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Environmental and economic assessment of integrated systems for dairy manure treatment coupled with algae bioenergy production

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HIGHLIGHTS

- ▶ Life cycle assessment (LCA), costing (LCC) of four dairy manure management options.
- ▶ Reference (REF) exhibits net energy consumption, negative net present value (NPV).
- ▶ Digestion with/without algae cultivation yields net energy production, positive NPV.
- ▶ Nutrient credits are critical to financial tenability of LCA-preferred options.

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ABSTRACT

Life cycle assessment (LCA) and life cycle costing (LCC) are used to investigate integrated algae bioenergy production and nutrient management on small dairy farms. Four cases are considered: a reference land-application scenario (REF), anaerobic digestion with land-application of liquid digestate (AD), and anaerobic digestion with recycling of liquid digestate to either an open-pond algae cultivation system (OPS) or an algae turf scrubber (ATS). LCA indicates that all three "improved" scenarios (AD, OPS, and ATS) are environmentally favorable compared to REF, exhibiting increases in net energy output up to 854 GJ/yr, reductions in net eutrophication potential up to 2700 kg PO_4-eq/yr, and reductions in global warming potential up to 196 Mg CO_2-eq/yr. LCC reveals that the integrated algae systems are much more financially attractive than either AD or REF, whereby net present values (NPV) are as follows: $853,250 for OPS, $790,280 for ATS, −$62,279 for REF, and −$211,126 for AD. However, these results are highly dependent on the sale price for nutrient credits. Comparison of LCA and LCC results indicates that robust nutrient credit markets or other policy tools are required to align financial and environmental preferability of energy production systems and foster widespread adoption of sustainable nutrient management systems.

1. Introduction

Algae are increasingly considered a promising feedstock for bioenergy production, because they are highly productive, can be grown on marginal land in fresh, brackish, or even saline water, and they do not directly compete with food production (Benemann and Oswald, 1996). Despite this, there are significant environmental and financial challenges that must be overcome before algae cultivation and conversion can be made sustainable (Clarens et al., 2010; Lundquist et al., 2010). One particularly important challenge is procurement of low cost, low energy-intensiveness nutrients, most notably nitrogen (N) and phosphorus (P). It has been demonstrated that nutrient procurement is one of the most energy intensive processes and can constitute up to 50% of energy consumption during algae cultivation when fertilizers are used (Clarens et al., 2010; Stephenson et al., 2010). On the other hand, nutrient-rich wastes from animal agriculture pose significant environmental challenges such as regional eutrophication and global warming potential. As an example, water quality impairment in the Chesapeake Bay (the largest estuary in the United State) has been partially attributed to excess runoff and discharge of nutrients from farms, of which 18% of N and 25% of P arises from animal wastes (Chesapeake Bay Foundation, 2004). Animal waste is also an increasing source of greenhouse gas (GHG) emissions, including methane (CH_4) and nitrous oxide (N_2O). The US Environmental Protection Agency (EPA) estimates that GHG emissions from

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animal wastes increased by almost 60% during the period between 1990 and 2009 (EPA, 2010). Therefore, there is significant interest in leveraging possible synergies between algae-derived energy production and animal waste management to simultaneously improve the environmental sustainability and economic attractiveness of each individual system.

Open pond systems (OPSs) have been the best studied configuration for large scale algae cultivation. Several previous reports have estimated the environmental impacts and economic costs of algae-derived energy sources produced in OPSs, and this configuration is generally considered to be the most practical option for near term deployment of algae-to-energy systems (Clarens et al., 2011; Lundquist et al., 2010). Use of partially treated wastewaters as nutrient source for mass algae culture in OPSs has been shown to improve the environmental performance of algae-to-energy systems by reducing virgin fertilizer consumption and also offsetting energy requirements for N and P removal in a municipal wastewater treatment plant (Clarens et al., 2010; Lundquist et al., 2010; Pittman et al., 2011). Both benefits increase with increasing effluent N and P concentrations; however, there have been few comprehensive LCA studies to analyze the use of nutrient-rich animal wastes as nutrient source. This is surprising given the much larger N and P concentrations in animal wastes and several previous reports which have demonstrated bench-scale algae growth on these media (Markou and Georgakakis, 2011).

The so-called "algae turf scrubber" system (ATS) is one alternative to OPSs for algae cultivation at large sale. This system has been the topic of several previous technical assessments, which have documented its ability to produce sustained algae yields of up to 40 g dry solids (DS)/m^2-day. ATS systems have also been shown to mediate efficient nutrient removal; up to 2,500 kg N/ha/yr and 490 kg P/ha/yr, from river water, agricultural runoff, animal manure effluent, or industrial wastewater (Kebede-Westhead et al., 2003; Mulbry et al., 2008a,b). Pizarro et al. (2006) evaluated the economic feasibility of using ATS to treat dairy manure effluents on large dairy farms (1000 cows). This assessment did not include a full scale environmental life cycle assessment (LCA), and it only accounted for one of several possible financial benefits associated with use of an ATS system; namely, efficient recycling of nutrients into algae biomass such that purchase of N and P is not required for sustained algae cultivation. Some additional financial benefits of these systems could include: sale of algae-derived electricity; sale of N, P, and/or CO_2 credits in a regional or national trading market; and sale of post-digestion residuals as nutrient-rich soil amendment (i.e., fertilizer). It is necessary to account for all of these elements within a life cycle costing (LCC) framework to fully understand and anticipate the financial performance of farm-scale ATS systems. It is also necessary to assess the environmental performance of ATS systems, using a life cycle assessment (LCA) framework, such that full information is available for sustainability decision making about possible integration of algae farming and nutrient management.

This study was conducted with three specific objectives: (1) assess the relative environmental performance of OPS and ATS systems for manure nutrient management on small dairy farms using LCA; (2) assess the relative financial performance of OPS and ATS systems for manure nutrient management on small dairy farms using LCC; and (3) compare the overall environmental and financial performances of OPS and ATS systems with two conventional manure nutrient management strategies (anaerobic digestion and on-farm land application) to evaluate which strategy is optimally sustainable. We focused on small farms (i.e., 100 cows) because this is roughly the size of a typical farm in the Southeastern USA (Groover, 1998), and it is expected that the growing nutrient trading program in this region could increase the attractiveness of these systems for local farmers.

2. Methods

Four manure nutrient management strategies were evaluated using complementary LCA and LCC frameworks. These include: Scenario REF (reference), where manure waste is managed using conventional on-farm land application; Scenario AD (anaerobic digestion), where manure waste is subjected to anaerobic digestion for biogas production and nutrient recovery; and Scenarios OPS and ATS, where post-digestion liquid waste is used as nutrient source for algae cultivation in an open pond system (OPS) or algal turf scrubber (ATS), respectively, and resulting algal biomass is co-digested with dairy waste for enhanced bioenergy production. These scenarios are depicted schematically in Fig. 1. In all cases, nutrient concentrations and other characteristics of dairy manure were based on Van Horn et al. (1994). On-farm waste application (for scenarios REF and AD) was assumed to occur during the crop growing season, which is March through September in the Southeastern USA. Algae cultivation was assumed to occur from March through November (Mulbry et al., 2008; Pizarro et al., 2006). Wastes generated and collected outside of the biomass growing season were stored on-farm in lagoons.

Systems boundaries for all four scenarios were "cradle to gate" for dairy manure management systems, encompassing all processes associated with dairy manure treatment; including collection and storage of the waste, extraction of raw resources for production of required energy/material inputs, production of bioelectricity for on-farm use or sale to the local grid, and disposition/export of residual materials. All facilities and processes associated with cow breeding and manure collection were excluded from analysis, because they are held in common for all evaluated scenarios and it was assumed that these items would already be in place at all farms trying to decide among the four evaluated scenarios. Environmental impacts associated with construction of capital infrastructure and equipment were calculated by multiplying required material inputs by their corresponding database impact factors, as obtained from the ecoinvent database (Weidema, 2007). These quantities were divided by an assumed 20-years useful life to facilitate direct comparison with annual impacts arising from operations in each scenario. The functional unit was defined as management of as much manure is produced on a 100-cow farm, to account for the multiple functions of the various systems, including: nutrient recycling, biomass production (corn in REF and AD, or algae in OPS and ATS), energy production, and creation of soil amendment.

LCA models accounted for three types of environmental impacts: net energy use (EN), net eutrophication potential (EUT), and net global warming potential (GWP). LCC models were constructed using the LCA mass-flow models as basis (Figures S1, S2, and S3 of the SI). The outcome of the LCC analysis was computation of net present value (NPV) for each system, based on three types of cash flows: initial outlay, annual operating cost, and annual revenue. Initial outlay was the total capital investment required for purchase of materials and equipment, construction costs, and miscellaneous costs. Annual operating costs included energy, labor, and capital depreciation. Annual revenues accounted for five possible sources, not all of which are achievable for a single scenario: (1) sale of corn (for REF and AD); (2) sale of biogas-derived bioelectricity (for AD, OPS, and ATS); (3) sale of N and P treatment credits, using the 80% of REF nutrient loadings as "baseline" and assuming that the nutrient loading reductions achieved by each "best management practice" (AD, OPS, and ATS) are eligible to be sold (Branosky et al., 2011; Maryland Department of Agriculture, 2008); (4) sale of carbon dioxide (CO_2) credits within the national carbon market (for AD, OPS, and ATS) (Cap-and-Trade Program, 2012; Chicago Climate Change, 2011), which is the reduction of CO_2 emission compared to scenario REF; (5) sale of post-digestion