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An economic assessment of algal turf scrubber technology for treatment of dairy manure effluent

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ABSTRACT

Controlling the input of nitrogen (N) and phosphorus (P) from dairies and other livestock operations into the surrounding air- and water-sheds poses both technical and economic challenges to the agricultural community. The purpose of this paper is to assess the economics of algal turf scrubber treatment technology at the farm-scale for a hypothetical 1000-cow dairy. Costs were developed for farms with and without anaerobic pretreatment. The majority of capital costs were due to land preparation, installation of liner material, and engineering fees. The majority of operational costs were due to energy requirements for biomass drying, pumping water, and repayment of capital investment. On farms using anaerobic pretreatment, waste heat from burning of biogas could be used to offset the energy requirements of biomass drying. In addition, biogas combustion exhaust gas could then be recycled back to the algal system to supply dissolved inorganic carbon for optimal algal production and pH control. Under the best case (algal system coupled with anaerobic digestion pretreatment), the yearly operational costs per cow, per kg N, per kg P, and per kg of dried biomass were $454, $6.20, $31.10, and $0.70, respectively. Without anaerobic digestion pretreatment, the yearly operational costs were 36% higher, amounting to $631 per cow, $8.70 per kg N, $43.20 per kg P, and $0.97 per kg of dried biomass. For perspective, a recent survey of 36 Maryland dairy farms found long-term annual profits of about $500 per cow. As no market currently exists for manure grown algal biomass, our cost analysis does not include any value of the biomass generated during manure treatment. In addition, there are a variety of potential uses for the algal biomass from manure treatment that could defray treatment costs. Future opportunities for dairies to participate in nutrient trading approaches to watershed nutrient management may also become important.

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1. Introduction

Controlling the input of nitrogen (N) and phosphorus (P) from dairies and other livestock operations into the surrounding air- and water-sheds poses both technical and economic challenges to the agricultural community (Adey et al., 1993; Kaiser, 2001; Van Horn et al., 1994). During storage and land application of manure effluents, large amounts of N are lost to the atmosphere due to volatilization of ammonia. Recent estimates suggest that animal waste contributes 18% of the N and 25% of the P inputs to the Chesapeake Bay (Chesapeake Bay Foundation, 2004) where water qual-

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ity has declined dramatically due to eutrophication (Horton and Eichbaum, 1991). Ecologically sound manure management on farms is vital to minimize losses of valuable plant nutrients and to prevent nutrient contamination of the surrounding watershed. The challenge for ecological engineering is to develop technologies that can economically treat manure as a waste source and, ideally, transform it into a useful byproduct.

An alternative to land spreading of manure is to grow crops of algae on the N and P present in the manure and convert manure N and P into algal biomass. Most efforts in using algal production for wastewater treatment have been focused on treatment of municipal waste effluents using suspended microalgae (Benemann and Oswald, 1996; Green et al., 1995). Wastewater treatment using attached algae (periphyton) has also been reported and has potential advantages in how the algal biomass is harvested and dried (Hoffman, 1998). One technology using periphyton, termed algal turf scrubbers (ATS) (Adey and Hackney, 1989; Adey and Loveland, 1998), is relatively simple in design and yields an algal biomass that can be easily harvested on adapted farm-scale equipment. Previous work in this laboratory has demonstrated the use of ATS periphyton to remove N and P from dairy manure effluents (Kebede-Westhead et al., 2003; Wilkie and Mulbry, 2002) as well as the use of the resulting biomass as an organic fertilizer (Kebede-Westhead et al., 2004; Mulbry et al., 2005). The purpose of this paper is to assess the economics of ATS treatment technology at the farm-scale for a hypothetical 1000-cow dairy.

2. Treatment goals

Within the economics and technology appropriate to farming systems, manure treatment systems should:

(1) Achieve >80% reduction of atmospheric emissions (ammonia-N, methane, odor compounds) from manure.
(2) Concentrate and stabilize nutrients from manure effluents so that the nutrients can be efficiently recycled on-farm or exported off-farm.
(3) Operate year-round so as to greatly reduce or eliminate storage of manure effluent in lagoons.
(4) Accommodate a wide range of dairy effluents with variable nutrient and solids content.
(5) Achieve >80% recovery of manure N and P at an overall cost of <$5 per pound N ($11 per kg N).

3. Description of the proposed system

3.1. *Algal turf scrubbers*

Algal turf scrubbers are a new technology for treating wastewater that utilize multi-species assemblages dominated by benthic, filamentous algal taxa (Adey and Loveland, 1998). This technology was developed by Dr. Walter Adey of the Smithsonian Institution and has been shown to be effective for improving the water quality of agricultural runoff (Adey et al., 1993), domestic sewage (Craggs et al., 1996), and industrial wastewaters (Adey et al., 1996). The system consists of an attached algal community growing on screens in a trough through which polluted water flows. The algal community is a high diversity system with 30 or more species of algae, along with associated microbes and micro-invertebrates. When operated at neutral pH values, this living community provides most of the water treatment by uptake of inorganic compounds in primary production and breakdown of organic compounds in community respiration (Adey and Loveland, 1998).

This system is modeled on the algal turf community found on coral reefs, which have some of the highest recorded metabolisms of any ecosystem (Adey and Goertemiller, 1987). Metabolism of the algal turf scrubber is controlled by manipulating water depth and flow rates, use of natural or artificial light sources, control of herbivores and frequency of harvest. All of these factors can be adjusted to maximize metabolism and, thus, to maximize water treatment capacity. Harvesting is particularly important since this action rejuvenates the community and leads to high growth rates. In fact, biomass production rates of algal turf scrubbers are among the highest of any recorded values for constructed ecosystems (Adey and Loveland, 1998). Many pollutants are taken up in algal biomass and are removed from the system through harvest (Adey et al., 1996). If these pollutants are not toxic, the harvested material can be processed into a useful byproduct such as a fertilizer or feed. If the pollutants are toxic, the harvested material must be disposed of, usually through land filling or incineration.

3.1.1. *Operating parameters*

The proposed treatment system (Figs. 1 and 2) is designed on the basis of operations at the Dairy Research Unit of the USDA/ARS facility in Beltsville, MD (USA) (Wilkie and Mulbry, 2002). In this confined animal operation, manure, urine, sawdust (used as bedding material) and variable amounts of water are mechanically scraped from the barns into an underground sump on a continuous basis. This mixture (about 12% total solids (TS)) is pumped to a screw press separator where the majority of solids are removed, and the manure effluent (about 5% TS) is fed at intervals to an anaerobic digestor for biogas production. The digested effluent is subsequently stored in an open lagoon prior to land application in the spring and fall. The proposed system assumes that one-third of the manure N and P are lost due to ammonia volatilization in the barns and/or removed with manure solids during solids separation prior to treatment of the manure effluent (Fig. 1) (Chesapeake Bay Foundation, 2004). Manure solids are composted prior to land application on- or off-farm. The remaining two thirds of the manure N and P (200 g TN and 40 g TP day^{-1} cow^{-1} or 73,000 kg TN and 14,600 kg TP $year^{-1}$ for 1000 dairy cows) are pre-treated by anaerobic digestion followed by algal treatment using an 11 ha system. In Maryland the algal system could be operated for approximately 9 months of the year with reduced productivity in the fall and winter months coinciding with reduced light levels. Under this scenario, all digested manure effluent is treated immediately except for material that is collected and stored during the three coldest months (approximately December–February). This growing season would obviously vary with geographic location and affects the size of the treatment area.

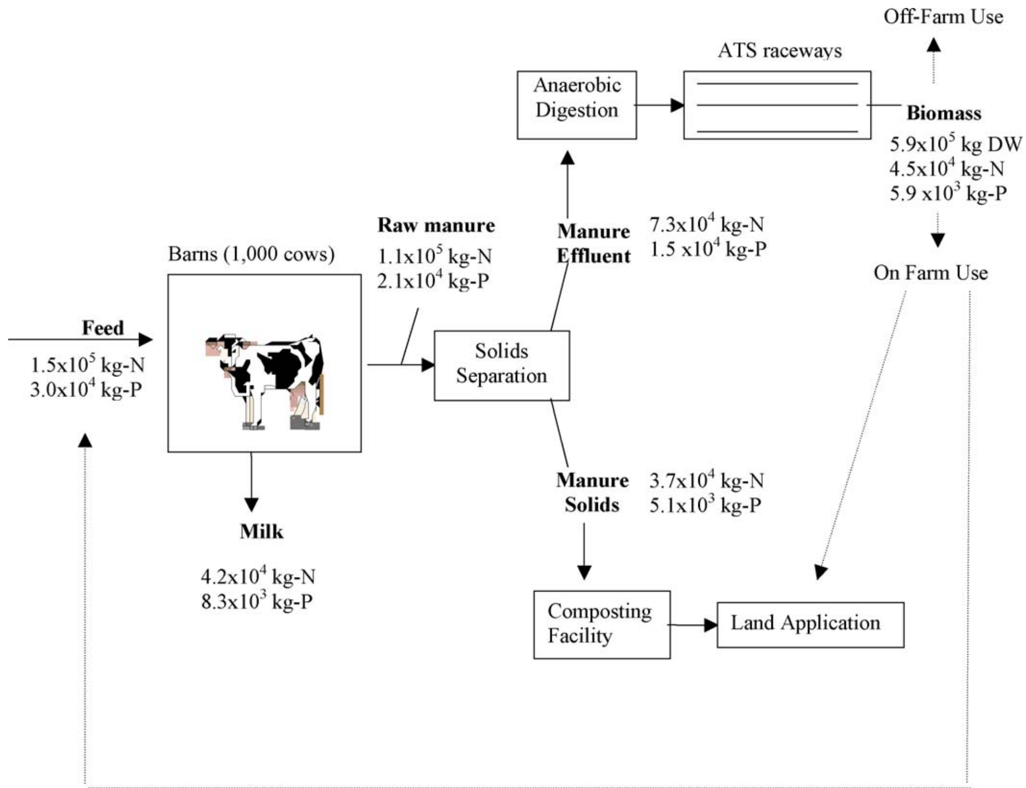

Fig. 1 – Schematic diagram of nutrient flow in the proposed treatment system. Manure from dairy cows in free-stall barns is mechanically scraped (or flushed with water) and the resultant manure slurry is subjected to a solids separation step prior to treatment of the solids by composting and treatment of the effluent by anaerobic digestion and algal scrubbing. Values for input N and P, milk N and P were adapted from Van Horn et al. (1994, 1996). Biomass from the algal scrubbers is either recycled back into farm operations (as a feed supplement or fertilizer) or exported from the farm.

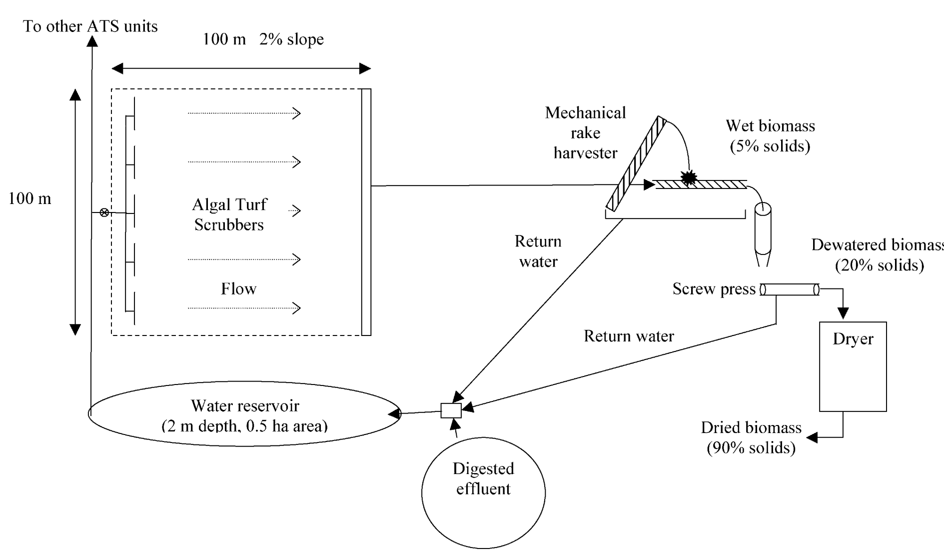

Fig. 2 – Schematic diagram of 1 ha ATS unit with associated equipment and water reservoir. Manure effluent is added continuously to the equalization reservoir. Algal biomass is harvested weekly, removed from ATS effluent using a mechanical rake, dewatered with a screw press, and dried using a belt drier. A 1000-animal farm-scale system would be composed of eleven 1 ha ATS units that would share reservoirs and the harvesting, dewatering, and drying equipment.

3.1.2. *Manure characterization*

The absolute and relative concentrations of different components in dairy manure are dependent on the breed of animal, amount and composition of feed as well as water use in the barns. Van Horn et al. (1994) summarized manure composition values from a variety of literature sources and we used their value of 300 g TN excreted per cow per day. There is considerable variation in estimates of the proportions of manure N and P that are removed during solids separation. At the USDA facility, the solids content of the raw and separated effluents average 12% and 5%, respectively. For the purposes of this assessment, we assume that the solids separated manure effluent contains 200 g of TN and 40 g TP per day per cow (equivalent to 73 kg TN and 14.6 kg TP per year per cow).

3.1.3. *Manure loading rates*

Results from laboratory scale algal scrubbers using diluted anaerobically digested dairy manure show maximum productivity (roughly 20 g D.W. m^{-2} day^{-1}) at loading of 2.5 g TN m^{-2} day^{-1} (Kebede-Westhead et al., 2003). We used this value for the average manure loading rate in the ATS. This corresponds to an approximate P loading rate of 0.5 g TP m^{-2} day^{-1}. For this assessment, we assume 9 months (270 days) of algal production per year. Using a yearly average of 2.5 g TN m^{-2} loaded on ATS per day, 270 days per year yields N and P loading rates of 0.675 kg TN and 0.135 kg TP m^{-2} $year^{-1}$ (6750 kg TN and 1350 kg TP ha^{-1} $year^{-1}$). Assuming that solids separated manure effluent from each cow contains approximately 73 kg TN and 14.6 kg TP per year (shown above), then each hectare of ATS raceways will treat the yearly solids separated manure effluent from about 92 cows.

3.1.4. *Algal biomass characteristics and productivity*

At a loading rate of 2.5 g TN m^{-2} day^{-1}, harvested ATS biomass contains about 5% total solids at harvest and simple mechanical dewatering yields biomass containing 20% total solids. Algal biomass would be stabilized by drying to 90% solids (10% moisture) and would contain 40% C, 7.5% N, 1.5% P and an ash content of about 15%. We estimate an average biomass productivity rate of 22 g m^{-2} day^{-1} (at 10% moisture content) (Kebede-Westhead et al., 2003). This value corresponds to field-scale productivity rates of 220 kg ha^{-1} day^{-1} and 2420 kg day^{-1} (653,400 kg per 270-day operating year) for an 11 ha treatment system for 1000 cows.

3.1.5. *Biogas and energy production from anaerobic digestion of manure*

Values for biogas and energy production from anaerobic digestion of dairy manure have been estimated previously (Van Horn et al., 1996, 1994). Assuming each cow produces 5.73 kg of manure volatile solids (VS) day^{-1}, and anaerobic digestion yields approximately 350 L of biogas kg^{-1} VS, biogas production is roughly 2000 L day^{-1} cow^{-1}. Assuming biogas is composed of 60% methane with an energy content of 8.90 kcal L^{-1}, total energy production is estimated at 10.7 Mcal cow^{-1} day^{-1}(Van Horn et al., 1994). For a dairy farm with 1000 cows, the total energy production would be 10,700 Mcal day^{-1} or 3.9×10^6 Mcal $year^{-1}$.

3.1.6. *Energy requirements for biomass drying*

Harvested algal biomass (4000 kg per ha) would contain roughly 5% solids. After dewatering (3000 kg water removed from 4000 kg harvested biomass) the algal biomass would contain 20% solids (1000 kg per ha) and could be subsequently stabilized by drying to 90% solids (220 kg of dried product per ha). The calculated energy requirement for drying 780 kg water from 1000 kg of dewatered biomass (using an energy consumption of 1.2 Mcal kg^{-1} H_2O) is 932 Mcal ha^{-1} day^{-1}.

Table 1 – Capital cost estimates for manure effluent treatment system (for 1000 cows)

	No pre-treatment ($)	Pre-treatment with anaerobic digestor ($)
Site preparation, grading, compaction ($34,000 ha^{-1})[a]	374,000	374,000
HDPE liner and installation costs ($33,000 ha^{-1})[a]	363,000	363,000
Pump[b]	93,000	93,000
Carbon dioxide sumps, diffusers ($4000 ha^{-1})[c]	44,000	44,000
Roads, drainage ($7000 ha^{-1})[a]	77,000	77,000
Electrical supply and distribution ($3000 ha^{-1})[a]	33,000	33,000
Instrumentation and machinery ($500 ha^{-1})[c]	5,500	5,500
Land cost ($3500 ha^{-1})[a]	38,500	38,500
ATS Screen ($6090 ha^{-1})[a]	67,000	67,000
Algal harvester[a]	85,000	85,000
Mechanical dewatering to 20% solids[d]	35,000	35,000
Algal drier[e]	135,000	135,000
Subtotal	1,350,000	1,350,000
Engineering and contingencies (15% of subtotal cost)[c]	202,500	202,500
Total direct capital	1,552,600	1,552,600
Working capital (25% of net operating cost)[c]	123,000	81,900
Total capital investment	1,675,600	1,634,500

[a] Values provided by Hydromentia, Inc. based on a proposed 11 ha 189,000 m^3 day^{-1} treatment facility for agricultural wastewater.
[b] Value based on a single 189,000 m^3 day^{-1} pump for the 11 ha treatment area.
[c] Benemann and Oswald, 1996.
[d] FAN screw press (www.fsaconsulting.net/pdfs).
[e] Belt drier with evaporation capacity of 9000 kg water day^{-1} to yield biomass with 10% moisture.

Table 2 – Annual operational cost estimates for manure effluent treatment system

	No pre-treatment ($)	Pre-treatment with anaerobic digestor ($)
Power for mixing[a]	165,500	165,500
Power for harvesting and dewatering[b]	13,200	13,200
Power for drying[c]	173,300	0
Labor and overheads[d]	62,400	62,400
Maintenance, taxes, insurance[e]	77,600	77,600
Total net operating cost	492,000	327,500
Capital charge[f]	139,100	135,700
Total annual costs	631,100	454,200
Cost per cow if biomass is dried[g]	631	454
Cost per cow if biomass is not dried[h]	454	454
Cost per kg N if biomass is dried[i]	8.70	6.20
Cost per kg P if biomass is dried[j]	43.20	31.10
Cost per kg N if biomass is not dried[k]	6.20	6.20
Cost per kg P if biomass is not dried[l]	31.10	31.10
Cost per kg of dried algae[m]	0.97	0.70

[a] Electricity cost for 189,000 m^3 day^{-1} pump for 270 days (assuming $0.06 per kWh).
[b] Electricity cost for mechanical rake harvester and FAN screw press.
[c] Electricity cost to remove 7000 kg day^{-1} water from 11,000 kg day^{-1} wet biomass for 270 days assuming energy consumption of 1.389 kWh kg^{-1} H_2O at 46% thermal efficiency.
[d] Estimate for two full-time equipment operators at $15 h^{-1}.
[e] Calculated as 5% of total direct capital cost Benemann and Oswald, 1996.
[f] Calculated as 8.3% of total capital investment.
[g] Total annual cost divided by 1000 cows.
[h] Total annual cost minus the cost of power for drying divided by 1000 cows.
[i] Total annual cost divided by 73,000 kg N from 1000 cows.
[j] Total annual cost divided by 14,600 kg P from 1000 cows.
[k] Total annual cost minus the cost of power for drying divided by 73,000 kg N.
[l] Total annual cost minus the cost of power for drying divided by 14,600 kg P.
[m] Based on 653,400 kg algal biomass produced during 270 days.

For an 11 ha treatment area and 270 days of operation per year, the corresponding total energy requirement would be 2.8×10^6 Mcal $year^{-1}$.

4. Results

Estimated capital and annual operational costs for the proposed treatment system are shown in Tables 1 and 2. Costs are shown for a system without anaerobic pretreatment and for a system that includes anaerobic pretreatment. The majority of capital costs were due to land preparation, installation of liner material, and engineering fees (Table 1). The majority of operational costs were due to energy requirements for biomass drying, pumping water, and repayment of capital investment (Table 2). On farms using anaerobic pretreatment, waste heat from burning biogas could be used to offset the energy requirements of biomass drying (Table 2, column 2). In addition, biogas combustion exhaust gas could then be recycled back to the algal system to supply dissolved inorganic carbon for optimal algal production and pH control (the costs of such a carbon recycling system are not included in this analysis) (Benemann and Oswald, 1996). Under the best case (algal system coupled with anaerobic digestion pretreatment), the yearly operational costs per cow, per kg of N, per kg of P, and per kg of dried biomass were $454, $6.20, $31.10, and $0.70, respectively. Clearly, these calculated values are dependent on the many parameters outlined in the assessment. The operational costs are particularly sensitive to the costs for repayment of the capital investment (the “capital charge”). The capital charge (calculated here as the annual charge required to pay off the facility within a 20 year period at 5% interest) accounts for 21–28% of total annual costs.

5. Discussion

5.1. *Comparison with alternative treatment systems*

Other ecologically engineered alternatives to the algal turf scrubber exist for treating dairy and other types of animal manure. Constructed wetlands have been tested extensively for this purpose (Cronk, 1996; Hunt and Poach, 2001; Schaafsma et al., 2000). Wetland cells are usually positioned after a lagoon or solids separator and they function primarily to reduce BOD and nitrogen. Although relatively short-term studies (1–3 years duration) have demonstrated that constructed wetlands can effectively treat manure wastewater, their long-term capacity for phosphorus treatment is limited (Poach et al., 2003).

High-rate algal ponds also have been utilized for treating manure effluent (Costa et al., 2000; Craggs et al., 2003; Dugan et al., 1972; Goh, 1986; Olguin, 2003). In this technology suspended phytoplankton and bacteria in slow moving, shallow raceways are used to metabolize the manure pollutants. Advanced integrated high rate ponds have evolved from passive, facultative ponds and they are used for treating domestic sewage (Green et al., 1996, 1995; Nurdogan and Oswald, 1995). Given their demonstrated performance in treating other types of wastewater, high rate pond technology has significant potential for treating dairy manure effluent.

Finally, Hillman and Culley (1978) described a duckweed (*Lemna* sp.) system for treating dairy wastewater (Hillman and Culley, 1978). A hypothetical design was proposed for a 100-cow farm operation, utilizing a sequence of lagoons, but no empirical performance data was given.

Thus, alternative treatment systems have been proposed and tested. Unfortunately, however, very few published studies report economic costs for treatment systems. Hammer et al. (1993) reported some data for a swine wastewater constructed wetland in Alabama but only capital costs were given. The total cost for about 6000 m^2 of constructed wetland was $12,800. Interestingly, an old study projected costs of $70 per ton of dried algae for a high-rate pond system (Martin and Madewell, 1971) to treat waste from poultry, swine, and cattle operations. However, drying costs were not included and an updated analysis is needed to assess the viability of this alternative.

5.2. *Byproduct value of ATS algae*

As no market currently exists for manure-grown algal biomass, our cost analysis does not include any value for the biomass generated during manure treatment. However, there are a variety of potential uses for the algal biomass from manure treatment. Fresh dewatered biomass could potentially be mixed in with animal feed (and substituted on a protein basis for soybeans) (Wilkie and Mulbry, 2002). Although this use for the biomass would avoid drying and transportation costs, such use would be relatively low value and the potential exists for disease transmission. Dewatered biomass could also be bulked with other agricultural wastes and composted. This use would be of little direct value but would also avoid drying and transportation costs.

Although more expensive to produce (Table 2), dried algal biomass is considerably easier to utilize because the nutrients are concentrated and stabilized, pathogens are eliminated, and it is easily ground for different formulations. Recent studies focused on use of the dried biomass as an organic fertilizer demonstrated that it was equivalent to a commercial organic fertilizer with respect to plant mass and nutrient content (Mulbry et al., 2005). Although the composition of the dried biomass varies with loading rate, heavy metal content is well below regulatory limits (Kebede-Westhead et al., 2004). The home consumer market is the most attractive with respect to price with retail prices of \$2–3 kg^{-1} for comparable organic fertilizers. However, the pricing at which the dried algal biomass could successfully penetrate this market is unknown.

6. Potential for nutrient trading credits

Beyond any value that the algal biomass may have as a fertilizer, feed supplement, or chemical feedstock, there are other potential sources of revenue to offset the costs of manure treatment. Nutrient trading is a market-based approach that allows pollution sources with high treatment costs (such as municipal wastewater treatment facilities in this case) to obtain pollution reduction credits from sources (dairy farmers in this case) that can reduce their nutrient contribution to the watershed at a lower cost (Greenhalgh and Sauer, 2003).

6.1. *Nitrogen credit*

A range of N credit values have been cited in different studies and models relevant to the Chesapeake Bay watershed. Greenhalgh and Sauer used relatively conservative values of $2 and $5 per lb N ($4.4 and $11 per kg N) among the different options tested in their model on the economic and environmental impact of different policy options to reduce agricultural nutrient inputs into the Mississippi River and Gulf of Mexico. Values for potential nutrient trading credits may also be developed from incremental cost estimates for upgrading municipal wastewater treatment (MWTP) in the Chesapeake Bay watershed (Chesapeake Bay Program, 2002). Values ranged from $8 per lb N ($17.60 per kg N) for annualized incremental MWTP tiers 1 and 2 targets (to achieve effluent discharge levels of 8 ppm) to $14 per lb ($30.80 per kg N) for annualized MWTP tier 3 costs (to achieve effluent discharge levels of 5 ppm). For dried algal biomass containing 7.5% N, N credit values of $2, $5, $8, and $14 per lb N correspond to $0.33, $0.82, $1.32, and $2.31 per kg, respectively, for values of dried algal biomass. All but the lowest value would cover the projected cost of manure treatment using algal production.

6.2. *Phosphorus credit*

Corresponding values for P treatment credits are $5–7 per lb P ($11–15 per kg P) (Greenhalgh and Sauer, 2003). The value of $5 per lb P was reported to be equivalent to MWTP cost for achieving 1 ppm TP and $7 per lb P was reported to be equivalent to MWTP cost for achieving "<1 ppm" TP. Although the values from potential upgrade costs wastewater treatment to achieve improved P discharge limits are somewhat difficult to separate out from costs of improved N treatment, the Chesapeake Bay report separates out an incremental cost for TP reduction of about $1 per kg P (Chesapeake Bay Foundation, 2004). However, nutrient trading credits for P reduction would be about seven-fold less than N credits since the algal biomass contains only 1% P. A credit of $11 per kg P would be equivalent to only $0.11 per kg dried algae and would represent roughly 10% of treatment costs.

7. Conclusion

For perspective, the cost of manure treatment must be compared with the profits from dairy operations. Johnson and coworkers surveyed 36 dairy farm owners in Maryland for the years 1997–2003 and found long-term annual profits of about $500 per cow (Johnson et al., 2005). Based on this relative value, costs of treatment projected in this study for an ATS system are very high and would consume most profit ($454 per cow for algal system coupled with anaerobic digestion pre-treatment) or exceed profit ($631 per cow for algal system without pre-treatment). However, the economic balance becomes more favorable if values from algae as a byproduct (e.g. fertilizer sale) and nutrient trading credits can be realized. In addition, there are many opportunities for agricultural grants or cost-sharing at the state and national levels that could defray capital and/or operational costs. The USDA's Environmental Quality Incentives Program (which provides up to 75% cost share of capital costs to a maximum of $450,000 per 5 year farm bill cycle) would be important in this regard. These kinds of economic considerations must be dealt with if dairy wastewater treatment is to be mandated in the future.

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