The Rationale for Recovery of Phosphorus and Nitrogen from Dairy Manure

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This publication explains the rationale for implementing emerging phosphorus and nitrogen nutrient recovery technologies on dairies, with a particular focus on the Western United States. Although dairy operations are emphasized, the lessons learned are readily applicable to feedlot, swine, and poultry operations, as well as other industrial and municipal organic solids and wastewater treatment facilities. The specific technology requirements will vary, depending on the qualities of the waste streams being processed.

Manure Management and Environmental Issues in the United States

In one year, a dairy cow generates liquid and solid manure that contains 58 lb phosphorus, 168 lb ammonia (a form of nitrogen), and 336 lb total nitrogen (ASAE 2005). Dairy manure is expensive to transport, so it is generally applied to nearby fields, which sometimes leads to excess applications of nutrients. The ongoing trend of increased numbers of dairy cows per farm in the U.S. (USDA-NASS, 2010) results in greater concentrations of manure, bedding, and urine being produced by the dairy operation. This increases the transport distances (and costs) required for appropriate land application of manure. In 2000, only 1% of large dairies (those with more than 1000 animal units) were applying phosphorus at agronomic rates, while only 23% were applying nitrogen at agronomic rates (Ribaudo et al. 2003). More recent data indicate that larger operations apply manure to cropland at rates that are more than three times higher than smaller farms, suggesting that excess nutrient applications are still an issue, particularly for large operations (MacDonald and McBride 2009). This observation is also supported by a recent study of manure application to field corn (the receiving crop for more than half of all applied manure), which found that the vast majority of dairies applied manure to fewer acres than would be needed to meet best management practices for nutrient management (USDA ERS 2011).

The loss of phosphorus and nitrogen to the environment during manure management can contribute to a number of significant water and air quality concerns:

- **Phosphorus and Nitrogen Eutrophication.** Both phosphorus and nitrogen can be lost through runoff or infiltration and leaching at manure storage locations and field application sites, as well as through soil erosion. Losses increase substantially as nutrient application exceeds the plant needs (Bock and Hergert 1991; Schlegel et al. 1996). Once lost from agricultural systems, phosphorus and nitrogen can migrate to lakes, rivers, estuaries, and coastal oceans. Overabundant nutrients can then lead to excessive growth of algae and aquatic weeds and subsequent oxygen shortages (Carpenter et al. 1998), fish toxicity (Ward et al. 2005), habitat loss (NRC 1993; Jeppesen et al. 1998) and decreased species diversity (Sutton et al. 1993).
- **Nitrate Pollution of Water Sources.** Infants under six months of age who ingest high levels of nitrates in the water supply can acquire blue baby syndrome. Symptoms include bluish skin, stupor, brain damage and in severe cases, death (US-EPA 1991).
- **Ammonia Volatilization.** An estimated 70% of total manure nitrogen is lost as ammonia during manure management and application on U.S. dairies and feedlots (CAST 2002). Ammonia is highly reactive and contributes to the development of ultra-fine particulate matter (PM 2.5) in the atmosphere. PM 2.5 has detrimental effects on overall air quality and human and animal health (Erisman and Schaap 2004; McCubbin et al. 2002; Archibeque et al. 2007).

Greenhouse gas emissions are also a concern of current manure management practices. Dairy cattle create direct and indirect emissions of greenhouse gases throughout the production process, with over half of direct emissions generated by manure management (US-EPA 2013a). There is significant variation in emissions depending on the types of manure management systems; with higher methane emissions coming from liquid manure management systems. These liquid manure systems are increasingly used in dairy operations (US-EPA 2013a), leading to recent increases in greenhouse gases associated with manure management. In total, manure management for dairy cattle in the U.S. contributed an estimated 46% of the greenhouse gas emissions associated with manure management for all livestock and poultry in 2011; or 0.48% of gross greenhouse gas emissions in the United States (this was an estimated 32.4 million metric tonnes, MT; US-EPA 2013a).

Factors Contributing to Nutrient Overloading

Because phosphorus and nitrogen losses increase rapidly when they are applied in excess of plant needs, one strategy for minimizing losses to the environment is to ensure that manure applications do not provide more nutrients than can be taken up by the crops being grown on the land. However, there are many factors that can contribute to nutrient loading at higher-than-recommended levels, despite the potential for negative environmental impacts (USDA ERS, 2011):

- The expense of transporting manure to distant fields. This is particularly true for liquid manure, but also applies to "dry" manure, which contains significant moisture (Henry and Seagraves 1960; Ribaudo et al. 2003; Heathwaite et al. 2000).
- Reluctance to apply manure to food crops due to environmental and food safety concerns (Guan and Holley 2003; Ribaudo et al. 2003), which largely limits the land base available for manure application to forage fields (USDA ERS 2009).
- Variability in the nutrient form and content of stored manure, and the timing of nutrient availability to plants (especially for nitrogen) can lead producers to apply extra manure or supplement with inorganic fertilizer (USDA ERS 2011; Davis et al. 2002: Eghball et al. 2002; Power et al. 2001; Alva et al. 2005).
- The NPK ratio of manure may not match the ratio needed by crops, necessitating additional inorganic fertilizer for proper nutrient balance (Frear et al. 2011; USDA ERS 2009).
- Broadcast application of manure, a widely used method, may encourage nutrient loss and runoff (USDA ERS 2011).
- The crop producers' tendency to target nutrient application toward high-yield goals, rather than average yields (USDA ERS 2011), may result in an over-application during years when conditions are average or below average.

Water and Air Quality Issues in Dairy Regions of the Western U.S.

Dairies in many regions of the Western U.S. are facing increased pressure from growing public concern about nutrient-related water and air quality issues. In some cases, regulation of dairies has increased as a result of these public concerns. High levels of phosphorus in the middle Snake River and in cropland soils are a concern in the Magic Valley of Idaho (IDEQ 1998; Leytem and Bjorneberg 2009). Nitrate issues and excess nitrogen in water have received increased attention, and studies suggest that manure applications play a role in a number of areas, including the Tulare Lake Basin and Salinas Valley of California (Viers et al. 2012), the Magic Valley of Idaho (Baldwin 2006), the Yakima Valley of Washington (US EPA 2012a), and the Abbotsford-Sumas aquifer along the U.S. and Canadian border in Washington (Mitchell et al. 2005). Nitrogen eutrophication of surface water is an important concern in the Yakima Valley, particularly because the Middle Columbia River bull trout and the Middle Columbia steelhead (both listed under the Endangered Species Act) spawn or rear in this watershed. Air quality is a significant concern in the San Joaquin Valley, where air pollution exceeds the Federal standards for ultra-fine particulate matter (US EPA 2012b), and in the Yakima Valley, where meeting air quality standards remains an ongoing concern (Pruitt 2013).

Average Emissions from Dairy Cows in the United States

Average emissions for dairy cows in the U.S. were estimated at 6.2 MT CO_2e/head/yr in 2011 (1 MT = 1 megagram [Mg] = 10^6 gram [g]), with 3.2 MT CO_2e/head/yr specifically from manure management (US-EPA 2013a). This does not include nitrous oxide (N_2O) emissions associated with grazing, or indirect CO_2 emissions from fertilizer synthesis, diesel use, and transportation. Emissions are commonly expressed using carbon dioxide equivalents, CO_2e, which indicates, for a given mixture and amount of greenhouse gas, the concentration of carbon dioxide that would cause the same global warming, when measured over a specified timescale, normally 100 years.

Manure: Liability or Resource?

While most discussion of dairy manure focuses on negative environmental consequences, the nutrients and carbon in manure have important potential values. Many crop producers who use manure, use less commercial fertilizer, and thus are impacted less from spikes in fertilizer prices (USDA ERS 2009). However, nutrients in manure are only valuable when there is a nearby market for those nutrients. Meanwhile, dairy producers have to utilize manure in a way that complies with stringent storage and application regulations that often specify loading rates and timing. This generates highly localized markets for manure where, in some areas, crop producers pay for manure, while in other areas producers require dairies to pay them for accepting the manure (USDA ERS 2009). Managing manure is major consideration for dairy producers, and one that comes with high potential costs in areas where there are few crop producers willing to accept manure (USDA ERS 2009).

Recovering, Concentrating, and Partitioning Nutrients from Manures

As a result of the increasing costs of nutrient management for dairy manure, increased attention is being paid

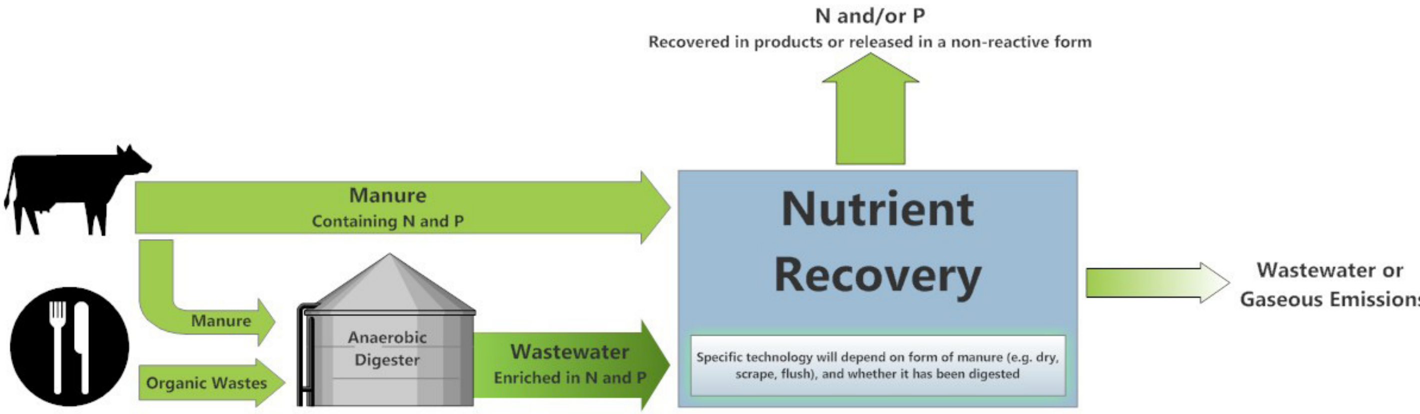

Figure 1. A generalized schematic of the phosphorus and nitrogen nutrient recovery process. Image created by Nick Kennedy.

Figure 2. Commercial-scale phosphorus and nitrogen nutrient recovery facility integrated with a dairy anaerobic digester, Lynden, WA. Photo courtesy of Eric Powell.

Figure 3. Commercial-scale recovery of phosphorus solids, integrated with a dairy anaerobic digester in Bio-Town, IN. Photo courtesy of Doug Van Ornum.

to the development of commercially viable nutrient recovery technologies. Although only a few technologies are widely commercialized at present, several nitrogen and phosphorus recovery technologies have recently emerged, which have the potential to improve nutrient management on dairies. Some of these technologies are most appropriately used on specific forms of untreated dairy manure (e.g. scrape, flush), while others are more appropriate when combined with anaerobic digestion (AD) as part of an AD system (Figure 1). Specific approaches also vary in that some recover both phosphorus and nitrogen (Figure 2), while others focus primarily on one nutrient (Figure 3).

Each of these technologies has costs associated with installing, operating, and managing the system. The most promising of these technologies successfully minimize expenses or generate concentrated nutrient products that can be sold to offset costs. Because manure management is already a primary concern for dairy producers, a process that recovers nutrients, and lessens the environmental and regulatory issues described above, is likely to be appealing—even if the profits are not overwhelming.

Benefits and Challenges to Nutrient Recovery

Nutrient recovery has the potential to transform dairy nutrient management by reducing the amount of phosphorus and nitrogen in liquid and solid wastes. Some nutrient recovery processes dispose of these nutrients in a non-reactive form. For example, biological nitrogen recovery can transform ammonia or organic nitrogen into non-reactive nitrogen gas that can be released into the atmosphere without negative environmental impact. However, most nutrient recovery technologies produce concentrated nutrient products that can be more economically transported than manure. Such products include bio-ammonium sulfate crystals (21:0:0:24[S]), phosphorus-rich solids (3:2:1 + micronutrients, dry weight), and phosphorus containing struvite crystals (6:29:0:10[Mg]) (Figure 4). In some cases, the nutrient recovery processes generate a product, which is more stable, homogenous, and predictable than manure. This can make the products more appealing to crop producers, who can store them, better control application rates, and in some cases, control the application method (Figure 5). Blending of nutrient recovery products,

Figure 4. Nutrient recovery products including (left to right) bio-ammonium sulfate crystals, phosphorus-rich solids, and phosphorus containing struvite crystals. Photos of ammonium sulfate crystals and solids courtesy of Craig Frear. Photo of struvite crystals courtesy of Keith Bowers.

Figure 5. Preparing to apply bio-ammonium sulfate solution to fields. Photo courtesy of Craig Frear.

with or without inorganic fertilizers, has the potential to produce products with desired NPK balances. Lastly, the processing time for these nutrient products, and (in some cases) exposure to high temperatures, can diminish real and perceived environmental and food safety risks that lead some crop growers to avoid manures. Some nutrient recovery products, such as struvite and ammonium sulfate, are pathogen-inert chemicals.

However, most nutrient recovery products are not yet fully developed. Products from various technological processes are often heterogeneous, have inconsistent form, and may

Figure 6. Phosphorus-solids without drying or pelletizing. Photo courtesy of Craig Frear.

require further processing to dry, or make product handling and application manageable (for example, compare the wet phosphorus solids in Figure 6 with the dry, homogenous crystal products shown in Figure 4). Products with diminished (but not eliminated) pathogen risks may still be unappealing to food crop producers. Further development of economical dewatering technologies and consistency of fertilizer form, function, and performance are needed. This will allow nutrient recovery to generate a consistent product that can be easily applied with crop producers' existing equipment.

Markets for these products have not yet matured due to limited availability and unproven fertilizer efficacy. Additional research is needed to demonstrate the ability of these products to meet the specific needs of growers. Some products may be appropriate in specialized situations, while others may be used more generally. For example, ammonium sulfate will acidify soils, and therefore may be particularly useful to maintain drip line irrigation systems, and amend soil pH in applications such as blueberry production. In contrast, struvite may be more widely used as a phosphorus source, because of its dry, granular form. Together, these steps could lead to the market development and increased revenues required to adequately cover the costs of implementing various nutrient-recovery technologies.

In addition to the nutrient products, almost all phosphorus and nitrogen nutrient recovery processes generate wastewater (Figure 1). If this wastewater has reduced amounts of phosphorus or nitrogen, it may be less likely to exceed the required nutrient regulations on nearby soils. However, because it has less phosphorus or nitrogen, the NPK ratios are quite different than manure, with much higher ratios of potassium and other salts. Therefore, it will be essential that any cropland receiving the low-nutrient wastewater be effectively monitored for salt content. Changes in crop selection and rotation on dairy forage fields may be necessary to accommodate the distinctive characteristics of the nutrient-diluted wastewater.

The Role of Nutrient Recovery in Achieving Environmental Quality

Regulation has played an important role in nutrient management, and undoubtedly will continue to do so. However, there are limits to the effectiveness of a purely regulatory approach. As Aillery and colleagues (2005) have pointed out, a tighter regulation to protect water quality from nitrogen in manure that is applied to cropland, has the potential to cause changes to manure management that reduce losses of nitrogen-nitrate, by trading those for losses of nitrogen-ammonia (which is currently unregulated). This trade-off would create a negative impact to air quality. Implementing regulatory strategies for nutrient management without viable technology options to concentrate and export nitrogen from dairies will likely encourage further examples of this type of shifting.

Implementing nutrient recovery technology may become a cost-effective approach to improving nutrient management at a watershed level, through the replacement of imported chemical nutrients by crop-farms with manure-derived nutrients already in the watershed. However, it is important to note that nutrients can still be lost from nutrient recovery products or from nutrient-diluted wastewater, especially if these are applied with improper application rates or timing. Nutrient recovery technologies need to be part of a comprehensive strategy at the watershed level to address issues of nutrient balance, equitable distribution of costs and benefits, and improved nutrient application timing and methodology.

Anaerobic Digestion and Nutrient Recovery

On its own, anaerobic digestion (AD) is not a nutrient recovery technology. The AD process creates an anaerobic environment (without oxygen) in which naturally occurring microorganisms convert complex organic materials in manure and other wet organic byproducts, such as food processing wastes, to biogas, which is a source of renewable energy (US-EPA 2006). The process also reduces greenhouse gas (GHG) emissions, decreases odors, stabilizes waste, and decreases pathogen counts (Martin and Roos 2007; US-EPA 2004; US-EPA 2005; US-EPA 2008). Although the process changes the form of nitrogen and phosphorus in manure, it does not appreciably decrease the total amount of nutrients, most of which are concentrated in the liquid effluent that is a product of the AD process (Frear et al. 2011).

An increasing number of dairies that practice AD have begun to import and co-digest food wastes along with manure in order to enhance biogas production and AD project profitability. However, this practice often exacerbates nutrient management concerns, by increasing the import of nutrients to the dairy. In a study of co-digestion, Frear et al. (2011) showed that supplementing manure with 16% organic wastes by volume at a dairy in Washington State increased phosphorus and nitrogen 13% and 57%, respectively (Figure 7). (In this case, co-digestion also increased biogas by 110% and tripled gross revenues from anaerobic digestion.)

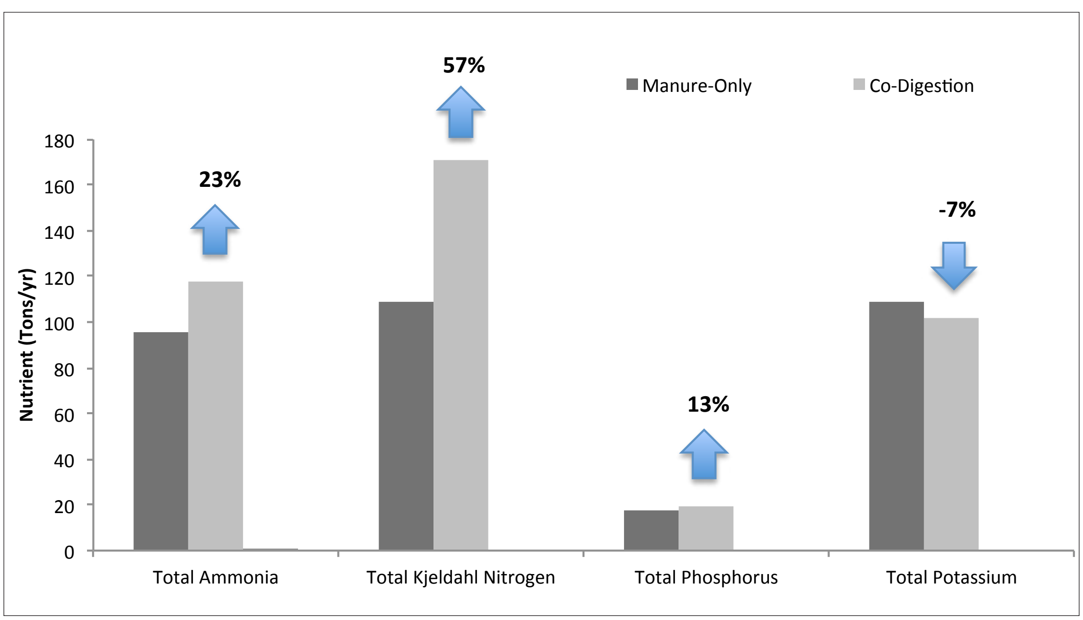

Figure 7. Modeled nutrient impacts of co-digestion with 16% organic wastes on a dairy in northwest Washington (Yorgey et al. 2011).

Anaerobic digestion creates unique opportunities for nutrient recovery (Figure 1). In addition to transforming nutrients from organic to inorganic forms, the AD process can assist in nutrient recovery by providing important process inputs such as heat, electricity, and processing infrastructure. It also alters the effluent's ammonia and solids concentration, temperature, and form of phosphorus, which can facilitate the application of certain nutrient recovery approaches (Frear et al. 2011). In return, nutrient recovery can assist the AD process by generating a combined system that can lessen dairy producers' nutrient concerns—something AD alone simply cannot do. Furthermore, potential income from the sale of recovered nutrients can contribute to the economic feasibility of an AD project. Coppedge et al. (2012) showed that income from nutrient and fiber products can represent a substantial portion of a digester's gross revenue.

Nutrient recovery technologies have the potential to stimulate adoption rates for AD. Adoption rates have been slow, with just over 190 digesters in operation on dairy farms in the U.S. as of April 2014, representing only 4% of dairy cows (US-EPA, 2014; USDA ERS 2013). This number would need to increase considerably to meet the joint U.S. and dairy industry goal, which is for the dairy industry to reduce its climate impact by 25% by the year 2020 (Innovation Center for U.S. Dairy 2011). Integrated nutrient recovery technologies have the potential to address one of producers' top concerns related to AD adoption, and thus may be more appealing than stand-alone AD technologies.

A combined AD-nutrient recovery system has greater capital and operating costs, but also (depending on the system) has the potential to generate greater revenues and profits. This "add-on" nutrient recovery technology reflects an ongoing trend to use AD technologies as a platform for other technologies that work synergistically to provide operational and economic benefits. Refined natural gas is probably the most developed of these add-on technologies, and has been particularly important for improving project economics in regions with low electricity prices.

Conclusion

Current manure management strategies may not be adequate to meet the environmental challenges facing the dairy industry today. Technologies that recover, concentrate, and partition nutrients may contribute to a solution to these problems, in combination with improved regulatory structures, markets, and enhanced wastewater and fertilizer application management. Many of these nutrient recovery solutions work in concert with AD technologies, which provide additional benefits in the form of renewable energy and GHG emissions reductions.

These emerging nutrient recovery technologies are still under development, with particular effort being made to reduce costs and produce products that are easy to transport, store, and apply at chosen rates with chosen application methods. Pathogen risk reductions and organic certification are also receiving ongoing attention. Together, these efforts aim to produce an economically viable option for nutrient management that makes sound business sense for dairy producers.

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By **Georgine Yorgey**, Associate in Research, Center for Sustaining Agriculture and Natural Resources, Washington State University; **Craig Frear**, Assistant Professor, Department of Biological Systems Engineering; **Chad Kruger**, Director, Center for Sustaining Agriculture and Natural Resources; and **Tara Zimmerman**, Associate in Research, Center for Sustaining Agriculture and Natural Resources.

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