A Life Cycle Assessment of Dairy Manure Management

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1. Abstract

A life cycle assessment (LCA) was performed in order to holistically analyze the dairy waste management systems currently in place at California dairies. This assessment was completed for Sustainable Conservation, an environmental services nonprofit whose mission is to bridge the gap between businesses, landowners and policy, so that they can further improve the sustainability of California. The technologies our team analyzed were sorted into flush systems, scrape systems, simple and advanced forms of solid separation, composting, covered-lagoon anaerobic digesters, and plug flow digesters. Bedding, soil application and uncovered lagoons were also incorporated into hypothetical scenarios in order to better assess the emissions from realistic combinations of technologies that may be found on dairy farms. We researched values for electricity use, water consumption, carbon dioxide, methane, ammonia, nitrate, nitrous oxide, sulfur dioxide, volatile organic compounds, phosphorus and biogas. Through our studies, we found that uncovered lagoons are the greatest emitters of both ammonia and greenhouse gases and that further studies are necessary to fill the apparent knowledge gaps.

2. Introduction

The state of California has a long and rich history in the dairy industry. It stands today as the largest dairy state by production and has some of the most unique laws and regulations in the country. Policy, climate, culture and size all contribute to making California's dairy industry so complex. California is the only state to not have a milk market that has prices set at a federal level and farmers are often paid less for their milk than in any other state. Despite this, California boasts large amounts of fertile land with year-round, ideal weather, which consistently deems the state as a popular destination for dairy farms. California is also at the forefront of the movement to create a more sustainable planet, and this too has put pressure on the dairymen to begin to improve inefficiencies within their farms. One of the issues that has recently become the focus of scrutiny is the waste management practices at dairies. In September of 2016, Governor Jerry Brown signed Senate Bill 1383, which delegates the authority to enforce the most sustainable manure management practices to state organizations such as the California Air Resources Board, the California Department of Food and Agriculture, State Energy Resources Conservation and Development Commission and the Public Utilities Commission (California Legislature, 2016). These agencies must conduct their own research and conclude as to which manure management processes are technologically realistic, economically feasible and do not displace negative externalities to another state or country (California Legislature, 2016). The technologies under review include flush systems, scrape systems, advanced solid separation, anaerobic digestion, and composting (California Legislature, 2016).

In order to understand the environmental implications of using these technologies, we have partnered with Sustainable Conservation to analyze the various manure management scenarios that are commonly employed in California and to draft a report. With this understanding, our goal was to perform a life cycle assessment. The purpose of this research is to not only aid the work of Sustainable Conservation, but to be considered during legislative proceedings as well. While our values stem from secondary data, we also travelled to Northern California to visit several dairies and interview industry experts for guidance on data collection and to gain a new perspective on dairy operations.

3. Background

3.1 Scrapers

Around 20% of dairy farms in California use scrape to initially collect and consolidate manure slurry (Beene et. al) that is around 7- 22% total solids (Fleming, 2005). Common types of manure scrapers include automatic alley scrapers (Figure 1), skid-steer scrapers, and manure vacuums (Figure 2). Alley scraper systems are common for dairy cows in open lots (Beene et. al). They usually consist of a metal or rope cable chain, motor(s) powered by electricity to operate the cable or chain and thus pull or push the scraper, and a metal scraper wide enough to scrape an entire alley of manure (usually around 10 feet wide) with a rubber or metal blade edge that comes in contact with the floor. Rubber is ideal for more liquid manure and floors that may not be completely smooth and do not rust in contact with water and other liquids. On the other hand, metal is ideal for colder temperatures that can freeze manure and may rust depending on the material used ("Waste Management Equipment," ND). Alley scrapers are typically operated on concrete floors that either have slots to push the manure underground to a holding channel or unslotted floors that can push manure towards a temporary holding pit at the end of a lane (Lenkaitis, ND). Some floors contain a linear groove to accommodate the cable/chain and to prevent friction.

Skid-steer scrapers consist of scraper blades attached to skid-steer loaders and are ideal for frozen waste. Manure vacuums are vehicles that scrape and collect manure into a tank via suction. This manure can then be unloaded into a holding pit or lagoon at a rate as fast as 3000 gallons per fifty seconds ("Manure Vacuum", ND). Manure vacuums and skid-steer scrapers can maneuver in more directions than alley scrapers that are integrated within a building's infrastructure. From the holding pit, the scraped manure can then undergo either solid-liquid separation, composting, or anaerobic digestion. While the process of scraping does not involve any water consumption, some farms may precede or follow scraping with flushing.

3.3 Flush

Flush systems on dairy farms are used to clear out manure from feeding lots and stalls and direct it to flush lanes, which run between the barn stalls. The effluent then begins to flow out with assistance from small one-to-four degree slopes designed into the floor. The water dilutes the manure so that it can be easily removed from the flushed areas and conveys it to a holding pit or solid-liquid separator. The waste water is eventually taken to an anaerobic lagoon that holds the water for months before being applied as irrigation. The lagoon contains all wastewater from the dairy operation and includes inputs from, originally, potable water that is used to clean milking parlors (University of California Davis, 2016). The lagoon water is used for crop irrigation in order to help grow plants that can then be used to feed the cows and the lagoon water can also be recycled for future flush processes. The concentration of each lagoon's content is dependent on the processes used to treat the water before it is stored, which then affects how its components settle into tiers at different depths (University of California Davis, 2016). While the flush to lagoon cycle is a closed circuit, water is gained through milking parlor sanitation and lost through evaporation and for crop irrigation (University of California Davis, 2016).

3.3 Solid-Liquid Separation

Solid-liquid separation encompasses a series of technologies that divide raw manure or manure slurry into solid and liquid fractions, each of which has specific end-use functions. After collection of slurry following flush or scrape, the effluent is pumped to the area of separation. California dairies typically employ a simple separation mechanism like a stationary, vibrating, or rotating screen, which filters out the large solid particles. The efficacy of solid-liquid separation is typically measured with separation efficiency (Table 1), which can be defined as the mass of a given compound in the solid fraction, divided by that in the input slurry (Provolo, 2013). On average, about 75% of the solids remain in the liquid stream following simple separation (Provolo, 2013). Centrifugation, an advanced method of separation, retains as little as 31% of the solids in the liquid stream (Provolo, 2013).

The resulting solid fraction is smaller by weight and volume compared to the liquid fraction due to raw manure's inherent imbalance of liquids and solids (about 88% liquid from lactating cows (Lorimor et. al.)) and further dilution after being flushed. This solid fraction is characterized by high amounts of dry matter (DM), phosphorous (P), and organic matter (Provolo, 2013). These qualities make the solid fraction desirable to produce cow bedding or as an input for compost (Provolo, 2013). Dewatering also reduces the density of the solid fraction and eases its transport to other dairies or processing facilities.

The liquid fraction, still containing organic nutrients from dissolved solids and small particles, can be used for fertigation, due to having an optimal nitrogen (N)-to-phosphorus (P) ratio as well as an optimal total ammonia nitrogen (TAN)-to-total nitrogen (TN) ratio (Provolo, 2013). With most of the large particulates having been removed, the effluent can be efficiently pumped to a plug flow digester or straight to an anaerobic lagoon (before fertigation) without much risk of clogging the pipes (Provolo, 2013).

The environmental impacts associated with various separation techniques primarily stem downstream from the uncovered lagoon stage. Overall, simple separation systems tend to have a relatively low capital cost and require little maintenance, but come with low separation efficiencies. Centrifugation represents the most advanced separation system used commercially at dairies. This type of system, though seldom employed due to its high capital cost, has the highest nutrient and dry matter separation efficiency by far.

3.4 Anaerobic Digestion

Anaerobic digestion is the process of breaking down organic materials by microorganisms, without the presence of oxygen (EPA AgSTAR, 2016). Although many biodegradable inputs, such as food waste, municipal solids, animal manure, and the combination of these can be anaerobically digested, this report will focus only on anaerobic digestion of dairy cattle manure (EPA, 2016).

This report considers two forms of anaerobic digestion technologies: 1) covered lagoons and 2) Plug Flow Digesters. A covered lagoon is an earthen basin with a cover that collects the biogas produced from the manure within (Figure 3). Covered lagoons are the most popular form of anaerobic digestion in California and requires inputted manure at a dry matter content of 0.5-3% (San Joaquin Valley Dairy Manure Technology Feasibility Assessment Panel, 2017). Covered lagoons are used with flushed manure (Prasad et. al., 2014). Plug flow digesters (Figure 4) are concrete tanks that create an anaerobic environment for manure with a dry matter content of 11-14% (Penn State Extension, 2017). Plug flow digesters are used with scraped manure (Prasad et. al., 2014). Once introduced into the anaerobic digestion process, the cattle manure undergoes multiple biological and chemical processes to ultimately produce two end products: digestate and biogas (EPA, 2016).

This waste management method has gained popularity among many dairy farmers because of the method’s many benefits including decreasing odor, pathogen reduction, and economic revenues from biogas use in the form of natural gas production, electricity production, and use as a production fuel (EPA AgSTAR, 2016). However, this report investigates biogas utilization only in the form of electricity production. As for the digestate, this report considers its direct use for field application. Qualitative benefits are also not considered.

3.5 Compost

Composting is a technique used by dairy farmers to transform cow manure into a stable fertilizer through a variety of aeration methods. After the farm has separated solid from liquid manure, the dry matter becomes compostable. Because manure is very high in nitrogen content, carbon-rich materials like sawdust, woodchips, and straw are added to achieve a C:N ratio of about 30:1 (Bass, 2012). During the compost process, microorganisms break down the manure and organic materials while reducing the weight, volume, and moisture content by about half (Alberta, 2005). It may then be stored until convenient for the farmers to apply it on the farm's feed crops or sell it. When managed correctly, compost improves water holding capacity, air infiltration, and kills weeds and pathogenic bacteria. Additionally, unlike commercial fertilizers, compost releases nutrients into cropland very slowly, so nutrients are available for a longer period of time without reapplication. For this report, our client requested compost to be studied in the form of active turned windrows. These windrows are mechanically aerated by a front-end loader or a windrow turner. This method requires inputs of water, electricity, fuel, bulking agents, and oxygen to create a quality compost.

4. Methods

4.1 Scope

This study analyzed, solely, the environmental emissions and impacts from dairy manure collection and management systems, without consideration of economic factors. Furthermore, we based our data with the assumption of a 1200-cow dairy farm, which is the average farm size in California (California Department of Food and Agriculture, 2016).

4.2 Farm Trip

The processes we investigated included the collection of manure by flushing, scraping, the separation of collected manure via simple and advanced methods of solid-liquid separation, anaerobic digestion of the manure through covered lagoons and plug flow digesters, composting of the manure, and field application of treated manure. Through data acquired from peer-reviewed literature, the team gathered a basic understanding of each process and the different combinations in which they could be implemented (Appendix: Process Flow Diagrams). However, the team better grasped the reality of these systems after visiting dairy farms and speaking with experts on all aspects of the processes.

From April 20th to April 23rd, the team visited dairy farms to speak with experts in the dairy and manure management industries. The team visited the University of California (UC), Davis in Davis, California, and spoke with Dr. William Horwath and Dr. Frank Mitloehner. While there, we also visited the UC Davis Dairy Farm. Afterwards, the team visited Fanelli Farms in Hilmar, California and Joseph Gallo Farms in Atwater, California.

While visiting the dairy farms, we were able to ask specific questions to the farm managers and experts in regards to data gaps from the literature reviews such as the amount of water used per day for flushing and the amount of electricity produced per day from the combustion of biogas. Specifically, Professors Horwath and Mitloehner answered questions the team posed and recommended additional resources to fill any gaps we had in the data. Professor Horwath assisted the team with understanding the volatilization processes of the different chemicals in dairy cow manure. Professor Mitloehner confirmed that studies investigating specifically the greenhouse gas emissions for flush and scrape technologies were extremely few, if at all existent. This helped our team pivot from searching for data that was not there, to, instead, classify many of the emissions from these two technologies as knowledge gaps. We had a conference call with Professor Meyer, who helped us understand any conceptual uncertainties we had regarding the effluent of anaerobic digestion. She confirmed that the solid content decreases after anaerobic digestion, which results in the need for further solid-liquid separation if the solid portion is to be used as bedding or compost.

Visiting the dairy farms in person cemented our understanding of the processes that occur on-site. The greatest takeaway from the visit was gaining the knowledge to form the most common baseline manure management process in California, which is flush to simple solid-liquid separation to a temporary holding of the liquid effluent to an uncovered lagoon, where the effluent is ultimately used to irrigate crops not grown for human consumption (Appendix: Table 4).

4.3 Life Cycle Assessment

Life cycle assessment (LCA) is a technique to analyze the impacts of a product or service from cradle to grave. In other words, LCA considers everything from the extraction of raw materials to the disposal of the product in order to provide a holistic impact analysis of a good. However, due to time constraints, this project focuses solely on the inputs and outputs of the manure management technologies within the farm. In this context, the LCA is completed, not on a product, but on the process of manure management. Inputs are the materials and resources needed to perform the manure management technologies, like electricity, and outputs are waste products and emissions resulting from the production process, like methane (Figure 5). It must be stressed that as with any LCA, when performing the calculations, the team made assumptions to address inconsistent or unavailable data (Appendix: Assumptions).

4.3.1 Functional Unit

A functional unit is the unit in which the inputs and outputs are communicated, and ultimately compared. The main functional unit used in our LCA was kilogram (kg) of an emission per metric tonne (tonne) of manure. Any data gathered in a different unit had to be converted to match this functional unit (Appendix: Calculations). These conversions were completed using the 100-year time horizon global warming potentials published in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Mhyre, 2013). A functional unit allows all of the inputs and outputs to be totalled, in order to compare the impacts between different processes. Although most of the emissions used this functional unit of kg emissions per tonne of manure, two (2) inputs, water and electricity consumption, did not. Electricity values were communicated as kWh/tonne manure and water consumption values in gallons per day, since these units were more appropriate.

4.3.2 Process Flow Diagram

LCA requires a process flow diagram, a qualitative diagram that establishes the processes that constitute to the life cycle of the good or service of focus. In this report, each process flow diagram is referred to as a *scenario* and each step within that scenario is referred to as a *process*. Because there are different combinations in which the manure management systems can be utilized, the team had to produce multiple process flow diagrams (Appendix: Process Flow

Diagrams). The team produced 19 different process flow diagrams; however, due to time constraints and the client's priorities, eight (8) were analyzed in detail: Scenarios 1-8 (Appendix: Process Flow Diagrams). Note that the nineteen process flow diagrams are non-exhaustive.

4.3.3 Data Collection

The next step for the LCA was to input quantitative values into the process flow diagrams. Due to the time constraints of this project, it was not realistic for our team to gather sufficient and reliable quantitative air and water quality data from dairy farms first-hand. Instead, like with the conceptual understanding of the dairy farm, the team relied on secondary literature to collect the environmental emissions values produced by the different manure management technologies. Input data considered were electricity and water consumption. Output data included air emissions, water emissions, and quantitatively-expressed coproducts. Air emissions considered were carbon dioxide (CO_2), ammonia (NH3), nitrous oxide (N_2O), and methane (CH_4). CO_2, nitrous oxide (N_2O), and CH_4 were further converted to CO_2e. Volatile organic compounds and sulfur dioxides were also considered for air emissions, but data was unavailable for these emissions. Water emissions considered were phosphorus (P) and organic nitrogen (N). Coproducts considered were electricity produced from collected biogas and fertilizer produced from composting.

The team only collected quantitative emissions data that met two criteria. First, the data was sourced from peer-reviewed journals, publications from governmental agencies (such as the Air Resources Board), or experts in the industry. Secondly, the emission data had to be expressed as a numerical value, instead of a percentage emissions decrease compared to a baseline process. For example, field application of digested effluent had to be collected in units of kg/tonne manure as opposed to X% lower than the emissions produced by field application of undigested manure.

If multiple values or studies were used for a specific process, the mean value was reported. Whenever possible, processes reflected consistency with upstream processes. For example, depending on whether the same manure is collected via scrape or flush, affects downstream emissions produced in processes such as composting. For this reason, we collected data for emissions produced by composting flush manure as well as by composting scrape manure. It is important to note that this was not always possible. Furthermore, inputs and output processes not relevant to a scenario is denoted by an “N/A” in the cell. Finally, input or output processes that are relevant but not found, are denoted by a “no data” in the cell.

4.4.4 Base Calculations

When all of the data was collected, the values were summed to provide the emissions on a per tonne of manure basis from total inputs and outputs resulting from each process flow combination (Appendix: Tables 4-11). Again, because the units were the same for each input and output type, regardless of which process the value was representing, a simple sum was quickly produced.

4.4.5 Offset Calculations

We calculated offsets from the generation of fertilizer from composted manure and offsets from the electricity ultimately produced from the biogas collected from plug flow digesters and covered lagoons. Creating fertilizer from manure offsets the emissions produced by making conventional fertilizer and producing electricity from biomethane offsets the emissions released by producing electricity conventionally, such as from combusting natural gas or burning coal. To calculate the electricity offset, we used the electricity sources used in California. The weighted average of the electricity offsets for different energy sources can be found in Table 2 and the subsequent computation is in the Calculations section of the Appendix.

5. Results

Process calculations of environmental emissions are featured in the Calculations section of the Appendix. Below, are graphical representations of the data collected.

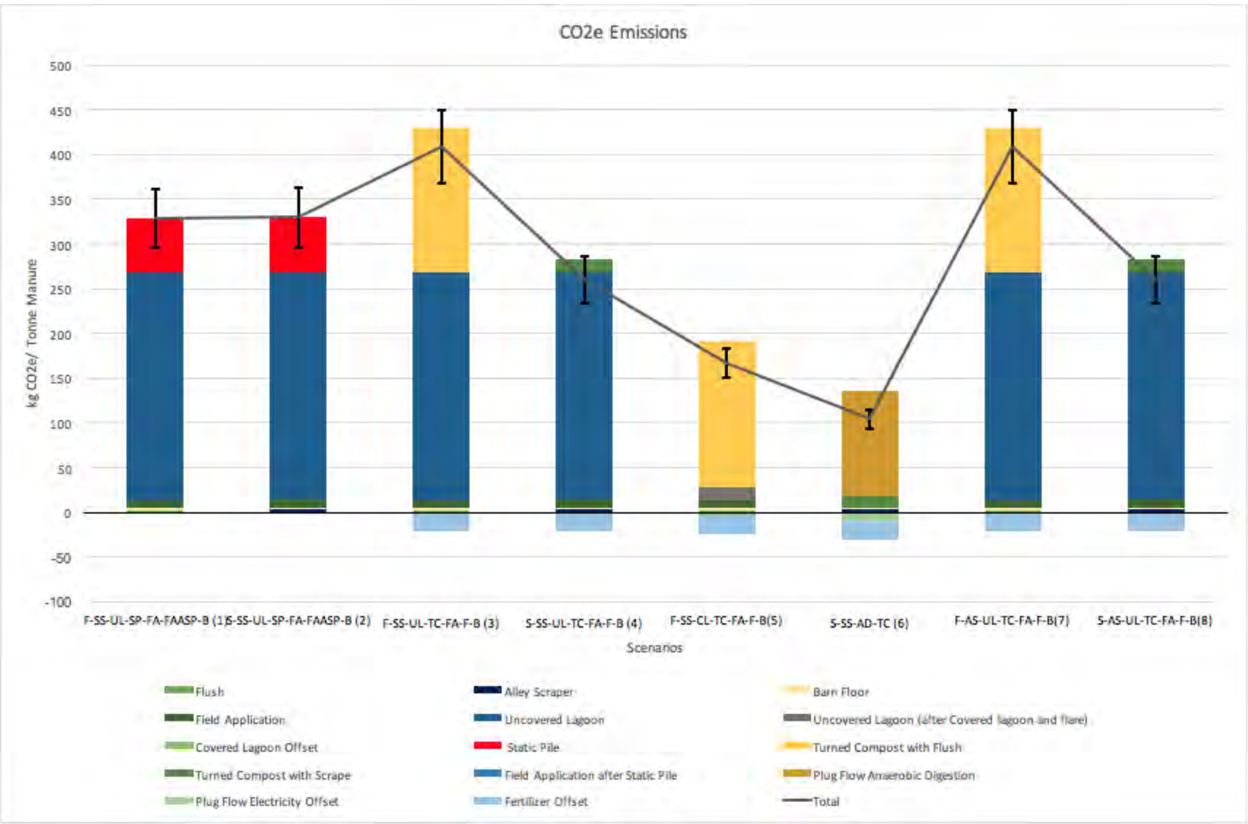

Figure 6: A graph representing the carbon dioxide equivalent emissions released by the eight (8) processes analyzed. The dark blue trendline displays the net emissions produced by each process after accounting for offset credits. Error bars are +/- 10% of the net emission to account for variations in data.

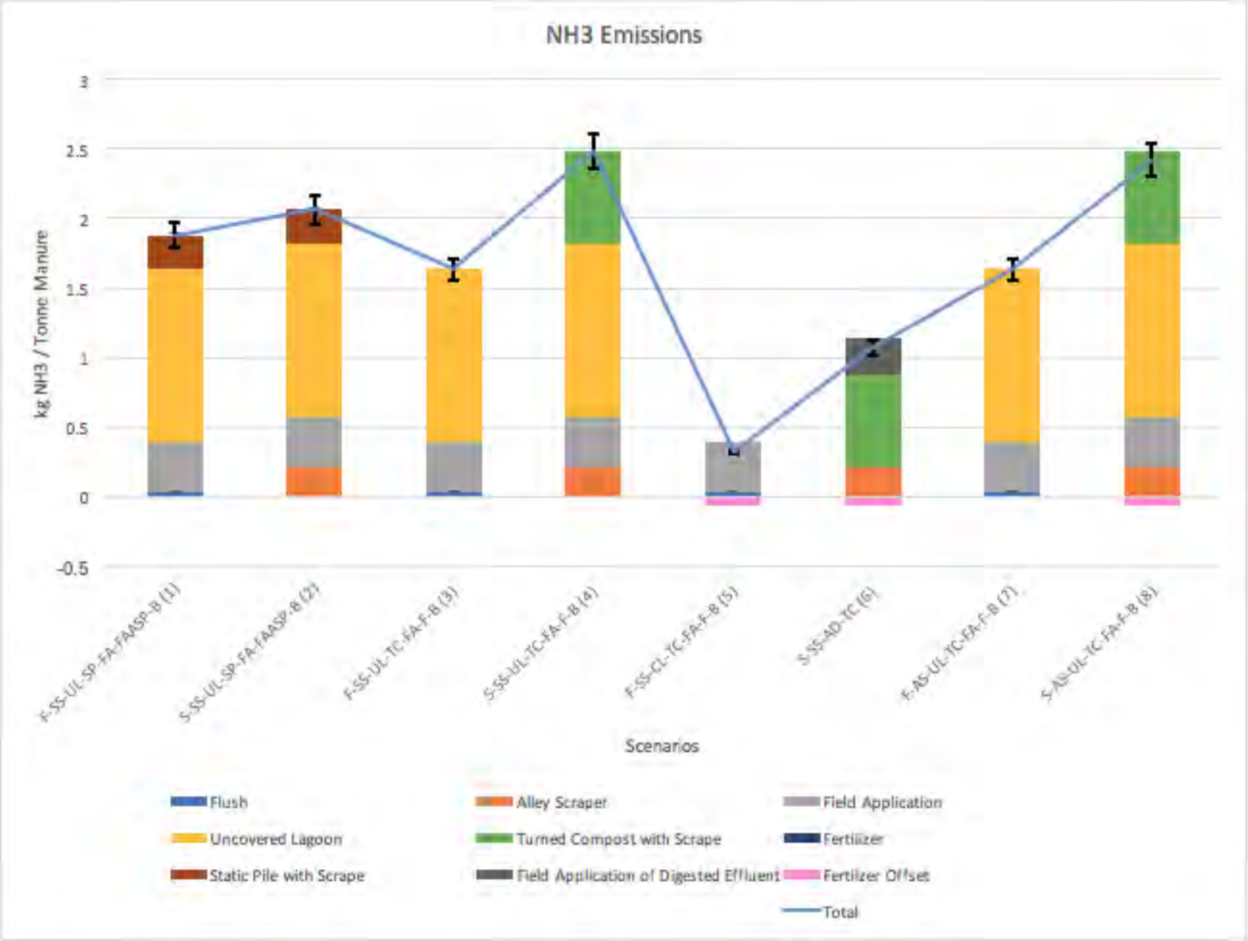

Figure 7: A graph representing the ammonia emissions released by the eight (8) processes analyzed. The blue trendline displays the net emissions produced by each process after accounting for offset credits. Error bars are +/- 10% of the net emission to account for variations in data.

	Environmental Impacts from Dairy Manure Management								
	Water Consumption	**Electricity Consumption**	**CO2e**	**CO2**	**NH3**	**N20**	**CH4**	**P runoff**	**N runoff**
1	F	AS	UL	TCAF	UL	SP	SP	FAODE	SP
2	MP	ALS	TCAF	ALS	TCAS	TCAF	UL		TCAF; TCAS
3		SS	AD	F	FA	TCAS	TCAF		FAODE
4		TCAF; TCAS	SP		SP	UL	TCAS		
5			ULACLF		FAODE	FA	FA		
6			TCAS		ALS	ALS	ALS		
7			FA		FAASP	F	F		
8			ALS		F				
8			F						
9			B						

Table 1: Relative environmental impact of processes, ranked from greatest (1) to least (9). Refer to Appendix: Legend for acronym descriptions.

As seen by Figures 6 and 7 as well as Table 1, the uncovered lagoon is the dominant source of both carbon dioxide equivalent and ammonia emissions.

6. Discussion

6.1 Discussion of Results

Due to a lack of data, we were unable to analyze nitrogen runoff and phosphorus runoff in depth. However, because of water leachate potential, additional research should be executed in the future. Additionally, we did not analyze water usage in depth because we found that the processes that use water are usually minimal and that those that use a larger amount of water, such as flush at 13,778.90 gallons per tonne of manure, tend to use recycled lagoon water. We were unable to find how often freshwater is injected to dilute the constant reuse and increasing concentration of manure in lagoon water. Finally, due to a lack of data about manure vacuums and skid steer scrapers, only alley scrapers were analyzed.

6.1.1 Uncovered Lagoon

In every scenario that does not include a plug flower digester or covered lagoon, the uncovered lagoon dominates greenhouse gas emissions in dairy manure management. As a result, we advise that efforts to reduce GHG impacts from dairies focus on the mitigation of uncovered lagoon emissions. Digesters represent one effective (albeit expensive) method of accomplishing this, although we suspect that modifying upstream processes like solid-liquid separation techniques would also affect uncovered lagoon emissions. More studies that compare uncovered lagoon emissions after different methods of manure separation and collection are required.

Unfortunately, we came across our largest range of values for the most important variable of GHG emissions. Emissions ranged from 41.29 to 643 kg CO_2 e/tonne manure for separated slurry. We took an average of the values from four studies (254 kg CO_2 e/tonne manure). With more time and resources, we would have pursued further verification of these values. Finally, we were able to obtain uncovered lagoon values following covered lagoon and flare as well as of unseparated slurry. With limited data, our research suggests that separating slurry results in a significant decrease of emissions downstream in the uncovered lagoon stage.

6.1.2 Scrape vs. Flush

Scrape systems use little to no water in comparison to flush (13,778 gallons, most of which is recycled water) but our findings showed that scrapers have more environmental emissions. Flush emits 2.6 kg CO2e and 0.033 kg NH3 per tonne of manure, which is less than alley scrapers that emit 3.29 kg CO2e and 0.214 kg NH3 per tonne of manure. While scrapers can collect a majority of the manure mass, a thin film of manure may be left on the ground, which may create in-barn volatile organic compounds emissions (Sustainable Conservation, p. 52). On the other hand, flush will remove almost all manure from the ground. This is important to keep in mind because with SB 1383, California may consider switching from flush to scrape in an effort to conserve water, but we find this unnecessary because often the water used for flush is from recycled water.

6.1.3 Covered Lagoon vs. Plug Flow Digester

As seen in Figures 1 and 2, the scenarios that include anaerobic digestion (5 and 6) emit the least carbon dioxide equivalent. With this knowledge, it may seem easy to make the decision to mandate the implementation of either plug flow digesters or covered lagoons on dairy farms. However, the situation is not so black and white. Although they are the lowest environmental emitters, plug flow digesters and covered lagoons are the most expensive technologies of the ones studied. Both of these technologies can often have a capital and annual operating cost of over $1 million, which is unreasonable for a farmer without financial assistance (Lazarus, 2015).

Additionally, plug flow digesters are many times required to be operated and maintained by the farmers, themselves. Without the proper knowledge and skills necessary to upkeep this complex technology, owning and operating the technology becomes a hassle, to the point where decommissioning or selling the digester becomes common (AgStar, 2017). There are multiple factors that must be balanced when comparing manure management technologies on dairy farms, including environmental, economic, and maintenance burdens.

6.1.4 Compost

Turned compost contributed a surprisingly high level of CO_2e emissions to the scenarios. This is because the process of aerobic decomposition and mechanical turning generates more emissions than leaving the dry manure in a static pile. However, dairy farmers are going to generate massive amounts of dry solids regardless of the treatment type. Composting is a great way to stabilize and make use of the manure that will inevitably be created. The composting process reduces odors, pathogens, weeds, and creates a nutrient-rich fertilizer than may be used on-site for crops.

The emissions from composting are a bit difficult to compare because many studies did not include CO_2 as part of the greenhouse gas emissions. This is because CO_2 is considered biogenic by the California Air Resources Board; it is a natural part of fermentation from a static source, rather than emissions from a source like fossil fuels. Thus, the CO_2 emissions from the study used for turned compost with scrape appear to be smaller than turned compost with flush, when they are actually much higher.

6.1.5 Electricity Offset

In order to calculate the assumed emissions from standard methods in California, data was obtained from the California Energy Commission (Table 2). The chart cited the sources of electricity generation in the state and what proportion of the total electricity yield was generated from each separate source. Data was also provided on the CO_2 e emissions that could be associated with each energy source. Each data point for emissions was multiplied by its proportion of use for electricity generation and all emissions were added to calculate a holistic number depicting the emissions resulting from a standard California mix. This number is 382.94 g CO_2 e/ kWh. The chart and calculations used to derive this number can be found in Table 2 of the appendix. The California energy mix is actually quite clean compared to a state that may still source much of its electricity from coal. Due to this, it is more environmentally harmful to produce electricity with a covered lagoon digester or a plug flow digester than it would be to use the standard California mix.

These technologies are beneficial to farms in that they reduce emissions and create a desired product, but in terms of energy, they are more envirnmentally potent with their resulting emissions compared to the standard California mix of energy sources.

6.1.6 NH4 vs. CO2

The NH_3 graph (Figure 7) is similar to the CO_2e graph (Figure 6) with the covered lagoon dominating the emissions. However, the two graphs do not correlate completely. GHGs have more studies available because they are more of a concern, making the CO_2e results more reliable. This demonstrates that there may be discrepancies in the future when trying to lower overall emissions because one technology might lower CO_2e emissions, but will subsequently increase ammonia. This effect should be taken into consideration because it is difficult to standardize emissions. For example, Scenario 5 has the least amount of total NH_3 at 0.2803 kg per tonne of manure, and the second lowest amount of CO2e emitted at 166.47 kg per tonne of manure. On the other hand, Scenario 6 has the lowest CO_2e at 3.239 kg per tonne of manure and the second lowest NH3 at 1.069 kg per tonne of manure. These variations occur because of different processes within each scenario, not because of variations in emissions of the same processes. The dominating contributor of CO_2e in Scenario 5 is turned compost with flush at

163.085 kg per tonne of manure while the dominating CO_2e process in Scenario 6 is plug flow anaerobic digestion at 117.025 kg per tonne of manure, which is slightly less than that emitted by turned compost with flush in Scenario 5. In terms of NH_3, the dominating contributor in Scenario 5 is field application at 0.3123 kg per tonne of manure while the dominating process is turned compost with scrape in Scenario 6 at 0.67 kg per tonne of manure. The dominating processes of different environmental emissions are unique and thus difficult to compare.

6.1.7 Combinations

Per our data, one of the greatest sources of greenhouse gas emissions is Scenario 3 Appendix. This is compared to Scenario 5, the second-lowest source of carbon dioxide equivalent emissions. The two scenarios are completely identical except for the fact that Scenario 5 has a covered lagoon before the uncovered lagoon. Most of the emissions that would have been released from proceeding directly to the uncovered lagoon is captured in the covered lagoon, decreasing the overall carbon dioxide equivalent emissions. When we began our research, we focused on finding data on individual technologies. However, this displays that the specific succession of technologies matter in terms of its magnitude of environmental impact. By strategically combining the order of technologies it is, indeed, possible to decrease greenhouse gas emissions produced on dairy farms.

In Scenario 5, the uncovered lagoon stage emits greenhouse gases of 14.61 kg CO_2 e per tonne of manure. As a result of a preceding covered lagoon, uncovered lagoon emissions decrease by about 94% relative to Scenario 3. This result confounded us not only because of the stark decrease in emissions, but also because we expected much of the lessened environmental burden to stem from the avoided GHG emissions from producing electricity on-site with biogas. As it turns out, the emissions avoided from electricity generation with a covered lagoon are only 3.08 kg CO_2 e per tonne of manure, and almost all of the positive environmental impacts of having a covered lagoon are realized downstream in the uncovered lagoon stage. One explanation for this lies in that California's electricity grid mix is much cleaner compared to other states. In other words, California can produce one unit of conventional electricity with a relatively small environmental burden. Hence, any offset produced by the covered lagoon would be more significant in states that produce electricity mainly from fossil fuels like coal and natural gas. The other, more abstruse explanation is that covered lagoons are ineffective at producing electricity relative to other sources of generation like solar ranches, wind farms, and cogeneration (electricity and heat) plants. Ultimately, the positive environmental impacts of installing a covered lagoon are realized in the form of decreased downstream uncovered lagoon emissions, not via electricity production. Overall greenhouse gas emissions in Scenario 5 are down 36% relative to.

6.2 Barriers Faced

In our research we faced multiple limitations. Dairy farms are highly customizable in terms of amount of cow manure produced per cow, amount of recycled water used, type of bedding used; thus the technologies are usually customized for every farm and emissions vary as a result. Scrapers, solid liquid separation systems, and digesters also vary in emissions, design, and size because they are commercial products sold by a variety of vendors.

In terms of geographic scope, we initially tried to limit our research to data pertaining only to Californian dairy farms but because this information is limited, we had to include studies that focused on dairy farms in areas such as the Midwest and Europe. In these locations, emissions may be different as a result of climate, especially in wintertime (e.g. snow, colder temperatures than California).

In terms of the LCA, we were unable to conduct primary research and relied on secondary emissions data from peer reviewed journals instead, with some technologies such as anaerobic digesters having more information than others such as scrape and flush. Different articles had different assumptions and methodologies, thus the team had to make critical assumptions for emissions calculations such as rate of manure production and rate of biogas production. There are few studies that focus on the manure management systems as a whole; most studies offered environmental emissions information as a side note when discussing other topics in dairy such as ideal settings for animal husbandry.

In terms of emissions data, we had to standardize each data point using a per tonne of manure functional unit. However, the conversions were difficult when the emissions data was provided using an area or time metric (e.g. emissions per square meter or emissions per day). In addition, we calculated a majority of the CO_2e emissions of processes by adding N_2O, CH_4, and

CO_2 but some studies already provided a CO_2e value, thus CO_2e does not always equal the sum of N_2O, CH_4, and CO_2.

Furthermore, because of the criteria we implemented for data collected--1) data from peer-reviewed publications, government publications, or industry experts and 2) data expressed in numerical values instead of percentages--we were limited in the data we could use, and our study may have reached conclusions inconsistent with previous similar studies.

Lastly, we found no data on emissions pertaining to different types of technologies in succession such as what the emissions of manure in an uncovered lagoon are if there was a covered lagoon beforehand. The covered lagoon may cause the manure transferred to the uncovered lagoon to have less of an environmental impact than simply having only an uncovered lagoon. Also, for the static solid pile, studies often did not include CO2 emissions because they are considered biogenic by the California Air Resources Board. Thus, static pile CO2 equivalent emissions appeared smaller than they actually are. Our calculations face uncertainty because different sources provided a wide range of emission values. For sources that did not specify all upstream processes, although emissions may be acceptable, we cannot, with certainty say how accurately it reflects the process flow diagrams we produced, which further adds uncertainty to the values that were collected for this study. As for the varying data on the web, again our team took average values of the data we found, which lessens variability but adds another aspect of uncertainty due to the distribution of the values.

6.3 General Recommendations for Future Research

Every individual and institution conducting these analyses would benefit greatly from more available data. More specifically, what is required are more studies that focus on evaluating one process or stage of manure management while varying upstream processes. For instance, we came across an abundance of studies that measured uncovered lagoon emissions, but none that did so for each common solid-liquid separation technique upstream. From an LCA standpoint, it is clear that the employed method of solid-liquid separation greatly affects the chemical and volumetric compositions of the resulting solid and liquid fractions; in turn, selected separation techniques affect uncovered lagoon emissions. Most studies we found did not go beyond denoting whether the manure in the lagoon was separated at all. This is just one example --

processes like field application, compost, and other downstream processes all depend on their respective upstream processes. Ultimately, the interdependent nature of the environmental impacts from manure management practices coupled with a lack of data made it difficult to conduct a holistic LCA.

6.4 Future Research by Technology

6.4.1 Scrape

In the master spreadsheet, only emissions data for alley scrapers and skid-steer scrapers are referenced. Future research should initiate the study the environmental impacts of manure vacuums. Scrape research should be conducted in different environments- cold and hot temperatures, low and high humidity, different types of flooring (slotted vs. unslotted), as well as scraping in procession or succession with flush. Research about waterless scrape systems are crucial in a state like California that is prone to drought.

6.4.2 Flush

Flush data was very limited and the one study that gave specific data pertaining to the emissions released during a flush process on a dairy farm lacked downstream effects. The study compared flush emissions to scrape emissions as well as type of flooring used with these processes, but if the flush emits less than a scraper, there might be more emissions in a process down the line and it should be noted that future studies are needed that compare entire dairy processes which can then highlight the changes in overall emissions for the entire system in place.

6.4.3 Solid-Liquid Separation

As mentioned, many of the environmental impacts stemming from employing various solid-liquid separation techniques are realized downstream of the separation process; but for separation itself, our team would like to see more studies that combine various separation techniques, as well as cost-benefit analyses for different scenarios. Of the solid-liquid separation studies we gathered, just a single one (Provolo, 2013) took on the monumental task of profiling combinations of separation technologies. This study was performed in Italy, but we would like to see similar research take place in California's Central Valley or in other regions that have a Mediterranean climate.

6.4.4 Anaerobic Digestion

Future research is needed to better understand the environmental impacts of anaerobic digestion and biogas use on dairy farms. First, plug flow digesters and covered lagoons are systems are custom-designed for dairy farms. Therefore, in the future, an LCA similar to this should be completed that finds a way to standardize the different, customized technologies.

Additionally, although there are LCAs completed for the conversion of biogas to natural gas injection into pipelines, vehicle fuel, and electricity, these studies use municipal waste, swine manure, or co-digestible material as the biogas source. There is little to no research available regarding the environmental impacts of biogas utilization with the source of the biogas as dairy cattle manure. Due to the different impurities present in biogas of different sources, research of biogas utilization specific to dairy cattle manure must be conducted in the future to truly understand the impacts caused by biogas collection in dairy farms.

6.4.5 Compost

In general, compost could benefit by simply having more available studies. Beef cattle, swine, and poultry manure have many studies about compost, but California dairy farms have very few. Future compost research should include exact information about the composition of the compost such as percent solids, bulking material, and mass of the tested pile. Many studies are vague about the compost composition, which makes it difficult to calculate emissions when combined with other steps in the manure management process. For our analysis, we needed to know the exact amount of manure that contributed to each compost pile, but studies often did not specify. In addition, there are limited studies available that analyze dairy cow manure for composting; most studies use beef cattle, swine, or poultry manure. More available data from dairy cow manure would greatly benefit dairy farmers looking to implement this strategy.

7. Conclusion

Due to limited time and resources, our team was unable to touch upon all of the important aspects that impact sustainability at dairies. Due to this, we conclude with four future recommendations.

Firstly, moving toward the future, we place the highest priority on gathering further data on emissions produced by manure management technologies. This is because there are currently too many knowledge gaps and assumptions made in this area of study. Before mandating a specific technology to all farms, dairy farms should be required to collect emissions data and this should be accessible to all on a public database. This will allow farmers to estimate their baseline environmental impacts and produce more effective legislation.

Secondly, many of the technologies investigated are expensive. A detailed economic analysis of the various manure management technologies would complement our environmental impact analysis. Ultimately, dairies only adopt technologies that now or in the future improve their financial bottom line (unless mandated). As tempting as it is to ask dairy farmers to always put the environment first, this approach is both idealistic and naive; there are other pressing issues that drive decision-making at dairies on a daily basis. For many, dairies represent family businesses whose profitability severely affects the wellbeing of their owners, employees, and future generations. As students living in an entrenched metropolis, we are consistently cultured and tempted to drive regulations that prioritize the environment without hurting our wallets (i.e. higher milk prices). In doing so, we often neglect the interests of dairy producers and squeeze them to their last penny. It comes as no surprise that many dairymen and women feel victimized as a result of political action that is seemingly always directed toward putting consumers and the environment ahead of producers. The dairy industry requires policies that consider the interests of all stakeholders, including the environment -- a cost-benefit analysis of the manure management technologies we analyzed would go a long way toward encouraging policy directives that do so.

Thirdly, the results sometimes show that although one process may decrease CO2e emissions, it may increase its NH3 emissions as a consequence. It is necessary to first, find a way to standardize different emissions such as air emissions vs water quality impacts to allow for accurate comparison. Secondly, it is also required to prioritize the environmental emissions to be combatted.

Finally, to achieve a significant reduction of harmful environmental impacts stemming from dairies, it is also imperative to look at aspects beyond manure management. According to the Air Resources Board, enteric fermentation (i.e. flatulence) from dairies accounts for 20% of California methane emissions (CARB, 2017). Recently, several studies have explored the feasibility of altering diet to reduce enteric fermentation in lactating cows. Diet and nutrition, not included in this study, are key areas that deserves more attention. We recommend allocating grants and other resources toward studying how to reduce enteric fermentation, including an LCA that considers resulting manure composition of cows on various diets.

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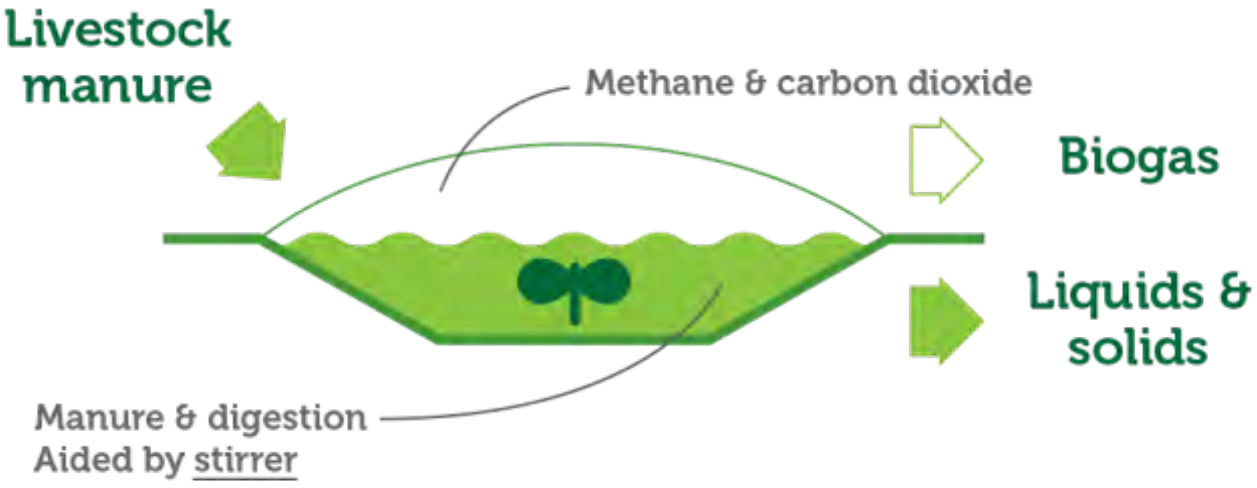

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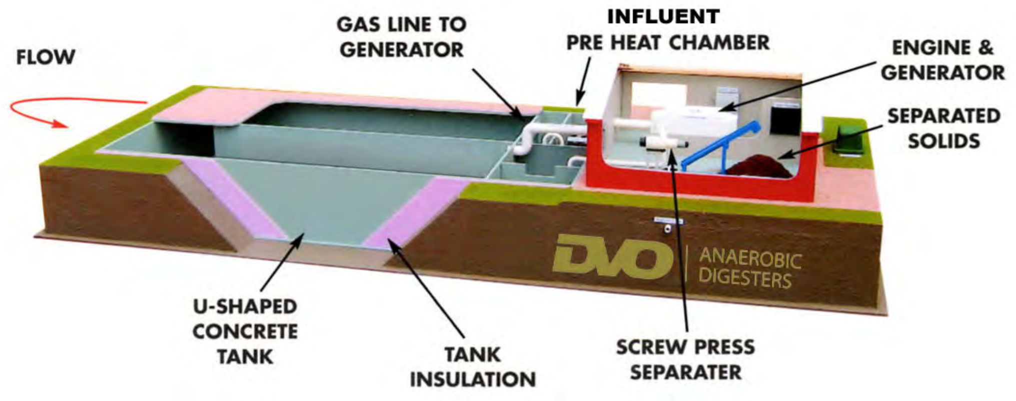

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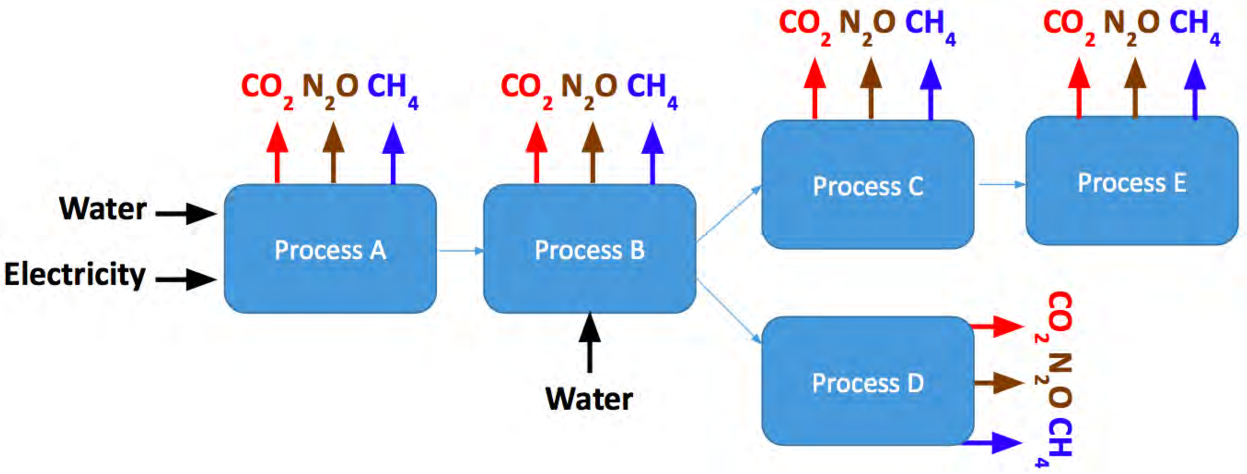

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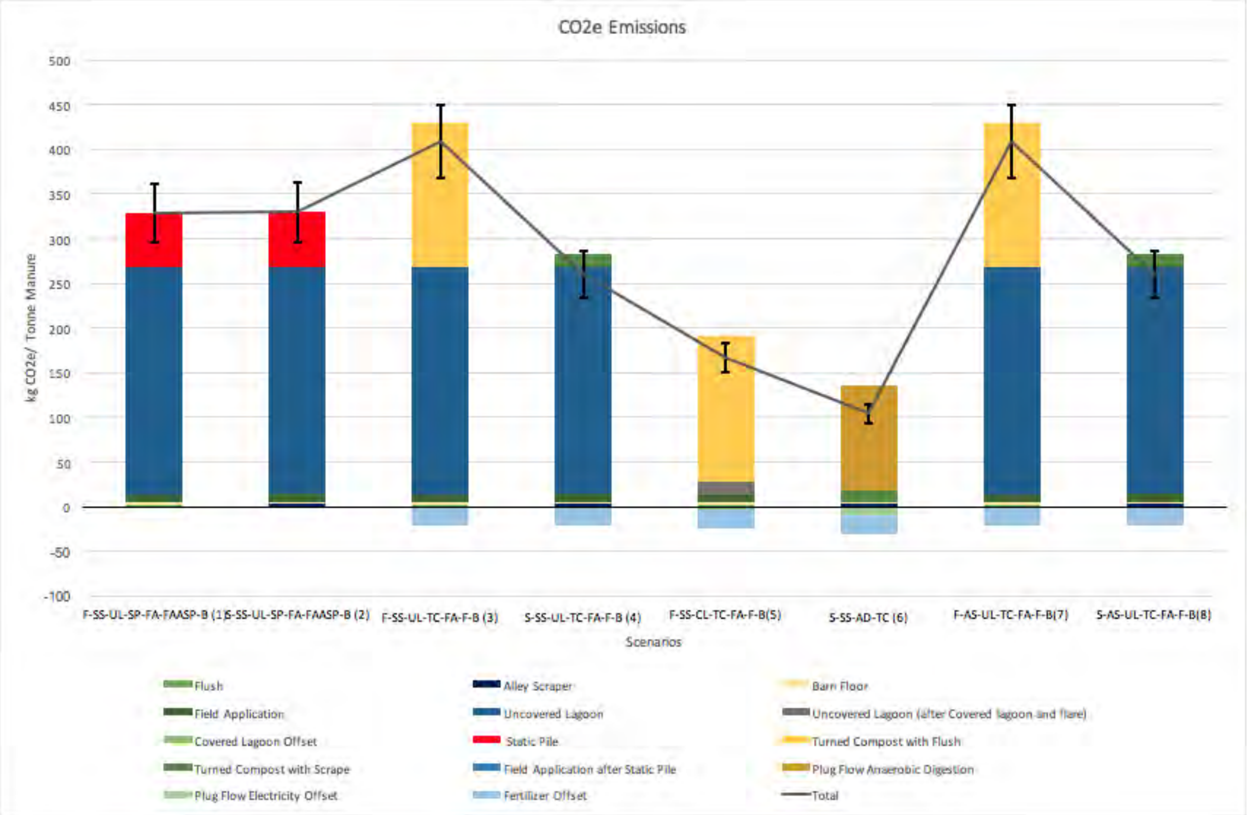

Figure 6: A graph representing the carbon dioxide equivalent emissions released by the eight (8) processes analyzed. The dark blue trendline displays the net emissions produced by each process after accounting for offset credits. Error bars are +/- 10% of the net emission.

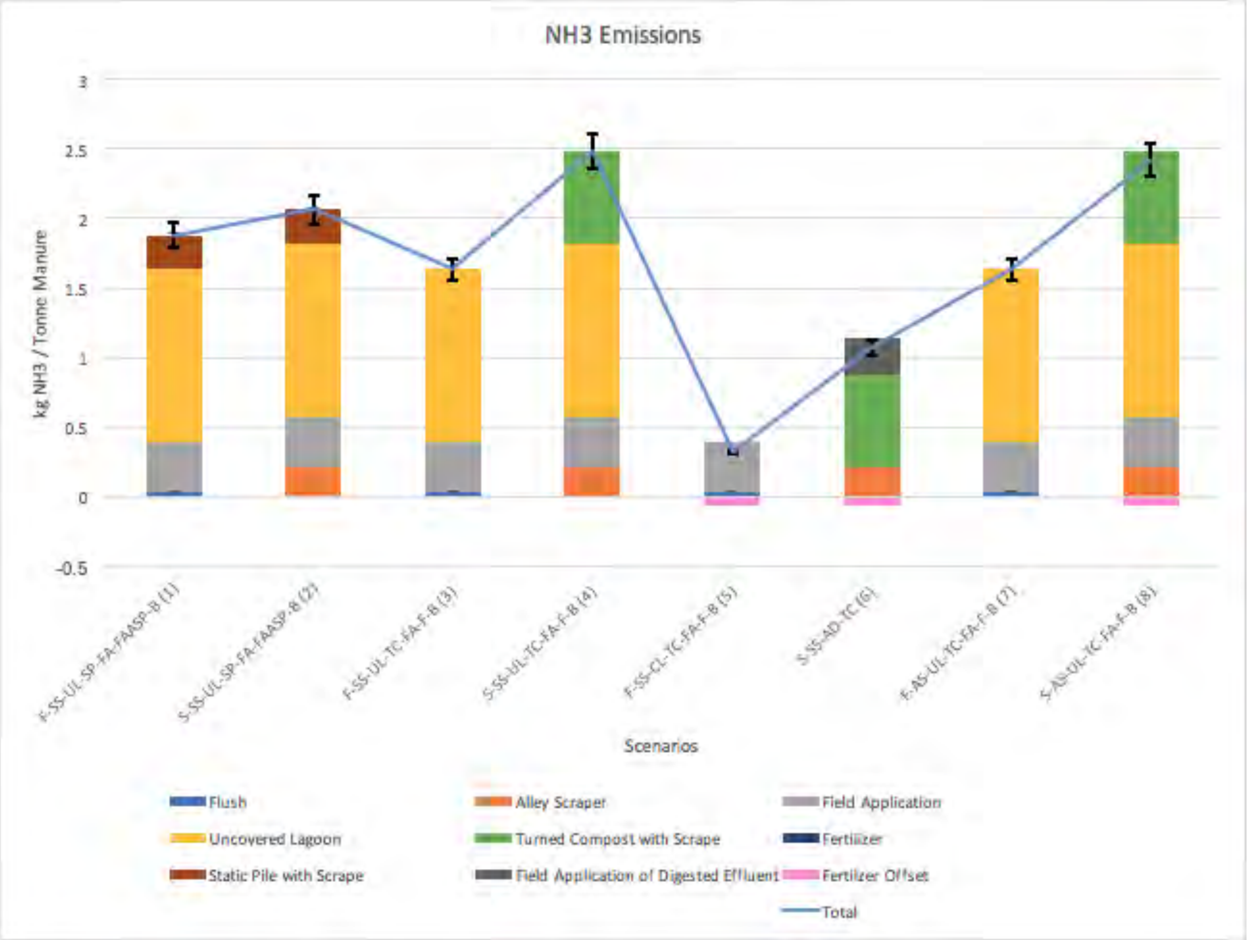

Figure 7: A graph representing the ammonia emissions released by the eight (8) processes analyzed. The blue trendline displays the net emissions produced by each process after accounting for offset credits. Error bars are +/- 10% of the net emission.

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Separation Efficiency			
Technology	**Dry Matter**	**Nitrogen**	**Phosphorous**
Stationary Inclined Screen	20-25%	4-7%	8-12%
Vibrating Screen	3-25%	2-7%	1-34%
Rotating Screen	4-24%	5-11%	3-9%
Screw Press Separator	13-64%	4-36%	3-28%
Sedimentation	8-12%		
Filtration & Chemical Separation	82%	52%	35%
Sedimentation	45%	20%	40%
Sedimentation & Chemical Separation	78%	40%	66%
Centrifugation	60%	29%	72%

Table 1: Separation efficiency by technology for each of dry matter, nitrogen, and phosphorous (Provolo, 2013).

Electricity Offsets

	Mix	g CO2e/kWh	Range	Weighted Average (g CO2e/kWh)
Coal	0.06	1050	660-1050	63
Large Hydro	0.054	11		0.594
NG	0.44	700	380–1000	308
Nuclear	0.092	19	3–35	1.748
Biomass	0.026	69	8.5–130	1.794
Geo	0.044	0		0
Small Hydro	0.009	0	2-20	0
Solar	0.06	100	13–190	6
Wind	0.082	22	3–41	1.804
Oil	0		530–900	0
				382.94

Table 2: Calculated California electricity mix emissions. (Nyberg, 2016)

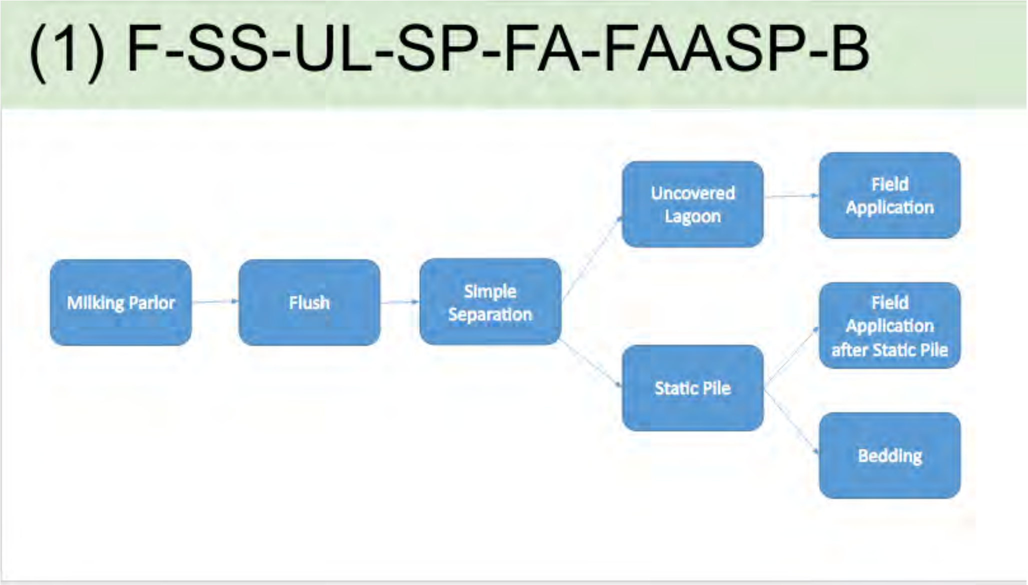
Appendix

Appendix: Legend

- S = Scrape
- ALS = Alley Scraper

- F = Flush
- SS = Simple Solid-Liquid Separation
- AS = Advanced Separation
- B = Bedding
- FA = Field Application
- FAASP = Field Application after Static Pile
- UL = Uncovered Lagoon
- CL = Covered Lagoon
- TC = Turned Compost
- FE = Fertilizer
- AD = Plug Flow Anaerobic Digestion
- MP = Milking Parlor
- FAODE = Field Application of Digested Effluent
- TCAF = Turned Compost After Flush
- TCAS = Turned Compost After Scrape
- ULACLF = Uncovered Lagoon After Covered Lagoon and Flare
- N/A = Not applicable

Appendix: Process Flow Diagrams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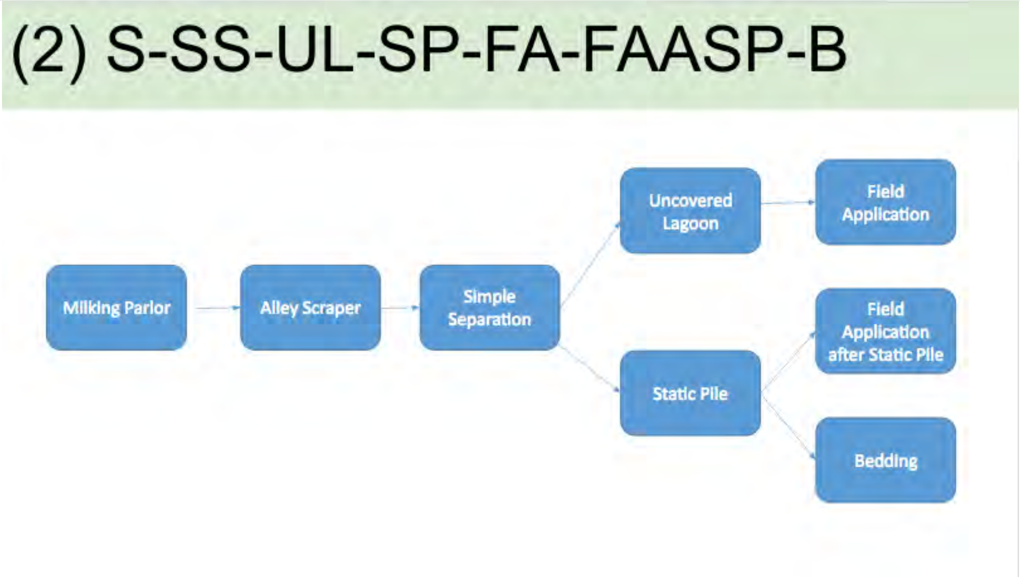
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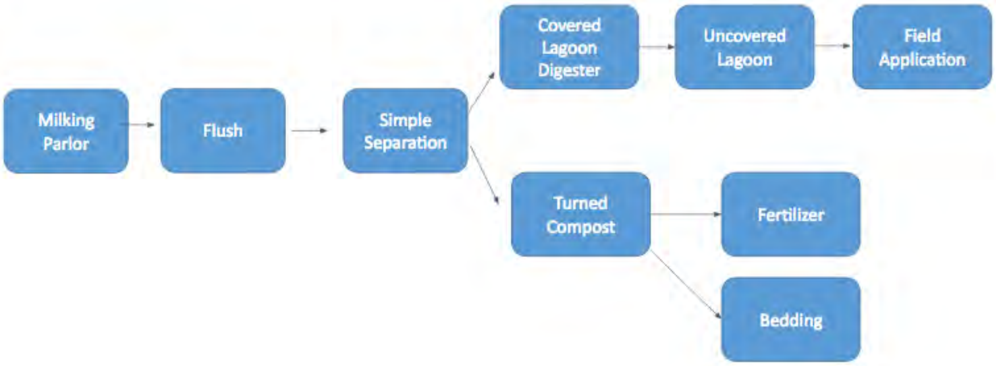
(5) F-SS-CL-TC-FA-FE-B



Milking Parlor

Flush

Simple Separation

Covered Lagoon Digester

Uncovered Lagoon

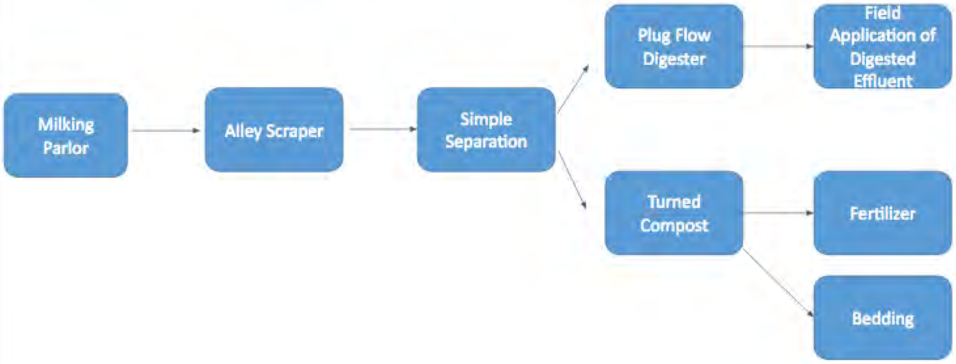
Field Application

Turned Compost

Fertilizer

Bedding

(6) S-SS-AD-TC - FAODE - FE - B



Milking Parlor

Alley Scraper

Simple Separation

Plug Flow Digester

Field Application of Digested Effluent

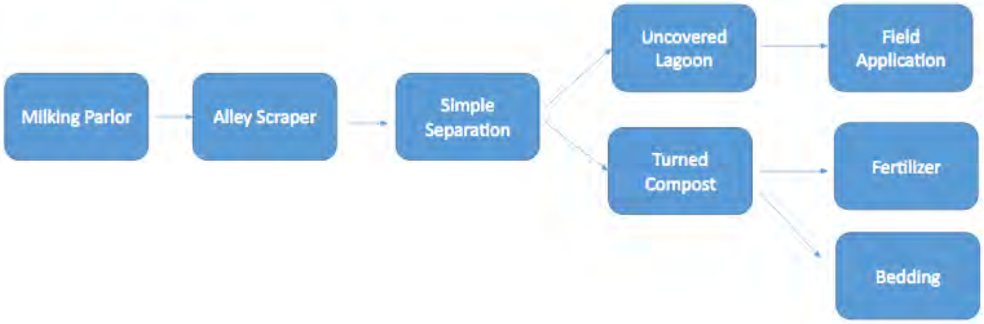
Turned Compost

Fertilizer

Bedding

(3) F-SS-UL-TC-FA-FE-B

(4) S-SS-UL-TC-FA-FE-B



Milking Parlor

Alley Scraper

Simple Separation

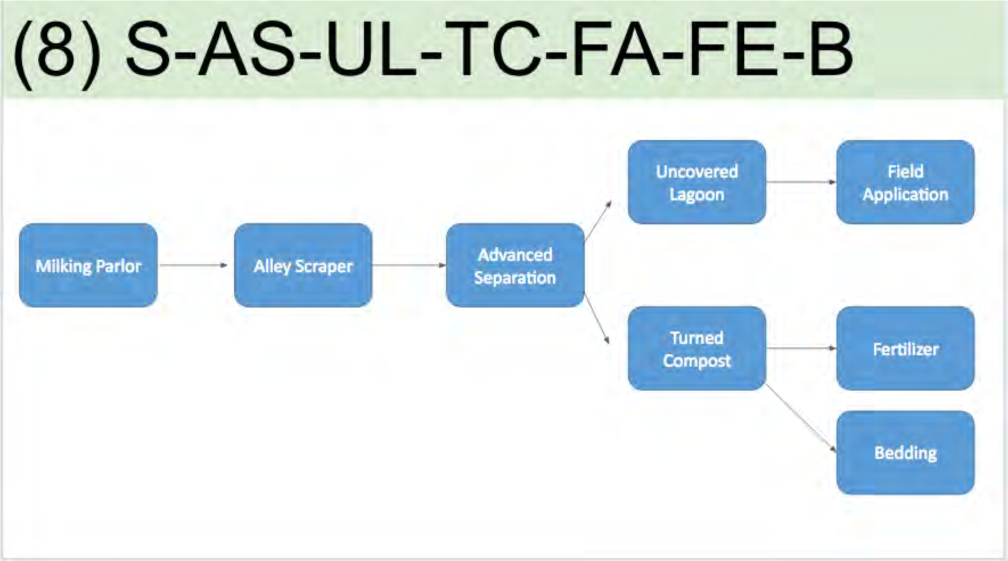
Uncovered Lagoon

Field Application

Turned Compost

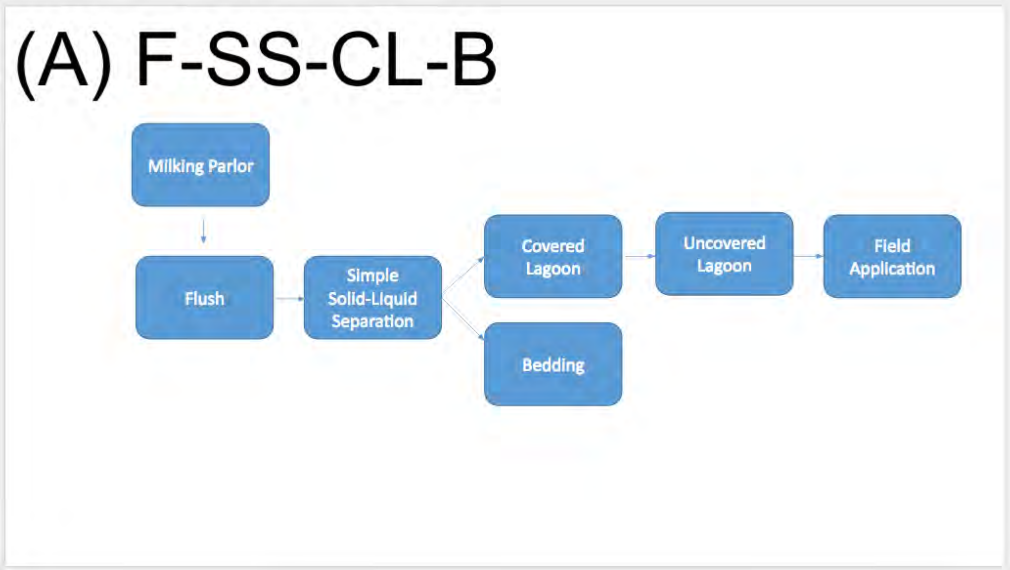
Fertilizer

Bedding



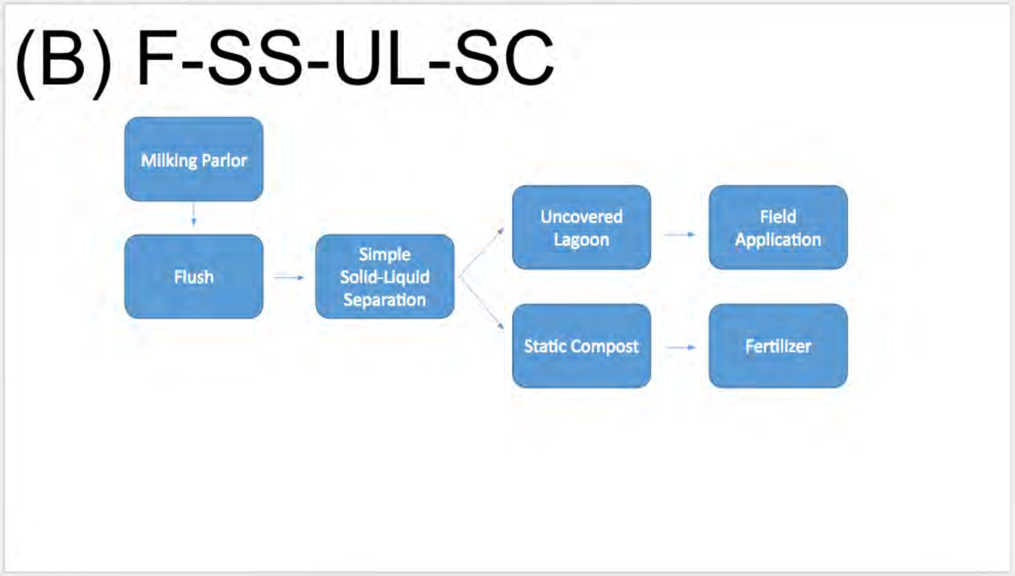
(8) S-AS-UL-TC-FA-FE-B

Milking Parlor
Alley Scraper
Advanced Separation
Uncovered Lagoon
Field Application
Turned Compost
Fertilizer
Bedding



(A) F-SS-CL-B

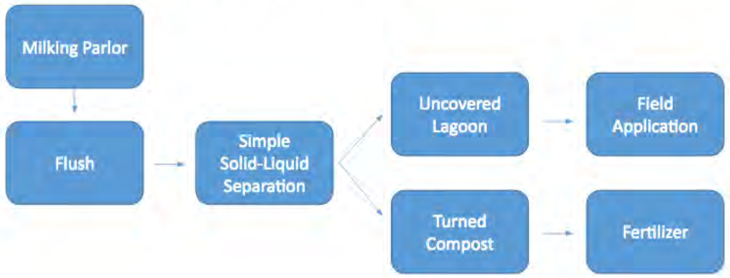
Milking Parlor
Flush
Simple Solid-Liquid Separation
Covered Lagoon
Uncovered Lagoon
Field Application
Bedding



(B) F-SS-UL-SC

Milking Parlor
Flush
Simple Solid-Liquid Separation
Uncovered Lagoon
Field Application
Static Compost
Fertilizer

(C) F-SS-UL-TC



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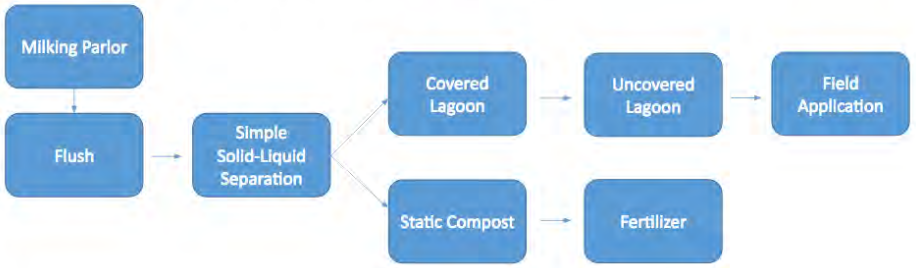

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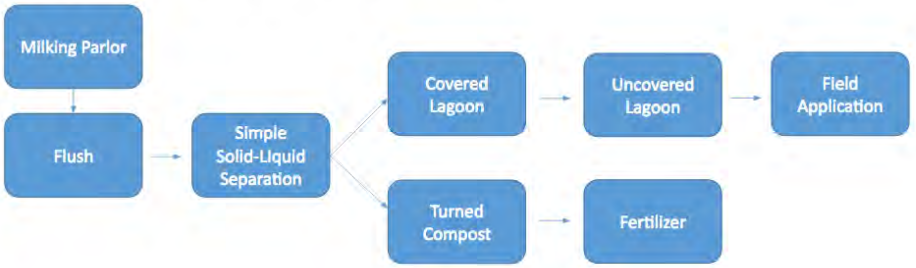
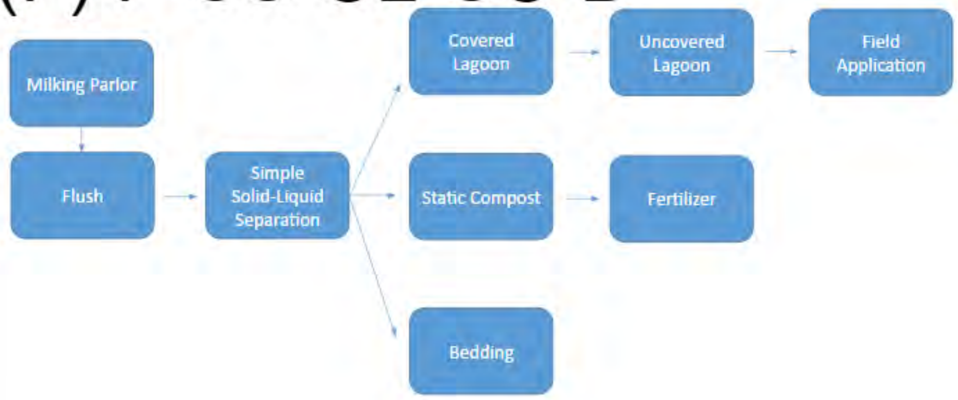
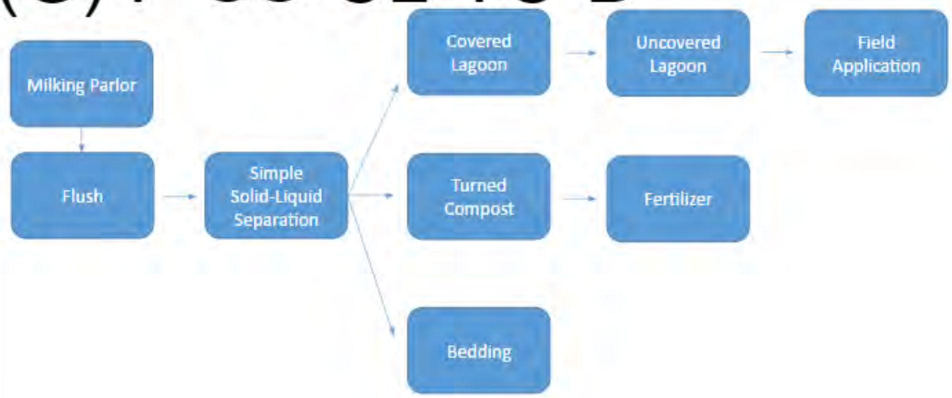


(F) F-SS-CL-SC-B

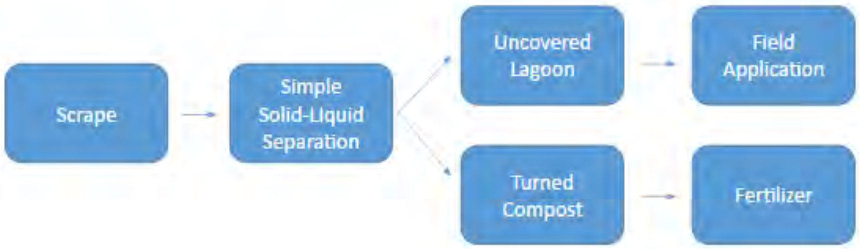


(G) F-SS-CL-TC-B

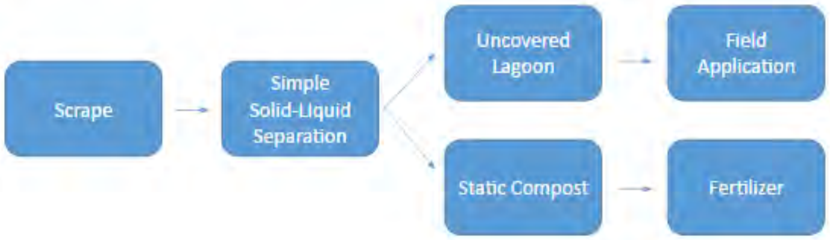


(H) S-SS-UL-B

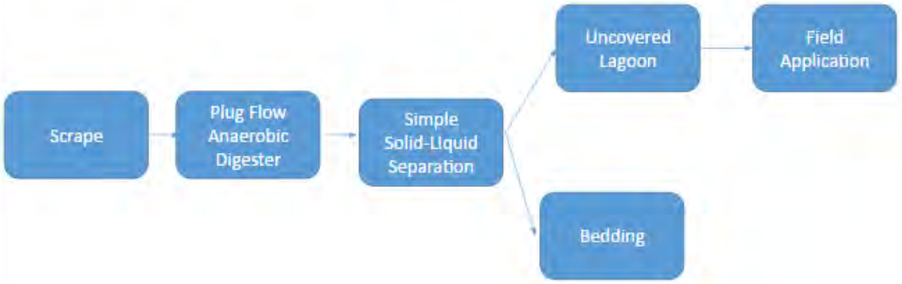
(I) S-SS-UL-TC



(J) S-SS-UL-SC



(K) S-AD-SS-UL-B



Appendix: Definitions

Alley Scraper

Alley scraper systems consist of a metal or rope cable chain, motor(s) powered by electricity to operate the cable or chain and thus pull or push the scraper, and a metal scraper wide enough to scrape an entire alley of manure with a rubber or metal blade edge that comes in contact with the floor

Centrifugation

A technique whereby a strong centrifugal force is used to separate and settle solid particles in a mixture.

Covered Lagoon

A type of anaerobic digestion process; a lagoon of manure covered by an impermeable cover. The anaerobic digestion produces biogas and a stable, nutrient-rich effluent.

Fertilizer

The finished compost product that can be used for feed crops on-site or transported off-site.

Field Application

Applying either the separated solids or liquids (irrigation) directly to the field without compost

Field Application After Static Pile

Applying the separated solids directly to the field after drying

Field Application of Digested Effluent

The mostly liquid (5.69% dry matter for the purpose of our project) outflow that is produced from a plug flow digester. Emission values represent emissions produced only from runoff and volatilization of effluent components, not the emissions produced from spreading the effluent onto the field.

Flush

Used to clear out manure from the flush lanes that run throughout the barns where the cows spend much of their day. Flush systems pump water into these lanes, which run between the barn stalls, and it then begins to flow out due to small one to four degree slopes designed into the floor

Milking Parlor

A room used for the mechanical milking of cows; present on all dairy farms. This process was used to represent the constant water consumption that will be used in this area.

Process

Each step within a scenario.

Scenario

A process flow diagram containing different processes that constitute a possible combination of technologies on a dairy farm.

Solid-Liquid Separation

A series of techniques that are used to separate raw manure slurry into solid and liquid fractions, each of which has different end-use functions.

Static Compost with Flush/Scrape

Compost generated from either separated solids or scraped manure, then formed into static piles that are aerated with fans or perforated pipes. Emission values represent emissions during the composting process.

Turned Compost with Flush/Scrape

Compost generated from either separated solids or scraped manure, then formed into windrows and mechanically mixed with a window turner. Emission values represent emissions during the composting process.

Uncovered Lagoon (unseparated slurry)

An in-ground lined pit that stores manure after it has been flushed from the barn floor, but is not separated.

Uncovered Lagoon

An in-ground lined pit that stores manure after it has been flushed from the barn floors and undergone solid-liquid separation

Appendix: Assumptions

Assumption	Why was the assumption needed?	Where is it relevant?	Source (if applicable)
120 lb/manure*cow*day	Necessary conversion factor	Calculations	http://articles.extension.org/pages/15476/liquid-manure-storage-ponds-pits-and-tanks
Dry matter content of excreted	Necessary conversion	Caclulations	http://msue.anr.msu.edu/uploads/

manure is 12.5%	factor		files/ManureCharacteristicsMWPS-18_1.pdf pg.3
For anaerobic digestion, flushed manure uses covered lagoons, whereas scraped manure plug flow digesters	To justify not creating neither a scenario with flush to plug flow digesters and nor one with scrape to covered lagoon	Process flow diagrams	http://www.sciencedirect.com/science/article/pii/S1537511014001329 https://www.researchgate.net/publication/49639489_Pile_mixing_increases_greenhouse_gas_emissions_during_composting_of_dairy_manure
The density of slurry and digested effluent are the same as water. 1kg/L	Necessary conversion factor, with no one consistent value. This assumption was used because both have a composition that is majority water.	Calculations	
Studies conducted on farms with approximately 1200 cows	This is the average size of dairy farms in California.	Calculations and Assumptions	https://www.cdfa.ca.gov/dairy/pdf/Annual/2016/2016_Statistics_Annual.pdf
Flush uses recycled water only.	We were unable to find how often freshwater is injected to dilute the constant reuse and increasing concentration of manure in lagoon water.	Process flow diagrams	
Compost was assumed to be 100% manure because of discrepancies within studies.	To standardize the compost emissions calculations into units of kg/tonne manure.	Emissions Calculations	
All technologies assumed to be in good condition--ex: no leakage of lined lagoon pits	To focus the scope of our study	Scope and Calculations	

Appendix: Calculations

Scrape Emissions

- **Electricity (Cell B2 of Master Spreadsheet):** Average of Automatic scraper (lying area) of Barn B3 [(94 Wh/ 1 cow*day) * (1 cow*day/ 120 lb manure) * (2204.62 lb manure/ 1 tonne)*(1 kwH/ 1000 wH) = 1.726 kWh/ tonne of manure] and B2 [(86 Wh/ 1 cow*day) * (1 cow*day/ 120 lb manure) * (2204.62 lb manure/ 1 tonne)*(1 kwH/ 1000 wH) = 1.726 kWh/ tonne of manure]= 1.652 kWh/ tonne of manure (Baldini, Ferrari & Rossi, p. 7)

- **CO_2e (Cell C4 of "Master Spreadsheet"):** Summation of CO_2, N_2O, and CH_4 values (see below).

- **CO_2 (Cell C5 of "Master Spreadsheet")** (1278 mg gas / m^2 hour) * (24 hour / 1 day) * (5.75 m^2 / cow) * (cow*day / 120 lb manure) * (2.204 lb/ 1kg) * (1 kg / .001 tonne manure) * (1 kg / 1000000 mg) = 3.239 kg CO2 / tonne of manure (Baldini, Borgonovo, Gardoni & Guarino, p. 65)

- **NH_3 (Cell C6 of "Master Spreadsheet"):** (237 g NH3/ton manure) * (1 ton manure/ 0.907185 tonnes of manure) * (1 kg/ 1000 g) = .214 kg NH3/ tonne of manure (Aguirre-Villegas, Larson, p. 176)

- **N_2O (Cell C7 of "Master Spreadsheet"):** (.28 mg gas / m^2 hour) * (24 hour / 1 day) * (5.75 m^2 / cow) * (cow*day / 120 lb manure) * (2.204 lb/ 1kg) * (1 kg / .001 tonne manure) * (1 kg / 1000000 mg) = 0.000709688 kg N2O / tonne of manure (Baldini et. al, p. 64)

- **CH_4 (Cell C8 of "Master Spreadsheet"):** (21.36 mg gas / m^2 hour) * (24 hour / 1 day) * (5.75 m^2 / cow) * (cow*day / 120 lb manure) * (2.204 lb/ 1kg) * (1 kg / .001 tonne manure) * (1 kg / 1000000 mg)= 0.054139056 kg CH4 / tonne of manure

Flush

- **Water (Cell D3 of "Master Spreadsheet"): (**750 gal water/cow/day) /(0.0544311 tonne/cow/day) = 13,778.9 (University of California, Davis, 2016).
- **CO_2 e. (Cell E4 of "Master Spreadsheet"):** CO_2 (1.594) + N_2O(0.0005kg/ tonne manure)+ CH_4 (0.0312)= 2.6 kg CO_2 e/ tonne manure (Baldini et al, 2016).
- **CO_2 (Cell F4 of "Master Spreadsheet"):** (604 mg/ m^2/ head CO_2)/(0.0544311 tonne/cow/day)= 1.594 kg CO_2/ tonne manure (Baldini et al, 2016).
- **NH_3 (Cell F5 of "Master Spreadsheet"):** (12.55 mg m^2/head NH_3)/(0.0544311 tonne/cow/day)= 0.033 kg NH_3 / tonne manure (Baldini et al, 2016).
- **N_2O (Cell F6 of "Master Spreadsheet"):** (0.19 mg /m^2/ head N_2O)/(0.0544311 tonne/cow/day)= 0.0005 kg N_2O/ tonne manure (Baldini et al, 2016).
- **CH_4 (Cell F6 of "Master Spreadsheet"):** (11.81 mg /m^2/ head CH_4)/(0.0544311 tonne/cow/day)= 0.0312 kg CH_4/ tonne manure (Baldini et al, 2016).

Inclined, Mechanical Separation (Simple)

- **Electricity (Cell J2 of “Master Spreadsheet”):** ((0.53 kWh/tonne manure) + (0.4 kWh/tonne manure + 0.8 kWh/tonne manure)/2)/2 = 0.575 kWh/tonne manure

Centrifugation (Advanced Separation)

- **Electricity (Cell L2 of “Master Spreadsheet”):** ((4 kWh/tonne manure) + (4.3 kWh/tonne manure + 7.3 kWh/tonne manure)/2)/2 = 5.65 kWh/tonne manure

Barn Floor

- **CO_2 e (Cell N4 of “Master Spreadsheet”):** (38 kg CO_2 e/head/year) *(1 year/365 days)/ (1 head = 0.0544311) = 1.9127 kg CO_2 e/ tonne manure (Owen et al, 2014).

Field Application

- **CO_2 e (Cell P4 of “Master Spreadsheet”):** (2.4 kg CO_2 e/tonne manure + 15.694 kg CO_2 e/tonne manure)/2 = 9.05 kg CO_2 e/tonne manure
- **NH_3 (Cell P6 of “Master Spreadsheet”):** (75.8 g NH_3 /tonne manure + 548.8 g NH_3 /tonne manure)/2 = 312.3 g NH_3 /tonne manure or 0.3123 kg NH_3 /tonne manure
- **N_2O (Cell P7 of “Master Spreadsheet”):** (6.4 g N_2O /m^3 manure) * (1 kg/1000g) * (1 m^3/993 kg) * (1000 kg/1 tonne) * (265 CO2 GWP/N20 GWP) = 1.71 kg CO_2 e/tonne manure
- **CH_4 (Cell P8 of “Master Spreadsheet”):** (0.0197 kg/m^3 manure) * (1 m^3/993 kg) * (1000 kg/1 tonne) * (28 CO2 GWP/CH4 GWP) = 0.555 kg CO_2 e/tonne manure

Uncovered Lagoon (Average of 4 studies)

- **(1) CO_2 e (Cell S4 of “Master Spreadsheet”):** (5.24 Mg CO_2 e/cow/year emitted)*(1000kg/Mg)*(1 year/ 365 days)*(1 cow/0.0544311 tonne manure) = 264 kg CO_2 e/ tonne manure (University of California, Davis, 2016).
- **(2) CO_2 e (Cell S4 of “Master Spreadsheet”):** (12,775 kg CO_2 e/head/year)*(1 year/365 days)*(1 cow/ 0.0544311 tonne manure)= 643 kg CO_2 e/cow/year (Owen et al, 2014).
- **(3) CO_2 e (Cell Q4 of “Master Spreadsheet”):** (41.29 kg CO_2 e/m^3 manure) * (993 kg/tonne manure) * (1 tonne/1000 kg) = 41.12 kg CO_2 e/tonne manure
- **(4) CO_2 e (Cell Q4 of “Master Spreadsheet”):** (66.351 kg CO_2 e/tonne manure) * (993 kg/tonne manure) * (1 tonne/1000 kg) = 65.9 kg CO_2 e/tonne manure)
- **(Average):** (264 kg CO_2 e/tonne manure + 643 kg CO_2 e/tonne manure + 41.12 kg CO_2 e/tonne manure + 65.9 kg CO_2 e/tonne manure)/4= 254 kg CO_2 e/tonne manure

Uncovered Lagoon After Covered Lagoon and Flare

- **CO_2 e (Cell W4 of “Master Spreadsheet”):** ((4.95 Mg CO_2 e/ cow/year mitigated)/(5.24 Mg CO_2 e/cow/year emitted)) = 0.94*(uncovered lagoon emissions=254 kgCO_2 e/tonne manure)= 239.39 kg saved/tonne manure. 254-239.39 = 14.61 kgCO_2 e/ tonne manure (University of California, Davis, 2016).

Covered Lagoon

- **Electricity Generation (Cell Y14 of "Master Spreadsheet"):** Gallo Farms 1.4MWh/3200 cows
    - 3200 cows*(120lb/cow)*(1ton/2204.62lb)=174.18tons
    - 1400 kWh/174.18=8.04 kWh/tonne manure
- **CO_2 e offset (Cell Z4 of "Master Spreadsheet"): (**8.04 kWh/tonne manure) * (0.38294 kg CO_2 e/ kWh for standard California mix of electricity generation)= 3.08 kg CO_2 e/ tonne manure offset (Nyberg, 2016)

Turned Compost with Flush

- **Electricity (Cell AC2 of Master Spreadsheet):** (Front-end loader: 0.33 kWh/ incoming Mg) + (Windrow turner: 0.24 kWh/Mg)= 0.57 kWh/tonne manure (Levis and Barlaz 2013)

- **Water (Cell AC3 of "Master Spreadsheet"):** (900 gallons of water added to compost windrow)/(46 tons of manure per windrow)=19.5 gallons/tonne manure (Michel et al. 2003)

- **CO_2e (Cell AC4 of "Master Spreadsheet"):** Summation of CO_2, N_2O, and CH_4 values (see below).

- **CO_2 (Cell AC5 of "Master Spreadsheet":** Average of two studies. (156 kg CO_2e/1200 kg manure)/1.2=130 kg CO_2e/tonne manure (Ahn 2011). (105 kg CO_2e/900 kg manure)*1.1=116.7kg CO_2e/tonne manure (Mulbry 2014). (130+116.7)/2=123.35 kg CO_2e/tonne manure

- **N_2O (Cell AC7 of "Master Spreadsheet"):** Average of two studies. (8.7 kg CO_2e/1200 kg manure)/1.2=7.25 kg CO_2e/tonne manure (Ahn 2011). (13.3 kg CO_2e/900 kg manure)*1.1=14.4 kg CO_2e/tonne manure (Mulbry 2014). (8.7+14.4)/2=10.835 kg CO_2e/tonne manure

- **CH_4 (Cell AC8 of "Master Spreadsheet"):** Average of two studies. (44 kg CO2e/1200 kg manure)/1.2=36.6 kg CO2e/tonne manure (Ahn 2011). (19 kg CO2e/900 kg manure)*1.1=21.1 kg CO2e/tonne manure (Mulbry 2014). (130+116.7)/2=28.9 kg CO2e/tonne manure

Turned Compost with Scrape

- **Electricity (Cell AG2 of Master Spreadsheet):** (Front-end loader: 0.33 kWh/ incoming Mg) + (Windrow turner: 0.24 kWh/Mg)= 0.57 kWh/tonne manure (Levis and Barlaz 2013)

- **Water (Cell AG3 of "Master Spreadsheet"):** (900 gallons of water added to compost windrow)/(46 tons of manure per windrow)=19.5 gallons/tonne manure (Michel et al. 2003)

- **CO_2e (Cell AG4 of "Master Spreadsheet"):** Summation of CO_2, N_2O, and CH_4 values (see below).

- **NH_3 (Cell AG6 of "Master Spreadsheet"):** (670.5 g NH3/tonne manure)*(1kg/1000g) = .67 kg NH3/tonne manure (Amon 2001).

- **N_2O (Cell AG7 of "Master Spreadsheet"):** Value taken from Amon et al. 2001. Table 9.

- **CH_4 (Cell AG8 of "Master Spreadsheet"):** Value taken from Amon et al. 2001. Table 9.

Fertilizer

- **NH_3 (Cell AE6 of "Master Spreadsheet"):** No ammonia emissions after spreading the fertilizer on the field (Amon 2001).

Fertilizer Offset

- **CO_2e (Cell AF4 of "Master Spreadsheet"):** (1589.76 kg CO_2 e/tonne manure) * (0.12 g solids/1 g slurry) * 0.5 (effectiveness of dairy-made fertilizer compared to industry-grade) * 0.2275 (separation of solids in raw slurry from solid-liquid separation) = 21.70 kg CO_2 e/tonne manure

- **NH_3 (Cell AF7 of "Master Spreadsheet"):** (19.6 g NH_3 /300 kg fertilizer) * 3.33*(1kg/1000g) = .065 kg NH_3 /tonne manure

Plug Flow Anaerobic Digestion

- **Electricity Generation (Cell AK14 of "Master Spreadsheet"):** (1.4 kWh/day/cow) /(0.0544311 tonne manure/cow/day) = 25.7 kWh/tonne manure (Artrip et al, 2013).
- **CO_2 e (Cell AL4 of "Master Spreadsheet"):**
    - (5926 kg CO_2 e/cow/year)*(1 year/365 days)/ (0.0544311 tonne manure/cow/day) = 157.49 kg CO_2 e/ tonne manure (Artrip et al, 2013).
    - (3129 kg CO_2 e/cow/year)*(1 year/365 days)/ (0.0544311 tonne manure/cow/day) = 76.56 kg CO_2 e/ tonne manure (Artrip et al, 2013).
    - (157.49 kg + 76.56 kg CO_2 e/ tonne manure)/2 = 117.025 76.56 kg CO_2 e/ tonne manure (Artrip et al, 2013).

Plug Flow Anaerobic Digestion Electricity Offset

- **CO_2 e offset (Cell AN4 of "Master Spreadsheet"):** (25.7 kWh/tonne manure) *(0.38294 kg CO_2 e/ kWh for standard California mix of electricity generation)= 9.84 kg CO_2 e/ tonne manure (Nyberg, 2016).

Field Application of Digested Effluent

Calculation of the mass balance multiplier that applies for digested effluent N & P emissions:

  - ○ (7.6kg solid/cow*day)/(0.0544311 tonne manure/cow*day)*100=13.97% solids in influent manure (Martin, 2005)
  - ○ (56900mg solids/L effluent)*(1 L effluent/1 kg effluent)*(kg/1,000,000mg) *100=5.69% solids in digested effluent (Martin, 2005)
  - ○ (13.97%/5.69%)=2.455

- **NH3 (Cell AO7 of "Master Spreadsheet"):** (271mgNH3/kg manure)*(1000kg/1 tonne manure)*(1kg/1000,000mg) =0.271kgNH3/tonne manure (Holly et.al., 2017)
- **N Runoff (Cell AO14 of "Master Spreadsheet"):** 1135mg Organic N/L effluent*(1L effluent/1kg effluent)*(1kg/1,000,000mg) *(2.455)*(1000kg manure/1 tonne manure)*(0.008)=0.022kg N runoff/tonne manure (California Air Resources Board, 2016 & Martin, 2005)
- **P Runoff (Cell AO12 of "Master Spreadsheet"):** 715mg Organic P/L effluent***(**1 L effluent/1kg effluent)*(1kg/1,000,000mg) *(2.455)*(1000kg/manure/1 tonne manure) *(0.008)=0.014kg P runoff/tonne manure (California Air Resources Board, 2016 & Martin, 2005)