Treatment of dairy manure effluent using freshwater algae: Algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers

Walter Mulbry *, Shannon Kondrad, Carolina Pizarro, Elizabeth Kebede-Westhead

United States Department of Agriculture, Beltsville Agricultural Research Center, Building 306, Room 109, BARC-East, 10,300 Baltimore Avenue, Beltsville, MD 20705, USA

ARTICLE INFO

ABSTRACT

Cultivating algae on nitrogen (N) and phosphorus (P) in animal manure effluents presents an alternative to the current practice of land application. The objective of this study was to determine values for productivity, nutrient content, and nutrient recovery using filamentous green algae grown in outdoor raceways at different loading rates of raw and anaerobically digested dairy manure effluent. Algal turf scrubber raceways (30 m^2 each) were operated in central Maryland for approximately 270 days each year (roughly April 1–December 31) from 2003 to 2006. Algal biomass was harvested every 4–12 days from the raceways after daily additions of manure effluent corresponding to loading rates of 0.3 to 2.5 g total N (TN) and 0.08 to 0.42 g total P (TP) m^{-2} d^{-1}. Mean algal productivity values increased from approximately 2.5 g DW m^{-2} d^{-1} at the lowest loading rate (0.3 g TN m^{-2} d^{-1}) to 25 g DW m^{-2} d^{-1} at the highest loading rate (2.5 g TN m^{-2} d^{-1}). Mean N and P contents in the dried biomass increased 1.5–2.0-fold with increasing loading rate up to maximums of 7% N and 1% P (dry weight basis). Although variable, algal N and P accounted for roughly 70–90% of input N and P at loading rates below 1 g TN, 0.15 g TP m^{-2} d^{-1}. N and P recovery rates decreased to 50–80% at higher loading rates. There were no significant differences in algal productivity, algal N and P content, or N and P recovery values from raceways with carbon dioxide supplementation compared to values from raceways without added carbon dioxide. Projected annual operational costs are very high on a per animal basis ($780 per cow). However, within the context of reducing nutrient inputs in sensitive watersheds such as the Chesapeake Bay, projected operational costs of $11 per kg N are well below the costs cited for upgrading existing water treatment plants.

Published by Elsevier Ltd.

1. Introduction

Water quality in the Chesapeake Bay has declined dramatically in the past 50 years, primarily because of eutrophication (Horton and Eichbaum, 1991; Chesapeake Bay Foundation, 2004). Restoration of the 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 Foundation, 2004). Approximately $19 billion is needed to achieve 2010 bay restoration goals that include nitrogen (N) and phosphorus (P) reductions of 45 million kg year^{-1} and 3 million kg year^{-1}, respectively (Chesapeake Bay Commission, 2004). Although agricultural sources are estimated to contribute roughly 40% of the N and P inputs in the 166,000 km^2 watershed, keeping land in agricultural use is important for health of the watershed because agricultural lands generally export less N (17 kg ha^{-1} year^{-1}) than land in urban/suburban development (30 kg ha^{-1} year^{-1}) (Chesapeake Bay Foundation, 2005). The challenge and opportunity for the agricultural community is to develop and implement technologies that can reduce export of farm nutrients into the watershed while increasing farm profits (Chesapeake Bay Foundation, 2006).

Among agricultural sources of N and P, animal manures (poultry, dairy, beef, and swine) are estimated to contribute 18% of the N and 25% of the P that enter the Chesapeake Bay (Chesapeake Bay Foundation, 2004). An alternative to the current practice of spraying dairy manure effluents on agricultural fields is to grow crops of algae using the effluents and thus convert manure N and P into potentially valuable algal biomass. There is considerable literature on the treatment of raw and anaerobically digested swine manure effluent by immobilized algae (Jimenez-Perez et al., 2004), algal cultures, (Ayala and Bravo, 1984) and suspended algae in high rate pond systems (Costa et al., 2000; Goh, 1986; Olguin et al., 1997, 2001; Olguin, 2003). Algal productivity, nutrient content and nutrient recovery using attached algae with dairy and swine effluents have been studied in laboratory-scale algal turf scrubber

---

(ATS) units (Wilkie and Mulbry, 2002; Kebede-Westhead et al., 2003, 2004, 2006). The objective of this study was to determine comparable values using outdoor pilot-scale ATS raceways and dairy manure effluent.

2. Methods

2.1. Algal turf scrubbers and dairy manure

Algal biomass was produced from four 30 m² outdoor pilot-scale ATS raceways (Fig. 1). Two raceways were constructed at a 1% slope and two were constructed at a 2% slope. Each raceway consisted of a 1×30 m section of 0.75 mm landfill liner (Gundle Linings Technology, Houston, TX, USA) covered with 6 mm mesh nylon netting (Apex Mills, Inwood, NY, USA), a 3700 L underground concrete sump at the base of the raceway, a tipping trough at the top of the raceway, and a submerged water pump (Zoeller Pump Co., Louisville, KY, USA) in the sump to deliver a flow rate of 93 L min^{-1}. The recirculating effluent consisted of fresh water (untreated well water or chlorinated drinking water) and daily additions of raw or anaerobically digested dairy manure effluent from the USDA's Dairy Research Unit in Beltsville, Maryland, USA. Although rainwater was usually sufficient to replenish water lost to evaporation, additional fresh water was added as needed to maintain an effluent volume of 3500 L. The characteristics of Beltsville dairy manure effluent have been described (Wilkie and Mulbry, 2002). The mean raw manure effluent nutrient values were 1600 mg L^{-1} total N (TN) and 230 mg L^{-1} total P (TP). However, nutrient concentrations in the dairy manure effluent varied more than 4-fold throughout this study, primarily because of seasonal changes in water use in the dairy barns. The carbon content of the manure effluents was not measured routinely, but varied with type of manure. The C/N ratios of raw solid-separated and anaerobically digested dairy manure effluents ranged from 9 to 12 and 4 to 6.5, respectively. Typically, 20–60 L of manure effluent (containing 500–2300 mg L^{-1} TN and 85–300 mg L^{-1} TP) were added every morning to each raceway to achieve loading rates corresponding to 0.3–2.5 g TN and 0.08–0.42 g TP m^{-2} d^{-1}. In the spring of 2004, experiments were conducted to determine the effect of carbon dioxide supplementation on algal productivity and nutrient recovery using raw dairy manure. In these experiments, raceway effluent pH was maintained between 7.0 and 7.5 on one of two raceways using a pH controller to regulate the flow of carbon dioxide into the effluent sump (addition of carbon dioxide lowered effluent pH). The other raceway did not receive carbon dioxide. In the summer of 2006, experiments were conducted to qualitatively test the effect of minimizing rapid water temperature increases during the summer months on algal growth. During this period, raceway effluent temperature was maintained below 32 °C using temperature controllers to regulate inflow of untreated well water (15–20 °C) into the effluent sumps. Since this treatment also diluted the raceway effluents, the loading rates reported during this period (June–July 2006) are overestimates. Grazer populations of chironomid larvae were controlled by adding Bacillus
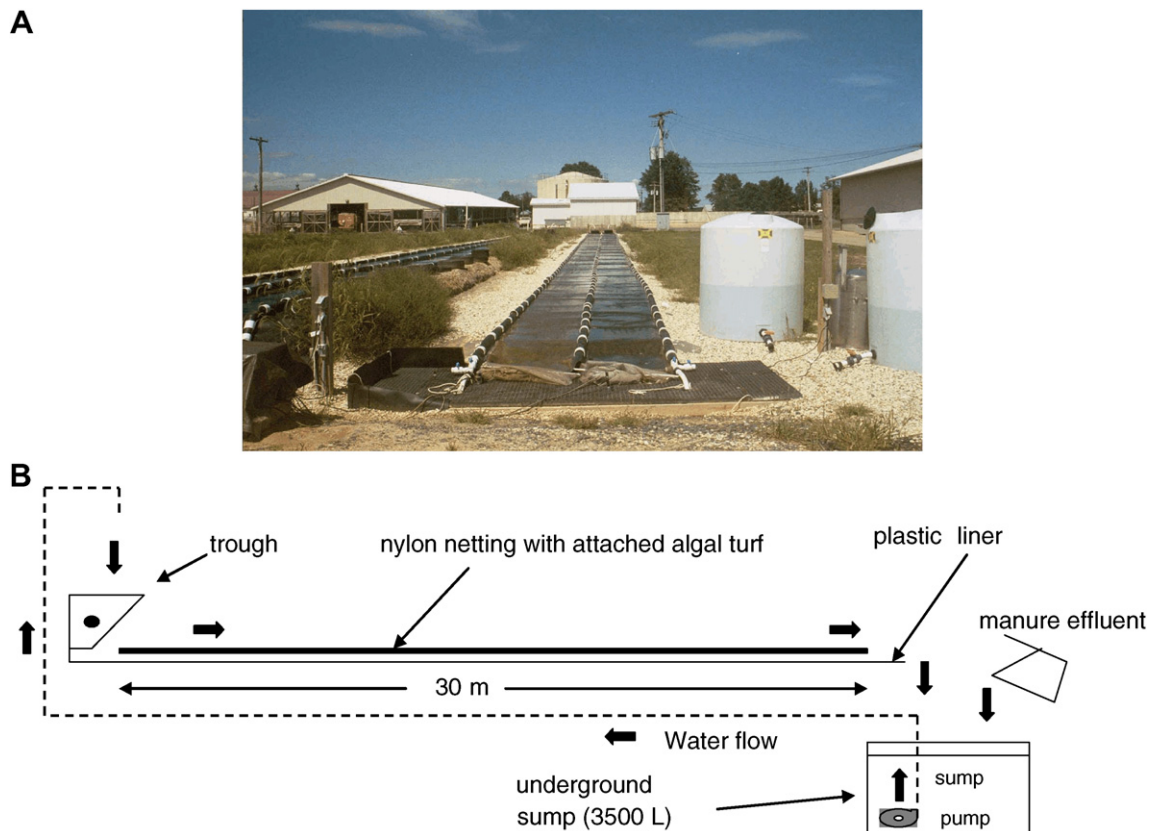

Fig. 1. Photograph (panel A) and schematic drawing (panel B) of pilot-scale raceways at the Dairy Research Unit in Beltsville, Maryland. Each raceway is 1 m in width, 30 m in length, and has a water depth of 1–3 cm. Two raceways (left of center in panel A) were constructed at a 1% slope and two raceways (center in panel A) were constructed at a 2% slope. Raceway effluents (approximately 3500 L for each raceway) are contained in four separate underground concrete tanks covered by plastic grating (foreground in panel A) and are continuously recycled from the sumps to the top of the raceways using four separate sump pumps at a flow rate of 93 L min^{-1}. A trough at the top of each raceway fills and tips over, releasing pulses of effluent that wash over the attached algal turf every 8–15 s before draining into the concrete sump at the base of the raceway. Raw or anaerobically digested dairy manure effluent (20–60 L d^{-1}) is added daily to the recirculating scrubber effluent of each raceway. Water from adjacent storage tanks is added only when rainwater is inadequate to replenish water lost to evaporation.

thuringiensis subspecies israeliensis ("Aquabac-xt", Becker Microbial Products, Plantation, FL) to the raceway effluent after each harvest. Wet algal biomass (approximately 5% solids content) was harvested every 4–12 days using wet/dry vacuums, dewatered by sieving the harvested material through 2 mm mesh nylon netting (Aquatic Ecosystems, Apopka, Florida) to approximately 10% solids content, then air dried for 48 h using electric fans to approximately 90% solids content. Air-dried biomass was ground in a Wiley Mill (Thomas Instruments, Philadelphia, PA) 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 TP.

2.2. Analysis of manure, ATS biomass and ATS effluent

TKN and TP were determined using total Kjeldahl block digestion followed by flow injection analysis (model 8000, Lachat Instruments, Milwaukee, WI) (APHA, 1995). Elemental analyses of the algal biomass were determined using inductively coupled plasma analysis (APHA, 1995). Samples of raceway effluent and water drained from the wet algal biomass after harvest were collected and stored at −20 °C prior to analysis for TKN and TP. Concentrations of algal biomass components were adjusted for moisture content and are reported on a dry weight basis.

2.3. Statistical analyses

Calculation of means, standard error values, and best-fit regression values for algal productivity, algal composition, nutrient loading rates and manure composition were performed using Prism 5.0 software (Graphpad Software, San Diego, CA).

3. Results

3.1. Algal productivity and composition

Replicate ATS raceways (Fig. 1) were operated in central Maryland for approximately 270 days each year (roughly April 1–December 31) from 2003 to 2006. Indigenous algal consortia colonized the ATS raceways within three weeks of operation in May 2003. There was no attempt to seed the raceways with specific organisms. Although water flow was stopped (and the ATS nets left to dry) each year during freezing weather (usually January–March in Maryland), algal consortia typically recolonized the raceways within two to three weeks of restarting the system in April. The consortia was dominated by filamentous green algae including *Rhizoclonium hieroglyphicum* (C.A. Agardh) (the most abundant species), *Microspora willeana* Lagerh., *Ulothrix ozonata* (Weber and Mohr) Kütz, *Rhizoclonium hieroglyphicum* (C.A. Agardh) Kütz and *Oedogonium* sp. Raw or anaerobically digested dairy manure effluent was added daily corresponding to nutrient loading rates of 0.3–2.5 g TN and 0.05–0.40 g TP m^{-2} d^{-1}. Algal biomass was harvested every 4–12 days depending on the loading rate and extent of algal growth. Observations from 2003 and 2004 indicated that productivity values for filamentous algae were generally higher and more sustainable in raceways constructed using a 2% slope rather than 1% slope. Consequently, only the 2% slope raceways were used in 2005 and 2006. Although there are relatively few data points for loading rates above 1 g TN m^{-2} d^{-1}, mean algal productivity values increased from approximately 2.5 g DW m^{-2} d^{-1} at the lowest loading rate (0.3 g TN, 0.05 g TP m^{-2} d^{-1}) to 24 g DW m^{-2} d^{-1} at the highest loading rate (2.5 g TN, 0.40 g TP m^{-2} d^{-1}) (Fig. 2, panel A). Mean algal N and P contents increased roughly 2-fold over the range of loading rates up to maximums of 6.8% N and 1.0% P at an effluent loading rate corresponding to 1.8 g TN, 0.30 g TP m^{-2} d^{-1} (Fig. 2, panels B and C). The ash content of
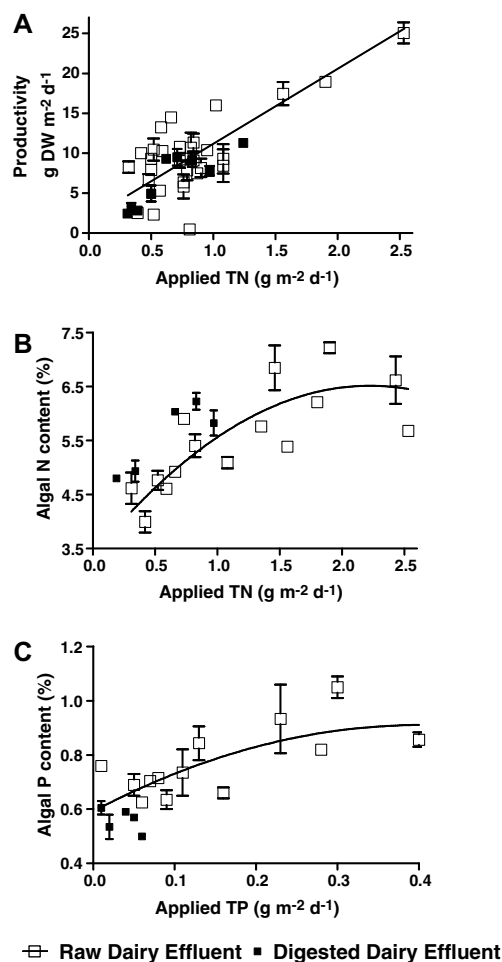

Fig. 2. Algal productivity, algal N content, and algal P content as functions of manure effluent loading rate. Algal productivity (g DW m^{-2} d^{-1}) (panel A); algal N content (% of DW) (panel B) and algal P content (% of DW) (panel C) are shown as functions of applied manure effluent TN or TP. Raceways were operated using raw and anaerobically digested dairy manure effluent (open and filled symbols, respectively). Data points represent mean values of 2–8 measurements collected from 2003 to 2006. Error bars are standard error. Lines are linear (panel A) or polynomial regressions (panels B and C) of values corresponding to algae grown using raw dairy effluent.

the algal biomass generally ranged from 12% to 18% of DW with a mean value of 16 ± 6.1% DW. Ash content values were highest (up to 30% of DW) in the spring immediately after system startup but showed no relationship to the effluent loading rate, type of manure, or whether or not the effluent was supplemented with CO_2 (not shown).

The elemental compositions of 40 representative algal biomass samples were determined by ICP and the results from a subset of those samples are shown in Table 1. With the exception of N and P concentrations, concentrations of other components did not change significantly as a function of effluent loading rate, type of dairy manure effluent (raw or digested), date of harvest, or whether or not CO_2 was bubbled into the effluent to maintain neutral pH.

3.2. Effect of loading rate on recovery of manure N and P in algal biomass

The recovery rate for a particular element is a function of algal productivity and the element's content in the biomass. In this case, the absolute amounts of N and P recovered in the algal biomass

Table 1
Elemental composition of dried algal biomass (mg kg^{-1}) grown using four manure effluent loading rates

Element	Loading rate (g TN m^{-2} d^{-1})			
	0.49 ± 0.02 (*n* = 5)	0.85 ± 0.76 (*n* = 6)	1.90 ± 0.01 (*n* = 2)	2.53 ± 0.01 (*n* = 2)
N	65,500 ± 6700	49,500 ± 8100	74,000 ± 1700	54,500 ± 5600
K	9350 ± 1700	9350 ± 760	12,150 ± 200	10,700 ± 50
P	9400 ± 600	8200 ± 1300	11,000 ± 100	8200 ± 1200
Ca	18,000 ± 9200	9750 ± 1400	13,550 ± 1000	11,000 ± 1350
Mg	4550 ± 650	3700 ± 650	3950 ± 200	3450 ± 350
Fe	2700 ± 600	3750 ± 750	3300 ± 250	2950 ± 350
Zn	360 ± 50	540 ± 110	830 ± 40	650 ± 30
Al	1850 ± 550	3000 ± 900	1900 ± 200	1800 ± 250
Mn	340 ± 60	450 ± 80	670 ± 30	550 ± 70
Cu	65 ± 20	100 ± 25	130 ± 20	120 ± 30
Mo	DL	DL	DL	DL
Pb	DL	DL	DL	DL
Cd	0.29 ± 0.04	0.41 ± 0.05	0.51 ± 0.01	0.52 ± 0.03

[1] Values are means ± SD of 2–6 samples from weekly harvests. *n*, Number of samples.
[2] DL, values were below our detection limit. The detection limits for Mo and Pb were 2 and 7 mg kg^{-1}, respectively.

generally increased with loading rate because of increases in N and P content and in productivity. However, percentage recovery values for N and P in the biomass generally decreased as loading rate increased (Fig. 3, Table 2). Percentage recovery values were very similar for N and P, and mean values generally ranged from 70% to 110% at effluent loading rates corresponding to less than 1 g TN, 0.15 g TP m^{-2} d^{-1}. At higher effluent loading rates, N and P recovery values ranged from 50% to 80%.

3.3. Effect of manure type on productivity and nutrient recovery

Although the raceways were primarily operated using raw dairy manure effluent, algal productivity and nutrient recovery values
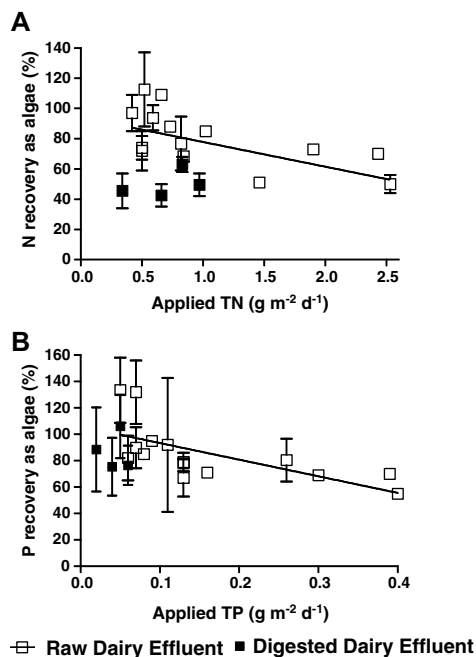

Fig. 3. Recovery of manure effluent N and P as functions of manure effluent loading rate. Recovery of manure effluent N (panel A) and P (panel B) in dried algal biomass as functions of applied manure effluent TN or TP, respectively. Raceways were operated using raw and anaerobically digested dairy manure effluent (open and filled symbols, respectively). Data points represent mean values of 2–8 measurements collected from 2003 to 2006. Error bars are standard error. Lines are linear regressions of values corresponding to algae grown using raw dairy effluent.

Table 2
N and P balances for pilot-scale raceways using raw dairy manure effluent at four manure effluent loading rates. Values are the means of 3–8 separate weekly measurements ± SD

	(*n* = 8)	(*n* = 8)	(*n* = 4)	(*n* = 3)
Input (m^{-2} d^{-1})				
N (g)	0.51 ± 0.01	0.83 ± 0.01	1.73 ± .20	2.50 ± 0.06
TP (g)	0.08 ± .01	0.12 ± .01	0.24 ± .02	0.40 ± .01
Output (m^{-2} d^{-1})				
Algal biomass (g DW)	8.3 ± 2.5	11.0 ± 2.9	18.2 ± 1.5	25.1 ± 2.3
Algal N content (%)	4.8 ± 0.5	5.4 ± 0.6	6.9 ± 0.5	6.3 ± 0.7
TN in harvested algae (g)	0.39 ± 0.12	0.59 ± 0.16	1.26 ± 0.10	1.58 ± 0.14
Algal P content (%)	0.69 ± .05	0.80 ± 0.11	0.90 ± 0.19	0.86 ± 0.05
TP in harvested algae (g)	0.06 ± 0.02	0.09 ± 0.02	0.16 ± .04	0.22 ± 0.02
Recovery (%)				
N in harvested algae	83 ± 25	72 ± 24	51 ± 4	57 ± 13
P in harvested algae	91 ± 12	79 ± 24	80 ± 16	62 ± 11

were also determined using relatively low loading rates (less than 1 g TN, less than 0.07 TP m^{-2} d^{-1}) of anaerobically digested dairy manure effluent. At these loading rates there were no apparent differences in algal productivity, N and P content, ash content, or N and P recovery using raw or digested dairy effluents (Figs. 2 and 3).

3.4. Seasonal effects on productivity and nutrient recovery

Nutrient concentrations in the dairy manure effluent varied more than 4-fold throughout this study, primarily because of seasonal changes in water use in the dairy barns. Although the mean raw manure effluent nutrient values were 1600 mg L^{-1} TN and 230 mg L^{-1} TP, low water use during the winter months resulted much higher values (2300–2800 mg L^{-1} TN, 300–440 mg L^{-1} TP). During hot weather (when water sprays are used to cool the animals in the barns) manure nutrient concentrations were generally lowest (roughly 1000 mg L^{-1} TN, 130 mg L^{-1} TP). This variation in effluent nutrient concentrations made it difficult to maintain consistent nutrient loading rates on the ATS raceways (Fig. 4). Since differences in loading rate resulted in differences in algal productivity, it is correspondingly difficult to directly determine seasonal effects on algal productivity from these results. At the highest loading rates (2.4 g TN m^{-2} d^{-1}), algal productivity values in the spring months were approximately 24 g DW m^{-2} d^{-1} (Fig. 4, panel B). Algal productivity values in the winter months (November to December) were approximately 5–7 g DW m^{-2} d^{-1}, but these low values also corresponded to much lower nutrient loading rates (0.4–0.8 g TN m^{-2} d^{-1}) (Fig. 4, panels C and D).

During 2003, the first year of operation, algal productivity values were relatively consistent and varied primarily as a function of loading rate (Fig. 4, panel A). However, in 2004 productivity values decreased from 25 g DW m^{-2} d^{-1} to less than 1 g DW m^{-2} d^{-1} in mid-May and did not increase through the end of the year (Fig. 4, panel B). Although similar low patterns of productivity were observed during the summers of 2005 and 2006, productivity levels increased in the October of both years and continued into December (Fig. 4, panels C and D). In 2006, the period of high algal productivity appeared to be extended into late July by the use of temperature controllers to decrease the daily maximum effluent temperatures to below 32 °C.

3.5. Effect of carbon dioxide supplementation on productivity and nutrient recovery

ATS effluent pH values followed a diurnal cycle and ranged from minimum values of 6.8–7.0 at sunrise to pH 9–10 by the late morning or early afternoon as carbonate was removed by algal photo-
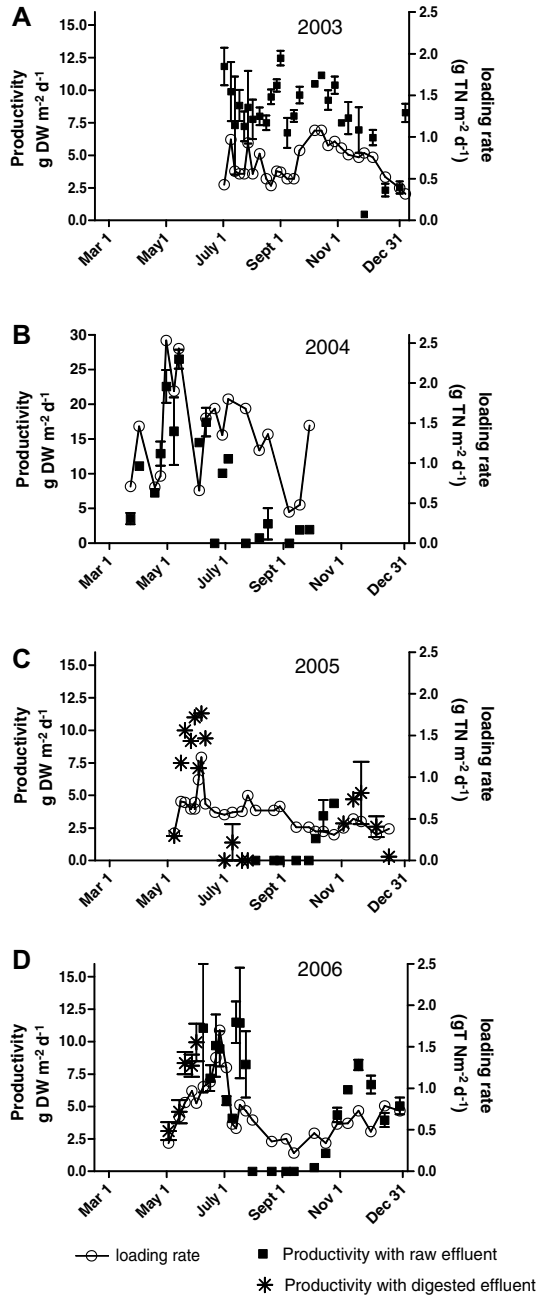
Fig. 4. Algal productivity and manure effluent loading rates from 2003 to 2006. Algal productivity values (g DW m^{-2} d^{-1}) are averages for 2–4 raceways using raw or anaerobically digested dairy manure effluents. Note that the scale of the right side y-axis in panel B is different than in panels A, C, and D. Error bars are standard error.

Fig. 5. Algal productivity and manure N and P recovery as functions of manure effluent loading rate. Algal productivity (g DW m^{-2} d^{-1}) (panel A) is shown as a function of applied manure effluent TN. Recovery of manure effluent N (panel B) and P (panel C) in dried algal biomass are shown as functions of applied manure effluent TN and TP, respectively. Raceways were operated using raw dairy manure effluent with carbon dioxide supplementation or without (open and filled symbols, respectively). Data points represent single measurements. Lines are linear regressions of values corresponding to algae grown with carbon dioxide supplementation.

synthesis. To determine whether algal productivity and/or nutrient recovery could be increased by carbon dioxide supplementation, effluent pH was maintained between 7.0 and 7.5 using pH controllers to regulate the bubbling of carbon dioxide into the effluent sump. Raceways were operated with raw dairy manure effluent. Results showed that there were no differences in algal productivity or N and P recovery from raceways with carbon dioxide supplementation compared to those without supplementation (Fig. 5).

4. Discussion

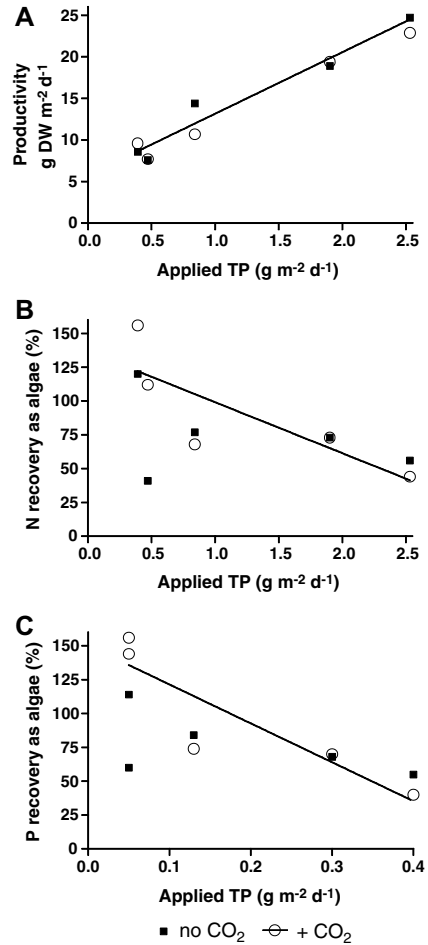Productivity, nutrient content, and N and P recovery values from algal biomass grown in the outdoor raceways are comparable to previously reported values using indoor lab-scale ATS units and anaerobically digested dairy manure effluent (Kebede-Westhead et al., 2003). Results using lab-scale units showed increasing levels of productivity (up to 19 g DW m^{-2} d^{-1}), and nutrient content (up to 6.5% N and 1.1% P) with increasing loading rate (up to 2.4 g TN, 0.37 g TP m^{-2} d^{-1}). Nutrient recovery values (in algal biomass) using lab-scale units were 40–60% of effluent N and P. Total N and P recovery values (that include N and P in water drained from harvested algal biomass as well as residual N and P in the recirculating ATS effluent) were 50–70% using lab-scale units. Based on values from periodic sampling of the outdoor raceway effluents and water drained from harvested biomass (not shown), we estimate that the nutrients in these liquids account for approximately 5–10% of input N and P at all loading rates. Taking these values into account, our estimates of total recovery of input manure effluent N and P in the outdoor raceways are 60–90% and 70–100%, respectively (Table 1).

With regard to other components in the algal biomass, the concentrations of Cd and K reported here are similar to previously reported values from indoor lab-scale ATS units using anaerobically digested dairy effluent (Kebede-Westhead et al., 2004). However, concentrations of Al, Ca, Cu, Fe, Mg, Mn, and Zn reported here are two to three-fold higher than values from the lab-scale ATS units.

At present, it is unclear whether these differences are significant or are simply due to differences in batches of manure.

Possible uses of the algal biomass include its use as a feed supplement or slow-release fertilizer (Wilkie and Mulbry, 2002). The maximum tolerable dietary levels (MTDL) in dairy cow feed for elements measured in this study are (in mg kg^{-1}): Al (1000), Cd (0.5), Fe (1000), Mo (5), Mn (1000), Pb (30), and Zn (500) (NRC, 2001). Although the levels of algal Al, Fe, and Zn exceeded these levels, we have no complementary information about the solubility or bioavailability of any of the constituents in the algal biomass. With regard to using the algal biomass as a fertilizer, loadings of heavy metals in the algal biomass would be well below regulatory limits at amendment rates based on available N or P fertilizer equivalents (Kebede-Westhead et al., 2004). Recent studies focused on the use of dried ATS biomass as a slow-release organic fertilizer have demonstrated that it is equivalent to a commercial organic fertilizer with respect to plant mass and nutrient content (Mulbry et al., 2005, 2006).

Although the pilot-scale outdoor raceways described in this paper demonstrated high levels of productivity (greater than 20 g DW m^{-2} d^{-1}) in the spring, these levels were not sustained through the remainder of the year. We believe that low algal productivity in the summer months is primarily due to high water temperatures and grazing by snails. These obstacles may be overcome by increasing the reservoir size or by using single-pass ATS systems such as that designed for removing P from agricultural drainage water in southern Florida (Hydromentia Inc, 2005). Recent results from a 6-month pilot project using the Hydromentia system showed productivity values of 11 to 14 g DW m^{-2} d^{-1}. The harvested biomass contained approximately 3% N, and 0.5–1% P and 37–49% ash.

A recent assessment of the nutrient recovery potential and economic cost of an on-farm ATS treatment system to treat dairy manure effluent used "best case" values that were extrapolated from laboratory results (Pizarro et al., 2006). Using those values (average productivity of 20 g DW m^{-2} d^{-1} for 270 days per year at an average manure effluent loading rate corresponding to 2.4 g TN, 0.37 g TP m^{-2} d^{-1}), the yearly operational treatment costs per cow, per kg N, per kg P, or per kg of dried biomass were $454, $6.20, $31.10, and $0.76, respectively (Pizarro et al., 2006). The assessment did not include any value for the algal biomass or for any treatment value. Our current results suggest that a more conservative average productivity value of 10 g DW m^{-2} d^{-1} for 270 days per year (at an average effluent loading rate of 1 g TN, 0.15 g TP m^{-2} d^{-1}) would be more realistic. On a hectare basis, these values are equivalent to a yearly productivity value of 27,000 kg DW algal biomass ha^{-1} at a loading rate of 2700 kg TN, 400 kg TP ha^{-1}. Using these values, treatment costs increase about 70% compared to values from estimates using a mean productivity value of 20 g DW m^{-2} d^{-1}. The revised cost estimates for the yearly operational costs per cow, per kg N, per kg P, or per kg of dried biomass are $778, $10.70, $53.30, and $1.31, respectively. Within the context of reducing nutrient inputs in sensitive watersheds such as the Chesapeake Bay, these costs are still well below the estimates of $19 per kg N cited for upgrading existing water treatment plants (Chesapeake Bay Commission, 2004). Sale of the dried algal biomass as an organic fertilizer could also provide a significant source of revenue (Mulbry et al., 2006). Widespread use of this material in lieu of inorganic fertilizers in urban/suburban areas could help reduce fertilizer-related nutrient losses from these areas.

References

APHA, 1995. Standard Methods for the Examination of Water and Wastewater, 19th ed. American Public Health Association, Washington, DC.

Ayala, F., Bravo, R., 1984. Animal wastes media for *Spirulina* production. Arch. Hydrobiol. 67 (3), 349–355.

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

Chesapeake Bay Foundation, 2004. Manure's Impact on Rivers, Streams and the Chesapeake Bay: Keeping Manure out of the Water, p. 26, <www.cbf.org/site/DocServer/0723manurereport_noembargo_pdf?docID=2143>.

Chesapeake Bay Foundation, 2005. Vital signs: assessing the state of Chesapeake agriculture in 2005, p. 15, <http://www.cbf.org/site/DocServer/StateOfAg.pdf>.

Chesapeake Bay Foundation, 2006. A guide to preserving agricultural lands in the Chesapeake Bay region: keeping stewards on the land, p. 18, <http://www.cbf.org/site/DocServer/CBFPreservingFarmland_Finalpdf?docID=5943>.

Costa, R., Medri, W., Perdomo, C.C., 2000. High-rate pond for treatment of piggery wastes. Water Sci. Technol. 42, 357–362.

Goh, A., 1986. Production of microalgae using pig waste as a substrate. In: Barclay, W.R., McIntosh, R.P. (Eds.), Algal Biomass Technologies. Cramer, Berlin, pp. 235–244.

Horton, T., Eichbaum, W., 1991. Turning the Tide, Saving the Chesapeake Bay. Island Press, Washington, DC.

Hydromentia Inc., 2005. S-154 Pilot Single Stage Algal Turf Scrubber Final Report. South Florida Water Management District Contract No. C-13933, p. 81.

Jimenez-Perez, M.V., Sanchez-Castillo, P., Romera, O., Fernandez-Moreno, D., Perez-Martinez, C., 2004. Growth and nutrient removal in free and immobilized plantonic green algae isolated from pig manure. Enzyme Microb. Technol. 34, 392–398.

Kebede-Westhead, E., Pizarro, C., Mulbry, W.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., 2004. Treatment of dairy manure effluent using freshwater algae: elemental composition of algal biomass at different manure loading rates. J. Agric. Food Chem. 52, 7293–7296.

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.

Mulbry, W., Kebede-Westhead, E., Pizarro, C., Sikora, L.J., 2005. Recycling of manure nutrients: use of algal biomass from dairy manure treatment as a slow release fertilizer. Bioresour. Technol. 96, 451–458.

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

NRC, 2001. Nutrient Requirements of Dairy Cattle, seventh revised ed. National Research Council, Washington, DC, p. 408.

Olguin, E.J., 2003. Phycoremediation: key issues for cost-effective nutrient removal processes. Biotechnol. Adv. 22, 81–91.

Olguin, E.J., Galicia, S., Angulo-Guerrero, O., Hernandez, E., 2001. The effect of low light flux and nitrogen deficiency on the chemical composition of *Spirulina* sp (Arthrospira) grown on digested pig waste. Bioresour. Technol. 77, 19–24.

Olguin, E.J., Galicia, S., Camacho, R., Mercado, G., Perez, T.I., 1997. Production of *Spirulina* sp. in seawater supplemented with anaerobic effluents in outdoor raceways under temperate climatic conditions.. Appl. Microbiol. Biotechnol. 48, 242–247.

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.

Wilkie, A.C., Mulbry, W., 2002. Recovery of dairy manure nutrients by benthic freshwater algae. Bioresour. Technol. 84, 81–91.