or after drainage for chironomid control in the summer of 2009, indicated little evidence of physical diffusion.

Nutrients

Water samples were collected at the inflow and at the outflow of the ATS before harvests. These samples were acidified and stored, usually at 4 degrees C, prior to analysis for total nitrogen (TN), nitrate-nitrogen (NO3-N), total phosphorous (TP) and orthophosphate-phosphorous (PO4-P). The water samples were also analyzed ammonium-nitrogen but the resulting values were below detection limits or non-interpretable. Biomass samples were analyzed for TN and TP after oven-drying.

Algal Community Structure

Samples of algae from the scrubber were collected periodically and examined with a compound microscope for the purpose of describing the structure of the community at the time of almost every harvest. Two or three samples from each turf along with a sample of the green water and a sample of the slough were routinely collected before each harvest and these were examined to rapidly assess the dominant alga taxa and the overall condition of the system. Samples were collected for a more in-depth assessment of the species composition of the turfs on 7/23/08, 8/1/08, 10/27/08, 4/7/09, 6/12/09, 7/17/09, 10/9/09. These samples were carefully examined in order to construct a species list of algal taxa found on the scrubber.

RESULTS

Water Quality

Water input to both of the ATS came from the Muddy Run Reservoir, which is filled from and drained to the Susquehanna River on a daily basis in the operation of Exelon's pumped-storage hydroelectric facility. The quality of the input water to the ATS was thus modified from the ambient river conditions by a relatively short retention time in the reservoir. At one seasonal extreme, during the summer, input dissolved oxygen concentration was low at around 4 mg/l with about 50% saturation and pH was about 7.5. At the other seasonal extreme, during the winter, input dissolved oxygen concentration was high at around 12 mg/l with about 90% saturation and pH was about 8.0. Passage of the input water through the ATS increases dissolved oxygen concentration, percent oxygen saturation and pH in proportion to ecosystem metabolism of the ATS, as will be discussed in a later section of this report. During mid-day these increases are dramatic with dissolved oxygen concentration and percent saturation more than doubling and pH increasing by nearly two units from top to bottom of the ATS raceways. These increases are especially noteworthy given that the turnover time of water in the systems was between 7 and 10 minutes.

Average nutrient concentrations (n=17) of the input water were as follows: 0.89 mg/l NO3-N, 1.38 mg/l TN, 0.06 PO4-P, and 0.12 mg/l TP. These nutrients were reduced by uptake in algal growth as the water passed along the ATS raceway. Mid-day removal percentages are given in Table 1. These data are point measurements within the diurnal cycle and they represent the maximal uptake rates since uptake is proportional to ecosystem metabolism and ecosystem metabolism is highest at mid-day.

Biomass Production

There were three components of algal biomass production for the ATS based on the methods described above: the biomass harvested with the wet/dry vacuum (vacuum harvest), the biomass contained in the water drained from the vacuum harvest (green water) and the biomass that sloughed off the turf between harvests and that was collected in the net at the bottom of the system (slough). Overall biomass production data are summarized in Tables 2a and 2b with seasonal and growing season averages. Average total daily production was slightly higher for the aluminum ATS (14.0 g/m2/day) in comparison with the wooden ATS (11.7 g/m2/day). Peak production occurred in the summer months for both ATS. The highest daily production occurred on the aluminum ATS on July 28, 2008 at 24.5 g/m2/day.

Vacuum harvest contributed about half of the growing season production for the aluminum ATS and about 30% of the total for the wooden ATS. These samples were dominated by a mixture of filamentous green algae (Spirogyra was dominant) and filamentous diatoms (Melosira was dominant) along with pinnate diatoms and bluegreen algae (Oscillatoria and Phormidium).

Green water biomass production contributed 42% of the aluminum ATS production and 66% of the wooden ATS production. These samples were strongly dominated by fragments of filamentous diatoms and by pennate diatoms, with practically no filamentous green algae. Averaged over the entire study, average greenwater concentration was 14.2 g dry weight/liter and average greenwater volume was 7.4 liters/m2 of turf for the aluminum ATS. Average greenwater concentration was 11.3 g dry weight/liter and average greenwater volume was 8.0 liters/m2 of turf for the wooden ATS.

Slough biomass production contributed about 5% of the total production for both ATS. These samples were strongly dominated by the filamentous green alga, Spirogyra, though all species from the turf were present in small amounts. This portion of the overall production was the most difficult to measure and more study is required for adequate quantification. Problems occurred when the slough bag would become detached between harvests. Also, in the fall season deciduous leaves from nearby trees fell and collected in the slough bags and it was not possible to physically separate leaves from the algae in order to quantify slough.

Nutrient Uptake Rates

Nutrient uptake by the ATS was found by multiplying biomass production rate (g dry weight/m2/day) by the nutrient contents of the biomass (%). These data are illustrated for the aluminum ATS in Figures 2 and 3. Data for biomass production in these figures is from Table 2a. Although the magnitudes of nutrient contents differed between the different components of biomass production, the ratios between nitrogen (N) and phosphorous (P) are about 8 to 1 for the different components. For the aluminum ATS total uptake rates are 0.34 g N/m2/day and 0.04 g P/m2/day.

Ecosystem Metabolism

Diurnal curve analysis of ecosystem metabolism provides a holistic view of the functioning of the ATS. Dissolved oxygen concentration at the bottom of the systems rises during the day due to photosynthesis and falls at night due to respiration. pH at the bottom of the systems also has this diurnal pattern of change but this reflects dissolved CO2 dynamics since pH is inversely proportional, in a non-linear fashion, to CO2 concentration dissolved in the water.

The dissolved oxygen rate-of-change graph for 6/11/09-6/12/09 is given in Figure 4. This graph uses the convention of starting diurnal curves at midnight (12:00AM) so a break is shown where the data begins on one day and ends on the next day (6/11/09 on the right and 6/12/09 on the left). Analysis of this particular diurnal curve yielded a net production value of 20.5 grams O2/m2/day. By using a metabolic conversion of 0.728 grams dry weight/gram O2 produced (Remmert 1980), the net primary production for this date was 14.9 grams dry weight/m2/day which is the same order of magnitude as summer 2009 biomass values (see Table 2b). Values for net production from the other diurnal curves are given in Table 3 and they also indicate the general consistency between the measurement of net production by biomass harvest, as described earlier, and by the dissolved gas analysis of the diurnal curves.

An interesting feature of most of the diurnal curves is the minor role played by community respiration in the ATS. Respiration occurs when oxygen change is negative. As an example of this issue, note that oxygen change never was negative for the rate-of-change graph given in Figure 4. Day-time respiration is masked by net production, but at night the rate-of-change of oxygen should become negative. Although some negative rates-of-change did occur on some of the diurnal curves, these rates were always relatively low. In part, the negative rates-of-change at night were mitigated by apparent turbulent diffusion at the top of the system due to the wave generation mechanism. This effect was measured to be an immediate increase of 1 – 2 mg/l of oxygen once the input water enters the system. Corrections for this increase were made in the analysis of the curves. Thus, total oxygen increase at the bottom of the system is partly due to ecosystem metabolism and partly due to physical, turbulent diffusion.

Algal Community Structure

A total of 195 species were identified from six algal phyla on the aluminum ATS over the study period (Figure 5) and a total of 196 species were identified from five algal phyla on the wooden ATS (Figure 6). Many of the species were rare in the context of frequency of occurrence: 103 species or 53% of the total community were found only once (a frequency of 1/26 or 4%) on the aluminum ATS and 92 species or 47% of the total community were found only once (a frequency of 1/22 or 5%) on the wooden ATS. Thus, as is typical of any ecological community, most of the species in the algal turf community were rare.

Five species were found in at least half of the samples on the aluminum ATS (from the genera Navicula, Cyclotella, Spirogyra, Ulnaria and Melosira) and nine species were found in at least half of the samples on the wooden ATS (from the genera Navicula, Diatoma, Ulnaria, Nitzschia, Cyclotella, Melosira, Spirogyra, Syndra and Monorapidium).

DISCUSSION

Overall Productivity

The two ATS raceways at Muddy Run had net productivities that were comparable to other published outdoor studies from the Chesapeake (Mulbry et al. 2008, in press). Growing season averages were also higher than any reported net productivity from a natural aquatic plant community from the Chesapeake Bay (Table 4). The amplified productivities of the ATS over the natural communities is presumably due to the energy subsidies of the engineered design that the ATS receive from the artificial substrate and pulsing water flows but high species diversity may also play a role as will be discussed in the next section.

However, there are reasons to question whether the ATS productivities measured at Muddy Run might be less than what could have been achieved. General predictions for ATS productivity suggested that >30 grams dry wt./m2/day might be possible (Adey and Loveland 2007). In fact, higher productivities have been measured in similar ATS raceways in the more southerly portions of the bay on the Wicomico River in Virginia (W. Adey, personal communication) and at the Virginia Institute of Marine Science at the mouth of the York River (E. Duffy, personal communication).

One possible cause of reduced productivity in the Muddy Run ATS studied here was artificial shading from the walls of the raceways. A preliminary study was made in the late fall 2008 to test this hypothesis. Shading by the walls may be suspected to be significant at this season, due to the reduced angle of the sun in the sky. Algal biomass was harvested from five sections of the aluminum ATS and then these sections were allowed to grow back. At the next harvest biomass in the shaded half of the raceway was gathered separately from biomass in the unshaded half of the raceway. After processing, the results indicated 20% greater production in the lighted half of the system compare to the shaded half. Thus, shading may well be limiting productivity of the ATS at least during certain times of the year.

One remarkable finding of this study was the relative lack of effect of chironomid herbivory on overall productivity of the ATS. This observation comes from comparing productivity during the summer of 2008, when no chironomids were found on the ATS, to productivity during the summer of 2009, when chironomids were abundant and their feeding creating bare areas on the screens with no filamentous algae. Apparently, productivity shifted from filamentous species to single-celled species during the chironomid outbreak and this pattern is indicated to some extent by the changes in proportion of the vacuum harvest (which was dominated by filamentous species) in relation to the greenwater harvest (which may have had greater contribution from single-celled pinnate diatoms). This pattern of biomass harvest productivity and herbivory was also found with oxygen-based productivity estimates. In general, there seemed to be some indication that the greenwater proportion of total productivity increases with stress, as noted above with chironomid, since this proportion was higher in the spring and fall when temperature and/or light levels may be limiting the metabolism of the system. The proportions of total productivity from vacuum harvest, greenwater and slough will have potentially significant implications for commercial-scale harvesting techniques, so this topic deserves further study.

Another hypothesis about limitations on Muddy Run ATS productivities concerned the slough component of biomass harvest. One idea was that slough biomass was being lost in the outlet water and that there was therefore biomass production missing from the totals reported in Table 2. Slough was difficult to measure due to problems with the bags attached to the outlet pipe at the bottom of the raceways. To test this hypothesis of missing slough biomass production, short-term (5 minutes) collections of slough were made over four diurnal cycles in summer-fall 2009. These data averaged 1.4 grams dry wt./m2/day for the aluminum ATS and 1.0 grams dry wt./m2/day for the wooden ATS.

These values are consistent with the longer term (5-7 days) collections of slough reported in Tables 2a and 2b so the hypothesis is not supported. The only other possibility is that the missing slough passed through the collection bags, both during the short-term and the long-term collections. If this situation is occurring, finer mesh collection bags will be required to sample this missing biomass and alternative processing techniques will be required to collect, dry and weigh it.

Algal Diversity

The sheer magnitude of the diversity of algal species found on the two ATS at Muddy Run is amazing. Nearly 300 species were found on the two scrubbers, which together make up only about 60 m2 of surface area. To some extent the high diversity of algal species on the ATS is due to the species diversity in the source communities for the systems. Ultimately, the source of species is the Susquehanna River, which is a lotic or flowing water ecosystem. However, the river water is passed through the Muddy Run Reservoir before it reaches the ATS. The reservoir is a lentic or standing water ecosystem. Thus, since different species are adapted to lotic vs. lentic ecosystems, these two sources probably contribute to the high diversity of the scrubbers.

Another factor that may have contributed to the species diversity on the scrubbers is the spatial heterogeneity of the systems. The scale of the systems is actually large, due to their 300' length and water flowing over this scale dimension created a mixture of regular, longitudinal zones and irregular, scattered patches. This spatial heterogeneity offers more opportunities for species colonization than would an equivalent surface area of a uniformly distributed environment.

The vertical structure of the turf community may contribute to the species diversity of the systems. The character of the algal communities is dominated by filamentous species, more-or-less attached to the screen, that form a "canopy" over the turf. Most of the rest of the community are single-cell "understory" species, some epiphytic on the filaments but many others just growing unattached among the filaments. Thus, the multicelled filaments themselves contribute to the diversity but they also may facilitate the presence of single-celled species.

Finally, there is a heterogeneity in time imposed on the scrubbers due to seasonal change in temperature and other factors. As with other ecological communities, a seasonal succession of species occur since different species are adapted to the different conditions of the seasons. Since the sampling of the turf communities spanned at least one annual cycle, the seasonal succession of species contributed to the diversity of the systems.

Understanding the causes of the high species diversity of the Muddy Run ATS deserves more study. The diversity seems to be higher than would be expected from any single natural algal community. A further question is whether or not the high diversity contributes to the high productivity of the ATS relative to natural communities as was discussed earlier. This kind of question illustrates the importance of studying the ecology of these systems in order to maximize their functioning in nutrient removal and biofuel feedstock production.

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Table 1. Average nutrient removal efficiencies measured at mid-day during spring-fall 2009 (n=17). These data were calculated by dividing the output concentrations (at the bottom of the systems) by the input concentrations (at the top of the systems).

Nutrient component	Aluminum ATS	Wood ATS
N-NO3	18%	27%
P-PO4	17%	50%
Total N	28%	37%
Total P	9%	17%

Table 2a. Biomass production of the Aluminum ATS at 2% slope. Data are grams dry weight/m2/day. Numbers in parentheses are the months included in the seasons.

Season	vacuum harvest	greenwater	slough	total
Summer 2008 (6-8)	14.2	2.4	1.4	18.0
Fall 2008 (9-11)	6.2	4.2	0.5	10.9
Winter 2008-2009 (12-3)	---	---	---	---
Spring 2009 (4-5)	4.0	8.6	0.7	13.3
Summer 2009 (6-7)	11.6	4.6	1.4	17.6
Fall 2009* (8-10)	6.6	6.3	0.7	13.6
Growing Season Averages (fall 08-summer 09)	7.3 (52%)	5.8 (42%)	0.9 (6%)	14.0

* at 0.5% slope

Table 2b. Biomass production of the Wooden ATS. Data are grams dry weight/m2/day. Numbers in parentheses are the months included in the seasons.

Season	vacuum harvest	greenwater	slough	total
Fall 2008 (10-11)	1.8	6.2	---	
Winter 2008-2009 (12-3)	---	---	---	
Spring 2009 (4-5)	1.3	10.3	---	
Summer 2009 (6-8)	4.8	6.6	0.9	12.3
Fall 2009 (9-11)	4.2	6.1	0.2	10.5
Growing Season Averages (spring 09-fall 09)	3.4 (29%)	7.7 (66%)	0.6 (5%)	11.7

Table 3. Net primary production for the Muddy Run ATS raceways as measured by diurnal oxygen curve analysis. Data are in units of grams O2/m2/day.

Dates	aluminum ATS	wooden ATS
9/17/08-9/18/08	11.1	---
10/29/08-10/30/08	6.2	9.8
12/18/08-12/19/08	6.8	2.8
4/7/09-4/8/09	4.0	3.4
6/11/09-6/12/09	4.0	12.3
7/30/09-7/31/09	15.8	21.6
8/13/09-8/14/09	15.9	17.4
9/25/09-9/26/09	20.9	22.1
11/12/09-11/13/09	8.4	8.1

Table 4. Comparison of growing season productivities for the ATS systems at Muddy Run and various natural aquatic plant communities of the Chesapeake Bay. Data for natural communities have been converted from various units to grams dry weight/m2/day, according to the footnotes given at the bottom of the table.

Plant community type	Net productivity	Reference
Aluminum ATS at Muddy Run	14.0	this study
Wooden ATS at Muddy Run	11.7	this study
Submerged aquatic vegetation*	2– 8	Stevenson 1988
Emergent marshes**	11.3	Wass and Wright 1969
	8.8	Johnson 1970
	4.9	Cahoon 1975
	3.1	Turner 1976
Phytoplankton***	2.5	Selner and Kachur 1987
	2.0	Boynton et al. 1982
	1.5	Harding et al. 1999

* calculated assuming dry weight is 50% carbon.

** calculated assuming that annual belowground net production equals annual aboveground net production and assuming a 9 month growing season.

*** calculated assuming dry weight is 50% carbon.