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Nutrient removal from agricultural drainage water using algal turf scrubbers and solar power

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HIGHLIGHTS

- We test algal turf scrubbers using agricultural drainage water and solar power.
- Algal growth rates using daytime flow were 3-fold lower than rates using 24-h flow.
- Nitrogen removal rates appear to be correlated to ATS water flow rates.
- Projected nutrient removal costs were much higher than those from previous studies.

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ABSTRACT

The objectives of this study were to determine nutrient removal rates and costs using solar-powered algal turf scrubber (ATS) raceways and water from an agricultural drainage ditch. Algal productivity using daytime-only flow was 3-lower compared to productivity using continuous flow. Results from this and other studies suggest a non-linear relationship between flow rate and nitrogen removal rates. Nitrogen (N) and phosphorus (P) removal rates averaged 125 mg N, 25 mg P m^{-2} d^{-1} at the highest flow rates. Nutrient removal rates were equivalent to 310 kg N and 33 kg P ha^{-1} over a 7 month season. Projected nutrient removal costs ($90–$110 kg^{-1} N or $830–$1050 kg^{-1} P) are >10-fold higher than previous estimates for ATS units used to treat manure effluents.

1. Introduction

Restoration of estuaries such as the Chesapeake Bay pose 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). Drainage ditches are a common feature within the Chesapeake watershed and are especially widespread on the Bay's largely agricultural eastern shore. Over 1300 km of ditches, maintained by virtue of special assessments from affected landowners, drain 74,000 ha of land on Maryland's Eastern Shore. Although these ditch systems were originally designed for rapid drainage of fields, they also provide a potential conduit for nutrient and sediment export into Chesapeake Bay tributaries.

One approach for removing drainage water nutrients is to deploy water treatment systems along narrow strips of land adjacent to the ditches. 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, 2013; Craggs et al., 1996; Mulbry et al., 2008; Mulbry et al., 2010; Sandefur et al., 2011). ATS systems offer a verifiable means to remove dissolved nutrients and yield a biomass suitable for use as a slow-release organic fertilizer (Pizarro et al., 2006; Mulbry et al., 2006).

Nutrient removal rates in ATS systems are functions of algal growth rates and algal nutrient content. In general, both growth rates and nutrient content are highly dependent on the influent water quality; increases in effluent nutrient concentrations lead to higher algal growth rates and to higher N and P content in the harvested algae. For example, an ATS project treating diluted dairy manure effluent yielded nutrient removal values of approximately 1000 mg N, 150 mg P m^{-2} d^{-1} (Mulbry et al., 2008). In contrast, an ATS project using agricultural drainage water (containing lower levels of influent N and P than that used in the manure ATS project)

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in southern Florida reported 3-fold lower nutrient removal values (300 mg N, 75 mg P $m^{-2} d^{-1}$) (Hydromentia Inc., 2005). Results from a more recent ATS project using lab-scale ATS units along three Chesapeake estuaries yielded roughly comparable results to those from Florida (Mulbry et al., 2010). However, the Chesapeake estuary ATS results varied considerably by location. In the best case (Patuxent River), daily removal rates of 250 mg N and 45 mg P m^{-2} were equivalent to removal rates of 375 kg N and 68 kg P ha^{-1} over a 150 day season. However, nutrient removal values were nearly 10-fold lower over the same period at a second site (Bush River) with comparable water quality.

The primary objectives of this study were to determine nutrient removal rates and costs using pilot-scale ATS raceways located along a primary agricultural drainage ditch on Maryland's eastern shore. Since drainage ditches are typically far from the electrical grid, raceway water pumps were powered by solar photoelectric arrays. Two water flow regimes were tested to determine the effect of water flow rate on algal growth and nutrient removal.

2. Methods

2.1. Construction and operation of algal turf scrubbers

Six pilot-scale ATS raceways (each containing 50 m^2 growing area) were constructed at a 2% slope in a field adjacent to at a primary agricultural drainage ditch (Mason Branch) near Bridgetown, Maryland. Each raceway consisted of a 1 × 50 m section of 0.045 mil EPDM pond liner (AKT Specialty Co., Newbern, TN) covered with 6 mm nylon mesh screen (Industrial Netting Co., Minneapolis, MN) and a 10 L tipping trough at the top of the raceway. PVC pipe (10 cm diameter) covered with black plastic sheeting separated the raceways. Influent water was delivered to the raceways using two independent solar arrays. Each array was connected to a variable speed well pump (described below). Effluent from all of the raceways drained through the mesh screen into a single EPDM lined sump (approximately 6 × 2 × 1.5 m (depth), 18 m^3 capacity) prior to draining into an existing field drainage ditch and back into Mason Branch. Water depth in the sump was controlled using an adjustable PVC standpipe (40 cm diameter).

Wet algal biomass was harvested weekly by sweeping the biomass onto mesh screens at the base of the raceways using nylon floor brooms. After each harvest, sump water (typically about 1200 L) was thoroughly agitated to resuspend sediment and algal fragments and then pumped into a plastic tank for volume measurement and sampling. Harvested biomass from the raceways was allowed to air-dry between harvests in the open air prior to being collected and transported back to the lab for final drying (as needed) and analysis. In the lab, biomass was air-dried at 25 °C using an electric fan to approximately 90% solids content.

2.2. Solar panels and pumps

Two separate solar power systems were installed at the Bridgetown site in 2011 and 2012. The first system (solar array #1) was designed to pump water during daylight hours only. It consisted of twelve 80 W panels (0.96 KW) directly connected to a variable speed Grundfos well pump (model 95027443) (Aquaflow Pump & Supply Co., Shippenville, PA). The cost of the panels and accessories was $7800 (2013 US$) and the pump cost was $1800 (2013 US$). The second system (solar array #2) was designed to run water continuously over the raceways. It consisted of ten 220 W panels (2.2 KW) connected to eight 230 amp/hour 12 V deep cycle batteries and a Grundfos well pump (Green Energy Design of Easton, MD). The cost of the 2.2 KW system was $15,700 (2013 US$).

2.3. 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) (APHA, 1998).

3. Results and discussion

3.1. Experimental design

Experiments were designed to compare flow regimes: continuous flow (24 h per day) from a pump powered by the solar panel-battery system versus daytime-only flow from the pump powered by solar panels alone. The first experimental hydraulic regime (9 weeks) ran daytime-only flow (approximately 12 h of no flow and 12 h of 150 LPM flow) using solar array #1 through one raceway and continuous flow of 95 LPM using solar array #2 through another raceway. The second experimental hydraulic regime (10 weeks) ran combined flow from both arrays through four raceways. In this regime, each raceway received 12 h of daytime flow at approximately 64 LPM and 12 h of nighttime flow at 26 LPM.

Influent water quality from Mason Branch was not monitored. Results from a long-term monitoring study including upstream samples showed low levels of nutrients (<0.5 mg L^{-1} TN, <0.1 mg L^{-1} TP) during base flow conditions (T. Fisher, unpublished results).

3.2. Algal community composition

Throughout the growing season, the distribution of algae on the screens was characterized by two main zones. A 2–3 m long zone was found at the top of the raceways, immediately below the tipping troughs, where energy from the pulsing flow was the highest. This zone was dominated by a near monoculture of *Ulothrix*, a filamentous green algal genus which has a strong basal attachment cell. The rest of the screen had a brown-colored mat with small patches of concentrated filamentous green algae. The brown-colored mat was dominated by the filamentous diatom, *Melosira*, along with detritus and a diversity of pennate diatoms that were either free-living or epiphytic on the *Melosira* filaments. Green algal filaments from the genera *Spirogyra*, *Microspora*, and *Ulothrix* were found within the brown colored mat as subdominants but they also formed patches with higher density. Blue-green algae represented by the genera *Oscillatoria* and *Phormidium* were often present within the brown-colored mat but they were never abundant.

3.3. Algal productivity

Overall production of algal biomass found in this study (roughly 5 g dry weight m^{-2} day^{-1}) (Table 1) was low in comparison with other studies from the Chesapeake Bay region using different water sources and different experimental regimes. In other studies, algal biomass productivity ranged from 10 to 25 g dry weight m^{-2} day^{-1} (Adey et al., 2013; Sandefur et al., 2011). Although no single factor appeared to be responsible for the low productivity, low water flow rates, and low influent nutrient concentrations are likely to be the most important factors. Water flow rates in this study were generally lower and much more variable than those used in previous studies and contributed to the low algal productivity. Fig. 1, which includes both published and unpublished results from ATS studies using natural waters within the Chesapeake Bay watershed, suggests a non-linear relationship between water flow rates and nitrogen removal rates. Within the low range of flow