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ANAEROBIC DIGESTION AND RELATED BEST MANAGEMENT PRACTICES: UTILIZING LIFE CYCLE ASSESSMENT

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ABSTRACT Anaerobic digestion of dairy manure with energy recovery through biogas combustion is generally viewed as a positive environmental approach to increase the use of renewable energy. However, there are potential negative impacts associated with emissions of methane and nitrogen species during digestion and after spreading of digester effluent that have the potential to counteract the environmental benefits of anaerobic digestion. To promote best management practices, assessment of environmental impacts and investigation of their causes should be conducted using a broad perspective. A life cycle assessment (LCA) comparing environmental impacts of business-as-usual manure management with those of a manure management operation incorporating anaerobic digestion with combined heat and power generation was conducted. The case study, based on a medium sized dairy farm in northern New York State, USA, showed benefits across multiple categories due to the displacement of fossil fuels, and reduction of related emissions. Knowledge gained from the LCA was used to assess the benefits associated with various management practices. For example, design and construction of biogas systems must minimize the potential for fugitive emissions of biogas that can easily outweigh the climate change related benefits associated with fossil fuel displacement. This paper defines and explains the environmental trade offs associated with various manure management and energy recovery systems.

Keywords: anaerobic digestion, manure storage, climate change, eutrophication, lifecycle assessment, methane, nitrous oxide

INTRODUCTION Animal husbandry and associated waste management is known to cause significant environmental impacts. The chemicals of main concern in terms of environmental impact are methane, carbon dioxide, ammonia, nitric oxide, nitrous oxide, and nitrate (Rotz, 2004; Amon et al., 2006; Bertora et al., 2008). The shift in animal production from smaller distributed farms to concentrated animal feed operations (CAFOs) has resulted in large volumes of manure that must be disposed of responsibly (USEPA, 2008). The necessary manure management activities of these CAFOs has the potential cause significant environmental impacts, and concerns over these impacts continue and broaden as understanding of complex

interactions between agriculture and the environment deepens (Van Horn et al., 1994; Harrison et al., 2007).

Agriculture is the primary source of water quality impairment in the United States (USEPA, 2004). Current government regulations regarding manure disposal focus on limiting the amount of nutrients applied to land, as a means of reducing the emissions of nutrients to water (USEPA, 2003). Long term storage in earthen basins, which are employed by approximately half of all large animal feeding operations (USDA-APHIS, 2004), are often used to allow spreading of manure at times when nutrients are more likely to be taken up by crops and less likely to be lost to surface water (Rotz, 2004). However, while the storage of manure is seen as an effective practice for reducing the potential for nutrient loss through surface water, the loss of methane from these basins is now recognized as a significant source of greenhouse gases (GHGs) that can contribute to climate change. So while the CAFO regulations that require storage may be effective in reducing non-point source nutrient pollution entering our surface water bodies, they may be inadvertently increasing GHG emissions.

Escalating fossil fuel and fertilizer costs are forcing farmers to reconsider manure management options. Anaerobic digestion (AD) with energy recovery has been touted as an effective means for reducing the environmental impacts of manure management operations due to the reduction of methane released during storage of manure as well as the production of renewable biogas which can be used to displace fossil fuels (Ghafoori et al., 2006; Cuellar and Webber, 2008; Tikalsky and Mullins, 2007).

AD is used to create biogas from the biological breakdown of organic compounds. Biogas is a mixture of methane and carbon dioxide (approximately 60% and 40%, respectively) that has an energy value sufficient for generation of electrical power and heat. The most common reasons for dairy farmers to employ an AD system are to reduce electricity costs or to reduce odor during land application of the manure slurry. In addition, the nutrient value of the manure is retained through the process of digestion so that the slurry can still be used to displace mineral fertilizer use, making the recovered energy an added value.

Power generation from biogas has been shown to reduce fossil fuel consumption and global warming impacts of agricultural operations that employ the technology (Monteny et al., 2006; Clemens et al, 2006; Clemens and Ahlgrimm, 2001). For these reasons, AD/CHP systems have been touted as a means to reduce the environmental impact of agricultural activities, animal husbandry in particular. Although there are clear benefits to the use of AD/CHP, the initial cost of construction and start up, along with the ongoing requirements for operations and maintenance of such a system, are often roadblocks for farmers interested in implementing the technology. Analyzing the environmental impacts and benefits from a system-wide perspective of manure management operation will help to inform farmers, policy makers, and other stakeholders of the potential outcomes of widespread AD/CHP implementation.

The objective of the research presented here is to provide a systems perspective on the environmental impacts and the relative benefits associated with different manure management practices. Table 1 summarizes many of the currently published pros and cons associated with manure management practices. Life cycle assessment (LCA) is used as a tool to quantify and compare these environmental impacts to more systematically compare the overall and competing

benefits and detriments (ISO 14040). Life cycle assessments of anaerobic digestion processes have generally found that they represent a beneficial source of renewable energy (Ghafoori et al., 2006; Ishikawa et al., 2006). The knowledge developed in this research can be used to verify the overall benefits of various manure management practices (Table 1) and make recommendations for best management practices or identifying particular areas in which further research is required to more fully inform decisions about the wide scale implementation of AD/CHP.

Table 1. Summary of reported environmental benefits and concerns associated with manure management practices

Benefits	Concerns
Storage	
<ul style="list-style-type: none"> ▪ Reduces non-point source runoff and nutrient pollution of waterways (eutrophication) 	<ul style="list-style-type: none"> ▪ Uncontrolled release of methane, a potent greenhouse gas from the anaerobic environment of a lagoon
Anaerobic digestion with combined heat and power generation	
<ul style="list-style-type: none"> ▪ Odor control ▪ Controlled capture of biogas released under anaerobic conditions and beneficial use ▪ Displacement of fossil fuel consumption through biogas combustion for heat and electrical energy 	

RESEARCH APPROACH AND METHODOLOGY LCA was used as an analysis approach to model and evaluate environmental impacts related to manure management. A comparison is made between the use of storage versus direct spreading and the implementation of an AD system with combined heat and power (CHP) recovery. The study is based on North Harbor Dairy (NHD), a medium sized dairy farm (~600 milking cows) in northern New York State (NYS). Before building a large lagoon with three months of manure storage capacity as required under CAFO regulations, the standard manure management practice involved the daily collection, transport and land application of approximately 90m³ of sand-laden liquid manure slurry. Preliminary plans are under consideration for the construction of an AD/CHP energy recovery system, primarily for displacement of grid electricity use. This system would also include separation of sand from the manure to enable recycling of sand for bedding. Use of the AD/CHP system will alter the energy and resource use profile of the farm, as well as the chemical and biological properties of the manure slurry. The functional unit in this study is one day of manure management (90m³ of dairy cow slurry). All calculated flows are based on this quantity of manure processed.

LCA models were developed using the SimaPro software platform (Pre Consultants). For the comparisons presented here, the scope of the analysis was established to include only those processes, mass flows, and energy flows that could potentially change with a change in the manure management operations at the dairy farm. The introduction of heat and power generation through the use of biogas combustion will affect the electricity use of the farm, so the upstream

processes for production of grid electricity use are also included. Upstream emissions and extractions for propane and diesel fuel use on the farm were also included in the assessment. Figure 1 provides a simplified illustration of the system considered in this research.

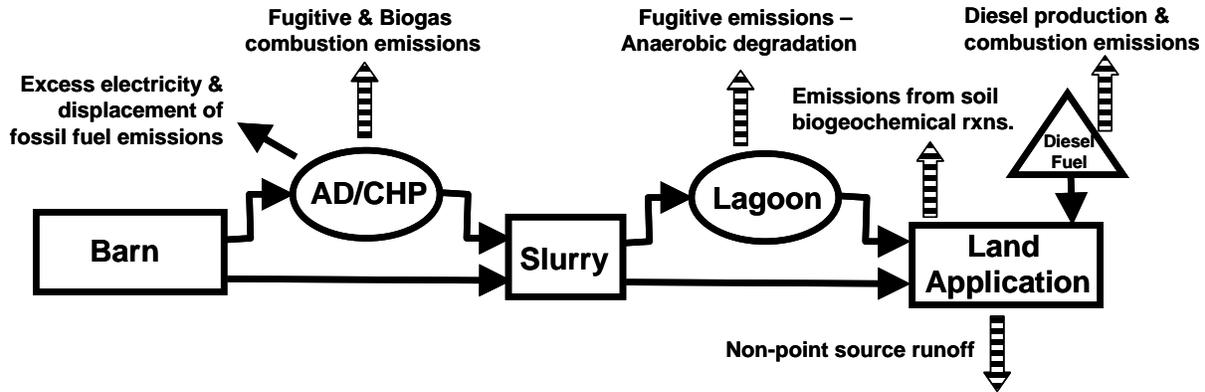


Figure 1. Simple schematic of the systems included in the LCA presented here. Manure flow scenarios from the barn include lagoon storage or direct land application and anaerobic digestion or storage and spreading of raw manure.

To compile a life cycle inventory for each of the scenarios, processes and mass/energy flows available from the ecoinvent database (Pre Consultants) built into SimaPro were used to a large extent. Processes that were specific to this study or not available by default in SimaPro were constructed using data available from peer-reviewed literature and/or results of laboratory testing specific to the case at hand. The mass balances of carbon and nitrogen species were evaluated on a fractional basis to account for the ultimate fate of all various species (Venczel and Powers, 2010). Uncertainty in the parameters used to estimate mass and energy flows were incorporated into the model through Monte Carlo simulations. Statistical distributions were developed for key parameters and over 1000 simulations were performed to generate a distribution of results. Table 2 summarizes the key input and output variables and their environmental impacts that are included in the model and the discussion here. The ReCiPe lifecycle impact assessment model was used to quantify the environmental impacts used in this research (Goedkoop et al., 2008).

Table 2: Environmental impacts considered in the research presented here

Environmental Impacts	Mass/Energy Flows
Climate Change	CO ₂ , N ₂ O, CH ₄
Terrestrial Acidification	NH ₃ , SO ₂ , NO _x
Marine Eutrophication	NO ₃ , NH ₃
Fossil Fuel Depletion	Fossil fuels used in all processes, including electricity generation

RESULTS AND DISCUSSION The results of this analysis are summarized in a comparative basis in Table 3. This table quantifies the relative benefits and detriments of storage and the implementation of an AD/CHP system. In general, the changes in the environmental impacts can be attributed to a few primary changes in the composition of manure due to the anaerobic environment in the lagoon or digester. The reducing anaerobic environment changes most of the

degradable organic matter into methane and carbon dioxide, which are captured in a controlled fashion (digester) and combusted, or released to the environment in an uncontrolled fashion (lagoon). Anaerobic conditions also result in a conversion of nitrogen species to ammonia.

Table 3. Summary of relative environmental benefits and detriments associated with manure storage and digestion

Storage vs. Direct Spreading			
Benefits		Detriments	
(% decrease with storage)		(% increase w/ storage)	
Marine Eutrophication		Terrestrial Acidification	
raw	36.3%	raw	128.2%
digested	44.5%	digested	128.9%
N ₂ O from lagoon		CH ₄ - Lagoon [#]	
raw	31.9%	raw	1243*
digested	40.9%		
NET GHG Emissions			
raw	12.5%		
digested	2.6%		
Digested vs. Raw manure (w/ storage)			
Benefits		Detriments	
(% decrease with AD/CHP)		(% increase w/ AD/CHP)	
Marine Eutrophication	16.0%	Terrestrial Acidification	45.1%
CH ₄ – Lagoon	42.1%	CH ₄ Fugitive - AD/CHP**	1618*
Fossil GHG emissions – energy	83.6%		
NET GHG Emissions			
Fugitive included	10.7%		
Fugitive excluded	42.6%		

* increase over zero emissions in comparison case. Value is total emission (kg CO₂ eq/d)

[#] CH₄ emissions associated with storage of raw manure in a lagoon contribute 24.5% of the total GHG (greenhouse gas) emissions in this scenario

** Fugitive emissions contribute 35.7% of total GHG emissions from the AD/CHP system

The fate of nitrogen species represents a substantial trade off in the nature of the environmental impacts associated with manure management. Both lagoon storage and digestion result in higher ammonia emissions than the direct application of raw manure to fields. Ammonia is a respiratory irritant, contributes to the formation of particular matter (PM) in the atmosphere, and forms acid rain. These detriments are countered by the benefits of reduced nitrous oxide and nitrate emissions that contribute to climate change and eutrophication, respectively.

Figure 2 provides a more detailed perspective of the complexities of the greenhouse gas (GHG) emissions associated with the manure management options considered here. There are significant changes in the types of gases released when manure is stored or digested. The storage of manure in uncovered lagoons has been blamed for increased methane emissions from the agricultural industry. With a global warming potential that is 21-24 times greater than carbon dioxide on a per mass basis, these methane emissions can contribute substantially to climate change. Indeed, the methane emissions associated with storage (Figure 2) are much greater for manure that is stored in an uncovered lagoon versus manure that is directly spread on fields. Digesting manure before storage does indeed reduce the uncontrolled release of methane emissions. Most of the methane in this case is captured and combusted for heat and electrical energy production.

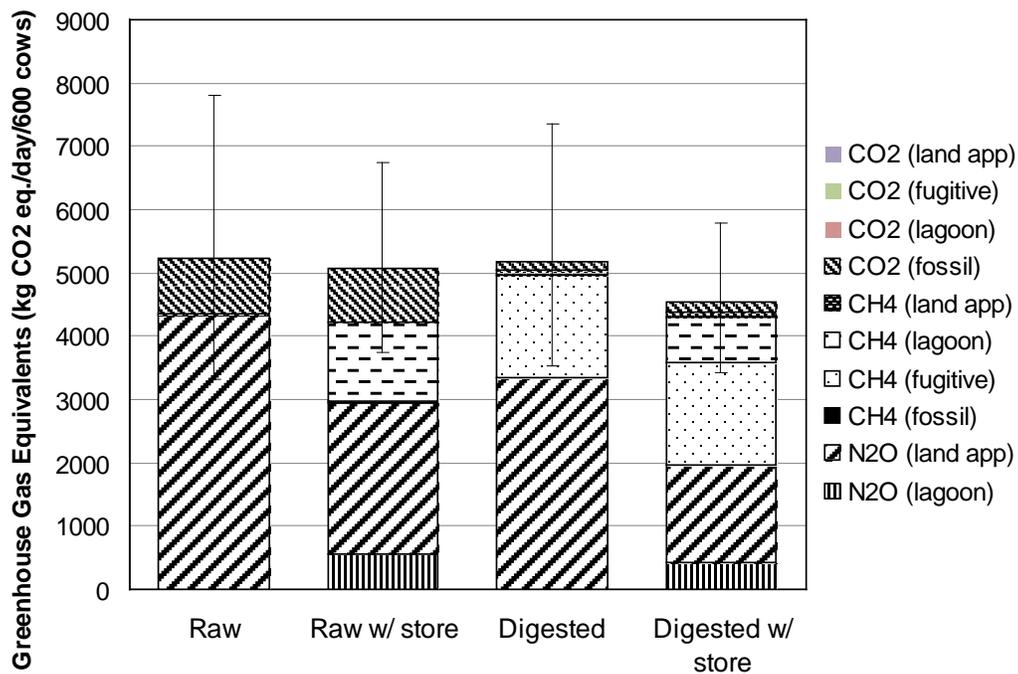


Figure 2. Greenhouse gas emissions associated with the direct spreading of raw manure, storage of raw manure before spreading, and digestion of manure before storage and spreading.

The information shown in Figure 2 and summarized in Table 3, however, shows that the concern over methane emissions is too narrow of a perspective and that other gases are more important in their contribution to the greenhouse effect. Nitrous oxide (N_2O) is a very potent GHG with a global warming potential of 298 g CO_2 eq/g N_2O . In an agricultural system, N_2O is released as an intermediate product from the series of nitrification and denitrification reactions that occur in the lagoon and in the soil. N_2O emissions are highest for the direct spreading of raw manure since a greater fraction of the nitrogen species in this case is available for denitrification. The very large error bars associated with the total GHG emissions (Figure 2) are due almost entirely to the uncertainties in N_2O emission rates. Storage, while generally denounced as bad for GHGs due to increased methane emissions, actually has a slightly lower net GHG emission rate than direct spreading of manure. The lower N_2O emissions in this case are the result of increased losses of N as ammonia before denitrification can occur.

The addition of an AD/CHP system helps to reduce GHG emissions in several ways. Methane emissions from the lagoon are reduced since most of the degradable organic matter in the manure is transformed into biogas in a controlled manner and captured for combustion. However, since there is some methane remaining in the digested manure and the digestion of organic solids in the manure continues, there are still some losses from the lagoon. The digestion process helps to reduce N₂O emissions by increases losses of nitrogen from the system as ammonia. Reducing degradable organic carbon during anaerobic digestion also lowers N₂O emissions since this organic fuel that is necessary for the denitrification process is consumed by other reactions. CO₂ emissions associated with fossil fuel combustion are also greatly reduced with the AD/CHP system due to the production and export of excess electricity that displaces electricity generation by fossil fuels. These benefits are less in New York State than might be realized in other regions due to the lower than average use of fossil fuels (~50%) to generate electricity in the Northeast.

In spite of these benefits, the results presented here also show the potentially significant contributions of fugitive emissions of methane from the digester and combustion system. Fugitive methane emissions can contribute as much as 25% of the total GHG emissions when an AD/CHP system utilized. Biogas can be emitted from cracks in concrete tanks, at the junction between a tank and a flexible and expandable cover, or from leaky valves and pipe fittings. The contribution of fugitive emissions to the total GHG emissions suggests the importance of careful construction, monitoring and maintenance of AD/CHP systems to reduce these losses. However, with proper design, construction and operation to minimize these fugitive emissions, AD/CHP systems can cut GHG emissions by over 40% in comparison to the storage of raw manure.

CONCLUSIONS The ability of various manure management practices to have an overall positive benefit to the environment is greatly affected by changes in the composition of the manure. By changing the nitrogen and carbon species in the manure, we can reduce environmental impacts. There can, however, be unintended consequences when a narrow perspective on emissions or environmental impacts is considered. By utilizing a broader lifecycle perspective, the environmental trade offs can be identified and quantified. The analysis presented here does confirm the general notions that lagoon storage before spreading of manure reduces eutrophication from nutrient runoff and that storage in an uncovered lagoon also increases the release of methane gases. However, this analysis also shows that:

- The release of ammonia from lagoon storage (with or without digestion) contributes to acidification and particulate matter formation. These detrimental impact must be weighed again the benefits of reduced eutrophication and N₂O formation.
- An AD/CHP system does reduce methane emissions from storage and carbon dioxide emissions from electricity generation. These engineering systems must, however, be designed, constructed and maintained properly to minimize the fugitive losses of methane to maximize the benefits.

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